Active Distributed Power Systems

Functional Structures for Real-Time Operation of Sustainable Energy Systems

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To Birgitta, Jenny and Jesper

Abstract

Present power system will face great challenges in several areas depending on the market economy, extensive global integration and constant need for more electric power, which will force the system to operate much closer to its stability limits. Meeting these challenges may involve improving and complementing or even total restructuring of the power systems.

New technologies are emerging such as renewable energy sources (RES) and power electronics, which in combination with information and automation will give opportunities to provide a number of services to the market. Market based operation may become a reality, where the management mechanism from contract to physical power transaction might get faster or even automated that could be an important advantage for renewable energy sources. Although, as several new generation units will be distributed and in same cases close to the consumption, local subsystems or distributed power systems would probably emerge to increase system reliability. Distributed power systems will function similarly to the present power system except for being down scaled and based on a high degree of automated functions. In such case the power system would in normal conditions still work similarly to present system where all distributed power systems are merged together. Only under special circumstances would affected distributed power systems disconnect, and later on, when appropriate, reconnect. In the meantime the individual distributed power system will run in "stand-alone" mode.

The thesis focus is related to real-time operation and control where a general information and functional structure for active distributed power systems has been studied. The structure is intended to provide future distributed power systems with a high degree in modularity, scalability, adaptability and autonomic behaviour enabling "plug-and-produce". Fundamental relations and principles are investigated as well as operation

and strategy methods enabling autonomous operation of the systems. The basic solution is made by down-scaling the common centralized structure for operating a power system to several active distributed power systems that interact by well-defined hardware and software interfaces.

In order to coordinate the system operation of active distributed power systems in real-time, a principal structure for distributed energy management system and information enabling market-based operation of renewable power sources is studied and adopted. Distributed functions for automated operation of various system configurations have been investigated to be able to automatically add and remove functionality due to changes in system configurations. The structure provides the means for condensing the necessary information for future needs on operation of new large RES (e.g. offshore wind power plants). The structure facilitates the expansion of new small RES (e.g. roof assembled solar power plants), where a new power unit is able to connect to an existing structure and then automatically adapt to the system.

Well-defined system information and communication are necessary for the functioning of real-time operation. A part of the work includes studies on uniformed information and communication structures for different levels of communication, ranging from process- to market level communication. Although, most focus has been on the operational structure layer including several signals enabling the management of common generation units as well as intermittent power units such as RES.

The information and functional structure is partly implemented in C++ modules and partly in the Dymola/Modelica simulation tool. Verifications are made both by simulation models and in a laboratory set-up. The verifications are performed for various system configurations where the simulation results agree with the experimental results.

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Abbreviations

AGC	Automatic generation control
APC	Automatic primary control
ASC	Automatic secondary control
ASM	Ancillary service market
ATC	Available transfer capacity
AVC	Automatic voltage control
BAM	Balance adjustment market
BD	Breaker device
BMU	Breaker and measurement unit
BRM	Balance regulation market
BSM	Balance settlement market
BU	Breaker unit
CF	Communication flow
CI	Communication interface
CM	Command management
CN	Communication network or node
CU	Control unit
DAB	Double active bridge
DCS	Distributed control system
DEMS	Distributed EMS
DG	Distributed generation
DM	Data management
DMS	Distributed management system

DPS	Distributed power system
EBA	Energy balance authority
EM	Error management
EMS	Energy management system
ESO	Exchange system operator
EU	Power exchange unit
EUa	Active power exchange unit
FACTS	Flexible AC transmission system
FDDI	Fiber distributed data interface
GB	Group block
GD	Generation dispatch
GM	Govern management
GSO	Generation system operator
GU	Power generation unit
GUa	Active power generation unit
HPP	Hydro power plant
HPS	Hybrid power system
HVDC	High voltage direct current
IA	Interchange Authority
IGBT	Insulated gate bipolar transistor
IPR	Intelligent power router
ISO	International standardisation organisation
LAN	Local area network
LD	Load device
LSO	Load system operator
LU	Power load unit
LUa	Active power load unit
LVDC	Low voltage direct current
MB	Management block
MCP	Market clearing price
MM	Market management

MMO	Market management organisation
MPPT	Maximum power point tracker
MTU	Multi terminal unit
MTUa	Active multi terminal unit
MVDC	Medium voltage direct current
NIU	Network interconnection units
NPP	Nuclear power plant
NU	Power transmission network unit
NUa	Active power transmission network unit
OA	Operational authority
OB	Object block
OCI	Operational communication interface
OPF	Optimal power flow
OSI	Operational signal index
PBA	Power balance authority
PE	Production exchange management
PEM	Proton exchange membrane
PF	Power flow
PI	Power interface
PLC	Programmable logic controller
PM	Production management
PMSM	Permanent magnet synchronous machine
PN	Power node
PRU	Power resource unit
PV	Photovoltaic
PWM	Pulse width modulation
RES	Renewable energy source
RM	Resource manager
RRM	Reserve resource management
RTDB	Real-time data base
SA	Security authority

SAF	System analysis function
SB	System block
SBI	Signal block identity
SBGI	Signal block group identity
SBGT	Signal block group type
SBT	Signal block type
SCADA	Supervisory control and data acquisition systems
SC	System control
SCC	System control center
SCI	Safety communication interface
SE	Simulation environments
SI	Signal index
SID	Signal identity
SiU	Sink unit
SO	System operator
SOC	State of charge
SoU	Source unit
SMES	Superconducting magnetic energy storage
SM	System management
SMS	Specific management systems
SPM	Set point management
SSO	Storage system operator
SSU	Source and sink unit
ST	Signal type
SU	Power storage unit
SUa	Active power storage unit
SZ	Safety zone
TCI	Trading communication interface
TGB	Turbine group block
TM	Transaction identity management
TSO	Transmission system operator

TU	Terminal unit
TUa	Active terminal unit
UC	Unit commitment
UCF	Unit commitment/coordinator function
UM	Unit management
UPS	Uninterruptible power supply
VSC	Voltage source converter
WPP	Wind power plant
WPSB	Wind power system block
WT	Wind turbine
WTC	Wind turbine control
ZPM	Zone protection management

Contents

Chapter 1

Introduction

The power system of today has been working rather admirably during the past half century. The system is built on well-known technology that has its advantages in a simple and robust structure that now faces great challenges in several areas described in the thesis background.

Meeting these challenges might involve improving and complementing or total restructuring of existing power systems. A takeoff with a future scenario primarily focused from a control point of view with expectations on a high penetration of information systems is discussed in the thesis motivation.

The thesis proposes a solution including information and functional structure for distributed power systems with the intention to handle the likely large extension of renewable energy sources and at the same time increase reliability. This is in general discussed and described in the second half of the chapter.

1.1 Background

Electricity is the most valuable form of energy and is essential for the development of civilisation. There is a strong correlation between quality of life and the use of electricity up to a rather high level of use. The major amount of electricity is being generated by means of fossil, hydro and nuclear energy. The population growth and the fact that only a part of the world's population is benefiting from electricity will increase the energy consumption considerably. Future growing demand will dramatically

increase the need for power generation and transmission, primarily due to those not yet supplied with electricity.

The consumption of fossil fuels for the generation of power is most likely one of the major causes of air pollution and global warming. Future electricity demands, by means of conventional electricity power supply systems, would cover a massive increase of emissions of carbon-dioxide and other pollutants to the atmosphere or be disturbed by other global risks and coming problems with lack of resources of oil and natural gas. The issue of global climate change is gaining greater salience in the scientific community. There now appears to be a consensus between the world's leading environmental scientists and informed individuals in the energy and environmental communities, that there is obvious human influence on the climate. Due to environmental influence and present draining of energy resources, the main purpose in the long term has to be a sustainable power system based on a high penetration of renewable energy sources (RES).

Consensus with the political forces and other forces in the society has a vital impact on power supplier's intention to invest in RESs. The environmental advantages with sustainable power system have caused many countries support integration and extension with government-backed incentives. The aim of these has been to stimulate the market, reduce costs and compensate for the unfair advantage currently held by conventional fuels, for example through state subsidies. A range of market stimulation mechanisms has been used in different countries. Traditional power system has a stochastic behaviour in consumption and almost deterministic behaviour in production. A high extension of RESs will gradually change the power systems to systems with highly stochastic behaviour in both production and consumption.

Regarding global integration, the trend points at new transmission lines/cables interconnecting a larger number of control areas. In the long term, it might end up in one entire power system covering all nations over the world. This will however increase system vulnerability and endanger

the reliability substantially if the functionality and controllability of present and forthcoming power systems are not increased simultaneous.

The ability of an electrical power system to maintain the balance of electric power and energy required by the customers under normal and abnormal conditions becomes even more complex with the deregulation in the power market. As a consequence of the deregulation the competition among the suppliers is growing while the power reserve margins are decreasing. This generates a tendency toward greater values of expected power and energy not supplied. The cost value, which the customers are willing to assess for energy expected by them but not supplied, is getting smaller. Consequently, the expected daily power balance may not be met due to the central electricity power reserve supply system is presently decreasing. The need to improve the electrical power system regarding reliability, maintainability and maintenance will probably increase to meet the customer's requirements. It is therefore important for the power suppliers as well as for the power users receiving and paying the electricity, to find an optimal compromise between lowering the risk of power failure and increasing the cost of building and operating a proper energy supply system that is sustainable.

1.2 Challenges and motivations

The power systems stand before huge challenges regarding impact on system reliability, which are described in Chapter 2 and briefly characterized as follow:

- *RES expansion*: The growing need for electricity in combination with environmental issues will force the expansion of sustainable power units and among them RES. The various RESs (solar, wind and hydro power) will be in a wide range of capacities and consequently increase distributed generation (DG), especially when solar power units become cost-effective. The expansion of RES will gradually change the power system to systems with highly stochastic behaviour in both production

and consumption, which eventually will have a large impact on the power balance.

- *Global integration*: The power systems are the largest and most complex interconnected systems of the technological age. With global integration this will expand even more. The global integration has so far lead to a higher utilization degree of primary and disturbance resources, which bring that the power systems are more close to their limits stability.

- *DC integration*: The global integration will contribute to the expansion of several DC interconnections at high voltage levels between nations. As DC technology develops the DC systems may be integrated at every voltage level down to the end user. Depending on usage the DC integration may support or weaken the power system.

- *Market and power system interaction*: Several new actors and markets will emerge where RESs probably would be fully integrated into the energy and ancillary service markets. Market based operation may become a reality, where the management mechanism from contract to physical power transaction need to get faster or even automated.

- *System operation*: Market actors will always strive for maximal profits that will lead to a high utilization degree of operational margins. The system operators must ensure controllable power units for both primary and secondary control. A continuously optimisation and coordination of the available controllable power units will be needed.

Meeting the challenges will require several areas of research to be investigated where some are considered here. The expectation is that the exploit of advanced technologies will change or transform the power system from a passive to a more active system where real-time information and automated functions will be necessary in order to increase system reliability. Future electric infrastructure will most certainly include self-healing transmission and distribution systems capable of automatically predicting and responding to disturbances, while continually optimising its own performance. This will be critical to meet the future electricity needs of an increasingly power exchange at several voltage levels.

The work presented is motivated by a future need of active DPSs with "stand-alone" and "plug-and-produce" functionalities as shown in Figure 1.1 where the transmission and distribution networks are regarded as separate subsystems including distributed controllable power units based on RESs. The DPS has to negotiate exchange of power with distributed

power units and adjacent DPSs. Appropriated controllable power units are needed to control the power exchange and manage the operation. Faults need to be managed and isolated within a DPS area so that the effect will not propagate to other DPSs where "stand-alone" operation is available as an emergency condition. The integration of distributed power units will make it possible to support the reliability of the system in emergency situations. RES and DG, especially those built on power electronic technology, will enable local services (primary and secondary control).
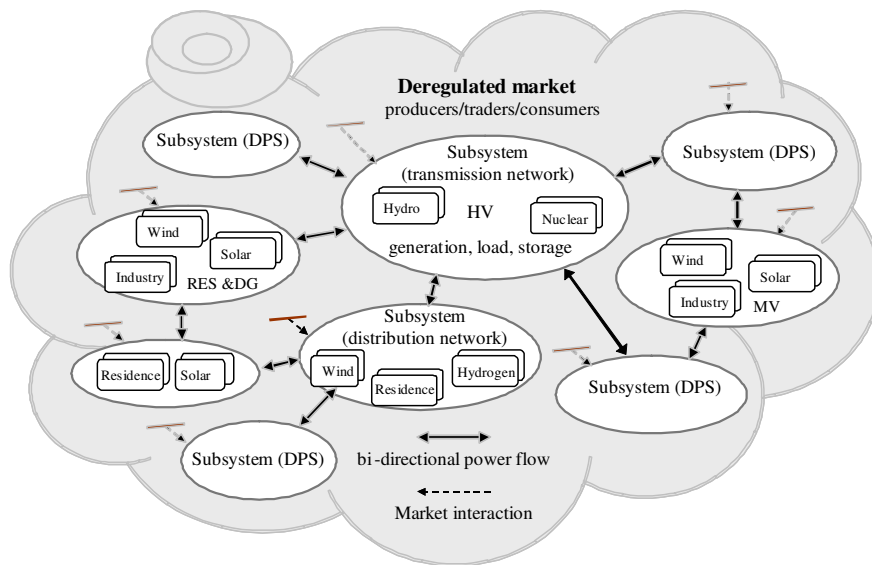
Figure 1.1: General power system based on several subsystems or distributed power systems (DPS).

Depending on voltage level, controllable power units will increase or decrease more or less frequent. For example at low voltage (e.g. solar power integrated in buildings) small distributed power units will be frequently connected and disconnected. This will put needs on the "plug-and-produce" functionality as the information will grow huge and not possible to manage manually at each new interconnection event for interaction. The integration of DG/RES and other power units need to automatically adapt to the system, which requires an active transmission and distribution network that have a high degree of automated coordination functions and well-defined interfaces for communication.

The large-scale and real-time distributed control requirements of the power system will increasingly challenge the state of the art in transmission and distribution system management. System operators will not be able to respond quickly enough to detect and correct problems of a DPS. One major challenge will be in replacing actors within the EMS organisation of generation, transmission and load managers. The tasks of these roles will, to a certain degree, be automated and responsible personal will only modify strategy constrains and limits to influence the directions in the automated decision-making for acting both toward the market and toward controllable power units. Once the technology and infrastructure are in place enabling communication and power to be transmitted bi-directionally over electric utility power distribution lines, the need for constant monitoring in real-time, on-line mode and other communications media will be needed. A complex information system is required to support the automated operation and control functions of an active DPS. Communication links are needed to transmit information between control centre locations. Technically, from being a limiting factor, the increasing communication capacity would provide possibilities for operating the DPSs in a different and more efficient way.

1.3 Objectives

The focus of this work is related to distributed real-time operation and control of power systems where the main objective is to develop a general information and functional structure for active distributed power systems (DPS). The intention is that the structure should provide future DPSs with a high degree in modularity, scalability, adaptability and autonomic behaviour enabling "plug-and-produce" and at the same time means for improved security and reliability. Consequently, the DPS should be able to manage a high penetration of renewable energy sources (RES) where the aim is to coordinate the operation between various power units in real-time. Fundamental relations and principles will be studied as well as operation and strategy methods enabling autonomous operation of the DPSs.

1.4 Contributions

The contributions of this applied research work are given in Chapter 3 to 9 and concluded in Chapter 10. The thesis is focused on a combination of distributed power systems (DPS), of renewable energy sources (RES), and, of system automation.

- The developed and investigated DPS structure has proven capable of adding and removing power units during operation.

- This includes a well functioning operating interface between power units (source as well as sink) and DPSs allowing seamless transitions when disconnecting or reconnecting from an adjacent DPS.

- DPSs based on power electronic converter technology enhance the control capabilities of distributed generation.

The potential of RESs, mainly wind power, is improved. It is proved that the controllability of wind power, especially with embedded power electronics, is more responsive than any other present generation unit according to system configuration and technology.

- Depending on the type of controllable power units in a specific control area, the wind power units are able to participate in both primary and secondary control.

For managing the coordination of the power units, a distributed energy management system structure has been developed including advanced programming modules for analysing, coordination and unit commitment.

- The structure is distributed and includes automated functions for "stand-alone" operation of various system configurations, and is able to automatically add and remove functionality due to changes in system configurations.

- The possibilities for analysing and controlling a system are very depending on the information available and on its structure.

Consequently, a part of the work has included the development of an information and communication structure, containing uniform communication interfaces. The information structure has been studied for different levels of communication, ranging from process- to market level communication. Although, most focus has been on the operational structure layer including several signals enabling the management of traditional generation units as well power units based on RESs. This has proven essential in achieving something close to "plug-and-produce".

The work has resulted in a module library including a number of different object oriented modules integrated for performing specific tasks at various levels.

- All signal management and central functions for coordinating power units are implemented in the module library and a general dynamic data and resource management system has been developed and included in the structure, which is the foundation for enabling "plug-and-produce".

- Simulation models have been developed with advanced controller structures in the time scale 0.1-1 seconds, where different energy sources have been investigated and modeled.

This work also resulted in several model libraries ranging from signal level to complete power systems.

- The software modules and simulation model library have been important when analysing and verifying various system configuration and structures.

A laboratory set-up was designed to verify the information structure and the automated management of various system configurations.

The test results proved that the structure responded the requested demands including the adding and removing of power units during operation, which corresponds to the capabilities of "stand-alone" and "plug-and-produce".

1.5 Outline of the thesis

The basis of this thesis and the academic work is presented in Chapter 1 where the description of a future possible migration to a complete automated power system is included. In Chapter 2, an overview of present power system ranging from process level to market level is described. Likely forthcoming changes of the power system are further illustrated that raises several new demands on the system structure and system operation. Approaching and existing technologies are described and exemplified in Chapter 3. Their potential is the basis for restructuring or complementing present power system. System actors and interactions are studied in Chapter 4, which includes a principal energy management system structure that manages several types of interactions at various system levels. A distributed power system structure is proposed in Chapter 5, which is based on distributed automation and information systems. In Chapter 6, operation and control for DPS are introduced. A distributed automation and functional blocks structure is applied for the management of the DPS. This contains a more thorough description of needed hardware and software. The information system structure with data and communication hierarchy

at different levels and control units are described in Chapter 7 where the fundamental resource management structure is adopted. In Chapter 8, the simulations and experimental validation for several test scenarios are described and performed. Most of the objectives of the work are here proven and fulfilled. Future applications using the results of this work are presented in Chapter 9 that also illustrate the similarities in different areas where the scalable DPS structure may be applied. The results of the work are concluded in Chapter 10 where further investigations and research are proposed. The theory and physics are implemented in the Appendix, where all models of included power units are built and described enabling the analysis and tests for the DPS.

1.6 Publications

Much of the work regarding information and functional structures for operating and monitoring a DPS is published in a number of conferences and workshops.

J. Svensson and P. Karlsson (2002), "Wind Farm Control Software Structure", Third International Workshop on Transmission Networks for Offshore Wind Farms, Royal Institute of Technology, Stockholm, Sweden, April 2002.

J. Svensson, P. Karlsson and A. Johnsson, "Information structures for Scalable Distributed Power System", EuroPES 2003, Marbella, Spain, September 2003.

J. Svensson, A. Johnsson and P. Karlsson, "Wind Power Plant Market and Operation Interaction- Principles for Information and Energy Management Systems", Fourth International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, Billund, Denmark, October 2003.

J. Svensson, and P. Karlsson, "Adaptive Signal Management", Third International Modelica conference 2003, Linköping, Sweden, November 2003.

Additional publications have been written by the author within the area of SCADA, control and information systems, and wind power. The first one was ordered by Värmeforsk (Thermal Engineering Research Institute) and the following four by Elforsk.

Tuszynski Jan, Svensson Jörgen, Implementering av "softPC", Thermal Engineering Research Institute of Sweden (Värmeforsk report) , Mars 2001.

Claus Bjerge, Peter Christiansen, Arne Hedevang, Anders Johnsson, Niels Raben, Jörgen Svensson, "Functional Requirements on Communication System for Wind Turbine Applications", June 2001 (Elforsk report 01:25).

Anders Andersson, Claus Bjerge, Peter Christiansen, Martin Heyman Donovan, Arne Hedevang, Anders Johnsson, Niels Raben, Jörgen Svensson, "Wind Power Communication – Verification report and recommendation", April 2001 (Elforsk report 02:14).

Anders Johnsson, Jörgen Svensson, "Wind power communication - Design and implementation of test environment for IEC61850/UCA2", April 2002 (Elforsk report 02:16).

Jörgen Svensson, Anders Johnsson, "Information structures for wind power plant operation and market interaction", September 2003 (Elforsk report 03:26).

The author has also co-authored the following four publications in the same research project where the contribution made is minor.

P. Karlsson and J. Svensson, "DC Bus Voltage Control for Renewable Energy Distributed Power Systems", IASTED Power and Energy Systems Conference, PES 2002 Conf. Proc., Marina del Rey, CA, USA, May 13-15, 2002, pp. 333-338.

P. Karlsson and J. Svensson, "Fault Detection and Clearance in DC Distributed Power Systems", IEEE Nordic Workshop on Power and Industrial Electronics, NORPIE 2002 workshop proc., Stockholm, Sweden, Aug. 12-14, 2002, CD-ROM pages 6.

P. Karlsson and J. Svensson, "DC Bus Voltage Control for a Distributed Power System", publication in IEEE transactions on power electronics, vol. 18, no. 6, pp 1405-1412, Nov. 6, 2003.

P. Karlsson and J. Svensson, "Voltage Control and Load Sharing in DC Distribution Systems", European Conference on Power Electronics and Applications, EPE 2003, Toulouse, France, Sept. 2-4, 2003.

Chapter 2

Power system survey

This chapter initiates with an introduction regarding the mechanisms and the driving forces of an electric power system. Approaching changes are discussed and described by simple means and further summarized in the end as requirements and needed improvements. The intention with this chapter is to point at approaching changes and demands that will cause impacts and consequently must be considered in transforming or complementing present power system.

2.1 Traditional power systems – an overview

This section presents a traditional power system more thoroughly by first illustrating the structure of the electric power system and secondly the market system. The description is more or less tackled from a control point of view.

The main purpose of an electric power system is to satisfy the customer demands in a reliable manner and as economically as possible. The market system includes deregulated and competitive electric power markets, where market actors have a range of alternatives with respect to their use of electricity and their payment for electricity services. They are able to participate in time-based markets and meet price-fixing that can vary widely depending on supply and demand. The market system manages the agreements on the services used for operation of the power system. The power system includes production, distribution and consumption units where process actors are responsible for interacting with each other to operate and support the load demand. Unresolved system planning problems or constraints will eventually become system operation problems

and constraints and will therefore affect customer reliability. A typical power system today, shown in Figure 2.1, is characterized by unidirectional power flow from the highest transmission capacity level to the consumption level. The system has, more or less, deterministic generation and stochastic consumption, where a majority of the generation is at the high voltage level.
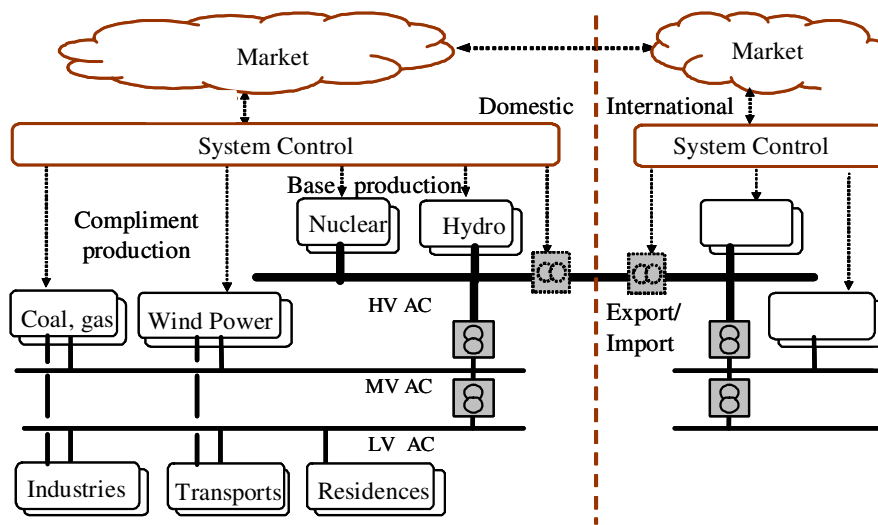
Figure 2.1: Overview of a traditional power system.

The system operation is performed in a monolithic system control hierarchy where one authority, the system operator, has the overall responsibility for maintaining the reliability and security.

Power system units

Societies have come to rely on electrical infrastructures in order to work effectively. Traditionally the power system is built up by power lines, transformers, generators, loads, and other equipment that are under the supervision and control of a single system operator, distribution operators and generation operators. Control centre operators maintain the system by preventing outages and insure reliable operation. The operational principals are intended to balance supply and demand without creating overloads, congestions, or similar problems. Operations are based not only on

maintaining a power balance but also on controlling the frequency and voltage of the system. Power reserves are provided throughout the system to manage the loss of any one unit at any time. Several power transmission networks and lines have been built up in order to transmit large volumes of energy over great distances that resemble highways for electrical power. The power system consists of generation systems (plants), transmission systems, distribution systems and a network of high-voltage transmission lines integrating these as illustrated in Figure 2.2.
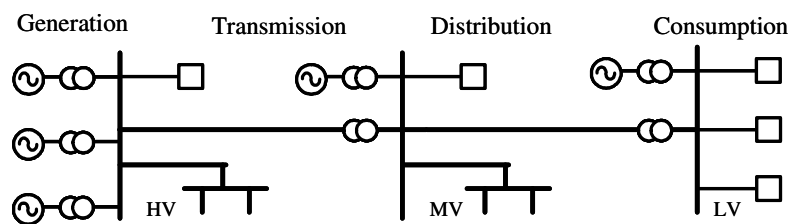
Figure 2.2: Electric power system overview, one-line diagram.

The Figure shows how these systems are interconnected and their functional structure is illustrated in Figure 2.3, where all the equipment are described as power system units with specific functions and different operating possibilities.
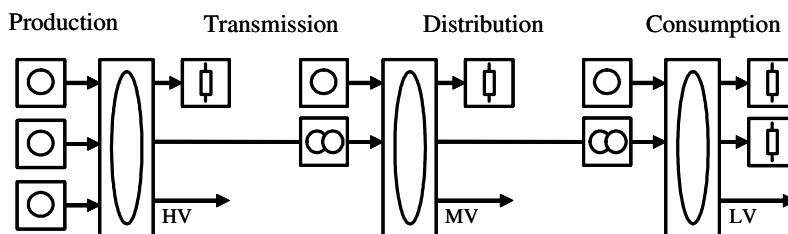
Figure 2.3: Functional structure.

The power system units can be divided in following system units:

- *Generation system units* have as their primary task to supply the power system with electric power and are placed in geographically dispersed locations where the system units normally contain more than one generation unit. Generation units operate based on different energy sources, e.g. thermal (oil, coal, natural gas, etc.), nuclear, renewals (hydro, wind, solar, tidal), etc. There are several conversion processes in conventional electric power plants, which often end up with turbines

transforming mechanical energy to electrical energy. The latter conversion mainly consists of synchronous generators driven by turbines. From the generation units, energy is delivered to the transmission system via step-up transformers. Generation units differ widely in capacity and controllability but can, so far, be considered as deterministic as most of them are able to generate at predefined power levels. Generation units are normally classified as base-, intermediate- or peak- load units. Base load units have a high load factor, in the range of 80%. They are normally designed to operate at a constant load level during normal operations. Peak load units are characterized by short start time and fast ramping rate and are used to serve the load for some hours of the day during peak demand periods. The load factors of these are usually ranging from 5% to 20%. Intermediate load units are used to follow the daily or seasonal load fluctuations, and the output of these plants is adjusted up or down to balance the variations of the demand during the day. The load factor of these ranges from 20% to 80%.

- *Transmission system units* have as their primary task to connect generation units to consumption points and create large power pools for increased reliability. High voltage AC transmission offers high transmission capacity and low transmission losses. The transmission system consists of several separate following networks servicing the same control area that operate at different voltage levels, usually at high (130kV) or very high voltages (400kV), and are interconnected almost only by substations. However, some large generation and load units are connected to the transmission system. The transmission network also serves to integrate adjacent power systems. The transmission network include various equipment to maintain voltage levels and phases, e.g. transformers (step-up/-down, voltage-regulators, phase shifters), lines/cables, series capacitors, shunt and series reactors, etc. A large number of circuit breakers and disconnectors are also included for equipment protection and the possibility to disconnect power units or areas with malfunction. Beside the possibilities in controlling the voltage and phases, the frequency and power balance is maintained by ordering specific generation units capable of managing the task.

- *Distribution system units* are similar in structure to the transmission system but cover a much smaller geographical area and have the main task to supply energy to consumers at standard voltage levels by single phase and/or three-phase AC connections. The distribution networks receive electrical energy from the transmission system at power delivery

points and the network system voltage is stepped down in stages by several substations. Conventionally, the distribution networks are built up as radial systems including equipments such as; distribution transformers, feeder sections, switches, fuses, reclosers, automatic load transfers etc.

- *Substation units* have the main purpose to transform the voltage level and normally also separate different systems by galvanic isolation. Conventional substations are passive power exchange units interconnecting to network systems. The included equipment for voltage transformation are power transformers, busbars, circuit breakers, disconnectors, potential and current sensors, fuses and other protection devices. Most of the substations have a firm physical transformation ratio and are not controllable.

- *Consumption units (loads)* are everything from lamps, machines and residences to hospitals, industries, cities or electrified railways that consume electric power from the transmission and distribution networks. Almost all loads consume electric power in a stochastic behaviour and are not controllable from a transmission system point of view.

- *Automation systems* have as its main task to enable a reliable and safety operation of the power system units by providing means for accurate information, supervision and system management. The automation systems include metering, communication, protection and control devices at field level, and additional protection systems, process control systems, supervisory control systems (SCADA, EMS, etc) at higher levels. Depending on the degree of automation, mostly system power units have more or less of these components embedded for managing the unit functionality locally and remotely, e.g. governor control is included at each generation unit and an automatic generation control at the system level that are interconnected by communication networks at different levels.

The combination of various generating source systems and several levels of transmission and distribution systems provides a partial degree of structural redundancy that enables the system to withstand single and several multiple contingencies without loss of service to consumers.

Power system operation

The power system may be divided into control areas, most typically by regions, although to some extent utilities are merging together to form a jointly operated control area consisting of several control areas. A control centre manages the operation of the power system within the control area and coordinates its activities with neighbouring utilities. The system operators' main goals are to maintain the power balance and system security within their control area. Maintaining the power balance implies on equality at all times between total power generation, load, import and export.

$$\text{Total [} Generation(t) + Import(t) \text{] = Total [} Load(t) + Export(t) \text{]}$$

System security implies on that power units must not exceed their power ratings, under normal or a single outage condition.

$$|p(t)| \leq pMax$$

Beside these goals, power quality considerations have to be taken where system frequency and voltage has to be kept within their operational limits.

$$fMin < f(t) < fMax$$

$$vMin < v(t) < vMax$$

This is achieved by coordination between specific system power units that are assigned certain tasks depending on their functional capacities, controllability. Each control area is operated by an individual system operator that maintains the area by several transmission system operations. Depending on the time frame for operating and maintaining the control area the control functions are classified as:

- *Primary control* maintains the balance between generation and load in the transmission system using turbine speed governors. Primary control is an automatic decentralized function of the turbine governor to adjust the generator output of a unit as a consequence of a frequency or voltage deviation offset in the control area. The primary control adjusts momentary to balance deviations and its reserve, spinning reserve, also covers a sudden loss of at least the largest running generation unit.

- *Secondary control* is a centralized automatic function to regulate the generation in a control area based on secondary control reserves in order

to maintain its power exchange flow with other control areas and to adjust the loss of capacity affected by a loss of production. The secondary control restores the frequency if a major frequency deviation occurs, e.g. the loss of a large generation unit, in order to free the capacity caused by the primary control and to restore the primary control reserves. Secondary control operates in the range of several minutes, and is separated from primary control.

- *Tertiary control* is any automatic or manual change of generators in order to restore an adequate secondary control reserve in the same manner as the secondary control covers the primary control. The restoration of an adequate secondary control reserve is in the range of 15-20 minutes.

Beside these control functions, essentials for maintaining the "highways", are functions for directing the electric power transportation by so called transmission power providers.
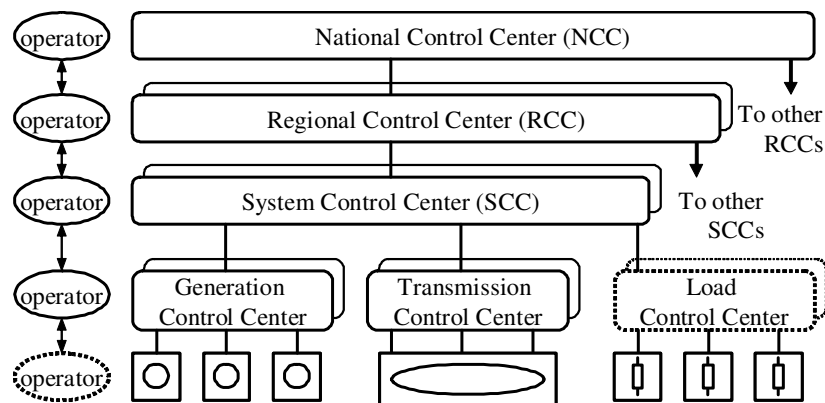
Figure 2.4: Vertical operation and control hierarchy.

The operators have several tools for operating the system, where the control system in the control centers includes several functions managing the system reliability. Modern power systems normally include a huge number of sensors throughout the system warning operators if critical limits are exceeded. The control and monitoring systems provide the operator with information about possible causes and consequences of a fault. This allows them to make a faster and better decision about what further action should be taken. Security and reliability data from protection systems are also embedded into the control and monitoring systems that

help operators to determine deviations and control both security and reliability risks.

Applied to the functional structure is an operation and control system that is highly vertically distributed as illustrated in Figure 2.4. The structure is designed to provide redundancy in a manner similar to that provided by the power system. The primary function of the human operator, whether in a power plant or the central system control center, is one of managing and coordinating resources, monitoring performance and reliability, and adjusting control parameters to maintain the desired quantity and quality of electrical supply over a long term. The operator is consequently an important and essential link at different levels and key points in the system. The operator is particularly adept at responding to abnormal situations where information from diverse but related sources must be integrated quickly to form a corrective strategy and to move toward a more secure operating condition.

Market system

The direction towards deregulated electricity markets has been developed to facilitate electricity trade and exist in several countries. In Europe, the EU directive on common regulations for the internal market in electricity denotes that each member country has the right of access to the electricity transmission and distribution networks. In future, this will probably lead to global markets within EU and thereafter or during this development, the globalization will extend even further according to [Kirby, *et al*., 1999]. The aims of the electricity markets are to facilitate the trade of electric power products. Thus the trading participants will have the possibility to balance their purchase and sale obligations in the short run. This requires that the electricity market:

- offers a neutral market where all trading participants trade at equal terms

- provides easy access and low transaction costs

- provides a neutral price reference for the whole power market

In deregulated and competitive electricity markets, actors have a range of alternatives depending on their usage of electricity and trade for electricity services. They are able to participate in several time-based markets and meet spot prices that can vary widely depending on supply and demand. The trading of electricity is normally conducted via either two known

traders (one seller and one buyer) or by several traders connected to a market as shown in Figure 2.5. Even though there are only two principally different ways of trading, numerous combinations and variations coexist.
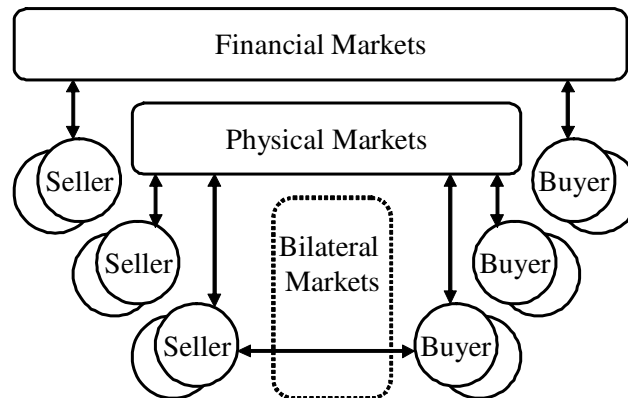
Figure 2.5: Electricity markets overview.

The establishing of contracts is basically done on bilateral-, physical- or financial markets:

- *Bilateral market*: In bilateral markets, buyers and sellers trade directly with each other. The contracts between each pair of participants usually differ. The actors could agree on different prices, quantities or different qualities of electricity. Also the duration of the contracts may differ.

- *Physical market*: Contracts on the physical market cover the real physical delivery of electricity. This is usually a short term market where the amounts for physical transmission for the following day are determined in day-ahead auctions. Buyers and sellers can independently place bids as a two-part auction. Even though buyers and sellers are independent when bidding, they are linked by the outcome of the auction, i.e. the market prices and quantities. These short term auctions are also called spot markets.

- *Financial market*: The part of the electrical market that not immediately corresponds to transmission of electricity is called financial market and can be compared with Eltermin in the Nordic system. This market includes long term trading products, such as Forwards, Futures, Call and Put Options up to 3-5 years ahead.

Market operation

Several markets are directly linked to the physical delivery of electricity from producers to consumers. Consequently, the physical stability of the power transmission and distribution system is affected by the supported deliveries.
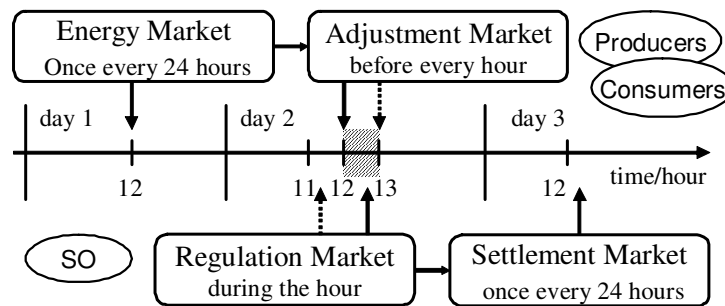
Figure 2.6: Physical market overview.

The physical market can be divided in:

- *Energy Market* or Spot Market is a physical market where energy prices and amounts are based on supply and demand. The market is a day ahead-market where bidding closes at noon for deliveries from midnight and 24 hours ahead. The actors are production and distribution companies, large consumers (e.g. industrial, cities), brokers and traders.

- *Balance Adjustment Market* (BAM) or Elbas Market is the physical trading of adjusting/regulating power where bidding closes 1 hour before the operating/delivery hour. BAM is an aftermarket to the energy market. The products traded are one-hour-long power contracts.

- *Balance Regulation Market* (BRM) is the physical real-time market covering operation within the hour. The BRM is an aftermarket to the energy market and its main function is to provide power regulation to counteract imbalances relative to planned operation according to the energy market trade. The products traded are one-hour-long power contracts. Only the SO of the control area manages the demand of the BRM and the actors on the supply side of the BRM can be both producers and consumers. The BRM may be subdivided according to the different services provided, e.g., according to the response time for

the regulation delivery. Secondary control and tertiary control capacity differs according to the response time for the capacity to be online.

- *Balance Settlement Market* (BSM) is linked to the BRM and handles the later settling of actor imbalances recorded during the past 24 hour period of operation. Only the SO for the control area acts on the supply side for settling imbalances. Actors with imbalances on the spot market are price takers on the BSM. Thus, the SO act as the intermediary between suppliers of power regulation (at the BRM) and actors in demand of balance (being settled at the balance market).

At the Energy market the bids for purchase and sale are collected by the market operator on the trading day which is the day before delivery at 12 noon. At this time the prices and volumes for the following day are calculated. The supply and demand curves for each hour are aggregated to one single supply curve and one single demand curve per hour. The intersection of the two curves represents the balance between purchase and sale bids as illustrated in Figure 2.7 a. The price at this intersection corresponds to the Market Clearing Price (MCP), the price for electricity in the considered hour. The suppliers are willing to offer the calculated volume at the calculated price while the buyers are willing to purchase exactly this volume at this price. If the MCP does not fall into the range of a participant's purchase or sale bids, this participant will not buy or sell at all. Since the bidding curves are usually very steep at the point of intersection, small changes in demand or supply result in high price fluctuations. Imbalances in the physical trade on the energy market must be levelled out in order to maintain balance between production and consumption. Deviations from the bids from all actors at the energy market increase the total imbalance at the hour for the overall grid. The regulation market and the settlement market may be regarded as only one market, where the SO is responsible for managing the system operation in the control area. The SO manages the balance and grid stability of the control area, by using the combined regulation and settlement market [NordEl, 2002]. The basic principle for settling imbalances is that actors causing or contributing to the imbalance shall accordingly pay their share of the costs for re-establishing the balance. However, the settling of imbalances within a control area might differ from area to area. If the bids by producers and consumers to the energy market are not fulfilled, the regulation market has to come into force. The producers send bids on the regulating market 1-2 hours before the actual production hour and power production from the bidding actors must be available within 15 minutes notice. Therefore only

fast responding power capacity is able to deliver regulating power. Thus, it will be necessary to pay for the difference between the sales bid to the energy market and the actual delivery to the market. If the power production is higher than the bid, other producers will have to regulate down or consumption must increase in order to maintain power balance. In this case, the producer with higher production than expected will get a lower price for the excess electricity produced than the energy market price.
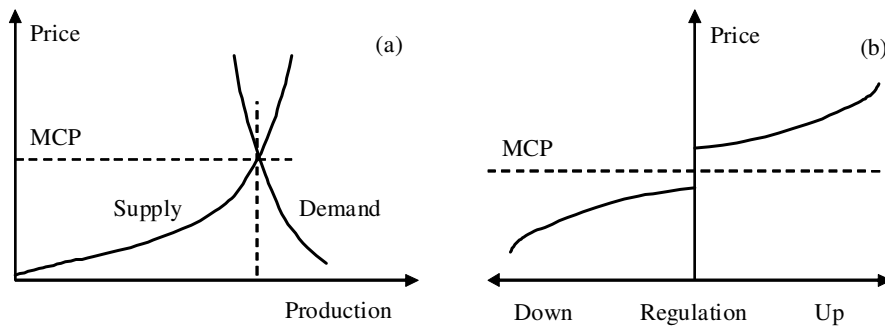
Figure 2.7: a) Intersecting supply and demand curves to get the price. b) Price calculation for the regulation market.

If power production is lower than the bid, other producers will have to regulate up to secure the power supply, or consumption must be reduced. Those other producers will obtain a price above the spot market price for the extra electricity produced, an additional cost, which has to be carried by the producer delivering lower production than expected. The more the producer is off track, the higher the price is expected to be, as shown in Figure 2.7 b. This two step price system gives incentives for the actors to avoid imbalances to a larger extent. This will also become a problem to solve when introducing a high degree of renewable energy resources into the system where the SO needs to call for even more regulating power to handle the power balance service.

2.2   System changes and transformations

This section describes the system impacts and transformations by illustrating a possible changeover scenario from conventional power

systems to systems with a high degree of integrated distributed power systems.

Extension of DG and renewable energy sources

Distributed generation was defined as generation units connected to distribution network systems close to the consumption in [Ackermann, *et al*., 2001]. However, distributed systems actually represent more than such a definition. Traditionally, the power flow is more or less unidirectional, from the highest level of capacity to the lowest, consumption level, which imply on a vertical hierarchy. Renewable energy sources (RES) are likely to interact differently with the power system in the future.
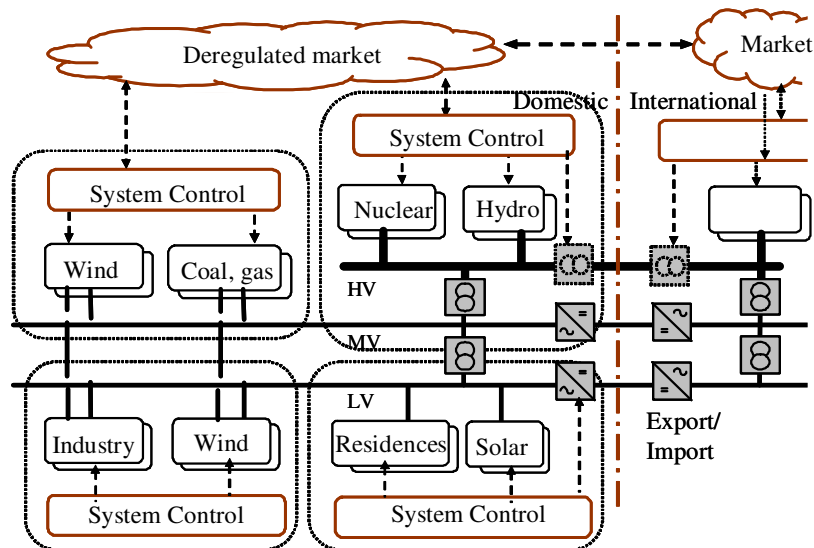
Figure 2.8: Impact by distributed generation and renewals. The dotted lines indicate areas that may operate independently of each other and consequently have their own system control.

As remarked already, approaching expansion of RES will gradually change the power system from deterministic production and stochastic consumption to systems with high penetration of stochastic production and stochastic consumption. However, the consumption could partly be deterministic, in a system with high degree of information utilisation where a majority of the consumers would have advanced load management and operation. The gradual changeover from deterministic to stochastic

generation will increase the need for bi-directional power flow as some areas could operate as local subsystems where the power excess have to transmit in reverse direction, Figure 2.8. As the distributed generation increases the system reliability could be affected. Traditionally the system control manages a few large generation units to obtain reliability and thereby closely monitor the real-time performance of those units. This is necessary since the failure of a single unit to perform as expected may have severe consequences, which must be handled immediately. The amount of information is small enough that the system operator can make use of it in real-time. In a coming extension of distributed generation it would be difficult for the system operator to manage the system in real-time due to the amount of information. Providing the same real-time information from hundreds or thousands of individual power units would cause an overwhelming amount of data that could not be managed in real-time by a single operator. An obstacle with distributed supply of services is that the system operator cannot deal with the large number of individual resources and that the communication requirements would be overwhelming.

However, this could be managed by aggregators handling the communications with a large number of distributed facilities that could provide the system operator with a compounded amount of capacity, similar to the system operator's interface with generating resources. They could also act as an interpreter between the electrical system and customers, which could be valuable resource in the system. The aggregator should then have real-time decision functions and interact with the markets by identifying RESs that are capable of participating in markets. The aggregator could establish communications with the system operator via the supervisory control and data acquisition system (SCADA), energy management system (EMS), and/or automatic generation control (AGC) requirements established by the system operator. These communications would enable the system operator to treat the RES aggregation as a single resource unit. Next the aggregator would establish a communications network to connect it to each RES.

Extension and integration of DC technology

As power electronic technology continuously evolves and several new controllable power units already are based on converter solutions, the degree of controllability of power units are increasing. Power electronics will be integrated throughout the entire power system from generation, load

and storage units to transmission and distribution networks as shown in Figure 2.9. New generation units based on full converter systems enable high controllability for production [Bahrman, *et al.*, 1999]. Transmission lines/cables like flexible AC transmission systems (FACTS) open up new possibilities in high-speed bi-directional power exchange between adjacent power systems. Beside the FACTS, new converter based substations will emerge that opens up fast and controllably power exchange between sub networks and between AC and DC systems.
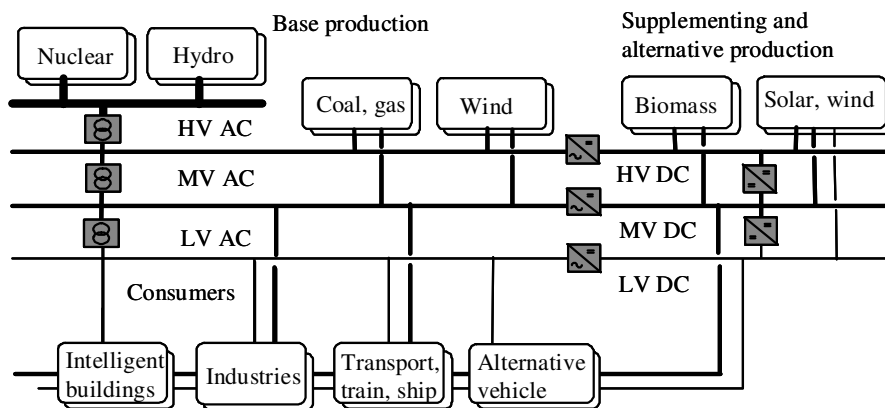
Figure 2.9: AC and DC integration.

Already today several loads are based on DC that imply on a future parallel supply of DC to consumers. There are several advantages with the integration of converter technology since high and fast controllability provides new opportunities. However, the lifespan of this equipment is probably less than half of the traditional and the opportunities in fast control during disturbances require fast operation that hardly can be managed by human operators. In other words, enabling such technology requires reflection regarding automated functions to manage fast system changes. Otherwise the risk of reduced system reliability is considerable.

Global integration

As new technology will evolve, the global integration of regions, nations and continents will extend. In the future, it is likely that every power unit supplying or demanding services will be able to interconnect and interact accordingly to predefined standards. However, meeting such a future will affect the decisions to build new interconnections between nations and

regions regarding the security and reliability issues. Through the sharing of operational reserves and installed capacity the system reliability may decrease. As a stand-alone power system, the security and reliability of the electrical supply is directly related to the type, size and amount of installed generating capacity within a control area. The requirement to provide operational reserves in proportion to the expected system contingencies would probably increase the costs of maintaining a reliable power system. Interconnecting with adjacent nations or regions provides an alternative source for operating reserves and support during emergencies. The global integration may have its advantages and disadvantages regarding reliability. In addition to providing access to operational reserves, power interconnections between nations and regions can provide alternatives to the available sources of energy supplies. For certain resources, such as RES, interconnection might be the only possible way of making these resources available to other control areas. Interconnections facilitate the development of these distributed energy resources for the benefit of the entire region. However, the risk of a system collapse will probably increase the demands on the capability of seamless disconnections between adjacent control areas, which call upon the possibilities for stand-alone functionality.

Additional actors and markets

The customer and market demands will probably stress the power system further. It is not unlikely that almost every future technical solution will be automated and that most personal actors will participate for economical interests, similar to the stock market. By watching the market, participants could decide if investing in additional flexibility would be profitable or not. Flexibility could be gained by adding distributed generation, controlling their load, or adding forms of storages. Even new bi-directional transmission lines could prove economical and consequently be constructed between different areas similar to fee-based highways. This process allows markets to optimise the power system and the individual participants businesses while minimising central planning and control.

Present market model will probably extend with additionally markets due to the emerging effects by a large amount of intermittent (stochastic) generation such as wind power and also new markets concerning reliability.

Compared to the energy supply business, the transmission network operation business is more complicated to deregulate for complete competition. A market model has to deal with the following technical issues:
- power quality (voltage)
- network losses
- transmission capacity (congestion, bottlenecks)
- system balance (frequency)
- system stability (reserve)
- restoration (black start)

In an open market these demands need careful planning, both in short and long-time, preventing too high risk not fulfilling customer demands [Kirby and Hirst, 2000]. Apart from the energy market structure, fewer official markets exist where important physical deliverables or power system support services are traded. A general heading for these markets might be:

- *Ancillary Service Markets* (ASM): The function of these markets/agreements is to provide/allocate primary, secondary and tertiary reserves for safe operation of the system within the operating hour, including frequency and voltage control. Furthermore, the needs for reserve capacity to counteract larger operation disturbances and black start reserves are generally allocated by individual agreements between selected actors and the SO. Presently, these (informal) markets are characterized by a few large actors on the supply side and the SO on the demand side.

- *Reserve capacity markets*: Incentives to compensate electricity producers for their reserve capacity. This could open up for storage such as pumped hydro and new storage technology.

- *Transmission Capacity Market*: Capacity for cross border transmission (import/export) to/from control areas is still traded via specific auctions or bilateral trade of transmission channels. The import/export transmission capacity trade is administered by the market operator. The market operator handles bottlenecks via so-called implicit where the power trading and the transmission capacity auction are combined into one transaction. This system allows actors to trade via the common exchange without considering the transmission capacities explicitly. However, this might be similar to the energy market in near future and might open up for technologies such as FACTS.

- *Reliability Markets*: A future reliability market could ensure higher reliability at certain control areas, both smaller and larger. This could for example be adopted by redundant power units, increased functionality (e.g. stand-alone abilities) etc.

The structures of future markets are in general very important for the functionality of power systems and the technical and economical efficiency of the systems. The technical possibilities for creating well functioning markets may to a large extent determine the type of actors that are present at the markets, the number of actors and the minimum volumes, or amount being traded, etc., and the transaction cost for managing markets. Correspondingly, such technical possibilities may to a large extent determine the supply at markets such as the regulating power market or potential markets covering ancillary services.

In particular, an increased supply at the regulating power market may reduce costs at this market and/or may increase the capability of the overall system as to accumulate intermittent production and consumption. This is important when the extension of renewable energy sources become a significant part of the total production due to its fluctuation and limited predictability. It will be important for the efficiency of the system and for the capability of the system to integrate RES such as wind power and solar power. Additionally the future penetration of RES will make load management systems important and also integrate the load to the reserve market and the ancillary market by offering interruptible load. Eventually, the power systems would probably fully integrate RESs into energy and ancillary service markets. Prices for energy and the ancillary services would change hourly (or faster) depending on system conditions and capacity. As the system become stressed prices would rise. Broadcasting prices would enable all resources, e.g. loads and generation, to respond and reduce reliability concerns. Price would be the dominant means of achieving desired response. Loads and generators that could not respond, due to their own economic or physical constraints by offering minor service to the market, would continue operating as locally commanded units unless the system operator interrupts for security reasons. However, those that have several services and could respond would receive economic benefits.

2.3 Structural needs in traditional and distributed power systems

The need, in the long time run, to replace fossil fuels by renewable alternatives is immense. Although massive effort is focused in attempts to accelerate the increase of alternatives the present rate is by all manners to low. The intention and conditions to develop mature and cost effective alternatives must be giving higher priority and is, to a great extent, an obstacle to be solved by governments and global authorities

Existing power systems are in need of change enabling a higher degree of stochastic production, real-time control and market interaction. Massive effort should be focus on research on new modular, adaptable and scalable distributed power system that can meet raising demands. The most likely obstacle is the expected higher cost of such a system that must be compensated by higher values for all involved.

Utilization of renewable energy sources

The expected large extension of RES, primarily wind power at the time being, will probably push the suppliers to improve the strategic value of RES in electric utility system operations and enable the ability to use RES as a valuable resource in advanced distribution automation systems.

The emerging generation of advanced, power converter-equipped RES and energy storage devices has the potential to provide additional functionality that will make it easier to configure and establish power systems. In addition to the high efficiency, low-emissions output, and low-maintenance advantages possible with advanced RES devices, additional power network capabilities can be incorporated through recent advances in power converter control technology. These advances can enable new, high-performance features such as "plug-and-produce" capability and high-speed transmission support. Using this power converter-based DPS architecture could allow wide-scale deployment of RESs in the power system [Lee, *et al.*, 2001]. The interaction and possible remotely operation of RES might prove very valuable in securing system reliability. RES can provide additional services to the distribution network in terms of stability and power quality [Nielsen1, 2002], which requires new possibilities and regulation of distribution networks to ensure active participation of RES and DG in the deregulated electricity market.

Distributed power system design

As future power systems likely will consist of numerous subsystems, e.g. intelligent buildings, vehicles, ships, village, regions etc, with the possibility to work as "stand-alone" systems, the basic framework for system and unit configurations needs to be more flexible and adaptable. In this framework the structure for real-time information and operation will play an important role for proper interconnections and interactions. DPSs are a natural extension of distributed energy resource applications to situations where the connected customers need power service levels above what is available from a traditional transmission and distribution network.

In the future, power systems might consist of hierarchies of numerous DPSs, configured with multiple levels and interconnections, with most or all of the distribution level load demand met by the DG assets within the local system. This architecture might create a robust system where all power units are working together to increase reliably and meet the power needs of the end-users. This recalls for active transmission networks where advanced interfaces are embedded at terminals connection the different source and sink units. Much research has been done on these issues.

One example of progress toward realization of an intelligent grid can be found in a new approach called the "MicroGrid" power network [Hoff, *et al*., 1997], and the "More Care" project [Hatziargyiou, *et al*., 2001], which is analogous to today's universally distributed computing networks, The MicroGrid is differentiated from the generically used term "microgrid". The approach to this power architecture links various DG technologies into small 'grid networks' with advanced functionality.

A MicroGrid power network is defined as two or more DG units configured in an electricity network and able to operate either in parallel with, or independent from, a larger transmission network, while providing continuous power to multiple load centers or end-users. The DG resources may be combinations of power generation and energy storage devices. The MicroGrid power network can be islanded and continue to meet the power needs of the loads within the network without interruption. An energy end-user connected to a MicroGrid power system can benefit from a secure, high-reliability, and high-availability power source that can be configured to withstand both short- and long-term interruptions in the utility supply system, while supplying continuous high-quality power to critical loads. MicroGrid power systems can have high 'fault tolerance', and can be

configured to be essentially immune to intentional or accidental damage in the centralized utility power network [Peças Lopes, 2003].

Another example is research on the intelligent power router (IPR) [Matsumoto and Yanab, 2002] that also builds on embedded intelligence within several routers in the power system similar to the internet structure. The approach builds on experience from power engineering, systems, operation and control, and information systems. Each IPR has embedded intelligence allowing the IPN to switch power lines, shed load and receive/broadcast local state variable information to and from other IPRs. The information exchange capability of the IPRs provides coordination among themselves to reconfigure the power network, even when the designated principal control center of the system has collapsed due to a natural or man-made disaster. The proposed approach is borrowed from computer networks, where data is moved over geographically distant nodes via data routers. In the event of a component or system failure, the IPRs will make local decisions and coordinate with other routers to bring the system, or part of it, back into an operational state.

One vision for future electricity systems is presented in [van Overbeeke and Roberts, 2002] [Hindsberger, *et al.*, 2003] where existing passive distribution networks are assumed to evolve gradually into actively managed networks. From this viewpoint it is both technically and economically the best way to facilitate DG in a deregulated electricity market. The basis for the vision is that the existing technical and regulatory structure of distribution networks is unable of supporting the evolution of the power system further. This means that the network should not be considered as a power supply system but a bi-directional highway system that provides connectivity between points of supply and consumption. The structural solution proposed is based on the use of local control areas or cells, enabling local network areas to act as independent islands.

An active transmission network is depending on high controllability that can be achieved by power electronic converter technology. For DC power systems based on converter technology this become highly controllable as investigated in [Karlsson, 2002], which prove the advantages of modular parallel interconnection of converters and their possibilities in controlling the power flow. The system investigated consisted of five converter stations interconnected to a DC bus. This research is the foundation for implementing superior autonomous operation and control functions.

Distributed Energy Management System

Interconnected power systems are highly complex mechanisms, and control of these systems becomes increasingly difficult with restructuring. Factors such as the entry of new participants, increases in cross-regional power exchanges, and new types and numbers of distributed generating resources and loads all contribute to complicate system planning and operations [Swarup, *et al.*, 2001]. Energy management systems (EMS) including SCADA systems are essential parts developing future distributed modular functions enabling interconnection between generating units and the markets [Srinivas, el al., 1998] [Murthy, 2002]. The functions needed must be accommodated by the new market and power system information structure. These functions range from assuring an adequate electricity supply through long-term planning of the generation and transmission system, to meet shorter term forecasted load by deploying existing resources through unit commitment, to assuring system security through automatic generation control, and operating the transmission system by controlling ancillary services such as reserves and black start capability [Kokai, *et al.*, 1998] [Azevedo, *et al.*, 2000].

Approaching DPS solutions will include all from a very small to a very large amount of new controllable power units with internal grids based on either AC or DC. A modular hardware and software structure will make it easy to expand the system. This also opens up for extended functions and new technologies enabling autonomous operation. In the design of an EMS [Ta-Kan, *et al.*, 1998], there is a need to know where the relevant technologies are heading, and what is expected to reach the objectives. Improvements have to be done in distributed operations, distributed databases, and communication networks and protocols. To be able to take advantage of these improvements, a distributed EMS structure is required.

With large scale and more complex functions [Jin and Renmu, 2002], distributed EMS software structures are needed to constitute distributed computer network so as to process the system information. This requires the structure of the software platform not only to ensure the system reliability, maintainability and reusability, but also to support flexible and scalable configurations to be seasoned with the objective systems of different scales [Zecevic, 1998]. In addition, the distributed EMS system is a new technique, and the relevant theories and techniques develop fast. To apply the new techniques into practice, the design of software platform must take full considerations of the various features.

Autonomous system operation

One of the new technical issues created by distributed generation (DG) interconnection are the possibilities in "stand-alone" operation. Stand-alone operation occurs when a part of the distribution system becomes electrically isolated from the rest of the power system. It could be desirable to permit such "stand-alone" operation to increase customer reliability, and this is often done where the DG provides backup power to the facility where it is installed. However, considerable engineering effort, control functionality, and communications infrastructure are necessary to make intentional islanding viable where the island includes a part of main system and other loads. This will bring up new requirements for coordinating the operation of the DG and the subsystem [Dy-Liacco, 1999] [Katayama, *et al.*, 2002].

Increasing possibilities to interconnect and participate on a power market bring larger amount of information to handle. For large power companies this is managed by several departments each including several persons that have specific tasks to interact both towards the control centres of the producing units and to the market system for always striving for maximum economical gain. The commerce is continuously increasing as new markets will be interconnected and further services will develop. This might not be appropriate for smaller companies that instead could feel forced to assign larger companies to handle this, for good or bad. This is one solution and should always be left as an alternative. A general solution with increased automatic operations connecting the producers generating units to the market could be a further development that opens up the possibilities even more [McClanahan, *et al.*, 1998] [Shimohammadi and Vaahedi, 2002]. This calls upon uniformed information structures enabling real-time operation and market interactions. The great uncertainty and expected fast changes in RES production should also raise demands for automated functions for controlling generating units by adequate information directly interconnected with responsible operator in charge for fast decision-making. Technology that increases the system operator's flexibility to observe or control the power system or that increases the throughput of the transmission system is useful in supporting market development. As RES will offer additional services, real-time information system will be needed for interconnecting system operators offering ancillary services.

Information and communication system

With the power system deregulation powerful driving forces, uncertainties, and new services are compelling electric utilities to make changes in the power system information infrastructure design. Expanding network services such as real-time monitoring are also driving the need for increased bandwidth in the communication network construction. These needs grow further as new remote real-time trading and operating applications become reality.

Present information management systems have to be restructured as more and faster information has become desirable by affected actors. Technological advances in networking have made it possible to develop a communication system for accessing real-time power system information over digital network or transmission lines. Faster decisions would increase system reliability, which also asks for new strategies to be developed in association with real-time information from other wide range signal sources. Currently, most communication technologies used in power systems only allows local control actions at the plant due to lack of efficient, high speed and bandwidth communication media [Kezunovic and Abur, 2004]. To minimize the risk of serious network failures and to be able to improve the economical optimization of electricity networks it is important to recognize that distribution networks can no longer be seen as passive additions to the transmission networks. The entire network must be operated as a closely integrated unit and for this purpose a number of technical improvements have to be implemented. In these future electricity networks the role of information and communication technologies will surely increase to improve network management and market operations [Nielsen2, 2002].

Interconnected power systems are highly complex mechanisms, and control of these systems becomes increasingly difficult with restructuring. Factors such as the entry of new participants increased cross-regional power exchanges, and new types and numbers of distributed generating resources and loads all act to complicate system planning and operations. EMS and SCADA systems are essential parts for developing future distributed modular functions that enable interconnection between generation units and the markets. The functions needed must be accommodated by the new market and power system information structure. These functions range from assuring an adequate electricity supply through long-term planning of the generation and transmission system, to meet shorter term forecasted

load by deploying existing resources through unit commitment, to assuring system security through automatic generation control, and operating the transmission system by controlling ancillary services such as reserves and black start capability. New well-defined communication interfaces have to be designed for communication and integration for both trading and operational purposes. Real-time data can be highly valuable information source for automatic operation and control to maintain system stability. It can also be used as a source to immediate operating decision-making in support of system recovery and for extensive analysis [Haiyou and Renmu, *et al.*, 1999] [Kezunovic, 2004]. According to the research, the widespread power outage in several power systems could have been avoided if fraction of the wide area loads had been shed for 30 minutes. Many breakups as well as outages demonstrate that wide area, comprehensive and real-time information exchange is becoming a critical factor for the future power system reliability and stability. The real time data applications range from very rapid control function to the very long-term functions such as expansion planning. With high-speed real-time measurement, proper protection and control actions could be taken to ensure the reliability of power system when event occurs. Fast, real time and comprehensive information acquisition and transmission are the key to wide area power system operation optimization and control [Kezunovic and Tayler, 2004] [deVos, *et al.*, 2001] [Schwarz, 2001]. To support such data communication requirements, the candidate communication architecture and technologies must be able to deliver operational data and dynamic real-time information and should follow standards such as described in [Schwarz, 2002] [IEC 61850, 2003] [IEC 61970, 2003].

2.4 Active distributed power system requirements

The main purpose for introducing active distributed power systems is to improve network survivability, security, reliability, and re-configurability. This might be obtained by implementing a high degree of distributed operation and coordination that mainly include:

- modular building units

- strategically distributed over the control area

- embedded advanced functions

- information exchange allowing fast real-time operation

This work was initiated by looking at a small scale distributed system with a high penetration of renewable energy sources as shown in Figure 2.10, where modular hardware and software applications are supposed to be tested and verified. Several objectives and requirement were determined where some of them are listed below. The system is configured with purpose to enchant as much functionally as needed. The system configuration is used for further investigations, which is described in following Chapters.
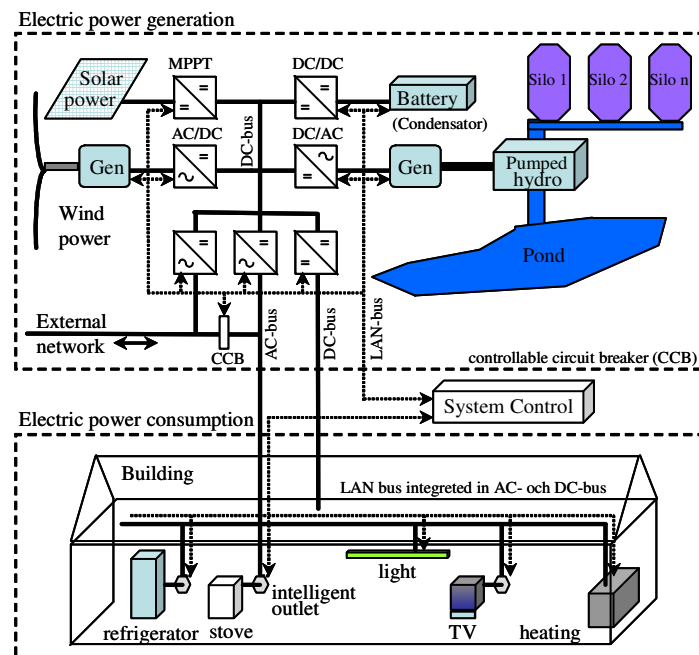
Figure 2.10: Active DPS configuration with high penetration of RES.

The main requirements include a number of desired properties for DPSs that corresponds to the objectives of this work such as:

- *Scalable*: Call upon a DPS structure that should be independent in system capacity size and able to increase or decrease incrementally. It should, for example, be applicable on large power system as well as for a wind power plant or a building.

- *Modular*: Apply on simple means for extension by well-defined system units and interfaces that simplifies connection and disconnection when

adding or removing power resources. This refers both to the hardware and software structure.

- *Flexible/Distributed*: The overall goal for the DPS unit in balancing the production and consumption should be achieved by coordination between many distributed program applications with local information and management, instead of only one single centralized point of control. This would give a much more flexible and general structure. However, the structure should be applicable both for distributed and centralized solutions. Flexible also refers to that the DPS should not be restricted in system configurations, which could be any composition of generators, loads, storages and transmissions, where the basic ideas and procedures remain the same.

- *Adaptable*: This approach deals with situations whereby the environment of the system is changing dynamically, with power resources (generators, loads and storages) connecting or disconnecting at unknown and irregular periods. This implies on dynamic execution of algorithms and resource management that always enables optimal operation during transformations in the system configuration.

- *Autonomous*: Improved system functions including automated decision-making, self-diagnosis and self-healing with purpose to minimize failures and enable faster restoring. The DPS should be able to connect or disconnect to the main power network or adjacent DPSs automatically. When disconnected they should be operated autonomously similar to traditional power systems, which require the "stand-alone" functionality. The DPS should always be aware of its own state and of adjacent DPS states and out of that make conclusions and decisions automatically.

The requested properties will require systems with a high controllability, which involve a high penetration of power converters and distributed automation using advanced programming techniques. It also involves an information and communication system for real-time operation where the data management has an important role in enabling the capability of "plug-and-produce".

Chapter 3

Potential of new technology

This chapter presents several general trends and ideas about future potential in present power system by adopting new technologies for system operation and control. The purpose is to demonstrate that renewable energy sources (RES) and converter technologies provide high controllability and consequently are able to add operational authority (values) to the system.

3.1 Introduction

New technologies are already integrated in the power system, although so far to a miner extent. Many of the technologies provide means to improve the system performance and thereby system reliability.
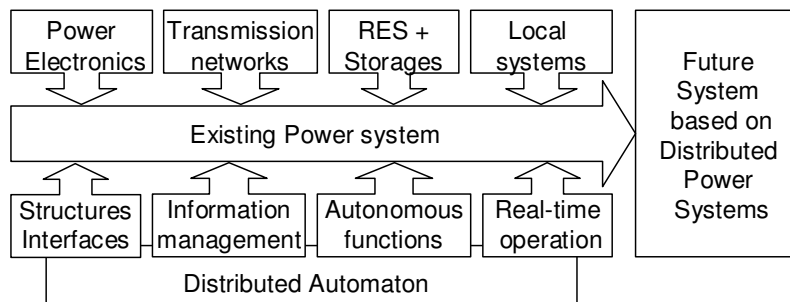

Figure 3.1: New technology overview.

Some of those, shown in Figure 3.1, may lead to the transformation of an existing power system to a future system based on distributed power systems. Power electronics and especially transistor technology is one of the key elements to increase system controllability and can be utilized in

about all applications regarding power system units. The development in this area is soon technically mature enough to be integrated in every power and voltage level in the system.

Numerous HVDC transmission lines exist for cross border interconnections based on thyristor technology but some new lines based on transistor technology have been built and are under investigations. Transmission network units are today more or less operating in passive or semi active manner but may be, with the integration of power electronics, more active enabling bidirectional power flow at several points or areas within the system.

Solar power technology has not yet reached a cost efficient solution but will probably be much utilized when this would occur. The potential is huge and there are several areas for extension. For example, buildings will probably have roof panels integrated with photovoltaic (PV) modules and isolated areas will enchant larger solar power plants as they demand much space. A one square meter area PV module may produce about maximum 100-200 watts depending on the incoming radiation. The localization of solar power will be very distributed and the capacity extremely varying from small unit in the range of single kW to large with several MW. This distributed generation may affect the power system reliability critically if not integrated properly.

Wind power technology is one of the fastest growing new electrical generations at present. Even if not proper from an economical point of view to build new power plants in some regions, the wind power is probably one of the cheapest. Some nations have planned goals for a capacity of up to 50 percent of the total electrical energy production during the coming decades. Controlling such amount of power will be complex and may demand some sort of power storage such as hydropower, which probably requires increased transmission capacity. The amount of wind power energy that can be incorporated into some national transmission networks is strongly affected by the amount of hydropower generated, where some nations will be able to integrate about 20-40 percent of RES.

The extension of distributed power generation and storage opens up for local power systems to be temporary operated serving local consumers, which may increase local system reliability. This will require the structuring of delimited areas and distributed automation technology for local system operation. The technology regarding distributed automation

includes the areas of information systems, automated advanced functions and real-time operations. The structuring and utilization of these are described in the next chapters, which propose a future system based on distributed power systems and distributed energy management systems.

3.2 Power electronics

Power electronics has been used for several low capacity applications for a long time at the consumption side. With the fast development in transistor technology, the power electronic has been extended to the production and network side as well. Several applications regarding renewable energy sources and new storage types adopt the technology.

Interconnecting national power systems has since long been applied by using traditional HVDC based on thyristor technology. As the transistor technology, especially insulate gate bipolar transistors (IGBT), has increased its power ratings and voltage level, the technology has proven suitable for HVDC transmission as well and will most likely be utilized during next coming extension and global system interconnections.

Converter circuits

The 3-phase voltage source converter (VSC) or AC/DC converter basically consists of three half bridges in parallel with a capacitor as shown in Figure 3.2. Two transistors build up every half bridge and each transistor has one diode connected in parallel.
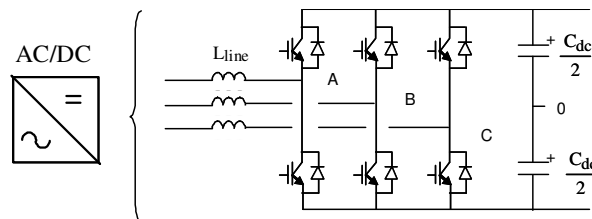
Figure 3.2: Schematic circuit of a 3-phase AC/DC converter.

This technology employs IGBTs as opposite to the thyristors used in traditional HVDC systems. The IGBTs switch very fast between two fixed voltages. Pulse width modulation (PWM) and low pass filtering are used to achieve control of both active and reactive power flow. The converter

stations are constructed as self-contained units and are therefore easily installed. The basic function of the VSC is that one of the transistors in a half bridge is on and the other one is always off. If both the transistors in the half bridge would be on, a shortcut of the capacitor occur. This is prevented by letting both of the transistors being off for a short period and then switch the transistors from on to off or vice versa.
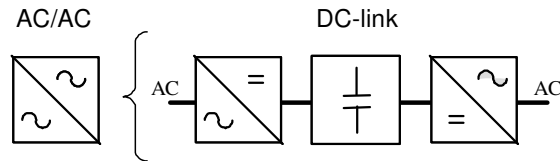
Figure 3.3: The back to back converter or AC/AC converter.

The front of the converter is connected to an inductive source due to the capacitive load. The capacitor C_{dc} also prevents disturbances from one side to affect the other. When the voltage, over the capacitor C_{dc}, is too low the converter will act as a 3-phase-diode rectifier. During start-up of the converters, the voltage over the capacitor is zero, causing high currents and consequently high risk for damaging the transistors, which is prevented by an inrush current limiter [Mohan, *et al.*, 2003] [Crappe *et al.*, 2000].
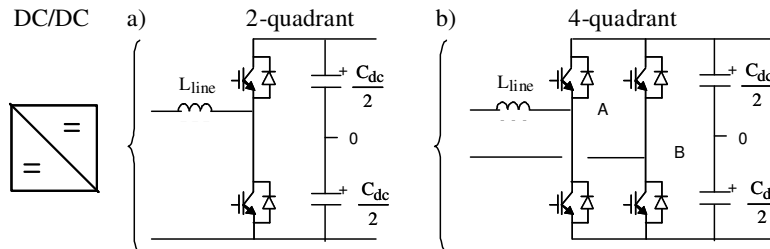
Figure 3.4: The DC/DC converter a) 2-quadrant b) 4-quadrant.

The back-to-back converter or the AC/AC converter consists of a force-commutated rectifier and a force-commutated inverter connected via a common dc-link as shown in Figure 3.3. The inverter maintains constant direct voltage and handles the reactive power exchange with the network while the rectifier side controls the torque and flux of the connected power unit, e.g. induction generator/machine.

The DC-link voltage is regulated by controlling the power flow to the AC network and the inverter operates on the DC-link, making it possible to

increase the output power of a connected power unit over its rated power [Carlsson, 1999] [Zhang, *et al.*, 2001]. Several different converter designs exist and the DC/DC converter is another common system component. The two-quadrant DC-DC converter consists of a DC link capacitor and one transistor half bridge as shown in Figure 3.4 a. The four-quadrant DC-DC converter has an additional half bridge as shown in Figure 3.4 b. The two half bridges, A and B, of the four-quadrant converter are switched so that one of them is switched off while the other one is switched on. Therefore the two half bridges are not off simultaneously. This is however not fully correct since actually both are switched off a very short period, the so called blanking time, preventing shortcut of the DC input.

The 4-quadrant converter has been most utilized at the consumption side, e.g. motor control, but is expanding in the supply and transmission side as well, which is later described for a double active bridge application.

Control

The converters are conventionally controlled by a fast signal processor able to collect measurements, process data and distribute control signals at a sampling frequency of 5-20 kHz depending on application [Mohan, *et al.*, 2003].
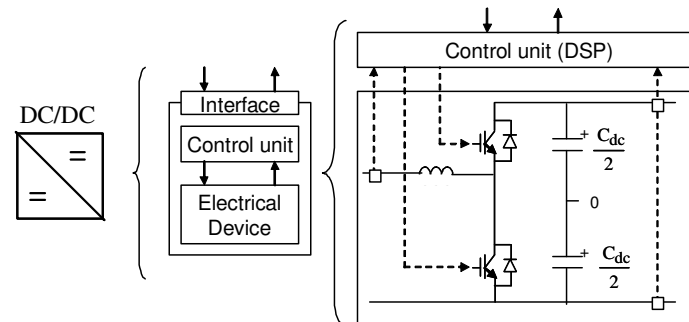
Figure 3.5: Converter control overview.

A control overview of a 2-quadrant DC/DC converter is shown in Figure 3.5 where the control unit includes all hardware and software for controlling the converter. The control unit collects inputs from sensors measuring the current and voltage in the circuit and calculates the on/off outputs to the transistors. The on/off switching is determined by using pulse width modulation (PWM). Figure 3.6 shows the resulting pulse pattern when a triangular carrier PWM is used for the four-quadrant

converter. The converter reference values are supplied to the modulator where they are transformed into pulses determining whether the upper or lower transistor of each half bridge should be on. This means that one voltage reference value must be generated for each half bridge, to form the pulse pattern for each half-bridge output potential.
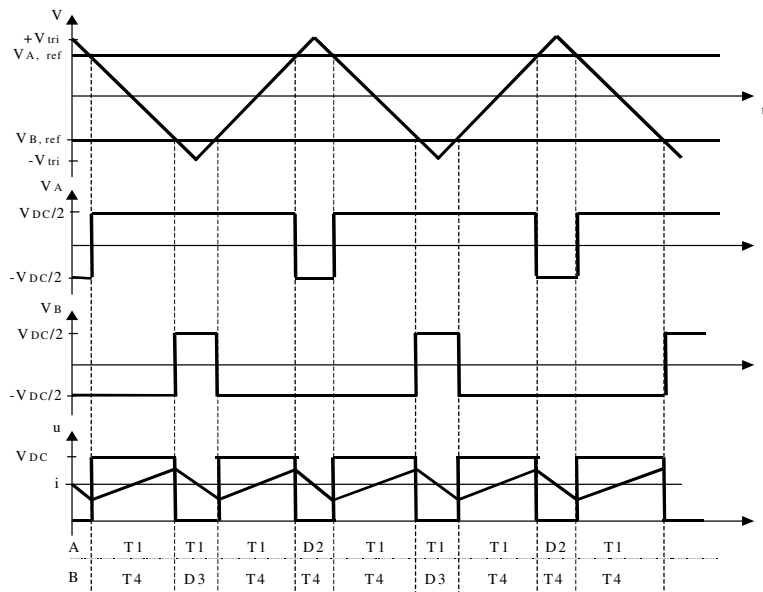
Figure 3.6: Modulation of an ideal four quadrant converter.

In order to generate this pulse pattern, the PWM uses a triangular carrier wave. The switching instants for a half bridge are determined by the crossings between the carrier wave and the voltage reference value for the half bridge. The reference levels are, $V_{a,ref}$ and $V_{b,ref}$, and are shown together with the triangle carrier wave V_{tri}. Also the potentials from the phase legs are V_a and V_b for each half bridge are shown. The voltage over the load is given by $u = V_a - V_b$. The interpretation of these pulse patterns is that for each half bridge, a high level and a positive reference will cause the upper transistor to conduct; else if the reference is negative the lower switch will conduct. In order to obtain the proper average output voltage for a certain reference value, the carrier wave amplitude has to be a function of the DC link voltage. The DC link voltage limits the maximum output voltage possible to supply to the load. The carrier wave varies

between minus half the DC link voltage, -VDC, to plus half the DC link voltage, +VDC.

Operation

Any type of converter will function as a highly controllable actuator in the system, enabling control of both active and reactive power. The power control is bi-directional and may be designed in various combinations of AC-AC, AC-DC and DC-DC. However, in normal operation, the power flow is from higher to lower voltage level. The power flow direction is commanded by specifying the minimum and maximum power exchange limits that corresponds to power import or export, e.g. P_{max} equals 50 MW and P_{min} equals -50 MW. These signals are used in the operational communication interface, described in next Chapter, and are connected to a superior control. In this case the main signals consist of the set point signal, command signal and govern signal. The command signal activates or deactivates the converter unit. The govern signal includes several modes of control such as power control and voltage control. The voltage droop control is suitable when sharing the load among other similar control units [Karlsson and Svensson, 2003]. The power converter unit can inform superior control systems about the limitations in power import and export. Additionally, the maximum and minimum power rates are compared with connected devices or units to determine the conditions for the interconnected chain of devices.

DC and AC transmission

There have always been challenges associated with transporting large amounts of power over a transmission network system. Recent requests for transmission service have resulted in new limitations of the system because of the need to buy and sell energy into different market locations. This has increased the need for improvements in transfer capability while maintaining a high level of reliability. This challenge has increased interest in creating a more robust power system through the use of new technologies applied to the existing transmission network.

One solution to improve power system control and transfer capability from one AC power system to another is achieved by using a Flexible Alternating Current Transmission System (FACTS) unit. These units improve system operation as they enable more accurate control of the

power flow, and better control of voltage and system stability. Several of the FACTS technologies are based on VSC [Bahrman, *et al.*, 1999].

Research has been devoted to develop new DC equipment to increase the transfer and control capability of the power system. DC lines/cables between a renewable power generation system and the common transmission network will most likely extend the range of distributed power systems as the VSC HVDC technology already is commercially produced.
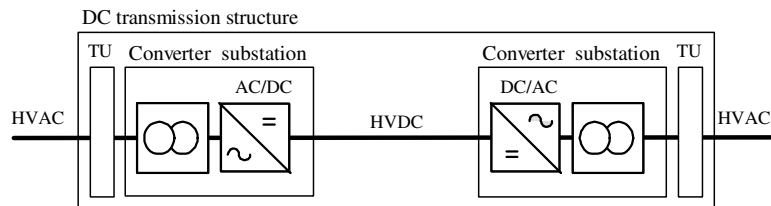
Figure 3.7: HVDC transmission structure.

The traditional structure of a HVDC transmission unit is based on thyristor converters, which have limitations in both controllability and the usage of more than two terminals. The VSC based HVDC transmission structure is therefore the basis for multi-terminal DC distribution as shown in Figure 3.7. The structure is designed by back-to-back VSC converters using PWM. Besides controlling the power flow bidirectionally, it can supply reactive power and provide independent dynamic voltage control at its two terminal units (TU). The two converter stations can be paralleled in a modular way, thus increasing redundancy.

The converters can be used for black start or to supply a passive load. Higher voltage designs can be used with transmission lines or cables to form point-to-point or multi-terminal transmission links. The controlled power transfer capability allows the exchange of power between the two networks while the voltage control stabilizes the voltage following line outages especially during peak load periods.

An alternative structure with the same function as for the VSC based transmission unit is the double active bridge (DAB) design. The double active bridge (DAB) is a VSC HVDC transmission that can be operated at various voltage levels between DC power systems. This requires a galvanic separation for large DC distribution systems to prevent the risk of elevated voltage levels occurring in the low voltage parts of a DC distribution

system in the case of a ground fault located in high voltage parts, which is explained in [Karlsson, 2002]. The (DAB) is a transmission system structure that corresponds to such requirements as shown in Figure 3.8. The DAB converter provides bidirectional power flow, a capacitive interface and also galvanic separation due to the transformer. The DAB converter is often designed to operate at high frequencies. Future DAB structures will have higher frequency that requires smaller transformers, which probably leads to standardized smaller power units.
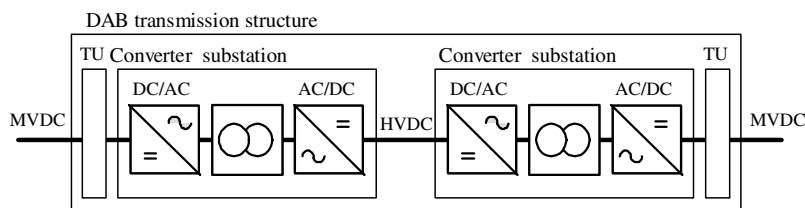
Figure 3.8: Galvanic separated double active bridge structure.

The galvanic isolation of the DAB is a desirable property since fault currents should not propagate through the entire DC distribution system. An example of a transmission system for an offshore wind power plant is described later.

Model design

In order to analyse and test the system that has been described in this section, various types of power electronic devices from AC to DC, and DC to DC have been modeled. In Appendix A.4, the PowerElectronics Library developed is briefly described, which includes several types of converters. Another converter library, in the time scales of microseconds, has been developed in [Karlsson, 2002] where the fundamental research and investigations for the more advanced converter models and proof of high control authority in several applications has been verified. Since the time scale for this work mainly is in the range of seconds a general converter model class has been developed. It is called a power exchange unit and represents several converter types, see Chapter 5 and Appendix A.6.

The results of the tests prove that there are no limits regarding controllability using converters. The restrictions lie in the interconnected devices that, depending on technology and physical laws, have their limits in controllability, which the converter has to adapt to. Depending on the

interconnected device or unit, the rate of frequency, voltage, power (active and reactive) control may be in the range of milliseconds. Additionally the power flow direction may be reversed at the same rate, which makes the converter technology extremely powerful if properly operated.

3.3 Sustainable power units

New applications based on RES are able to improve power system performance. The existing RES today are only used to generate maximum possible power. This situation will change, for example where control of RES can compete with control of other types of generation units. With a number of new approaches for RES operation, future RES technology will have a different role in the system. New technical solutions for RES will give the possibility to provide a number of services to energy market actors such as energy consumption customers, transmission service providers, and system responsible actors. The services include traditional power generation, balance power and reserve capacity, but also additional services such as reactive supply and voltage control, possibly also back-up supply and system black start or stand-alone operation.

Solar power

Solar power has the potential of supplying the world's population now and in the future in a sustainable way. Solar power plants can in principle be adopted everywhere and in all sizes. During an early introduction phase most of the solar power plants probably will be established in regions close to the equator. Research has shown that conversion to solar power would be profitable in the long run for many applications in remote areas even without calculating environmental costs. In the future, stand-alone electric power systems or soft connection of dispersed electricity generating stations to central electric power systems may become alternatives to central generation and transmission of electricity. It is quite clear that the potential future market is very large. The main problems today are the high cost of solar power equipment, the relatively low energy conversion efficiency combined with the very low purchasing power of many people living in the solar belt of the world.

As photovoltaic modules have no moving parts they are virtually free of breakdowns. The inverter and the charge controller (when a battery system is employed) are electronic equipment with a very low failure rate

[Watanabe, *et al*., 1998]. The expected trouble free production is at least 20 years. With the development of technology, the cost of the solar arrays is expected to decrease continuously in the future, making them attractive for residential and industrial applications.

Design

The majority of photovoltaic cells are made from crystalline silicon. Mostly mono crystalline material rejected by the electronic industry for reasons of impurity is used. The cell can also be made from multi-crystalline material, where the step is skipped in which a mono crystal is slowly grown from a small seed to a large block. This makes these cells less expensive while the efficiency becomes somewhat lower, 10-13 % as compared with 12-16 % for commercial mono crystalline. At least three different technologies exist:

- *Crystalline silicon technologies*: The technology has high durability. Twenty-year warranties are common for crystalline silicon modules. Single crystal tends to be slightly smaller in size per watt of power output, and slightly more expensive than polycrystalline. The silicon used to produce crystalline modules is derived from sand. It is the second most common element on Earth. However, the photovoltaic effect must be purified to an extremely high degree and such pure "semiconductor grade" silicon is very expensive to produce.

- *Thin film technologies*: This technology is also called amorphous - meaning "not crystalline" - may have an active material of silicon. Thin film panels can be made flexible and lightweight by using plastic glazing. The disadvantages of thin film technology are lower efficiency and uncertain durability. Actually, this family includes several different materials as amorphous silicon (a-Si), CdTe, CIGS and GaAs. A common feature of these PV-cells is that the semiconductors are applied to a surface in very thin layers (a few µm). The advantages are that less semiconductor material is used and that it is possible to make large PV-modules in a fully automated process. The technology is being greatly improved however. PV experts generally agree that crystalline silicon will remain the "premium" technology for critical applications in remote areas [Coors, *et al*., 1999].

- *Dye Sensitised Solar Cell*: This technology is also called the Grätzel-cell. Instead of two solid-state semiconductors, a dye solution and a solid state semiconductor (TiO2) are employed. The advantage of this

type is that the cells can be produced at a relatively low cost. No clean room is needed. At low light irradiation, such as in indoor applications, these cells are more favourable as the efficiencies of the other types decrease and become of the same order as the dye-sensitised cell. The disadvantages of these cells are their lower efficiency. A type of PV-cell that at present has the highest value of efficiency (officially 32.6 %, February 2000) is called the multi junction cell. It consists of two or more PV-cells stacked with different band gaps so each cell utilises different regions of the irradiated spectrum. [Lindgren, 2000].

Electrical system

A photovoltaic cell is similar to a diode, which is designed to promote the photovoltaic effect. In darkness, the voltage-current characteristic is described by the diode equation. When the PV-cell is illuminated, the iu-curve will move along the current along its maximum power point as shown in Figure 3.9 b. In other words, it produces a current approximately proportional to the irradiated power.
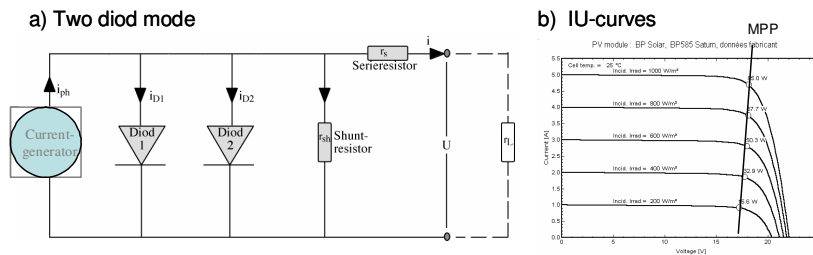
Figure 3.9: a) Electrical circuit of a photovoltaic cell; b) U-I graph with the maximum power point (MPP) line.

The current source generates a current proportional to the irradiation. In cases where higher accuracy is needed, two diodes in parallel are often used, where one models the characteristics at high irradiation and the other models the low power range. This is known as the two-diode model as shown in Figure 3.9 a. The parallel resistor models the leakage resistance of the semiconductor. The series resistance corresponds to the sum of the metallization resistance and resistance in the semiconductor.

A conventional PV-unit with PV-modules is connected in series to create a sufficiently large voltage as shown in Figure 3.10. A centralised full

bridge-inverter transports the energy from the PV-generator to the network. The inverter topology is a straightforward solution using as few components as possible. Optionally, a transformer could be used to insulate the voltage of the PV-plant from the network [Tadokoro, *et al.*, 1994] [Kim, el al., 1996]. When using only one inverter, which occasionally trips, there is no energy production until it is replaced or repaired.
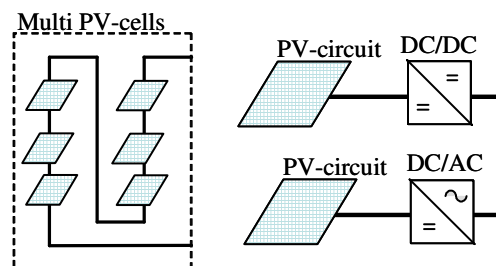
Figure 3.10: PV circuit connected to DC/DC or DC/AC converter.

Several configuration alternatives are possible for a distributed system. Regarding the number of connected PV-cells in series the voltage is increased but it also brings a risk in malfunction of the total PV-module. Solar power systems may be very sensitive to shading as this affect the whole module and decrease the efficiency radically.

Control

Various methods of maximum power tracking have been considered in photovoltaic power applications [Simoes, el al., 1998] [Chihchiang, el al., 1998] [Chihchiang, el al., 1996]. Of these, the perturbation and observation method, which moves the operating point toward the maximum power point by periodically increasing or decreasing the array voltage, is often used in many photovoltaic systems. It has been shown that the method works well when the insulation does not vary quickly with time; however, the method fails to quickly track the maximum power points. The incremental conductance method is also often used in photovoltaic systems [Chihchiang, el al., 1998]. The method tracks the maximum power points by comparing the incremental and instantaneous conductances of the solar array. The incremental conductance is estimated by measuring small changes in array voltage and current. These small changes may be induced by deliberate control action. A method, which improves this method and can identify the incremental conductance of the array more rapidly, has

been proposed [Simoes, el al., 1998]. However, with a DSP-based controller, maximum power tracking with perturbation and observation can be achieved rapidly and accurately by increasing the sampling frequency.

A complementary method has been developed that from out of several conditions starts the maximum power tracking by injecting a small disturbance in the control algorithm. This method always finds the maximum point even if the change in solar radiation is minor. The method has only been verified by simulation models.

Model design

The power production of solar power is highly depending on the environmental influence even though the equipment has no moving parts. A library including environmental inputs has been developed containing direct and indirect solar radiation and solar angle. The temperature of the PV cell is also considered and the ambient temperature and wind speed in the models. The environment parameters may be connected to real or calculated data. The developed PV-module is general and based on the two diode circuit including temperature dependence. The general module can be chosen to include several PV-cells in series and parallel, which enables the user to configure output voltages and power. The PV model is connected to a DC/DC converter and several simulations have been made testing the operation and controllability of a solar power unit. The models and simulations are described in Appendix A.5.1.

The results indicate that the solar power units are very fast but also very sensitive. As the technology has no rotation mass (inertia), the power changes are quickly following the environment disturbances, such as shading depending on solar angles and moving clouds. Although, as long as the irradiation is adequate, solar power can provide several services including primary and secondary control that may be of future importance especially in small distributed applications.

Wind power

The total available wind resource in the world today that is technically recoverable is about four times larger than the world's entire electricity consumption. Wind power is the most progressed and commercially available of renewable energy technologies and provides a total natural power source, which is both pollution-free and unlikely to ever run out.

Presently, it is one of the world's most growing new electrical generation sources. The wind energy industry is in an expanding phase and will probably remain like that for the coming decades. Wind turbines have been steadily increasing in both power output and efficiency trends, which are expected to continue. Wind power is among the cheapest of the renewable energy sources. At good wind sites it is already fully competitive with new traditional fossil fuel and nuclear generation. Its cost also continues to fall as the technology improves and the use of individual sites is maximized. Around the world, it is likely that 15-20% is an appropriate average figure for the potential penetration of wind power into national transmission systems.

Design

The power rating of a typical wind power unit today is 3 MW and test units are already erected with 4.5 to 5.3 MW. The turbines are about to reach such a size that they might be too large for handling maintenance or fatal failures according to economical aspects. The design of a wind turbine is based on standard components and well-known technology for all the important functions. Furthermore, the simplicity and robustness of the construction is vital considering reliability, maintenance and for operating and maintaining the plant. Present wind power systems use conventional horizontal-axis wind turbines. The turbines have mostly three blades, about 70 to 125 meters in diameter, which can be "pitch controlled" to meet the variable aerodynamic torque. The speed of the wind turbine is normally in the range of 10 to 20 rpm and is connected to the nacelle, which is placed upon a tower, 70 to 100 meters in height. Inside the nacelle the wind turbine is connected to the generator directly or via a gearbox. The generator types are either induction or synchronous machines with a typical speed of 1500 rpm, if equipped with gearbox, or about the same speed as for the turbine.

Electrical system

The electrical system or drive train of a wind power unit has several different solutions depending on choice of generator and control strategy. The choice affects flexibility and controllability differently and consequently the transmission network in providing services. Some of the various designs are shown in Figure 3.11. Traditionally induction generators connected via a gear box have been used due to the robustness, simplicity and low cost as shown in Figure 3.11 a. The turbine operates

with a fixed speed and the blade angel is either fixed in passive stall or
controllable by using active stall to compensate wind variations [Abdin and
Xu, 1998]. Reactive power is consumed from the network but can be
compensated by capacitor equipment or power electronics. The active
power control is limited as the variation in wind propagates directly to the
network due to the difficulty in controlling the rotor speed. One of the most
used designs at present is shown in Figure 3.11 b, which is a double fed
induction generator with variable speed pitch turbine and is able to control
both active and reactive power [Stavrakakis, *et al.*, 1999]. The variable
speed extracts more energy but also adjusts the blades often, which may
cause more component failures.
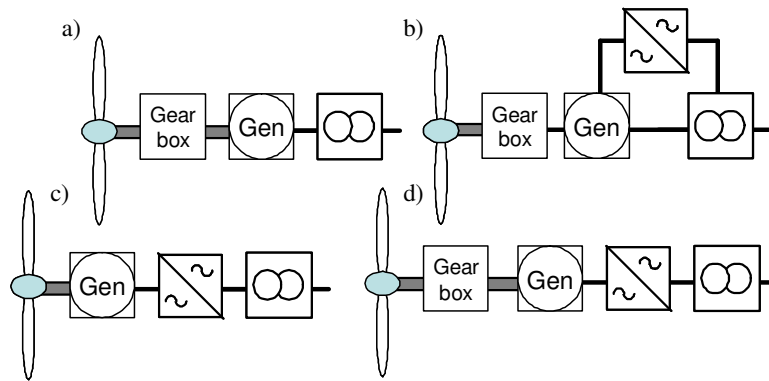
Figure 3.11: Wind turbine drive trains.

The rotor is fed from an AC/AC converter connected to the transformer
that takes 15-25 percent of the power flow on the drive train and reduces
the mechanical stresses and the fluctuations in delivered power. The
controllability is good in comparison with the first solution.

In Figure 3.11 (c), the direct connected (gearless) full converter solution is
shown.   The electrical system only includes a permanent synchronous
machine (PMSM), the AC/AC converter and a transformer [Graurs, 1996].
As the converter includes a DC-link, the generator is completely decoupled
from the transmission network. The converter can be used for controlling
the active and reactive power and the controllability is very high. The
disadvantages with present turbines using this solution are that the
generator required is large and heavy and that the converter is large as it
controls the total generated power. As weight is related to cost, the solution
is relatively expensive.

The fourth solution shown in Figure 3.11 (d) is basically the same as the previous except for using a gearbox enabling the use of traditional high speed generators. This solution means smaller generators and lower weight even when the gearbox is included. The disadvantage is that there is another component decreasing the reliability of the power unit. Furthermore, the gearbox, so far, is the most failure rated component statistically [Hilloowala and Sharaf, 1994].

Future wind power units

The present largest threat towards wind power business is the technical risk of the wind turbines. There has been and still is a continuous race among suppliers concerning turbine capacity. Some wind turbine generations will still be developed until a common and reliable platform for future design has been reached.

The future sustainable solution will most likely be based on as few components as possible, for reliability reasons, and with high controllability enabling several services to the transmission network. For those reasons the direct drive train with full converter is most promising. The generators will probably be lighter and produce a higher voltage level (e.g. 50 kV) and the turbine may have two instead of three blades. The power capacity will be limited by the logistic conditions and mechanical limits. For example the rotor diameter is about 125 meters for a 5 MW unit and the figures for larger sizes are about 170 meters diameter for a 10 MW unit and 250 meters diameter for a 20 MW unit, which may seem unrealistic. The tip speed is also a limiting factor that probably decreases with large units and consequently demands heavier solutions as the connection is nonlinear due to the basic torque equations. However, the next coming years most probably consolidates in the size of about 5-7 MW for a longer period creating conditions for the development of mature and reliable products for future offshore power plants.

Operation

The basic operation of an individual wind turbine is rather simple as each individual unit is autonomous and generates power according to the wind speed as shown in Figure 3.12.

The power production curves vary depending on unit design and supplier. The wind power unit starts to generate power at a cut-in wind speed of about 3-4 m/s. The nominal power is reached at about 13-15 m/s and the

cut-out speed is at 24-28 m/s. In between the cut-in and nominal wind speed the turbine strives to maximize the power production by adjusting the angle of the rotor blades. In between the nominal and cut-out wind speed the turbine gradually reduces its efficiency by adjusting the rotor blade angle out from the wind. The pitch controlled unit is in general treated here but as a comparison the stall controlled unit is also shown in the figure.
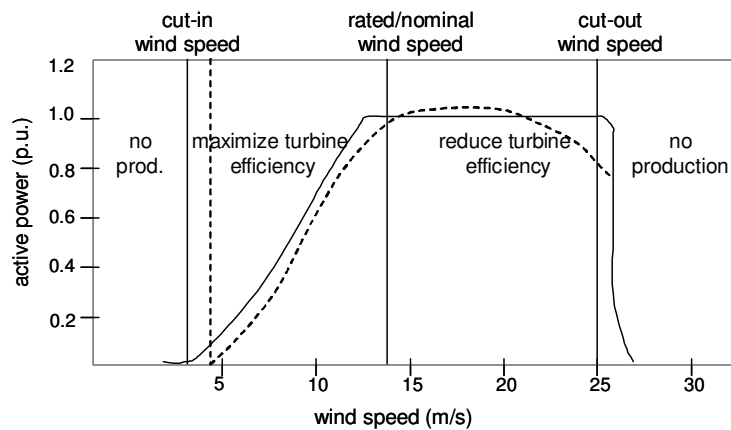
Figure 3.12: Power curves for variable speed pitch controlled (solid) and stall controlled (dashed) wind turbines.

The stall controlled unit has very limited controllability and may vary widely in the nominal wind speed area, which has several disadvantages [Muljadi, et. al., 1998].

Control

Almost all suppliers will have future wind turbines with variable speed and pitch control. The primary advantages are increased energy efficiency and reduced drive train loads [Thiringer and Linders, 1993], which is important with respect to the operational lifetime. As the turbines will be based on some type of converter solution the controllability will be high [Tsiolis, 1994]. In comparison with solar power, wind turbines are not as sensitive to wind disturbances regarding fluctuation in power production due to the rotating mass, 20-50 tons depending on unit size. The wind turbine control can roughly be divided in two control loops, one that coordinates the active power regulation by controlling the rotor speed according to wind speed

conditions and the other that regulates reactive power by controlling the voltage of the DC link. This is fast reversed in case of a weak network calling on primary control services. There are additional benefits regarding acoustic noise, power quality and control properties [Baars and Bongers, 1994]. Depending on system configuration a wind power plant will be able to provide a variety of services to the transmission network.

The control structure of a wind turbine unit is an important issue enabling high efficiency and fast control. This is also the basis for integrating command signal corresponding to several services that are described in this chapter under "wind power systems".

Model design

A wind turbine unit model based on future technology for power generation has been investigated. The models developed are based on subunits including both a process and control part. The model of the wind turbine is extensive regarding operation and control structures and has proven useful when switching between control loops due to different control strategies. The control speed is fast even for a large turbine. The turbine is able to reduce power production from 100 to 20 percent in 2-3 seconds. However, the performance depends very much on the aerodynamic control that may be in the range of 0.5 -10 seconds and the electric control that is in the range of milliseconds. Power control is consequently easily managed by the turbine unit and as the unit is able to control voltage and frequency, this opens up for stand-alone functions for distributed systems. The model and simulations are described in Appendix A.5.2.

Energy storage

Electrical energy storage may be a key emerging technology which is likely to find widespread application within electric power systems and end-user consumers. The current situation in the electricity market may offer opportunities for energy storage technologies, particularly in combination with RES generation, in which a few seconds to a few hours of electricity can be held for use at a later time. These systems can be located near the generator, transmission line, distribution substation, or the consumer, depending on the application. Storage can play a flexible, multi-function role in the electricity supply network in managing power resources effectively.

In combination with RESs, energy storage can increase the value of photovoltaic and wind-generated electricity by making supply concurrent with periods of peak consumer demand. Energy storage may facilitate large-scale integration of intermittent renewable resources such as wind and solar into the electric network. Strategically placed storage systems can increase the utilisation of existing transmission and distribution, which can be used to reduce the pressure on individual transmission lines that are near maximum rating by reducing substation peak load. Energy storage can also serve customers as a controllable demand-side management option that provide services, such as; improved power quality, uninterruptible power supply for outages etc.

Several energy storages are here briefly described, such as pumped hydro, compressed air energy storage (CAES), battery energy storage, flywheels, superconducting magnetic energy storage (SMES), super capacitors, and fuel cell/electrolyser systems.

- *Pumped Hydro*; Conventional pumped hydro facilities consist of two large reservoirs, one located at a base level and the other situated at a higher elevation. Water is pumped to the upper reservoir where it can be stored as potential energy. Upon demand, water is released back into the lower reservoir, passing through hydraulic turbines, which generate electrical power as high as 1,000 MW. The barriers to increased use of this storage technology include high construction costs and long lead times as well as the geographic, geologic and environmental constraints associated with reservoir design. The efficiency of pumped hydro is about 90 percent and is presently considered as the most cost effective storage [Morin, *et al*., 1993] [Hongwei, *et al*., 1998] [Hannett, *et al*., 1998].

- *Compressed Air Energy Storage* (CAES): CAES plants use off-peak energy to compress and store air in an airtight underground storage cavern. Upon demand, stored air is released from the cavern, heated and expanded through a combustion turbine to create electrical energy. In 1991, the first U.S. CAES facility was built in McIntosh, Alabama, by the Alabama Electric Cooperative and EPRI, and has a capacity rating of 110 MW. Currently, manufacturers can create CAES machinery for facilities ranging from 5 to 350 MW. EPRI has estimated that more than 85% of the U.S. has geological characteristics that can accommodate an underground CAES reservoir [Zink, 1997].

- *Batteries*: In recent years, much of the focus in the development of electric energy storage technology has been centered on battery storage devices. There are currently a wide variety of batteries available commercially and many more in the design phase. In a chemical battery, charging causes reactions in electrochemical compounds to store energy from a generator in a chemical form. Upon demand, reverse chemical reactions cause electricity to flow out of the battery and back to the grid. The first commercially available battery was the flooded lead-acid battery, which was used for fixed, centralized applications. Lead-acid batteries are often considered to be the "weak link" in renewable energy systems. However, today renewable energy batteries are better than ever, and so are the devices that regulate and protect them. Battery failures are rarely the fault of the batteries themselves. The valve-regulated lead-acid battery is the latest commercially available option. This battery is low-maintenance, spill- and leak-proof, and relatively compact. Zinc/bromine is a newer battery storage technology that has not yet reached the commercial market. Other lithium-based batteries are under development. Batteries are manufactured in a wide variety of capacities ranging from less than 100 watts to modular configurations of several megawatts. As a result, batteries can be used for various utility applications in the areas of generation and customer service.

- *Flywheels*: Flywheels are currently being used for a number of non-utility related applications. A flywheel storage device consists of a flywheel that spins at a very high velocity and an integrated electrical machine. The machine can operate either as a motor to turn the flywheel and store energy or as a generator to produce electrical power on demand using the energy stored in the flywheel. The use of magnetic bearings and a vacuum chamber helps reduce energy losses. A proper match between geometry and material characteristics influences optimal wheel design. As a result, engineers have focused on the development of materials with high working strength-to-density ratios. Flywheels have been proposed to improve the range, performance and energy efficiency of electric vehicles. Development of flywheels for utilities has been focused on power quality applications [Akhil, *et al*, 1997] [Hardan, *et al*., 1999].

- *Superconducting Magnetic Energy Storage* (SMES): SMES system stores energy in the magnetic field created by the flow of direct current in a coil of super conducting material. To maintain the coil in its super conducting state, it is immersed in liquid helium contained in a vacuum-

insulated cryostat. The energy output of this storage system is much less depending on the discharge rate than batteries. SMES systems also have a high cycle life and, as a result, are suitable for applications that require constant, full cycling and a continuous mode of operation. Although research is being conducted on larger SMES systems in the range of 10 to 100 MW, recent focus has been on the smaller micro-SMES devices in the range of 1 to 10 MW. Micro-SMES devices are available commercially for power quality applications [Tripathy, *et al*., 1991] [Torre, 1997].

- *Advanced Electrochemical Capacitors*: Super capacitors (or ultra capacitors) are in the earliest stages of development as an energy storage technology for electric utility applications. An electrochemical capacitor has components related to both a battery and a capacitor. Consequently, cell voltage is limited to a few volts. Specifically, the charge is stored by ions as in a battery. Small super capacitors in the range of seven to ten watts are available commercially for consumer power quality applications and are commonly found in household electrical devices. The development of larger-scale capacitors has been focused on electric vehicle.

- *Hydrogen*: Hydrogen is among the energy storage utilities that presently have greatest development rate. Regenerative fuel cell system technology for energy storage has been a power system concept for many years. Compared to battery-based energy storage systems, fuel cells has received relatively little attention or resources for development because the energy density and electrical efficiency were not sufficiently attractive relative to advanced battery systems. Commercial development of the proton exchange membrane (PEM) fuel cells for automobiles and other terrestrial applications and improvements in lightweight pressure vessel design to reduce weight and improve performance have created a possibility for a high energy density fuel cell energy storage system. Future developments in the areas of hydrogen and oxygen storage, pressure vessel design, higher temperature and higher-pressure fuel cell operation unitized regenerative fuel cells, and commercial development of fuel cell technology will improve both the energy density and electrical efficiency of fuel cell system [Carlsson, *et al*., 1998].

Control

The storage units are classified as short-term (fast) and long-term (slow) and have consequently different ways of operations. Regarding operation, the storage may by passive or active. The passive type is a buffer that consumes and produces power depending on the instantaneous power balance in the power system. The active storage tries to meet the network load, as for generation units, provided that its generation capacity (state of charge) gets too low the active storage behaves as a consumer or load unit.

In active operation, a short-term storage unit may be able to provide the network with ancillary services and consequently participate in a future market similar to a generation unit, as long as the storage unit is not empty. When recharging the storage, the unit will operate as a controllable load when there is surplus and it is permitted.

Model design

The model used for storage units is general and is basically built by mixing the properties of the generation and load units in combination with a storage device. The storage unit parameters are then used to adjust the controllability and storage capacity by an actuator and an energy storage device. The short-term storage unit include a converter unit enabling high controllability. Regarding DC electric energy storage elements, the same type of converter unit could be used for storage types such as batteries or fuel cells. The "RenewablePowerSystems" library explained in Appendix A.5 includes battery storage unit models that are constructed as described.

Loads

Load on the electric power system arises from customer demand, and it is the driving force behind every electric utility activity. Load units are today more or less not controllable and should always be provided according to theirs demands. However, even today some form of priority control exists that in case of a severe system failure selects load units to be disconnected. Assuming that future load units will be controllable or schedulable to a large extent, will give new perspectives on how load units should be operated and connected to the market.

In the short time perspective, schedulable load units are of highest interested and to determine some of those a list regarding both smaller and larger electrical loads is divided into following major categories.

- *Passive loads*: all load units not able to be controlled that are today the largest category.

- *Critical loads*: load units essential to maintain production or safety. Unscheduled shutdowns of these loads are not tolerated.

- *Schedulable loads*: in this category load units can be shut down temporarily without significantly affecting operations or worker comfort. Examples of such loads are air conditioning, exhaust and intake fans, chillers and compressors, water heaters, and battery charges. Electric water heaters represent a load that can usually be scheduled.

- *Controllable loads*: these are load units similar to the schedulable loads but able to adjust their consumption in a variable manner, e.g. by various power load control and even voltage control depending on included equipment.

The schedulable and controllable load units are able to provide future power system with additional flexibility in preventing outages. This can be utilized in several ways, for example by measuring all necessary loads in buildings, a load management control system can cut off e.g. resistive load needed for short periods, to handle load peaks. This will create a need of intelligent outlets and electrical units.

Control

Controlling load equipment is the first method that will be used to reduce loading in the event of a system contingency situation. Once a network emergency occurs or the network controller becomes aware that load requires shedding for system security reasons, load control will be activated to quickly reduce the load. Load control provides a readily available, easily controllable method to reduce load by a given amount.

The load management controller automatically regulates or limits operation in order to prevent set maximum demands from being exceeded. The type of controller best suited for a system operation is the one that can predetermine the demand limit and the demand interval. The overall usage of power would constantly be monitored from a distributed control system and the power usage of all the controllable load units will also be

monitored. By having this information the controller calculates when an overrun of the desired demand limit will occur. The controller will delay any shed action to allow time for loads to shed normally. When it is determined necessary to shed one or more loads to avoid the demand being exceeded, the controller, at the last possible moment, will shed the necessary loads by priority. In the future, load management functions probably will be employed automatically and implemented in distributed EMS system.

Model design

The Load library in Appendix A.5 includes several types of load units that are embedded in the building model. The overall building energy consumption is based on temperature balances and some statistic data but also include ventilations, schedulable electric water heaters and drilling machines representing fast load units. Selected simulation results are presented in the A.5.3 and A.5.4.

3.4   Sustainable power systems

New small local power systems as well as large power system based on RES are being evolved. Several local systems are very small covering a single building supply while others cover entire regions. The configurations and interconnection differ depending on producer/customer purposes and requirements.

Distributed system enabling "stand-alone" capabilities, expand for every new erected local system. However, their mutual possibilities in interacting the entire system are not much utilized. This will be an important issue as soon as solar power will start its expansion along with new types of storage possibilities. Distributed generation is almost always considered as connected to the distribution network at medium or low voltage level due to their relative small capacity. This is not the case regarding large offshore wind power plants that are being constructed. They will most likely be connected to the high voltage transmission network and will not be part of small distributed systems. However, if they are strategically placed they may provide the region with several services. Depending on view, this region is also a distributed system although much larger.

Large systems are characterized as single units that may effect or provide services to the national power system. In other words, high capacity power

units connected to the high or medium voltage transmission network. However, as single power unit may be composed of numerous subunits, the unit works as one controllable unit connected to the TSO. The production fluctuations of large generation systems based on RES are balanced by other generation units in the national power system. The function is similar to a smaller unit being up-scaled. The same view can be applied for a small local system. Several small local systems could work as an aggregated unit interacting with the TSO. This however, requires the implementation of distributed automation and advanced coordination functions, which is treated in Chapter 6.

The distributed power systems´ applications may differ depending on location and capacity and are here consequently divided in a description of local power systems and wind power systems, which correspond various distributed systems regarding scale and function.

Small local power system

In the future, stand-alone electric supply systems or "soft connection" of dispersed electricity generating stations to central systems may become feasible alternatives to central generation and transmission. This is the case in large areas of developing countries and may become a new approach also in the future in industrialized countries. Stand alone solar/wind hybrids with diesel engines are today generally used. In a future situation with price reductions of solar and hydrogen technology and at the same time increased prices of fuel a change to solar based supply will be feasible. There are many projects around the world utilizing solar, wind and hydropower with different storage types. Several configurations for renewable power systems have a great potential and some of them have been investigated during the last decade [Carlsson, *et al.*, 1998].

The potential market for stand-alone systems of different sizes is enormous in the world. For instance, approximately 20 GW of diesel power station capacity is installed around the world in the range of 5-150 kW per station and this is expanded every year [Carlsson, *et al.*, 1998]. With the assumption that the average power station size is 50 kW, 20 GW corresponds to 400 000 plants.

A large market for solar electric energy is emerging considering the fact that 2 billion people are still without any electricity. Due to population growth, this present number will not decrease in the medium-term future,

unless massive spreading of small stand-alone systems will take place. Given an estimated average peak demand of 10 kW for one of those systems which should supply about 100 people, an additional number of 20 million stand-alone electric power systems would be required to satisfy the needs of all people. Recent studies [Carlsson, *et al.*, 1998] indicate that solar system in the order of size below 1 kW may have the best market penetration possibilities for the nearest future. It is recognised that hybrid solutions in many applications are more cost- effective today, but that the future situation is in favour of solar power systems for small-scale DPSs.

Design

Investigations have been done of transient performance problems and penetration limits, associated with the connection of wind turbines in isolated diesel supplied power. In a diesel-wind turbine system of a small Greek island the impact of the connection or the parallel operation of the wind turbines on the frequency and voltage, as well as the transient stability of the system in case of short circuits in the network have been studied [Malatestas, et la., 1993]. Performance of the transient stability analysis of isolated diesel-wind turbine power systems for accurate assessment of their interaction has been made. Approximations in the various component models, when necessary, remain between limits that do not affect the accuracy of the analysis performed [Novak, *et al.*, 1994]. A general algorithm to simulate and assess the dynamic behaviour of any isolated diesel-wind turbine power system was analysed and implemented. The case studies were made on the French island of Desirade [Kariniotakis and Stvrakakis, 1995].

Another hybrid system developed included a 10 kW application comprising wind and solar collectors, each one having a 5 kW rating, with a lead-acid battery for storage and a 10 kW PWM inverter for the final output. The wind turbine generator is a 5 kW, 200 rpm, direct-drive, permanent-magnet, axial-flux machine based on the 'Torus' configuration. The three-phase output is rectified to form a variable voltage DC link. The power converter uses two DC-DC power converters connected in series, each with a bypass diode which conducts continuously when the corresponding source is not available [Crescimbini, *et al.*, 1996]. A design procedure for photovoltaic/wind hybrid power generation system has been investigated [Sikyung, *et al.*, 1997].

The hybrid system is composed of a DC/DC converter for photovoltaic energy conversion, a DC/DC converter for wind energy conversion, a four switch IGBT inverter converting the combined DC power to the AC power and a backup power battery. The desired battery size is important to meet the stable output and economic cost aspect since this system utilizes a fluctuating and finite energy resource. The purpose was to develop a sizing method for the PV/wind energy hybrid system with load sharing operation. The method demonstrates a simple tool to determine the desired battery size that satisfies the energy demand from the user with the photovoltaic and wind natural source. The method is verified on a 14 kW hybrid power system including a 10 kW PV generator and a 4 kW wind generator established in Cheju island, Korea.

Furthermore, there have been simulation and experimental verification of the dynamic behaviour of small autonomous power systems with photovoltaic, wind turbines and small hydropower. The combination of the hydropower plants and the diesel generators is of interest since they have quite different rates of power change. For the effective integration of the photovoltaic devices into the utility grid, a method for controlling the inverter's operation has also been done. According to this method the power demand from the network is monitored and control signals adjust the angle and the magnitude of the inverter's voltage. It is shown that this method improves power quality and stability of the interconnected system [Karlis and Dokopoulos, 1996]. A brief review has been presented of common electrical generation schemes for wind turbines and photovoltaics. Attention was mainly focused on the power converter interfaces used for the grid-connected operation of the renewable generators. The wind turbine soft starting arrangements are described and the most common variable speed operation configurations. The fundamental characteristics and requirements of the power conditioning equipment used in photovoltaics are outlined and the power converters of certain generators [Papathanassiou, *et al.*, 1995].

Several conclusions can be drawn from small-scale local systems based on solar power and fuels cell unit, and energy efficiency may all be an economically attractive part of a local system [Wenger, *et al.*, 1996]. There is a fairly good match between supply and demand on an annual, monthly, and hourly basis; fuel cells operated in a cogeneration mode with PV complement each other in terms of electricity supply because fuel cell electricity production peaks in the winter while PV electricity production peaks in the summer; [Hoff, *et al.*, 1997] a relatively small number of

customers (less than 50) can result in a reliable local system; customer loads that are more certain result in a smaller micro-grid; and local systems may represent a new market for PV, fuel cells, and energy efficiency.

Configurations

The original system configuration, Figure 2.10, covers several types of configurations where some are shown in Figure 3.13. The systems are divided in stand-alone and interconnected systems. Stand-alone systems based on a high penetration degree of RES are characterized by stochastic production and stochastic consumption systems that are more complex to operate. Depending on consumer demands the need for a momentary reserve capacity is inevitable unless the consumers accept intermittent disconnection and connection of the load.
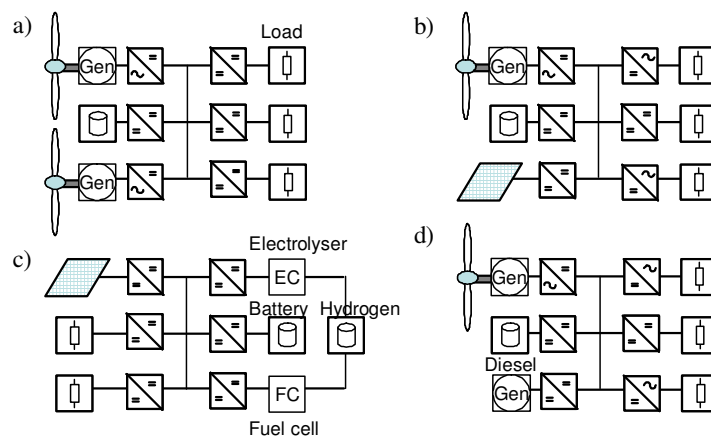
Figure 3.13: Different system configurations.

The usage of renewals to power a stand-alone system, or an island without connection to the mainland, requires an additional power unit. The wind or solar power cannot be guaranteed to generate electricity when needed, so storage units or an alternative power source are required. However, when renewables are integrated within a larger network the situation is very different and they are categorized as interconnected systems. The system configuration in Figure 3.13 has different assumptions in supplying the consumptions over time and has various needs for power reserves. As short description is summarized where system (b) and (c) is later more thoroughly investigated. In most areas the wind resource are strongest

when the solar resource is weakest, both seasonally and day to day. Also it is common for wind speed to increase at night when solar power is not producing at all.

A combination system allows for the most efficient and reliable exploitation of the natural resource available but both suffer from the intermittent nature of their resource as shown in (b). Regarding smaller local systems, wind power is not likely included as the neighborhood opinion would oppose if not even disturbing the owner himself. Consequently, small distributed system located close to or on buildings will probably include solar power and some storage type if keeping to RES.

The match between supply and demand taken to its limit (i.e., the instantaneous match between supply and demand) is the issue of system reliability. One way to provide system reliability is to pay the existing utility to manage the system imbalances. Another approach is to use this money to fund the operation of a DPS. A previous work, which focused on the generation aspect of reliability, showed that a DPS can provide system reliability [Wenger, *et al.*, 1997]. The DPS provides reliability by reducing the chance that all of the generation units on the grid will fail simultaneously or that all consumers on the grid will experience a peak demand at the same time.

Models and simulations

The system configurations have been studied by using model components from the library described. The system model includes numerous possibilities for parameter changes for each individual power unit and also the different strategies for managing the system. Some others have been investigated but the main purpose of the models for this work was to verify the modular approach with structures, interfaces that are the basis for further investigations concerning autonomous operation and control.

The autonomous systems investigated are able to supply a 10 kW top load and approximately 20.000 kWh per year that represents the average consumption in a Swedish household. The models are based on physical equations that have been adjusted in such way that each component except for the weather model also represents commercial products.

For comparison of storage utilization, a solar and wind power combination has been investigated with the system in Figure 3.13 (b), as several future

small local systems most likely will consist of solar power and some type of storage capability.

The results from the simulations have given that some parameters are more critical then others. In the system (b) case, the best efficient for the hydrogen gas production is to produce the gas in an electrolyser with high pressure and therefore exclude much or all of the compression that is needed for the storage. Time constants for the fuel cell and the electrolyser affect the dimensions of the battery considerably. The system control and strategy of the electrolyser and the solar power may also affect the efficiency considerably. In the system (b) case, the direct supply of the load is higher and consequently the demand on storage size lesser. Although, small local systems including wind power, will probably be less utilised due to disturbances such as noise and appearance of a rotating turbine.

In general, the systems are very expensive and have only values in autonomy applications like on an island without electric interconnection to the mainland. A secure stand-alone power supply based on either requires substantial energy storage. Combining the solar and wind power creates a supply with smaller storage requirement since the fluctuations have a statistical tendency to cancel.

Large wind power systems

Present and forthcoming wind power plant (WPPs) have proven to be one economical future sustainable energy source for power production even though they always, at least for the next decades, will be considered as a complement and not a substitute to existing energy sources. Numerous research projects have been identified in order to meet future needs concerning interconnection and interaction of WPPs to the common transmission network.

Wind power has been, and still is, a very small part of the total power generation business worldwide. The goal of several governments is a substantial part of renewable energy within the next decade that has influenced the market to expect a coming growth. However, some nations have had a very fast growth of wind power over the last few years and have temporarily stopped the extension. Wind turbine (WT) suppliers are about to reach a quality and size of WTs that can offer strong competition conditions on the market without government subventions. However, if the conditions (quality, size, efficiency, profitable) will be appropriate several

large WPPs with total installed capacity in sizes of hundreds to a few thousand MW will be placed in specific and most likely isolated locations. As WPPs generally are placed on wide areas with advantageous wind potential, a larger part of forthcoming WPPs will consequently be placed offshore. The next coming decades will likely lead to a wind power extension in the range of 30-80 GW total installed capacity. This rougly implies on an additional 20-80 large-scaled WPPs assuming that most of them will be in the range of 500-1500 MW. These new large-scale power generation systems will be placed close to existing power system, capable of managing them.

The pilot offshore WPPs that are being built today use an AC connection to the shore and the distances to the shore are also quite moderate. This is a well-known technology and a natural step for the first offshore WPPs [Petru, 2001]. However, in ten years, when the experiences from the first offshore WPPs have been evaluated and the next expansion starts, alternatives using a DC transmission will start to become cost-effective solutions. Future WPPs will become larger and will be situated at a farther distance from shore. The connection to the onshore transmission network must be at a point with high short circuit capacity and the transmission distance is, therefore, expected to be greater in the future than the 20 km used in the example. The controllability offered with the three systems using power electronics is also a great advantage for transient stability when connecting the WPP to a weak network. The cost of power electronics will be significantly lower in the future and losses will continue to decrease, so the advantages will outweigh the disadvantages.

The expansion of large-scale WPPs raises new issues concerning operational methods. Traditionally a wind turbine is controlled in order to produce as much power as possible. As part of a WPP, the wind turbine control has to be supervised from a higher level. WPPs tend towards sizes of hundreds of MW and must therefore be considered as a controllable generating unit, in a similar way as e.g. a hydro- or nuclear power unit. This requires a supervisory controller, here called the local EMS or wind power plant system controller (WPP-SC), as an interface in between the transmission operational system and the wind turbine units of the WPP. The WPP-SC will be responsible for the power set point distribution and proper scheduling methods for running the WPP optimally even in a limited output power mode. The challenge increases further when the WPP is required to have voltage and frequency control capabilities in case of a weak network.

WPP services and opportunities

New technical solutions for wind power give the possibility to provide a number of services to energy market actors such as energy consumption customers, transmission service providers, and system responsible actors. The services include traditional power generation, balance power and reserve capacity, but also additional services such as reactive supply and voltage control, possibly also back-up supply and system black start or island operation.

The success of RES has led to the need for a change in the role of presently, wind power plants, from a simple energy source that supplies power when the wind blows to a larger power plant unit that provides active regulation through capabilities similar to conventional centralized power plants. Advances in wind power system technology are allowing the development of wind power plants in areas previously thought not accessible. Currently, some regional transmission systems are experiencing high wind penetration: locations where wind energy makes up a significant share of overall power production for that particular region. This situation may require WPPs to stay online and avoid tripping during fluctuating grid conditions. Specifically, wind turbines may need to provide active transmission support to maintain the power balance and even help improve stability and reduce the risk of voltage collapses.

Using new technology integration enables WPP to provide solutions for active and reactive power regulation, voltage and frequency control and control system technology. Advanced control functions combined with real-time operation will improve operational control and grid stability. A high level of flexibility and modularity is central to provide the transmission operators with a range of options regulated by local conditions and regional transmission requirements, such as:

- *Fast Reactive Power Regulation*; The WPP enables reactive power regulation via power factor or voltage control to provide reactive power and transmission support during all load cases. The real-time distributed EMS system, which is capable of reacting and regulating the WPP, by the transmission network. This may be very fast with a reaction time in the range of 10-30 milliseconds depending on system design.

- *Active Power Regulation*; The fast pitch system for active torque control enables several new functions, which can contribute the site with specific design requirements such as:

- *Ramp-up/down function*; enables the WPP to meet certain pre-defined ramp up/down requirements (MW/minute).

- *Production Control*; total WPP output can be controlled to automatically stay below pre-set maximum production, which may be required under certain transmission conditions.

- *Frequency support*; additional production shedding can be enabled to support the transsisson if occasional high grid frequency occurs.

- *Active Production and Voltage Control*; The WPP may enable a central and external control of the production and voltage control. The WPP operator can adjust and implement new settings according to desired transmission production requirements enabling the transmission operator to direct active control.

The options and possibilities for approaching WPPs are primarily limited by the interconnection transmission capabilities, the WPP design, and costs contra values.

WPP Design

In this context a feasible future WPP design is described that is meant to manage several coming demands on future extension of large WPPs offshore. The design is not intended to direct future constructions into one single solution but an example handling several services towards the power market and system.

The principle structure of large WPPs is built on a high degree of modularization [Svensson, *el al.*, 2003] [Svensson and Karlsson, 2002] with well-defined interfaces and automated functions for decision-making.

As shown in Figure 3.14, a WPP module or subunit includes the following system units:

- *Wind Turbine Units* (WTU); including foundations that are based on permanent magnet synchronous machine (PMSM) directly connected to an AC/DC converter. The WTU units are able to work autonomously or directed by higher control-levels.

- *Internal transmission network*; in this case is based on DC. The WTUs are connected in parallel along the cable sections as a ring network, which provides a certain degree of redundancy. The information lines are connected along the power lines with bi-directional capabilities]

[Baur, *et al*., 2000] [Morren2, *et al*., 2001] [Karlsson and Svensson, 2002] [Karlsson and Svensson, 2003b].

- *Substation;* operating similar to a power tap. It raises the internal DC voltage from multiples of 10 kVDC to multiples of 100kVDC depending on the capacity of DC transmission cable. For galvanic separation, this solution also includes a transformer beside the converters as for the DAB structure. The converter substation enables high controllability and simpler means for disconnecting as well as being autonomous. For redundancy reason, it is appropriate with 2-3 such units in parallel permitting the WPP subunit to produce at partly capacity in case of failure.

Figure 3.14: Modularized WPP unit.
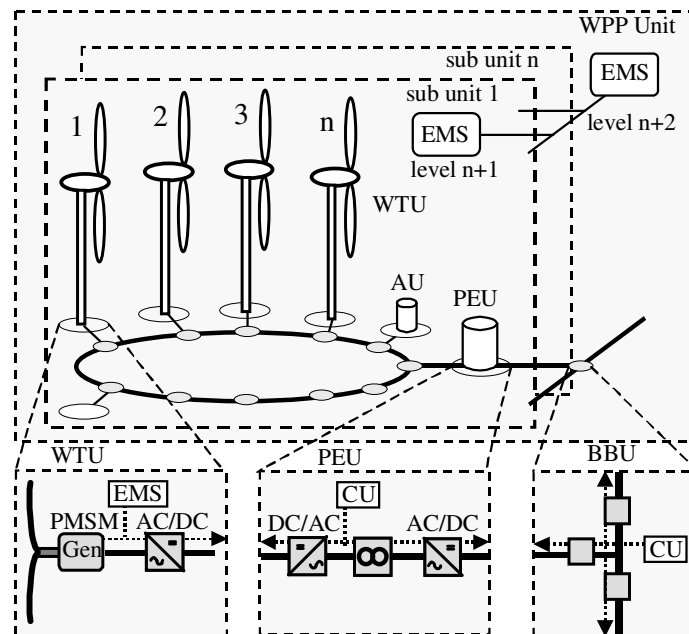
- *External transmission network*; The WPP subunits are connected to a multi drop high voltage DC transmission cable in the range of multiples of 100kVDC depending on capacity demands as shown in Figure 3.15. The cable might be connected directly to an onshore region or interconnecting several onshore regions or nations [Christensen, *et al*., 2001] [Bahrman, *et al*., 1999].

- *Auxiliary units*; are generation units aiding the WPP with electrifying the internal DC bus, which in this case is unnecessary due to the WT design with PMSM and AC/DC converter. This may be an internal diesel generator or equally. This unit is unnecessary if some of the WTUs have inbuilt small generators with purpose to electrify the internal electrical system of the WTU. This in turn enables the WTU to electrify the internal DC ring bus of the WPP subunit.

- *Distributed Automation* includes the information system within a WPP subunit that reaches from the control systems of the WT units to the subunit local EMS. The EMS of the WPP subunit internally manages and operates all the generating units and externally acts as one generation unit providing the next upper level with services. The next level EMS, assigned "level n+2" in the Figure, treats all WPP subunits as single generating units not actually aware of the number of WTs in each subunit. The capacity and different services provided by the subunits are the mainly information upwards. The HVDC transmission network communicates via the substation to the WPP-EMS as shown in Figure 3.15.
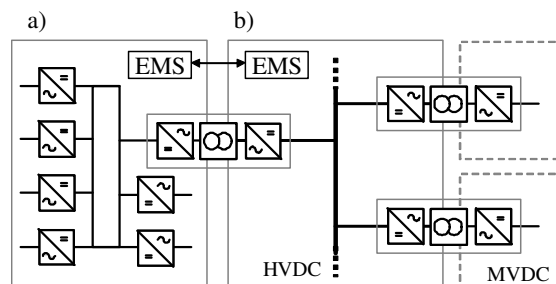
Figure 3.15: a) WPP internal DC network; b) HVDC Transmission network.

An entire WPP unit includes several subunits that are aggregated and operated as a single unit toward the transmission system. With a well-structured EMS based on dynamically properties, new units should be easily adapted at all levels to the information system.

Controllability

The demands on controllability on future large WPP units should be higher then for conventional units today. As the power system may have a large part of stochastically generating units, this might decrease system stability.

By introducing very high controllability on new additional units, this might become the opposite by aiding the present system with means to increase stability for certain control areas. This will only be actualized if the wind power becomes a considerable part of the total system generation. However, if following a long-term plan for extension of wind power, this should be considered at an early stage.

Controlling a WPP differs from a common generating unit primarily in power fluctuation due to the wind. A WPP is therefore regarded as a stochastic generating unit that demands accurate power measurements and reliable maximum power estimations to provide the energy management systems with correct real–time information for decision-making. The WPPs will then become a controllable stochastic generating unit.

Present offshore WPPs under construction are able to participate in both primary and secondary control. The controllability is depending on WT and WPP design. Even if individual wind turbines will have limited controllability the WPP might have several functions for control. Localization may be important not only for advantageous wind locations but also for proper weighting in capacity depending on adjacent control areas to be able to add a part of the total peak effect to the power system and also provide ancillary services.

In ongoing projects for large offshore WPPs massive effort is currently dedicate to partly investigation and implantation of additional control modes [Christiansen, *et al*., 2001] [Macken, *et al*., 2001] [Morren, *et al*., 2001]. Considerations due to the impact on the transmission network, led to more specific requirements towards the wind turbine manufacturers, operators and utilities.

It's not only the functions within the EMS of the WPP that will be affected when transmission network impact is to be better controlled. The wind turbine controllers (WTC) must be able to handle different control modes depending on superior control demands. The safety margins and reliability for existing power systems decrease as a consequence of the increasing share of installed WPPs. The following operation modes will probably be used by the local EMS (or WPP-SC) to run the WPP.

- *Indifferent*, is assigned when the transmission system EMS is indifferent in the WPPs operating mode. This implies that the WPP-EMS determine the mode of operation according to the local strategy.

-   *Min*, minimum power levels but still running might be useful when the transmission system EMS, for some reason, temporary have surplus and shortly after need the WPP to start as quickly as possibly.

-   *Max*, maximum power level result in that the WPP starts all WTs and command them to operate at maximum. The only different from present operation of WPP would be that the command was received from the external EMS and thereby externally forced.

-   *Balance*, is needed when the WPP have to participate in the power balance control. In this mode the power set point will be received from the transmission system EMS and further distributed to each single WT by the local EMS.

-   *Primary*, is used in case of a weak grid. In this mode the WPP must be able to participate in frequency and voltage control for the AC case and in voltage control for the DC case.

The possibilities for a WPP to participate in primary and secondary control are shown in Figure 3.16 where the interaction between the internal and external network is illustrated.
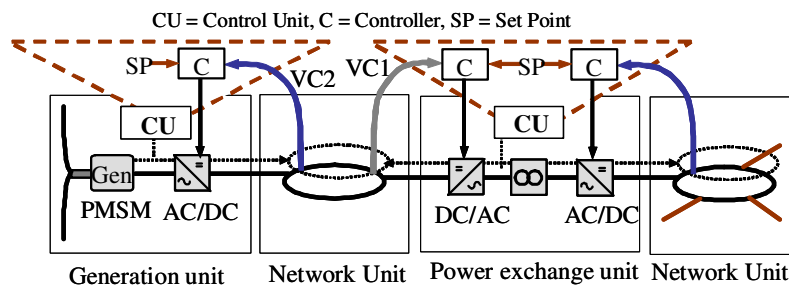
Figure 3.16: WPP controllability.

According to the proposed design, which is highly based on converter technology, there are mainly two control modes for regulating the internal voltage of the WPP subunit [Karlsson and Svensson, 2002] [Karlsson and Svensson, 2003b].

1. The converter substation units (CSU) control the internal DC-bus voltage and the WTUs produce at maximum according to wind speed.

2. A part or all WTUs control the internal DC-bus voltage and the CSU provides the transmission system with different ancillary services.

The controllability becomes very high where the WPP subunit is, per automatic, able to switch very fast between the two main control modes and as a consequence enable the CSU to provide the TSO with all the ancillary services as long as the WTUs can keep the internal voltage level. Even black start might be a service that WPP subunits are qualified to deliver, according to the auxiliary unit description above. Hence, black start units have to be located where they can be used and capable of re-starting other generators, where some WPPs might not be large enough or properly located.

Operation

Technically, a power system has its limits in handling a certain amount of stochastic power generation. A large amount of wind power set requirements on network operation and design. Considerations due to transmission capacity must be regarded according to localizations and new transmission lines have to be built to adapt to a future large-scale introduction of wind power in some locations. As the impact of wind power may affect the power system the operational options will be important. Numerous research projects are focusing on future needs concerning interconnection and interaction of WPPs to the common transmission network [Christiansen, *et al*., 2001].

With new technical solutions for large WPPs the role of the wind power can change into a more active role where WPPs can contribute to efficient and reliable operation of the power system. To support this more active role different types of operational and market-related information have to be managed at different levels in a system for monitoring and operation of WPPs [Svensson and Karlsson, 2002].

In order to deal with an increased number of operational functions the processing of the information may to a large extent become automated for operational actors [Katayama, *et al*., 2002], with increased demand for communication with generating units. The WPPs are in general owned and operated by one or more companies specialised in electric power production. The approach to operation and maintenance is based on remote supervision and monitoring of the plant with on-line functions and frequent updating of several operational data. So far, there has been no interaction to the central energy management system (EMS) enabling the WPP to participate in the power balance control. Traditionally a WPP is controlled in order to produce as much power as possible and acts consequently as a

load in the system [Svensson and Johnsson, 2003]. In order to meet requirements regarding the WPPs participation in the management of the transmission network, new perspectives have to be considered regarding controllability. From a TSO point of view, a WPP acts as a stochastic generation unit, with controllable power limitation, independent of size and number of WT units as shown in Figure 3.14. The main communication connection to the central EMS is the WPP´s local EMS that operates as an interface in between the central EMS and the WT units of the WPP. The local EMS is responsible for the distribution of power set points and control modes. This also involves proper scheduling and co-ordinated control methods for running the farm optimally independent of control mode. The local EMS and the WTCs are connected to a local area communication network. The distance between the controlling units results in long communication lines for interconnection. This requires that the amount of operational control signals, and their required bandwidth, should be limited and that the units should be as self-sufficient as possible, which normally is the case when managing WT units.

In next Chapter, a general EMS structure for market based operation of power units, and among them WPPs, is presented, with consideration of how new WPPs can be used to improve power system performance. The EMS and information structure are independent of the size of the wind power plant. It's applicable for single wind turbine units as well as for large WPPs. The structure provides the means for condensing the necessary information for future needs and requirements on operation of new large WPPs. These units may be connected to the power system and deliver energy and ancillary services in the same way as conventional power plants. The EMS structure facilitates the utilization of new services from WPPs. With well-defined EMS structures and interfaces a new WPP is able to connect to an existing EMS and then automatically adapt to the system in accordance with the "plug and produce" solution. This calls upon a modular control structure with potential for easy extension of the WPPs, which is significant depending on choice of structure in both the local EMS and the wind turbine controllers (WTC).

Models and simulation

The simulation models developed for WPPs include all physical equipment models with a high degree of modularization. Each unit consists of a process and control part with uniformed interfaces from the highest to the lowest level. Distributed automation is highly utilized on all information

and control levels and numerous function blocks are integrated in the structure as shown in Appendix A.5.2 and A.5.3. The information structure is vertical and condensed from lower to higher level in order to keep the essence of information left and minimize the amount of information data for high performance.

The distributed automation and software structures are flexible and can easily increase and add new functionality. Well-defined communication interfaces are used to interact with the automation structure throughout the system. Even inside each control unit, the same interface for inter process communication are used to keep every module as self-sufficient as possible. The control software modules permit easy methods for additional control modes and software blocks, e.g. when adding new wind turbine units to the WPP.

The simulation results prove on that the information structure work from the highest to the lowest level regarding signal management and processing to control each power unit.

3.5 Concluding remarks

Approaching technology will change and transform the power system. The new technologies are able to provide new power units and exciting with high controllability. It is just a matter of managing and operating them properly as they can increase or decrease system reliability depending on usage. Higher controllability should normally be the basis for increased reliability. However, if the management of the system units is too slow the opposite may occur, decreased reliability. For example, in future power systems, RES may take a large share of the total generation and the power fluctuations may be huge and rapid, especially regarding solar power. This implies on either unnecessary large momentary reserve capacity or automated operation functions as human operators will not be able to manage such situations. One solution is probably a compromize. Depending on the penetration share of RES, the reserve capacity needs to increase with additionally types of storage, and automated functions will probably increase in time as distributed automation will be developed and integrated.

Depending on local demands and applications, the utilization of distributed power systems may become feasible. The DPS may be used solely as an uninterruptible power supply (UPS) activated only when the main supply failure. With new active DPSs new technologies enable wide spread

generation on a smaller scale, especially future solar power and storages. These small scale DPSs will deliver power locally and in periods with limited local consumption they are able to sell the surplus of power produced to the interconnected transmission network, which requires bi-directional power flow capabilities. This will be the fundamental future problem to solve regarding information and control structures handling both the technical and open market issues.

Large DPSs including large WPP offshore will not raise the same problems even if they are supposed to be based on the same structures and interconnections. Larger systems are fewer and take much longer time to erect in comparison with small-scaled ones. Meaning that the TSO may have the time to interact and prepare new large WPP as for conventional generation units. The additional information flow will be limited.

In the small-scaled DPS case, this will differ regarding information flow connected to the TSO. The TSO will not be able to operate thousands of new small DPSs erected continuously, where each individual DPS may be erected in a couple of days. Moreover, the owners of these small DPSs will be able to interconnect the market and sell surplus power to other DPSs. A distributed information and functional structure will be needed enabling aggregations of services at local points in the system.

Chapter 4

Information system and RES interaction

This chapter specifies principlal structures for an energy management system (EMS) and information enabling market-based operation of RES and especially WPPs. General trends and ideas about future integration of RES are illustrated. The structure provides the means for condensing the necessary information for future needs and requirements on operation of new large RESs. These units may be connected to the power system and deliver energy and ancillary services in the same way as conventional power plants. The EMS structure facilitates the utilization of new services from RESs. With well-defined EMS structures and interfaces a new RES is enabled to connect to an existing EMS and then automatically adapt to the system in accordance with an "plug-and-produce" solution [Svensson and Johnsson, 2003] [Svensson2, *et al.*, 2003].

4.1 Market and power system interactions

The actors and their interactions are important in order to define the functions and responsibilities that exist to ensure the information structure of the interconnections. The main reason for this is to ensure real-time operation and define the roles of actors that may provide all or part of the functions or responsibilities for operation.

System mechanism

The main purpose of the electric power business system is to satisfy the customer demands in a reliable manner and as economically as possible. For reliable and secure service deliveries the system holds several actors depending on assignment for different companies and organisations. In this context they are all called market actors or operational actors depending on different operational and functional facilities.

As for all business systems in our society, each product needs to be interesting or essential to customers, which consequently attract investors and traders in doing business. The product is almost always either a service or a component, or both. The costumers' demands on the products are more or less the same, lower costs at higher quality, service and delivery speed. For production and trade this is achieved by open up for free competition so that customers can choose their supplier according to individual needs.
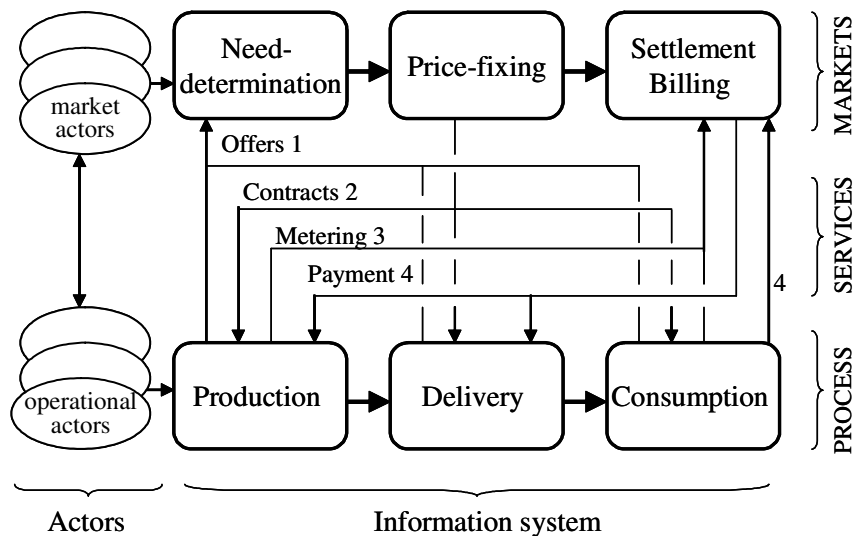

Figure 4.1: Market and process system functional overview.

The market and power system includes production, distribution and consumption units where market actors are responsible for interacting with each other to operate and support the physical power system. Unresolved system planning problems or constraints will eventually become system

operation problems and constraints and will promote efficient use of the process system units by providing incentives for improved reliability, efficiency, quality and safety.

The value chain of the electric power business process, illustrated in Figure 4.1, is similar for all business products and includes the following phases:

1. *Need-determination*: The market actors identify themselves for each other and define the conditions for their engagements. Supply and demand offers are collected and examined, which determine if there is a need for production and services. . A bid for a single hour is a sequence of price/volume curves for the intended hour. When bidding the curves, the profit of the producer may not be at its optimum. By adjusting the curves, the expected profit might be as expected, which is the gaming procedure and also a risk. The buyers are in a comparable situation and have to inform the market operator for each hour of the day how much they are ready to pay for a certain total volume.

2. *Production*: The producers strive to generate products at a rate corresponding to the consumer demands and are responsible for having at least the requested production capacity at the delivery-time. Otherwise penalties can be issued. Beside regulations, these are in general the incentives for reliable and secure production.

3. *Price-fixings*: The price determinations depend on the quantity provided and requested, and are determined by specific methods in different power markets. When agreements on the prices are done, contracts are signed and sent to those intended. Here the total price usually includes the transportation to a pre-defined delivery point.

4. *Delivery*: The deliveries are performed by the distributors that start according to the time schedule, received with the contract. The distributors are responsible for, at all times, having a reliable and secure path between the producers and consumers according to the contracts. The intended delivery paths must not be overloaded and it is up to the distributors preventing such incidents by careful planning. Depending on regulations and penalties the distributors might have alternative paths in case of failures or fast means maintaining the primary path with alternative services.

5. *Consumption*: The customers receive their products and utilize them according to the contracts. If the products not fulfil the agreements, the customers may receive compensation equal to the degree of deviation.

6. *Settlement/Billing*: During performed product delivery and utilization, the product amount is metered related to agreements. Deviations are assigned costs. Bills are created based on metered volumes and the prices defined in the contracts and sent out to the consumers. Payments are then distributed to the producers and distributors.

The mechanism includes several elements that are needed for the interaction between the market and power system. The elements are as follows:

- The system actors that include both market and operational actors.

- The system services and functions provided by the power system that are exchanged by the system actors in the market.

- The information system that includes information interfaces and an EMS structure enabling the system actors to utilize the services and activate the functions.

In the next sections these elements will be more thoroughly described that will lead to the introduction of distributed energy management systems.

System actors - an overview

The overall market and power system actors are shown in Figure 4.2, where the services between the market actors and the market are to some extent automated for some regions. Traders are the driving force always striving for maximal profits. They will likely develop several aiding automated functions and by that have more time for improving strategies and decision-making. Skilled independent traders will probably have several large companies to be managed and will consequently have needs for fast connection to receive information from all affected actors. New types of traders might emerge, depending on future investment flexibility and possibilities.

Future aggregators and traders would help both the system operator and the individual generators and loads by bringing together resources with complementary capabilities. Automated decision tools would handle interactions with different service markets. There will be few limits connecting different actors for market participation and enabling the system operator with real-time operation and information. Demand trading through the internet enables the forward- and real-time bidding into the markets, to maximise financial positions and assure a risk managed

balanced portfolio for all actors. Once the technology and infrastructure are in place enabling data to be transmitted bi-directionally over electric utility power distribution lines or other alternative communication paths, the need for constant monitoring in real-time, on-line mode, and other communications media will emerge.
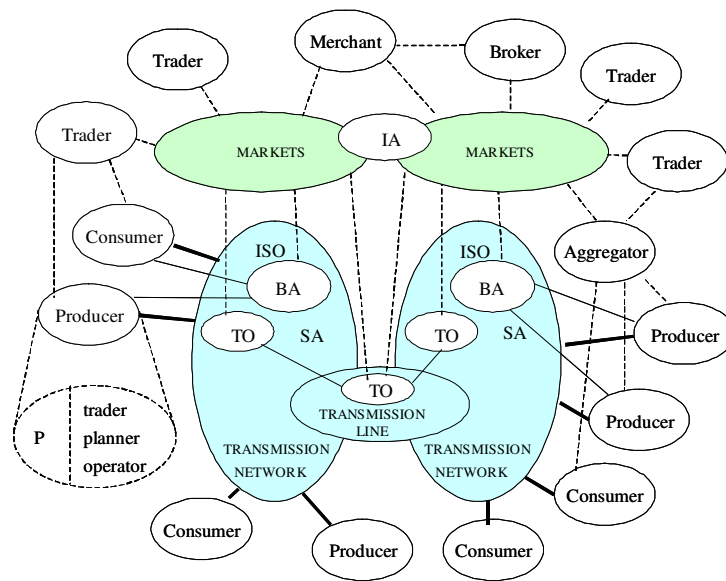
Figure 4.2: Overview of market and power system actors.

However, this increased need for exchanging information between the system operators, the aggregators and the market actors will require new technologies. Information and communication technology has been and will be a necessary tool to support the operation of the market and power system.

Market actors and interactions

The actors of the market system create the actual driving force for setting the requirements on increased system reliability. As a consequence, the market system must be structured such that the functioning and the interactions with other system parts become uniform and not restrict any actor to participate the market. The market model must also be flexible in

adding new specific markets and easy to interact [NERC, 2001] [Buyya and Vazhkudai, 2001].

The energy markets can be grouped in several categories, e.g. spot market, ancillary services market and transmission service market. A market place has to be set up for each service or services group. Each market also needs to be administrated. The rules for a specific market may be set by a Market Standardisation Organisation. Independent market operators are a guarantee that all market actors are treated equally. The interaction between actors in the market system is presented in Figure 4.3. The interaction is partly automated and partly manual. The information exchange is guided by the agreements made between the market actors.
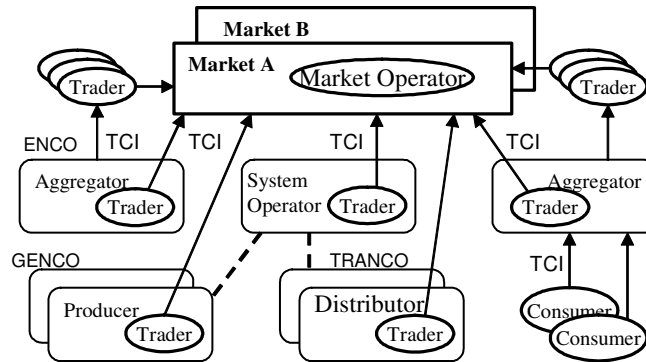
Figure 4.3: Connections and information exchange between market actors.

These agreements define the business relationship between the actors. Producers, transmission providers and consumers get access to the markets through the use of Purchasing/Selling Service (PSS) functions. But they typically make an agreement with an independent trader who takes care of the actual purchasing and selling on the different markets. The producers, transmission providers and customers forward their needs to the independent trader using the PSS. Due to the physical connection between transmission systems each market also needs to interact with markets for other transmission systems to establish agreements and settlements where the production and consumption is located in areas covered by different markets.

The electricity market holds several different independent actors, in this case also companies, but can basically be divided in the following groups:

- *Producers* that generate electric power into the network according to requested service and agreements. The production companies (GENCO) normally sell energy to a trader organisation within the same group of companies.

- *Distributors* are responsible for the transport of the electrical energy from the producer to the consumer. This takes place via the national transmission network and regional and local networks, which can be owned by different transmission and distribution network companies (TRANCO). The distributors may include a transmission service provider (TSP) connected to the market that corresponds to the trader, which could be both internal and external.

- *Consumers* are everything from industries to buildings that consume electric power from the electricity network and related services. The customers must have agreements with an electricity trader to be able to buy electricity. The customers also have agreements with the distributors (network owners) in order to be connected to the actual network. For connection and transmission, the consumer pays a network fee (network account). The consumers or customers may be served by a load serving entity (LSE) that secure energy and transmission.

- *Aggregators* may represent several consumers, distributors or producers, or any mixture of them. Each responsibility from individual actors is added depending on the aggregator mixture. They can have different roles such as *Electricity Supplier* and/or *Energy Balance Provider*. Both roles can exist within the same or different companies.

- *Traders* purchase or sell any kind of electricity service and are connected to the electricity market. They are included in all actor organizations having the supply/demand needs interconnecting to a market. A power trader could also be disconnected from the physical units acting only as independent merchants on the market.

- *System operators* are normally responsible for their national grid. This means ensuring that the generating units of the electricity power process system are working together in an operationally and reliable way. It also implies on that production and import corresponds to consumption and export.

- *Market operators* are responsible for the actual trade of energy, power capacity and services to ensure fair competition on the electricity markets.

There are several other actors managing the money flow in the business system such as merchant-, retailer-, broker-, settlement and billing companies. The trader company description in Figure 4.3 is general and may include all or a part of those business actors.

Operational actors and interactions

Overall system operation and control involve interactions on different time scales between units for production, transmission, and consumption. The transmission provider needs estimates or real values on the present status and generator output to optimise the operation and to verify the reliability of the system.
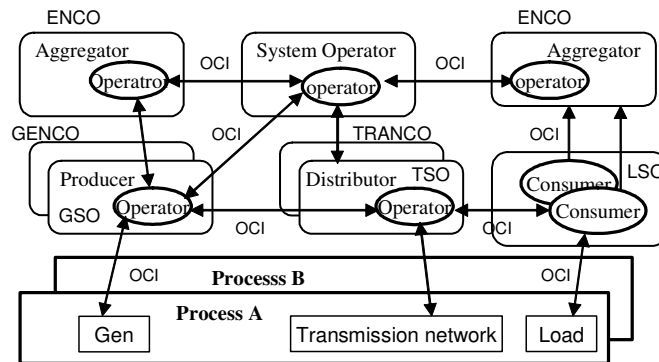
Figure 4.4: Connections and information exchange between operational actors.

More dynamic processes like voltage control and frequency control may involve direct interactions between power system units. Transient processes, for example breaker tripping, does not normally involve interaction between market actors, but is an internal operation. The base operator level only manages one power unit, e.g. generation unit, with the main task to start up, shot down or change the output level when commanded from higher level operators or for malfunction reasons. At normal operation the operator monitors the internal or local functions to prevent disturbances or at least be as prepared as possible handling them if such an event would happen. The operator also work as a backup to some of the automatic control system functions as electric power has to be provided continuously every day of the year. Automatic control systems require periodic maintenance and sometimes fail, so the operator is trained

to take over some of these slower control functions and to improve overall system reliability. Next level operator has similar assignments but as the underlying power units may be multiple, coordinated functionality is added.

Depending on national regulations and size on geographical control area there may be one or several system operators managing a control area. The operators are shown in Figure 4.4 and can be divided in the following categories:

- *Generation System Operator* (GSO); makes sure that electricity generated at the stations matches demand in accordance with strategies established by the respective producers. They monitor system frequency and must be prepared for several variables including reservoir levels, availability of generation units, and power and energy reserves to be maintained. In large modern processes, the GSO is expected mainly to deal with infrequent plant transients such as start up, shut down, and system failure. The operator has to detect and diagnose as well as to recover from system failure. The main assignments are to operate and maintain the generation unit and execute functional orders from higher level authority without risk for internal failures or making external disturbances. The operator also informs the higher level authority with adequate status and metering data such as maximum capacity, ramping rates, etc.

- *Load system operators* (LSO) are at present not common but may have assignments to adjust the demand on load if possible due to controllable loads. The LSO should make sure that electricity consumed at load units matches demand in accordance with strategies established by the respective consumers. They also monitor voltage and frequency levels enabling local decision-making in accordance with agreements. Normally this is managed by an aggregator connected to groups of both load units and generation units.

- *Storage System Operators* (SSO) are formally introduced with assignments similar to both the GSO and LSO from a TSO point of view. Additionally, the SSO maintain a certain storage level depending on several strategies regarding short or long term storages.

- *Exchange System Operators* (ESO) are the operating interface entity (e.g. substations) towards adjacent power systems managing the export and import at a certain physical connection point. The ESO operate the lines, equipment and automatic controls associated with

interconnections. Their responsibilities include conducting real-time transactions according to agreements negotiated by different transmission companies purchasing and selling electricity, as set out in the exchange schedules. They also analyse from a system security stand point all online available transmission capacity (ATC) and have also the ability to disconnect the interconnection under special circumstances.

- *Transmission System Operators* (TSO) have responsibility for ensuring that the system always balances production and import to consumption and export. This is maintained by continuously coordinating the GSOs, LSOs and import/export units (ESOs). The TSO ensures that there is sufficient regulating power and reserve capacity, which can eliminate imbalances due to outages, unexpected fluctuations in consumption and fluctuations in production of renewable power. The TSO operate and maintain the transmission facilities, executes switching orders and is responsible for local reliability functions. The TSO maintains predefined voltage levels, define operating limits, develop contingency plans, and monitors operations. If they are for some reason disconnected from the physical part providing the system frequency/voltage, depending on AC or DC system, they become SOs temporarily. Although, some nations do not distinguish between the SO and TSO and consequently the TSO then has the additionally responsible as for the SO.

- *System Operator* (SO) is responsible for a secure and reliable operation of a specific control area, which may include several minor control areas managed by TSOs, which is maintained by continuously coordinating the TSOs, GSOs and LSOs. As for the TSO the SO is responsible for maintaining the power balance but is also responsible for keeping the system frequency, primary and secondary control function. If the SO is not at the top level operation, higher level operators may coordinate several control areas in the same manner as the SO up to the national level. The SO is responsible for always having adequate reserve capacity for regulating power.

The hierarchy has its advantages and disadvantages from a control point of view. The advantage is that by collecting information and distributing orders at certain levels, the information is condensed to higher level instances that consequently have less data to evaluate. But depending on if decisions only have to be taken at the top level, the information path may be a security and reliability problem. As the operators traditionally, at

certain levels, exchange information via telephone, the information capacity is too low and critical at severe system events. Another risk is that most of the system operation functions are centralized and not accessed if disconnected. A local control area disconnected from these functions is normally closed down but could be prevented by automatically assign the TSO the same operating functions as the SO.

Market services and power system functions

There are several services that might be provided by future RES units to maintain a high operational reliability. These services are grouped and managed by different markets. Power generation is common for all generation units that produce electricity for consumption, thus the primary service is power generation that is traded in the energy market. The most used system service is the one that provides a transmission path for energy trading enabling the electric power transport from generation units to load units.

Ancillary services are required to maintain power system reliability and are being opened to competitive markets in regions where TSOs operate. The ancillary services are grouped as below:

1. *Regulation:* Primary frequency control during normal operation. Continuous maintenance of the minute-to-minute generation/load balance.

2. *Load Following:* Maintenance of the hour-to-hour generation/load balance.

3. *Frequency Responsive Spinning Reserve:* Short term operating reserve during disturbed operation. Immediate (30-second) response to contingencies and frequency deviations caused by generation and transmission outages.

4. *Supplemental Reserve:* Short term operating reserve. Non-immediate response to restore generation/load balance within 15 minutes of a generation or transmission contingency.

5. *Backup Supply:* Customer plan to restore system contingency reserves within 30 minutes if the customer's primary supply is disabled

6. *Reactive Supply and Voltage Control from Generation:* Injection and absorption of reactive power from generators to control transmission voltages.

7. *Network Stability:* Use of fast-response equipment to maintain a secure transmission system

8. *System Black start:* The capability to start generation and restore all or a major portion of the power system to service without support from outside after a total system collapse

The first five services deal with maintaining or restoring the real-energy balance between generators and loads. These services are characterised by response time, response duration, and communications and control between the system operator and the resource needed to provide the service. Because regulation requires continuous (minute to minute) adjustment of real-power transfers between the resource and the system, loads may not want to provide this service. Load following could be provided directly or through the use of an energy market price response on a time frame less than an hour. The contingency reserves are especially amenable to being provided by distributed resources.

For Reactive Supply and Voltage Control a distinction can be drawn between *Primary*, *Secondary*, and *Tertiary voltage control*. Primary voltage control is the local voltage control implemented by the voltage regulators of generating units. Secondary voltage control co-ordinates the action of voltage and reactive power control devices to maintain the requisite voltage level at a certain point in the network. Tertiary voltage control involves a process of optimisation, using calculations based on real time measurements, in order to adjust the settings of devices that influence the distribution of reactive power.

Service coordination authorities

As the market and operational actors are connected via the distributors and their delivery systems, an extensive service management is required to maintain the operational interaction between the market and power system.

The service coordinating authorities are responsible for a secure product delivery and reliable operation of the delivery system. This also includes interchange services between production- and consumption systems as well as neighbouring power systems. Many services are related to sustain system reliability that normally is defined as the ability to

- Ensure the normal operation of the power system

- Prevent/avoid disturbances or limit the number of disturbances

- Minimize the effects of disturbances when they occur

- Restore the affected area as quickly as possible

The various situations are managed differently depending on national regulations and technical solutions of the power system, and consequently the system operations. There are many advances in improved system reliability and some of them are related to the information exchange and the possibilities in automated decision-making in order to increase the speed of the system operation.

For managing the power system services several authorities exist that have different responsibilities requiring various types of service monitoring and coordination functions. Some of them are briefly described below.

- *Power Balance Authority* (PBA): Integrates resource plans ahead of time, and maintains load-interchange-generation balance within its control area and supports system frequency in real time. It is always the SO of the control area that also has the PBA. However, TSOs may temporary become PBA if disconnected from the main transmission network. The PBA have as the main responsibility for managing the primary and secondary control.

- *Energy Balance Authority* (EBA): The energy balance authority is financially responsible for the electricity that the trader sells always in balance with the electricity purchased to cover consumption. The EBA supervises the performance of the energy balance responsible actors, in order to verify that they deliver the exact amount of energy. According to [Strandberg, 2001] all production has to be planned and all consumption shall be proposed in accordance with the PBA (or SO) agreement with the EBAs. These plans and prognoses shall match what is delivered and retrieved in each access point. The EBAs have to report the total actual delivery and retrieval within a specific area. To avoid penalties for imbalance the EBA needs to follow the production and consumption in key points in the system. The EBA supervises the performance of Generation service providers and Load service providers. Similar actors are needed for supervising the performance of Ancillary service providers and transmission service providers. The service providers have to make analysis and forecasts on the production of these services and provide plans and prognoses to the balance authority. On the lowest level for balancing the energy are the e*lectricity suppliers,* which have supply agreements with the consumer. Each

electricity supplier (GSO, SSO, ESO) must be connected to an EBA in order to participate.

- *Security Authority* (SA): The Security Authority (SA) has the highest responsibility and manages all security and reliability related functions. The responsibilities include reliability, quality, protection (safety) and efficiency. The SA determines operating capacity limits within the pre-defined security area including all transmissions, substations and interconnections at all times. The SA receives the dispatch plans from the PBA and analyzes the dispatch schedule from a transmission security perspective. If the SA determines that the dispatch plans will endanger transmission security, the SA informs and directs the PBA to determine where the dispatch needs to be adjusted. The SA is responsible for real-time system security, which includes handling emergency actions such as; restrict and alter transactions, re-dispatch directions alleviating congestion, and ensuring energy balance and interconnection frequency. The SA is included at several levels of control areas, e.g. the regional and sub regional transmission networks.

- *Interchange Authority* (IA): The IA authorises valid and balanced interchange schedules between control areas. The IA may be connected to the ESOs in order to adjust the power flow depending on requests from the SA or PBA.

The authorities may differ from nation to nation but can be considered very similar depending on the functioning of the system and the control area to be operated. Although, even though present authorities usually are pre-defined and firm, future demand needs to be changed in a more flexible environment. The location and number of authorities may be different as power systems may temporarily split into smaller control areas, so called subsystems.

Information system

With the power system deregulation powerful driving forces, uncertainties, and new services are compelling electric utilities to make changes in the power system information infrastructure design. Expanding network services such as real-time monitoring are also driving the need for increased bandwidth in the communication network construction. These needs will grow further as new remote real-time trading and operating applications become reality.

Present information management systems have to be restructured as more and faster information has become desirable by affected actors. Technological advances in networking have made it possible to develop a communication system for accessing real time power system information over digital network or transmission lines. Faster decisions would increase system reliability, which also need new strategies to be developed in association with real time information from other wide range signal sources. Currently, most communication technologies used in the power system only allows local control actions at the plant due to lack of efficient, high speed and bandwidth communication media.

Interconnected power systems are highly complex mechanisms, and control of these systems becomes increasingly difficult with restructuring. Factors such as the entry of new participants increased cross-regional power exchanges, and new types and numbers of distributed generating resources and loads all act to complicate system planning and operations. Energy management systems (EMS), including supervisory control and data acquisition systems (SCADA) are essential parts for developing future distributed modular functions that enable interconnection between generating units and the markets. The functions needed must be accommodated by the new market and power system information structure. These functions range from assuring an adequate electricity supply through long-term planning of the generation and transmission system, to meet shorter term forecasted load by deploying existing resources through unit commitment, to assuring system security through automatic generation control, and operating the transmission system by controlling ancillary services such as reserves and black start capability.

4.2 Energy management system

In this section a general architecture for an EMS is introduced that may include complete autonomic actors and that should be possible to adapt independent on where in the system it is placed. The start out is from a fundamental idea and thereafter a principal functional structure with the purpose to illustrate the extent of different actors, functions and interactions.

Fundamental idea

The assumption, in the long perspective, is that the power system control centers will become unmanned and fully automated due to the huge amount of information and need to respond quickly. The automated control centers will be distributed at several locations in the same control area and able to form new smaller control areas periodically during emergency situations. The use of such technology will transform the transmission network from a passive to an active system where real-time operation and control are essential.
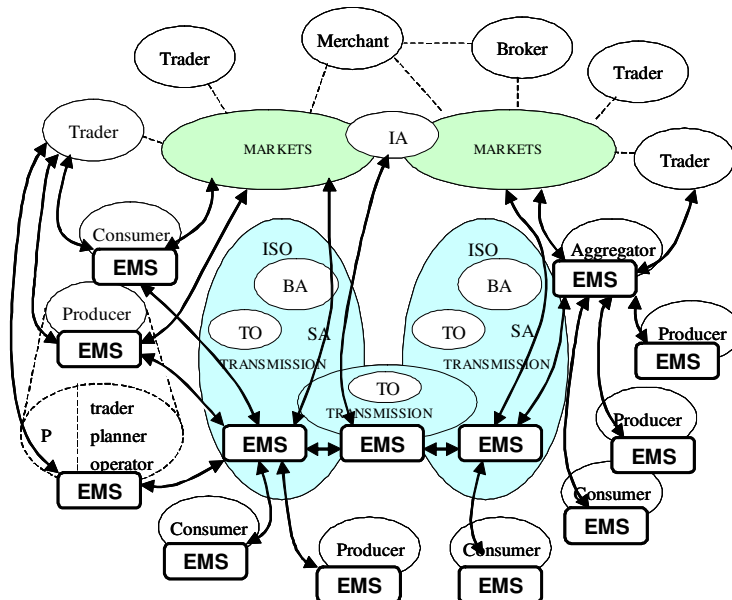
Figure 4.5: Overview of system actors replaced by an EMS structure.

The fundamental idea to achieve such development is to replace the actors in Figure 4.2 by an EMS structure representing automated actors as shown in Figure 4.5. The tasks of these roles will, to a certain degree, be automated and responsible actors will only modify strategy constrains and limits to influence the directions in the automated decision-making for acting both toward the market and toward controllable power units. The trend is already to increase the degree of automatic control instead of just assisting the operator. Operators have decreased in number due to increased automation and remote control by generating power units and

will probably go further ending with only a few or no personnel with operating responsibility, independent of the number of controllable power units.

The controlled, organized and relatively isolated architecture of today's control centres need to be more open and dynamic, and the connection with other actors and their system roles need to be uniform and modular. The term modular refers to a set of design characteristics that allows the use of basically the same EMS in different applications. The modularisation and standardisation of the EMS include several issues such as interfacing components, communication protocols, modeling, programming, operation and control strategies. The basic solution is to use a high degree of existing functions and gradually downscale and automate the operating actors within the EMS organization. The centralized structure for operating a power system is decentralized to several modules that interact by well-defined software interfaces. This involves an increasing number of automated decision-makers decreasing the size of problems to be solved. The automated process puts requirements on the communication interfaces to accomplish the information exchange. It is also generally difficult to connect different EMSs with other suppliers' devices or systems due to the different operating system and interfaces even though the same standards exists as described in [IEC 61970, 2003].

Principal functional structure

Existing energy management systems are gradually replaced by new structures for Distributed Energy Management System (DEMS). The proposed principles for DEMS are based on distributed open system architecture with easy upgradeability and extensibility. The structure is based on the previous described management levels including the actors and functions for the market, services and production levels.

The actors of a DPS unit have the EMS as an efficient tool to monitor and operate the complex power system and units for secure and reliable system and at the same time handle the purchase/sale of services towards the markets. Independent of type of power unit managing services, the general EMS hierarchy is divided in three general roles as shown in Figure 4.6.

The structure separates the market connection from the operational layer by the service management layer. The layers function in different time frames, which need faster decision-making in the direction from the market to the process.
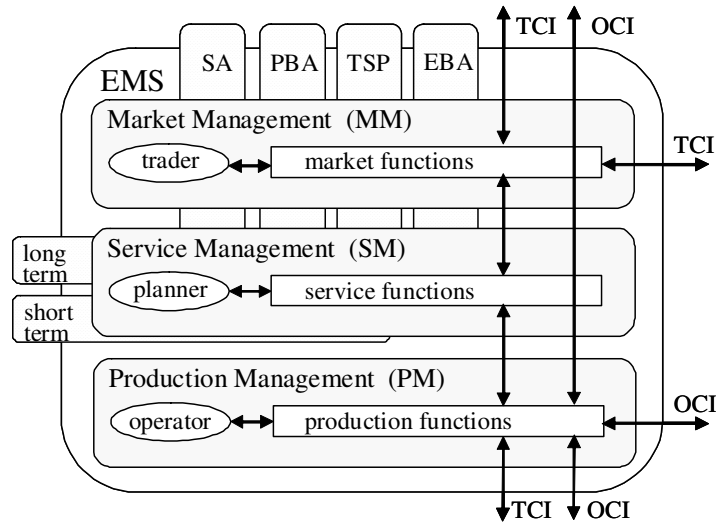
Figure 4.6: EMS principal structure hierarchy.

These roles operate within a well-defined control area managing all connected and controllable units.

- *The Market Management* (MM) corresponds to a market organization that involves several persons, dependent *traders*, evaluating the market and market price both in short- and long-term and that are directly or indirectly interconnected to markets. The market function block is composed of all available functions that can be used by the traders to participate in the market or to forward the management to an independent trader via the TCI.

- *The Service Management* (SM) corresponds to an organization that involves several persons, *planners*, that have aiding personnel such as analysts, meteorologists, short-time and long-time strategists that always strive to optimize the production and consumption balance in accordance to the transaction agreement received. The service functions (SM) block includes all functions intended to mange the different services used by the planner.

- *The Production Management* (PM) corresponds to an organization that includes the *operators* that supervises the power units in operation and may have direct connection to control each power plant. The production functions block includes several functions such as; automated generation control (AGC), generation dispatch and automatic voltage control (AVC) and. The resources are administrated by a Schedule Coordinator, which receives all needed data via the OCI.

The traders, planners and operators within the EMS organization handling resources, e.g. WPP units, are assumed fully automated, which enables market-based AGC and AVC. The automated actors only modify strategy constrains and limits to influence the directions in the automated decision-making for acting both toward the market and controllable resources.

The highest internal responsibility of the EMS structure has the operational authority (OA) that manages the internal setup and keep track on which actors and functions to be activated depending on the actual system and hierarchy placement. The OA are always prepared to enhance some of the coordination authorities, e.g. the EBA or the PBA. The OA should not be mixed-up with the operator in the PM layer.

General software structure

Viewing inside the MM, SM and PM blocks, they are in principle structured the same way. As shown in Figure 4.7, the base structure is built on the communication information management that authorizes and manages all in- and outgoing communication. The management block for information and communication authorizes connections according to if other EMSs or power resources would be connected with the lower or higher communication interface. All accepted resources are established in the real-time database (RTDB) that is dynamically constructed. The resource manager includes several functions to read and write to the object resources. The structure for managing these resources is essential for enabling the "plug and produce" capabilities, and is thoroughly described in the Chapter 7. The application functions are functions that normally create individual threads or processes that utilize the resource manager. For example, in the PM case the unit commitment process will have access to all the output connected resources. An analysis process will determine the condition of all resources in the system and forward the results to next instance for decision-making etc. The "Type of Role", in this case the operator process, has the main responsibility for the PM block and interacts

only when new directions are needed to maintain requested tasks. The SM and MM are similar with the exceptions that the application functions and tasks are different. The database is normally found in each block but could also work as a common database resource unit that interacts with all active blocks as shown in Figure 4.8.

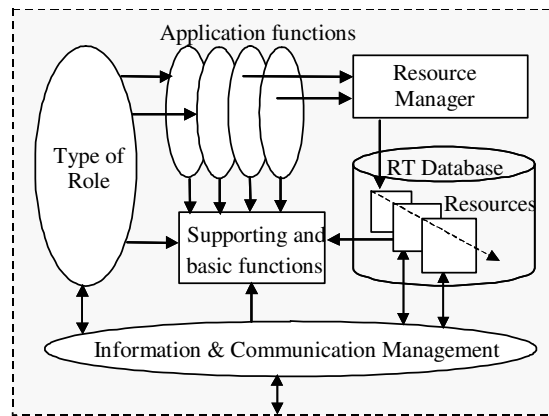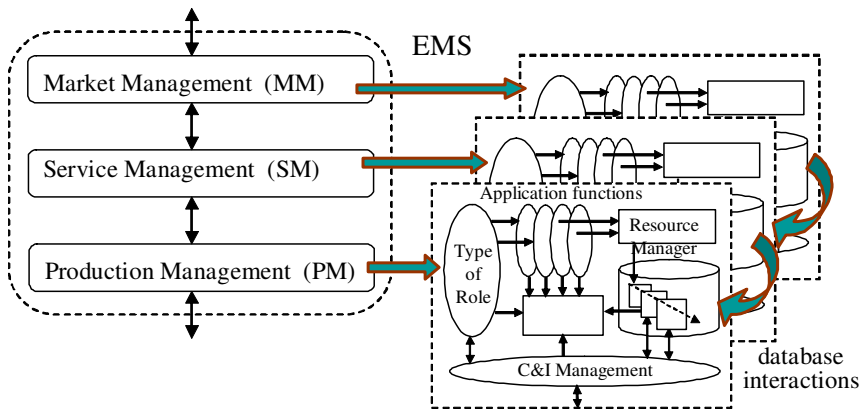**Figure 4.7:** Dynamic EMS base structure overview.

Figure 4.8: Three layer EMS interaction.

The application functions for the PM block are the actual system power functions that are both centralized and decentralized as described in Chapter 6.

Horizontal and Vertical Hierarchy

Energy management systems are normally placed and used sparsely in the power system. Their operational interconnections cover large areas that include a large number of power units and thereby a huge amount of information to be analysed and executed. With restructuring the only decent solution probably include several well strategic placed EMSs sharing this load of information and decisions throughout the system.
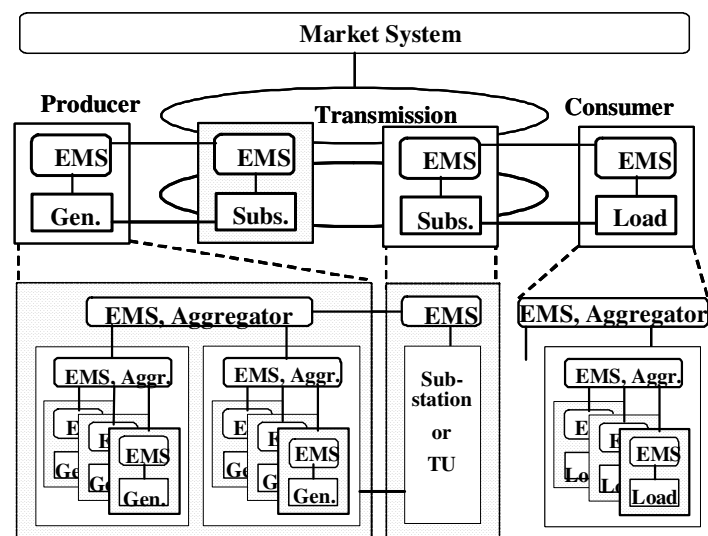
Figure 4.9: Distribute and aggregated EMS structure.

When acting towards an adjacent control area or between the transmission network and the power units as shown in Figure 4.9, the hierarchy is horizontal that implies an equal level of system management over the three EMS layers. The EMS structure is then distributed over the system and included in different units depending on system assignment, e.g. producer distributor or consumer. The information flow is then bi-directional enabling both sides to make decisions according to pre-defined conditions.

The three levels can be more or less active depending on EMSs hierarchy. For example, if using a strict vertical hierarchy, the EMS information is aggregated up to the top level EMS where the PM operates as the control center. At each level the EMS enclosure its resources and act to the next higher level as one merged resource, which reduce the management for the

next level. However, it is possible to distribute the responsibility by activating the functions locally. The EMS structure can be partly activated depending on strategy and local conditions. The levels of aggregation have theoretically no limits as shown in Figure 4.9. The named producer may actually contain several subunits containing additional subunit including generation units. The advantage by such functionality is that the next higher level of EMS operates the lower level power units as one power unit.

4.3 Information exchange

Increasing possibilities to interconnect and participate on a power market bring larger amount of information to handle. For large power companies this is managed by several departments each including several persons that have specific tasks to interact both towards the control centres of the producing units and to the market system for always striving for maximum economical gain. The commerce is continuously increasing as new markets will be interconnected and further services will develop. This might not be appropriate for smaller companies that instead could feel forced to assign larger companies to handle this, for good or bad. This is one solution and should always be left as an alternative. Although, a general solution with increased automatic functions connecting the producers' generation units to the market could be a further development that opens up the possibilities even more. However, this calls upon uniformed information structures enabling real-time operation and market interactions.

The power system has always been depending on an extensive exchange of information. The need to exchange information between the actors on the electricity market has gradually increased number of actors and their changing roles on the electricity market. At the same time, an increasing number of measurement and trading values have to be sent between the companies. The total information exchange becomes very large and communication demanding, which calls upon uniformed information structures enabling real-time operation and market interactions. Thus, there are two main needs for information exchange between these actors that can be divided into the following principal categories:

- *Market information*, where trade and settlement data are needed to upkeep the well-functioning electricity market by changing necessary information before, during and after the operation hour on consumption,

generation, trading, contracts etc. The market information consequently includes information regarding supply/demand, trading and settlement.

- *Operational information*, which is needed to keep the physical electricity system in reliable operation taking into account all the restrictions related to the networks and physical balance between generation and consumption.

Consequently, the information exchange needed for the market and power system interaction include two interfaces, the trading communication interface (TCI) and the operational communication interface (OCI) that are aimed for the market and operational actors. Although, there are additional communication interfaces, e.g. for protection, service and maintenance, where only the protection level is in the scope of real-time operation and control.

Trading Communication Interface (TCI)

The TCI is used between the market actors to provide an interface for exchanging information related to the process of negotiating, establishing and following up agreements. Although different agreements contain different data the basic content is the same.

Signal description

The data can be more or less detailed. In general, to identify what is exchanged between two traders the TCI contains the following groups of signals:

- *Verification and traceability*: type of source, trader ID, document type, document ID, document status

- *Physical location and routing*: area, location/routing direction, delivering/receiving part

- *Service information*: contract period, type of service, unit, quantity, min and max, min and max ramping rate, base price, price, interval

The first group contains information about the identities of affected traders and the document related signals refer to where in the process the offers are, e.g. the created need in the resources, offers, transactions, operational plans, settlements etc. The documents going from the first to last stage in a transaction process have the same identity while the status (prepared, active, and completed) is set according to where in the treatment a stage is.

The second group informs about the identity of physical power actors and which direction the power flow is intended. The last group gives information on the actual service to the market, energy and ancillary services, for purchasing or selling purpose.

The TCI signals are in detail described below where the implementation also needs an identifier for the message type used to exchange the information.

1. *Type of source* = {"production"; "transmission"; "consumption"; "aggregator"} defines what kind of source that provides the service. The "production" is for example a WT. In the case of a reactive power service the type of source could also be "consumption" in the form of a load with power electronics. It is important for the receiving part to know what type of source that delivers the service.

2. *Trader identity* = {"iiii"} identifies the actor who provides a bid. The "ii" is a unique code that identifies the trader.

3. *Document type* = {"need"; "bid"; "contract"; "operational plan"} defines the type of document included. The "bid" can be either purchase or sale bids. Demand schedules typically consist of demand/price pairs for an energy service on the highest level, sent to a purchase/selling group.

4. *Document identity* ={"ne-iii"; "bi-iii"; "co-iii"; "tr-iii"; "se-iii"} is a code used for traceability. The first part of the data name identifies during which phase (**ne**ed, **bi**d, **co**ntract, **tr**ansaction, **se**ttlement) the document is used and the second part "iii" is a unique index used for tracebility.

5. *Document status* ={"ne- sss"; "bi- sss"; "co- sss"; "tr- sss"; "se- sss"} defines the present status of the document. The first part of the data name identifies during which phase the document is used and the second part is a coding on the status for the document.

6. *Area* = {"sa- aaa"; "ia- aaa"; " ta- aaa"} defines the control area where the service is delivered. The control area may be any area that can be defined for co-ordinated trade and operation of a particular service. Transmission area (ta) is used to define an area in which a particular TSO is responsible for the transmission losses. The first part (sa) of the data name identifies a particular level of area definition and the second part (ia) is a specific number assigned to an area within a particular level.

7. *Location/routing direction* ={"sourceID"; "sinkID"} defines the position of the electric unit that provides or receives a service. The sourceID defines the location of the delivering part and the sinkID defines the location of the receiving part.

8. *Delivering part* = {"id"} and *Receiving part* ={"id"} specify the actors that provide a service and receive a service, i.e. the contract parties. The "id" is a unique code that identifies the delivering actor or the receiving actor.

9. *Contract period* = {"from"; "to"; "point of time of delivery"; "interval schedule"} defines the time interval of the contract. The "from" and "to" data are points of time.

10. *Type of service* {"power generation"; "power control"; "load following"; "frequency control"; "spinning reserve"; "supplemental reserve";

11. "reactive"; "voltage"; "back-up"; "network stability"; "black start/island operation"} defines what type of service is covered. The type of service matches the services described in clause 2.3

12. *Unit* = {"enumeration (of units)"} defines the unit of the service. The enumeration contains a list of SI based units and other units, such as [MWh, MVAr, MW/Hz, MWh/h].

13. *Quantity* = {"NN "} defines the amount of the specified service. The "NN" is MW or MWh.

14. *Min and max* = {"NN ", "NN"} defines the minimum and maximum amount (MW) of the specified service, the plant is able operate.

15. *Min and max ramping rate* ={"units/s ", "units/s"} defines the minimum and maximum ramping rate for the specified service. The "units/s" is a number, usually MW/s.

16. *Base prise* = {"NN "} defines the basic or fixed prise per unit or per time period for the specified service. The "NN" is the amount per time period or number of units.

17. *Price* = {"NN/unit"} defines the prise per unit for the specified service. The "NN" is the amount per unit. This also includes start-up costs etc.

18. *Interval* = {"NN/time period"} defines the interval for reporting of metered values. The "NN/time period" is the number of times per time period.

Operational Communication Interface (OCI)

For the power system operation it is advantageous to attain a well-defined and limited communication interface with uniform signals independent of control unit level. Regarding signal types for a wind turbine unit, the range of signals is large. In this case the attention is in fast real-time control and the signal scope is thereby divided in operational signals and none operational signals.

Signal description

The main purpose of the OCI is to enable the production level operational functions for different resources related to the services offered through the market. The OCI is divided in *operation* and *information* signals, which include discrete operation and control, and also signals for analysis, decision and metering purpose. The OCI contains the following groups of signals:

- *Operation*: transaction ID, command, govern, set point

- *Information*: error, status, data, calculated data

The *document ID* of the TCI is linked to the *transaction ID* of the OCI that justify the activation of the *command* and *govern* signals, which starts and set the control mode respectively. The *govern* signal is linked to the *type of service* of the TCI. The operation might be authorized from the GSO or the TSO according to agreements. The operator receive the information signals to confirm the intended operation. Further, depending on type of service in use, the information data is differently exploited. If using an ancillary service, the TSO has to determine actions according to the maximum and minimum available capacity and power rate, which constantly fluctuate in a WPP case. Even the nominal power will change depending on the number of operational WTs in the WPP. The OCI signals are described below.

1. *TransactionID* = {"unique identity figure"} is the initiate check signal for approval or denial to allow further operation. The signal is related to a unique identity of a completed contract

2. *Command* = {"quick stop"; "stop"; "ready"; "start"; "quick start"} is the basic operational signal for start and stop of the WT units. The "quick stop" command is assign in case of emergency. The "ready" command is used to prepare for a faster start and also as a check for no failure before the next coming "start"-command. In "ready", the unit is in a hot standby mode. The "quick start" minimizes tests and built-in delays enabling a faster start-up.

3. *Govern* = {"min"; "max"; "ramp"; "power control"; "voltage"; "reactive"; "frequency"} specifies the different modes of control. The "min" mode is used to assign a generation unit to some type of ready state (idle running) but not completely out of order. The "max" mode always strives for the unit's maximum generating output. If operating none stochastic generating units it is the same as the nominal output power. When an external power set point is used the mode is called "power control", se the Set Point signal explanation below, where "frequency-control" and "voltage control" mode can be selected in case of ancillary service.

4. *Set Point1* has no significant meaning unless the Govern signal is set to "power control", "voltage", "reactive" or "frequency". Then it is used as a set point received from higher unit levels.

5. *Set Point2* is a ramping set point enabling a smooth change prom one set point level to another to prevent disturbances in primary and secondary control.

6. *Error* = {"A-alarm"; "B-alarm"; "C-alarm"; "no error"}, informs the higher-level unit the degree of error in case of control unit failure. Each control unit has an error handler that analyzes and diagnoses all detected errors. The handler has a predefined strategy that determines the degree of error.

7. *Status* = {"blocked"; "intermediate"; "off"; "ready"; "on"}, informs the higher level of the unit or block status and mode. The mode signal operates as an acknowledgement for the command signals where "blocked" means that either a failure has occurred or that the unit has been locally authorised for some reason. The signal is assigned to "intermediate" when the unit is in a state not referred.

8. *Data* are measured or calculated values. As a minimum the power unit informs the environment about the current power. An estimated maximum and minimum power as well as ramping maximum and minimum values. Depending on the services provided by the generator selections from the following general list of measured data may be included; active power, reactive power, estimated max power, min power, nominal power, active energy, reactive energy, "frequency control energy", power rate (max), power rate (min), voltage (3-phase), current (3-phase), phase angle, frequency.

9. *Calculated data* include maximum available power, minimum available power.

Depending on the services provided by the generator selections from the following general list of measured data may be included; active power, reactive power, estimated max power, min power, nominal power, active energy, reactive energy, "frequency control energy", power rate (max), power rate (min), voltage (3-phase), current (3-phase), phase angle, frequency. The calculated data include the following: maximum available power, minimum available power.

In the later described implementation the OCI is realized by a vector with the length of 37 signals which contains all the information needed to run a fully automated power system as described above.

Information hierarchy

The information flow in the market and power system ranges from the lowest level of process information used for the local control of the power units to the highest level managing the market. The information is aggregated in several steps, and finally used as a basis for placing bids on energy markets. In the other direction, information is distributed down to the individual power units. Vertical information structures are used within the same operative managing area. Information aggregates upward and agreements, transactions and operations distribute downwards. Between adjacent operative management areas horizontal structures are used but, so far, almost all such information is manual.

As shown in Figure 4.10 the TCI is applied on several levels up to the market system. It is used between market actors and the markets to put purchasing and selling bids on the market and to get aggregated information from lower level instances. The market actors may also interact with other market actors to act on markets managed by other market operators. The result of the bidding on different markets is delivered to the MM of the EMS at the GSO, TSO, and/or load system operator (LSO). The break down levels presented is corresponding to the actors in the market (independent trader, merchants, brokers), the dependent trader within the MM and the planners within the SM. The result of the bidding on different markets is delivered via the TCI to affected actors. In order to manage the contracts and to operate the power plant, internal market functions for tracing the change from one active contract to another are used. However, there may be additional levels below or above the ones presented. For example, a contract may be split into several contracts and distributed to the next level below. At the second planner level the contracts are split into operation transactions, and then into

operation commands at the production control level. The SMs handle requests from the level below, which aggregate several resource capacities and functions and send the basis to compose the needs/offers to the next level above.

The other type of information that is forwarded from lower levels is settlement information, which is managed in the same way. In the other direction the SM distributes the contract information from the MM to different WPP subunits by scheduled transactions that in turn send operational commands to individual power units.
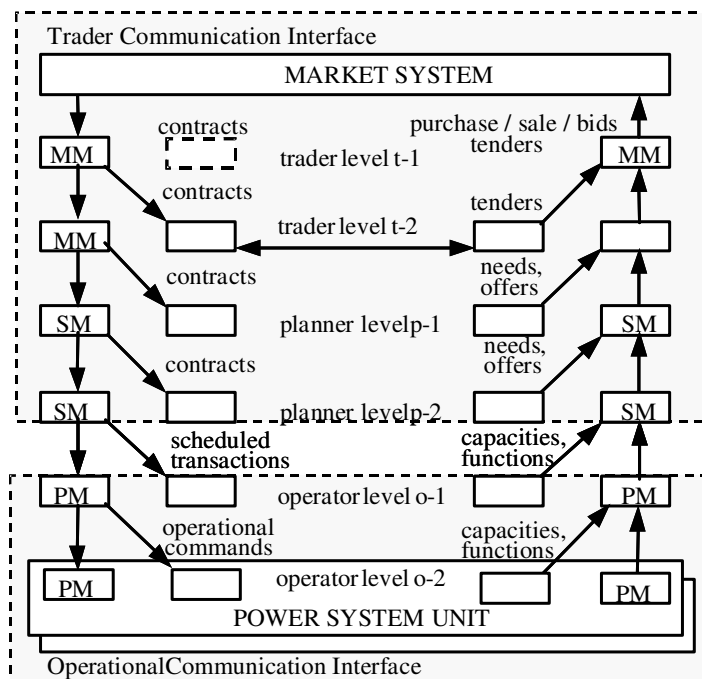
Figure 4.10: Information hierarchy.

The information on all contracts and transactions is stored in the EMS at each affected level. At production level the PM can be connected at several levels. The interface to each PM block contains the same groups of signal types for operation and information according to the OCI. The control and information signals are all treated in the PM blocks and are the main interface to upper level control units. The top level PM corresponds to the main control center. Each PM block analyses and diagnoses the signals

both from internal and external connections and determines the resulting output, which are stored and handled at each operator level.

Interface functions

The TCI has to handle requests from the level below, aggregate several requests and send a request to the level above. The other type of information that comes from lower levels is settlement information. This information will, if necessary, be aggregated and forwarded to the level above. In the other direction contract information from the different markets are divided for the different "units" below. The functions needed to handle trading information at the interface include aggregation and optimisation of bids, operational plans and settlements.

The information on all contracts is stored in the EMS. In order to manage these contracts and to run the power plant in accordance with the contracts, internal marketing management functions for tracking the change from one active contract to another are needed. The transaction can be initiated either by receiving a govern signal from the transmission service provider or by internally changing the operational mode in order to switch to a more economically favourable contract.

The control and information signals, included in the OCI, are all treated in specific management blocks and are the main interface to upper level control units. Each block analyses and diagnoses the signals both from internal and external connections and determines the resulting output. These unit functions store and handle the control and information signals at each level of control.

4.4   Market based operation of RES – an overview

Before RESs can have a more active role in the power system, in the short and long term perspective, several technical and organizational issues have to be solved. The integration of small and large RESs into the power system calls for new operational strategies where the limitations regarding generation capacity of RES are considered. A market-based operation of RES requires interaction with market actors and new functions to handle contracts. The great uncertainty and expected fast changes in RES production raise demands for automated functions for controlling generation units by adequate information directly interconnected with responsible operator in charge for fast decision-making. Technology that

increases the system operator's flexibility to observe or control the power system or that increases the throughput of the transmission system is useful in supporting market development. When RESs are able to offer ancillary services, real-time information system will be needed for interconnecting the TSOs. The operating environment for system operations that control the power system is shown in Figure 4.11. The power system holds different actors depending on assignment for different companies and organizations.
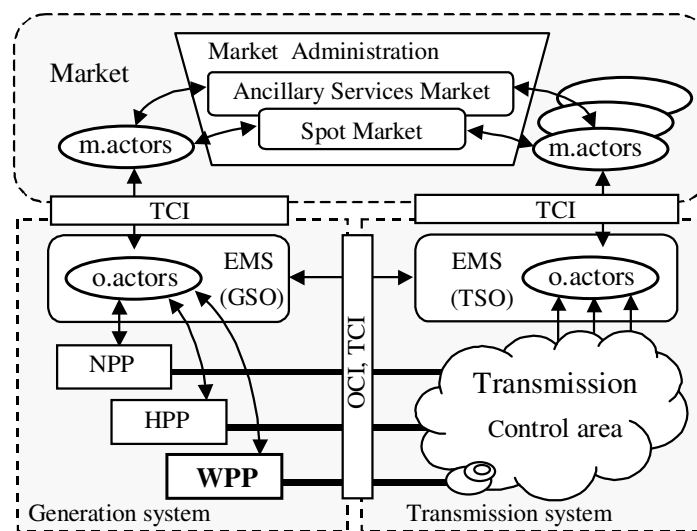
Figure 4.11: General overview of market and power system interaction.

Operative actors are partly responsible for interacting with other power system entities (producers, transmission providers and consumers) to operate and support the physical power system [Buyya and Vazhkudai, 2001] [Strandberg, 2001]. The market system manages the agreements on the services used for operation of the power system. Each operative actor interacts with a market actor to provide operative services to other actors. The market actors can either use some type of market place, ancillary service or spot market, to find a buyer or seller of a specific service or two market actors can make a bilateral agreement. Thus, there are two main needs for information exchange between actors. *Operational data* is needed to keep the physical electricity system in reliable operation taking into account all the restrictions related to the networks and physical balance between generation and consumption. *Trade and settlement data* are

needed to maintain the well-functioning electricity market by changing necessary information before, during and after the operation hour on consumption, generation, trading, contracts etc. Two interfaces, the Operational Communication Interface (OCI) and the Trading Communication Interface (TCI), are used for the exchange of these two categories of data.

The information and EMS structures, previously presented, are essential parts for developing future distributed modular functions that enable interconnection between power units and the markets. The functions needed must be accommodated by the new market and power system information structure. These functions range from assuring an adequate electricity supply through long-term planning of the generation and transmission system, to meet shorter term forecasted load by deploying existing resources through unit commitment, to assure system security through automatic generation control, and operating the transmission system by controlling ancillary services.

As RESs have several advantages in operation and could have high controllability, the TSO could enable access to use these services from the generation system operator (GSO). An obstacle today is that in an emergency situation the TSO does not have directly access to control large RES units according to the contracts. Currently, most communication technologies used in the power system only allows local control actions at the power plant due to lack of efficient, high speed and bandwidth communication media.

RES operation

A market-based operation of RES requires interaction with market actors and new functions to handle contracts. In addition, as described in [Kirby, *et al.*, 1999], opening markets may open up for other distributed resources such as controllable storage and load units. Competitive markets probably support technologies that have considerable low capital costs, are fast to install, and able to respond rapidly to changing market conditions.

Traditionally RES units are controlled in order to produce as much power as possible, which is desirable. Forthcoming RES units must be considered as controllable generation units, in a similar way as e.g. a hydro- or nuclear power plant. RES units differ from conventional generation units primarily in the way the power fluctuates due to the change in the wind speed and

solar irradiation. A RES unit is therefore regarded as a stochastic generating unit that demands accurate power measurements and reliable maximum power estimations to provide the EMS with correct real–time information for decision-making. So far, there has been almost no interaction to the common EMS enabling the RES to participate in both primary- and secondary system control. In order to meet requirements regarding the RES unit's participation in the management of reliability in electrical networks, new perspectives have to be considered regarding controllability. Depending on design, RES units are able to offer energy and ancillary services (for system reliability etc). RES units should be related to agreements towards transmission network owners and consumers according to conventional generation units. With new services to offer the market, there will be new possibilities for market-based operation of RES units as described in Chapter 3.

In the short-term perspective concerning rapid changing operation situations, a future market interaction to ancillary services may be essential for RES units in improving system reliability. In the time frame of seconds or less the variations for RES can be assumed negligible. Provided that the operation facilities are automated and fast, it will be the immediate capacity provided by the RESs that determines if a primary or secondary service is possible to employ. However, in the long-term perspective, the energy planning or management for a RES producer might become the most difficult matter to handle. If a producer with energy balancing responsibility has several generating units where the RES units are only a smaller part, there are minor problems in balancing the fluctuations due to the wind speed and solar irradiations. But as the RES penetration increases the need for forecasting become important to be able to trade on the market without too much risk. Forecasting tools need to become more sophisticated enabling power companies with exclusive RES to spread their risks by properly dividing the offers and services on the energy balancing market. This time aspect is a problem unless approaching forecasting tools will have high accuracy for the requested period or if the GSO has balancing capabilities in other generating units such as hydro power plant (HPP) and nuclear power plants (NPP). By decreasing the trading periods the deviations in power production could be reduced and at the same time increase system reliability depending on management, which calls for faster decision-making. This implies on a higher degree of automated operations in association with real-time information. Thus far, there has been almost no interaction to the EMS of the GSO or TSO enabling the

RES to participate in both primary- and secondary system control. Optional control modes are necessary for the RESs enabling ancillary services.

Contingency operation

In emergency situations, the TSO needs access to controllable power units by quickly increase or decrease their production level in order to maintain the power balance in the system. If a severe disturbance occurs that causes power units or power lines to be unexpectedly disconnected from the network, the TSO must start generators quickly to prevent system collapse. It is the TSO's responsibility to have this fast disturbance reserve available.

The TSO has normally purchased necessary disturbance reserves by signing long-term agreements and these reserves are during normal operation not used for balance regulation. However, in a disturbance situation these reserves may not be sufficient and the need for new reserve agreements is needed quickly. At present, when a disturbance reserve has to be used during normal operation in order to maintain the power balance, the TSO can announce a much higher price for balance power. If the situation is even more severe, so that all production reserves have been used to its maximum and the disconnection of consumption has to be ordered to maintain the balance of the electricity system, the TSO can announce an even higher price for balance power.

As speed in making those agreements becomes important, markets beside the bilateral one might be needed. Well managed markets for reserve capacity and ancillary service may meet such demands and depending on the information structure, the management from finding out the capacity need, making an agreement and the ability to operate a controllable power unit might take as low as a few seconds depending on the future progress in the automation of the process.

The operational actors are responsible to maintain secure operation. In a contingency situation the re-dispatch function may be useful by sending commands to generators to increase/decrease their output based on system security needs. In many systems, operators have access to tools that permit them to estimate the cost (a proxy for price) of their actions. Thus, operators generally have at least some awareness of costs. Increasingly, however, a larger portion of system generation (and also of load) is being bought/sold under merchant contracts that specify specific levels of production at any given time. This effectively eliminates adjustment of

generator output as a primary tool for maintaining system security unless contracts are written to grant the system operator this type of control. One approach to returning this control to the operator is to have generators offer increment/decrement (inc/dec) bids for their output. That is, generators indicate the price at which they are willing to increase their output by one MW (inc bids) or decrease their output by one MW (dec bids), with limits for both. This arrangement permits the operator to reschedule generation as before, at an explicit price. If an inc bid is exercised (a generator is asked to increase its out-put), the price of increasing the generator output by one MW becomes the marginal price of electricity at the generator location (this cost is also known as the locational marginal price, or LMP). Depending on the design of the market, the costs of re-dispatch can be either absorbed as part of the cost of system operations and paid by all participants using a cost structure in which these expenses are shared, or the costs can be charged to those "responsible" for the need to incur re-dispatch costs.

In a competitive environment, the problems of unit commitment and the necessity of having an appropriate available excess (reserve) generation can be resolved in a number of ways. Because of the time lags associated with the start-up and shutdown protocols for many generation units (and also the start-up and shutdown costs for these units), an appropriate organisational structure is needed for deciding what units should be in service ("committed") at a future time. The unit commitment problem can be addressed in various ways, from "command and control" measures (also called "administrative solutions") for ensuring reliability to purely market and contractual means for ensuring sufficient reliability. From an operations viewpoint, reliability depends on the units, loads, and transmission equipment that are available in real time, so it is impossible to entirely separate the problem of operations planning and unit commitment from the problem of providing reserves. Likewise, the ability to provide sufficient reserves or reserves from certain locations is entirely depending on the ability of the transmission system to support the transfers that would be required under contingency conditions.

4.5   RES integration and interactions

The section illustrates the principal interaction for a future distributed energy management system between the market and RES. However, as the focus for the work is outgoing from fast changing operation situations, the

market interaction is limited to a future market for ancillary services where RESs may be essential in improving system reliability in some control areas. In the time frame of seconds or less the variations for RES can be assumed negligible. Provided that the operation facilities are automated and fast, it will be the immediate capacity provided by the RESs that determines if a primary or secondary service is possible to employ.

The commerce is continuously increasing as new markets will be interconnected and further services will develop. This might not be appropriate for smaller companies that instead could feel forced to assign larger companies to handle this, for good or bad. This is one solution and should always be left as an alternative. Though, a general solution with increased automatic operations interconnecting and interacting the producers generating units to the market, could be a further development that opens up the possibilities even more, which is exemplified here.

Power company internal balance management

The trader, which might be the producer's own market management, MM, organization supply the planning management organization SM with contracts that both could have been requested by the SM or by external actors. The SM normally optimizes the possibilities in running the most economical composition of their power plants in operation. If the power company has other generating units than WPPs, the potential fulfilling the contract is less difficult. However, if it is only wind power in use it might be more complicated. Thus, power companies with energy balance responsibility operating different generating units have advantages in balancing wind power. As shown in Figure 4.12, the producer continuously receives information from each power plant, via the OCI, including present and forthcoming power production to be analyzed by the SM. Depending on the wind power part in relation to remaining generation, meteorologists and forecasting tools are more or less important. The energy planner decides the needs for the next hours of production and sends the information to the MM that determines the best portfolio towards the market. The trading via the market then results in several agreements/contracts, which then will be distributed by the planner as transaction orders to the production control centers. Depending on power plant localizations the transaction could be distributed in more then one way. For example if the WPP is large enough to supply the interconnected transmission system with ancillary service the planner might order this, via

the OCI, to command the power plant to participate in primary control. In this case it is less complicated to manage the wind power production as limitations can be done in the other power plants. However, if the WPP peak power part is close to what can be down-regulated in for example the hydropower, energy storage might be by-passed, which then becomes an economical issue.
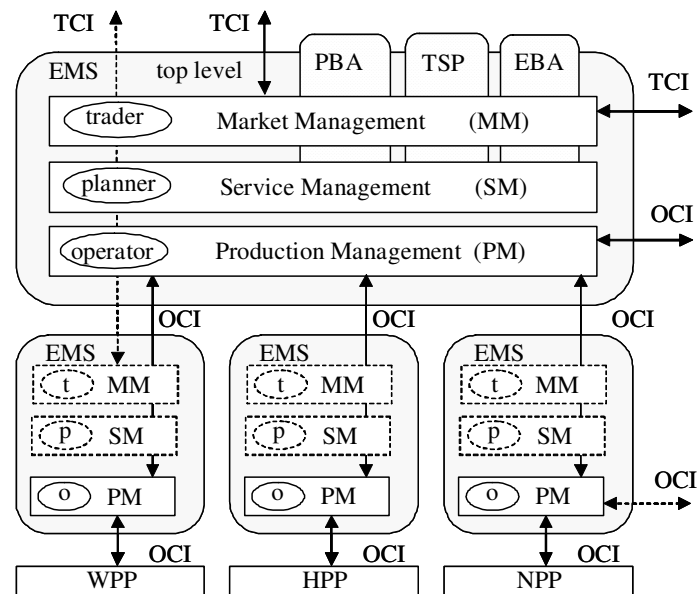

Figure 4.12: General information structure managing of several types of power plants.

The problem also gets worse if each power plant has individual profit demands. As distributed EMS software might increase information security and as well divide computer load capacity in an effective manner, the figure also shows individual EMS structures for each power plant. Depending on internal company information management they are more or less active. Normally if a company invests in additional power plants, their EMS information is aggregated in the company's central EMS. Left are, if necessary, only the operator(s). Depending on where in the system they are located and the type of units in control they have more or less functions distributed and activated. For example, the Energy Balance Authority (EPA) is responsible for balancing all energy service transactions and interacts with energy markets. The EPA supervises the performance of the

responsible actors, in order to verify that they deliver the exact amount of energy. All production has to be planned and all consumption shall be proposed to the energy balance responsible actors. These plans and prognoses shall match what is delivered and retrieved in each access point. The energy balance responsible actors have to report the total actual delivery and retrieval within a specific area.

Market interaction

All producers have the same rights and obligations regarding what information are exchanged with a particular market. The market interface is the same for all producers, but the complete information depends on which services are provided by a particular producer. If a producer cannot deliver ancillary services then the information related to that kind of services is not included.

Figure 4.13: General information structure for different ownership.
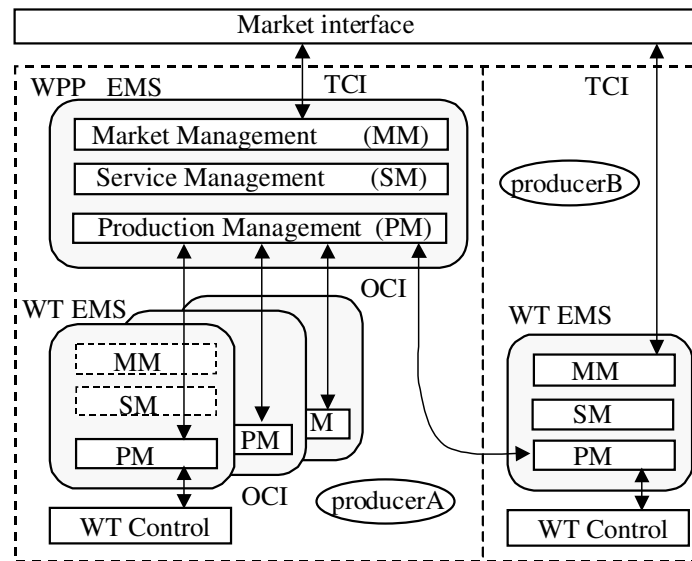
A general information structure should not limit the possibilities of having different owners and market actors within the same power area connected at the same electrical grid connection. As shown in Figure 4.13 the market interface (TCI) is the same for the two producers A and B. However, producer A interfaces the market at WPP level where producer B interfaces

at WT level. In the producer A case, the market management functions are implemented in the EMS of the WPP, together with functions for energy management. These functions manage all WTs in the WPP. There is no need for these functions in each WT as needed production information are aggregated. In the producer B case, the WT needs market and service management implemented at WT level. Traditionally these functions are not at site level, except for production control. The production control function at next higher level than the WT, the so called wind power plant system controller (WPP-SC), has the task to aggregate all information and distribute command signals However, looking in the near future for what should be needed in a highly increasing information system, all functions should have the possibilities to be distributed, for several reasons. Furthermore, if most of the management functions also will be automated this requires an information structure that manages distributed functions at any level.

For example, if a new owner constellation appears, a number of WTs may have new information connections. The new producer B then disconnects the coupling from producer A and depending on producer B´s own WT units makes a new connection either directly to the market or via another higher level EMS. Depending on producer A´s agreements and operative responsibility, it might be necessary to inform producer A of producer B´s production and control data enabling producer A improved planning and operation capabilities.

Transmission network system interaction

On power system level, operational information between the producer and the transmission provider is exchanged through an operational communication interface, OCI. The actual implementation of this interface could be done in several ways. For example, a signal from the TSO to disconnect a WPP could be transferred by a hardwired connection from the EMS of the TSO for production control to the EMS of the WPP as shown in Figure 4.14. The information is typically transferred on the production control level. Within a WPP, information is exchanged between production control at WPP level and production control functions in the WTs. All WTs in the WPP have the same communication protocol, OCI, connected to the next higher level PM (WPP-SC) where also the TSO might be remotely connected. A normal energy transaction is performed when the WPP is authorized via the TSO to start generating power.

If the WPP is connected to the local market through implementations of the TCI, it is also automatically connected to several other markets. The WPP then provides its services in an automated purchase/selling process, where the bids are automatically forwarded to the market. Settled agreements will then be distributed to all the affected units and among them the EMS of both the transmission unit and WPP unit.
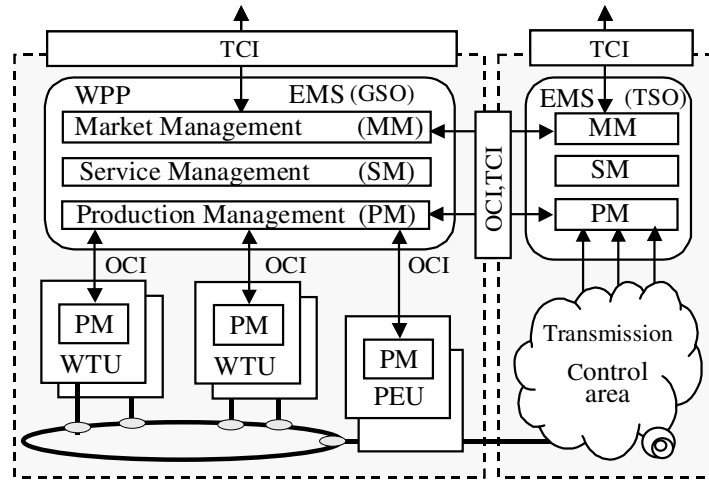

Figure 4.14: WPP and transmission system interaction.

The WPP EMS receives the agreement through the TCI together with a transaction ID for the schedule. The consumer and affected distributors gets the same ID for verification. Further, when it is time for operating the WPP according to the agreements, the operating control could be done from the transmission or WPP operator through the OCI depending on type of service.

Plug-and-produce scenario

This section presents a "plug and produce" scenario for connecting WPPs to the power system as illustrated in Figure 4.14. The scenario includes electrical connection and automatic establishing of connections to relevant energy service markets as well as connections to production control systems using the information structure and the interfaces presented in this chapter. For the scenario the following assumptions are made:
- The producer has established agreements with the energy related markets on which he intends to offer the services from his WPP.

- All legal permissions are in place and the WPP has been verified to fulfil all necessary technical requirements for connecting to the power network.

Plug and produce

A wind power company has invested in a new WPP with five 3 MW wind turbines. The operation of the wind turbines will be co-ordinated by a WPP system controller. The wind power company does not have a central dispatch centre but wants the production control functions to be located in the WPP. They also want to distribute the market functions to the WPP. Thus, the WPP shall act as a completely autonomous unit.

All the construction work has been completed, all systems have been tested, and the wind turbines are ready to be connected to the power system. However, before closing the breaker that will connect the electrical system of the WPP to the external network, the producer must establish a way to monitor and control the wind turbines in the power plant. Also, the network reliability authority requires the possibility of controlling the wind turbines. Finally, the producer has to make sure that the energy produced is delivered to a customer and paid for. Because the producer has bought a WPP with both OCI and TCI the connection process is simplified. The operational communication interface (OCI) describes the basic type of information that is available from the power plant and the control signals that may be sent to the power plant. After connecting the electrical interface the network company's control system is connected to the OCI of the WPP using some standardised protocol. Internally the OCI is also used to for the interface between the wind turbines to the plant controller. The next step is to connect the WPP to the relevant energy related markets.

The new WPP has been designed to provide all possible services. It can be run in an uncontrolled power generation mode and produce maximum possible power from the existing wind, but it can also be run in a power control mode where the active power level can be set. One variant of power control is load following where the production is adjusted to a specific load. The ability to control the active power based on the actual frequency makes the power plant suitable to also provide frequency control, both connected to the network and in stand-alone mode, and to act as frequency responsive spinning reserve and backup supply. The turbines are also designed for reactive power supply and voltage control.

The wind power company has selected a WPP where marketing management functions have been implemented in the WPP system controller. The implementation includes functions for managing all the services that the power plant may provide. Since the wind cannot be stored the usual operation mode would be to produce as much power as possible. The wind power company's strategy is to sell as much power as possible at the spot market. However, to avoid the costs for expensive balancing power a large part may have to be sold on the short-term market. At the same time there is often a local need for reactive power in the network to which the power plant is connected.

The WPP is connected to the purchasing/selling services of the different markets trough implementations of the trading communication interface (TCI). The TCI signals and services provide the means for automating the bidding process and generate control strategies based on the market clearing price received. The first step is to automatically connect to each market and to provide identification. The purchase/selling services check that there is a valid agreement for acting on the market and then gives access to the market. Based on energy prices prognoses and prognoses for wind speeds the next day the marketing functions calculate prices and the amount of energy for the spot market. The bids are automatically forwarded to the spot market. After the market clearance price has been determined the market operator transmits each participant's generation commitment (preferred schedule) that is below the market clearing price. The preferred schedule constitutes a sales contract for the purchase of a specified quantity at a specified price. The WPP controller receives the schedule through the TCI together with a transaction ID for the schedule. The customer (the contract partner for the energy supply) gets the same ID.

There is another process involved before the preferred schedule is returned to the WPP. There must be a way to transfer the energy to the customer that consumes the energy. A transmission service has to be available for the supply and delivery point and for the amount of energy agreed on. This service may also be provided on some type of transmission service market. For each supply of energy there must be a contract with the necessary transmission service providers.

When the time of start-up gets closer the EMS functions calculates the available surplus energy that is not covered by any contracts and forwards this data to the marketing management functions. The marketing management functions put together new bids and forward them to the spot

and ancillary markets. This may result in additional contracts for production. At start-up the production control functions transfer the transaction ID for the transmission service to the network operator using the OCI interface. The transaction id is checked to verify that the WPP is allowed to start supplying energy. And then the production can start.

As described above the WPP may also provide reactive power. The process for connecting to an ancillary market, and trade reactive power services, is similar to the process for energy production. In the end, the marketing management functions in the WPP keep track of several simultaneous contracts and decide which contract to be activated. As long as they do not conflict with each other several contracts may be active. Settlement data has to be produced for each active contract. After some time the TSO wants to activate the contract on reactive power supply. The TSO uses the OCI to send a Govern signal set to reactive power and attach the transaction ID. The production control functions check the transaction ID and then changes the operation mode of the WPP to reactive power. At the same time the production counters for reactive power is activated. After the contract period for each service is over the WPP delivers settlement date to the relevant market operator.

4.6 Concluding remarks

Several general trends and ideas about future RES integration and interaction are presented in this chapter. Until now, very little of these changes have been implemented in full scale. The purpose of presenting these trends and ideas is to point out how new applications of RES are able to improve power system performance and to prepare for future needs regarding EMS and information structures. The existing RES, mostly WPPs, are almost only used to transform maximum possible energy via instantaneously maximum power. With a number of novel approaches for wind power operation future WPPs may have new possibilities. New technical solutions for wind power give the possibility to provide a number of services to energy and ancillary services market actors such as energy consumption customers, transmission service providers, and system responsible actors. It is likely that wind power producers will, for long time, have to rely on additional types of production plants within the same company/organization or from another producer to fulfill the balance responsibility for their customers.

If real-time trading and operation may become reality, the management mechanism from contract to physical power transaction will get faster and become an important advantage for generation units based on renewables. Operation decisions might then be based on accurate real-time information. However, forecasting tools will have an important position for enabling wind power to participate at the market on the same conditions as conventional generation units. The automated process puts requirements on the interface for both market interaction and operation interaction with the market actors. As presented, the trading communication interface, TCI, and the operational communication interface, OCI, provide the interfaces needed to accomplish the information exchange. Standardised information structures and communication interfaces for market management, planning and production control is one step towards a future "plug-and-produce" system.

Finally, the integration of RES and other power units that should be able to automatically adapt to the system requires an active transmission network that has a high degree of the information and EMS structures presented including automated coordination functions. This implies on a break-down of national or regional control areas into local control areas, distributed power systems, as illustrated in Chapter 1. The vision requires an extended need for real-time communication and well-defined information structures to handle fast changes in the control area to ensure system reliability. This is introduced and further described in next chapter.

Chapter 5

Power system restructuring

The chapter initiates with an overview and principal description of a general distributed power system structure. The DPS model used for the analysis is introduced. The system automation hierarchy is investigated and appropriate superior controller units integrated in selected power units. The interconnection and interactions between system units are described that are the foundations for the introduction of the active terminal unit interface.

5.1 Introduction

Knowledge and experience from planning, erection, operation and maintenance of automated systems open up global opportunities in areas remote from large electric power systems and be competitive with other distributed electricity generation. In the future, DPSs will have the potential of becoming a challenger to large-scale central systems of today or to growing complementary systems in cooperation with the central system. It is therefore important to get practical experience of such stand-alone systems and their potential function in order to have the needed knowledge for the future applications. A more sustainable energy system has to be gradually introduced where new technology will be utilized.

As new technology evolves and renewable power sources develop the system will transform from deterministic to stochastic generation, where system information will be vital for the system operation. The system operation will not be limited to one physical point but distributed to several strategically locations always prepared in taking over control.

Principal definition

In evaluating the impact of market and technological change, it is appropriate to view the electricity infrastructure as two tightly coupled networks regarding power and communication. Consequently, the principal definition of an active DPS represents two networks based on a distributed functionality comprising:

- The physical power network of interdependent power production, delivery and consumption units that are grouped as sub-systems.
- The under laying communication network, including an information and functional structure for automatic operation and control of subsystems.

The principal properties of an active DPS is rather general and is here divided into two system levels.

- Power systems characterized as composed of active distributed power systems have the ability to split the system into operational subsystems and later on when appropriate, the ability to merge together. During "stand-alone" mode they operate and have the same functionality as conventional large power systems.
- A single active distributed power system is characterized by the ability to operate local power units supporting local consumption units similar to large power systems in a "stand-alone" manner when needed. This is more efficient and reliable by enabling automated system functions.
- The single active distributed power system is able to present itself as a single power unit. The multiple generator, storage and load devices embedded in the system may be aggregated into a single power unit with the capability of being dispatched like a controllable generation or load during abnormal operations.

There is no actual size limit of the control area of a DPS, which could be an intelligent car, house or an entire power system. The operational management of such systems ought to origin from the same fundamental structure depending on future requirements on mutual utilization.

5.2 DPS fundamental architecture

This section proposes principal ideas in the structuring of a distributed power system. The basic approach is a modular structure dividing existing systems into several levels of subsystems. Restructuring the power system with "the ideal" solution is close to impossible due to the constant changes

in demands and new possibilities. However, by designing a flexible and adaptable structure, it will provide means for extended durability. An important ambition in constructing future power systems should be attaining something close to "plug-and-produce" capabilities.

Principal functional modular structure

System restructuring, particularly large and complex systems like the electric power system, involves some basic principles to handle complexity. The basic aim is that independent of connecting a generation or load unit, the system should automatically configure and, if appropriate, prepare the unit for operation. The unit responsible should also automatically be able to participate in the market offering purchase or sale bids.

As complexity increases, a traditional solution is to divide a problem into sub problems with well-defined interfaces. Breaking a large system into smaller subsystems, called units/modules, is a natural way to handle complexity [Luo, *et al*., 1999]. The basic idea is that the subsystems are easier to deal with than the total system. It is important that the modules are isolated with well-defined interaction and interconnection interfaces. Modularization can be done hierarchically at a number of levels where units are decomposed into subunits, which are decomposed into sub subunits, etc. This creates a hierarchy of modules where decomposition makes design of each individual system more straightforward.

In Figure 5.1, the power system is divided into several subsystems or DPSs, each containing several power units managed by the EMS connected to a local market management organisations (MMO). The DPSs are supposed to have autonomic functionality and capabilities to inform adjacent DPSs or detached MMO through primarily three communication interfaces.

- *Trading communication interface* (TCI), which includes several signals for managing the purchases and sales towards the market.
- *Operational communication interface* (OCI) that contains all necessary operation and information signals for real-time control.
- S*afety/protection communication interface* (SCI) that ensures high security by informing adjacent power units for fast decision-making.

This opens up for new strategy aspects in localisation of new generation and storage capabilities. The DPS unit have a local administration, MMO, for managing the different markets. Similar to the physical power part this must be able to manage the local market in case of communication failure to adjacent or higher level markets, for security reason not losing the market mechanism. Normally the local MMO would be passive mainly acting as a concentrator/distributor interconnected to the active markets via the TCI. The local administration might then be activated depending on a failure situation and continue the normal electric power business, although with a smaller number of participants.
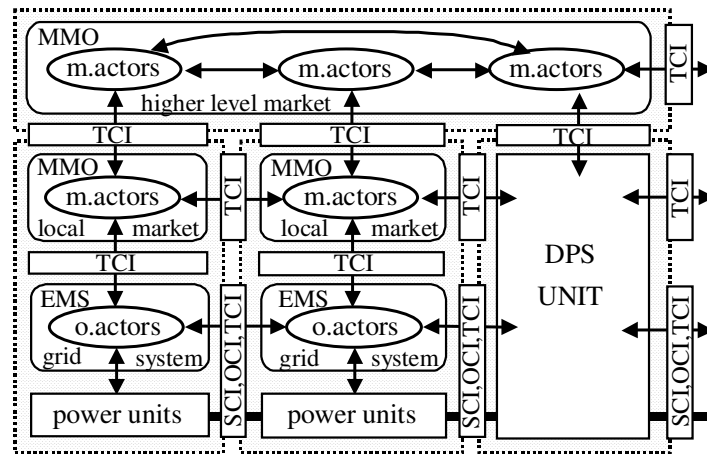

Figure 5.1: General market and power system divided into distributed power systems interacting the markets via individual EMSs.

The DPS unit works similarly to the present power system except for being down-scaled. The main DPSs unit, typically the one with highest power capacity, would in normal conditions still work as if all DPSs where merged together. Only under special circumstances would affected DPSs disconnect, and later on when appropriate, reconnect. In the meantime the DPS unit may be run in a stand alone mode. As with the demand on "plug and produce" for power units, a DPS should also be considered as a unit and consequently the same demands should apply on such a subsystem. Regarding power units, principally all source and sink entities connected to the DPS unit and among them RESs, could be placed in any control area and automatically interact with the local system operator and market. However, the RES capacity and controllability should be carefully

determined to maintain a well-balanced DPS control area for security and reliability reasons. The DPS could negotiate power exchange with adjacent DPSs through their internal energy management systems (EMSs) via the TCIs and the local MMO. Operational actors then control the exchange and managed operation of connection with adjacent DPS through the OCIs. Faults are managed and isolated within a DPS unit so that the effect will not propagate to other DPSs mainly by the internal security authority (SA) connected to the protection level via the SCI. Stand-alone operation is available as an emergency condition when the DPS unit is not capable of importing/exporting as much power as needed, where the local generator/load units will be operated in order to achieve power balance.

System unit classifications

All system units have an internal structure including hardware and software with well-defined interfaces and different automated intelligent decision-making depending on unit potential. Units may be constructed by other units and are easily interconnected by uniformed interfaces. For example the wind GU in Figure 5.2 could contain another DPS unit including a EU, NU and several wind GUs as shown in the Figure.

The principal design of a DPS unit is constructed as shown in Figure 5.2, where the network unit (NU) includes the following sub units:

- *Multi Terminal Units* (MTU), which normally are bus bar and single terminal units (TU) in the power system but could also correspond to intelligent outlets in smaller residential applications.
- *Connection Units* (CU) can be anything from small cables to long transmission lines.

The MTUs are connected in series with the CUs as a ring network, providing a certain degree of redundancy, where at least one MTU is interconnected to the markets via the network EMS. The information lines are horizontal connected along the power lines with bi-directional capabilities. The MTUs are placed to interconnect the service providers or consumers, which are the following network interconnection units (NIU) or source and sink units (SSUs).

- *Power Generation Units* (GU) that are nuclear power plant (PP) units, hydro PP, PP based on RES etc.

- *Power Load Units* (LU), which represents all consumers such as industries, residences etc.

- *Energy Storage Units* (SU), that might be pumped hydro, hydrogen, SMES, super capacitors etc., which are for both long- and short term usage

- *Power Exchange Units* (EU), which enable import/export service capabilities to adjacent DPS units, which might be conventional substations with transformers or new stations based on different converter structures. Large transmission units are comparable to the DPS structure, which is later described.

- *Auxiliary Units* (AU) that are the remaining group of units aiding the DPS with voltage control by reactive adjustments.
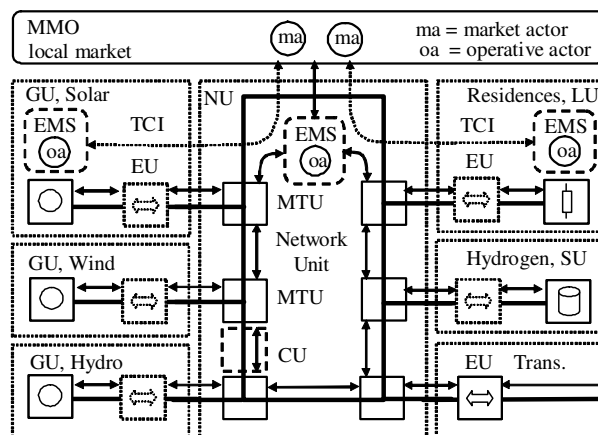

Figure 5.2: General DPS unit, information line (arrows), power line (bolded).

The SSUs might hold single entities but also a large number such as several power plants or aggregated loads. Beside the SSUs the exchange units (EUs) may be in between the MTU and SSU that operate similar to a power tap, which might enable infinitely variable power adjustments. Depending on system solution and design they might include transformers, converter or barely the exchange of information. The power exchange unit (substation) in-between power system or smaller internal units may differ in physical size, capacity and controllability. From an operational view they may seem the same as the distributed command signals and collected

information are managed alike. For this reason, the power exchange unit is introduced as shown in the Figure 5.3 that represents several types of power interfaces. In these cases the only passive type is the conventional substation based on the transformer. All types have also included the breaker and measurement unit (BU) at each side for protection reasons.

The exchange unit is a bridge to neighbouring systems and has a primary task to import or export power according to a specific control mode. The unit can have several configurations, especially hardware, and as a consequence also be connected in several ways. The communication interfaces enable the flow unit to be controlled from both sides where one of them has a higher priority.
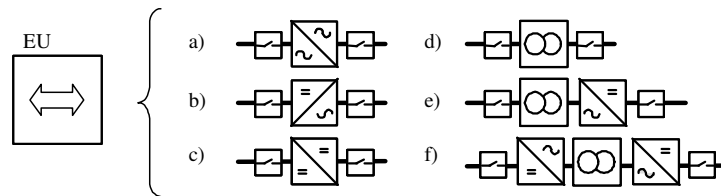

Figure 5.3: Power exchange unit overview.

The exchange unit may also be integrated in a generation, load or storage unit. Although, in such case, the exchange unit is operated by the superior control of that specific unit and consequently characterised as this, e.g. a converter based wind turbine unit includes several sub units where the exchange unit is one that interacts with the remain.

DPS units have different internal voltage levels depending on DPS capacity and might be based on AC or DC. It is likely that a great part of future DPS units will be based on internal DC interconnected by EUs with different types of converters depending on the connected SSUs. This enables high controllability and simpler means for disconnecting adjacent DPS units as well as being autonomous [Karlsson and Svensson, 2002].

Power and information flow interface

By always having in mind that all communication should be transmitted via the power lines for interconnection, de-limited uniform interfaces have to be used. Figure 5.4 shows the different control levels that traditionally are applied depending on power unit complexity. Connecting the power line

enables access to the power system information. All controllable power units are meant to have an EMS structure more or less activated. Depending on power unit, several control levels can be included. Vertical information structures are commonly used within the same operative managing area as for the most company structures. Information aggregates upward and commands distributes downwards. Between adjacent operative management areas, horizontal structures are used with three (TCI, OCI and SCI) main communication interface levels. Although, there are additional communication interfaces for service and maintenance that are not in the scope of real-time operation and control.
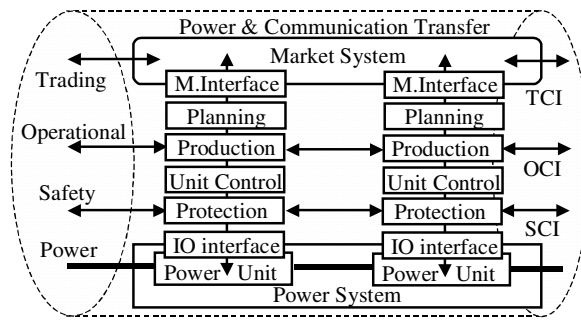

Figure 5.4: Power and information access through uniformed transmission medium.

The TCI is used between the market actors to provide an interface for exchanging information related to the process of negotiating, establishing and following up agreements. Although different agreements contain different data the basic content is the same. The data can be more or less detailed. In general, to identify what is exchanged between two traders. The TCI contains the following groups of signals:

- *Verification and traceability*: trader ID, document type, document ID, document status

- *Physical location and routing*: DPS unit ID (control area), delivering part ID, receiving part ID

- *Service information*: type of SSU, SSU ID, contract period, type of service, min and max quantity, min and max ramping rate, price specifications

The first group contains information about the identities of affected traders and the document related signals refer to where in the process the offers are, e.g. the created need in the SSUs, offers, transactions, operational plans, settlements etc. The documents going from the first to last stage in a transaction process have the same identity while the status (prepared, active, completed) is set according to where in the treatment a stage is. The second group informs about the identity of physical power actors and which direction the power flow is intended. The last group gives information on the actual service to the market, energy and ancillary services, for purchasing or selling purpose. As shown in Figure 5.1, the TCI-protocol is applied at several levels in the distributed market system. The result of the bidding on different markets is delivered via the TCI to affected actors, where the contacts are stored in the EMSs. In order to manage the contracts and to operate the power units, internal marketing management functions for tracing the change from one active contract to another are used.

The main purpose of the OCI is to enable the production level operational functions for different SSUs related to the services offered through the market. The OCI is divided in *operation* and *information* signals, which include discrete operation and control, and also signals for analyse, decision and metering purpose. The signals have several assignments and are in detail explained in Chapter 4. The OCI contains the following groups of signals:

- *Operation*: transaction ID, command, govern, set point (power, voltage, phase angle, frequency)

- *Information*: error, operational status, operational mode, operational state, active and reactive energy, active and reactive power, max and min power, nominal power, max and min power rate, voltage, current, phase angle, frequency.

The *document ID* of the TCI is linked to the *transaction ID* of the OCI that justify the activation of the *command* and *govern* signals, which starts and set the control mode respectively. The *govern* signal is linked to the *type of service* of the TCI. The operation might be authorized from the operator of the SSUs or the transmission operator according to agreements. The operator receive the information signals to confirm the intended operation. The state signal is mainly used to get indications on the robustness of the connected SSUs or DPSs predicting actions for support or disconnect. Further, depending on type of service in use the *information data* is

differently exploited. If using an ancillary service, the grid operator has to determine actions according to the maximum and minimum available capacity and power rate, which constantly fluctuate in a wind power plant case. Even the *nominal power* will change depending on operational wind turbines in the power plant.

The SCI is often separated by independent and unequal control units and communicates only by simple means with focus on high transmission rate. By using components fulfilling several control areas, efficiency and cost savings are possible without reducing safety. This also enables function integration, minimizing the number of control units, which of course is very load demand dependent. The main purpose of the protection level is to enable fast decision-making when a short circuit or an abnormal power flow occurs for a sustained period of time where the protective units should react to isolate the problem with minimum disturbance to the balance of the system. The SCI has signals for discrete operation of protective units with returned information on circuit breaker position and conditions. These units have intelligent measurement devices embedded for both local and higher levels analyse and metering purpose. The SCI has mainly the following groups of signals:

- *Operation*: command

- *Information*: error, status active and reactive power, 3-phase voltage and current, phase angel, frequency

Additional to the real-time data every new interconnection, per automatic, transmits static data with protective limits for respective power unit. At the lowest and fastest protection level the information is vertical and bi-directional, which means that every neighbouring protective unit is aware about their protective limits. Locally there is also vertical information communication for more complex security and reliability purpose.

5.3 System investigation

In order to find different system configurations and the management of those, the base system shown in Figure 2.10 (original picture) is here analysed and restructured. The building has a conventional connection to the distribution network and has been complemented with a supporting DPS that could operate as a UPS if the building is disconnected from the transmission network. By firstly analysing the several types of possible

system configurations the different possible DPS structures will come into view and secondly analysing the operation and control possibilities will prove on advantages with distributed automation and automated function.

Distributed system structures

The base system resembles a single DPS unit including several generation and load units connected to the building. In general this is managed by one centralized control system managing all controllable units.
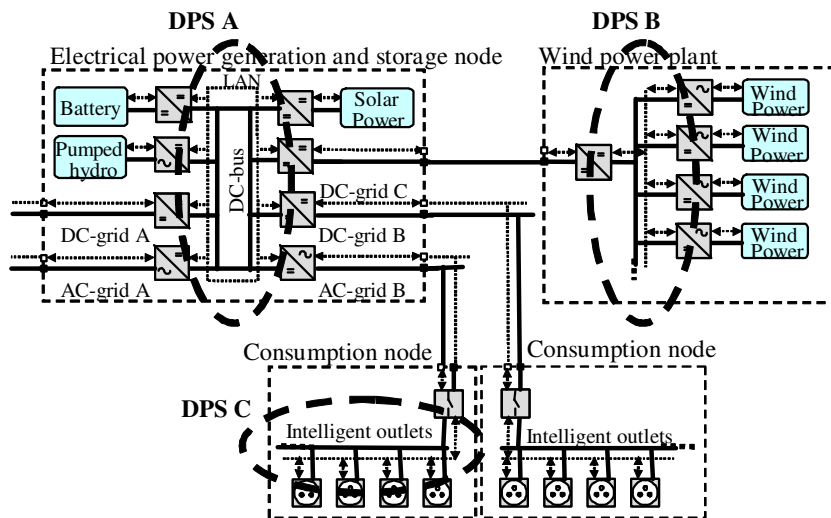

Figure 5.5: System decomposition, one line diagram.

The system includes several exchange units that could be manage differently depending on control strategies. This might be complicated when adding new power units at different locations in such system and also depending on different system failures. As shown in Figure 5.5 this small system actually has at least three subsystems which could be divided in a hybrid system (DPS A), wind power plant (DPS B) and intelligent building system (DPS C). In this case the conventional connection to the building from Figure 2.10 is not included. This system division might seem unnecessary if not trying to find a general solution. The transforming of Figure 5.5 to a functional structure is shown in Figure 5.6. Here an additional DPS D system is established, which corresponds to a transmission line as the distance to the wind power plant (WPP) is long.

The origin system now includes five subsystems according to following system classification:

- *DPS A*; a hybrid system including all types of power units. The network unit could be based on AC or DC.

- *DPS B*; a wind power plant including mainly generation units, in this case wind turbine units and an exchange unit to export the power. The whole plant can be considered as a single generation unit connected to DPS A.

- *DPS C1*; an intelligent building including load units and an exchange units. The internal network is here based on AC.

- *DPS C2*; as DPS C1 except for that the network unit is based on DC. Future buildings will most likely have solar power units on the roof that is here included as the generation unit. Between the building's two supply systems (AC and DC), an exchange unit may be connected.

- *DPS D*; a transmission line or cable. This system only contains two exchange units connecting the DPS A to the DPS B.

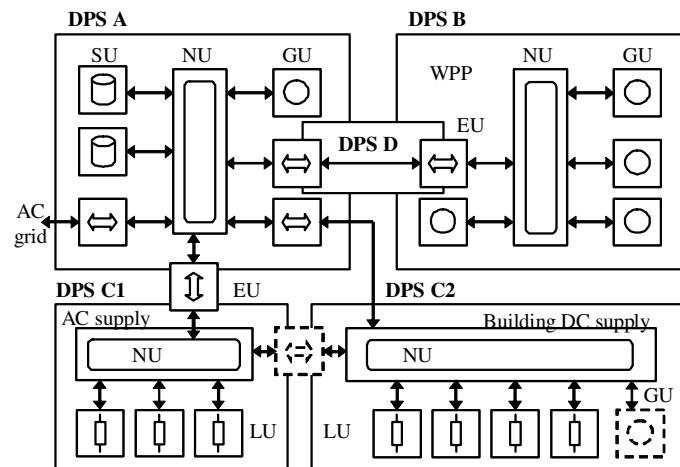**Figure 5.6:** Multi DPS functional system structure.

In this multi DPS system, DPS A has the central function to serve the other systems. The primary goal is to supply the building (DPS C1-C2) with AC and DC. This can be done either by importing power from the AC-grid, the wind power plant (DPS B), or by the internal power units. The internal units provide both production and storage. However, the multi system is

very sensitive if disconnected from the AC grid. The survival of such disconnection is very depending on the strategy before and after this occasion. By assuming that all exchange units in the system are based on converter technology, the conditions for a controlled and fast disconnection is prosperous. If the strategy before the occasion is to be as prepared as possible in supplying the loads, which is a common strategy, the aim is to load the storages before such an occasion. However, this is not an efficient way of operating the storage units. The wind power unit should also be contracted by at least two agreements, one for conventional energy delivery and the other enabling primary control. The same contract should be valid for the solar power unit and the storage units. Assuming that the wind power unit is producing at nominal power output due to the wind speed and that the solar power units are producing at half nominal power output due to the solar radiation, the conditions can not be much better before the disconnection. If the automated operation and control facility of each DPS unit is working properly, the DPS A is prepared of the disconnection just a fraction of a second before the disconnection due to the continuously information exchange. The information from the AC grid regarding its state, status or the maximum allowed power export to the DPS A may have indicated that something was about to occur. This has given the system control of the DPS A the opportunity to analyse possible generation units to participate in the primary control that was maintained by the AC-grid.

Depending on the information from all the connected DPSs, the DPS A knows exactly the present load and generation levels. Assuming that the production was larger than the load, the DPS A quickly needs to down-regulate the production and at the same time maintain the primary control. In this case the storages should not be fully loaded, which prevent them participating in the primary control. In other word, the storages should never be fully charged depending on usage.

In this case the DPS A command the DPS B via the exchange unit, according to agreements, that DPS B should provide the DPS A with voltage control as the internal network is based on DC. The automated system control of DPS B instantly change the control order within its system by distributing commands to each wind turbine unit to turn over to voltage control. This means that the exchange unit change its voltage control form controlling the voltage of DPS B to control the voltage of DPS A, all in droop mode. Furthermore, the DPS A coordinates remain exchange units and inform them of present situation. DPS C1 and C2 are still allowed to consume required power.

After some time the wind speed is about to fade and the DPS B informs the DPS A via the exchange unit that the primary control service is about to be disabled. The storage units have been prepared by adjusting an appropriate storage level enabling the participation in primary control. The storage unit smoothly joint the primary control before the DPS B stops participating. The storage and solar power units now jointly manage the voltage control of the DPS A that is based on DC. For same reason the solar unit in DPS A fails and disconnects. The storage unit now solely supplies the building (DPS C1 and C2). The DPS A informs the building system of the status, state level and the maximum power level to be used, which bring the internal system control of DPS C1-C2 to prioritize their consumption by distributing down regulations or stop commands to all load units depending on their priority and controllability.

As the storage is about to reach the low level, the DPS C1-C2 are aware of this and as the DPS C2 has solar power units this is commanded in primary control. After the disconnection to the DPS A, the DPS C2 may supply DPS C1 if there are some high priority load units included. Eventually the DPS C1-C2 is shut down.

Several different scenarios can be made but this exemplifies the advantages by having distributed system control and the usage of the exchange units. This is further investigated in Chapter 6.

As a large number of future exchange units will be constructed by converter technology, some principles are here described. The power units may be connected in several ways where some are further described below:

- Series interconnection

- Parallel interconnection

Series interconnection

In the described multi DPS system one rule is determined from an operating view. One single DPS never has two exchange units interconnected in series without forming a new DPS unit. This is adopted on the system D in Figure 5.6 that includes two exchange units. In the other cases, the exchange unit is single and a shared resource between the DPS system, which actually is the same between DPS A and DPS D concerning the exchange unit in-between. As shown in Figure 5.7, every side of an exchange unit is interconnected to a transmission network unit that, in this

case, is based on DC and also galvanic isolated. The control mode is changed very fast in order to alter the power flow from one direction to the reverse. If the local control units (CU) including the controllers (C) have an automated superior coordinated operation, the switch action is done in a fraction of second.
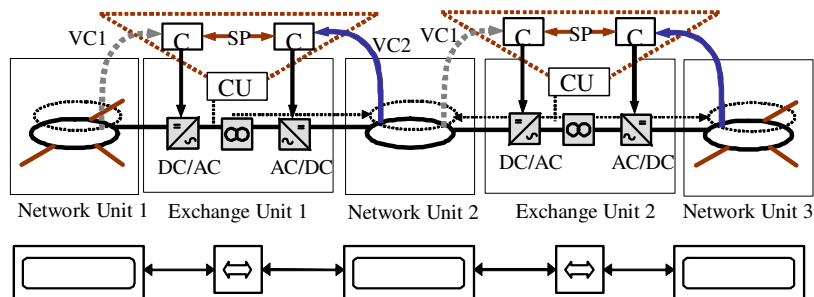

Figure 5.7: Exchange unit interactions with power lines (bolded) and communication lines (doted and arrowed).

For example, the voltage controllers (VC2) are measuring the voltage at their right side from the perspective of the exchange units, meaning that the power flow is directed from NU 1 to NU 3. The power flow then is reversed by changing the control loops to VC1.

Parallel interconnection

The parallel interconnection of power units is the fundamental reason for forming DPSs. The power unit modularity is adopted by this type of interconnection in each of the multi DPS system, which exemplifies different types of parallel interconnections. These can be categorized primarily in two groups:

- *Source division*; enables the internal network to be supplied by several source units, e.g. solar power, wind power, storage etc. From a large system perspective, every DPS is including generation units are divided in groups to support DPS units with a majority of load units. This is primarily done in the building example. The DPS A and B have been introduced as an UPS to the building.

- *Sink division*; enables several load units to be supplied by the internal network unit of the DPS. This is exemplified by the supply from DPS A to DPS C1 and C2. The major reason for this approach is that the load

units of these systems are based differently on AC and DC, and thereby regulated differently. Although, the C1 and C2 also function as backups for each other.

There are no technical limits in having power units in parallel, although differences in capacity size and construction design might cause some electrical diversities and control problems. In summary, the parallel structure gives the following advantages:

- *Modularity*; the modular design makes it easy to add new power units to the network unit. It also opens up for a more flexible system configuration from a control point of view.

- *Redundancy*: Depending on local or global system strategies the modular structure enables several similar power units to be interconnected, which may increase reliability by redundant units, e.g. storage units, generation units, three parallel smaller units instead of one large etc.

DPS structures, like previously described, will most certainly extend in future power systems. The possibilities in utilizations of power electronics have recently started and will most likely be much exploit in systems and power units being developed. However, the coordination of these fast devices need to be operated in a more automated manner to utilize the possibly speed in the technology. The next section and chapters will more in detail describe such possibilities and opportunities.

Distributed system operation

As already mentioned, the electric power society is facing an amazing transformation. For most of its history the electric power system has relied on larger and more efficient central generating units. Several indications point at that distributed small-scaled generating sources may be more common in the future. This opens up for a power system built on several subsystem such as DPSs. However, the centralized operation and control hierarchy will demand a supplement distributed structure in managing such system.

Outgoing from Figure 5.8, the system could be seen from a more flat perspective, where it is more obvious from a control point of view that the subsystems are similar as well as for the entire system. An approach to develop a distributed system operation and control structure is here made by breaking down the system into subsystems as shown in Figure 5.8.
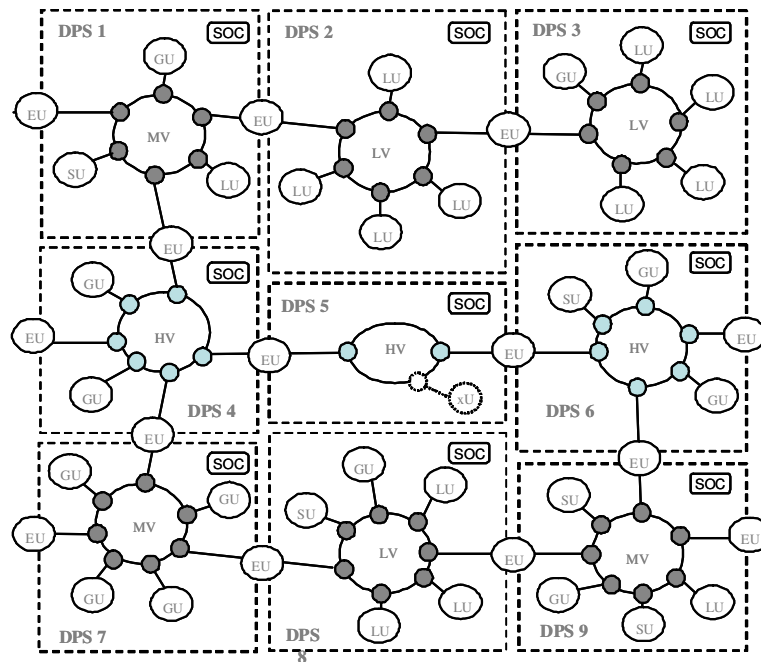

Figure 5.8: A flat power system structure divided in several operational subsystems.

The intension is that each individual subsystem should be able to operate and control its power resources autonomous if needed. For this reason, the subsystems or DPSs need to have a well developed information system and automated functions to maintain the functionalities when disconnected and at the same time interconnected to at least one local market for service exchanges. Conventionally, the power system is operated from an EMS including all requested functions and personnel to manage the system. By assuming that the EMS tool is developed in a more efficient and flexible way where the functionality is fully automated and distributed to each individual DPS system, the power system should be more responsive to fast

disturbances and thereby gain in reliability. Some new types or modified authorities need to be clarified and introduced, which are made in the Chapter 4. Even if using several DPSs, there is only one active system operator (SO) allowed in the same predefined control area. However, all possible stand alone DPSs will have semi-active SOs that are acting as aggregators. The aggregators are at all times prepared to take over the role of the SO when needed. The SO and aggregators are present in each DPS and always collect and distribute the information and in same time order their internal power units. Among power units, the exchange unit is the more important enabling such functionality. In Figure 5.8 it is shown that the exchange units (EU) are the DPS interfaces, which needs possibilities to be operated and controlled from two adjacent DPS units. This implies an operating entity managing the exchange of control and information from at least two authorities. The other power flows (generation, load and storage units) have only one interconnection and correspondingly only needs to be operated from one authority. However, this is not completely true. As various parts in the system are own and operated by different companies, a power unit may be operated by several authorities, even if not simultaneously. The owner (or in general, companies) has almost always a vertical control and information hierarchy, which means that several authorities are able to operate a power unit. Consequently, a general operating exchange entity is needed that can handle several operating authorities and select the one with highest priority depending on the local situation. Regarding different companies and power units, especially the network unit and the others, a horizontal hierarchy is used between the companies' EMSs. In the following section, the system operation and control (SOC) blocks in Figure 5.8 are considered as fully automated EMSs where their internal structure cover the interconnection from unit operation to market interaction.

Distributed and aggregated EMS structures

EMSs are normally placed and used sparsely in the power system. Their operational interconnections cover large areas that include a large number of power units and thereby a huge amount of information to be analysed and executed. With restructuring, the only decent solution probably includes several well strategic placed EMSs sharing this load of information and decisions throughout the system.

When acting towards an adjacent control area the hierarchy is horizontal. This implies on an equal level of system management. The information

flow is then bi-directional enabling both sides in making decisions according to pre-defined conditions. The distributed EMS is interconnected with each power unit trough an effective communication system that links all EMSs as shown in Figure 5.9. All EMS functions are embedded in each of the EMS within the DPS unit and can be activated or deactivated depending on assignment. One EMS acts as an active system master, collecting information and distributing orders to all the other EMSs.
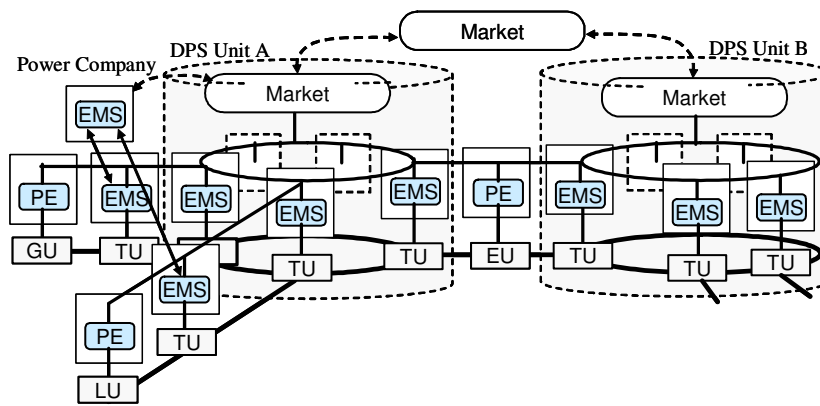

Figure 5.9: Distributed EMS hierarchy within DPS units.

The other EMSs have the same capability but are only semi-active regarding system management, meaning that they continuously collects and analyses the same system information as the master EMS but do not have the authority to coordinate operation and control. However, each semi-active EMS actively manages the local interconnection with a power unit and act as an intermittent interface controlling them. If for some reason, the master EMS not act properly or is disconnected, the remaining EMSs instantly check, according to a continuously updated priority list, which one should by assigned to be the next EMS master. As the semi-active EMS always is prepared by continuously analysing the system configuration, this is done in the range of milliseconds. The new master instantly informs itself about possibly system configurations and the best operation solution preventing a system collapse. As shown in the left side of the Figure 5.9, a vertical structure is used within the same company. The three internal EMS levels can be more or less active depending on the company size and its hierarchal structure, which also affects the EMS hierarchy. For example, if using a strict vertical hierarchy, the EMS

information is aggregated up to the top level EMS. This is then an example on an aggregated EMS structure. The EMSs need to communicate with the power units that conventional have local operators managing the power flow. By introducing the production exchange management (PE), an automated local operator (generation, load, storage or exchange system operator) is located on the top of each power flow. This is the last instance actually distributing the commands to the physical power units.

5.4 DPS extended architecture model design

The fundamental structure has to enchant both the electrical power flow and the information flow in a proper structural way, where the principal rules for building these must be simply and easily comprehensible. The intension is to find something close to building blocks that interconnects both the power and information domain in the structure to enable automated coordination functions interacting within the entire control area.

Principal idea

The principal idea in finding a structure for uniform building blocks starts out from the functional structure in Figure 5.6 where every power unit have been extended with an active terminal unit (TUa), which also corresponds to an active power node (PN). The TUa contains an EMS structure including the production management (PM) layer that interacts with a production exchange management (PE) entity as shown in Figure 5.10. The PE operates as an internal interface between the power unit and the TUa. The network unit has only TUa blocks at the boundary acting as active interfaces towards the power units.

The structure is based on the functionality of the system actors and interactions as described in the Chapter 4. Here the functionality has been automated and distributed throughout the system. The PE includes a local artificial operator as described in previous section only handling the local power unit. The TUa blocks include a distributed EMS structure activating adequate actors depending on the connected power unit. The information channels enable the actors (automated functions) to interact at several points in the system. The transmission network unit (NU) has the same functionality enabled at its TUa interconnecting the power units. The TUa acts as an interface that also automatically activates functions according to the interconnected power unit. The internal structure of the network unit is

later described but includes a more complex infrastructure regarding information and interactions. In achieving such functionality, the building blocks have to be classified which is described in the next sections. The automated functions and the information structure are described in the following Chapters.
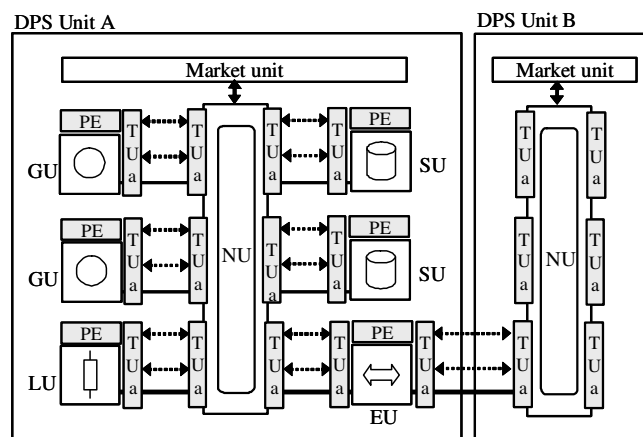

Figure 5.10: Functional system structure including active terminal unit (TUa) and production exchange (PE) management integration.

Basic sub structure principles

By assuming that every building block is constructed from out of either a node or flow entity independent of managing a power or information network, the structure is rather simple and shown in Figure 5.11. Regarding electric power, the node entities represent smaller or larger energy storages while the power flow entities represent the power transportation media. Regarding communication, the node entities represent data storages and management and the arrows the communication transportation media [Bouwmans, 2001]. Separately this is somehow rather simple but combining them in a proper way with principal frameworks enabling uniformed interfaces is more complex.

Basically, a node has only use of information from well-functioning power interconnections. Information from a disconnected power flow is only a burden for the management of the node regarding fast decisions. This implies on an advantage of having a combined physical flow of power and information that naturally limit the access of information to only provide

the node with adequate information regarding interconnecting power flows and their ability to support the node. In this case a positive flow is regarding as information in to the node as well as power. Consequently a negative flow is regarded as information and power out from the node.
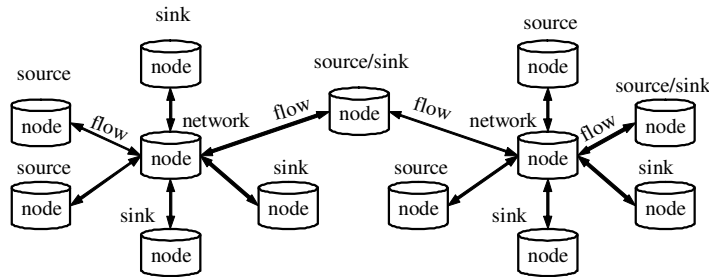

Figure 5.11: Node and flow (arrows) structure.

The sum of information flow and power flow are continuously evaluated in order to distribute necessary operational commands to maintain the pre-requested demands. The nodes and flows in the electric power domain are explained in the next section while the communication is explained in the Chapter 7.

Basic power building block structure

By introducing power node and flow entities, the system can be constructed only using these elements. The model structure is based on building blocks with the classic concept of a network of nodes and flows interconnected as shown in Figure 5.12.
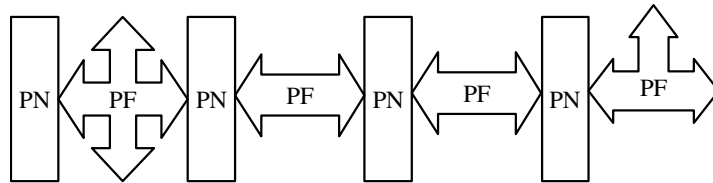

Figure 5.12: Power node and power flow interconnections.

The power nodes always have a power flow interconnected and never more than two connections, side A and B. The power flow may on the other hand have more than two power nodes interconnected, e.g. a bus bar with four

tie-lines would contain one power flow (the bus bar) and four power nodes (in this case, among others, circuit breakers) directly connected to the bus bar. This is defined as a terminal unit previous in this Chapter.

The integration of communication nodes (CN) and flows (CF) into the power domain are shown in Figure 5.13 where the CN is represented in every PN and PF that has embedded automated functions.
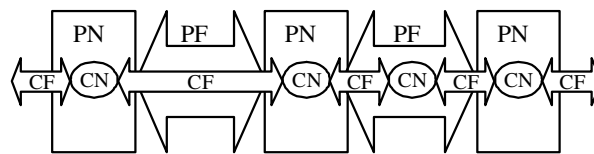

Figure 5.13: Power and communication interactions.

The power nodes are assumed to be placed in strategically positions within the power system and work as possible coordinators of interconnected power flows as well as for the circuit breakers.

System subunit classifications

A classification of the power node and power flow units, including the power and information domain, is described here. The basic power unit classification (NU, MTU, TU, GU, LU, SU and EU) is extended with an "a" at the end (NUa, MTUa, TUa, GUa, LUa, SUa and EUa) that implies on that the unit has been active due to extensive functionality. They are thereby disposed to take action or to effectuate changes as well as to be engaged or participating the active DPS activity.

Power nodes

Power nodes can be found at several levels that are later described. Although, the lowest level power node is the active terminal unit (TUa) that is the essence in enabling a general system structure and includes the same operation functionality as for an entire power system. The TUa should be regarded as an intelligent autonomous node provided with the capability to activate all necessary function to manage the local surroundings that may be constantly changing. Figure 5.14 shows the principal contents of a TUa that in future could be of any size, from small like a needle to large like a building, depending on power capacity.

The TUa includes a breaker unit that measure system states at both sides of the unit. The Breaker Unit (BU) includes an internal control unit and a breaker device (BD) interacting the EMS-PM layer via the communication node (CN). The two interfaces of the TUa include the power interface (PI) and the communication interface (CI) containing the TCI, OCI and SCI.
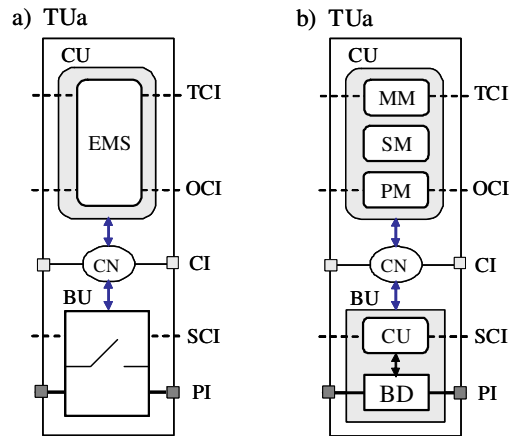

Figure 5.14: Active terminal unit (TUa) structure including the general EMS structure a) and in b) with the three layer internal EMS structure.

All TUa blocks have the final authority to disconnect the power if the internal security authority determines it necessary due to environmental disturbances. As the TUa includes the entire EMS structure, the node is able to operate and control all interconnected power units within its domain if authorized. The node is also able to interconnect to the local market to buy or sell services.

Power flows

The power flow sub units interconnect the TUa or power nodes and are the transport media enabling a power flow, e.g. generation devices (GD), load devices (LD) and exchange devices (ED). Depending on controllability and assignment, the power flows may act as a source, sink or transmission sub unit as in Figure 5.15. As the source and sink units are system end units, the TCI interface is not included; meaning that only the OCI and SCI are utilized within the communication interface (CI). The transmission sub unit, however, also distribute the TCI even though it is not used by the unit itself. The TCI is used by the interconnected power nodes that may be

connected to the market. Beside the described "power flows" there exists several others, e.g. a single connection unit (transmission line or cable) that serves as a passive power flow, the bus bar etc.
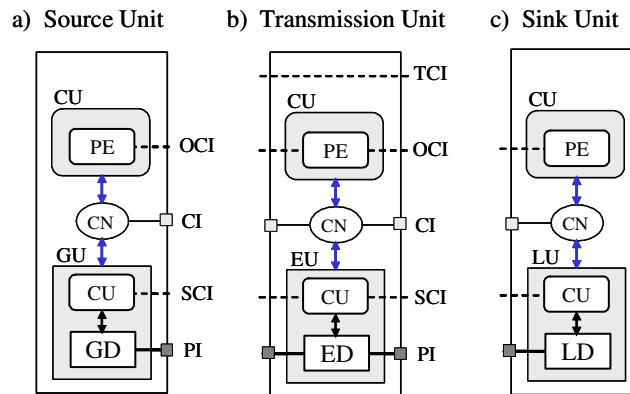
Figure 5.15: Power flow unit structure.

The PE module included in the superior control unit contains automated functions for managing the flow unit in the power and security domain. This means that even if the closest TUa connected command the power flow to change operation mode the PE may disagree and reject the order, for example of security reasons.

Active power unit classification

Power system units extended with either controllable power node and/or power flow entities, having all or part of the EMS structure embedded, are classified as active power units. The power units are divided in

- Active network interconnection units (NIUa); active generation, load, storage and exchange units (GUa, LUa, SUa and EUa).

- Active network units (NUa); represent transmission and distribution networks that have embedded terminal units as interfaces toward the active network interconnection units.

The NUa is the central system power unit interconnecting only the NIUs. The power units may be of active or passive type and also something in-between. For example, a conventional substation can be passive and a converter based station active, depending on usage.

Active network interconnection units

The active network interconnection units include the three end connecting elements (generation, load and storage units) and the interconnecting unit (exchange unit). From a transmission network perspective, the NIUs are considered as "active power flows" due to their ability in controlling the power flow.
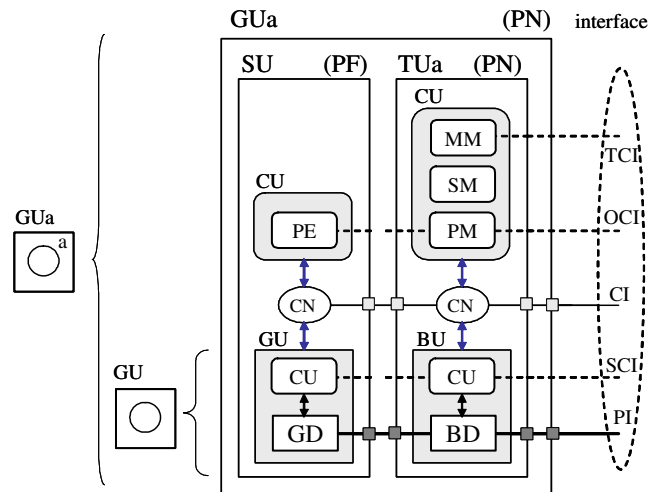
Figure 5.16: Active generation unit structure.

The generation unit is no more than a source unit as the load unit is a sink unit, both with unidirectional power flow. But the storage and exchange units are both source and sink units as they may have bi-directional power flow. The generation unit (GU), including the generation device (GD) and control unit (CU), is added with the superior operation module PE and the TUa. Combining these elements creates the active generation unit (GUa) with the uniformed interface including the TCI, OCI and SCI as shown in Figure 5.16. All communication is managed via the communication nodes (CN) that interconnects the communication flows.

The load unit and storage units are designed similar to the generation unit as shown in Figure 5.17 where the active units have been simplified only using the production management layer of the EMS. The active load unit (LUa) is a higher level power node including one power flow, sink unit (SiU), and one power node, the TUa. Consequently the subunit closest to the interface determines if the higher level unit is a power node or power

flow. The active storage unit (SUa) includes both a source and sink unit (SSU) that implies on bi-directional power flow capability.
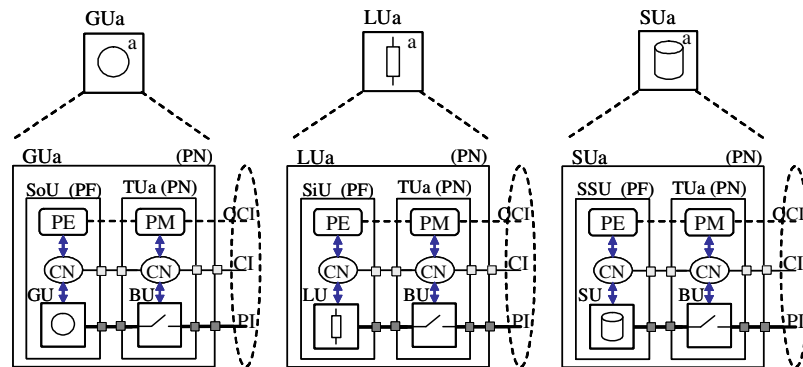
Figure 5.17: Active generation, load and storage unit structure.

The most complex source and sink unit is the active exchange unit (EUa) that is constructed as shown in Figure 5.18 and represent a higher level power node.
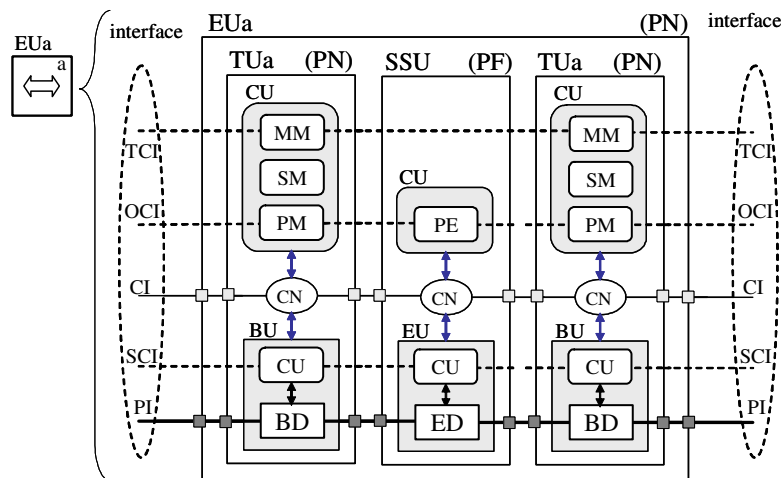
Figure 5.18: Active exchange unit (EUa) structure.

The EUa includes two sub power nodes and one power flow, where the PNs are the TUa and the PF a SSU. In this case the SSU includes an exchange unit containing an exchange device (e.g. converter), a control unit, and a superior CU including the PE block. The PE determines which

side that has the operating authority and thereby is allowed to operate the exchange unit. The EUa has two interfaces including the communication interface (CI) and the power interface (PI). These are always interconnected with two different DPS units and normally operated according to established agreements.

Depending on adopted technology the exchange device (ED) may provide bi-directional power flow and several ancillary services. These services may be utilized directly by the active transmission network.

Active transmission network units

The active network unit structure is based on the active multi terminal units (MTUa) and connection units where the TUa is much utilized. As the MTUs have automated operation and control functions they are capable of achieving improved survivability, security, reliability [Matsumoto and Yanab, 2002]. Each MTUa acts autonomously allowing them to switch power lines, shed load and receive/broadcast local state variable information to and from other MTUs. The information exchange capability of the MTUs provides coordination among themselves to reconfigure the power network unit.
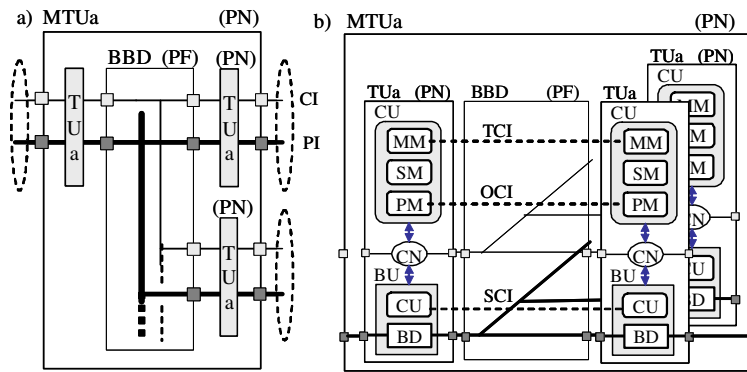

Figure 5.19: Active multi terminal unit (MTUa) a) simplified structure and b) extensive structure.

The MTUs autonomously determine their task using direct monitoring, zone area on-line security assessment and adaptive operations to establish coordinated control actions. They act to prevent abnormal operating conditions. In the event of a unit or system failure, the MTUs will make

local decisions and coordinate with other MTUs to bring the system, or part of it, back into an operational state. Each MTUa is able to operate on a mesh hierarchy making irrelevant whether its inputs from power producers, outputs to consumers, or other MTUs.

The MTUa contains a bus bar and one TUa for each tie-line as shown in Figure 5.19. The MTUa itself is classified as a power node as the closest unit to the interface is a power node or TUa. As mention, each individual TUa always has operation and control responsibilities to its connected SSU and it is only one of the TUa blocks that has coordination responsibility for the MTUa. This responsibility may concern a large control area that the MTUa depending on the operational priority or the MTUa and consequently the individual TUa. The DPS base core unit, the NUa, includes several MTUa blocks and CUs interconnected. The MTUa blocks are supposed sufficiently general that the principal structure could be used anywhere from a common bus bar to an intelligent outlet applications as shown in Figure 5.20, which implies fully automated EMSs. The MTUa may be able to have full control of the power flow as an intelligent power router depending on the types of interconnected exchange units (EU). If the bus is based on DC and all the EUs are based on converter technology, the controllability is almost unlimited. The configurations of the EUs are different depending on the application of the MTUa as shown in Figure 5.21.
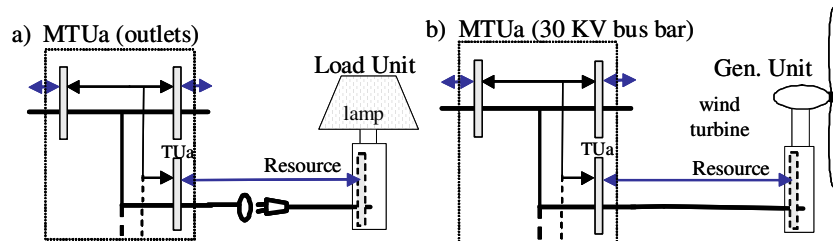
Figure 5.20: Active multi terminal unit applications a) outlet and lamp connection and b) bus bar and wind turbine connection.

If the MTUa is located within a conventional high voltage power system, the bus bar is based on AC and the EUs correspond to substations. A smaller application may include a DC based MTUa where the interconnected source and sink units also are based on DC, e.g. photovoltaic, batteries, fuel cells, etc.

The galvanic isolation may be important depending on grounding issues and obstruct the propagation of disturbances. At this point all needed units are described enabling the structure of the core unit of the DPS, the active network unit (NUa). The NUa is constructed from out of several interconnected MTUs and CUs (connection unit) as shown in Figure 5.22.
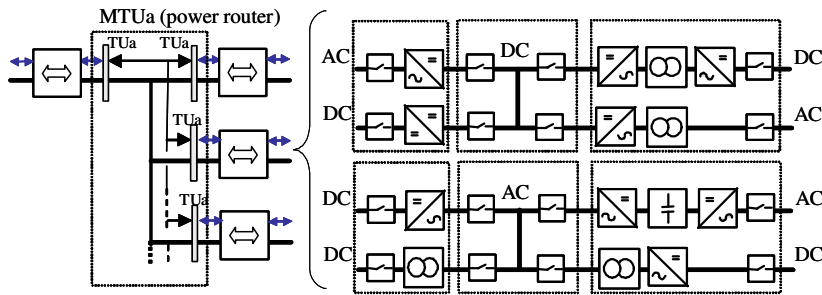
Figure 5.21: Active multi terminal unit applications.

The electric network structure could be of any type from radial to mesh. It has no limits but those given by capacity limits, redundancy aspects and strategical localizations. The operation of a NUa is very similar to that of an MTUa.
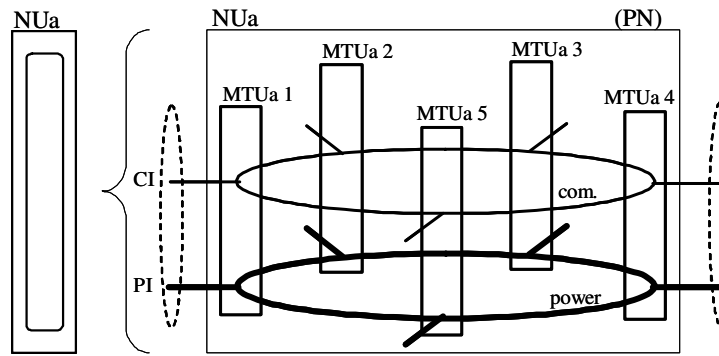
Figure 5.22: Active network unit based on several interconnected active multi terminal units.

Instead of several TUa connected as in the MTUa case, the NUa has several MTUs interconnected that function the same way. The MTUa with highest priority has the overall coordination authority of the NUa, which means that the TUa with highest priority within that specific MTUa is in

charge. Regarding redundancy this particularly NUa example has five MTUa blocks and consequently 15 fully automated EMSs always ready to take over. This also opens up for the NUa to split and merge in several sub NUa units.

For example, as shown in Figure 5.23, the original two NUa units, A and B, may be divided into four new active sub NUa blocks, sub NUa 1-4, depending on several circumstances and disturbances. As each MTUa contain at least one TUa, the one with highest priority take the role as system operator.
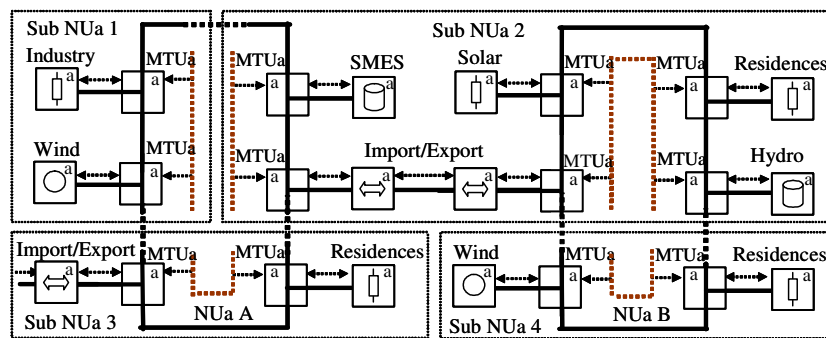
Figure 5.23: DPS split and merge example.

The scenario might be achievable if future power units will have an active role by using embedded intelligence allowing each active unit to make decisions both locally and coordinated, if demanded. It is also noticeable that systems like this scenario might need extended usage of storages, which are associated with costs. Consequently storages should be as small as possible without losing to much in delivery reliability. Roughly speaking, this means that the sources should strive to have just as much storage to produce as close to demand as possible. The condition for high controllability of the system is very much related to the various energy storages throughout the system as several small storage devices, especially in series, may cause system stiffness. However, depending on local strategies and requirements on reliability and survivability, storage units based on new technology might be more utilized in the future.

Interconnections and interactions

The interconnections of the DPS power units are mainly divided in the connection between:

- The network unit's internal interconnections of subunits
- The network unit's external interconnection of source and sink units

The description include the operational and protective layer as the may be separated.

The network unit's internal interconnections of subunits

In the operational layer the terminal PMs are, in normal conditions, directly connected to the main PM of the network EMS (embedded in one of the MTUa blocks) that manages all operations by interacting all terminal PMs. However, the local terminal PMs are always updated and will go from semi-passive to active state and take over the operating control from a higher level if this is incapable in operating or for strategically reasons. The TUa is consequently able to activate a full functional EMS structure locally.
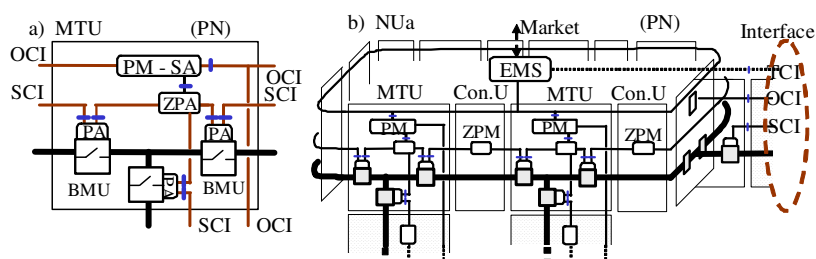
Figure 5.24: a) simplified multi terminal unit; b) active network sub unit interconnections based on MTUs and connection units.

The trading layer is also connected to the main PM via the terminal PMs and normally forwards the information to the local market administration. The network EMS operates, in this case, like a concentrator/distributor to the local market administration. Since the MTUa structure contains several TUa blocks, the operational capability may seem a little bit excessively used. Although, even if a future solution would make it possible to have all functionality embedded as for the proposed TUa, it would not (for redundancy reasons) be necessary with more than two EMS structures within an MTUa due to the small operation area. A decreased functional

structure of the MTUa is shown in Figure 5.24a where only the production management (PM) layer of the EMS is included. Basically, the MTUs include circuit breakers and measurements units (BU) for each branch either towards another MTUa or a SSU. The BUs contain intelligent measurement devices and software for breaker protection management, which has the last outpost responsibility in disconnection a power unit if pre-defined limits are exceed. The breaker protection is commanded from higher-level security or protection instances as the security authority that is embedded in the EMS-PM. The BUs are interacting with a zone protection management (ZPM) function that has enhanced potential detecting fault currents and is consequently authorized to operate the BU. As shown in Figure 5.24b, the protection layer connects the ZPMs to respective breaker protections. Future demands on integrated power and communication cable will probably lead to inbuilt ZPMs and cable data enabling automatic configuration both for protection units and affected controllers. The BMUs and ZPMs inside the TUa provide the SA, included in the terminal PM, via the SCI with requested information (vertical) to operate the BUs.

Network unit interconnection with source and sink units

The SSUs are interconnected to a NUa according to Figure 5.25, where the three interface communication layers automatically handle the configurations and prepare the unit for operational commands.

Figure 5.**25:** Source and sink unit interconnection.

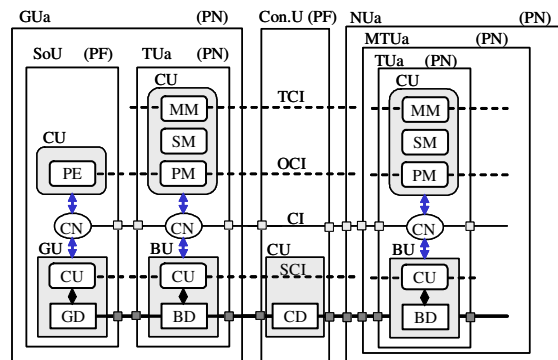The TCI and OCI are connected from the EMS of the SSU through the power flow unit and terminal PM to network EMS. The SCI is connected to the closest BU via internal control unit. Referring the SSU to a wind

turbine (WT) unit, the WT unit has automated production control and market service functions and acts as an autonomous unit where the internal control unit of the GU represents the internal unit control system including all control functions of the wind turbine, further described in Chapter 6.

The interface of the production layer, PE is adjusted and connected to the control system (CU) of the GU, which normally should be a minor effort even for older WT. As the WT is connected to the local market through implementations of the TCI, it is also per automatic connected to several other markets. The WT then provides its services in an automated purchase/selling process, where the bids are automatically forwarded to the market. Settled agreements will then be distributed to all the affected units and among them the EMS of both the grid unit and WPP unit.

The protection layer is also reconfigured and adjusted to adapt the protection system of the WT unit. The protection management is embedded partly in the GU and also placed as a local separate control unit in the BU of TUa that is linked to the PM. Within the PM the security authority is among others able to coordinate protection issues. The SA has the function of zone protection management that interconnect the measurement from to adjacent BUs and their protection management.

Transmission interconnections

The power transmission between two adjacent DPS unit is shown in Figure 5.26, where the active network units (NUa) are connected at each side of the active exchange unit (EUa). Here the EUa could be controlled from both transmission network operators of the NUs depending on service to be performed. This interconnection could correspond to a conventional substation where the exchange device (ED) contains a transformer and the breaker units (BU) within the terminal units are typical circuit breakers. The interconnection could also be based on different types of converter technology.

The interconnection for a transmission line between two adjacent DPS unit as shown in Figure 5.27, creates a new DPS due to the series connection of two active exchange units as earlier mentioned. Here the system management and operation of the transmission line are the same as for a DPS unit with only two active TUs and no own generation units interconnected, which is in accordance with a general structure. The function is in principal as for the EMS of the DPS but with fewer resources

to handle. The transmission EMS would in this case, for instance, activate the ATC function that is an important parameter for all actors participating in the power transaction activities.
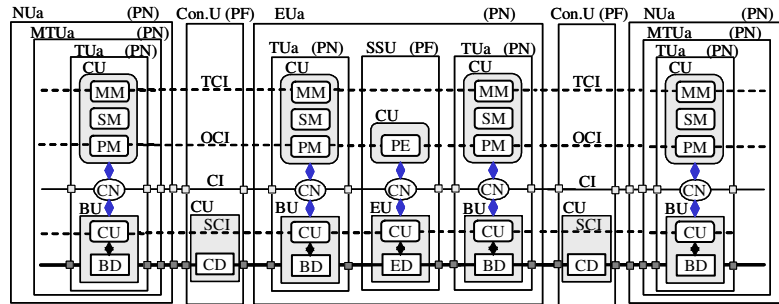
Figure 5.26: Power exchange interaction – substation.

The transmission owner can select to interact with the market through three communication paths, either through the DPS units or directly from the own EMS structure. Transmission services are available for the supply and delivery point and for the amount of energy agreed on. This service should be provided on the transmission service markets. For each supply of energy there must be a contract with the necessary transmission service providers.
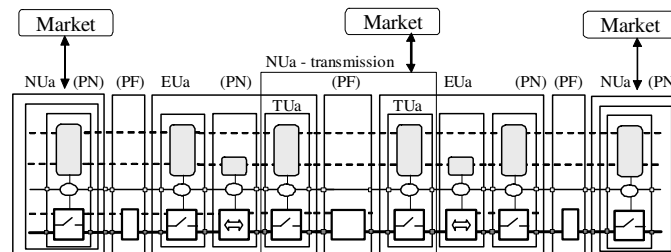
Figure 5.27: Power exchange interaction – transmission line.

The protection layer in this case is as for the others. Each active terminal unit has a local protection management controlling the states of each side of the node. Between each TUs is always an power flow interconnected that also corresponds to a zone for protection. The zone protection management is handled by the security authority of the TUa with highest priority via the SCI.

5.5 Model library and simulation

The model configuration has been fully utilized in the developed model library "Power Flow" described in Appendix A.6. Several simulations and verifications have been made that are described in the Chapter 8 where the results are presented.

5.6 Concluding remarks

Structures for DPS units including local market managing, principal power unit classifications, interactions and information have been proposed that have their main advantage in fast disconnecting and reconnecting to adjacent DPS units in case of failure. The structure is flexible and builds on autonomous DPSs that enclose defected DPS units until recovered or if possible supporting them to a stable state. There are numerous applications if a standardized scalable DPS unit can be accomplished. In power systems, it would be used from individual buildings, small capacity power system, to high capacity national power systems. It would also be applicable for power management in transportation applications (vehicles, ships etc.), which could enable simple interconnections to aid the power system and vice versa.

Chapter 6

DPS operation and control

Advanced functions for market management, planning and production operation are one step towards autonomous operations. The purpose of this chapter is to specify a general functional structure for production operation of DPSs and RESs, with consideration in how RES can be used to improve power system performance at normal and abnormal situations. The structure provides the means for operation of new large and small power plants based on RES. RES units connected to the power system deliver energy and will most likely provide ancillary services as conventional power plant units. The requirements on operation and control options will therefore be the same as for all power units. The structure facilitates the utilization of new services from RES and enables new power units to connect to an existing information structure and then automatically adapt to the system.

A distributed modular structure for the production layer of the EMS is presented. The structure allows straightforward extension for further distributed operation and control of distributed power systems and power units. A distinct separation between on/off control and closed loop control signals is used, with proper interactions inside specific software blocks in the control hierarchy. The functional structure has been partly validated through software blocks implemented in C++ modules connected to the Dymola/Modelica simulation tool where numerous models have been developed. The structure is the foundation to evaluate the differences in automated operation and control that has been tested through several simulations using different system configurations based on different operation strategies.

6.1 Autonomous operation – an overview

In order to manage the system operations the operators use several functions, some in real-time that can be found in operational tools/instruments throughout the power system. These tools range from "supervisory control and data acquisition" (SCADA) systems that monitor and display the status of the system in real-time to more sophisticated tools such as "energy management systems" (EMS). The EMS collects all available information data by real-time measurements of the system and gives a complete, real-time representation of the system state and status. Operators also have means at their disposal for direct control of the power system, for example the transmission network system. These include control of switching operations (inserting or removing lines and/or transformers), shunt injections (usually reactors and capacitors inserted at buses, mainly as a means to regulate the voltage profile), and control of regulating transformers and other series- and shunt-adjustable devices. Operators can also adjust system area set points to help regulate system frequency, control flows on exports/imports to/from other control areas, and maintain the power balance within specified limits.

Centralized and decentralized operation

The power system operation is, in general, divided in centralized operation, based on system wide information, and decentralized operation, based on local information. As the power system has a hierarchal structure both centralized and decentralized operation strategies are used. Slow events are often managed by centralized operations and fast events by decentralized operations. Each system power unit has its predefined functions where the generation and load system units usually are managed by decentralized functions and the transmission system work as an interconnecting network using centralized functions to coordinate the generation units. The overall responsibility is handled by the system management illustrated in Figure 6.1. The system management block traditionally embraces the SCADA/EMS and the operating personnel that are interconnected to several power resource units. The SCADA/EMS includes several functions to assist the operators and additional personnel experts may assist the operator during abnormal situations. The EMS is required to monitor and control the complex power system under changed environment for secure and reliable system operation. Safety, quality, reliability and efficiency,

and the long-term planning are primary aims of the power system. Expansion planning, maintenance and operational supervision are required to fulfil these requirements.
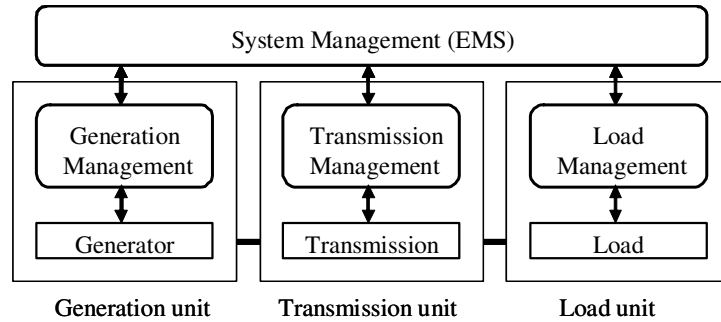
Figure 6.1: Centralized/decentralized automation and control hierarchy.

The transmission system provider for a particular control area uses the EMS for planning and operation of the transmission network system.
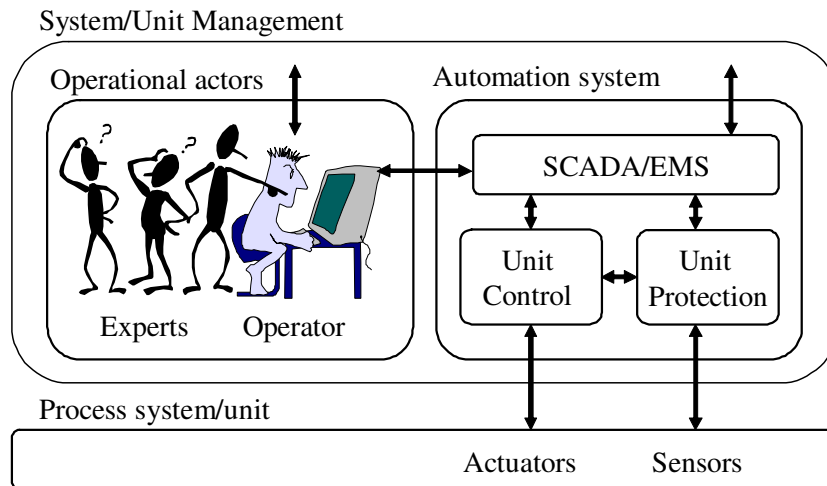
Figure 6.2: System/unit management structure.

The complexity of the control system hierarchy at different levels (e.g. regional and central levels) needs careful application. A regional level control centre will be self sufficient for the security and control of the

regional transmission system. In the event of power exchange between the regions, both the regional level control centres would be coordinating through the information links. The system management block may exist in several levels only differing in authority and specific functionality. Closest to the process level, e.g. within a generation unit, the system or unit management block is also interconnected to the automation system. The automation system includes the control and protection system that interacts and controls the process or generation unit according to the commands ordered by the operator as illustrated in Figure 6.2.

Autonomous operation

Several steps are to be made in reaching an autonomous system operation and control. Traditionally each level of control in the system has some type of so called process control independent if managing a breaker unit, a generation unit or a DPS unit.
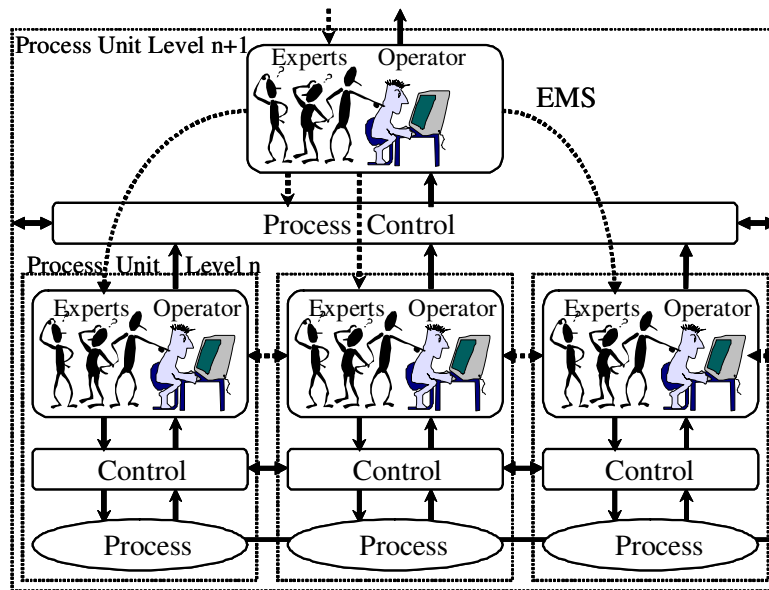
Figure 6.3: Traditional operation interaction.

The operation, however, is traditionally handled by operators. They monitor the process and are prepared to act in case of disturbance or commanded to change operation mode. Operation modes are normally changed according to a predefined scheduled. Operator decisions are,

among others, made by different instruction lists depending on events. An experienced operator normally manages most of the instructions by heart and possible rare events are periodically trained in simulators to make the operator prepared for such situations. However, some events or disturbances are more difficult to handle and some may not have been known and prepared for. In such case the operator's process knowledge, operating experience and personality are key figures to ride out the situation. Depending on organisation size the operator may have experts to call for in rare and grave situations. Then the combined knowledge and experience may be enough to solve the situation. Another important issue concerning operation is the interaction between several process level operators, both horizontal and vertical. Operators and experts may come to different decisions due to various disturbances and the orders in a vertical hierarchy may be confusing for lower level operators. Another issue is the speediness in sending orders. As shown in Figure 6.3, the doted communication paths indicate that information is transmitted by telephone, which is the case in traditional system at higher level operations.
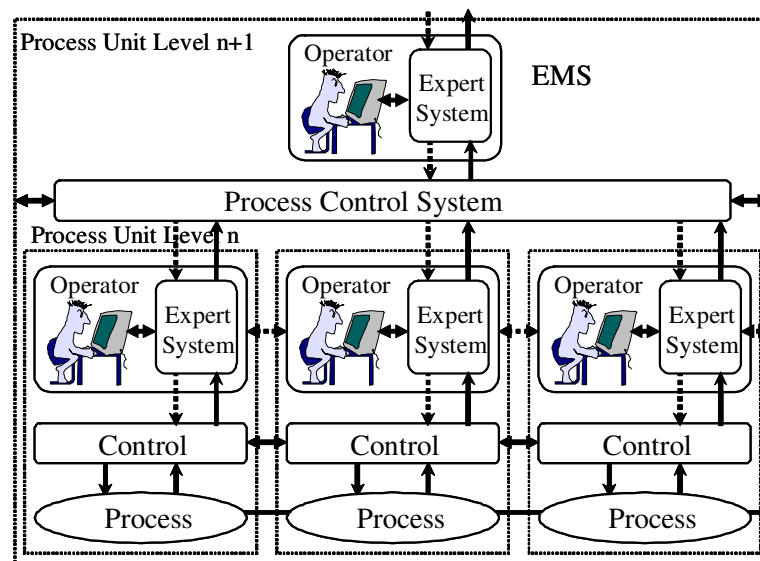
Figure 6.4: Semi- autonomous operation interaction.

Some operating systems have so called expert systems with the main purpose to analyse process information and warn and prepare the operator in making the right decisions as shown in Figure 6.4. In this expert system

some of the expertise and instructions lists are embedded based on some type of knowledgebase. They differ for different processes, process levels and nations. However, this is a semi-autonomous operation system where the communication may be both digital and by telephone.

In a system with fully autonomous operation, the operator and the experts are replaced by a computer including advanced software functions managing all types of operation and disturbances as shown in Figure 6.5. In such system all process levels know exactly what to do in all known situations and are able to react in fractions of seconds. They are also able to handle situation where higher levels orders are interrupted. Future intelligent software will probably learn how to handle new situations in an adaptable approach.
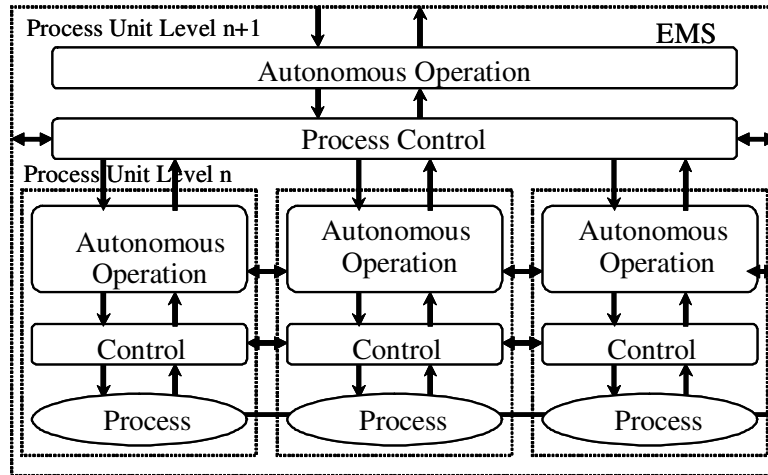
Figure 6.5: Autonomous operation interaction.

There is of course a backside to this also. Systematic software error and viruses may impact such a system hard and thereby the reliability of the system, which is the main aim to improve. In other words computer system security and authorization will play an even more important role in future information society.

Intelligent System Agents

Researches are actively trying to find solutions to replace some operation functions by so called artificial intelligence. The reasoning element must use some form of artificial intelligence such as agent software. Intelligent

agents are software entities that carry out some set of operations on behalf of an operator or another function with some degree of independence or autonomy, and in so doing, employ some knowledge or representation of the operator's goal or decision. Applying intelligent agents into power system problems has had mixed reviews [Wildberger, 1997]. Intelligent agent based tools have been applied only to well-defined problems, such as processing alarms. New intelligent agent tools are needed to aid human operators in the overall decision-making process. A key element is developing multi-constraint optimization tools that accommodate all the relevant objectives for operating a power system. An additional goal is to develop autonomous agents for reasoning and optimizing system operations. These agents would operate at the higher levels of the control hierarchy and assist in the decision-making process for routine, but critical, system performance measures. The logic for these autonomous agents would extend down to the process level, where they could interact with lower level autonomous operators. They could help to minimize system outages. In this work intelligent agents has been investigated but the term is not used. However, proposed structures with autonomous decision-making and operations implies in the exchange of operators by intelligent agents.

6.2 Distributed automation architecture

The development within information technology is constant at high rate both regarding increasing capacity and decreasing size. A few decades ago a computer system required an entire room regarding space. Today a corresponding system might be imbedded within a shoebox and in another couples of decades the same computer capacity might be embedded in the eye of a needle. The only part limiting the size might be the interconnection to communication mediums, e.g. if the computer devices are embedded in humans, clothes, outlets, cables, etc. The limits in placing artificial intelligence will be immense.

Focusing on the development of software modules for computer-based operation and control, new automated functions will open a new dimension for critical or abnormal situations. Real-time requirements may include: continuous operation, execution depending on external events, direct and immediate information inflowing from outside the system, immediate information processing for system operation and control, direct effect on the controlled process units, and distributed processing. Consequently, operation and control software systems may easily become very complex

systems. Furthermore, the integration of new advanced functions to achieve more flexible and efficient operation of the system control, and to exploit more fully the digital hardware capabilities, will increase the complexity of control software system [Tuszynski and Svensson, 2001]. The complexity of control software system aimed for DPSs is managed by a well-defined architectural structure. The automation architecture of a DPS unit is here divided in the functional hierarchy and the control system hierarchy as shown in Figure 6.6. The distribute control system (DCS) is divided in hardware and software structures. The hardware basically includes process computers (PC) or control units (CU), communication devices etc. Depending on control level, several input and output devices such as sensors and actuators are included. The software part includes several programs such as the operating system and several other basic functions for supporting the application programs and its functions. The function contents vary depending on control levels and are structured as the functional block hierarchy, which is fundamental in reaching well structured software.
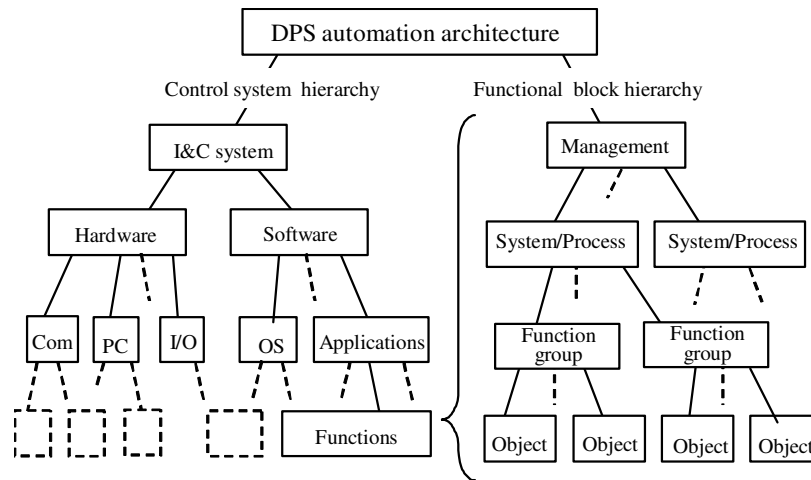
Figure 6.6: DPS automation architecture overview.

An important part is also the information structure that is based on the intended information flow in the system, where data protocols in between communicating control units are conducted, which is described in next Chapter. The functional part includes a hierarchy of different levels of control blocks such as object, function and system control levels. The

architecture includes modular structures and well-defined interfaces for the DCS. In the following sections the DCS and the functional hierarchy are described.

6.3 Distributed control system

DCS improve power system reliability and are one part in identify and isolate defective sections of the electric network unit, transferring the disconnected load units to working sections of the system with minimal delay. Real-time functions decrease manpower and time involved in field data measurement and programming during implementation. Computer automation addresses several areas within information technology that are utilized with DCSs.

System control levels

The further investigation is limited to the bottom layer of the EMS, the production management (PM), and the lower control levels that have been more thoroughly implemented and tested. However, this is today commonly most of the contents within an EMS. The power units differ widely in the range of control depending on type and size of the unit. For larger power plants, the control system configuration is very much the same except for the software functions. The principal hardware configuration can therefore be assumed to be the same for system and unit control.

Configuration

Traditionally control systems are operated 24 hours a day and acts as the nerves of the electric power system. Its principal functions are to:

- monitor and control the power system and units

- co-ordinate power units at normal and abnormal system situations

- handle power system emergencies and outages

The system configuration is shown in Figure 6.7. It is a client/server configuration consisting of servers, engineering workstations and process stations, which are mutually connected through local area networks (LANs) using FDDI (Fiber Distributed Data Interface). The servers are front end processors, SCADA servers, supply/demand control servers, and file

servers. The engineering workstations provide the human interface. Additionally there is also an input/output signal management working as the interface between the control functions and the process. This is responsible for a well functional information exchange from and to the process instrumentation at regular intervals or under demand [Tuszynski and Svensson, 2001].

The operational personnel carrying out process functions have the principal objectives to generate and dispatch electricity as efficiently and economically as allowed under all practical constraints and ensure personnel safety and power system security.
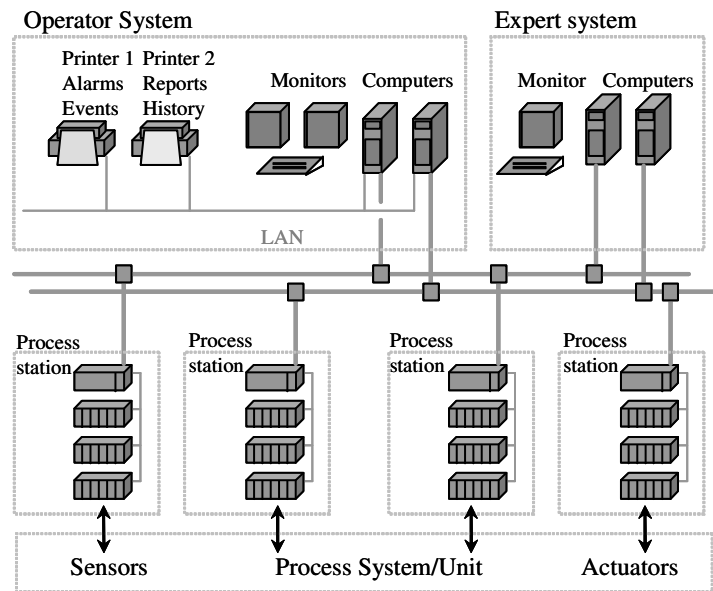
Figure 6.7: Control system hardware structure.

The main functions and applications available in the control system:

- *Supervisory control and data acquisition (SCADA)*: SCADA performs two essential tasks; it telemeters data back from remote sites and facilitates remote control from the System Control Centre.

- *Alarm processing*: Alarm processing processes the data collected and alert the System Control Engineer immediately if an alarm condition is detected.

- *Expert system*: Analyzing and checking functions with aim to help the operator in preventing inadvertent failures and ensure the safety with the electricity system and thereby reliability

- *Analytical and forecast tools*: Analytical and forecast tools are provided in the EMS to assist the operator to evaluate the status of its power system/unit, forecast the system demand in future, analyze and determine the schedule for power units and to manage the system in a reliable and effective manner.

- *Real-time database* (RTDB): System data area for external and internal fast communication.

- *Historical and future database*: Large volume of historical and future data to be stored and retrieved. The historical and future database gets its data from the RTDB.

- *Operator training simulator*: This provides hands-on training for System Control Engineers for normal, emergency and restorative control of the power system

- *Engineering workstation:* Working interface and application to check, reprogram and update software functions.

- *Operator interface*: Allow for interaction between operator and controller. They must be able to provide the operator with relevant information about the plant behavior. Must also provide a means to modify control parameters and strategies.

- *Special functions:* Special functions, e.g. automatic busbar re-configuration, three phase fault interconnector trip, etc., are built in the EMS to automate functions that normally require system control engineer's action. Many of these are specifically developed for emergency situations where the speed and correctness are vital.

In Figure 6.8, the principal functional structure of the control system is shown. These are only the major functions which may include several more depending on system and unit assignments. The System control is divided in the following two function groups:

- *Sequence logic functions:* Specify how and in what order the plant operations should be executed. They allow the transition between the various operating states. Enable and disable the continuous control functions as required.

- *Regulatory control functions*: Evaluate control algorithms for driving the continuously varying signals in the process.

The system protection block has several assignments depending on control level in the system hierarchy. Basically the protection block includes functions to monitor critical variables to avoid the process entering unsafe operating regions. They depend heavily on the physical characteristics of the plant and on the safety requirements of the process. Several functional groups are currently performed in many control systems.
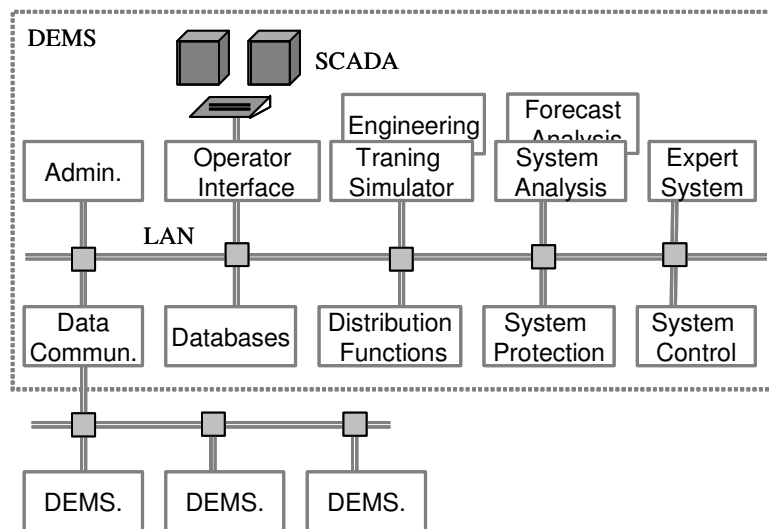
Figure 6.8: Control system functional structure.

This work includes some of these functional groups including the signal management functions. Development in information technology over time will gradually decrease the physical size of this hardware that at present takes up a great deal of space. Looking far in the future this hardware might be small enough to be placed within an outlet, as proposed in the Chapter 5.

System and unit control functions

Depending on system level and commitment there are numerous functions available that in some cases are automated and some cases managed by the

operator. These functions are be classified as centralized and decentralized. One example is the system control part.

Centralized power system functions

The system control block in Figure 6.8 includes the centralized functions for transmission network system control included in the EMS, aimed for the TSOs and SOs, where some of the more essential are listed below:

- *Automated primary control* (APC) is a new function for the DPS enabling the system to automatically choose adequate number of power units for primary control.

- *Automated secondary control* (ASC) is a new function for the DPS enabling the system to automatically choose adequate number of power units for secondary control. This is very similar to AGC with the extension to cover all the four power unit categories separately.

- *Resource dispatch* (RD) is a new function similar to the GD function except for that the RD is used for each power unit category and tries to achieve optimal operation according to a requested group set point for each individual power unit category by maintaining the best combination of units to fulfil the set point request.

- *Automated generation control* (AGC) is a function that automatically adjusts a control area's generation to maintain its interchange schedule and share of frequency regulation. This AGC primary operates in the secondary control domain and consists of numerous sub-functions that use several of the ancillary services.

- *Generation dispatch* (GD) is a function achieving optimal economy in the operation of the power system, which adjusts the output of each generator according to its efficiency, its fuel and operating costs, and its associated transmission losses so that the incremental production cost of each power unit is equal. This control function is included in AGC and is performed in the range of minutes.

- *Unit commitment* (UC) is a function optimizing the overall efficiency of the power system operation, which requires appropriate scheduling of the power units by selecting the type and number of units available. Prior to the day being analyzed, optimization analyses are performed based on information of each power unit's expected controllability and availability. These analyses rank the units according to predefined priorities.

- *Reserve resource management* (RRM) is a function determining various power reserve units by calculating their power capacity and ramping rates. Reserve resources are necessary to protect against sudden loss of generation capacity and are categorized in two types, spinning reserve and nonspinning reserve. Spinning reserve is the difference between the total capacity of activated generation units and the total present output of those generation units. The non spinning reserve is the amount of generation capacity that can be activated in 10 minutes or less.

The system protection block in Figure 6.8 includes several functions for network analysis and protection where some are listed below:

- *Automatic voltage control* (AVC) is a function determining the optimal scheduling of reactive power resources and designed to operate at certain voltage rating. Voltage regulators and control of reactive power at the generators and consumers connection point are coordinated in order to keep the voltage within the required limits and avoid voltage stability problems.

- *Optimal power flow* (OPF) is a function using optimization methods for performing steady-state network analysis. The OPF is used for operator load flow, security analysis, security enhancement, and AVC.

- *Available transfer capacity* (ATC) is a function determining the transfer capability remaining in the transmission system for further utilization over and above already committed capacity.

- *Security and Outage Scheduler* (SOS) is a function always considering the analysis results and if needed disconnect sections of the control area or ordering the unit commitment function to shut down or start-up power units in order to prevent a system collapse.

Decentralized power unit functions

The decentralized functions are normally performed locally by generation units and their GSOs that may be operated in several control modes. In this work they are also applied for the LSO, SSO and ESO. Power resource units differ in control ranges regarding capacity, response time and control capability. Some units are independent on environmental changes whereas others are directly affected by the change in for example wind speed and solar radiations. These intermittent resource units are not able to provide control functions at all time but may have an important future role when the management of power systems is able to handle this. The power

resource units interconnected with the transmission network requires different types of control functions that can be ordered from higher level authorities or the centralized power system functions. The control functions are listed below:

- *Power Constraint Control* limits the nominal power output of the power unit to a predefined set point.

- *Power Minimum Control* limits the power level to a minimum without shouting down. This might be useful when there is a temporary surplus in the system and shortly after is requested to start as quick as possibly.

- *Power Maximum Control* results in that the power units are commanded to operate at maximum. This is usually the same as the nominal power output depending on the power unit type, e.g. some renewals as wind power only reaches nominal power depending on wind speed.

- *Power Balance Control* enables the power unit to reduce the power production of the power unit at a predefined rate and later to increase the power output, also at a predefined ramp rate. This function is used for secondary control.

- *Power Rate Limitation Control* limits the increase in power production to a predefined set point. This is normally used when changing set points for power units not used for primary control.

- *Droop Frequency Control* is used at the generator level. The governor control senses its own shaft speed and adjusts the energy input to the prime mover (engine, steam, or hydro) that is driving the generator. The governor controls are designed so that the generator output will increase in response to a decrease of the generator shaft speed and vice versa. This control function is accomplished within several milliseconds and belongs to the primary control.

- *Load Frequency Control* is used in order to maintain a constant system frequency at all loads levels, the reference point of the governor control must be adjusted and the droop frequency control characteristic shifted, depending on the system load. This control function is performed every 2-6 seconds.

- *Voltage Constraint Control* is used to adjust the voltage level at a specific point by regulating the reactive power in an AC system.

- *Droop Voltage Control* is used corresponding to the Droop Frequency Control except for adjusting the voltage instead of the frequency. This function is only used in a DC network system.

These functions are normally achieved by using generator speed control (governor action) and/or generator terminal voltage control (excitation system) at the local power unit. Developing the improved operation interactions of these functions opens up opportunities to increased system reliability.

Control hierarchy

The control hierarchy of the centralized and decentralized function are shown in Figure 6.9 where the hierarchy is divided in three levels.
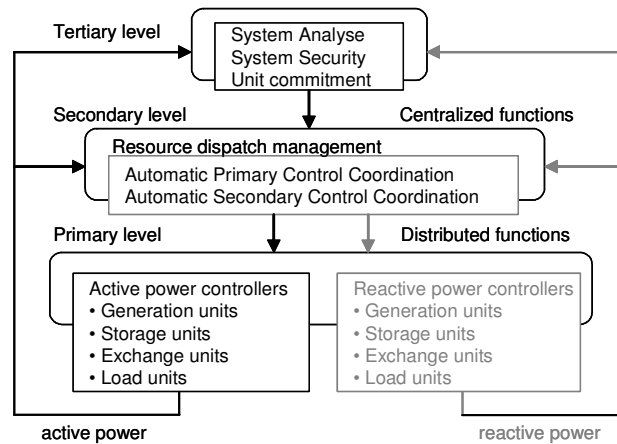
Figure 6.9: Control hierarchy overview of centralized and decentralized functions.

At the highest level, several system functions are used for analysing and controlling the features for the operation of the system. The next level fulfils the demands from the upper level by coordinating the system resources and the lowest level perform the actual order/service requested. All control and information needed for the operation is exchanged by the OCI.

Autonomous coordination functions

The system calls for a number of operation strategies depending on design, run modes, load following, economics and other disturbances in which some have been implemented in this work. The simplest solution would be to start enough generation units to cover the maximum load and leave them

running. This solution, however, would be applicable for very simple systems. In systems with a high number of power units it would be necessary with some type of allocation functions. As the problem is basically a production - consumption adjustment it is natural with a production allocation, where to choose the most effective producer configuration of generation units to meet the actual load variations and coordination of produced electrical power in cogeneration units.

This section presents a possible solution for autonomous operation and control of a DPS by using advanced software functions/modules. A flexible strategy is proposed that online manages numerous system configurations. The rule-based strategies and decisions are presented as well as several algorithms for managing the power units. Renewable energy sources are adopted in the DPS that also has "stand-alone" capabilities depending on the power units employed. After the introduction, rule-based strategies are proposed and thereafter an analysis regarding different system configurations are described.

Software block structure

Software structures include many aspects on how to aggregate certain amount of data and functions for a process unit [Al-Agtash, *et al*, 2000]. The grouping can for example be based on geographical placement or by a function in a subsystem. It is most common, in case of new construction, to combine these by construct the subsystem in the same area or at least nearby. All construction drawings then follow a specific pattern, which divide the system into subsystem, functional groups and objects. In order to simplify all involved in a project and have a save working time, all naming of physical components and process sections should be analogous for the control software from field to monitoring level.

Architectural classifications are the solution to develop flexible software and well-defined communication interfaces. Since there are no standards for the information structures necessary for control software structures, different companies classify the information entities differently. When stand-alone automated control units are to be integrated they must have increased knowledge about their own states. This again might push the information handling towards a more flexible approach, which sometimes manufacturing engineers unfortunately find hard to deal with since it requires a more abstract computational training. However such systems scale up are much easier when the size of the system as a whole increases,

and have much better flexibility with respect to both reconfiguration and error recovery [Tang and Lasseter, 2000] [Ta-Kan, *et al.*, 1998].

6.4 Autonomous coordination functions

The operation of DPSs in weak networks, suitable for intermittent stand-alone systems, with a high penetration of RES may face several technical and structural problems. These problems, not present in large interconnected networks, are mainly caused by

- The variations of power production and consumption that both may be of stochastic nature depending on RESs

- The limitation of controllable primary and secondary power units within the control area and the access of them

- The scheduling and unit commitment capability regarding fast mechanism for changing operating control modes of available power units

The main operation and control problem with DPSs is to be able to ensure power supply in spite of large variations of power production and system configurations while maintaining the primary and secondary control within acceptable limits. Furthermore, optimizing the operation involves the selection of the best combination of power units to balance the power flow depending on DPS operating limits and constraints. For the functioning of the DPS, it is important to separate the control into two groups as for the conventional power system:

- Operation strategy; which involve decisions about the power flow on a time scale of several seconds to hours and actions to improve system operation. This involves the dispatch or unit commitment of included power units within the DPS.

- Control strategy; which is in the range of milliseconds to seconds and include the mechanism of primary and secondary control. This also involves the possibility for individual power unit to quickly change from one control mode to another.

The operation and control strategy for the DPS structure is fundamental for the interaction and interconnection of several DPSs. Although, the controllable power units within the DPS have individual controllers that perform continuously control, the optimal operation of the DPS can only be

achieved through the use of a superior control system that analyses the system as a whole and make decisions of the best mode of operation and control strategy.

General operation and control strategy

An operation strategy for DPSs should determine the best mode of operation by combining the available power units. The operation strategy should aid the superior controller system and operating authority to decide how many and which power units to be actived. There are mainly four different types of power units, generation units, load units, storage units or exchange units, and they are operated either as sources or sinks. The order of in which the power units are started and at what service they are started in depends of what strategy the operator of the DPS has assigned.

The main objective for the DPS is to supply the load units with as much power as needed at all time according to agreements. If the generation units not are able to supply the load units completely, the load units are limited in power supply in correspondence with the system generation capacity. The generation units are only capable to generate power and they are the main source within the DPS. These units have the highest priority when supplying load units. If a generator can provide more power then needed by the load units, they can store energy in the storage units for reserve in cases when the generation unit capacity is to low. They can also be used to provide power to support adjacent DPSs with power when asked for.

In this operation strategy the generators will try to load the storage units before the DPS is allowed to export any power. The reason is that the system will try to have the best possible opportunity to support its own loads by itself and adequate loaded storages will give that opportunity.

It is only when both the load units and the storage units are satisfied as the DPS is allowed to export power. However, if the power from the generators is not sufficient the system can ask an adjacent DPS for assistance. The remaining amount of power that the DPS needs will then be imported from this DPS in order to supply the own load units. If the storages have to low energy level, they will also be charged up but only in case the load units have all the power requested.

The storage units can be used to store energy which later can be used as support if the generators are weak for the moment or the loads have a

temporary peak in there demands. They are only used as a support when the generators and exchange units are unable to deliver enough power for the loads. But they are charged at any time as the capacity of the generators is higher than the demands of the loads. To have a well-balanced power system there should be at least two source units in primary control within the DPS. These source units momentary and automatically increase or decrease power to the system in order to keep the voltage or frequency at the right level. The response for disturbances is thereby very fast managed by these primary units.

The determination of system configuration and capacity

In order to operate the system, the first task for an autonomous system is to determine the configuration and the capacity of the system. This is done by receiving all information of the available power resource units. It is at this point assumed that all resources connected, automatically establish an information exchange with all necessary data according to the OCI. As for the conventional procedure (reserve resource management) of calculating system reserves (generation) for different capacity levels according to Appendix D, the some procedure is made for all the four categories of power units in this work. This creates a real-time data base that always includes the actual information divided in several groups of controllability and capacity. For example, the result in one moment could be 20 MW secondary control capacity of generation units, 5 MW primary control and 2 MWh capacity of storage units, and 15 MW none controllable load units. As the system, in this case, has no exchange units, the system is determined as a stand-alone system with a system configuration based on generation, storage and load units. Depending on the individual power unit sizes the system would approve to start up the system by distributing lumped system set points for each power unit category according to the procedure in Appendix E.3 that is included in the unit commitment function.

Operating reserves

The operating authority (OA) is responsibility to supply adequate power to meet all loads instantly and also to provide operating reserves to meet all loads as demand changes over the next minutes and hours. This additional power capacity has to be available in order to prevent system collapse in case of a sudden loss of the largest power unit and also the loss of RES production caused by the fluctuation in solar irradiation or wind speed, which are related to secondary control requirements unless they are the

largest unit in the DPS. There are formal policies specifying how much operating reserve is required, how quickly it must be available, and how to utilize different types of power resource units toward the reserve requirements. The reserve resource management is used for collecting all information necessary to determine the DPS reserves and capacity levels. This is divided in the four power unit categories and thereby calculated for each category. The operating reserves are divided in the following classes.

- *Regulating Reserve*, an amount of spinning reserve responsive to AGC, which provide for normal deviations in area control error (ACE), primarily due to errors in load forecasting. This will also be affected due to errors in generation forecasting due to a large penetration of RES.

- *Contingency Reserve*: An additional amount of operating reserve sufficient to reduce ACE to cover the immediate loss of the largest generation unit in operation or a sudden increase of the demand, which would result from the most severe single contingency. At least 50% of this operating reserve shall be spinning reserve, which automatically respond to deviation in the primary control.

- *Spinning Reserve*: Unloaded sink units, which is synchronized and ready to serve additional demand. It consists of Regulating Reserve and Contingency Reserve.

- *Nonspinning Reserve*: That operating reserve not connected to the system but capable of serving demand within a specific time.

The contingency reserves have to be adequate to continue power delivery when the DPS's largest power unit fails. Resources for contingency reserves must be able to be ramped up very quickly. A portion of contingency reserves can be load units that have agreed to be interrupted when a contingency occurs. Depending on individual DPS strategy, the contingency reserve can be reduced by the participation of a reserve-sharing group with neighboring DPSs. In this way, each DPS only has to provide a part of the contingency reserves required by the group. The reserve resource function calculates the actual operating reserves available continuously and compares the result with the operating reserve requirements according to the capacity levels. The capacity levels, shown in Appendix D, are used to decide the operation mode and set points for each power unit category. Parameters that are calculated are among others:

- Maximum capability: This parameter gives information about how much a certain group of power units (generation, load, storage and exchange) can provide.

- Raise Regulating Capability: Gives information about how much more capability that can be used for primary control.

- Falling Regulating Capability: Gives information about how much capability that currently is used for primary control.

- Current Generation: Capacity that currently is used.

- Minimum capability: The minimal capacity that the units need to be operating at while they are on.

The calculated capacity levels for each power unit category inform the operating authority of the system configuration and the possibilities in operating these. The capacity levels also trigger the functions for automatic primary and secondary control as the limits are exceeded in order to adjust the power units back within the boundaries. All information used for power balance and system capacity level calculations are provided from a power resource manager connected to a real-time database described in the next chapter.

Priority management

The power units in the DPS receive different priority numbers depending on the main purpose and strategy of the system. The priority numbers indicate the relative priority of power units and actions in the control algorithm. Priority numbers are used different at different level of decisions and operational situations. By assigning priority numbers to all power units, the management load of these is reduced as a part of the problem to be solved, which enable faster decision-making. The next following sections shows how the priority management is adopted for the

- Start-up operation strategy

- Shut-down operation strategy

- Abnormal operation strategy

- Normal operation strategy

In the normal operation strategy, the operating authority is coordinating its activities with the power balance authority in order to maintain the supply/demand balance by secondary control. In the other three cases, the

operating authority is coordination its activities with the security authority that affects the management of primary control.

Start-up operation strategy

The idea for this strategy is to have enough primary controlling units working in droop mode and the rest of the generation units as power controllers (secondary control). In Figure 6.10 it is shown how much power the primary controllers should generate. The power produced by these units is never allowed to enter the upper safety zone A1.
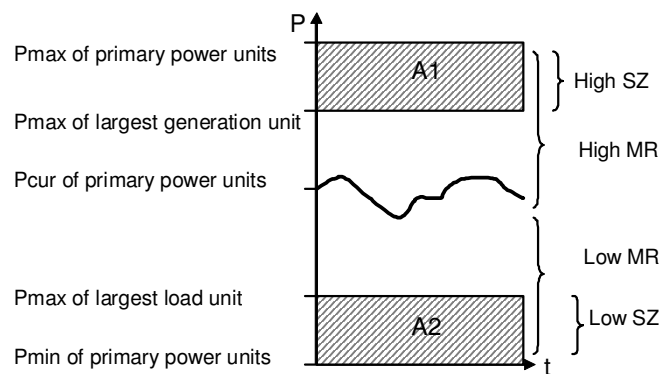
Figure 6.10: Power limit levels for the primary controlling units.

This in order to always be able to cover the generation from a suddenly break or disconnection of the largest source unit. Then the primary controlling units are able to quickly compensate for that loss of power by entering the zone A1. The system will then slowly adjust to the new circumstances by adding another source unit in power control mode (secondary) or reducing the set point for the sink units. The power production of the primary controlling units will then go back into the allowed area. The security zone A2 is working in a similar way. But this zone has the purpose to protect the system from sudden losses of the largest sink unit. The DPS aim to obtain the power produced by the primary controllers in the middle of these safety zones as much as possible but it is allowed to reach the levels of the safety zones during normal operation as well.

Then the sum of the safety zones are about as much as the maximal power productions of the primary controlling units and the zone, where these units

are allowed to operate, will be very small. In these cases another generation unit will be started in droop mode (primary) and the margin for these units will become increased. In the cases when there are no more source units available to start up the system, a source unit will change from secondary control mode to primary control mode and solve the problem in same way. The order for different source unit types to be used for primary control is:

1. Generation units

2. Storage units

3. Exchange units

If there are any generation units in the system that are not yet used, they are the ones to be first used for primary control. If there are no more generation units available, the fast storage units are used for this purpose. Finally when all other options are used the exchange units are used for the primary control. The reason for having higher priority on the storages then on the exchange units is that the system becomes more reliable if the exchange units are working in secondary control mode as much as possible. The adjacent DPSs connected via the exchange units are also the last ones disturbed to avoid any possible cascade effects. If the exchange units are used for primary control on one power system, the option for primary control for the other one disappears. In other words, to maintain a high flexibility the exchange units are kept for secondary control and only used for primary control as a last option. Such option occurs when the DPS only includes load units and exchange units, which is the actual case for most of the buildings and industries.

After selecting a power unit category according to the above priority order, the next selection procedure is started among that particularly category, e.g. storage units. This is made in the following search rules for startup of each power unit category.

1. Highest priority

2. Fastest startup-time, depending on primary or secondary control

3. Largest Power capacity, size

4. Longest down time

5. Shortest operating time, total

By assigning priority numbers to all power units, the workload (management) of these is reduced as a part of the problem to be solved. If

five storage units with the some priority are found the next rule for fastest start/up time is used for selection (this is most important for the primary control). If this should not be enough at the selection, the next rule selects the largest unit. In normal case, one or two steps for the selection rules are needed. However, regarding a DPS including wind power plant with twenty generation units and one exchange unit all selection rule may be used.
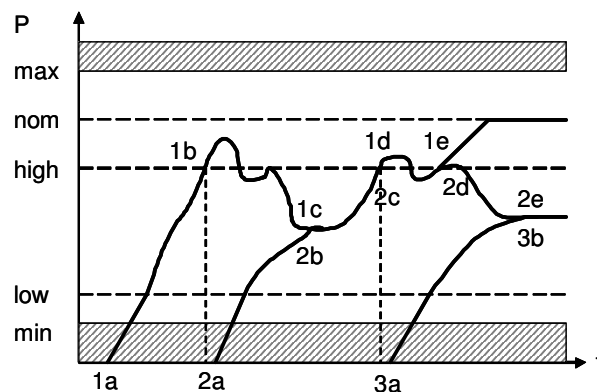
Figure 6.11: Start-up operation strategy overview.

If the superior control system has, for same reason due to wind conditions, determined to increase the capacity, all generation units may have the same priority, start/up time and power capacity. Then the additional rules are used by first selecting for the unit with the longest time not operating and secondly for the unit with the shortest operating time as a total. This illustrates that the rules cover several types of DPS configurations. The search rules are applied for both primary and secondary control.

For dynamical purposes the system can automatically change a unit from power control (secondary) to voltage control (primary) when needed. This is done when all of the available generation units are used and the priority for order of change for the unit types is the same one that is stated above. The algorithm (implemented in the automated primary control function) of the primary and secondary control is shown in Figure 6.11. The first source unit starts up in primary control at (1a). As the unit reaches the high level load level (1b), a new start command to a second unit is produced (2a). These both units share the load as shown (1c and 2b). When the two units reach the high load level at 1d and 2c, a third source unit is started (3a). If this unit is large enough or the load is low enough, the first unit turns over

to secondary control at its nominal power level (1e). The second and third units now share the load. The primary control sequence is shown in Appendix E.1. After started at least two units in primary control the secondary control is activated and coordinated to release primary capacity. The secondary control sequence is shown in Appendix E.2. The startup sequence for the generation units is to start and produce power at its minimum regulating capacity before following according to a power set point.

The shut down sequence is very similar to the startup sequence except for regulating down to its minimal regulating sequence before being shut off. The signals transmitted in this part to the power units, contain information about the command mode, govern mode and set point to the power units according to the OCI.

Shut-down operation strategy

If the DPS for some reason has determined to shut down completely, this is done by ordering the power units off in the following priority order:

> 1. Exchange Units,   not conflicting with primary control
>
> 2. Storage Units,   not conflicting with primary control
>
> 3. Generation Units,   not conflicting with primary control
>
> 4. Load Units,   the highest priority load units left
>
> 5. Source Units,   primary control

If the system are using primary control units other than exchange units, the power flow from the adjacent DPSs are first disconnected. Dependent on speediness requirements, this is done in a controllable manner, which means that the DPS changes to stand-alone mode. If the DPS contains storage units these are shut downed before the generation units. Along the shut down of power capacity the load units are also in parallel down regulated or disconnected. Only the highest prioritized left supplied by the primary control units in stage four are order to off. After total reduction of load units, the primary control units are shut down in the same order as for stage one to three.

Several power units may be included in every power unit category and the search rules for selecting the individual power units are as follows:

> 1. Lowest priority

2. Slowest startup-time, depending on primary or secondary control

3. Smallest power capacity, size

4. Longest up time

5. Longest operating time, total

The individual power unit with lowest priority is first selected. If several units have the same priority, the one with slowest start-up time is chosen. This is done in order to have the fastest left in case of the shut down sequence should be canceled and the DPS should quickly start again. Rule four and five are used to differentiate between several identical power units included in the same DPS control area as for the wind power plant example.

Abnormal operation strategy

When a DPS experience an abnormal situation the operating reserve capacity should be able to quickly balance its generation and interchange schedules to its load units. The primary operation reserve is only used as a temporary source of emergency energy and intended to be restored so that the adjacent DPSs are prepared to withstand the next contingency. A DPS unable to balance its generation and interchange schedules to its load units have the authority to down regulate or remove sufficient load to permit correction of its ACE.

The APC function is responsible for automatically search for available primary control units if requested by the security authority. The changes in the primary control units trigger the function to activate the primary reserves to an acceptably level. All four power units (generation, storage, exchange and load) may be available for the APC. A power unit can be set to one of three APC control modes:

- *Voltage Droop Mode* - This mode is operated by using the "vdroop" of the "govern" signal and the "set point1" for the voltage reference point.

- *Frequency Droop Mode* - This mode is operated by using the "fdroop" of the "govern" signal and the "set point1" for the frequency reference point.

- *Off* - Unit is not used for APC control. The GSO controls the generation output. In this case the "govern" signal is assigned to "intermediate".

In order to determine the best suited combination of power units to survive an abnormal operation situation, a priority algorithm has been adopted. The classification of power unit categories is using a mechanism that allows the selection of these depending on the actual circumstance and system configuration as shown for start up and shut down of the DPS.

If the abnormal situation causes a power deficit, the resources may be operated differently. The momentary balance is managed by the primary units activated. However, depending on if the DPS include one or more exchange units with limited controllability, all adjacent DPSs are as well affected by the disturbance. Although, the adjacent DPSs may not be affected at all if the exchange units are based on converter technology and the disturbed DPS is able to restore the balance by itself.

If the primary control capacity is not sufficient, an instant search for new primary control units starts according to agreements and the activation of them are made in the following priority order.

1. Increase very fast storage unit capacity that has sufficient SOC level.

2. Increase very fast generation units capacity

3. Increase exchange unit capacity for import

4. Decrease load unit capacity

In each category of power units for step one to three, the search rules of individual power units are according to those described in section "start up strategy". The step four imply on the total consumption that is made according to the search rules for individual power units described in section "shut down strategy". The secondary resources are thereafter operated in order to cover the primary reserves as described in normal "operation strategy".

If the abnormal situation causes a power surplus, the momentary balance is here also first managed by the primary units activated. If the primary control capacity is not sufficient, an instant search for new primary control units starts according to the following priority order.

1. Increase very fast storage unit capacity with low level SOC

2. Decrease very fast generation unit capacity by deactivating those with a high minimum power level

3. Increase exchange unit capacity for export

4. Increase fast controllable load unit capacity that for some reason not are fully utilized

In each category of power units for step one, three and four, the search rules of individual power units are according to those described in section "start up strategy". The step two is made according to the search rules for individual power units described in section "shut down strategy" with the additional search rule (condition) for finding units with as high minimum power level as possible. The secondary resources cover the primary reserves as described in normal "operation strategy".

Normal operation strategy

At normal operation conditions, the power supply and demand is balanced by the power balance authority that aggregates and deploys the resources. These resources are divided according to the four categories, generation, load, storage and exchange units, which are able to supply a diverse mix of services. The categories are separately handled by respective management functions that are able to raise and lower output or demand in response to control signals or instructions under normal conditions.

The general procedure for normal operation is shown in Figure 6.12. The operating authority total variability is composed of internal changes in load, frequency, losses, unscheduled unit changes, scheduled changes in unit output, interchange transaction ramps, and regulation transactions. A regulation transaction involves moving variability from one DPS to an adjacent DPS affecting its ACE. The ACE is provided by the interconnected exchange units at all times. Power that is not provided by the own DPS is supplied by the adjacent DPS. The ACE is the sum of the internal DPS variation plus the variation provided by all the interconnected DPSs. The operating authority is responsible to ACE variations by issuing dynamic schedules to the different sub management categories. The automatic secondary control (ASC) algorithm (similar to the AGC) automatically generates dynamic schedules that are transmitted to the generation, load, storage, exchange management functions.

The ASC function is responsible for monitoring Area Control Error (ACE) and requesting changes in control area generation in order to bring ACE to an acceptably low level. All four power units (generation, storage, exchange and load) may be available for the ASC. A power unit can be set to one of five ASC control modes:

- *Base Mode* - unit used for ACE control. This mode is operated by using the "power control mode" of the "govern" signal and the "set point1" for adjusting the power output.

- *Max Mode*- unit used for ACE control. This mode is operated by using the "max" of the "govern" signal that adjusts the power unit to its maximum power capacity. Dependent on the speed rate requirements, the "set point2" signal can be used to speed up the power rate.

- *Min Mode*- unit used for ACE control. This mode is operated by using the "min" of the "govern" signal that adjusts the power unit to its minimum power capacity. Dependent on the speed rate requirements, the "set point2" signal can be used to speed up the adjustment.

- *Ramp Mode* - ASC uses system operator entered values for scheduled unit commitment to ramp to a new value of generation output. Unit does not respond to ACE control. Here the "govern" signal is assigned "ramp", the "set point1" for the aimed power output and the "set point2" signal for limiting the increase rate of power output.

- *Off* - Unit is not used for ASC control. The operator controls the generation output. In this case the "govern" signal is assigned to "intermediate".

Depending on agreement, the ASC is able to change the power unit control modes for individual power units very fast and thereby immediately coordinate them for various purposes. The management for this coordination is rather complex and includes several algorithms. The management algorithms search for the best combination in order to meet the requested schedule including either a total increase or decrease for the individual category. After finding a sufficient solution the embedded automatic dispatch actions send the command signals to individual power units and compared to the actual power supply-demand balance within the DPS control area. The basic rules for increasing and decreasing power capacity for the power unit categories are as follows.

1. If any sink (loads, storage, exchange) are off, switch on the units in priority order starting with the highest priority sink unit not in operation and/or authorize permission for a schedule sink unit to start according to agreements.

2. If any source (generation, exchange, storage) are off with higher priority than those in operation, start-up the highest priority source

> unit not in operation and/or authorize permission for a schedule source unit to start according to agreements.

This is the basic algorithm for start up and shut down of power units, which is the normal procedure to start schedules due to energy exchanges related to agreements. The algorithm for adjusting supply-demand variations is divided by if there is a deficit or surplus of power in the DPS.
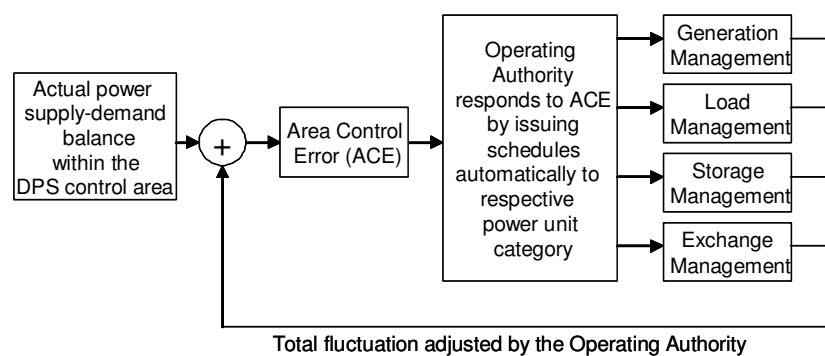
Figure 6.12: Actual power supply – demand process block diagram.

If there is power deficit in the DPS, the capacity is changed by following priority order:

1. Increase generation unit capacity
2. Increase storage units capacity
3. Increase exchange unit capacity
4. Decrease load unit capacity

If there is a power surplus in the DPS, the capacity is changed by following priority order:

1. Decrease generation unit capacity
2. Decrease storage units capacity
3. Decrease exchange unit capacity
4. Increase load unit capacity

Each of these actions creates a lumped set point for the actual power unit category to be adjusted, which is not related to individual power units. The

set points are transmitted to the lower level management functions including the resource dispatch function as described below:

- *Power generation management*: The power generation management has as its primary assignment to search and command individual generation units according to the lumped set point received. The function determines which generator to be operated and that fulfill the requirement. The selection of individual generation units is mainly decided by the priority and capacity of the unit. All of the generators are assigned with a resource priority indicating the significance of the unit. The lower priority numbers the more significant. The generators with the lowest priority are the one that is started first according to the individual start

- *Power load management*: Load management is classified as short-term and long-term control. Both approaches make use of controllable loads to vary the total demand matching the available power generation. Therefore the system is divided into several loads, with different priorities, that can be switched in and out in an appropriate controlled manner. Short-term control is implemented by distributing set points to different load units, normally low priority loads. Load units can be gradually added or removed from the system based on power variations. If the lumped set point received is lower then present, an immediate search for controllable loads is performed to decrease the load. The next outcome for reducing the load is simply to disconnect them by priority order.

- *Energy storage management*: Basically there are two groups of storage types that can be used as a part of the operation strategy, short-term and long-term storages. The short-term storage is an efficient way to buffering power surplus in the system, for example renewable energy and load fluctuations. The fast short term storage units are used both for primary and secondary control. Storage units are regarded as conventional generation units when loaded and have any priority number depending on the design objectives. However when the storage capacity is low, the active storage is considered as a controllable load unit that may imply lower priority number. The lumped set point for the total storage units indicates the power limits for the function as well as the total state of charge to be achieved. The storage management function determines by itself how to fulfill these requests by controlling the individual storage units.

- *Power exchange management*: This function manages all power exchange with adjacent DPSs by operating the exchange units. The lumped power set point received, determines the total limits for import and export of the DPS. This information is transmitted to adjacent DPSs as well as received via the exchange units. The individual units are managed according to agreement between the different DPSs. As long as the individual operations not exceed the total DPS limits, all the power exchange is adjusted by this function. In case of a power deficit or surplus, the management function tries to combine its own resource within the limits until a new lumped power set point is received. It is always the power exchange management task to uphold the set point given, e.g. if one exchange unit stops a new search is immediately performed in order to cover the stopped.

The search rules for the management functions are alike and corresponds the individual search rules for individual power units for start up and shut down. A flow scheme illustrating the power generation management function is shown in Appendix E.2. This procedure is nearly the same for the load, storage and exchange management functions.

6.5 Functional block structure overview

Future accessibility of more powerful hardware and software will extend the application of computer-based control systems. Control software systems substantially increase in size and complexity. System structures become modular, so that different modules can be distributed at different control levels. All types of modules can be created and embedded in some type control device. Dependencies between modules produce complex patterns of communication within the system. As a consequence, the integration of modules in a large control system can be very complicated. The use of high level languages makes structured software modules less difficult and the dependencies between modules are actually a larger problem than the programming of the advanced algorithms.

Traditionally, the relation between two software modules is much more complicated since not only parameters and functions results are shared, but also global variables. In order for the various modules to correctly interpret the data they operate on it is necessary that the access to the data is well controlled. In many cases this control is assured through a procedure-call interface. In complex systems a large number of interactions between modules need to be managed in terms of both the data that is transferred

and control over the data transport itself. The possible large number of interfaces to be managed is one of the major difficulties experienced in designing large complex systems structures. For flexibility at connecting and disconnecting, it is essential that the communication between modules is not fixed during the design but can be established as the need occurs. A great deal of effort has been done in solving the above problems. Nearly all the approaches have concentrated on providing more powerful structures and tools for the implementation of the functional block structure approach. High level programming languages and real-time operating systems are one way of solution that has been used.

General distributed control unit architecture

Automation control systems address a number of areas within information technology where several are utilized with DCSs, which include the following hardware and software equipment:

- *Hardware Configuration of the DCS*. The configuration of a DCS computer system includes several computers, which serve as a dispatching platform and a distribution management platform.

    - Computer Units

    - Communication Networks

- *Software Configuration of the DCS*. The software system adopts an open and standard configuration, a unified operating system, a unified database and a unified data management.

    - Application functions

    - Basic functions

    - Data management

    - Databases

    - Communication management

The system is based on either optic fiber or power line communication channels that integrate the control units. The basics for managing the system information is a uniform information and communication system that provides functions on terminals and information interaction with dispatching automation, utilization business and control systems.

Control unit hardware hierarchy

The control unit hardware hierarchy of a distributed power system can be characterized as shown in Figure 6.13 with several control levels mainly including computer/control units (CU) and communication networks (CN) interconnecting them. The division in five levels with *field*, *process*, *unit*, *production* and *management*, corresponds to the hierarchical structure for DCS described in [Olsson and Piani, 1992].
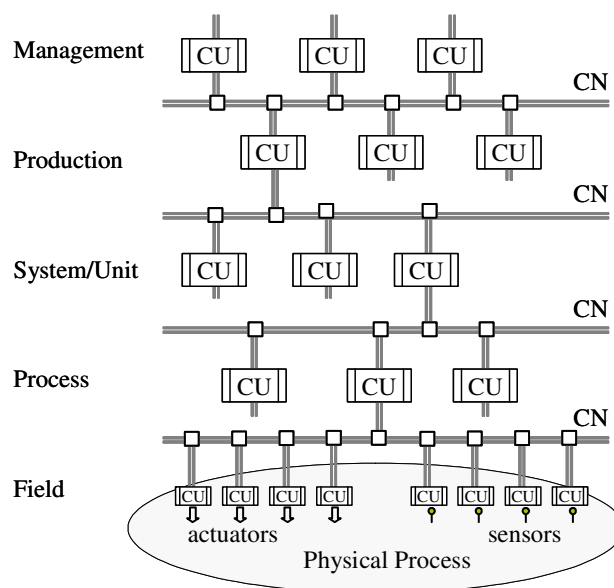
Figure 6.13: Control unit hierarchical structure.

The CUs have various functional tasks depending on control level and could manage everything from an intelligent sensor to an entity power system. At process level, the CUs are named differently but could normally be divided in the "process control unit" and "process protection unit". At each control level the information flow has to be executed and interacting with other function blocks in different control levels as shown in Figure 6.14. The communication between CUs is managed by specific data protocols. The data protocols are uniformed and stored in the real-time databases.
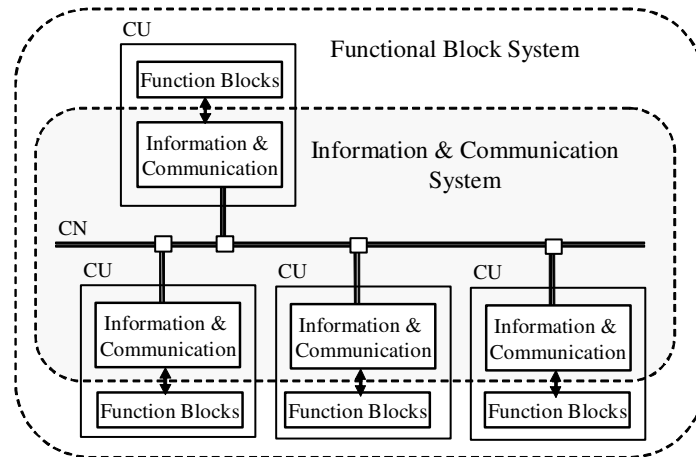
Figure 6.14: Control unit interaction.

The function blocks interact with a general resource manager (RM) that handles e.g. power resource units, communication interfaces etc. By handle all input and output communication via the RM the functions blocks become more general regarding the number of units to be controlled.

Functional software block system

Functional software blocks are an important part of the power system that put demands on the capability to be included into a larger control system. Thus it is very important for functional blocks to provide the means to be coordinated with all other power system control units. Distributed automation models for power systems have been utilized for a while and support the implementation of large-scale vertical and horizontal hierarchical automation structures consisting of several levels, with the power units at the bottom level. However, the trend toward a global deregulated market of the electric power system implies on major changes in the management of the upper levels in these structures. In such a system it is expected that power units used for system control will be commanded as self-supported energy production/consumption units.

Functional block hierarchy

Regarding control software blocks there are several suggestions in the naming and number of each software block level. In [Tuszynski and Svensson, 2001] three levels are used, *object*, *functional group* and *plant*. These are the most common used in power relation areas. A framework that features multiple dimensions for modeling is discussed in [Huang, *et al.*, 1995], where the functional hierarchy is decomposed in several sub level functions. However, sometimes it is hard to differ between the function levels and component system levels (functionally and geographically) concerning software hierarchy.
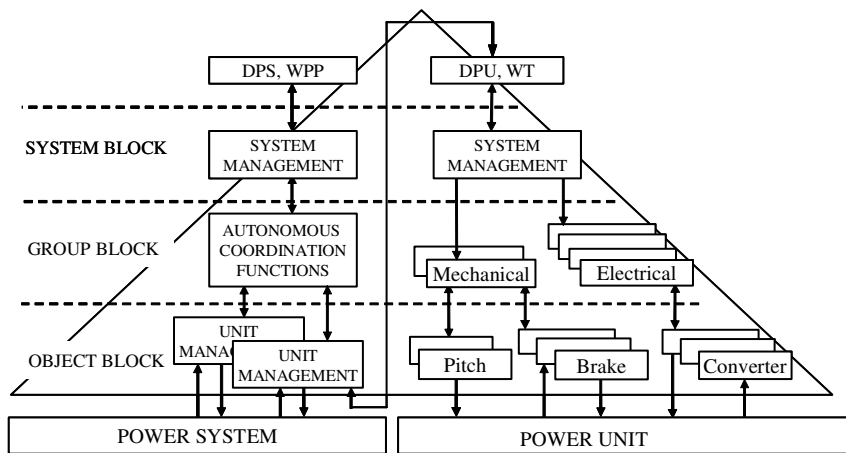
Figure 6.15: Functional block hierarchy overview.

Operators are in general more familiar with a hierarchy based on components, where the system or plant is broken down into related program sections that are well-defined functions. Regarding a DPS or a WPP it might be advantageous to use a division of several levels, but by applying three main layers of process related levels each of these levels could attain remaining levels as shown in Figure 6.15. The component decomposition notion means that a system is decomposed into finer and finer sections of functions extending downwards in the pyramid.

A brief explanation of each software block is described below. The blocks are primarily focused on the process construction and decomposed thereafter. The number of hierarchy levels may increase depending on system complexity. For example, there might be several sub system blocks and sub group blocks. The system nomenclature is very general and can

include one or several power plants or just a subsystem in a large system, e.g. should both a WPP and a WT be classified as a system or should the WT be a subsystem or group. It is in general depending on how it is used in the context. When constructing a single WT, this is a well-defined and self-sufficient generation unit that could be classified as a system. When viewing from a higher level into a WPP, the WPP is functionally regarded as a single system if the WPP is controlled by a WPP-SC and in this case the WTs are regarded as subsystems. The control block hierarchy here proposed for the DPS is mainly divided in a hierarchy of three base levels (System, Group and Object), and are explained as follows:

- *System Block* (SB), is characterized by a clearly defined area of equipment or units with delimit functions and is principally regarded as a separate process. The block distributes and collects its signals from underlying group blocks. From a power unit point of view, a typically SB is the "WT-SC" that is autonomously controlled, which means that all-necessary control and safety systems for proper operation are self-contained. From a power system point of view the SB is found in the "DPS-SC" (WPP-SC) software that is required to have specific algorithms for allocation and coordination of all power units (WTs). This block receives overall commands for the entire WPP and must as a consequence distribute them further.

- *Group Block* (GB), is aimed for repetitive and usually complex functions. In addition to the basic operations for the SB, the GB is also affected by the inputs of the process measurements. In general, the GB coordinates groups of object blocks that have some sort of predefined function and interconnection, e.g. a turbine with pitch control and related brake and sensors for wind, rotor torque and speed would compose a functional group with purpose to produce mechanical power. From the DPS point of view the GB includes all functions for autonomous allocation and coordination of power units

- *Object Block* (OB), is from the power unit point of view closest to the process (field equipment level) and is the interconnection and interaction to the process. In this case, there are mainly two sets of OBs, one for control (on-off control or continuous control) and one for information (special data collection or measurement values). The control OB can be divided in additional sub block levels, e.g. set point trajectory control level, dynamic control level and actuator level (which physically interacts with the process). The information OB can also be divided in additional sub block levels, e.g. value management (filtering), value transformation and

hardware sensor level. The sensor level receives its analog data directly from the electrical transmitter equipment. In the DPS point of view the GB is represented of the power units and the individual management of those.

Each software block level is usually built up by sub blocks such as logic, sequences or special functions, all depending on what is most appropriate for that particular block in the process section. The blocks are in general programmed in accordance with the "IEC 1131-3" standard. On OB level there are good opportunities for reuse and standardisation. These blocks are in most cases connected to standard components of brakes, valves, sensors etc. Higher block levels are more complicated to standardise depending on the complexities through all different combinations of underlying blocks. This usually ends up with the responsible engineers and their software engineering knowledge.

General logical control unit

It is common that control units (controllers, PLCs, operator stations, SCADAs etc.) have predestined placement in a control system hierarchy. By changing the normal approach of control system structures and start out from different specific process sections, the available control and information signals of those can be aggregated and enclosed. This is usually named distributed control and normally embraces several aspects. Assume that control units and communication equipment had infinite capacity and that the cost were negligible, the control units should then probably be a part of every possible delimited function. Next following section strives to define such a general unit that could be found at any level of construction.

The control and communication system is in general divided in hard-, soft- and information structures, where the soft part includes a hierarchy of different levels of control software blocks as described in previous sections. The information structure is based on the intended information flow in the system, where data protocols between communicating control units are conducted. The structure of control units is independent of hierarchic level and differs only in their unit functions and selected control software block level.

The purpose with information and function enclosure is that restriction in range for both variables and functions can be achieved in the control software. By preventing other control units or function blocks from other parts in the software program the possible dependences are minimized.

When a modification in a specific part of the software is made, only non-protected variables and functions must be considered.
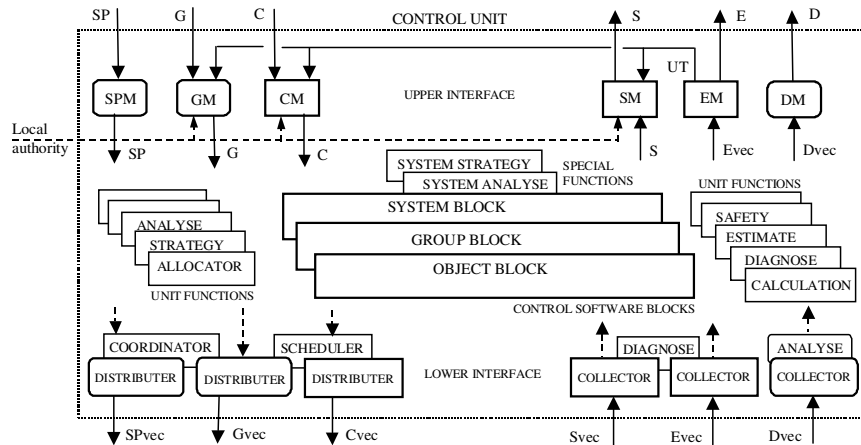
Figure 6.16: General functional block structure and interfaces.

This implies that the software structure is more flexible, robust and easier to maintain. The basic idea is to capture all data, condense and convert data to information, aggregate data to appropriate units, move the information to units when needed, share information in real-time and strive for an information structure enabling a high degree of "autonomous operation". Additionally, every control unit should be independent of control system level, have the same set of communication interface and the same features regarding specific unit functions. The unit should also be, as far as possible, self-sufficient, which means that it will detect and diagnose it's own errors and further report to other units in need.

A control unit is considered as an enclosed data quantity consisting of aggregated signals from a well-defined process section with several internal and external properties as shown in Figure 6.16. The external properties indicate the type of signals the unit can receive or transmit, while the internal properties describe how the unit handle the received signals. A control unit can be of physical or logical nature. In the physical case the software program is dedicated to a substantial hardware and in the other case it is treated as an abstract hardware. Several logical control units can then be combined and resided in the same substantial hardware. It is preferable that control units can be identified as part of the physical process section. This means that the control software structure better describes the

real function of the process. The software blocks that have been identified in the process should consequently be derived in the program source code within a control unit, which can be characterised by the following attributes

- *Identity*

- *Interface* (higher and lower with input and output signals)

- *Condition* (error, status, states)

- *Properties* (specific unit functions)

- *Process control blocks* (system-, group- and object block)

The *identity* indicates that the control unit can be visualized and is the only way to locate it. The *interface* is uniformed independent of hierarchy level and divided in upper and lower level with specific software function blocks for treatment of input and output signals at both levels. The *conditions* are internal protected variables that are the result of the function blocks, e.g. status and error. The unit *properties* are special functions that describe what type of action the control unit can perform, e.g. signal analysis, signal estimation, system analysis, error detection, safety management, strategy etc. The unit functions interact partially with the unit interfaces and partially with the *process control blocks*.

The control and information signals are all treated in specific management blocks and are the main interface to upper level control units. Each block analyses and diagnoses the signals both from internal and external connections and determines the resulting output. These unit functions store and handle the control and information signals at each level of control. The upper interface interconnection of signal management function blocks is shown in the upper part of Figure 6.16 and explained in the next chapter. The lower unit interface may have various advanced unit functions depending on the lower level control units. This is explained more in detail in Section 6.6. The main purpose of the lower interface is to allocate and distribute the control signals (command, govern and set point) and receive data by collecting and storing the information signals (error, status and data) before further usage inside the control unit. In most cases the lower interface only consists of vectors with control and information signals including the identity to intended receivers. When managing several similar parallel units a coordinator and scheduler function might be used as in the WPP case. In same cases, diagnosis functions are needed to provide proper information to superior strategy functions. Internal functions are also

available for special information signal treatment, e.g. calculators, analysis, diagnoses, estimators etc.

At higher-level control software blocks, more sophisticated function might be used, e.g. expert system, system analysis, system estimation, system diagnoses, system strategy etc. The expert systems are, for example, capable of providing expert advises in some well-defined domain. They are also able to reach decisions from new, uncertain and incomplete information with a specified degree of certainty. Regarding control unit specific configurations, several functions can be used, e.g. authorisation, priority, subscription etc. Authorisation at different level will of course interfere with higher-level controllability. In case of priority usage, several units can be forced to change operation mode to let higher priority units run in advance. This means that the affected unit locally have to handle the situation. In the control system hierarchy several additional functions are needed, e.g. service, maintenance, logging, storage, redundancy, monitoring etc. Some of these might be useful in lower domains, e.g. service and maintenance functions might interact at all levels to make sure that that particular component is in proper condition and that operational actions are conducted to prevent personal or equipment damages.

6.6   Distributed power system block structure

The system block structure starts out from the EMS structure that is embedded in each active terminal unit (TUa) throughout the DPS. Although, only the bottom layer, the production management (PM) block handling the centralized control, is described in this section.

The operating task of the EMS production management (EMS-PM) layer is to continuously monitor the operating conditions and to optimise the DPS depending on superior commands. The EMS-PM ensures that the DPS's main objectives are achieved and maintained independent of disturbances and resource limits. By implementing the proposed interface in a DPS, the control block hierarchy becomes as shown in Figure 6.17, where every power unit transmits its information signals to the superior control unit (EMS-PM), which in turn distributes the control signals to each power unit via the production exchange (PE) management block. The EMS-PM provides system parameters as e.g. minimum up and down time, ramp rate and other constraints. However, as earlier mention only fast operational signals are considered here.

The EMS-PM handles several power unit types and is able to manage abnormal situations when some of the power units are beyond control. This could be the case when either the communication line is broken or there is a local operator of a power unit that by some sort of agreement always runs the unit at maximum. Basically this means that the EMS-PM has means for flexible control functions that permits several control situations. Algorithms for schedule and control strategies of power units are, at the moment, in focus and become more difficult depending on the grade of flexibility requested.
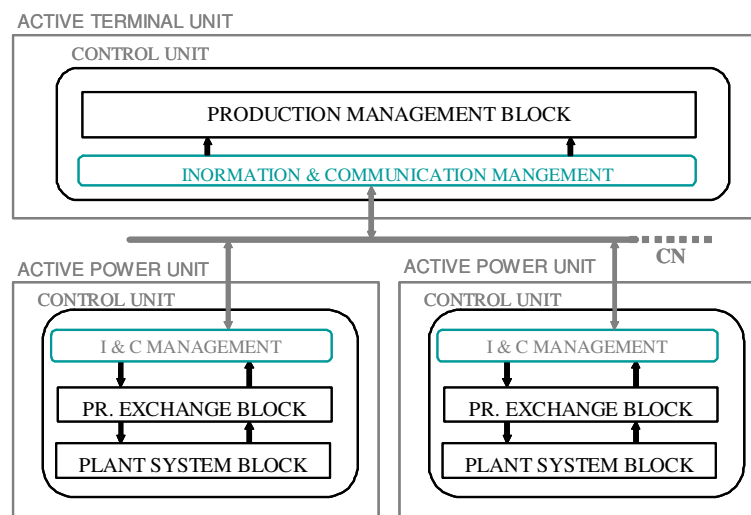
Figure 6.17: DPS management block structure overview.

The solution of scheduling faces additional difficulties due to the randomness of in both production and consumption due to the stochastic nature of RES and load utilisations. Scheduling of power units is to determine which units should be committed and how these units should be dispatched to meet system-wide demand requirements.

Production management block structure

When looking at the functional block structure of the EMS-PM as shown in Figure 6.18, the interface signals are found at each internal level between the functional blocks. Here, all higher-level control signals and lower-level information signals are analysed in the "system analyse function" in order to find the current states of the power units. Depending on the strategy, the

DPS system block determines the number of units that should be turned on/off and the control mode to meet the pre-requested demand.

The requested number of power units is sent to the scheduler that activates its start sequence and continuously remains that number of units running. The control coordinate block receives the govern-signal for each power unit and continuously distributes the set points in case of "balance" Govern mode. This block is also responsible for allocating the units in respectively primary and secondary control fractions explained below.
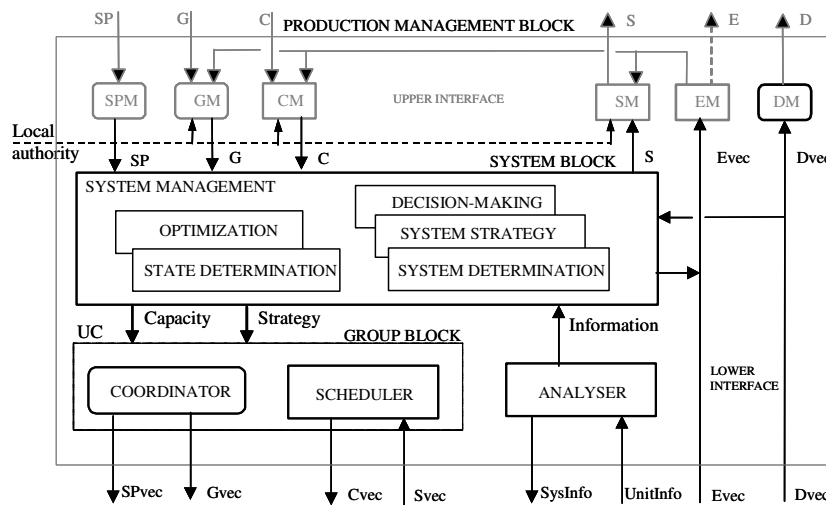
Figure 6.18: Production management block structure.

The group of functions described in this section is the central part for the operative system management of the DPS. The EMS-PM block and several unit functions represent the main methods for proper means of managing power units. The functional blocks are briefly described below:

- *System Block* (SB), has a main objective to allocate power units to ensure that available production resources are adjusted in most optimal way to fulfil the operational requirements. This is achieved by continuously supervising the power units' conditions and optimise according to available real-time information. Through information received from the system analysis and system strategy functions, the SB determines the system power unit configuration and transmits the requested capacity to be in operation to the unit commitment block.

- *System Analyse Function* (SAF); derives different types of operating states for the system based on the information received from each power unit via the OCI. This information is used by other functions in decision-making and evaluation of permissable conditions. The SAF include system fault diagnosis, which identifies faults before occurring, and determines their causes when already occurred. The system reserve determination is another analyse function that is used to always have the various reserves within their limits. As earlier described, the SAF continuously keep track on the current and estimated maximum power of each interconnected power unit in the DPS and thereby the total utilization degree. The developed functions for this purpose, the "CalculatePowerCapacity" and "AnalysePowerCapacity", are further described in Section 6.7.

- *System Strategy Function*; evaluates the system performance and determines which strategy to be used under present circumstances (types of power units available, number of active units and ready units, power demands, etc). Depending on number of operating modes in the function, the modes will be switched according to the pre-defined levels of the states, derived in the SAF. This function contains the core of how to operate the power units optimal under assumption that the needed information is accurate. The procedure is described in section 6.4.

- *Unit Commitment Function* (UC) is able to divide the power units in four separate control areas; the generation, exchange, storage and load management. Each of these blocks includes the USF and UCF blocks. The UC has also the ability to divide the power units in several groups and consequently assign them in different govern modes, which increase the control flexibility. This is actuated by assigning the "govern" and "set point" signals and further transmitting them to the controlled power units. If all power units or a group of units are meant to participate in the primary or secondary balance control, the UC distributes the management to the coordinator block, which have its own strategy for dividing the balance units in primary and secondary control groups.

- *Unit Commitment/Scheduler Function* (USF), is included in lower unit interface and performs time-sequenced decisions for automatic system operation, for example, unit scheduling of power units based on automated secondary control demands. The main task is to ensure sufficiently number of power units in operation to uphold the requested power capacity by the SB. The USF has specific queues for power units in ready, operation and off, in order to keep track on which unit that is in turn to start or get ready. Depending on system configuration the algorithm prevent units being off or

on too long and in case of shut down command, choose the one with longest operating time. Another important task for USF is to start and stop units according to predefined schedules due to agreements.

- *Unit Commitment/Coordinator Function* (UCF); belongs to the lower unit interface and is activated when the total or parts of the power units are assigned to participate in the primary or/and secondary control. The UCF is able to split the operating units in primary and secondary control algorithms according to the "start-up operation strategy" described in section 6.4. The primary and secondary control is used at all times in order to maintain the power balance of the DPS within the security limits on-line.
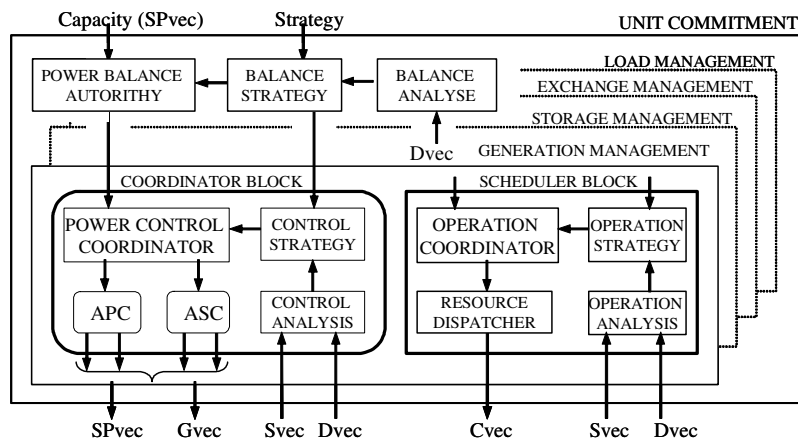
Figure 6.19: Unit commitment block structure.

The main algorithms of the UCF belong to the *power coordinator* block shown in Figure 6.19, which transmits the requested power capacity and strategy signal to the *automatic primary control* (APC) and *automatic primary control* (ASC) function blocks. The *control analysis* block determines the power capacity and state of connected resources in order to divide them in primary and secondary groups. The *control strategy* block at this level is responsible for providing the coordinator with proper information for the right selection between primary and secondary control both during normal and abnormal situations.

The APC block selects an adequate number of power units and distributes the govern signals to activate them in primary control mode. This is done according to the diagram in Appendix E1 in order to start up a system, momentarily adjust for fast power deviations and to cover a sudden loss of

the largest power unit in operation. In its simplest shape the power units in primary mode share the load in proportion to the power capacities by "droop control".

The ASC block distributes set point signals to all active power units in secondary control mode according to Appendix E2. The units in secondary control are thus responsible to ensure fast response to varying set point requirements. The secondary control function is able to divide the power units in different groups according to response time and capacity. For example, when closing up a requested set point, it is useful to have means to gradually switch faster (fine adjustment) power units in secondary mode to a group with less responsive power units (coarse adjustment), in order to decrease the participation of too many power units for fine adjustment.

Production exchange block structure

The production exchange block receives and processes the signals from the production management block and the plant system block. This control block finally determines which signals to be sent down to the plant system block and which ones to be sent back to the production management. The production exchange block works as an interface between all types of power units and the production management block. Therefore, the block is flexible concerning the number of entries and exits. For the generation, load and storage units, it manages two inputs and two outputs OCI interfaces. Regarding exchange units an additionally pair of input and output interfaces are managed as this is operated from two different DPSs. This is exemplified in the next chapter. The production exchange block structure shown in Figure 6.20 includes mainly the following software block structure.

- *Operational communication selector block* allocates communication interfaces and determines which authority that is allowed to control the unit. This is done with a command priority signal that each system has to send. The power system with the highest priority gets permission to control the power unit. But if any of the power systems command the unit to shut down, the unit has to shut down for security reasons. So even if one side has the authority to take command of over the unit, both sides have to agree about when the unit is allowed to start according to agreements and transaction identities. The block collects the information from all of the inputs. Almost all of the signals that are connected from side A are also going out from side B and vice versa. The exception from that rule is

information concerning the resource and the information concerning how much the unit is able to import and export. The import and export information is limited to the maximum capacity of both sides. The incoming signals from side B are coupled to the A side in a similar way.

- *Object Block*, continuously supervises the communication flow conditions and optimises according to available real-time information. Through information received from the unit analyse and strategy functions, the SB determines if the power unit should be in operation.

- *Security limiter block* limits the set point signal according to the units interconnected and their maximum operating ratings. The unit itself is protected by the limiter if authorized function tries to operate the unit with higher values than it is designed for. However, the signals from the production management block are never thought to send a higher set point command than the unit is able to manage.
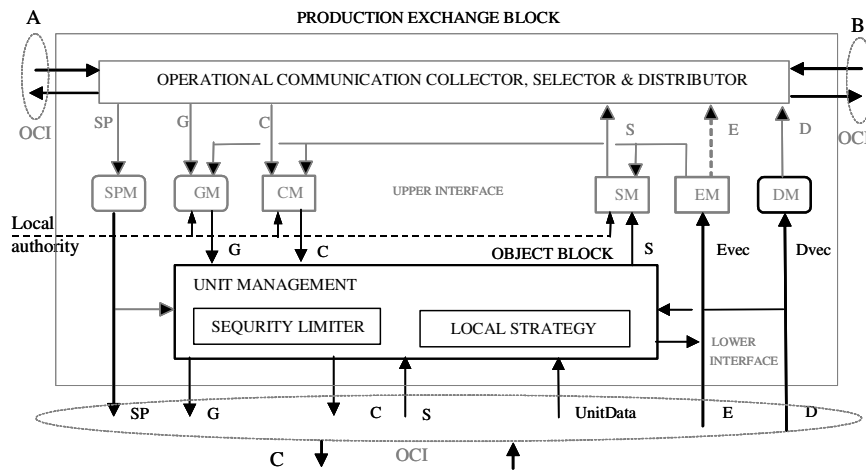
Figure 6.20: Production exchange block structure.

The lower interface is connected to the plant system block structure via the OCI that is described in the next section. All the OCI interfaces are managed by the interface manager, which is based on the same principles as for the resources manager that is thoroughly described in Chapter 7.

Plant system block structure

The plant system block structure is more or less applicable for all types of power plant units and in this section the structure is described for an individual wind turbine (WT) unit. WTs are autonomously controlled, which means that all-necessary control and safety systems for proper operation are self-contained. They don't depend on external control devices to perform their basic operations. In a WPP the WT units are controlled by the EMS-PM or wind power plant system controller (WPP-SC) for co-ordination with the electric network. In order to conduct operation and maintenance, a central system (SCADA) for supervision and operation of the WT units is essential, as the wind turbines typically are located remotely and at far distance from the operator. As earlier stated this requires limited and well-defined communication interfaces for adequate operation and control. The units should be delimited in such a degree that the system would be able to handle temporary communication interrupts.
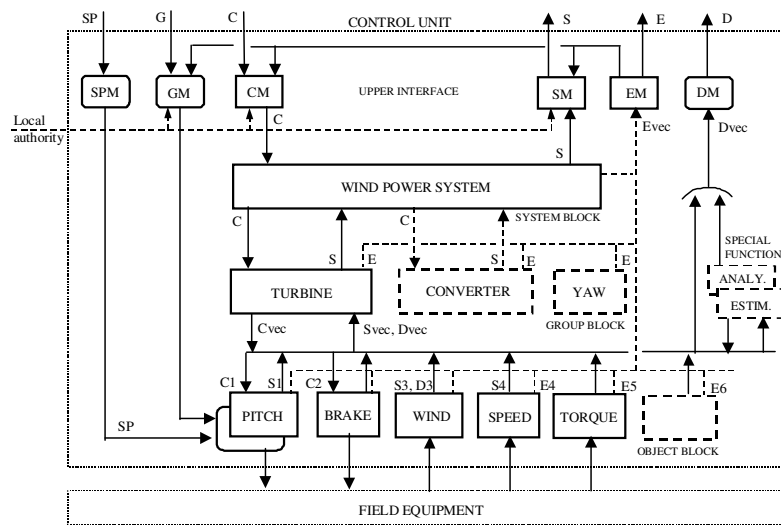
Figure 6.21: Wind turbine controller block structure.

The control and information signals for operating a WT unit can be seen in the upper part of Figure 6.21, which is a configuration example based on a gearless solution with pitch control. The upper interface is the same as for the WPP-SC and works correspondingly. The wind power system block is responsible for starting and stopping all underlying group blocks in a

correct sequence. The status signals from these group blocks are the only lower level signals to resolve condition for continuing the sequence at this system block level. The next layer of group blocks then handles and activates a pre-defined group of equipment to achieve a certain function. At this level the state changes according to environmentally changes, e.g. the wind speed decreases to a level out of chance for generating power. In the proceedings a selection of control blocks are described, which are a fractional part of all control blocks concerning the WT. However, by selecting the "wind power system block", "turbine group block" and "pitch control object block an understanding of each control level in the structure is attained.

- *Wind Power System Block* (WPSB), starts out from a main base sequence that mainly corresponds to the status signal. This is a general approach that works for the most cases of control as shown in Figure 6.22. Several sub sequences can then be extended from the states "activate", "deactivate", "start-up" and "shutdown". Normally, several start-up sequences are configured that start according to different conditions, e.g. the command signal choice normal "start" or "quick start".
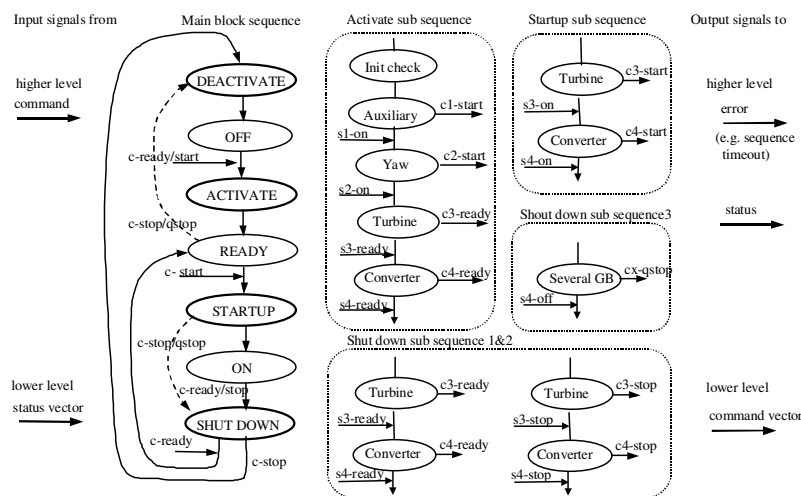
Figure 6.22: Wind power system block overview.

For the WT, internal checks and verifications of the control system will be started initially, and then auxiliary systems will be activated to be able to run the other process sections. After some initialising check controls have been performed, the yaw control functional group will get its command

control to turn the nacelle up towards wind. Some of the other group blocks will get ready signals that prepare them by certain initial check controls and activate necessary equipment to be ready for start commands or environmental conditions. The WT is in normal operational mode when reaching the "on" state. This implies that the WT is prepared for running different control modes according to the govern signal. The block will remain in this state until a new command or a failure occurs. When conditions for activating the "shut down" state is fulfilled, there are several sub sequences to stop the WT, e.g. by normal "stop" or "quick stop" command. In general, there might be an additional type of emergency shut down sequence that commands a so-called uncontrolled stop to the under laying group blocks.

When locking further down in the control block structure of the WTC, the group blocks are aimed to respond to a specific delimited process section as in the following group block description.

- *Turbine Group Block* (TGB), handles the mechanical part for generating. As shown in Figure 6.23 the input signals to this block are the command signal, wind speed, rotor speed, rotor torque and status signal for the controlled object blocks. As for the WPSB, a main sequence is used that is extended at certain states respectively. Once the main sequence is activated an initialisation check control for this particular process section is performed and all needed equipment are prepared for starting the turbine, e.g. the servo motors for pitch control and the brake. Suppliers have certainly different solutions in how to, for example, operate the brake. One solution is, as exemplified in the figure, to release it in ready state, which implies that the turbine would have negligible motions and no load on the brake. First when "start" conditions occur, the turbine blade will pitch according to the pre-defined control mode and accelerate. When reaching a specific level of rotor speed the turbine group block will turn over to the "on" state that will affect other group blocks to start as consequence.

The TGB will then be in "on" state until receiving a new command signal, failure, or reaching the limits of the wind or shaft speed. When a condition for shutting down the turbine occurs, one "shut down" sequence is activated depending on type of condition. In the low wind speed case the TGB enters the "ready" state after finishing the "shut down" sequence and automatically attempts to start if the condition for "start up" is reached. It is noticeable to mention that the WPSB in this case, still is in "on" state even if the turbine group block is in "ready" state. The WPP-SC is however aware of this and will not take any action unless commanded.

The conditions for state transitions are determined in special condition blocks that are placed first in each sequential software block, e.g. in the TGB case, the wind speed condition block continuously checks the predefined limits for setting the intended outputs. According to normal procedures, several conditions might then be considered for fulfilling the state sequence transition demand. The input signals are, as shown in Figure 6.23, only the status and data vector signals from the lower-level interface and the command signal from the higher-level interface.

For security reason, special safety function blocks are used to determine when a specific process section reaches predefined safety limits. Safety functions are generally assigned to dedicated control units, which require a high degree of isolation from other control and logic units. This is basically performed, by breaking out all affected functions in a separate control unit. In the TGB case, maximum limits for the shaft torque, wind and shaft speed are supervised. There are also limits for the maximum generating power and mechanical vibrations. The supervision function is enclosed in the safety software block that determines if the TGB must shut down.
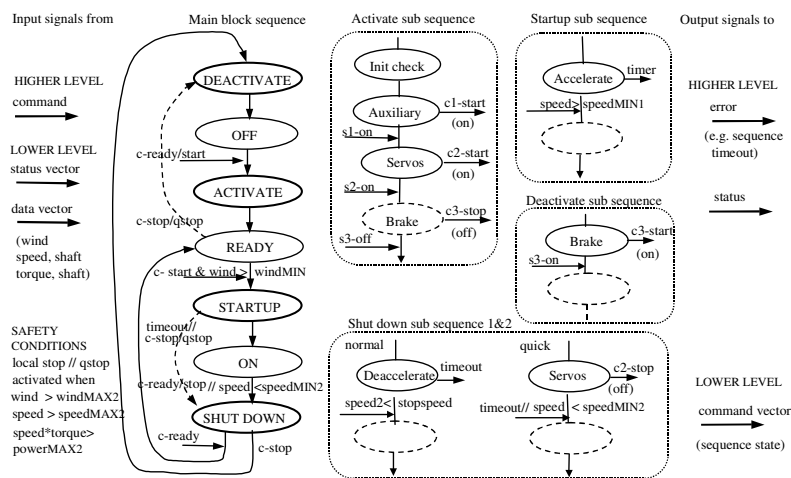
Figure 6.23: Turbine group block overview.

Remaining (functional) group blocks are design correspondingly to their specific interaction with the process and will operate in a similar way as previous explained. There are different types of object blocks for process interaction. The less advanced have only simple on/off logic internal blocks

to determine the state of the object block. In Figure 6.24 it is shown how a logical object block interacts with a general control object block.

The "logical object block" switches the "pitch control object block" on/off in a similar way as for a brake object block. Instead of actuating a brake the controller is activated. In the controller object block, means for handling the control modes are implemented by specific switches and a gain schedule for the controller.

- *Pitch Logical Object Block* (PLOB), has only the ability to turn on or off an object. The command assignment function block detects incoming command signal and determine if the object should be "on" or "off" by activating the SR flip-flop. Depending on signal philosophy the command signal could be exchanged with a "state"-signal of the superior group block, which implies that the object would have to know each state for on/off by itself. The advantage is that the group block would only transmit one signal to the lower object blocks instead of a vector with on/off signals for each object. The Govern management is also depending on the sequence state of the group block, which is another reason for using the state-signal.
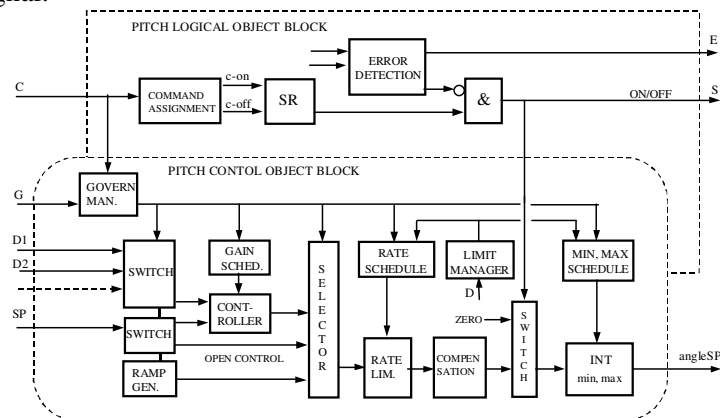
Figure 6.24: Pitch control object block overview.

- *Pitch Control Object Block*, includes normally a PI-controller with anti-windup and bumpless transitions between the different Govern modes. The Govern management block determines the control mode depending on the superior Govern signal and the state signal received from the *Pitch Logical Object Block*, e.g. the TGB might be a separate control unit with its local error management that interfere with the higher Govern signals. During normal operation the different control modes are applied at this block level.

The control mode switches several blocks to adjust for the specific purpose. Predefined parameters are scheduled for specific gains, rates and limits. The limit manager function block determine limit values depending on acceleration, deceleration, rotor speed, wind speed etc., according to the WTs present operational conditions. It is also possible to adjust different trajectories (ramps) with end targets and to choose between different feed back couplings. The controller structure is general and allows easy extension of the Govern signal by adding new parameters to the schedulers.

Regarding the different control modes proposed the signal flow between control blocks would need bi-directional capabilities, i.e. when switching from "balance" mode to "primary". This should not interfere with the control structure or prevent separation of different control object blocks. Wind turbines have, in general, specific control units for the turbine control and synchronisation equipment.
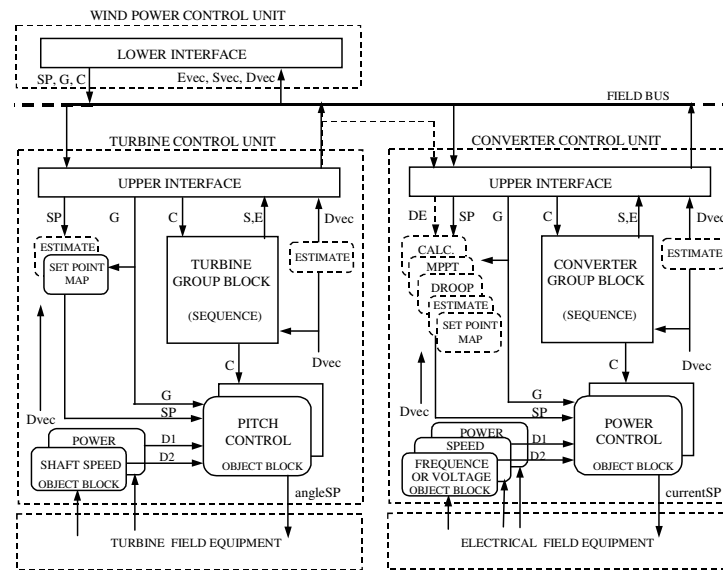
Figure 6.25: Modularised wind turbine controller structure.

As the control system is partly distributed the control blocks must have well-defined delimitations and functions as shown in Figure 6.25. By using the same communication interface for both external communication and internal process communication and having well-defined functions, the potential in easy decomposing of a certain function block become obvious.

Here the turbine group block and related object blocks have been taken out from the software structure shown in Figure 6.21 and enclosed with its own new upper unit interface. The same is applied for the converter group block, which then also become a self-govern control unit.

The turbine and converter controller units could handle several configurations depending on wind turbine control philosophy, which is supplier dependent. In the turbine control unit case the set point to the pitch control object block is determine by the set point map function block or from the upper set point signal according to the govern mode. The govern mode interacts with the set point map and pitch controller object, which selects the predefined settings, e.g. when switching from power control and speed control. Power estimations might also be used as basis for set point calculations and are in any case determined at this level for higher-level system analysis.

When the wind turbine participate in balance control the pitch angle is adjusted either by a predefined set point map or by using a feed back measured value internal or external regarding its own unit. The converter unit might have several configurations in this case. A common solution is power-speed mapping when connected to the grid. The converter control unit would then, in principal, be separated from the turbine control unit. When switching over in "primary" mode the converter control unit becomes the primary controller. Here the adjustable droop control is preferable, which enable the total load to be distributed between the generation units. This has been investigated and proven well suited in a modeled DC-system with several WT units [Karlsson and Svensson, 2002] [Karlsson and Svensson, 2003]. In "primary" mode, the turbine control unit switches automatically from power control to speed control due to the govern signal change.

In conclusion, the above configuration example shows the easiness in distributing several functions in the control software structure that basically is shaped in accordance to the control and information signals.

6.7 Functional software implementation

The functional block structure is partly implemented in the programming language C++ and partly in the simulation tool Dymola/Modelica. The block structure for the individual plant system control (power units) is static, meaning that no actual change of the implemented communication or functional block structure occur during operation. The DPS-SC is,

however, changing depending on the altering number of power units interconnected. This imply on a communication and functional structure that may change rapidly depending on DPS application. Such structures are dynamic and not possibly to implement unless utilizing dynamic programming techniques. This is but one reason using C++ integrated to Modelica. The other reason using the C++ structure is for the experimental verification, which is highly valued as the structure verification become more reliable. The C++ structure is described in Appendix B.

Interconnection to the information and communication system

The interconnection to the information and communication system is thoroughly described in the next Chapter and should only be seen as an infinitive system enabling automatic interaction by using the developed resource manager.
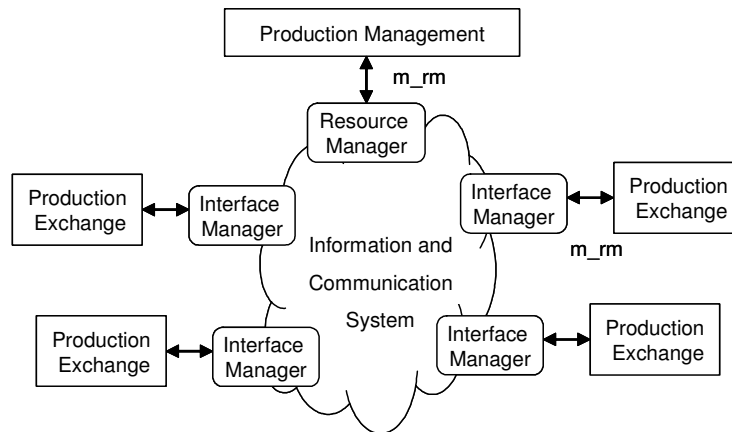
Figure 6.26: PM and PE module interconnection to the information and communication system.

As shown in Figure 6.26, the production management (PM) block is only connected to the resource manager handling all system power resource units. The reference pointer "m_rm" is used by several functions in the PM and the production exchange (PE) block is similar connected by the interface manager. The interface manager is based on the same software as the resource manager with exception of pointing at communication interfaces instead of power resources. That is why the reference name "m_rm" is the same for both the PM and PE block.

Production management module design

Most of the modules developed in the production management module are within the power domain. All automated functions are included in this module, which operates and coordinates the power units of the DPS. To be able to maintain a minimum safety level of the power system, a safety routine is included in the module that interacts with the security domain, which is sparsely developed. The safety routine has its focus on the voltage level and different actions are being made if the voltage level droop too much as the experimental test system is based on an internal DC transmission network.

Production Management
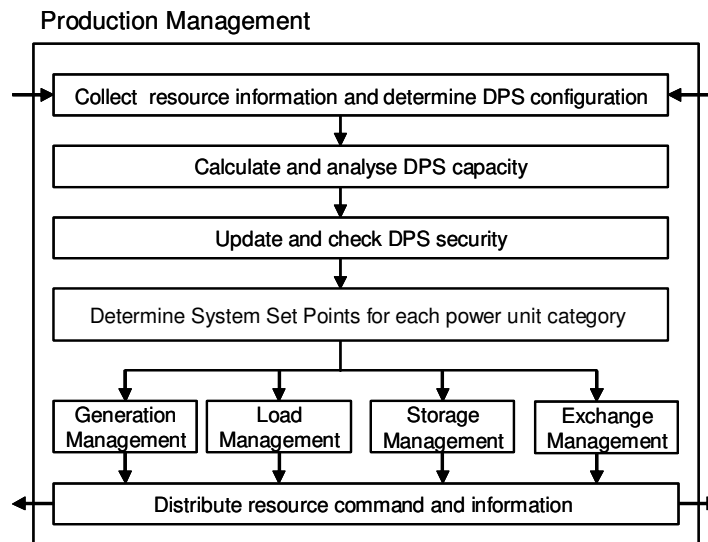
Figure 6.27: Functional flow scheme of the production management module.

All modules are processed by calling the update function separately for all modules and the functions are executed according to the functional flow scheme shown in Figure 6.27. These steps of executing are described separately in the following sections.

Step 1: Collect resource information and determine DPS configuration

In this first step all information from the resource manager "m_rm" is collected and the system configuration is determined by sorting all power

unit types in the "m_resourceNr" vector shown in the *getResourceNr* function below.

```
void ZProductionManagement::getResourceNr(void)
{
  for (int i=0; i<PRT_SIZE; i++)              // PRT = Power Resource Type
    m_resourceNr[i] = 0;                      // reset counter
  if (m_rmOK) {
    rSize = m_rm->getResourceSize();    // number of resources at this moment
    for (int rID=0;rID<rSize;rID++) {
        if ( PRT_GEN == m_rm->getValue(rID, PR_TYPE) )
          m_resourceNr[PRT_GEN]++;
        if ( PRT_LOAD == m_rm->getValue(rID, PR_TYPE) )
          m_resourceNr[PRT_LOAD]++;
        if ( PRT_STOR == m_rm->getValue(rID, PR_TYPE) )
          m_resourceNr[PRT_STOR]++;
        if ( PRT_EXCH == m_rm->getValue(rID, PR_TYPE) )
          m_resourceNr[PRT_EXCH]++;
      ………………
  if ( m_resourceNr[PRT_GEN] > 0 )   genOK = true;
  if ( m_resourceNr[PRT_LOAD] > 0 )  loadOK = true;
  if ( m_resourceNr[PRT_STOR] > 0 )  storOK = true;
  if ( m_resourceNr[PRT_EXCH] > 0 )  exchOK = true;
} } }
```

The resource vector include the number of each power unit type (GENeration, LOAD, STORage and EXCHange units) and is then used in several functions where the number of respective power unit type is needed. For later determination and analysing of the system configuration, the genOK, loadOK, storOK and exchOK are assigned.

In the "CalculatePowerCapacity" function all data and information concerning power capacity for each power unit type is determined, e.g. how much is the power unit currently producing, the maximum and minimal power.

```
void ZProductionManagement::calculatePowerCapacity(void)
{
  ……
  if ( m_resourceNr[PRT_GEN] > 0 )
    pGenerationCapacity();
```

```
  if ( m_resourceNr[PRT_LOAD] > 0 )
    pLoadCapacity();
  if ( m_resourceNr[PRT_STOR] > 0 )
    pStorageCapacity();
  if ( m_resourceNr[PRT_EXCH] > 0 )
    pExchangeCapacity();
  ......
}
```

The collected data is used to calculate several system parameters and capacity levels that are used to decide the operation mode and set points for each power unit category. Parameters that are calculated are among others:

- Maximum capability: This parameter gives information about how much a certain group of power units (generation, load, storage and exchange) can provide.

- Operating Reserve: Provides additional power capacity that can be used to serve customer demands.

- Raise Regulating Capability: Gives information about how much more capability that can be used for primary control.

- Falling Regulating Capability: Gives information about how much capability that currently is used for primary control.

- Current Generation: Capacity that currently is used.

- Minimum capability: The minimal capacity that the units need to be operating at while they are on.

The capacity calculation is very similar for all of the four power unit type categories and the "pGenerationCapacity" function is here briefly described. In order to get all capacity levels according to Appendix D, the state of operation and control mode are used for searching. The state of operation could be "off", "ready" and "on" and the control modes could be "drop", "pcontrol", "pmax", "pmin" and "intermediate" (not controllable). In addition, the minimum, current and maximum power is requested. In total this means 45 different assignments for calculating the systems generation capacity. For example, the first assignment in the function below is the "pGenOnMax1" that gets the maximum calculate power possible for all connected generation units that are "on" and in "drop" control mode.

```
void ZProductionManagement::pGenerationCapacity(void)
{
  // Generation Regulating Capability and Capacity
  pGenOnMax1 = getAttributeSum(GEN, ON, VDROOP, P_MAXC);
  pGenOnCur1 = getAttributeSum(GEN, ON, VDROOP, P_CUR);
  pGenOnMin1 = getAttributeSum(GEN, ON, VDROOP, P_MINC);

  pGenRdMax1 = getAttributeSum(GEN, READY, VDROOP, P_MAXC);
  pGenRdCur1 = getAttributeSum(GEN, READY, VDROOP, P_CUR);
  pGenRdMin1 = getAttributeSum(GEN, READY, VDROOP, P_MINC);

  pGenOfMax1 = getAttributeSum(GEN, OFF, VDROOP, P_MAXC);
  pGenOfCur1 = getAttributeSum(GEN, OFF, VDROOP, P_CUR);
  pGenOfMin1 = getAttributeSum(GEN, OFF, VDROOP, P_MINC);
  …………………………
  // Assign all capability levels by the power matrix
  pMinPlantCapability =  pGenOnMin1+pGenRdMin1+pGenOfMin1+
                  pGenOnMin2+pGenRdMin2+pGenOfMin2+
                  pGenOnMin3+pGenRdMin3+pGenOfMin3+
                  pGenOnMin4+pGenRdMin4+pGenOfMin4+
                  pGenOnMin5+pGenRdMin5+pGenOfMin5;
  ………………………..
  // Assign the generation capacity vector m_gCap
  m_gCap[CLI_PMAX6] = pMaxPlantCapability;
  m_gCap[CLI_PMAX5] = pMaxCapability;
  m_gCap[CLI_PMAX4] = pMaxPlusSlowCapability;
  m_gCap[CLI_PMAX3] = pMaxPlusFastCapability;
  m_gCap[CLI_PMAX2] = pMaxSynchCapability;
  m_gCap[CLI_PMAX1] = pMaxRegCapability;
  m_gCap[CLI_PCUR0] = pCurGeneration;
  m_gCap[CLI_PMIN1] = pMinRegCapability;
  m_gCap[CLI_PMIN2] = pMinSynchCapability;
  m_gCap[CLI_PMIN3] = pMinMinusFastCapability;
  m_gCap[CLI_PMIN4] = pMinMinusSlowCapability;
  m_gCap[CLI_PMIN5] = pMinCapability;
  m_gCap[CLI_PMIN6] = pMinPlantCapability;
  m_gCap[CLI_EMAX1] = 0.0;  // Only assigned for storage and exchange units
  m_gCap[CLI_ECUR0] = 0.0; // Only assigned for storage and exchange units
  m_gCap[CLI_EMIN1] = 0.0;  // Only assigned for storage and exchange units
}
```

After calculating all the 45 values a power matrix including these values assign all the capacity levels according to Appendix D, which for the generation units include 13 levels and consequently 13 power matrixes in the software code. The last three levels are used only for storage and exchange units. The generation capacity levels are then assigned to the "m_gCap" vector that is used in several functions. The same procedure is then conducted for the load, storage and exchange units, which assign respectively capacity vector, m_lCap, m_sCap and m_eCap. After the execution of these calculations, all needed information is received for further system analyses.

Step 2: Analyse and calculate DPS capacity

In this step, analyses and calculations are made in order to determine if the actual DPS configuration is able to operate. The "analysePowerCapacity" function determines the type of power units connected to the DPS. The information is used to decide the set points for the different power unit types. This part of the program also determines needed levels of the safety zones for the power units in primary and secondary. In order do so the largest unit, which is operating as a generator, is found and determines how large the upper safety zone (SZ) A1 should be. In the same way, the lower safety zone A2 is determined by checking the capacity of the larges load unit.

```
void ZProductionManagement::analysePowerCapacity(void) {
    …………..
    // power units operating as sources
    largestGenOn   = findLargestByCondition(GEN, ON, ALL, P_CUR );
    largestStorOn  = findLargestByCondition(STOR, ON, ALL, P_CUR );
    largestExchOn  = findLargestByCondition(EXCH, ON, ALL, P_CUR );

    // power units operating as sinks
    largestLoadOn  = findSmallestByCondition(LOAD, ON, ALL, P_CUR );
    smallestStorOn = findSmallestByCondition(STOR, ON, ALL, P_CUR );
    smallestExchOn = findSmallestByCondition(EXCH, ON, ALL, P_CUR );
    ……………
    reserveUpp[3] = {largestGenOn, largestStorOn, largestExchOn};
    reserveDown[3]= {largestLoadOn, smallestStorOn, smallestExchOn};
    m_systemLimits[RESERVEUPP] = maxV(reserveUpp,3);
    m_systemLimits[RESERVEDOWN] = maxV(reserveDown,3);
}
```

Finding the largest source power units is done by the "findLargestByCondition" function that searches the, at the moment, largest generation, storage and exchange unit operating as a source. Correspondingly, the "findSmallestByCondition" functions searches the largest load, storage and exchange unit operating as a sink. The naming "smallest" may be confusing but refer to the largest negative power value. The "m_systemLimits" vector is then assigned by the largest source and sink unit at the moment.

Step 3: Update and check DPS security

In step 3 the "SecurityUpdate" function primarily checks the voltage level. If the voltage level is to low, no unit except for the ones in droop mode is allowed to operate in order to prevent system collapse. In this function, the maximal export and import power of the system is also calculated and distributed to the affected power units within the DPS, which is shown in the source code example below. This is done in order for the power units to know the power limits of the system, which is especially important for the exchange unit. The exchange unit is able to inform the adjacent DPSs of how much power that can be provided to the different sides that prevent one side from draining the other side from power without permission or authority.

```
void ZProductionManagement::securityUpdateSequence(void)
{    ............
    if ( rSize >= 1 )  {
        // get maximum export and import capability for the DPS
        pExp = m_gCap[CLI_PMAX5]+m_sCap[CLI_PMAX5];
        pImp = m_lCap[CLI_PMAX5] + m_sCap[CLI_PMIN4];
    ............
    for (int id=0 ; id < rSize ; id++ ) {
        // inform all power units
        m_rm->setValue(id, OSIOUT_P_MAXC, pExp);
        m_rm->setValue(id, OSIOUT_P_MINC, pImp);
    ............
}  }
```

This is the actual trigger that may disconnect adjacent DPSs. For example, if adjacent DPSs is interconnected via an exchange unit and the unit suddenly needs more power than the DPS can manage, the export will be limited or reduced to zero depending on DPS strategy.

Step 4: Determine system set points for each power unit category

In this step the "DecideSetpoints" function is used where the major calculations are made and roughly divided into two parts. The first part manages the *primary control* and decides which and how many power units that should be assigned in droop control. The second part, secondary control, manages all of other power units not participating in primary control mode. This calculates the power capacity that has to be added by the source units to support the sink units with requested power capacity. Although, if the generation units are not able to support the load units by them selves, the exchange units and the storage units participate and supply the extra power. If the generation units are able to produce much more power then the load units' request, the system tries to store and export the power surplus. This function does not address individual power units. The set points distributed to the unit commitment functions are lumped as total set points divided in each category of power units.

The primary control part starts out from the source code below that sets the conditions for searching primary resources and then search for the number of possible power units (generation, storage and exchange units) that are able to participate.

```
……………….
// set conditions for searching possible primary power units
condIndex[5] = {RTYPE, RSTATUS, GOV_STATUS, RPRIORITY, P_MAXC};
condValue[5] = { GEN, ON, VDROOP, 0, 0};

// search possible primary resources and their number
if ( genOK && ……..) {
  condValue[0] = TYP_GEN;
  rNumber = getResourceNrByCondition(condIndex, condValue, 3);
 }
if (storOK && ……)  {
   ……….
if (exchOK && ……) {
 ……….
if ( rNumber >=2 )
   enableSecondaryControl = true;

if (((genOK || genOK && (exchOK || loadOK || storOK)) || ( exchOK &&
          (loadOK || storOK)) || (storOK && loadOK)) && rNumber == 0)
```

```
    addPrimaryControl = true;  // try to electrify the network

if ( (genOK && (exchOK || loadOK || storOK)) ||( exchOK
              && (loadOK || storOK)) || (storOK && loadOK)) && rNumber > 0)
{
    pGenOnMaxDroop = getAttributeSum(ALL, ON, VDROOP, P_MAXC);
    pGenOnCurDroop = getAttributeSum(ALL, ON, VDROOP, P_CUR);
    pGenOnMinDroop = getAttributeSum(GEN, ........ P_MINC);
    pGenOnMinDroop -= getAttributeSum(STOR, ...., P_MINC);
    pGenOnMinDroop -= getAttributeSum(GEN, ......, P_MINC);

    if (pGenOnMaxDroop <= (m_systemLimits[SL_RESERVEUPP] +
            m_systemLimits[SL_RESERVEDOWN] + pGenOnMinDroop))
        addPrimaryControl = true;
}
...............
```

The algorithm first checks if there are any primary resource units activated and starts electrifying the network if not already done. If more then two primary units are activated the secondary control gets permission to starts its sequence. As the DPS is started and more than two primary resources are available, the algorithm continuously check the system limits and adjusts according to them by adding or removing primary control resources.

```
//Function to provide primary control to adjacent DPSs.
condValue[0] = SA_TYP_EXCH;
.......
Vector* rIDvec = getResourcesByCondition( condIndex, condValue, 1);
if ( rIDvec !=NULL && !lowVoltage )
{
    id = rIDvec->elementAt(0);
    if ( export =  m_rm->getValue(id, OUT_P_MAXC) >= exportLimit )
        addExternalPrimarControl = true;
    else
        addExternalPrimarControl = false
}......
```

At this level, the permission for providing primary control to adjacent DPSs is authorized. The source code example above shows the principle, which is called upon if at least one adjacent DPS ask for primary control

services. This searches for the interconnected exchange units and compare the maximum requested power with the possible system export. If the DPS consider itself able to aid, the addexternalPrimaryControl trigger is assigned true.

The secondary control part in step 4 is implemented according to the partial source code below, where the assignment of each power unit category is assign zero at the beginning.

```
void ZProductionManagement::decidePowerSetpoints(void)
{
  if ( m_rmOK ) {
    m_setpoints[SP_GEN]  = 0;
    m_setpoints[SP_LOAD] = 0;
    m_setpoints[SP_STOR] = 0;
    m_setpoints[SP_EXCH] = 0;
  …………
  // get needed information from actual system analysis and primary control
  pGenOnMaxDroop = getAttributeSum(ALL, ON, VDROOP, P_MAXC);
  pGenOnCurDroop = getAttributeSum(ALL, ON, VDROOP, P_CUR);
  PGenCurrent = m_gCap[CLI_PMAX5] - pGenOnMaxDroop;
  powerForDroop = (pGenOnMaxDroop - m_systemLimits[SL_RESERVEUPP]
                                  + m_systemLimits[SL_RESERVEDOWN])/2;

  //Calculate secondary control setpoints.
  // DPS configuration A
  if (genOK && loadOK && enableSecondaryControl)
  {
    if (PGenCurrent >= -m_lCap[CLI_PMAX5] - powerForDroop)
        m_setpoints[SP_GEN] += -m_lCap[CLI_PMAX5] - powerForDr
    else
        m_setpoints[SP_GEN] += PGenCurrent;
  }
  // DPS configuration B
  if (genOK && storOK && enableSecondaryControl)
  {
    if (((m_gCap[CLI_PMAX5] - m_systemLimits[SL_RESERVEUPP] ) > -
    m_lCap[CLI_PMAX5]) && (m_sCap[CLI_EMAX1] > m_sCap[CLI_ECUR0]))
    {
      if ((PGenCurrent + m_lCap[CLI_PMAX5]) –
              m_systemLimits[SL_RESERVEUPP] >= m_sCap[CLI_PMIN4])
```

```
          m_setpoints[SP_GEN] += m_sCap[CLI_PMIN4] - powerForDroop;
      else
          m_setpoints[SP_GEN] += PGenCurrent;
    }
    if ((m_gCap[CLI_PCUR0] - pGenOnCurDroop + pGenOnMaxDroop –
                                powerForDroop + m_lCap[CLI_PMAX5]) > 0)
            m_setpoints[SP_STOR] = -(m_gCap[CLI_PCUR0] –
                pGenOnCurDroop + pGenOnMaxDroop - powerForDroop
                + m_lCap[CLI_PMAX5]);


        if ((m_gCap[CLI_PCUR0] - pGenOnCurDroop + pGenOnMaxDroop –
            powerForDroop + m_lCap[CLI_PMAX5]) >= m_sCap[CLI_PMIN4])
        m_setpoints[SP_STOR] = - m_sCap[CLI_PMIN4];
} } }
// DPS configuration C, D , E, etc
if ( next configuration …etc )
……………
……………
if (loadOK && ……) //
{
    storageTemp = 0;
    exchTemp = 0;
    genTemp = m_gCap[CLI_PCUR0] - pGenOnCurDroop + pGenOnMaxDroop
                                – m_systemLimits[SL_RESERVEUPP];


    if ( m_sCap[CLI_PCUR0] > 0 && storOK )
        storageTemp = m_sCap[CLI_PCUR0];
    if ( m_eCap[CLI_PCUR0] > 0 && exchOK )
        exchTemp = m_eCap[CLI_PCUR0];


    m_setpoints[SP_LOAD] = min2( ( genTemp + storageTemp + exchTemp),
                                        m_lCap[CLI_PMAX5] );
}
……………
```

The DPS available secondary control resources are thereafter determined by mainly using the system capacity information and the primary control resources deployed. With this information as basis, the function continuously determines the lumped set points for the four power unit categories as shown. At least seven possible DPS configurations are

checked that calculates these set points, which later on are distributed to respective unit commitment category. At the end of this function the lumped set point for the controllable loads are assigned, which is determined by summarizing the available source units. This is then compared with the total requested demand of the load units.

Step 5: Unit commitment

The unit commitment is firstly divided in the four power unit categories and secondly each of them is divided in a primary and secondary control management. The management of these is very similar and the generation management function is here more thoroughly described.

The "GenManagement" function has as its primary assignment to search and command individual generation units according to the lumped set point delivered from the DecideSetpoints module. The function determines which generator to be operated and that fulfill the requirement. The selection of individual generation units is mainly decided by the priority and capacity of the unit. All of the generators are assigned with a resource priority indicating the significance of the unit. The lower priority numbers the more significant. The generators with the lowest priority are the one that is started first.

The primary control part of the "GenManagment" function gets its requests from the superior function "decideSetpoints" that trigger the signal addPrimaryControl if needed. This trigger activates the primary control function as shown below by first activating generation units in state "ready". If the "addPrimaryControl trigger still is activated, available storage units in ready is activated and thereafter the exchange units.

```
………………
if ( addPrimaryControl )
{
  condValue[0] = TYP_GEN;
  condValue[1] = CMD_READY;
  addPrinaryControl = setSourceToDroop(condIndex, condValue, Voltage);

  if ( addPrimaryControl ) {
      condValue[0] = TYP_STOR;
      condValue[1] = CMD_READY;
      addPrimaryControl = setSourceToDroop(condIndex,condValue, Voltage);
```

```
    }
  if ( addPrimaryControl ) {
      condValue[0] = TYP_EXCH;
      condValue[1] = CMD_READY;
      addPrimaryControl = setSourceToDroop(condIndex,condValue, Voltage);
    }
  if ( addPrimaryControl )  {
      condValue[0] = TYP_EXCH;
      condValue[1] = CMD_START;
      addDroop = setSourceToDroop(condIndex,condValue, Voltage);
}
```

…………………

The actual procedure in finding the units is done in the "setSourceToDroop" function that searches the units by priority order and power capacity as shown in the partial source code below.

```
bool    ZProductionManagement::setSourceToDroop(int    condIndex[],    int
condValue[], int nominalVoltage)
{
    addDroop = true;    priority = PRI_HIGH;   dir = DIR_IMPORT;
    rNumber = getResourceNrByCondition(condIndex, condValue, 2);
    …………………….
    if (rNumber > 0) {
      condValue[2] = findMinValue(RPRIORITY, priority, condIndex,
                                                condValue);
      id = getResourceByCondition(condIndex, condValue, 3);
      if ( id >= 0 )  {
       m_rm->setValue(id, COMMAND, CMD_START);
       m_rm->setValue(id, GOVERN, GOV_VDROOP);
       m_rm->setValue(id, _SETPOINT1, nominalVoltage);
       m_rm->setValue(id, DIRECTION, dir);
       addDroop = false;
    } }
    …………………..
    return addDroop;
}
```

The conditions for searching are set by the arguments of the function and the resource manager "m_rm" is utilized for operation of the individual power unit.

The secondary control part of the "GenManagment" always tries to achieve the lumped set point task from the superior "decideSetpoint" function. The search procedure is mainly done in similar to the primary control part regarding priority. However, if more then one generator with the same priority number is found, the power is divided between them with respect to their capacity. Meaning that if there are two generators that should split a power set point between them and one of them is twice as large as the other. The larger one will also produces twice as much power in comparison to the smaller one.

```
…………………………
powerToBeIncreased = m_setpoints[SP_GEN] - SPgen;

    if ( powerToBeIncreased > DELTA_LIMIT )
    {
       condIndex[5] = { RTYPE, CSTATUS, GSTATUS, RPRIORITY, P_MAXC};
       condValue[5] = { GEN, ON, PCONTROL, 0, 0};
       priority = findMinValue(RPRIORITY, PRI_HIGH, condIndex, condValue,
1);
       for (int i = 0; i < m_resourceNr[GEN] && powerToBeIncreased > 0; i++) {

         condValue[3] = priority;
         condValue[1] = CMD_ON;
         powerToBeIncreased = turnOnSetpointAsCondition(condIndex,
                                          condValue, powerToBeIncresed);
         if ( powerToBeIncreased] > DELTA_LIMIT ) {
           condValue[1] = CMD_READY;
           powerToBeIncreased = turnOnUnits(condIndex, condValue,
                                              powerToBeIncresed );
         }
         if (powerToBeIncreased] > DELTA_LIMIT)) {
            condValue[1] = CMD_OFF;
            powerToBeIncreased = turnOnSetpointAsCondition(condIndex,
                                        condValue,powerToBeIncresed);
         }
         priority++; // priority significance decreases with higher figure
    }
…………………..
```

As shown in the partial source code above, the new lumped setpoint is compared to the actual "SPGen". In case of a difference, indicating on that

power generation is to be increased the algorithm starts with increasing power set points in already activated generation units. If the trigger "powerTobeIncreased" still is higher than the limit, the units in "ready" state are activated and if that is not enough, units not activated become activated. When to power instead is to be decreased the algorithm is very much the same but reverse. The units with lowest priority and in secondary control are first down regulated towards its minimum if needed.

………………………
powerToBedecreased = SPgen - m_setpoints[SP_GEN] ;

if (powerToBeDecreased >DELTA_LIMIT)
    {
      condIndex[5] = { RTYPE, CSTATUS, GSTATUS, RPRIORITY, P_MAXC};
      condValue[5] = { GEN, ON, PCONTROL, 0, 0};
      priority = findMaxValue(RPRIORITY, lowestPriority, condIndex, condValue, 1);
      for (int i = 0; i < m_resourceNr[PRT_GEN] && powerToBeDecreased>0; i++)
      {
          condValue[3] = priority;
          //decreases resources in PCONTROL towards PMIN
          condValue[2] = GOV_PCONTROL;
          powerToBeDecresed = turnOffSetpointAsCondition(condIndex,
                                    condValue, powerToBeDecresed);
          //decreases resources in PMAX towards PMIN
          if (powerToBeDecreased>0) {
              condValue[2] = SA_GOV_PMAX;
              powerToBeDecresed = turnOffSetpointAsCondition(condIndex,
                                      condValue, powerToBeDecresed);
         }
          //Turn off resources in PMIN
          if (powerToBeDecreased>0) {
              condValue[2] = SA_GOV_PMIN;
              powerToBeDecresed = shutOffUnits(condIndex, condValue,
                                    powerToBeDecresed);
         }
          priority--;
      }
}
……………………..

If the power reduction is not sufficient, the generation units in maximum mode are next to be operated. These units are controlled towards their minimum power level if necessary. The last action for reduction is to shout down the units. As the priority significance increase with lower figures the "priority" variable decreases after each search according to priority. The flow scheme for this algorithm is shown in Appendix D.3.

The function "TurnOnSetpointsAsConditions" is the actual function dividing and distributing the generation to be achieved. Dependent on the conditions sent by the arguments, the function manages resources that are operating in different state. The partial source code below shows how the search algorithm among resources in "ready" state is implemented.

```
Double ZProductionManagement::turnOnSetpointAsCondition(int
condIndex[], int condValue[], double powerToBeIncresed)
{
   rNumber = getResourceNrByCondition( condIndex, condValue, 4);

   if ( rNumber > 0 && condValue[1] != CMD_READY ) {
      ZIntegerVector* rIDs = getResourcesByCondition( condIndex, condValue, 4 );
      pMax = getValueSum( P_MAXC, rIDs);
      pCur = getValueSum( P_CUR, rIDs);
      product = (pCur + powerToBeIncresed)/pMax;
      for (int j = 0; j < rIDs->size(); j++ ) {
         id = rIDs->elementAt(j);
         if ( product < 1 )
             SP = (getResourceValue(id, P_MAXC))*product;
         else
             SP = getResourceValue(id, P_MAXC);

         m_rm->setValue(id, COMMAND, CMD_START);
         m_rm->setValue(id, GOVERN, PCONTROL);
         m_rm->setValue(id, OSIOUT_SETPOINT1, SP);
         m_rm->setValue(id, OSIOUT_DIRECTION, IMPORT);
      }
      if ( product < 1 )
          powerToBeIncresed = 0;
      else
          powerToBeIncresed -= pMax - pCur;
      }
} }
```

The first step includes finding all units and storing their identities in the "rIDs" vector. The total maximum possible power to generate and current power are calculated in order to determine if the requested power increase can be handled directly by those resources, which imply on the "product" value in-between zero and one. Thereafter the individual set points are distributed to each individual resource for this priority category assign by the superior function calling the "TurnOnSetpointsAsConditions". If these resources cover the demand the returning variable "powerTobeIncreased is set to zero.

The "LoadManagement" function is similar to the genManagement but instead determines which load units that will be activated respectively deactivated. The one with highest priority is even here decided by a priority number, which works in the same way as for the generation units. The startup and shut down sequence is also implemented in the same way.

The "StorManagement" and **"ExchManagement"** functions are also similar to the genManagement and the program sequences determine which power units that fulfill the set points demands for the storages and the exchange units. Except for the command, govern and set point signals an additional signal "direction" is also used for these units. This signal order the units in which power flow direction the unit should have, export or import.

Production exchange model design

A flow scheme for the production exchange block is shown in Figure 6.28 that illustrates how the program is working for the exchange unit communicating with two adjacent distributed power systems and directly to the power unit. In the selector block the program decides which one of the distributed power systems that is allowed to control the converter. This is done with a command priority signal requested from each DPS. The power system with the highest priority gets permission to control the power unit. But if any power system side instruct the power unit to shut down, then the power unit has to shut down. Thus even if one side has the authority to take command of how the power unit is supposed to operate, both sides have to agree about when the power unit is allowed to start.

The limiter is, if needed, limiting the set point signal down to the converters maximal operating value. This is done for security reasons. It should not be possible to run the power unit with higher values than designed for. The set point command from the production management is

never supposed to send a higher set point command than the power unit can manage. The "distribute command and information" part manages the signals that are sent back to the production management by mixing and cross coupling the signals. First, it collects the information from all of the inputs. Almost all of the signals that are received from side A are also going out from side B and vice versa.
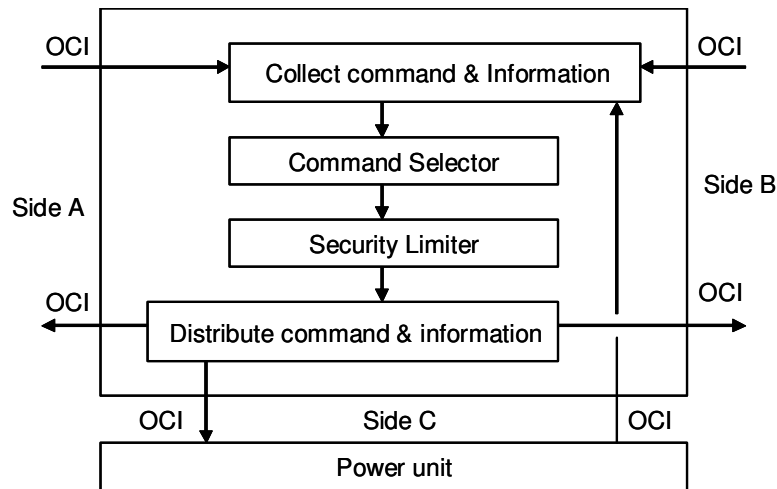
Figure 6.28: Functional flow scheme for the production exchange module.

The exception from that rule is information concerning the resource and the information about how much the power unit is able to import and export. The import and export information is limited to the maximal capacity of both sides. For example if side A can export 1000W but side B can only import 700W the import signal on the output of side B will be 700W. Corresponding limitation to the export signal is being implemented. The signals coming in from side B is coupled to side A in a similar way. The production exchange block is general and work for all types of power units. Therefore, it is very flexible concerning the number of entries and exits. For the generators, loads, and storage units, it only has two inputs and two outputs. The program is able to handle that situation as well by setting suitable initial values on the side not connected to any power system.

6.8 Concluding remarks

The basic idea of this chapter is to describe on advanced coordination functions enabling autonomously operation of a DPS. In order to achieve autonomous operation several issues have been addressed where the functional structure is fundamental from a control point of view. The implemented structure of the DPS is distributed and not restricted in system configurations, which can handle any composition of generation, load, storage and exchange units, and where the procedures remain the same. The coordination functions manage situations whereby the environment of the system is changing dynamically, e.g. power units connecting or disconnecting at unknown and irregular periods. The modular algorithms applied give simple means for extension by well-defined system blocks and interfaces. The implementation is primarily solved by adopting dynamic programming of algorithms and resource management that always enables optimal operation during transformations in the system configuration. The modular algorithm rapidly decomposes complex decision making processes into search paths that seek desired solutions by assigned priorities. The modular algorithms are made possible by using the general resource manager described in next chapter. The structure and functions have been validated mainly through software blocks implemented in C++ connected to the developed library "powerFlow" in the Dymola/Modelica simulation tool, which is thoroughly described in the Chapter 8.

Chapter 7

DPS information and communication

The Chapter proposes a uniformed information and communication structure for real-time operational that provides "plug-and-produce" capabilities. The purpose is to specify such structures, with consideration in how RES can be used to improve power system performance and to enable autonomous system management within a DPS. The structure provides means for condensing the necessary information for future needs and requirements on operation of new large power plant units based on RES. RES units connected to the power system will most likely be able to provide any ancillary service as for conventional power plant units. The information structure facilitates the utilization of new services from RES, e.g. wind power plants. With well-defined interfaces, new power units will be able to connect to an existing information structure and automatically adapt to the system. The information structure has been verified through software blocks implemented in C++ modules and connected both to the Dymola/Modelica simulation tool and the experimental set-up.

7.1 Introduction

The various ways of information and communication and information quantity are enormous and not always for good. Society has already crossed the point when the possibilities in receiving information almost always are too much depending on management. Actors or systems not filtering or condensing the available quantity of information easily become overloaded. Structured uniformed interfaces with limited information exchange are one solution condensing data. However, this is not always

easily as various actors and systems have different functionalities and consequently different needs and demands. Basically the communication system assists the operators, users and other interested parties in performing their tasks by provision of services [Schwarz, 2001]. The system is open in the sense that "anyone shall be able to get information on anything from anywhere", once they have authorization to the system. The system, however, is adapted to individual users and services provided accordingly by means of configurations, set-ups etc. Faults in the communication system should not cause malfunction of an individual power unit. The system is designed in a way that faults of a subsystem interfere as little as possible with functions of the communication system as a whole.
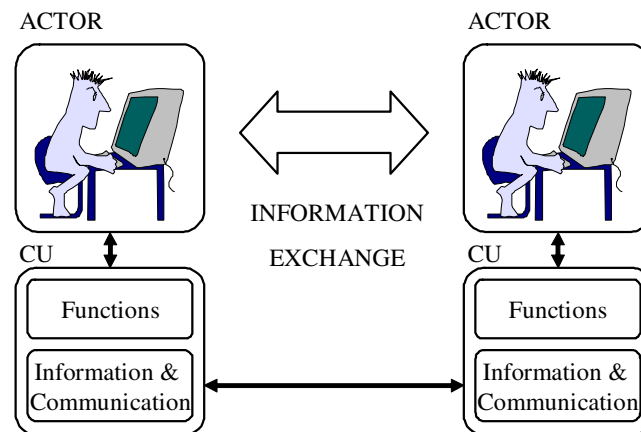
Figure 7.1: Basic information exchange.

The DPS unit represents one or more power units. The aspects of the power units defined in this part cover the information and information exchange between control units within the DPS. The control units providing information and their information exchange are shown in Figure 7.1 and include primarily the following entities:

- *Actors* that exchange information with computer control units (CU) to perform a communication function

- *Computer control units* including a "functional" block and "information and communication" block that exchange information internally

- *Information exchange* services that exchanche information with specific data types between external "information and communication" blocks

Maintaining a well working information system requires uninterrupted interacting between these entities and the information levels, within a DPS unit. This requires a communication link between overall control units and the individual power unit controller in accordance with [IEC 61850, 2003].

The overall control unit for this work is the EMS of a DPS conducting an overall governing of the power unit output and the electric network capability. Several functions are needed in managing the communication system and and at the same time achieve somtinh close to "plug-and-produce". The basic functions of the system can be grouped in two main categories, "Operational and control functions" and "System management functions".

Operational and control functions

The operational and control functions are needed for the normal daily operation and abnormal situations to manage the power units. They are used to collect process or system information to the EMS that are able to distribute the system control, e.g. by commands, throughout the DPS unit. This is done by well-defined communication interfaces including interface information and functions, which is explained latter in this chapter.

Communication system management functions

Communication system management functions include both functions for system support and for system configuration and maintenance. System support functions are used to manage the information and communication system itself (e.g. network management, time synchronization, and self-checking of communication equipment). The functions support the total system and have no direct impact on the process. System configuration or maintenance functions are used to set-up (maintain) the system. The system configuration and maintenance functions include the setting and changing of configuration data and the retrieval of configuration information from the system. The most important examples of communication system management functions are:

System Support

- Network management
- Time synchronization
- Self checking of communication equipment

System configuration and maintenance

- Identification of attributes and services for communicating objects/devices (control units)

- Software management (version control, download, activation and retrieval of software)

- Configuration management (download, activation and retrieval of configuration data)

- Setting (parameter set)

Plug-and-produce

In order to enable "plug-and-produce", the information and communication system needs to include a structure with functions for database management and resource management. The structure presented later in section "Data management" provides the means for automatic management of all power resource units entering or leaving the DPS and at the same time establishing the predefined information exchange between expected actors (automated coordination functions). As described in Chapter 6, the automated coordination functions only have to be connected to the "resource manager" that always have all the pwer units within the DPS connected and ready to collect or distribute information.

Communication performance

The response times of most operational functions and, therefore, of the related communication do not need to be much faster than one second. System management functions, which have to be available for the operators and control systems, are of low time critical nature. Regarding safety of persons, plant and electric network, the communication system should not be of critical nature. No functions regarding safety of plant and electrical network should be based on the communication system, All safety functions must be self-contained in the power units or in the control devices where systems interface and will trip automatically. In situations where the communication system is completely inaccessible, the power unit may be forced to a shutdown by alternative means.

Regarding optimization of the operation, the communication system has time critical functions including both control and supervision functions. Set points for power control and "start" and "stop" commands are the most time critical functions. Periodic on-line operational data is essential for the

optimization of the operation. Finally the operators need to know the status of the communication system to be able to rely on the presented data.

The time critical functions are used with a high priority and are transmitted with a minimum of delay. Delays may occur due to transmission errors, low capacity or low bandwidth of the transport media or network faults. It is essential for the proper design of the communication system to select methods that minimize such properties. Time critical functions must be based on fast and reliable transmission of a number of selected data types. Services and functions not defined as "critical" in the above-mentioned are "non-critical" in the sense that delays and order of transmission is of minor importance.

7.2 Information and communication architecture

The intention of the structure on information and communication is to specify accurate terms for establishment an operation and control of a DPS for transfer of data between the local control unit in a power unit and remote EMSs. The structure may be applied for single power units as well as for entire DPS units. The structure includes principles for data transfer and handling as partly described in [McClanahan, *et al*., 1998] [Bjerge, *et al*., 2001] [Kezunovic and Abur, 2004], but not how all the data shall be used.

System overview

An automated DPS is very much depending on a well defined communication structure. Disturbances can occur at any time and they have to be taken care of immediately. It is therefore important that the power units within the DPS have a great deal of coordination and local strategies to endure possible failures. The speed in the communication network is crucial to make the system dynamical and special consideration has been taken to make it as fast as possible. The DPS requires at least one EMS production node to enable the coordination of the power units. That EMS-PM node collects all the values from the power units and in return distributes control signals [Jin and Renmu, 2002].

The communication system used in this work is built up according to Figure 7.2 a). The communication system of a DPS should be of ring type with a proper number of power nodes (EMS-PM) managing the system operation and control. The system becomes more disturbances tolerant by

using more than one power node. As already described in previous Chapters, the structure is built on at least one power node at each interconnection power flow (power unit). If only using one power node within the DPS and this would break or lose its communication to other power units the system might collapse.
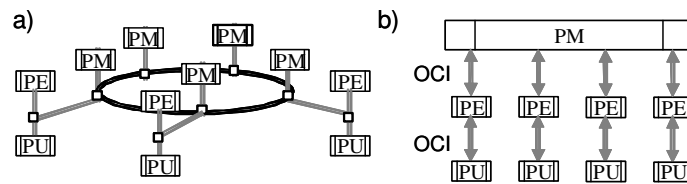
Figure 7.2: a) Overview of the DPS communication system. b) the actual power flow between PM and PE blocks.

As shown in Figure 7.2b, the operational communication interface (OCI) is used throughout the system. It can be found between the PM and PE blocks and the PE block and the power units (PU). The OCI signals transmitted from the PM contain all necessary data to operate the power units. Before the signals reach the power unit, they first have to pass the PE module. This block checks the signals making certain they not exceed the capability of the power unit and that the sender is authorized. The OCI signals from the power unit contains information about power unit status and all necessary measurements regarding actual power productions/consumptions. The system is supposed to be of the type plug-and-produce means that there are no limits in the number of power units connected to the PM block. The new unit should not have to run any special installation programs to be able to connect to the system and should also able to connect or disconnect at any time.

Principal structure

In DPSs, the local communication network (CU) system is the link between the power units and their control units and the local unit controllers, Figure 7.3. Embedded in each control unit is an information and communication block that together with the communication network forms the entire information and communication system. The active EMS in the DPS is a superior control unit that may be a "WPP controller" or a system control centre conducting an overall governing of the power units output and the electric network compatibility. Within the DPS a more general superior

control is adopted by the structure of the distributed EMS. The communication between CUs is managed by specific data protocols. The information and communication block include communication, data and resource management to support functions for supervision and operation of DPS units. The functions needed are used by the system and unit operators.
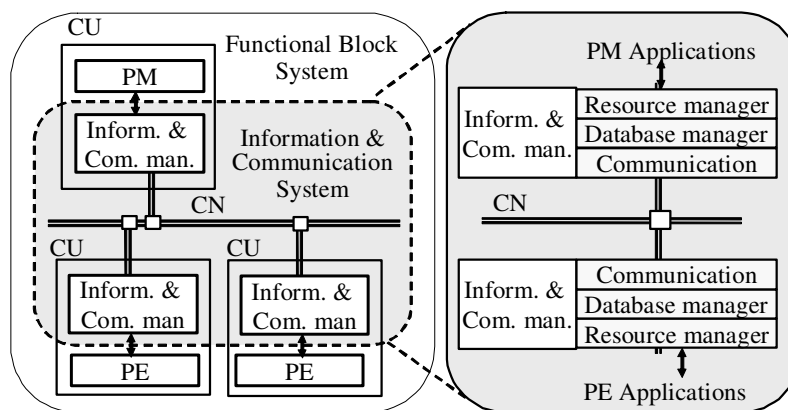
Figure 7.3: Communication between control units and overall supervision and control functions.

The structure of the system as shown in Figure 7.3 can roughly be described by the following parts:

- *Communication System***:** The communication system include the communication network and communication devices embedded in each control unit and is used for:

  - Exchange information between the TUa:s (EMS-PM control level) within the NUa.

  - Exchange information from an active power unit (PE control level) to a TUa (EMS-PM control level) where information is accessible for an application (automated coordination functions).

  - Exchange information to an active power unit (PE control level) from a TUa for distribution of commands, operational settings etc.

  - Exchange information within an active power unit from PE control level to plant system control level.

  The different types of data communication coexist on the same communication network using the same protocol, OCI.

-   ***Data management*:** The different operational functions need access to data in the power plant and the sending and receiving parts should be able to interpret and handle the data. Therefore, the data structure defined includes a distributed real-time database together with the data types and other characteristics. The data is grouped and organized by different resource types in an object oriented manner.

-   ***Resource management*:** The interface between the database and the application functions is handled by the resource management. This is general and able to mange any resources depending on predefined configurations. The data protocols are uniformed and stored in the real-time databases. The function blocks interact with a general resource manager that handles e.g. power resource units, communication interfaces etc. By handle all input and output communication via the RM the functions blocks become general regarding the number of units to be controlled.

All these parts are from one point of view the basis for enabling a DPS system with "plug-and-produce" behavior. The management of a communication system requires several fundamental services for proper interacting. Some of those services and functions are described in next section.

7.3   Communication networks

The focus of this structure is the support of functions for operation and control of power units, which are implemented in the control units. Several functions may be implemented in a single device or functions may be distributed over several lower level control units. Functions communicate with functions in other control units by the means of this structure. Thus from an application point of view different power units interact to perform different functions. For example, to stop a generation unit from a distributed EMS, the EMS needs to know which generation unit to access (unit name/identity, e.g. "generation unit 1"), The name "generation unit 1" identifies the real unit, but the model of the unit is typically implemented in a power unit controller close to the power unit as a power resource. After the command is executed the controller may be configured to send a status to the EMS indicating that the unit has stopped.

Various types of communication networks exist that include different structures and hierarchies. These bring different advantages and disadvantages according to the applications needed in this case a DPS.
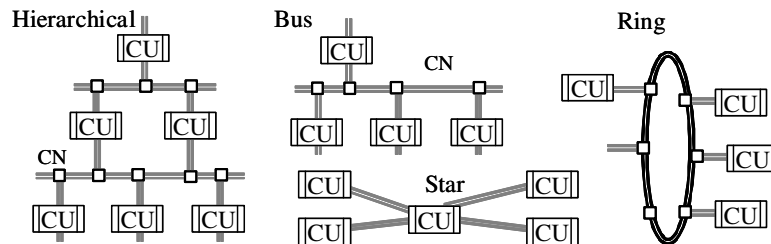
Figure 7.4: Communication network topologies.

As shown in Figure 7.4 there are several communication topologies [Olsson and Piani, 1992] within the DPS where some are described below:

- ***Hierarchical topology:*** The hierarchal topology is normally adopted within larger power units such as hydro or nuclear power plants that contain several interconnected process systems. The communication levels correspond to the functional software block levels described in Chapter 6. The lowest level here is an intelligent sensor or actuator and the highest level coordinates all lower functions to mange the interaction with the electric network. The vertical interface protocol is the OCI. For redundancy each level could be duplicated, e.g. parallel communication networks and control units. This is adopted in various degrees depending on the security level of the power unit, e.g. nuclear power plants may have triple redundancies.

- ***Bus topology:*** This topology could be found in smaller power units such as breaker and measurements units that might have one control level. It is also used in the terminal units that interconnect several power nodes. As the information flow is assumed to be integrated in the power lines within a DPS this would be a frequently used topology if using existing system.

- ***Star topology:*** The star topology might be found in smaller units as for the bus topologies but is not preferable as it is more sensitive to failures and not suitable for general structures.

- ***Ring topology:*** This topology is properly adopted suitable for future DPS units. This is a flat topology that provides single means for the

information exchange methods regardless of the location. For redundancy reasons this should be doubled meaning that at least two channels for each protocol should be adopted in the same power line/cable. If a break or interruption should take place there is always at least one additional communication connection.

Depending on requirements all possibilities (in any combination) are likely to be used in one or other way (may be at the same time). The information and communication structure can be applied to any topology. The structure can be applied inside a single power unit independent in size to provide communication between intelligent subsystems (e.g., generator controller, converter controller, etc.).
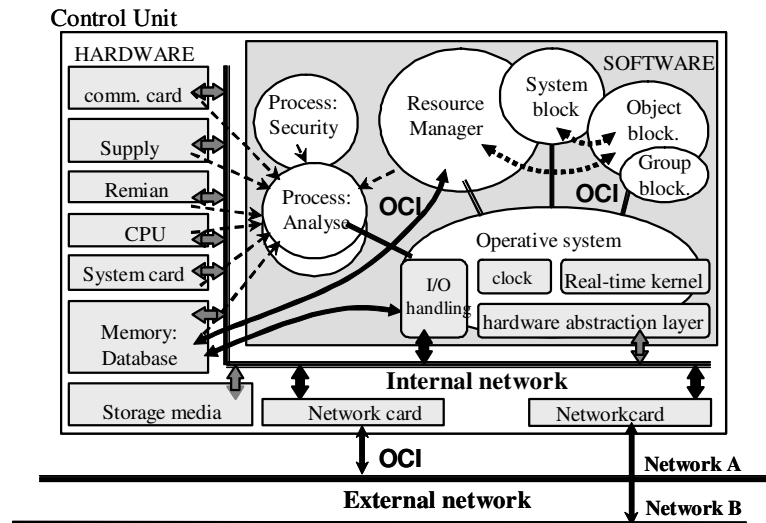
Figure 7.5: Internal and external communication network interaction.

Control software blocks have been discussed and the interaction between them are seldom described or mentioned, although this is one fundamental issue for constructing self-sufficient software structures. By looking inside a control unit (computer) there are many similarities in the way the basic information and communication works. As shown in Figure 7.5 the control unit is divided in a hardware and software section where the software applications communicate by the internal communication network (intercommunication). The principles of this system are almost identical to the external communication. The application software processes are communicating via the same interface (OCI) as for the external system. This is achieved by having the same requirements on the software blocks as

for the control units. The major differences are the physical communication lines (parallel or serial exchange) and thereby the communication speed. As information technology develops the transfer capacity increase rapidly. Even if the inter process communication always will be faster due to smaller distances and parallel signal lines, the difference will be more insignificant for applications like the DPS structure.

Communication mechanisms

There are several communication mechanisms for exchange of data contained in control units. The data can be provided periodic, on demand, and event driven information exchange of various data types as decribed in [Bjerge, *et al*., 2001] [Andersson, *et al*., 2001] [Johnsson and Svensson, 2002]. The basic services and functions for managing the communication system are briefly described below and are implemented in the software structure:

- *Basic Services*: The main objective for the communication system is to transfer data to and from control units at different control levels. In order to accomplish this the basic services of the communication system include the following:
    - Connection establishment and release
    - Authentication and acces control
    - Identification of functional object and devices (TM)
    - Information exchange, data access and transfer
    - Reliable transfer of data over a network
- *Data Transfer Principles*: All data can be transferred according to one of the following principles:
    - Periodic data transfer (all data or only data that has changed since last transfer)
    - Data transfer on request
    - Event driven data transfer
    - Command transfer
    - Set point transfer
- *Different types of data, protocols:* The specific information exchanged included in the OCI supports the following types of data:

- Binary control commands to the power units (CM)

- Binary control modes to the power units (GM)

- Set points sent to the power units (SPM)

- Binary Signals/Status data from the power units (SM)

- Alarms, Events, Counters, Timers (EM)

- Measurements/analogue data from the power units (DM)

The different types of real-time data are grouped as data blocks. Real-time data include measurements/analogue data, binary signals/status data and schedules. Schedules could be start/stop schedules for individual power units. The use of different types of data for the DPS applications is further described in Section "Data Management".

- *Mapping between functions and ways of communication*: Data are either polled at the communication node or periodic and automatic sent out from the node. The important requirement is the 'scanning rate' (maximum delay). Alarm data is sent from the power units on occurrence. Setting data in and giving orders to the power units are sent when needed, which is managed by the interface functions latter described in this chapter.

- *Communication protocol stack functionality*: The layered architectural guidelines of the International Standardisation Organisation (ISO) Open Systems Interconnect (OSI) reference model has been tested and used in some project related to this work. The model includes the 7 layers model as described, which are related to wind power plant operation and communication.

Communication interface information

The communication interfaces differ depending on type of communication, and there are several in a DPS. In this work the three interfaces TCI, OCI, and SCI have been discussed where the first two are more thoroughly described in previous chapters. In this section the focus on the OCI that is implemented and tested. However, the information and communication structure developed is general and could easily be extended in the same way for other communication interfaces. The data management within DPSs is the process of structuring information flow in uniformed data object blocks. To describe the data blocks exchanged between control units, classification and naming principles have been used. By definition, it

is a given data block on a given logical path with given communication attributes. The main components are summarized mainly by the terms data, type, performance, and path. "Data" describes the content of the information and its identification as needed by the functions. "Type" describes the structure of the data, i.e. if it is an analog or a binary value, if it is a single value or a set of data, etc. "Performance" means the permissible transmission time, the data integrity and the method or cause of transmission (e.g. periodic, event driven, on request). "Path" contains the logical source and the logical destination.

The OCI signals used in the system represent a vector with different data values describing the sender and receiver. The signals in the interface vector are easily extended as the entire structure is built on dynamic vectors. The signal used for implementation in this work and their function is described here. The naming convention used throughout the structure is based on the signal classification described, later on, in the Resource model implementation. The OSI prefix used stands for "Operational Signal Index" and is used as specific index places in one interfaces vector, which not should be mixed up with the Open Systems Interconnect (OSI) above. The data blocks are partly divided as described in the next section about resource types.

The "communication head" data block

- *OSI_DESTINATION*; informs the system to which destination the OCI is being sent. In this work this number represents the last 2 numbers in the TCP/IP number on the receiving control unit.

- *OSI_SOURCE*; informs the receiving control unit from where this OCI is coming. It is also used to respond to the right address.

- *OSI_NUMBER*; running number, automatically assigned to keep track on the validity of the message.

- *OSI_BTYPE*; block type, automatically assigned

- *OSI_BVERSION*; block version, automatically assigned

- *OSI_BSIZE*; block size

The "configuration" data block group

The configuration group is used by the production exchange control level to inform all the power nodes in the system the type of resource and possible usage of the connected power unit.

- *OSI_RTYPE*; the resource type corresponds to each power unit type {"Generator", "Load", "Storage", "Exchange"} and is declared by a number from 3 to 6 and the number correspond to the order in which they are stated above.

- *OSI_RIDENTITY*; the resource identity corresponds to individual power units of the type as above resource type.

- *OSI_RPRIORITY*; this signal is used to inform the system which priority the power unit has in comparison with others.

- *OSI_RSTRATEGY*; type of strategy for individual resource. The strategy is correlated to the different choices of operation a resource have in abnormal situations.

- *OSI_RSTATE*; {"normal"; "alert"; "abnormal", "breakdown"}. This is correlated with the different states a power resource can be in when activated in "on" status. The "alert" state is activated according to external and internal events that may case a major disturbance. The "abnormal" state is activated when major actions to prevent breakdown is needed. When the resource unit no longer is able to uphold the predefined tasks the "breakdown" state is activated that also automatically command the resource to shutdown.

- *OSI_RERROR*; resource error that is correlated to the number and degree of various internal errors. This also affects the RSTATE.

The "operation and control" data block

The operation and control group is used by the production management to set the different power units in predefined mode of operation to work in.

- *OSI_TRANSACTION*; transaction due to contract and authorization.

- *OSI_CPRIORITY*; the command priority signal informs the power unit of which authority to take command from. This information is mostly used by the exchange unit which has to decide from which side that it will be controlled in order to know the power flow direction and mode of control.

- *OSI_COMMAND*; {"stop"; "ready"; "start"} is the basic operational signal for start and stop of the units. The "stop" command is assign when the unit is supposed to be off. The "ready" command is used to prepare for a faster start and also as a check for no failure before the

next coming "start"-command. In "ready", the unit is in a hot standby mode. The "start" tells the unit to be in its operational mode.

- *OSI_DIRECTION*; the direction of commanded power flow is used by the exchange and storage units in order to export or import electric power.

- *OSI_GOVERN*; {"min"; "max"; "power control"; "voltage"; "droop"} specifies the different modes of control. The "min" mode is used to assign a generation unit in some type of ready state (idle running) but not completely out of order. The "max" mode always strives for the unit's maximum generating output. If operating none stochastic generation units it is the same as the nominal output power. When an external power set point is used the mode is called "power control", se the Set Point signal explanation below, where "voltage control" and "droop control" mode can be selected in case of low voltage on the electricity network.

- *OSI_SETPOINT1*; energy, power or voltage set point which has no significant meaning unless the Govern signal is set to "power control", "voltage", or "droop".

- *OSI_SETPOINT2*; ramping set point enabling a smooth change from one set point level to another to prevent disturbances in primary and secondary control.

The "operation and control status" data block

These signals are used to inform the production management block about the status and data from each individual power unit.

- *OSI_TRA_STATUS*; The transaction status

- *OSI_COM_STATUS*; The command status returns the value of which command mode as the power unit is operating.

- *OSI_GOV_STATUS*; The govern status – returns the value of the actual govern mode of the power unit.

- *OSI_DIR_STATUS*; The direction status returns the value of the direction of power flows controlled by the power unit, importing or exporting.

The "limits and measurements" data block

These signals contain information data of the power units' maximal limits and measurements.

- *OSI_E_NOM*; informs the system of the unit's nominal energy level, only used by the storage unit and exchange unit and between adjacent DPS units.

- *OSI_E_CUR*; informs the system of currently energy level, primarily used by the storage unit and exchange unit.

- *OSI_E_MAXC*; informs the system of the power unit's maximal energy level, used by the storage unit and exchange unit.

- *OSI_E_MINC*; informs the system of the power unit's minimal energy level, used by the storage unit and exchange unit.

- *OSI_P_NOM*; informs the system of the power unit's nominal power level.

- *OSI_P_CUR*; informs the system how much power the unit currently produces/consumes.

- *OSI_P_MAXC*; informs the system of the power unit's calculated (estimated) maximal power level.

- *OSI_P_MINC*; informs the system of the power unit's minimal power level.

- *OSI_P_AUX*; informs the system how much auxiliary power that is needed to start up the power unit, used in blackout situations.

- *OSI_DP_CUR*; dpCur – Informs the system of the unit's current ramping rate.

- *OSI_DP_MAX*; informs the system of what the power unit's maximal ramping rate.

- *OSI_DP_MIN*; informs the system of what the unit's minimal ramping rate.

- *OSI_V_NOM*; informs the system about the predefined nominal voltage level close to the power unit.

- *OSI_V_CUR*; informs the system about the current voltage close to the power unit.

In the implantation, the data blocks are used as one communication data vector in order to minimize the management of several communication

blocks. However, the structure is prepared for splitting the data interface into several smaller interfaces.

Information hierarchy

Technical systems for monitoring and control can be broken down into blocks in several levels [Svensson and Karlsson, 2002]. The interface to each block contains the same groups of signal types for operation (Command, Govern, Set point) and information (Error, Status, Data). The interface to the control unit as well as the internal interfaces to the blocks within the control unit can be described using these groups of signals.
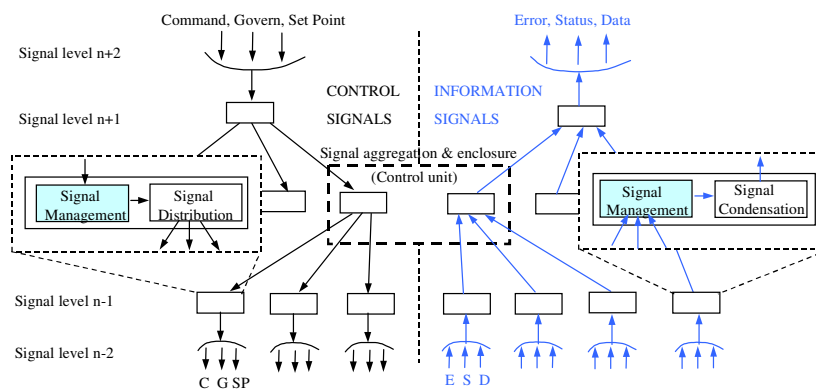
Figure 7.6: One level within the hierarchy for operational information.

The signals could be found throughout the structure from top to bottom and at certain levels analysed and diagnosed for further transmission as shown in Figure 7.6. The fundamental principles for information management are to:

- Capture all data

- Condense and convert data to information

- Manage the information while storing data

- Aggregate data to appropriate units

- Move the information to units in need, when needed

- Share information in real time

The content and management are the same at each level. However the exact meaning of each signal differs between the levels. The "power setpoint"

signal at power unit level is a distributed scalar setpoint compared to the "power setpoint" signal used at system level that is a vector.

The information flow direction is upwards in the control system hierarchy, which implies that the signal management part receives all signals from underlying levels and transmits the condensed or summarised results upwards. The supervision and signal management (analyse and diagnose) is made independent of the higher levels in the hierarchy. The control flow is correspondingly downwards in the hierarchy which implies that the signal management block receives all its signal from higher levels and then distribute them further to lower levels.

Vertical information structures are naturally used within the same operative managing area as for the most company structures. Information aggregates upward and commands distributes downwards. Between adjacent operative management areas horizontal structures should be used but so far almost all such information is manual.

Interface functions

The control and information signals are all treated in specific management blocks and are the main interface to upper level control units. Each block analyses and diagnoses the signals both from internal and external connections and determines the resulting output. These unit functions store and handle the control and information signals at each level of control.
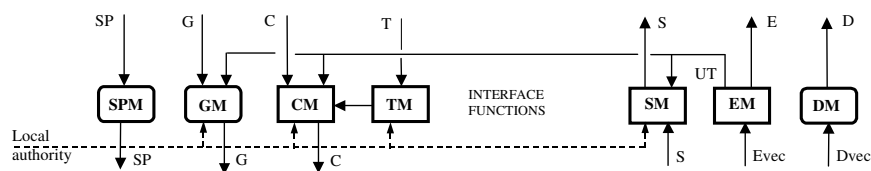
Figure 7.7: OCI interface functions.

The upper interface interconnection of signal management function blocks is shown in 7.7 and is briefly explained as follows.

- *TransactionID Management* (TM) is the initiating signal checking from both sending and receiving sides to acknowledge that they have the same transaction information. If both sides give the same transaction identities, it is prepared for one of the sides to take control and send a proper command signal according to data from transaction information.

- *Command Management* (CM) is responsible for the unit's operational command signal and receives its signals from an external higher level, internal level or a local operator. The signals are evaluated and sent to the highest level of the internal control software block hierarchy in the unit. Among internal signals that affect the command signal has the unit trip the highest authority, which instantly shut down the unit by assigning the command signal in normal "stop" or "quick stop". The block has also special authority and priority capabilities as options.

- *Govern Management* (GM), has mainly the same inputs signals as for the CM function except for the govern signal that, depending on local strategy, interact with higher choice of control mode. The ending destination for the govern signal is a control object block where the interaction with the process is performed.

- *Set Point Management* (SPM), handle the received set point and distribute it either within the control unit or to next lower level control units. The aim is, as for the govern signal, that the signal at the end has to reach the intended control object block. In general, if the actual control unit doesn't contain such a block, the set point is further distributed via the lower unit interface.

- *Error Management* (EM) is responsible for determining type of failure for the control unit. All control software blocks included in the control unit have an error flag that is received by the EM. There are several strategies for error diagnoses and this type of summarising all the error flags gives few restrictions in choice of algorithms. Once the EM has determine an A-alarm the unit will trip itself by transmitting a signal (unit trip) to the CM, GM, and SM that treat the signal and perform pre-defined actions in order to minimise the consequences.

- *Status Management* (SM) determines the status of the control unit, which could include several lower control units and transmits the signal to higher level. If a unit trip occurs or a local authority receives control, the SM assign the status signal as blocked.

- *Data Management* (DM), selects and, if needed, summarises the measured values or data and transmits them further upward in the hierarchy. Two main data signals are used in the WPP case; the current power and the current estimated maximum power of the unit. (p_cur, p_min, p_max, p_nom, dp_min, dp_max)

The lower unit interface may have various advanced unit functions depending on the lower level control units. This is explained more in detail

in Section 6.6. The main purpose of the lower interface is to allocate and distribute the control signals (command, govern and set point) and receive data by collecting and storing the information signals (error, status and data) before further usage inside the control unit. In most cases the lower interface only consists of vectors with control and information signals including the identity to intended receivers. When managing several similar parallel units a co-ordinator and scheduler function might be used as in the WPP case. In same cases, diagnosis functions are needed to provide proper information to superior strategy functions. Internal functions are also available for special information signal treatment, e.g. calculators, analysis, diagnoses, estimators etc.

Communication network and interface model design

Communication interfaces are used in almost every technical application that needs signals to be exchanged. Control units may be embedded in components of varying sizes, where a component itself might be aggregated of others according to the design and structure [Svensson and Karlsson, 2003]. Depending on complexity, there are several signal levels both for horizontal and vertical interconnections as described in the communication topologies section.

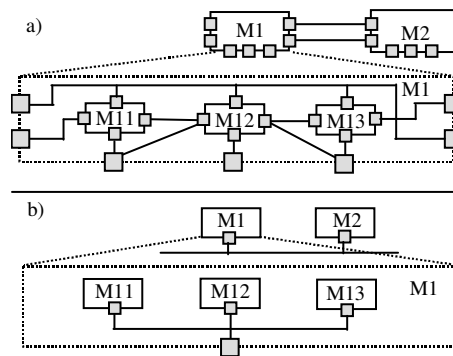**Figure 7.8:** a) A combination of interconnections with different types of interfaces (terminals) at several levels; b) a general signal bus using one type of interface enabling a plain structure.

This is complicated in real systems but even more in simulation environments (SE). Several SEs have hierarchical possibilities in modeling and defining communication interface types (terminals) for signal

exchange. However, numerous possibilities easily become a trap when using a multilevel hierarchy of signal interconnections. In Figure 7.8a it is shown that several different data interfaces easily become disordered as the system gets larger. Different interfaces represent various groups of signals that need to be used for connecting the models.

It is easy to complicate the model structure by extending the number of interface types, which cause many and tricky connections. For example, if adding a new type of interface in model M12 in Figure 7.8a, each model at all levels need to be reconstructed by adding new interfaces. If modeling a large model with many levels of aggregations it becomes even more complex. This is simplified by using a model representing a general communication bus, as shown in Figure X1b, where every instance is interconnected to the same bus independent in information level if so desired. Depending on the number and types of communication interfaces there are alternative configuration opportunities for the signal exchange in the models. For example, if throughout using the same interface it might be practical for the user to be spared assigning identities to every single communication node. One model solution for the Figure 7.8b case requests a vector based signal bus, where the bus vector merges together all the data interface vectors. Although, this bring in a problem with always keeping in mind the correct number of indices depending on the number of connected components. Even the index of each component has to be determined if a general approach is used. In this case it is necessary to define the exact number of signals in every data interface to be connected and the bus needs a pre-defined vector index according to number of connected components. If a uniform terminal is used with a large number of signals where several models are not using but a small amount of interface signals, the SE will have an unnecessary high number of signals to handle. It is therefore desirable to be able to choose which internal module signals to be exposed by limiting the interface signals.

The developed structure is general and based on a signal bus (communication network) that automatically assigns the components with their identities and enables the user to mainly focus on the signal to be exchanged and not on the underlying structure and functions that manage the signal communication. The structure is adaptive to different user specific desires and also able to resemble several types of communication, e.g. between software processes, computers or in automation systems. One solution based on Modelica interconnected to a C++ library is further described and exemplified in Appendix A.7 that presents an adaptive signal

management Modelica library, "SignalFlow", interconnected with a C++ class library. The library simplifies the signal exchange in large simulation models based on modular designs, which should correspond to the signal flow for real applications by representing common networks as models with general interfaces. The library enables automatic configurations during simulation using dynamic vectors and has additional functions for exchanging several types of signals in both continuous and discrete mode. The work is an outcome for enabling "plug and produce" capabilities in distributed power system applications that is exemplified.
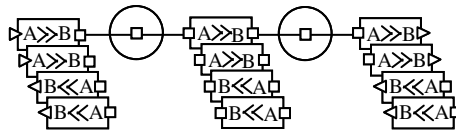
Figure 7.9: Dynamic number of connections.

The principles of the library are based on a communication nodes and communication flows models with no direct limitation in connecting the number of node and flow models, as the structure is dynamic. Each new connection creates a new object that might be automatically removed if disconnected a predefined amount of time. The structure is simple and can be connected with unlimited flows between nodes, Figure 7.9, and at any hierarchy level. In the simplest case one node is used as a communication bus where all flows are connected to that single bus.
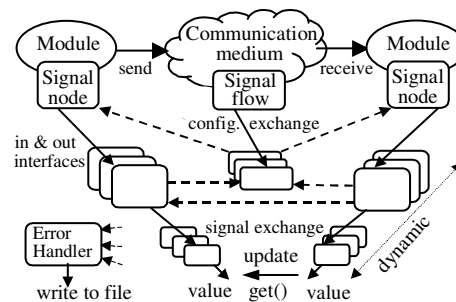
Figure 7.10: Signal management design overview.

The flows are normally embedded in some user specific model, hiding the pre-defined communication interface that are interacting the bus. The communication interfaces between control units are represented by the

communication flows that actually serve as the configuration between senders and receivers where the communication interface and protocol is a part. The underlying software structure enabling automatic configuration and interconnection over the communication network between control units is based on object oriented programming using dynamic vectors. The basic idea is that independent of different types software modules there should be simple means to establish signal configuration and connection via some type of communication media to another module as shown in Figure 7.10. This design works both in a SE and for real applications. This calls for either an automatic translation from the modeling language to the target application or a smooth software interface between the SE and the chosen program language. As the Modelica language has nice facilities for external function calls the main functions of the library is implemented in a C++ library [Modelica, 2002] [Freiseisen, *et al*., 2003] [Remelhe, 2003]. A module could be a software process, thread or a model in a SE where the communication media could be an external or internal communication link [Svarstad, *et al*., 2001]. The design is divided in a hardware and software structure, where the physical part, communication lines, transmitters and receivers are developed in the Modelica languages and the software functions in C++. The principal structure in Modelica builds upon the communication nodes and communication flows where the nodes may represent a temporary storage, transmitter or receiver. The communication flows represent the communication lines between the signal nodes with the main tasks, in initiating mode, to inform the connected nodes about the configuration and, in operation mode, to control that the physical line is in order for signal transmitting. The nodes create in- and output interface objects dynamically according to the communication interface configurations as described. The interfaces in turn create individual signal objects for each specified signal. An input interface then points to an output interface of another communication node where the configurations are checked before switching to operation mode. During operation, each signal object updates the data when trigged by the node. Every failure or configuration error is reported to an error manager that writes the needed information in a file or to the log window in the SE.

7.4 Data management

The following section is a description of principles for representation of data storages and management. The intention is to establish rules and

principles for what data and what services shall be available from each power unit.

Resource databases

Databases and the management of those are enormous and the structures are very depending on the system applications. A general structure in control system applications is shown in Figure 7.11 where the database is divided in distributed real-time and special databases.
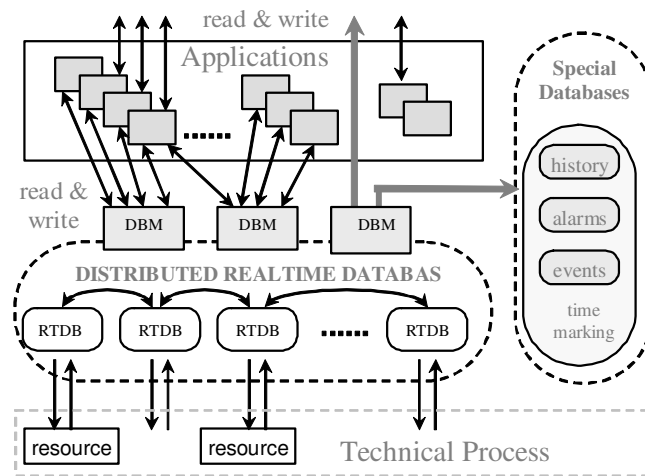
Figure 7.11: Database structure overview.

The special databases are here categorized in history, alarms and events. These are stored in several different time frames according to predefined time markings. In this work the focus is in the distributed RTDBs that are divided in control units representing the production management and production exchange control level. At production management level several resources are used for coordination purposes. In Figure 7.12 three domains are shown:

- The power domain coordinating power resource units

- The security domain mainly coordinating protection resource units

- The distributed EMS domain updating and managing the different power node identities and information.

The power domain primarily manages power units wherein the automated operating authority has the disposal of several functions as well as the interaction with the security authority within the security domain. The security domain primarily manages protective units but have also authority to control power units via the operator if needed. The DEMS domain continuously keeps tracks on all other DEMSs within the control area. The primarily assignments are at all time to know which DEMS that are master and the next ones in queue according to a predefined priority list. In the aggregator assignment case the DEMS also identifies its place in the hierarchy. Depending on the DEMS assignment, active or semi-active, various extents of functions are activated both in the power domain and the security domain.
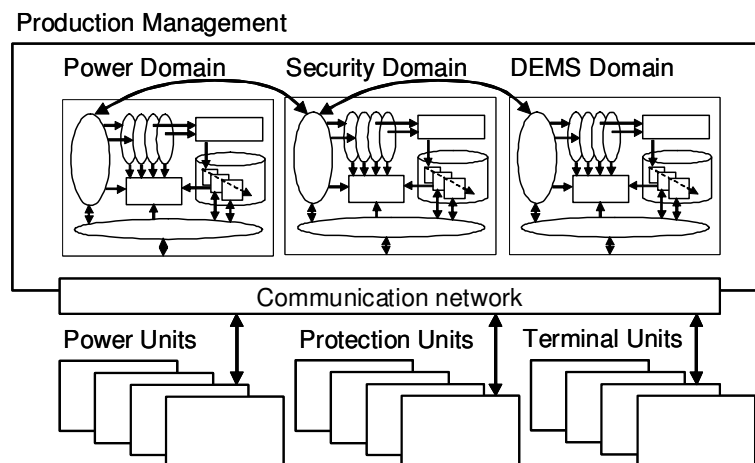
Figure 7.12: Production management structure.

These coordination domains can be seen as three different processes coordination their resource units separately. However they have functional relationship according to previously described power balance authority and security authority. As the proposed DPS structure may contain several power units including full functional EMS, every such power unit must know of each other in order to know which one that is active and next to come depending on disturbances. The structure of the production exchange control level is basically the same except for that the resources are only in and out communication interfaces.

Resources types

Within the DPS the EMSs are able to receive changed values or may receive values periodically independent if they have changed since the last transmission or not. Values may also be sent on demand by polling which is the primary adopted way in this work. The different operational functions of EMS access information from the power units and the sending and receiving control units are able to interpret and handle the information as intended. The data exchanged is defined together with other characteristics of the information. Information is represented by a number of attributes. The total set of information, the naming, the type and default value of the information are defined according to the structure and to the following principles:

- Each resource is self-descriptive (generic part) and the system has a service (resource manager) to extract the information contained in the EMS real-time database. It is then possible to issue an identify request and get a list of all resources in the DSP, their names and possibly a short description for each object. It is also possible to get the attributes and services for each resource.

- A hierarchical name structure and an object data directory specialized for DPSs are used.

- During information exchange the messages for real-time information include the following parts: name or unique Identification, value(s), time tag, and quality information.
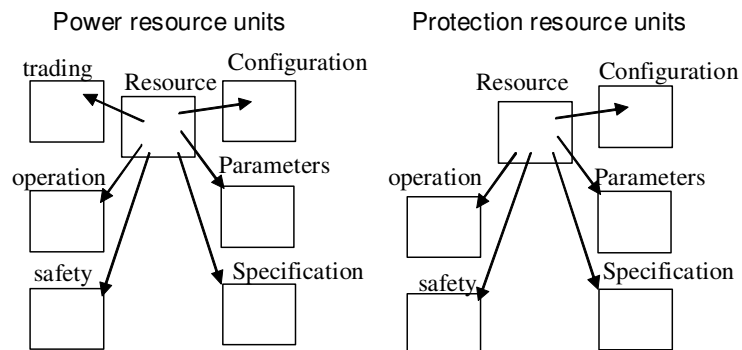

Figure 7.13: Resource structures.

Basically, resource data should be possible to be moved from any data area between control units in the DPS depending on authorization and functional activities. As the DPS has several resources the data objects are connected to the different resource types of the system. The basic principle of describing the information model for single power units is shown in Figure 7.13. The resources are categorized in Power resource units and protection resource units.

The power resource units correspond to every interconnected power unit in the DPS (generation, load, storage and exchange units).

Resource signal classification and structure

An important issue concerning signal classification is how to enable several types of configurations without making it too complex. The following signal classifications are used to configure the signal flows.

- *Signal Identity* (SID); enables a signal to have a unique identity, but this might imply obstacles regarding dynamical capabilities

- *Signal Index* (SI); specifies exactly where in the vector or position the data is placed. This is how the signals in this implementation are used to read or write the value of the signals in the data vector.

- *Signal Type* (ST); specifies that each signal must be specified by a unique type (e.g. command, power set point, etc)

- *Signal Assignment* (SA); specifies a set of values that each signal can be assign with.

- *Signal Block Type* (SBT); a predefined number of signals forms a block type, which could be a uniformed (protocol), e.g. TCI, OCI, SCI. This is used in the head of the OCI signal description.

- *Signal Block Identity* (SBI); the SB may have its own identity to differ several SB apart. E.g. OCI input and OCI output.

- *Signal Block Group Type* (SBGT) can be used if several SBTs are connected between the same source and destination as in the PM and PE case that have several resource of the same type. The unique group identity enclosures SIs, STs or/and SBTs. E.g. the resource types are typical SBGs. In the communication configuration this is named as OSI_RTYPE.

- *Signal Block Group Identity* (SBGI) is used to separate several SBG apart as in the power unit case where all have the same SBGT but are

physical different units. This is named as OSI_RPRIORITY in the communication configuration.

Signal flow configurations must at least have a specification on a SI or ST. Normally the SI is used as a unique identity that can be found anywhere in a system model. However, if using a model with several power units of the same type and signal interface together with a higher-level control unit collecting and distributing signals, the SBT and SBGI are requested as for the DPS case. The mapping of the existing power resource unit (PRU) information to the signal classification model is done as follows:

- *PRU trading*; corresponds to the communication interface TCI, which is assign SBT_1 = 100.

- *PRU operational*; corresponds to the communication interface OCI, which is assign SBT_2 = 200.

- *PRU security*; corresponds to the communication interface SCI, which is assign SBT_3 = 300.

- *PRU specification*; general power unit information of resource name, identity, type, services. This is assign SBT_4 = 300

- *PRU configuration*; information including the specific communication setup for the resource, e.g. polling, polling rate etc. This is assign SBT_2 = 400 .

- *PRU parameters*; information on operating limits, controllability, etc., which is assign SBT_3 = 500.
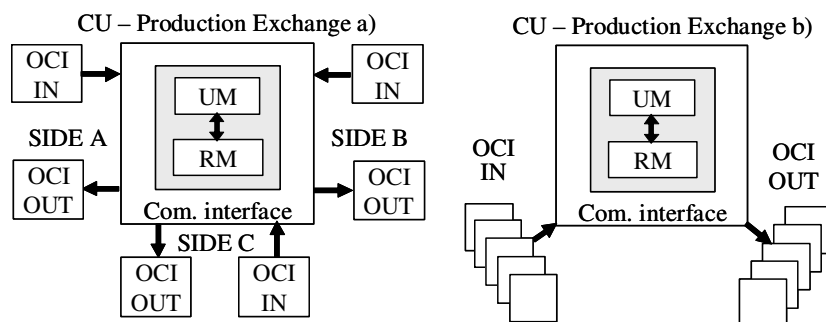

Figure 7.14: The production exchange interface; a) 3 side interface approach; b) general interface approach.

These data groups provide the information that can be accessed with the information exchange procedures/methods for each defined power unit. The communication models and the information exchanged are modeled applying an object oriented approach. Each data group is modeled as separate vector objects similar to the communication interface.

An example of the classification usage is the production exchange (PE) block that has several sides of information required. In Figure 7.14 a, the 3 side interface is shown. This is how the exchange power unit is configured. Side A and B are connected to the DPS A respective DSP B and side C is connected to the physical resource, e.g. converter station. As the PE module only manages one power unit resource the main processing is in managing the OCI interfaces. This is done by connecting several OCI interfaces to the single software resource in the resource manager (RM). The resource then name the different interface in accordance with the signal interface classification.

All OCI interfaces are of the same signal block type SBT_2 and are separated by signal block identities SBI that are assign as follows:

- Side A, OCI in, SBI=101
- Side A, OCI out, SBI=102
- Side B, OCI in, SBI=201
- Side B, OCI out, SBI=202
- Side C, OCI in, SBI=301
- Side C, OCI out, SBI=302

The interface structure is however general and is not limited to the number of interface connections as shown in Figure 7.14 b. This works very much like the software procedure with messages and queues. However in this case every time period for decision requires that all authorized authorities are considered. The authority with highest priority is able to operate the resource but all the remain, in this case only the other side of the exchange unit, are able to stop it. As already declared the resource manager of the PE only manages communication interfaces. The production management and production exchange interaction is shown in Figure 7.15. Here the resource manager of the PM manages power resource units (PRU) that theoretical can be of any number. The interconnection of the physical resource via the PE to the PM is established via the resource manger of the PE that manages

the OCI interfaces. The mechanism for information exchange between these resources is described in the next section.
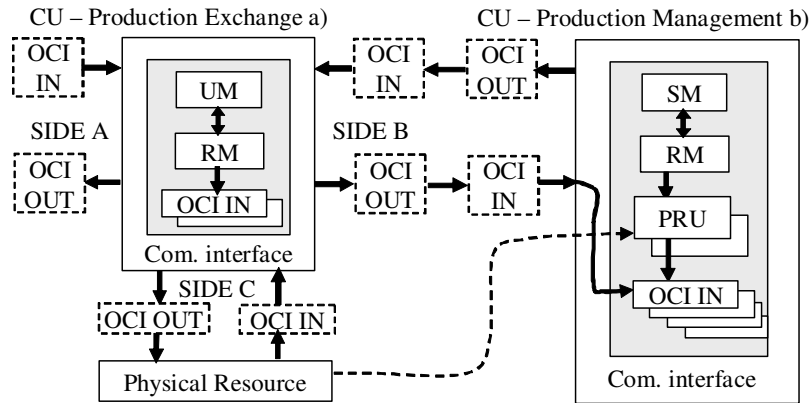
Figure 7.15: PE and PM interface interactions.

Resource database and information exchange model design

The structure of the real-time database is shown in Figure 7.16 where the resource data groups are created each time a new power unit is connected. As the resource manager is built out of dynamic vectors, the number of resources continually changes with the number of power units in the DPS.
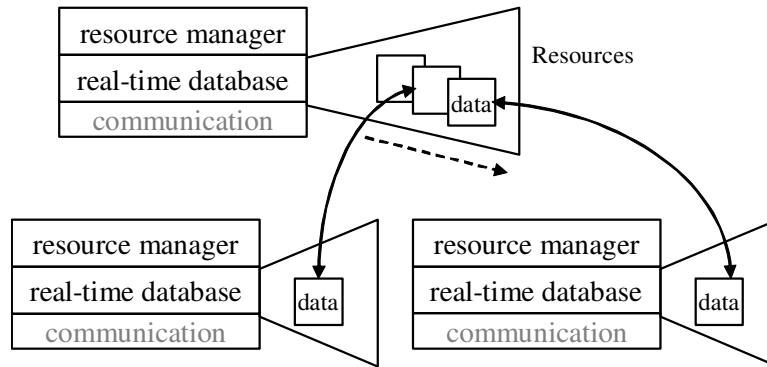
Figure 7.16: Data resource management structure.

For the traditional power system this may not be useful but for smaller systems this will be important. For example, intelligent buildings with

several power sources and sinks (e.g. loads and future solar power) may be more frequently connected and disconnected to a minor DPS like a community.

Regarding future vehicles they could be considered as very small DPSs that certainly would be frequently connected and disconnected. Therefore the management of the resource manager and their information exchange become vital for the operation of such systems. The information exchange is, in one way, managed by the resource managers in the DPS independent of if it is a PM or PE module to be served as both have the OCI communication interfaces included.

Information exchange procedure

The information exchange is based on server-client services for communication between power units and the included control units. These services are used for the following information exchange methods:

– Resource establishment

– Information exchange

– Resource removal

The same information exchange methods are used both in the model structure and the experimental part of this work.

Resources establishment procedure

When a new resource requests connections to provide services, the resource specification is first checked and then confirmed as shown in Figure 7.17. If the specification corresponds to predefined requirements, the resource gets assignments in which information for the communication setup are included, network identity etc. The resource manager creates a new resource object by calling the function "addResource".

The function for this is partly shown below where the OCI protocol is include in the DataInterface that is about to be connected. A new resource is created the same time as the network identity of the resource is assigned. After the creation of a new resource the communication interface OCI is connected to the resource.

```
void ZResourceManager::addResource(ZDataInterface* interfaceRef)
{
  ......
    ZResource* resource=new ZResource(interfaceRef->getGroupID(), m_bt);
    resource->addInterfaceRef(interfaceRef);                    // bt - blocktype
    m_rv->addElement(resource);
  ......
}
```
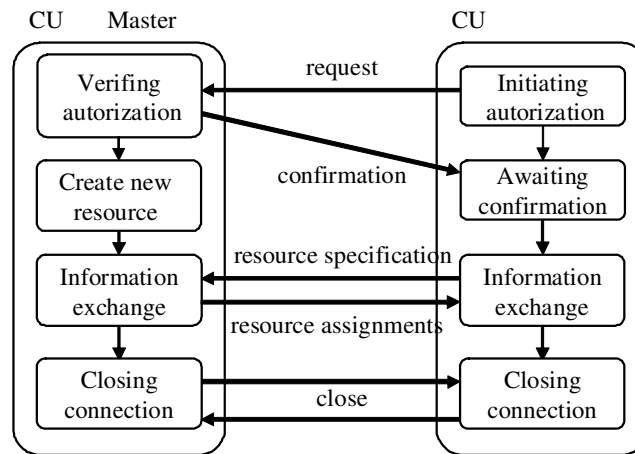

Figure 7.17: Resource initiation procedure.

Information exchange

The transactionId is used as an authorization signal. The authorisation model defines the mechanisms for the authentication and restriction for access to operational functions of a server device. The authorisation model provides secure information exchange. The conceptual procedure is shown in Figure 7.18.

The information exchange model is partly provided by a concrete communication model and service mappings. Several functions are included in the structure to handle the exchange of operational data between resources, which is here briefly explained. The functions for reading and writing between resources are basically done be the getValue and setValue functions below.

```
double ZResourceManager::getValue(int rIndex, int bType, int bNr, int bIndex)
{
    ZResource* resource = m_rv->elementAt(rIndex);
    double value = resource->getValue(bType, bNr, bIndex);
    resource = NULL;
    return value;
}

void ZResourceManager::setValue(int rIndex, int bType, int bNr, int bIndex,
double value)
{
    ZResource* resource = m_rv->elementAt(rIndex);
    if ( resource != NULL ) {
        resource->setValue(bType, bNr, bIndex, value);
        resource = NULL;
    } }
```
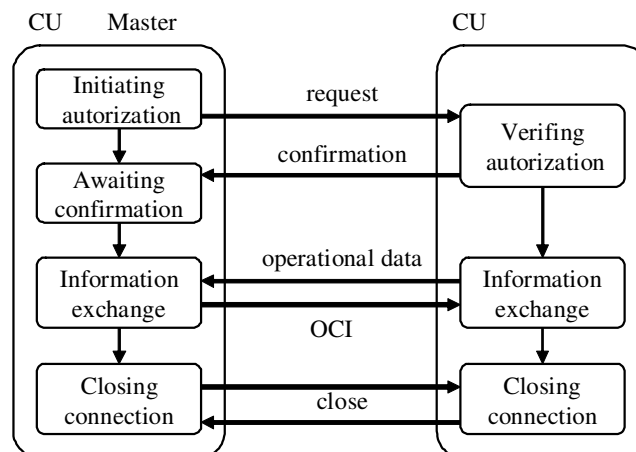

Figure 7.18: Information exchange procedure.

These functions enable the possibilities to set and get all signals from the connected resources. The function arguments correspond to the described signal classification. The "rIndex" is the automatically assigned resources identity and the "bType" is the block type that corresponds to different sets of data groups. The "bNr" is used when several data groups of the same type is used. For example, several operating authorities may have access to the same power unit, which involve several OCI interfaces with the

possibility to order the power unit. This might seem dangerous but is controlled by authority priorities that only enable the one with highest priority the control.

These functions are called upon by the following example where the usage of the signal classification is shown.

```
m_rm->getValue(SI_RIDENT., SI_BT_OCI, 0, OSI_PCUR);
m_rm->setValue(SI_RIDENT., SI_BT_OCI, OSI_COMMAND, SA_CMD_START);
```

The "getValue" example reads the current power of the actual resource and the "setValue" example writes the new order to start the resource. The resource also receives the "govern" and "set point" signal in the same way.

Resource removal

For different reasons, the resource may not respond to requests. If no response has occurred after a certain time the resource is removed from the information structure by the following function.

```
void ZResourceManager::removeResource(int resourceID)
{
    int rSize = m_rv->size();
    if ( resourceID >-1 && resourceID < rSize )
        m_rv->removeElementAt(resourceID);
}
```

The function simply verifies the identity by getting the size of the dynamic vector and removes the resource.

The examples for managing the communication is only a fraction of what is implemented but gives guiding outlines in how the procedures of this structure is structured and operated. Further details according to the functions are described in the Appendix B.

DPS unit interactions

The basic concept of the interaction between a network unit and a generation unit is shown in Figure 7.19. The "active generation unit" (GUa) operate and control the generation unit (GU) via the superior control level PE. In this case the PE might only be operated from one side, the terminal unit included in the "active network unit" (NUa). Initially the resource manager of the PE creates a interface resource toward the physical

resource. As the unit management (UM) is ready with local configurations the units try to connect themselves to the nearest power node (PN), which is located in the terminal unit.
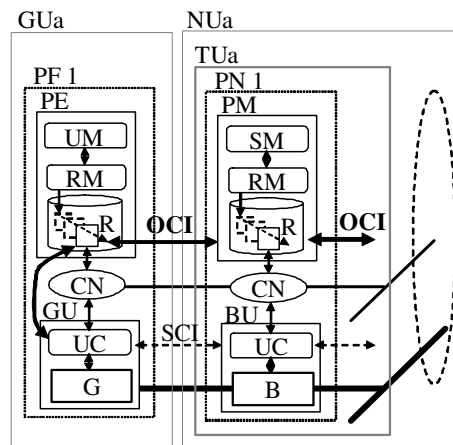
Figure 7.19: Network unit and power unit interaction.

As the PN accept the request the PM creates a power resource unit and requests needed information to authorize the start of the GUa via the communication interfaces of the RM. All communication is transmitted via the communication nodes (CN) included in each unit.

Depending on the size of the NUa there may be many TUa that in a future system structure could include numerous power nodes. This implies that there are several possible places for the system management (SM) to operate. However, within each DPS only one is active as a system operator. The others are either passive or semi-active regarding power flow control. Every PN directly connected to an active power flow unit has distributed assignments. They are always updated with the latest information regarding operation and local strategies. In Figure 7.20, a TUa or a NUa is shown. From a system operation point of view they work in similar ways.

In this case there are three power nodes where one is active and the others semi-active. If, for some reason, the master is disconnected the next in order will take over. At system management levels all information exchange are manage by the usage of the internal resource manager. The resource manager can be used by any application program by for example

creating one manager for power unit resources and another for communication interfaces.

TUa or NUa
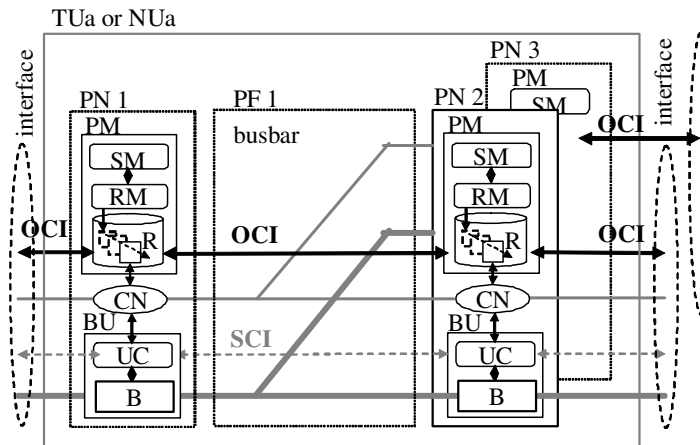
Figure 7.20: Internal terminal unit interaction.

At this application level function calls are made for power unit resources. Several resource managers can be created as for the rest of the structure. They are managed by a dynamic vector as:

```
....
   ZResourceManager* rm = new ZResourceManager(cv, cvSize, flow);
   int rmID = rm->getID();   // gets the identity as several RM could be used
   m_rmv->addElement(rm);
…
```

The argument "cv" is the configuration vector that, among others, includes the type of resources that should be managed, which in this case are the power resource units. This prepares the RM with all needed information to create new resource objects including the interface vectors described.

At the highest level within the SM the RM´s several functions need to know the number of power resources connected to the DPS. This is managed by the following function.

```
int class::getResourceNrByCondition(int index[], int value[], int size) {
   int nr = 0;
   if (m_rmOK) {
      int rSize = m_rm->getResourceSize();
```

```
    for (int rID=0;rID<rSize;rID++) {
        bool ok = true;
        for (int i=0; i<size && ok; i++){
            ok = value[i] == m_rm->getValue(rID, index[i]);
        if ( ok )
            nr++;
    } }
    return nr;
}
```

This function enables superior functions, e.g, system analyses, to get the exact number of resources out from a specific type and several other conditions. For example, if asking for the number of exchange units that are started in power control the condition vector is assign as follows:

```
condition[1] = SA_TYP_EXCH;
condition[2] = SA_CMD_START;
condition[3] = SA_GOV_PCONTROL;
```

This condition vector is then used as an input to the function getResourceNrByCondition that returns the number of such resources. The condition vector is frequently used at system level and works as an effective filter condensing the correct system information

In the unit commitment case it is useful to find the exact individual resource, which is done with the following function that also use a condition vector filtering requested resources.

```
int class::getResourceByCondition(int index[], int value[], int size)
{
        int nr = 0;
        if (m_rmOK) {
        int rSize = m_rm->getResourceSize();

        for (int rID=0;rID<rSize;rID++) {
            bool ok = true;
            for (int i=0; i<size && ok; i++)
                ok = value[i] == m_rm->getValue(rID, index[i]);

            if ( ok )
                id = rID;
```

```
        }}
        return id;
}
```

After getting the resource identity, the unit commitment function is able to get local information by the "getResourceValue" function.

```
double ZProductionManagement::getResourceValue(int rID, int index)
{
        double value = 0.0;
        if (m_rmOK) {
            int rSize = m_rm->getResourceSize();
            if ( rID-1 < rSize )
                    value = m_rm->getValue(rID, index);
        }
        return value;
}
```

If the resource corresponds to the requests, the orders are distributed by the "setAttribute" function.

```
void ZProductionManagement::setAttribute(int rID, int index, double value)
{
        if (m_rmOK) {
            int rSize = m_rm->getResourceSize();
                    if ( rID-1 < rSize )
                  m_rm->setValue(rID, index, value);
}             }
```

These are examples on how to use the information and communication structure that includes many special internal functions for the management of different types of resources and their interactions.

Data and resource management model design

The signal management design as described in previous sections in this Chapter is the foundation for the further extension of the resource management. The communication node is here upgraded by several functions for interconnection and interaction with the resource management software. As the communication node is general in its implementation a

new unit enabling different modules to be connected is used as shown in Figure 7.21.
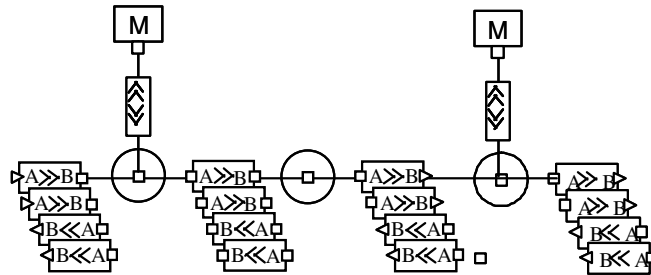
Figure 7.**21:** Module interconnection to the communication model.

The modules, in this case, are the PM and PE that include the resource manager module. The interconnection flow element is similar to the communication flow elements.
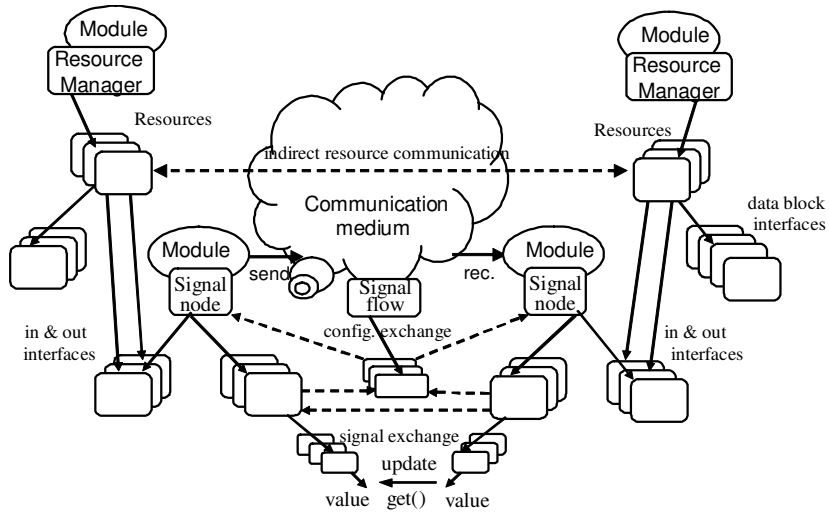
Figure 7.22: Information and communication design overview.

They differ in the configuration as these modules have multiple communication interfaces. The signal management design described in previous sections is here extended with the resource management model as

shown in Figure 7.22. The additional structure is implemented in Modelica and interconnected to the C++ library. Further description and simulations are described in Appendix A.

The resource module structure is initiated when a configuration including the resource type is called upon. The resource manger then consists of an empty reference vector awaiting a power resource unit's initiation call. This is indirectly done via the communication node that creates the input and output interface objects dynamically when requested. When the communication node has a new interface the resource manager connects itself to the communication node and searches for communication interfaces that have to be connected to the resource. When a proper interface is found the resource manager creates a resource object that in turn creates and connects all needed data interfaces in accordance with the resource type. The communication interfaces are directly connected via the communication node. During operation, each recourse object updates requested data.

7.5   Concluding remarks

As an outcome of previous investigations, communication is employed in the simulations. An adaptive signal management structure, based on object-oriented dynamical programming, has been developed and introduced. A simulation library, "SignalFlow", has been developed in Modelica, where the model components are interconnected to the signal management structure. An additional resource management has been developed to manage the power resource units of the DPS. The presented results verify that the structure meet the predefined requirements. The structure forms a base level layer enabling adaptation for higher-level control and information flows. It is also an example on how to develop function calls, interacting external programming languages with a simulation environment.

Chapter 8

Analysis and Verification

In this chapter, the information and functional structure is verified using a small distributed power system that is analyzed and implemented based on the investigation in previous Chapters. The analysis and verification are performed by both simulation and experimental tests. The simulation tests are based on the model and module libraries developed in the work. The experimental tests are based on a three-converter system interconnected to the AC network and an internal DC network. The simulation and measurement results verify the main objective for "plug-and-produce".

8.1   Approach

The approach is based on the usage of several scenarios where functionality is increased gradually by adding one power unit at the time and also by combining the types of power units and their signification.

The DPS model used is shown in Figure 8.1, where all power units are represented enabling various DPS configurations and scenarios. The test scenarios are configured by connecting active power units to the active network unit (NUa) that are intended to automatically adapt to the system and start interacting. The different types of active power units, generation unit (GUa), load unit (LUa), storage unit (SUa) and exchange unit (EUa) are used in at least one scenario configuration. The scenarios include electrical connection and automatic establishing of connections between the production management (PM) and production exchange (PE) systems using the information and functional structure developed in the work.

The NUa for this verification is only represented by one active terminal unit (TUa) and consequently only one PM module. Although, this sufficient in testing the indented part of the work as the TUa might be the fundamental future intelligent power node existing close to all electrical equipments.
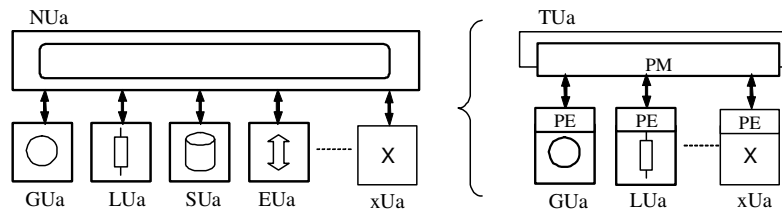
Figure 8.1: Analysis and verification model.

The analysis model is general and could be used for other areas as described in Chapter 9. Although, this chapter include many of the tests performed for this work, many pre-tests made to provide these are not included. Numerous simulation test benches for different time scales have been successively verified and included in the model libraries.

Purpose

The general purpose for the analysis is to prove the "stand-alone" and "plug-and-produce" concept by verifying the modular information and functional structure for an active DPS.

Limitations

The thesis work covers selected parts of the power system from the bottom field layer to the market where only the operational layer is analysed and verified in the analyse and verification.

In the laboratory, only three converters were available, which have caused same minor adjustments in the control strategy for some scenarios regarding the coordination of primary and secondary control and their safety zones.

8.2 Test scenarios

The aim for this work is to build and test a number of small distributed test scenarios. In order to achieve this several well-chosen scenarios have been configured to make sure that the different parts of the system are tested. The DPS is tested both in a simulation environment and in a laboratory environment. The same tests are made by simulations as well as in the laboratory. This section explains the tests scenarios and the purpose for each scenario.

Scenario 1

The first scenario includes only one active generation unit (GUa) connected to the active network unit (NUa), as shown in Figure 8.2. The power unit selected in this setup could also have been a storage unit or an exchange unit, which had worked similar to fulfill the purpose.

NUa

GUa
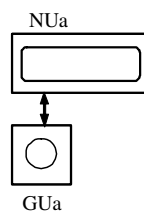
Figure 8.2: Setup for scenario 1.

The purposes are to test the start up and electrification of the DC power system and to verify that the communication between the production management and the production exchange is working properly. This is essential enabling next following tests with more advanced scenarios.

The tests for this scenario may appear a little bit different between the simulation and the laboratory test. In the laboratory, the generation unit is represented of a converter station, where it is important to verify that it really works as intended. Tests of all the different control modes of the converter have to be verified before the unit can be tested in the automated system.

Scenario 2

This scenario includes one active generation unit, load unit (LUa) and network unit, connected according to Figure 8.3. The generation unit is responsible for the voltage level of the local DC-network unit. During start up no power unit except the one able to control the voltage of the network unit is permitted to start. The generation unit is started in droop mode to control the voltage. When the DC voltage has reached its rated voltage limit the load unit, starts to consume power from the DC-network unit. The generation unit should then automatically compensate with as much power as the load unit is consuming.
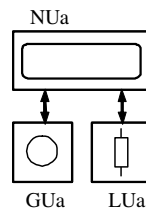
Figure 8.3: Setup for scenario 2.

The power that the generation unit is able to produce will be a fixed value but the power that the load unit requests to consume will vary in a sine-shaped curve. The idea of the test is that the power as the load unit want to consume will be higher than the generation unit is able to produce in some occasions. This is done to check if the system is able to manage this situation without getting unstable. If the load unit is requesting more power then the generation unit can provide, the maximum power set point permitted for the load is changed to be equal to the maximum power provided by the generation unit at that moment.

The purpose of this scenario is mainly to verify that the parts of the software program managing the load (load management) are working as intended. But it is also used to make sure that the droop mode for the generator is working as intended to maintain a stable voltage level in the DC-network unit.

The expected power curve is shown in Figure 8.4, where the power generated by the generation unit G1 follows the power consumed by the load unit. The power as the load unit L1 requests to consume is shown with a broken line and the actual with a full line. The power for the generation

unit G1 is drawn in a full line on the positive side of the power axes. The small bump in the beginning illustrates the power needed to charge the network unit.
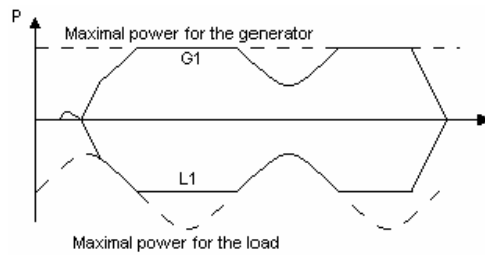
 Figure 8.4: Expected power curve for scenario 2.

The power as the load unit requests to consume will be followed except for when the limit for what the generation unit can produce. Then the set point for the load unit will be locked to the maximal power provided by the generation unit.

Scenario 3

This scenario includes two generation units, one load unit and one network unit as shown in Figure 8.5. Correspondingly to the first scenario, there is one generation unit controlling the voltage of the DC-network unit. Before the voltage has reached its rated voltage no other power units are allowed to be activated.
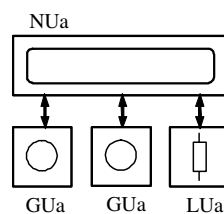
Figure 8.5: Setup for scenario 3.

The maximal power that each generation unit is able to produce is set to be a constant value while the power requested from the load unit will be sine-shaped as in the previous scenario. When the load unit consumes more

power then half of the maximal power of what the droop mode generation unit can produce, the second generation unit will provide the remain.

This purpose of the scenario is to verify the primary and secondary control function. This is done by checking that the generator controlling the voltage is producing power at half of its capacity as much as possible according to the primary control function. It also checks that the function of the primary and secondary control coordinates as intended by operating a second generation unit in secondary control mode.
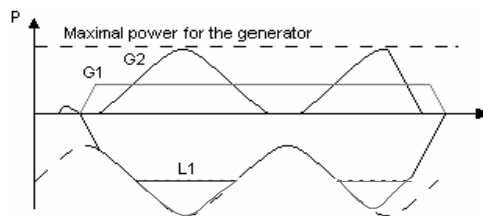
Figure 8.6: Expected power curve for scenario 3.

The expected power curve for this test is shown in Figure 8.6. The power produced by the droop mode generation unit (primary control) is showed in grey and the power produced by the second generation unit (secondary control) is showed in black on the positive side of the y-axis. The power as the load unit consumes is showed in black on the negative side of the y-axis. The first thing that occurs is that generation unit G1 charges the network unit until it has reached its rated voltage level. After that, the load unit L1 starts to consume as much power as requested. When the power consumption of the load unit has reached half of what the generation unit G1 can produce, the second generation unit G2 provide needed power to cover the rest of the power requested by the load unit.

Scenario 4

Scenario 4 includes one generation, storage, load and network unit as shown in Figure 8.7. The generation unit has a time-varying maximal capacity and is regarded as a wind turbine unit. Both the load unit and the storage units have constant power capacities.

The idea of the test is that the storage should store energy when the generator have a high capacity and add energy to the network unit when the generation unit (wind power) has a low generating capacity. The generation

unit manages the primary voltage control by operating in droop mode similar to the other scenarios, and will try to keep the droop mode unit at half of its capacity.
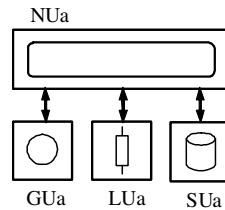
Figure 8.7: Setup for scenario 4.

The purpose of this scenario is to test the storage management module in order to verify that it is working correctly. The expected power curve looks is shown in Figure 8.8. The grey curve on top of the graph is representing the amount of energy the wind power unit can produce at any given time.
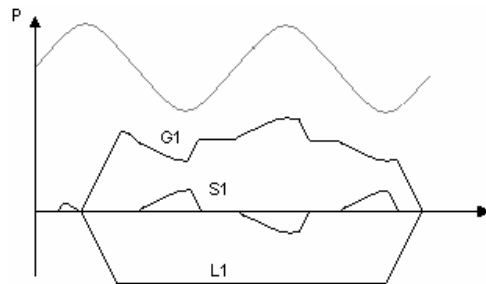
Figure 8.8: Expected power curve for scenario 4.

The test procedure is intended to first start the generation unit G1 that controls the voltage on the grid. Thereafter, the load unit L1 will start to consume as requested. When the load unit consumes more power then half of the capacity of the generation unit, the storage unit will start and share the load. The generated power of the storage unit should be enough to keep the generator to produce power at half of its capacity.

Since the storage unit is chosen to be small it will get drained rather quickly. That is what happens when it goes to zero the first time. The load unit will still get all the power needed but the safety distance upwards for the generation unit can no longer be maintained. After a period, when the capacity of the generation unit is high, the storage unit will start to charge.

The storage unit will reach its upper limit shortly after and stop charging. Normally, the second generation unit stated, in this case the full loaded storage unit, will share the load equally. However, due to the small capacity of the storage unit, the system determines to only aid the primary control unit.

Scenario 5

Scenario 5 is very similar to scenario 4. This system includes one generation, load, network and exchange unit (EUa) as shown in Figure 8.9. In this system as well as in the system in Figure 8.5 there is one generator with a variable maximal production capability and one load, which is supposed to consume power at a constant level.
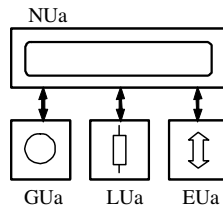
Figure 8.9: Setup for scenario 5.

The exception is the exchange unit, which is intended to work as a transmission link to a similar adjacent DPS. This test is about verifying the exchange management module.
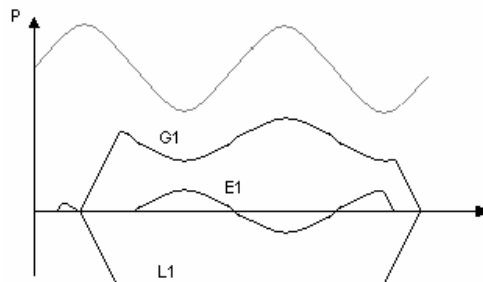
Figure 8.10: Expected power curve for scenario 5.

This module functions very much like the storage management module regarding the intension to manage a bi-directional power flow. It does

however differ in some aspects from the storage unit since it doesn't have any energy storage and can therefore not become empty or full.

The purpose for this test is to show that the exchange unit works as intended. The test for the exchange unit is made in the same way as for the storage unit and the expected power curve for the test looks like in Figure 8.10. The grey curve is representing the maximal power capacity of the generation unit G1. The exchange unit E1 will always try to keep the power produced by the generator G1 at half of maximal capacity. Meaning that, it will try to import power to the power system when the power from generator is not sufficient and try to export power from the system when the generator has high capacity.

As shown in the expected curves the result is similar to the storage case except for that the exchange unit is not limited by the energy storage capacity.

Scenario 6

This scenario includes three generation units and one load unit interconnected to the network unit according to Figure 8.11. This scenario has not been tested in the laboratory as only three converter station where provided, meaning that the verification is only performed by the simulation program. The three generation unit will have a constant power capacity while the capacity of the load will be time-varying. The consumption of the load unit will follow a ramp, which will continue to get a higher and higher power consumption all the time.
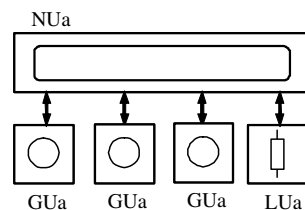
Figure 8.11: Setup for scenario 6.

The purpose for this scenario is to test the start-up sequence that is described previously in the part about control strategies. The basic algorithm, if system includes several generation units, is that the first and second generation unit should start in primary control mode and the third in

secondary control mode. However, the third will also be started in primary control mode if needed. The scenario is also intended to test that the generation units are operating within predefined safety limits. The expected power curve for this scenario is shown in Figure 8.12. This Figure shows that the first generation unit G1 starts in droop mode and supplies the load unit. When the power level for the generator G1 reaches 80% of its maximal value, the second generation unit G2 will start, also in droop mode. Since both of these units are working in droop mode they will share the power that is supplying the load unit. The droop mode generators are not allowed to produce more power then half of their maximal capacity in order to have some safety margin if any of them should fail. Since the power demand from the load unit still increases and the droop generators already produces power at half of their maximal capacity, the third generator G3 starts and supports the load unit with the extra power needed.
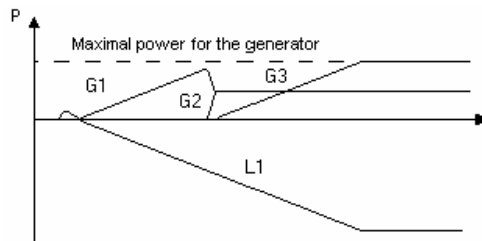
Figure 8.12: Expected power curve for scenario 6.

This generator is started in power control mode (secondary control). The power generated from this unit is allowed to produce equal to half of the maximal capacity of the droop mode generation units (primary control). This since the droop mode generators must be able to cover for generation unit 3 if this suddenly would fail or loose its contact to the network unit.

Scenario 7

Scenario 7 includes three load units and one generation unit interconnected to the network unit as shown in Figure 8.13. The power capacity for the generation unit will vary and the load units will have constant power demands but at different values. The load units have different priority assigned in order to be able to choose which one to be turned off if needed. Depending on how large the power capacity for the generator is, the different load units will work at different power capacity levels.

The purpose for this scenario is to check that the right loads are turned on according to what have been described in the strategy part in previous chapter. The test also verifies the some of the functions in the load management module. The expected power curve for this scenario is shown in Figure 8.14. The dashed line shows the maximal capacity for the generation unit and the solid line shows the power the unit should generate.
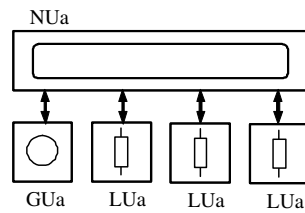
Figure 8.13: Setup for scenario 7.

The solid lines, on the negative side of the power axis, show the power that the load units are supposed to consume. The load unit with the highest priority will be turned on and supplied first. When the power capacity for the generation unit increases, the load units with lower priority are turned on according to priority.
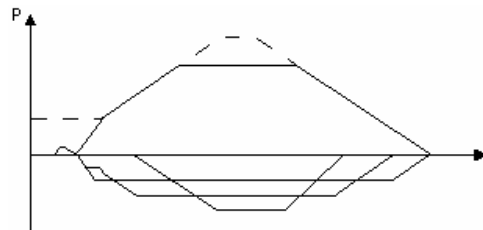
Figure 8.14: Expected power curve for scenario 7.

The same happens when the power capacity for the generation unit decreases. It is the generators with the lowest priority that will be down-regulated first by decreasing the power set point, in order not to overload the generation unit.

8.3 Verification by simulations

In this section, small DC DPSs are simulated based on described scenarios to verify the information, operation and control, and algorithm structures

developed. The simulation focuses partly on the dynamics of the system and partly the functioning of the software structure. Simulation result are presented and discussed, where simulation is proven an effective working process preventing unnecessary failures before experimental verification. A description of the simulation tools and how the coordination programs work are also explained.

Simulation set-up

The simulation program tool used in this work is Dymola and the programming language used is Modelica. Dymola/Modelica has a dynamical environment based on graphical programming where the system is built up by modules that are connected to each other. Several model classes are provided by Modelica that contain many components needed to build up a system. It is possible to develop your own model classes by using some of the modules that are provided by Modelica. By using this feature, there is no limitation to use only the standard modules provided by Modelica. It is also possible to link programs developed in C++ to Modelica and make them interact. This makes it possible to use the same source code in the simulations as used in the experimental system set-up. The simulation models are more thoroughly described in Appendix A.6, where the advantages in modularization are obvious.

Simulation of scenario 1

This first simulation is to make sure that all connections between Modelica and the program source code are working as intended and to show how the start-up sequence of the DPS works.

This system include only one generation unit and its only purpose is to set the voltage to the system to the nominal value, which is 150V. The result of the simulation is shown in Figure 8.15. The dashed line shows the voltage set point for the system and the solid line shows the actual voltage in the network unit of the DPS.

The generation unit controls the voltage by the droop mode. The droop mode controller does only have a proportional part that normally causes a stationary error from the set point. But since there is no load in the system this error is very small. The start-up sequence of the generator is shown in Figure 8.16.

The dashed line shows the command signal. This signal orders the generation unit to be on, ready or off (assigned 4, 5 or 6). The solid line is the govern signal that assign the generation unit its operating control mode. The dotted line shows the set point that is sent to the unit. In this plot, the set point is down-scaled a factor 10 to fit in this figure.
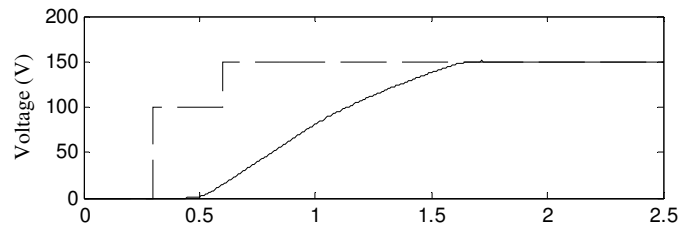
Figure 8.15: Result of simulation 1.

The first thing that occurs is that the generation unit gets a command signal that order it to be off, se the dashed line. The value of that signal is 4, and is sent to the unit with a delay of 0.1 seconds, reflecting the time it takes for the generation unit to automatically identify itself in the system and for the system to automatically create the resource in the resource manager and thereafter analysed and processed by the production management module.
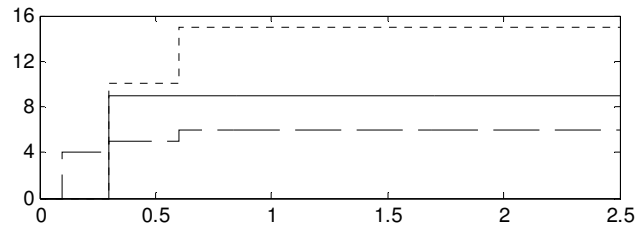
Figure 8.16: Result of start up signals from simulation 1.

Then the system orders the generation unit by the command signal to go to its ready state, represented by value 5. At the same time the govern signal changes value to 9 which order the unit in droop mode when started. The reason to why the set point is set to 100V at first is to make adjustments for when the system is going to be tested on the physical units.

The final step is when the command signal changes to the value 6, which order the unit to start. At the same time the set point will change to the

nominal voltage value of the DPS. That is the normal procedure to start up a unit. Units that are started up in power control mode will get a different govern signal value and the set point will go to its final value at once.

Simulation of scenario 2

This scenario is following the description of the scenario 2. The main reason for simulating such a system is to verify all of the algorithms that later are going to be used for the tests on physical units. This test is mainly done to check that the control programs for the load are working and the result of the test is shown in Figure 8.17. The load unit has a sinusoidal need for power that has an offset of –500 W and amplitude of 300. The frequency is 0.05 Hz. The maximal power that the generator can produce is fixed to 600W. The reason for choosing these power and voltage levels is to make this simulation as close to the coming test on the real converters as possible.
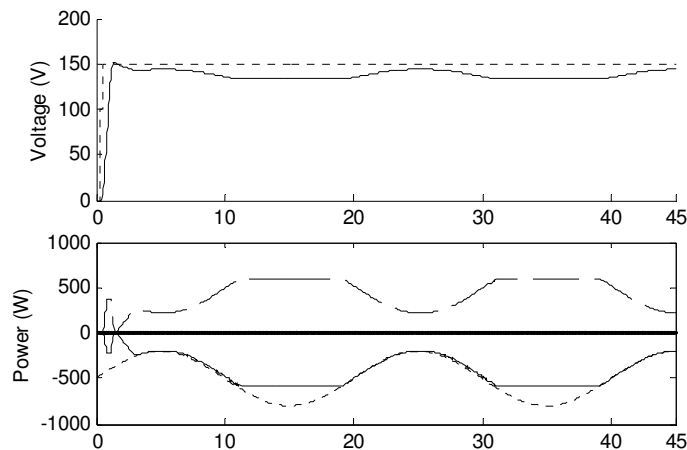
Figure 8.17: Result of simulation 2.

The upper Figure in Figure 8.17 shows the voltage in the DPS. The dotted line is representing the voltage set point in the system and the solid line the actual voltage. Here it is clearly shown that the generator is controlling the voltage in droop mode. Since the droop mode controller only has a proportional part there will be an error, which is proportional to how much power that the droop mode unit have to deliver to the DPS.

The lower graph in Figure 8.17 shows the power values in the DPS. The dashed line shows how much power that the generator delivers to the DPS and the solid line shows how much power that the load unit consumes. The dotted line is representing how much power the load requires.

The generator is properly following the consumption of the load unit until the consumption requested is more power then the generation can provide. When this occurs, the set point for the load unit will be locked to 600W, which is the capacity limit of the generation unit. The result of this test corresponds well with the expected scenario description.

Simulation of scenario 3

This simulation test corresponds to the scenario 3 description. The specification of the load unit is similar as in the previous scenario i.e. a sinusoidal power curve with an offset of –500W and amplitude of 300W and a frequency of 0.05 Hz. Both the generation units have a maximal capacity of 600W. The simulation is done to verify the generation management program. The generation unit operates in power control mode and is supposed to keep the droop mode unit at half of its capacity, in this case 300W. The result of this simulation is shown in Figure 8.18.
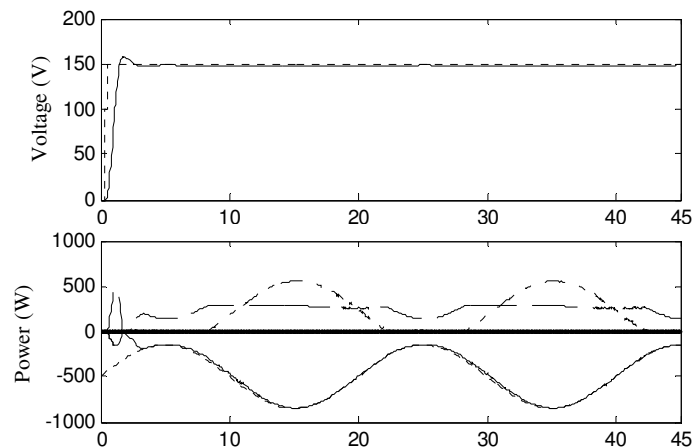
Figure 8.18: Result of the simulation of scenario 3.

The upper graph in the Figure shows the voltage values in the DPS. The dashed line in the upper graph shows the voltage set point and the solid line shows the actual voltage. The properties for the generation unit operating in

droop mode are exactly the same as for the one in the previous simulation. However, the voltage level does not vary that much due to the second generation unit.

The lower part of Figure 8.18 shows the power values in the DPS. The dashed line shows the power produced by the generation unit in droop mode and the dashed-dotted line shows the power produced by the second generation unit. The solid line shows the power that is consumed by the load and the dotted line shows the power that the load requires. Since the generation units, together, are able to cover the consumption of the load unit at all times, the load unit never is ordered to decrease its consumption. That is clearly shown in the graph where the solid and the dotted line are on top of each other. It is also possible to see that the generation unit in droop mode actually is producing 300W almost all the time.

The two dips in the power production of the droop mode generator are there because the load does not demand any more power at those points. This is possible since the other generation unit takes care of the extra power production as intended. The simulation test corresponds well with expected results.

Simulation of scenario 4

This simulation experiment corresponds to scenario 4. The generation unit controls the voltage in the network unit and has a variable maximal power capacity, which is sinusoidal with an offset of 1000W, amplitude of 350W and a frequency of 0.05 Hz. The load is a constant load unit with a power consumption of 500W. The storage unit has a maximal charging capacity of 150W and a maximal discharging capacity of 150W. The storage unit is chosen to be quite small in order to force the storage to become full, just to check that the charging and discharging management works as intended. The maximal storing capacity of the storage unit is 1000Ws, its minimal energy level when the storage is considered as empty is 200Ws and the initial energy level is the storage in 700Ws. The reason for not choosing the minimal energy level to zero is in case the storage has a power overshoot when it is supposed to turn off from discharging. Then the storage would try to discharge from an empty storage, which is not possible.

The result from this simulation is shown in Figure 8.19. The graph in the top of figure shows the voltage level in the DPS, the solid line shows the actual voltage level and the dotted line shows the set point. The middle

graph shows the power values in the DPS. The dashed line is the power produced by the generator and the dashed-dotted line is the power caused by the storage and the solid line is the power consumed by the load. The dotted line shows the maximal power the generator can produce.
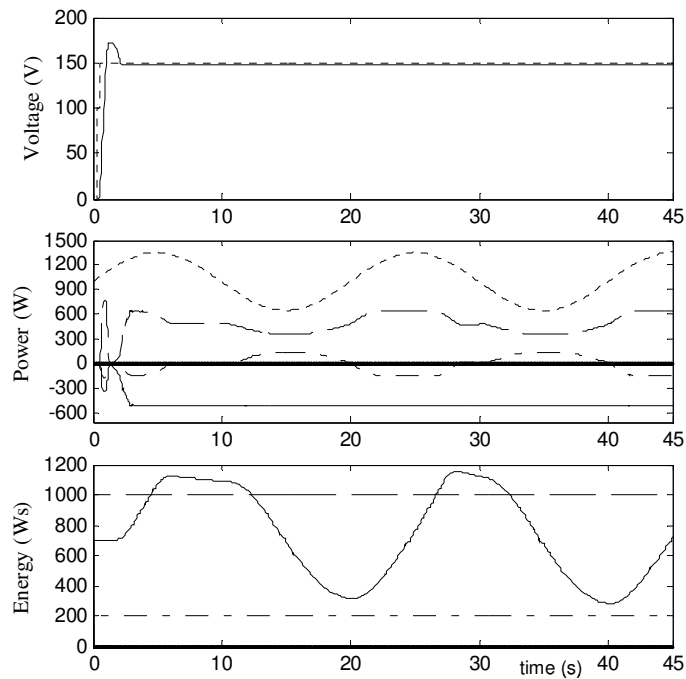
Figure 8.19: Result of the simulation of scenario 4.

The plot in the bottom of the graph shows the energy levels of the storages. The dashed line shows the maximal storage limit, the dashed-dotted line shows the minimal storage level and the solid line shows the actual energy stored, state of charge (SOC). Since the generator is operating in droop mode, the system will try to keep the generator at half of its power-capacity. The storage unit tries to charge and discharge energy to compensate for the power variations.

In the beginning of the middle graph it is shown that the generator can produce more power than requested of the load unit and the storage therefore starts to charge. The storage become full shortly after starting to charge and its set point is set to zero. The set point of the storage remains at

zero until after about 11 seconds when the maximal capacity of the generator has dropped a bit. The storage unit then starts to discharge to keep the distance between the maximal power the generator can produce and the power that it actually produces at a safe level. It continues until the maximal capacity level of the generator is high enough to allow the storage to charge again. From the lowest graph in Figure 8.19 it is shown that the energy that is stored exceeds the maximal storage level. That is because it takes some time for the storage to stop charging when the set point is set to zero.

Simulation of scenario 5

This simulation corresponds to the earlier described scenario 5. The generation unit manage the voltage controlling part in the DPS as shown in Figure 8.20. It has a variable maximal power capacity that is sinusoidal with an offset of 1000W, amplitude of 350W and a frequency of 0.05 Hz.
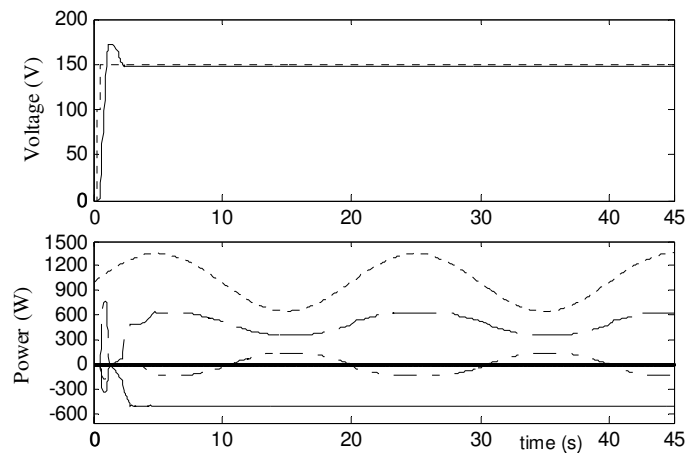
Figure 8.20: Result of the simulation of scenario 5.

The load unit is a constant load with a power consumption of 500W. The exchange unit has a maximal import capacity of 150W and a maximal export capacity of 150W. As in the simulation test 4, the system will try to keep the generation unit, which is started in droop mode, at half of its maximal capacity. The exchange unit is always able to export and import from the adjacent interconnected system. The simulation results prove to agree well with the expected results.

Simulation of scenario 6

This simulation test verifies the system described in scenario 6. The generation unit is of the same type with a constant maximal capacity of 600W. The load unit, however, has a power capacity that is changing in time. The load unit start consuming power after 5 seconds and the demand increases along a ramp like shape until it reaches 1500W.
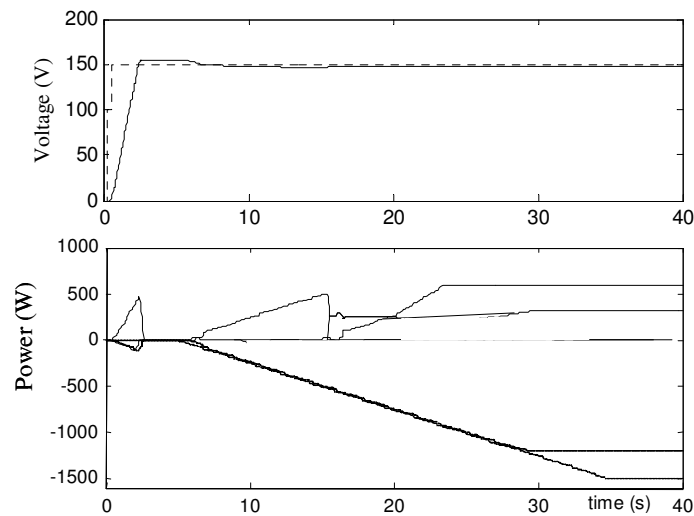
Figure 8.21: Result of the simulation of scenario 6.

The results from this experiment are shown in Figure 8.21. The upper graph in shows the voltage in the DPS. The dotted line shows the voltage set point and the solid line shows the actual voltage. The voltage in this simulation is stable all the time, which proves that the power levels are well-balanced. The lower graph shows the power levels in the DPS. The solid lines on the positive side of the power axis shows the power produced by the generation units and the solid line on the negative power axis shows the power as the load unit is consuming. The dotted line on the negative side of the power axis is the requested power from the load unit. The first bumps in the picture are due to the power network is electrified. After 5 seconds in the simulation, the load unit starts to consume power. To maintain the power balance in the DPS, the droop mode generator add the same amount of power as the load consumes. When the generator has reached 80% of its maximal capacity, the next generation unit starts. This generator starts in droop mode as well and produces the same amount of

power as the first generator. The droop generators do not produce more power then half of their. The third generation unit starts shortly after the second generator.

This generator starts in power control mode and the increase of power coming from that generator follows the increasing power consumption of the load unit. The third generator does not however produce more power then 600W since that is the highest value that the generators in droop mode can cover in case of a failure by that generator. The load unit is not allowed to consume more than 1200W since it is the highest amount of power as the generators are allowed to provide.

Simulation of scenario 7

This simulation is based on the system described in scenario 7. The three load units have constant but different power demands priorities. The load with the highest priority has a power demand of 200W, the one with the middle priority has a power demand of 400W and the lowest priority has a power demand of 500W.
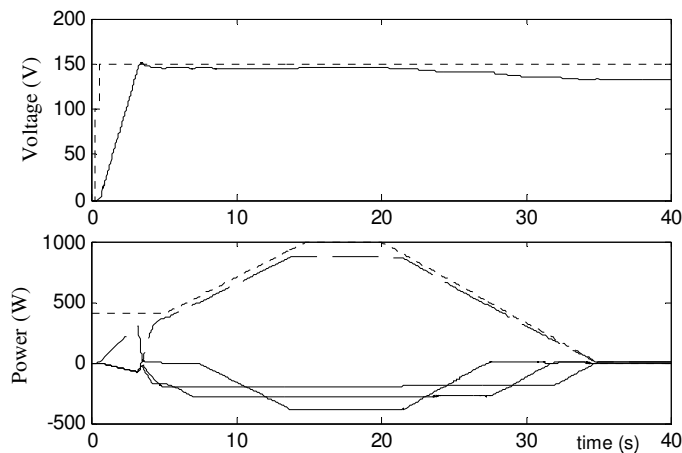
Figure 8.22: Result of the simulation of scenario 7.

The generation unit has a start capacity of 400W that is increased to 1000W, later on decreased to zero. The result is shown in Figure 8.22. The upper graph shows the voltage in the DPS. The dotted line shows the voltage set point and the solid line shows the actual voltage. The lower

graph shows the power curves in the system. The dotted line is the maximal power as the generator can provide and the dashed line is the actual power that the generator provides. The generator is started in droop mode and generates as much power as needed, as long as it is within its capacity limits.

The solid lines on the negative axis show the power consumed by the different loads. The bumps in the beginning of the picture are due to the electrifying of the system when the voltage increases. When the voltage is set, the load units are activated. Since the load units have different priorities, they get their power demand fulfilled at different times. The smallest load with the highest priority is the first one operating at full capacity, which is 200W.

As the power capacity of the generator increases, the load with the middle priority will use all of the additional power until its requirement is satisfied. After that the load with lowest priority is able to consume some power. The same thing occurs when the capacity of the generation unit decreases, meaning that it is the load with the lowest priority that has to decrease its power consumption while the others can continue to consume as much as requested.

8.4 Experimental verification

A small DC DPS is implemented based on the scenarios and result in previous section. After the verifications by simulations, the experimental part is a natural step in the verification process before applying new ideas in real systems. The very same software modules, developed for the simulation verification, are used in the experimental part, which is a strong advantage in the development chain. The main purpose of verification tests are to examine how well the operation and control algorithms and structure work on a small real system, and to verify the flexibility and modularity of the system. The tests of the laboratory setup are based on the first 5 scenarios.

Experimental setup

The experimental set-up is formed by three-phase converters connected to a 135 V, 50 Hz three phase AC grid via a transformer and three inductors, one per phase according to Figure 8.23. The three-phase transformers

create a galvanic isolation between the AC-network and the converters. The transformers are connected in YNy with the voltage ratio of 235 / 75. The voltage level on the secondary side is low since the maximum allowed DC voltage is 200V.
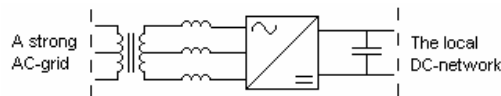
Figure 8.23: Schematic picture of one converter setup.

The minimal DC voltage on the DC-side is determined by the amplitude of the voltage on the AC-side by the ratio of $V_{DC}/V_{LL} = 1.35$. In this case the DC-bus voltage is equal to 100 V for the converter line-to-line voltage 75V. The voltage on the DC-side therefore has to be between 100 and 200 volts. The maximal rated power for the transformers is 2000VA, which sets the limit for the capacity. The line side filter inductors, 3 mH each, are inserted between the converter and the transformers. Since the maximal voltage allowed on the system is 200 volts, and the minimal voltage is 100 volts, 150 volts is a suitable voltage level for the tests.
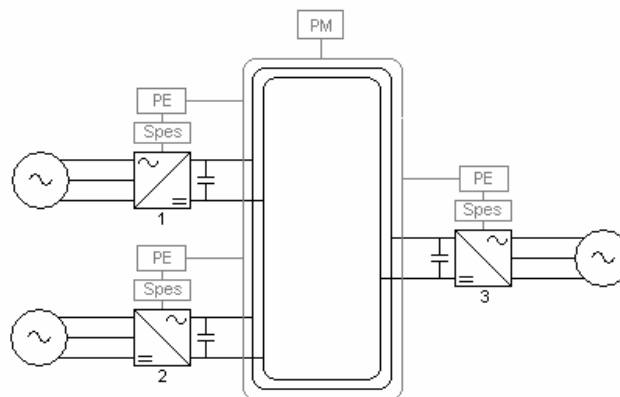
Figure 8.24: The system configuration of the investigated DC DPS.

Since the power converters have bi-directional capability, they are operated as earlier described power units. The power converter acting as generattion units are used to supply a local DC-network with power and to maintain a stable voltage level by using a tree phase AC network as a power source.

At least one other converter is operating as a load unit and is therefore consuming electric power from the local DC-network and thereby exporting the power back to the AC-network. The tests are performed by using three converters connected as shown in the Figure 8.24. Since the set-up is based on three converters it is possible to use the third converter as additional generator unit, storage unit, or exchange unit. The converter must receive information about the type of power unit it is suppose to be and the block Spes in Figure 8.24 provides that information. The Spes block gives the information as a number and it also inform the converter where the upper and lower power limits are, how fast it is allowed to increase its power and its nominal voltage level. If it is a storage unit it also provide information of how much energy it is able to store.

The PM block contains all of the automation information and algorithms. Its purpose it to make sure that the DC-grid has correct voltage level and it is trying to support the loads with as much power as possible with the generators that are connected. It is this block that decides what state the converters is supposed to be in and what set point each converter should have when they are in their active mode. The PE block finally provides the converter with the signals needed to operate it as intended at a certain point of time. It never assigns any set point higher than permitted from Spes.

Test and set-up of communication system

An automated power system is very much depending on a well-defined communication system. Disturbances can occur at any time and has to be managed immediately. It is important that the power units within the DPS have a well working communication system enabling fast coordination for operation and control. The bandwidth of the communication network is crucial in making the system responsive, and special consideration has been taken for this reason. This work includes different types of information paths that have to be solved before a fully automated DPS could be set up in the laboratory environment. The communication paths included are:

- *Converter-PC communication*: This communication link is very important because without it the converter would be impossible to control. The communication is taken care of by a program in Matlab.

- *PC-PC communication*: The different converters have to be controlled by a computer. Since the production management program has to know

what every converter is doing, all of the computers have to be able to communicate with each other.

- *Matlab - C++ communication*: The communication between all of the different units is done by Matlab but the control program is written in C++. Therefore it is necessary to find a way to use C++ files from Matlab.

- *Matlab-Matlab communication*: this is used when the production management and production exchange program are handled from the same computer. In this case it is unnecessary to use the global communication when it can be done with internal communication within the computer.

The laboratory tests on the different communication paths are further described in Appendix C.

Test of scenario 1

This first test is a start-up test but since this test uses real components there are a number of objects that had to be considered to prevent malfunction. In order to make sure that everything worked properly several start-up tests where done.

In this scenario not only the control program and its different control modes where checked, but also the communication between dSpace, the computer and the output signals managing the inrush current device and transistor switching. The steps in the list below were performed before the converter could be connected to the automation system.

1. The command mode of the converter changes state from state "off" to state "ready". In the state "ready" an enable signal is sent to the inrush current device. This step makes sure that the voltage on the DC side of the converter reaches 100 volts without overloading the diodes of the converter.

2. The govern mode of the converter is set to voltage control, the set point is assigned to 100 V and the control mode of the converter is changed from "ready" to "on". When the converter is in its "on" state, an enable signal to the switching of the transistors activates and the switching starts.

3. The set point for the voltage is now changed to 200 volts and then changed back to 100 volts again. The actual voltage over the capacitor now follows the set point without any noticeable delays.

4. The govern mode of the converter is changed to droop control. This control mode is also meant to control the voltage on the DC-side but the control algorithm does not have any integral part, which will lead to a small stationary error to the set point. The test of this control mode is made in the same way as described in step 3.

5. In this step the power control part is tested. Since the voltage level has to be between 100 and 200 volts and the load is 50Ω, the power delivered from the converter has to be between 200W and 800W.

6. The govern signal is changed to power control and the set point for the power is set to 200W. The power set point is then slowly changed to 100W and then changed back to 25W.

7. The command signal for the converter is finally changed back to "off". Now both of the enable signals are deactivated, which turns off the switching and disconnects the inrush current device.

When the converter has passed these test steps, the converter station is considered approved for further test regarding automatic control. Every new converter has to go through the same tests procedure before it is approved to be used in the more advanced scenarios later on.

The following automatic start-up test is done to show how the start-up performs and is done on one computer station. Since both the production management and production exchange program have to be running at the same time, and both of them have to he controlled by Matlab, there have to be two Matlab programs running in parallel. First the production management program is started. When it has started and is waiting for any units to contact and identify themselves, the production exchange program is started. Now all the contacts and identifications are done automatically and the start-up is similar the one in simulation test 1. The result of the experiment is shown in Figure 8.25. Here it is clearly shown that between 0.1 seconds and 0.55 seconds the converter is in its ready mode when the capacitor is charged up through the resistors in the inrush current devise. At time 0.55 the converter turns to on state and assigns the set point 150 volts, which is the nominal voltage for this system. The control algorithm that is downloaded to the dSpace does however not allow rapid voltage changes and limit the step change in the voltage set point with a ramp of 200

volts/second. This is why it takes some time for the voltage to reach its set point at 150V. The result of this test shows that all of the communication links within the computer work as intended.
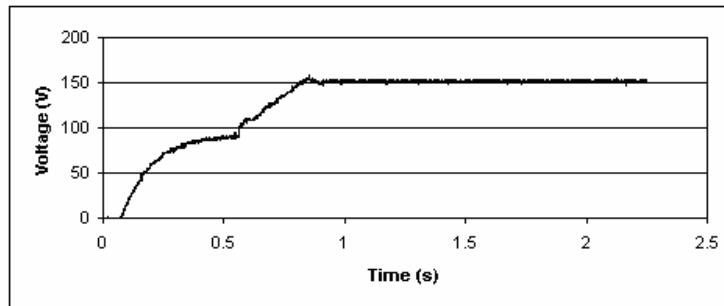
Figure 8.25: Measurements of scenario 1.

Although, the TCP/IP communication is not completely tested in this test, since the communication between the production management and production exchange program is managed in a local storage file on the same computer station.

Test of scenario 2

Scenario 2 brings that two converters are needed for this test, one that controls the voltage of the DC DPS, and another one that creates a disturbance by consuming power from the system. This means that the second converter has to be able to export power to the AC-network. This operation has not yet been tested and is here tested manually. The manual power control test from scenario 1 only covered the possibility to import power from the AC-network and not the opposite.

The first converter station is started in droop mode and controlled the voltage on the DC power system to 150 V. When reaching voltage level, the second converter station starts in power control mode. The power set point then smoothly decreased from zero down to minus 800W. The test prove that there are no problems with this mode of operation and this two-converter system is now ready to be tested automatically. As described in the specification of scenario 2, the maximal power of the load acting converter changes is consumption according to a sine-shaped waveform with an offset of 500W, amplitude of 300W and a frequency of 0.05 Hz.

The generator on the other hand is set to have a maximal out power capacity of 625W. The result is shown in Figure 8.26. The upper graph shows the voltage in the system. In the lower graph, the black curve is the power delivered to the system by the generator, the dark grey curve is the power consumed by the load and the light grey curve is the maximum power that the load requires.
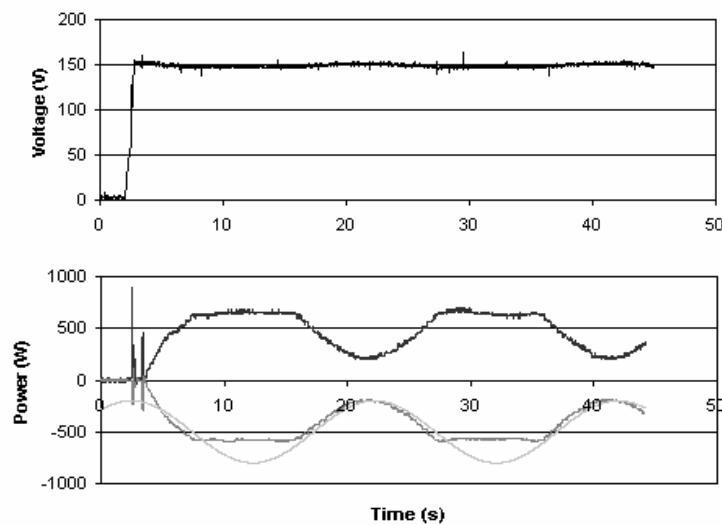
Figure 8.26: Measurements of scenario 2.

Note the difference in the voltage level in the system when the generator is working hard in comparison to when it is working less loaded. The voltage level differs a bit since the generator is in droop mode. Just as was showed in the simulation, the load was not allowed to get more power than the generator was able to deliver. The first spike in the power curves in the beginning of the lower graph in Figure 8.26 is caused from the second contactor in the inrush current protection device. The spike occurs if the voltage over the capacitor has not yet reached 100 volts. When the second contactor turns on it shortcuts the resistors that cause a higher current through the diodes. The second spike is created when the power switch for the converter acting as a load is turned on manually.

The result of this experiment proves that the expectations are fulfilled. The first generator starts in droop mode and sets the voltage of the DC power

system to 150V. When the system voltage reached 90 percent of the nominal voltage the second converter (load) started. This converter is started in power control mode and tries to consume power according to the grey curve in the lower graph. When the load converter demands more power, the set point for the load unit is set to what the generator is able to produce at its maximum. But when the load is asking for less power then the generator is able to produce, the power set point for the load is assigned according to the load demand. This test also prove that the TCP/IP communication used by Matlab works where each converter station includes an individual computer. In order to manage the information exchange between the production management program and the production exchange program, a TCP/IP communication for the remote computers is used as described in Appendix C.

Test of scenario 3

This experimental test includes three converters according to scenario 3. One of them is acting as a load unit and the other two as generation units. The power that the load unit consumes varies with respect to time as in the previous experiment. Thus the maximum power for the load is sine-shaped with an offset of –500W, amplitude of 300W and the frequency 0.05 Hz. The maximal power that the generators can produce are constant and with the size of 600W each. The specification is chosen as in the previous experiment, so it is possible to see the difference when a second generation unit is added to the system.

The result of this experiment is shown in Figure 8.27. The upper graph shows the voltage of the system. The lower graph shows the black curve and the power generated from the generation unit controlling the voltage level. The grey curve is the power produced by the second generation unit and the dark grey curve is the power consumed by the load unit. The light grey curve shows the maximal power that the load wants to consume. The system is started with the load already connected to the production management program, but it does not get permission to start until the voltage level is close to its nominal value. When the first generation unit is added to the system it is assigned in droop control mode and the voltage of the system increases to 150V. When the voltage level is reached, the load unit get permission to start and consume power. After 9 seconds the second generation unit is added to the system. But since the power consumed by the load is low when it is added, the second generation unit do not get

permission to start until after 12 seconds. As explained in the description of scenario 3, the system is always trying to keep the power generated from the generator(s) in droop mode at half of its capacity.
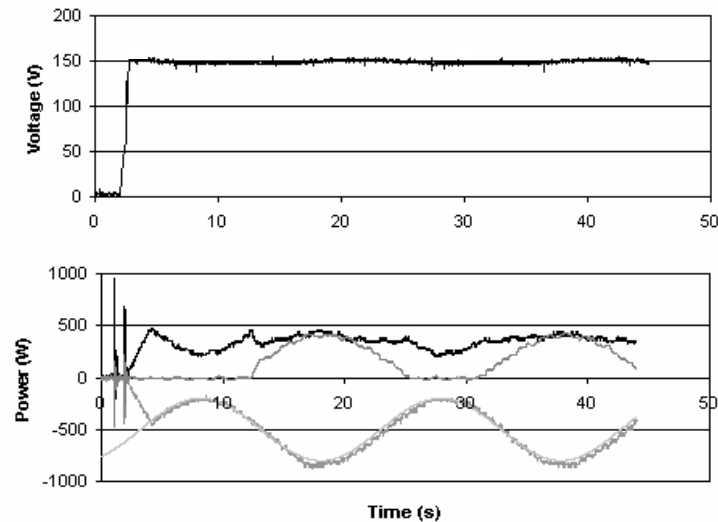
Figure 8.27: Measurements of scenario 3.

In this experiment it would mean that the black curve in the lower graph would have a constant value of 300W + network losses, which is roughly shown. The peak in the power curve at 12 seconds is due to the start-up time for the second generator. It therefore has to add some more power than expected to avoid a voltage drop. The reason for the dip of the black curve at the time 27 seconds is that the load doesn't demand any more power.

Test of scenario 4

This experimental test is a 3-converter system corresponding one generation, load and storage unit. The generator in this experiment has maximal output power capacity that varies with respect to time and could be seen as a wind power plant. The maximal power curve is sinusoidal with an offset of 1000W, amplitude of 350W and the frequency 0.05 Hz. The storage unit has a maximal output and input power capacity of 150W. The maximal amount of energy that the storage unit is able to store is 1000Ws,

and when the energy stored is less then 200Ws it is considered empty. The initial amount of energy that the storage has when the experiment starts is 700Ws. This storage is chosen to be a small storage in order to be able to check that the storage really shuts down when it is empty or full. The load in this experiment is chosen to have a constant maximal power capacity of 500W.
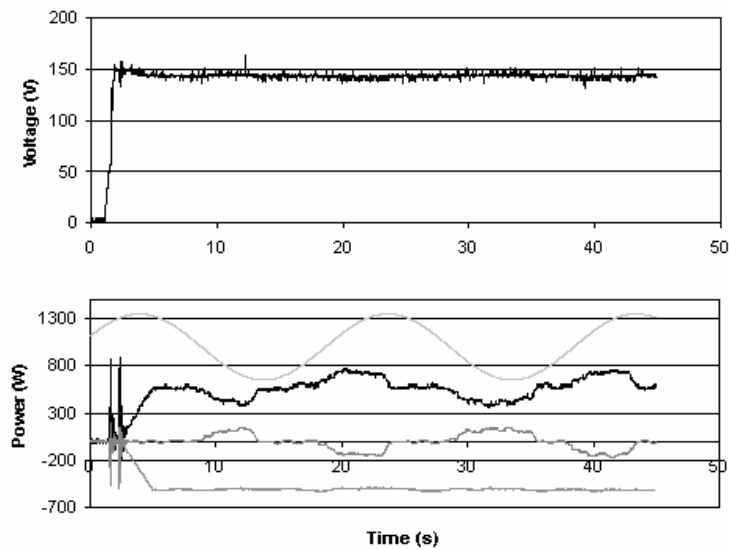
Figure 8.28: Measurements of scenario 4.

The result of the experiment is shown in Figure 8.28, where the upper graph shows the voltage. The black curve in the lower graph shows the power generated by the generator and the light grey curve shows the maximal power capacity that the generator is able to produce. The dark grey curve shows the power produced by the storage unit and the grey coloured curve represents the power consumed by the load unit.

The generation unit is first connected to the system and thereafter the load unit. When the voltage in the system has reached 90 percent of the rated voltage, the load gets permission to start.

The storage unit is added to the system after about 8 seconds and then immediately starts to generate power. The system is designed to always try to keep a safe distance between power produced by the droop units and the

maximal power they are able to produce. That is why the storage add power to the system even if the generator could manage to support the load unit by itself, load sharing. After 13 seconds the storage is empty and cannot deliver any more power. When 18 seconds have passed, the safety distance for the generator is high enough to let the storage store energy, which could be used at a later occasion. The storage reaches maximal storing capacity after a short time. After 23.5 seconds the storage is full and cannot store any more energy so the power set point for the storage is assigned zero.

The result of this experiment is as expected, which shows that the storage management module developed work as intended. However, the power-regulating controller for the storage does not operate really as supposed. This shown in the graph between 30 and 34 seconds, when the set point is set to 150W and the power produced is quite disturbed. The reason for this is probably that the dSpace interface card that belongs to the storage converter adds some disturbance to the control signals that is connected to the converter. This card is a modified card that earlier has been used in a laboratory context. The modification did however not work properly. Lots of time has been spent to try to solve the problem but the error could not be found. Although, this error does not affect the main purpose of the experiment, which is to show that the algorithms are working and to show that the system is dynamic and adaptable.

Test of scenario 5.

The aim of this scenario is to make sure that the exchange management module works as intended.

This experimental test is described in scenario 5 and includes 3 converters. The setup is very close to the setup from experiment 4, where the major difference is the replacement of the storage unit with the exchange unit. The maximal energy that the exchange unit is able to import and export from the DC-power system is for this test set to 150W in both directions. Since this exchange management module requires two power systems to work properly and only one was available for this experiment, a simulated additional system was created connecting one side the converter interface. The generation unit managing the voltage of the DC-power system has a maximal power capacity that varies with respect to time. The variations follow a sinusoidal curve with an offset of 1000W, amplitude of 350W and

a frequency of 0.05 Hz. The maximal power of the load unit requires constant 500W.

The result of the experiment is shown in Figure 8.29. In the upper graph the voltage of the DC system is shown. The black curve in the lower graph is the power produced by the generator and the light grey coloured curve is the maximal power that the generator can produce. The dark grey curve is the power that is generated by the exchange unit and the grey curve is the power consumed by the load.
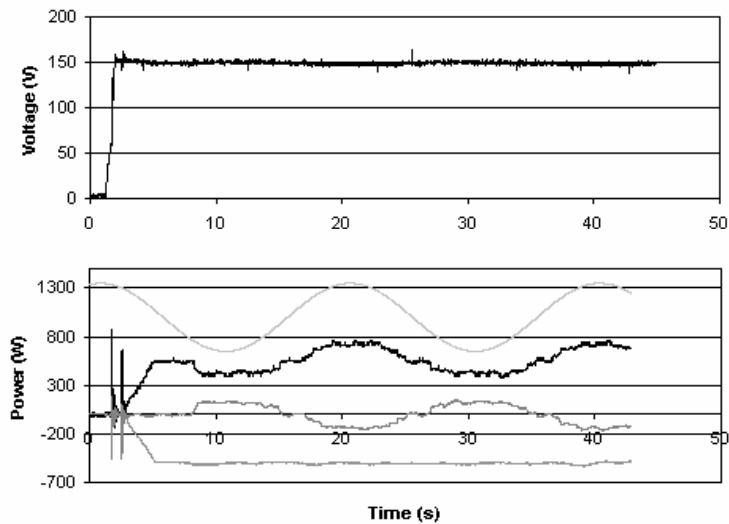
Figure 8.29: Measurements of scenario 5.

In this experiment the generation is the first one added in the information system and the load unit second. As in the previous experiments the generator is not allowed to start until another unit, that is not a generator, is added to the information system. So the generator sets the voltage in the system when the load is added. The load is started when the voltage reached 90 percent of the nominated voltage level. Since the generator could support the load with all the requested power, the load was assigned to consume power at its maximal capacity.

The exchange unit is added to the information system after about 8 seconds and immediately starts to operate with the system. As in the previous experiment, there is a safety margin between the power produced by the

unit in droop mode and the maximal power that the unit can produce and has to be maintained. The exchange unit is not able to produce more energy then 150W, which is reached after a short period. After a while the safety margin for the generator is large enough and the need from the exchange unit less significant. The power set point for the exchange unit then decreases. Later on, the maximal power from the generator is high enough to export power. Since the exchange unit always is able to export in this setup, this is also what happens. However, the power exported is never higher then 150W.

This experiment really shows that the concept of plug-and-produce works. The time between 5 and 8 seconds when only the generator and load unit were connected to the information system the generator supported the load by itself. It was not until the exchange unit was introduced after 8 seconds that the generator could get some support to feed the load with power.

Complementing tests

Complementing tests have been made to verify that the concept of plug-and-produce is working with this setup. The base of tests has been made out of two power units, one acting as a load unit and one as a generation unit according to scenario 2. A third power unit has been added and withdrawn from the system and the result of the test has been investigated.

The first set of tests that were made for these purposes was a test without permitting any converter to start at all. The purpose for this test was to verify the type of signals transmitted between the computers. The reason the converters were not permitted to start in this test was that they did not have to be on for the test and the programs were stopped at several events, which would lead to a system out of control. All of the three converters were added and removed from the production management program in different orders. The only limitation in this system was the converter station running both the production exchange program and the production management program. When this converter is added to the system it is not possible to take it out from the system. That is because it is using a local file on the computer to handle the communication with the production management. This problem is of course possible to solve by separating the two modules to different computer stations, but was not implemented in this work.

The second category of test was made with the converters on. The same tests that were checked with the converters off were conducted, but this time to verify that the converters operated as in previous experimental tests.

The results of the tests proved that the system can handle both the addition of another power unit and the removal of power units from the system, and can adapt to the new condition that occurs depending on new system configurations, all in real-time operation.

8.5 Summary

In this verification part, a small DC distributed power system has been tested both in a simulation environment and in a laboratory environment where power converters have been operated as power units. The tests have verified that the information and functional system structure is dynamic and adaptable, which includes managing several different system configurations as well as connecting and disconnecting new power units to the system at any time online. The simulation and laboratory results made proved to be very similar. That means that results from coming simulations can be used as reliable results and that they are very likely also applicable to a full scale system. The system is dynamical and can handle disturbances that may appear at any time. The rate of command signal updating in the real system can be increased by using a faster communication network or having a network that is dedicated for the power system. The communication in the real power system can also be increased by having the production management process on a separate computer. The concept of "stand-alone" and "plug-and-produce" is working as intended, which were the main objectives for the work.

Chapter 9

Applications

This chapter presents and illustrates some applications, embracing a wide range of areas, which may be useful by adopting active distributed power systems. The proposed information and functional structure may be partly or fully integrated depending on system demands. The applications are very different in aspect of environmental or individual needs and values, which in many cases is related to the standard of living and/or environmental influence.

9.1 Southern Sweden as a DPS in the Nordic power system

The de-regulation of the electricity market has increased the demands on the transmission networks and the interconnection with adjacent nations in the Nordic power system. Bottlenecks in the Norwegian and Swedish transmission networks may be a large problem with additional external interconnection and the extension of RES. The planning and operation is no longer closely coordinated with the generation units, which has lead to more varying energy and power exchange. Consequently, this increases the demands on capacity of the transmission networks and their operational flexibility.

The Nordic power system consists of several subsystems where a functional overview is shown in Figure 9.1. The subsystems are here roughly divided in Norwegian, Finland, northern and central Sweden, southern Sweden, and western and eastern Denmark. The AC interconnections are mainly represented by single EUs (AC substations) and the DC interconnections, each by two EUs (DC/AC substations) and a

DC cable. The Nordic system is very well suited for RES due to its large amount of hydro power. Technically the system could manage a large impact of RES. Although, the market needs to be changed as this is not adjusted for large fluctuations caused by RES. Norwegian are about to expand the wind power and have a large potential in managing the fluctuations technically. However at a certain degree of wind power expansion this will cause several constraints due to transmission capacity, which probably will be enforced.
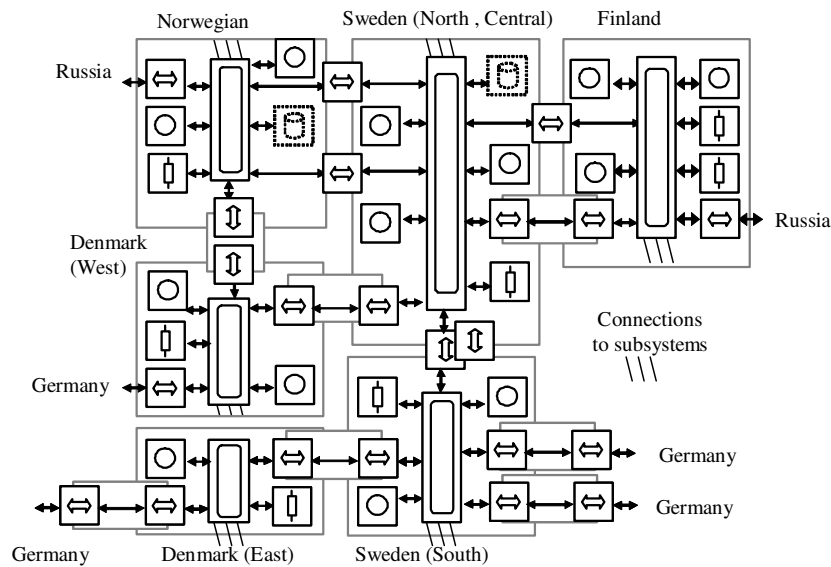
Figure 9.1: Principal functional overview of the northern electrical power system.

A future energy surplus will be exported, which may become a market by itself with green certificates. Sweden has a large generation in the north with a large amount of transmission to the south. The major part of wind power is very likely to be placed offshore in the southern of Sweden due several parameters, which may be become an advantage or disadvantage depending on future system operation. Denmark has already a large share of wind power and manages much of the fluctuation by the external interconnections.

The RES expansion and the market extension will stress the Nordic power system further where some major power failures have occurred during the latest years and one of them in the southern Sweden and eastern Denmark. The power failure (23 September 2003) occurred after some relatively fast events that resulted in a total blackout of more than 6000 MW capacity and was not completely restored until about 6 hours after the event. The possibility to prevent and restore such outages is improved by adopting a well-defined structure utilizing new technologies. Beside the structure there are physical constraints that always will be improved during time such as, communication bandwidth, computer performance, power unit controllability and the ability to respond quickly. The fundamental subjects to be considered regarding abnormal situations are as follows:

- *Fast controllable power units*: Some future power plants based on RES and transmission exchange units need to be constructed with high controllability providing the transmission network units (NU) ancillary services in the southern of Sweden. This will be the case with a high degree of power converter technology and an operational interaction enabling the TSO to quickly switch the mode of operation as described in Chapter 3.

- *Real-time information exchange*: Co-operation and communications between control centers (TUs) and controllable power units need to be assured with clear protocols so that misinterpretations are minimized during emergency situations. An efficient basis for the exchange of operational information is achieved by a closed and separated communication network implemented in the power lines with the communication protocols and their interactions as described in Chapter 4. The basis for always having the latest power resource information available is a general "resource manager" function. This function automatically manages all interconnections with the power units via the communication protocols in order to collect and distribute real-time information which is in accordance to Chapter 7. This is also fundamental for achieving something close to "plug-and-produce" which will be essential with the extension of small DG, especially solar power.

- *Temporary area delimitations*: As some areas during outages become disconnected it is important for these to be able to operate in "stand-alone" mode temporary. In order to enable control areas for such operation a fundamental structure for distributed power systems is needed as described in Chapter 5, which is active and open for

alternations in the system configurations. Information exchange in real-time operations has to be on such a level that the status of the subsystems is known in all co-operated control centers. This is achieved by the integration of active terminal units with the embedded EMS structure located at several strategical locations within the subsystems. Just before or during an abnormal situation the operating authorities is automatically assign to one terminal unit (master) to make any needed preventive or corrective action.

- *Automated decision-making*: With increasing real-time information exchange between control centers the TSOs will be distressed. Human performance in control centers during abnormal and restoration situations are essential to minimize consequences of a disturbance. A fast understanding of the situation is a fundamental need for fast decisions in abnormal situations. With the increased amount of information and demand on fast response, several decisions need to be automated in order to evaluate and react quickly enough. This is assured by adopting the automated coordination functions implemented in the EMS structure, which include separated management of each power unit category (generation, load, storage, and exchange units). The coordination functions are regarded as automated operators and described in Chapter 6.

By enclosing the southern part of Sweden and look at its future external interconnections and generation units, some of the thesis work is exemplified by a scenario with the aim to better prepare the system for such abnormal situations. In next coming decade, the southern part of Sweden can be regarded as a well-defined subsystem (DPS) as shown in Figure 9.2 with EUs equivalent to the following eight high-voltage interconnections:

- 1 controllable DC interconnection to Eastern Denmark

- 2 controllable DC interconnections to Germany

- 2 none controllable AC interconnections to central Sweden

- 1 new controllable interconnection to central Sweden

- 1 new controllable interconnection via Krieger's Flak to Germany.

- 1 new controllable interconnection via Midsjöbankarna to a Baltic State.

The existing generation units will probably be extended with the following

- 1 new large offshore wind power unit (WPU) at Krieger's Flak of at least 1000 MW.

- 1 new large offshore WPU at Midsjöbankarna of at least 1000 MW.

- 3-6 new offshore WPUs of 50-150 MW.

- 1-2 new gas turbine units (GTU) of 100-300 MW

- 1-3 new combined heating and power units (CHPU) of 50 -150 MW

Assuming that all new power generation and exchange units are included with active terminal units they become active power units. Furthermore, it is assumed that the transmission network is highly integrated with an information and communication system interconnected to several internal active terminal units, which enables a high degree of automated operating ability.
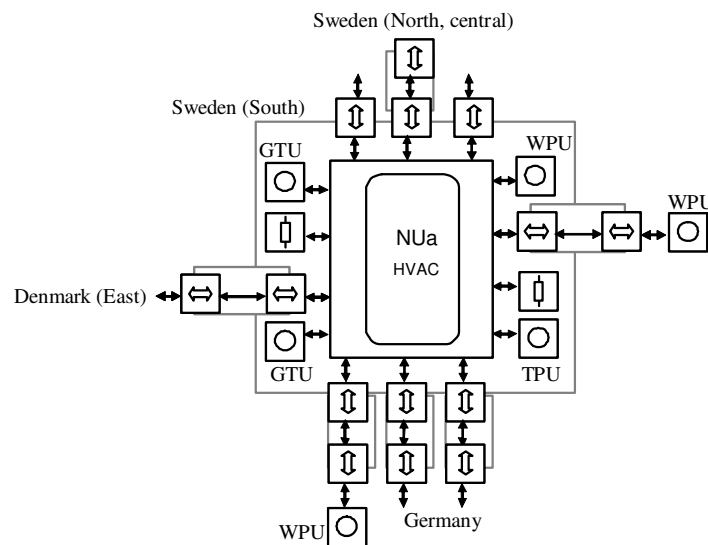
Figure 9.2: General functional overview of the southern electrical power system of Sweden.

At the power failure 23 September 2003, several parts from just before the event until fully restored may have been prevented or reduced. As the EUa:s constantly exchange information of both side of the units, the adjacent DPSs always have information of their status and states. This information would have put the southern part of Sweden in an "alert" state

where the temporary master EMS (automated TSO) in some of the TUa:s would have prepared very fast primary services to be activated. In this case, the two major wind power units that are assumed to be constructed with very high and fast controllability as described in Chapter 3 would have been temporary operated in primary control mode. Other fast power units would have been ordered ready. Information to adjacent DPSs about the change of the internal DPS "state" would also instantly been sent via the interconnected EUa:s and among them the interconnection to eastern Denmark. As the coordination function "exchange management" also sends limited transmission capacity signals via the EUa:s, the next signal from the central Sweden DPS would have limited the power exchange very quickly in this case. An automatic switch to primary control of the large wind power units would have been the only possibility to prevent a blackout that quickly. Depending on the supply and demand situation the EUa:s would have limit the total export according to priorities. This may had disconnected the eastern Denmark DPS that had come in the same situation to be solved by managing its own power units.

If the blackout had occurred anyway, the restoration process had started immediately. As the resource manager within the master EMS had instantly known all available power resources and their status, a temporary configuration had been determined automatically. From out of that the EUa:s had been limited to no export and only asked for import capacity. The load units would have been turned off in the initiation phase. The very fast primary units with "system black start" capability had energized the DPS and fast primary units had been ordered to be activated. The load units had been gradually turned on due to priority order according to the "load management" function. Depending on possible power surplus, the EUa:s had allowed export by increasing the power transfer limits, which may have been enough to aid the eastern Denmark DPS if not already activated. Depending on the time for reconnection to the central Sweden DPS, the gas turbine units had take the major part of the primary function and the most of the wind power units had turned over to the origin maximum power mode of operation.

As exemplified, in the next coming decade wind power will be the dominant RES at medium voltage and later on at high voltage level where some very large power plants will be connected. With the solar power breakthrough the medium and low voltage level will have a large expansion of generation units. The DG will then be able to provide the higher voltage level DPSs with ancillary services by aggregating the power

units to act as one controllable power unit. These aggregated units are then the result of DPSs and their structure. The lower voltage level DPSs will be operated in the same way as the southern Sweden DPS.

9.2 Future large offshore power systems

At present, numerous projects are aimed for the extension of wind power plants (WPP) offshore at medium distances as shown in Figure 9.3. This has caused several discussion and investigations regarding the interconnections and interactions from a system operational and capacity view of point. The WPPs are considered as a great source of problems due to their fluctuating production and also due to electrical quality aspects. The short distance WPPs will be interconnected at medium voltage levels (100+ kV) and at present by AC cables. Several DC transmission sea cables exist, based on thyristor technology, interconnecting nations and islands.
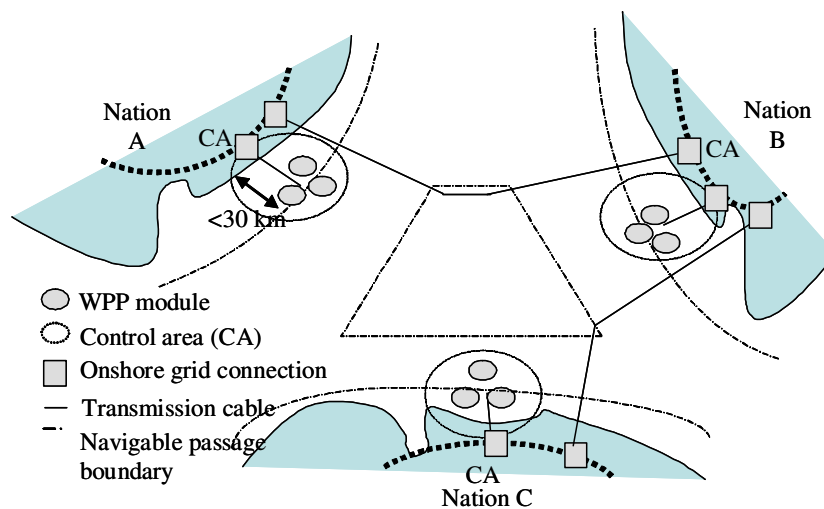
Figure 9.3: RES offshore at medium distance.

Many new such interconnections are planned that will be based on transistor technology. WPPs located close to the shore are disturbing the local opinion that is neither pleasant by the visual impacts or the possible noise caused by the turbine units. Therefore the next coming large WPPs will be placed at medium and long distances sites with good wind

conditions and if possible at low deep shallows. Combining the plans for both large WPPs and new transmission cables will enable new future offshore power system possibilities as shown in Figure 9.4. Here, numerous WPP modules are interconnected to an offshore transmission network system based on multi droop technology connected onshore at high voltage levels (400+ kV). The network interconnects three nations by active terminal units enabling the "old" land based power systems with several high quality and fast services.
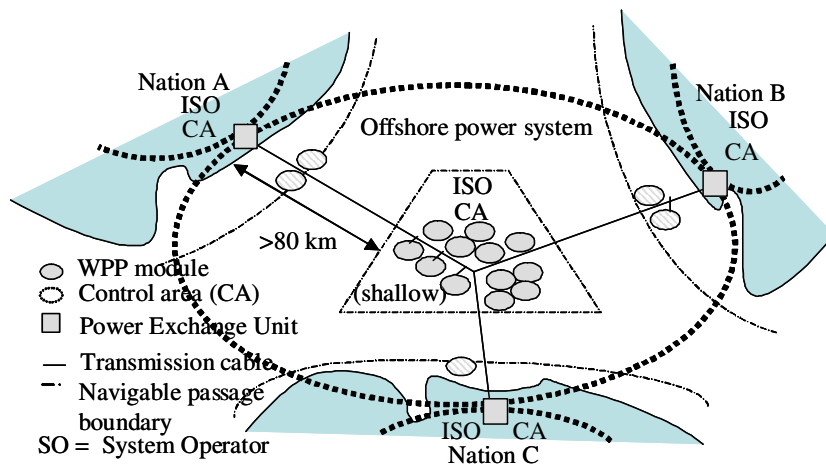
Figure 9.4: RES offshore at long distance.

If the infrastructure for those large power plants would be prepared already now with features described in this thesis, then it will be possible to gradually extend the system with new types of power units (e.g. various solar power units assembled in several ways). This will finally result in an offshore future power system including various types of sustainable generation and storage units serving both the land based power systems and also large ships with for example hydrogen at sea. Such a system could be made faster and more reliably than ever and provide strong interconnections between present power systems. This also moves the question of if the interconnections between nations may or may not imply on lower stability to if new strong offshore power system may provide both sides of an interconnection with increased stability.

The structure would be modular and capable of adding or removing new offshore DPS unit/modules see Figure 9.5, as described in previous

chapters. This includes a well functioning operating interface between power units and DPSs allowing seamless transitions when disconnecting or reconnecting in case of malfunctions. The main transmission network unit as shown in Figure 9.5 is constructed by active network units (NUa), active multi terminal units (MTUa) and DPS units.
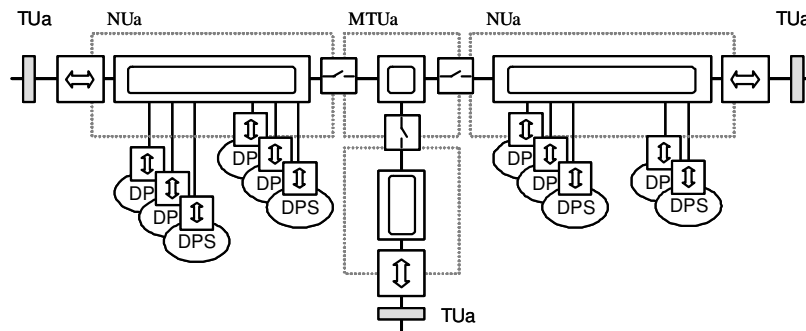
Figure 9.5: Functional structure of the offshore power system based on several DPS units.

The NUa include several MTUa or TUa units in order to connect the DPS units. At the three ends of the system, active terminal units are located to interact to the land based power systems that automatically provide the services requested. The multi terminal units enable new DPS units to be connected, which may be WPPs or other power units.
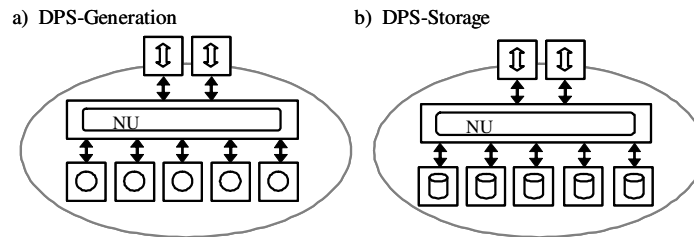
Figure 9.6: Offshore DPS functional structures a) generation units; b) storage units.

The DEMS structure in the NUa would only be located in the active terminals connected to DPSs, onshore power systems and offshore DPS unit. The DPS units, in this case, include an internal NUa interconnected to the main transmission cable by two exchange units for redundancy reasons.

The other units connected are likely of same type, e.g. generation units (wind solar) as shown in Figure 9.6a, storage units (hydrogen) as shown in Figure 9.6 b. In this case the DEMS structure is only located in the exchange units as these DPSs are very similar to only one generation or storage units with redundant interconnections.

A future global integration of power systems may be achieved by gradually interconnecting nations either by direct DC transmission lines/cables or offshore active power systems where best appropriate. This will probably always be a changing process with no absolute end solution. Although, the way information and functions is utilized will simplify the operation and control during the changes and transformations, which is correlated to system flexibility and reliability.

9.3   Extension possibilities in developing countries

The developing countries suffer a high degree of exclusion from several infrastructure services where one is the electric power infrastructure. The electric infrastructure is essential to provide several other infrastructures to function such as:

- The basic infrastructure that covers all the main common-user services as energy and water supply, transport and telecommunications, sanitation and waste facilities, etc.

- The social infrastructure includes facilities such as schools and hospitals.

- Economic infrastructure that provides services to a wide range of users and also structures the environment in which people live and work. Work is provided by the development of an industry that among other things demands electricity.

The electrification of small villages is one important fraction of what is needed to build up such infrastructures. However, some new requirements for DPS are needed in order to enable the extension:

- *Transportability*: Each unit delivered to the DPS site and assembled there should not exceed the volume and weight limits set by common vehicles used on rugged overland routes and the weight limit set by small, manually operated crane gear used for assemble active power units or parts of them at the location. The volume limit and the

combined weight limit which are to be applied to transportation of DPS units should be limited by the size of a container.

- *Quality*: Each component or unit of DPS should be delivered to its place of operation in a state which is factory assembled and tested in order to provide high reliability.

- *Mass-manufacturability*: In minimising the total costs of each individual DPS, the power units have to be classified in rather few production series and in a large number of each production series to be manufactured. This probably demands the manufacturers to automate their production lines and make the products cheaper.

- *Service and maintenance*: The containers should be equipped with remote monitoring devices, enabling the unit to transmit reports or alarm when needed. As the units are autonomous no operators are needed. The container unit should be constructed to withstand outside environment influences and disturbances in order to minimize the period of service. Several of these tasks could be managed by local population.

The power units that are subject to all the above constraints and, depending on the size of DPS are:

- *Generation units*; would be mostly based on solar photovoltaic panels and the maximum power point tracking converter may be included close to the panels or embedded in a container depending on connection distances.

- *Storage units*; would probably be based on water electrolyser, hydrogen storage and fuel-cell for long-term usage. For short-term usage or standby batteries would be used.

- *Network units*: based on connection units (cables) and multi terminal units.

The usage of containers or alike is important and may be utilized in various ways. A suggestion is that a container could be configured as a multi terminal unit shown in Figure 9.7a. The container consists of an internal bus bar based on DC connected to several converters with the possibilities of various tasks. Internal short-term storage units may be included, for environmental protections, depending on external interconnections. The operation and control is managed by the included control system (corresponding to the EMS) that is connected to all internal devices via an

LAN. The container content and its functional capability are in correspondence with the active multi terminal unit shown in Figure 9.7b. This could also be seen as a power router described in [Matsumoto and Yanab, 2002] that is able to switch the internal connections between its in and output connections in all combinations. A possible extension of DPSs is then made by making all necessary equipment and power units adaptable to containers. Some containers could be constructed to be used as hydrogen storage and during transportation loaded with cables and other electrical equipments. Others could be loaded with solar panels sections ready to be placed on and around the container to avoid site specific installations as much as possible. Solar panels could also be placed on the roof of the building where it is best suited depending on solar direction, shading and roof angle. Much work could be prepared before the arrival of the containers such as cable digging and ground management intended the containers.
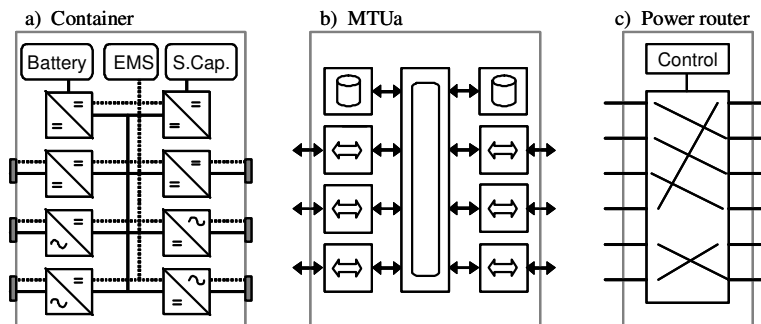
Figure 9.7: a) Autonomous container construction; b) active multi terminal unit; c) power router.

As shown in Figure 9.8, a MTUa could be placed close to small villages and as all preparatory work is assumed to be done the cables are connected to the unit. The MTUa is pre-set to provide all connected load units (building) with pre-requested electrical properties and the solar sections automatically starts to produce power in accordance with supply demands. As the supply demand increase, the extension can be made by simply adding a new MTUa that is automatically adapted to the system. As time goes by and several villages have been supplied with similar devices, interconnections between villages are made by connecting affected MTUa. This will form an active network unit (NUa) as described in Chapter 5 that more effectively could utilize the generation and storage units throughout

the increasing system. The system is simply extended in all parts as the power units are modular and easily transported to almost any location. As the infrastructure grows and, in time, when container based units are replaced by permanent power units, the containers can be moved to next area of need.
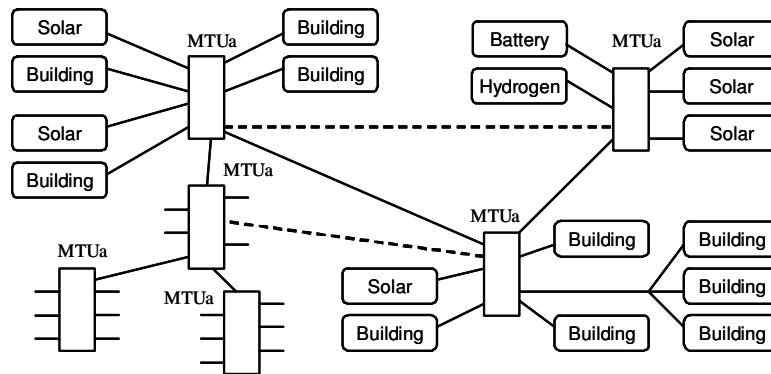
Figure 9.8: Principal extension of electrical infrastructure.

The procedure may look simplified not take several things into consideration, but the principles are still possible if the costs for such equipment could be significantly decreased. The principle is also very well suited for temporary residences as for several expeditions.

9.4 Transport vehicle and vessels

The transport sector put enormous development effort on future technology with purpose to minimize environmental pollutions. For example, in the vehicle industry several new types of cars are under development. The hybrid models have several different configurations regarding power supply and even the electric motor cars have different solutions. Independent of configuration, future vehicles should basically have the same information and functional structure fore the internal energy and power management as for power systems. The car is actually a mobile DPS that is not much utilized as a fraction of the 24 hours of the day, depending on the driving habits of people. When not used, the car is supposed to be recharged by whatever fuel needed. In future, this could probably be done in several ways. Furthermore the vehicles could have a more active role towards the local power system.

All future vehicles could provide the network with services and not only consuming the power from it. This means that they could be a part of total system and consequently should apply the same electric infrastructure. If a car would be constructed in a modular manner as in Figure 9.9, the storage units (diesel, battery, hydrogen, etc.) could have the same dimensions and embedded in standardized devices/units. The wheels could be regarded as load units but also as exchange units. In the exchange unit case, the autonomous unit include a wheel, a machine, a converter and control unit. This unit export power from the internal NUa (NU1 in the figure) during acceleration and import during retardation, which is common in electrical or hybrid car configurations.
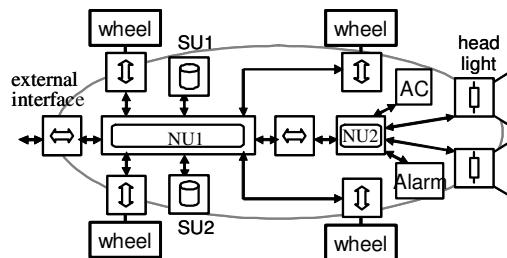
Figure 9.9: DPS structure embedded in a vehicle.

The modular structure provides the car industry and the customers with several opportunities. For example, it could be solely an electric car by using the both standardized storage unit places for batteries or it could be some type of hybrid car using a small-scaled gas turbine for one of the storage places. The gas turbine should then be operated at constant speed (base load) and the battery for peak loads (primary control). As storage or generation units for cars develop, the storage places are easily used for those as long as the standardized format and interface are kept uniformed. The internal power network would probably be divided according to capacity and priority. In Figure 9.9 there are only two active network units (NUa) included, the high capacity (NU1) and low capacity (NU2). Roughly, the NU2 may include all comfort electrical devices and NU1 all functional units for moving the car. This is only a principal example on how to adopt the structure where the actual subsystems and their different interconnected power units should be carefully configured. Moving to vessels the same principle could be used by exchanging the four wheels to one or two propellers. Regarding a sail ship this is the same as the system may import power to the internal NUa, if needed/allowed, when sailing or

export from the internal NUa when having the sails down and still at sea. In the motor ship case the propellers would be just regarded as load units. In large ships, the structure would resemble the power system with several sub DPSs as the system include numerous electrical applications and devices. During harbour visit, the ships may be connected to the local power system, similar as in the vehicle case, supplying or demanding services.

9.5 Concluding remarks

The basic DPS structure is implemented in application examples not only including the EMS structure for operation and control. Although, this should remain unaffected by all other specific management systems (SMS) by only communicating through the production exchange (PE) management modules, which is the basis for keeping it modular and simple. For example, independent if applying the DPS structure in an intelligent building, a vehicle or a vessel, the SMS for applications such as lighting coordination management, elevator coordination management, propeller or wheel coordination management etc, should not be integrated in the EMS software structure. The SMS programs should, if possible, only be used for setting on/off schedules that are distributed to each local intelligent device. The local device then always activates itself by asking the production management (PM) module for permission via the PE. The significance of each device/unit is, as described in earlier chapters, managed by priority order according the EMS strategy. Individual priorities are locally assigned in the intelligent devices/units, which is important for the function of the system during abnormal situations. For example, in a car the break devices should have the highest priority making the EMS always supplying those units independent of operational situation. In conclusion, the configuration of the DPS-EMS should only be in accordance with the basic principles, which enable the settings of primarily the strategies and specific priority orders of the internal functions for the DPS. The power units connected could be managed according to SMS where the initial settings like unit type, priority, capacity are assigned and will be identified and get permission to operate via the PE interface exclusive. Although some small devices are not included, many functions could use the same control unit platform where the PE software is separated from the intended device/unit.

Chapter 10

Conclusions

The thesis presents a possible solution for making the power system adaptable for future changes and disturbances such as the extension of distributed generation and renewable energy sources. Means for scalable and autonomous distribution systems are proposed, which might provide greater reliability and improved survivability depending on local system configurations and possibilities. A summary of the obtained results is first given and secondly some future research topics are proposed.

10.1 Summary of results

The applied research was mainly in the area of distributed power systems, renewable energy sources and system automation with focus to develop a general information and functional structure for automated system operation. The results of the thesis are here summarized and include:

- Principal structure for distributed power systems
- Potentials of renewable power sources
- Distributed energy management system structure
- Information and communication structure
- Advanced real-time functions for system operation and control
- Object oriented module library and simulation model libraries

Principal structure for distributed power systems

A principal structure for DPSs has been developed and investigated where power units and their interfaces have been classified. The structure is modular and has proven capable of adding or removing power units during

operation. This includes a well functioning operating interface between power units and DPSs allowing seamless transitions when disconnecting or reconnecting. The structure is scalable and is applicable for larger power systems as well as for smaller, such as buildings or stand-alone system. It may even prove applicable for vehicles, vessels and aircrafts depending on technical solutions.

The DPS structure is open and flexible and has only operational restrictions depending on system configurations. Regarding the control area delimitation the DPS is able to automatically disconnect from the main system and maintain operation. However, the possibility and duration of islanding operation is much depending on the power unit types included in DPS. For example, if the requirement on maintaining the DPS operation during a longer period is high and the system has a high penetration of intermittent generation units (renewals), a storage unit is likely needed that may increase the value to DPSs. Storage units enhance the operating flexibility of a DPS and should also be considered based on the overall DPS reliability and not just for intermittent generation units when balancing investment costs contra level of reliability. The reliability degree varies according to power network configuration and the controllability of interconnected power units. If possible, the network should be of active type based on active power nodes and active power flows connected in a ring structure valid for both power and communication. Depending on local demands, new DPSs should be based on active solutions while existing systems might partly convert into such when appropriated or possible.

Potentials of renewable power sources

DPSs based on converter technology enhance the control capabilities of advanced distributed generation. The potential of renewable energy sources, mainly wind power, have been investigated. The controllability of wind power may be more responsive than any other present generation unit depending on system configuration, technology and possible market interaction. It has been investigated that wind power units are able to participate in both primary and secondary control and even provide black start service. The design and controllability of a wind power unit (plant) will correspond to the service demands on the power network interconnection. This could vary widely depending on localizations and the capabilities of existing power units. A wind power plant designed as proposed DPS structure containing wind turbines based on power

electronic converters, will have the highest controllability related to other WPP structures.

Distributed energy management system structure

A principal structure for distributed energy management system containing three management layers has been developed interacting both the market and power system. The structural functions are general and basically support distributed system management for all operational actors and their responsibilities, e.g. producers, distributors and consumers. As the structure is distributed and fully automated, the system management could be placed at various levels in the power system and also at numerous single points in the system. As the DEMS structure is embedded in all active power nodes, they are also represented at every branch or power terminal unit in the system.

At process level, or production management layer, a control system structure has been developed for the operation and management of isolated power systems with high penetration from RES. This includes functions for automated operation of various system configurations. The structure has proven capable of automatically adding or removing functionality due to changes in system configurations or suddenly limits of power units.

Information and communication structure

The possibilities for analysing and controlling a system are much depending on the information available and its structure. Consequently, a part of the work have included the development of a real-time information, database and communication structure containing uniform communication interfaces for mainly three levels and also enclosed interface functions managing most of the data. The information structure has been studied for different levels of communication, ranging from process- to market level communication. Although, most focus has been on the operational structure layer including several signals enabling the management of common generation resources as well as intermittent power recourses such as RES. Among other things, a general dynamic data and power resource management system has been developed and included in the structure, which has proven essential achieving something close to "plug and produce".

For redundancy reason, it is preferable using a ring bus for communication. However, this depends a lot on the transmission network structure of the power lines/cables and their placement as the operational information between transmission operators and interconnected power resource operators is supposed to be transmitted via the power lines, either by optic fibres or the power line communication. Laboratory tests have shown that the communication speed was sufficient for distributed real-time operation. This of course depends on the type and amount of information requested from each power resource, and also by the type of strategy regarding the distribution of decision-making over the network.

Advanced real-time functions for system operation and control

Advanced programming modules have been developed for analysing, scheduling and unit commitment enabling the DPS to be self-configurable, self-operative and self-healing. Together with the information structure the DPS is provided with the "stand-alone" and "plug-and-produce" capabilities. Each module includes several functions and algorithms. Functions for managing different types of power units have been developed such as generation management, load management, storage management, and exchange management. The functions are mainly using a rule-based algorithm for decision-making and the determination of system configurations. The management functions enable automatic operation and control for different system configuration. Priority based algorithms for system coordination and unit commitment have been adopted that are general and easily extended. Strategic operation algorithms to start up, maintain normal operation and shut down adequate power units have also been developed to cooperate in both primary and secondary control. General searching algorithms are developed in finding adequate information from the resource management system. The modules are managed in real-time, and they collect and condense all needed resource data, analyse and process the information, and finally distribute orders throughout the system for local processing.

Object oriented module library and simulation model libraries

The work with central and distributed operations, and advanced real-time functions have resulted in a module library including a number of different modules that are integrated for performing specific tasks at various levels. The modules contain several object oriented classes programmed in C++,

which has been the most central part enabling a dynamic programming structure that adds and removes resource objects when needed. All signal management and central functions for coordinating resources are implemented in the module library, which are related to transmission network operation. The same module library was both connected to the simulation tool and also in the laboratory, which proved to be useful when verifying the same test cases first by simulation and later on in the laboratory.

Verifying the work by simulations has lead to the development of several model libraries handling different time scales. Advanced modeling tools and control techniques were needed to allow the operation of a wide range of RES and transmission network solutions. The object-oriented modeling language Modelica and the simulation program Dymola have been used and they are most appropriate for modeling of large systems. Simulation models have been developed with advanced controller structures. In the long time scale, several different energy sources have been investigated and modeled. The following model libraries have been developed:

- *SignalFlow*, which includes models for the entire information system applicable at all control levels. This is based on active communication nodes and flows that interact with the software module library.

- *ControlFlow*, which mainly includes models corresponding to process control systems. It ranges from sensors, actuators to flow chart blocks and regulator blocks for local control. All communication between the function models and the control units are based on the SignalFlow library.

- *PowerElectronics*, contains several types of converters that are frequently used as the demands on controllability have become important. The models are also divided depending on time scales and are based on the SignalFlow and ControlFlow libraries.

- *RenewablePowerSystems*, contains sub libraries for wind power, solar power, storage and loads. The models vary from single units to plant systems and employ the above three libraries.

- *PowerFlow*, is mainly used for verifying the EMS structure and the network operation of various DPSs. Most of the models are simplified and interconnected to the C++ module library. All experimental test scenarios have been modeled and verified using this library.

Experimental results

The software modules and simulation model library have been used when analysing various system configuration and structures. The final test of the work was done experimentally based on the simulations. A laboratory set-up was designed to verify the information structure and the automated operation and control functions for different system configuration. The laboratory set-up included three converter stations interconnected via an internal DC-bus and a local network for communication. The test results proved that the structure managed the requested demands on "stand-alone" functionality and that the adding and removing of power units worked as "plug and produce".

10.2 Future work

Although the presented work proposes increased reliability by introducing active power networks with a high degree of automated functions, the decision-making can never be better than the information provided. As the information is based on a large amount of data transmitted from the power units, the basic local operation and its strategies are essential when the communication is out of function. Correspondingly, extended methods regarding local strategy and control have to be more properly investigated as the system should not be shut down as a result of a communication failure.

Extended investigations regarding communication performance is needed finding bottlenecks throughout the hierarchy from process to market level. For example, pushing the limits might result in an increased market rate improving the market conditions for intermittent power units. Depending on future penetration level by renewals, the market rate might be important or/and the efficiency of forecasting tools.

Alternative algorithms for information searching, decision-making, resource management and resource coordination might improve the efficiency and thereby the performance. However, this has not been a limit in this research since there have been a small number of power units. Studies with numerous power units (hundred to thousands) could be evaluated in finding computing limits and improvements.

The interconnection and interaction between power units, including RESs, and the power transmission network need to be further developed to reach

an interface standard. Such standards must be universal in a move toward plug-and-produce capability. However, more can be done, especially in increasing the functionality of active network units. Expanding this functionality is a key element in helping modernize the power network, creating an even more efficient electric power system.

The developed module and model library should be seen as a foundation or framework for further model extension and verification tool when studying new system configurations. The model library has an open structure where the model components easily can be modified and extended. As the DPS structure is rather complex ranging in several time domains, new models needs to be developed at the service and market levels. However, there are many possibilities since the libraries cover several working areas regarding power delivery systems using information system.

The laboratory set-up could be extended using several DPSs with various configurations for different applications. Further investigations on disconnecting and reconnecting DPSs could be valuable to study the operating limits depending on interconnected power units.

The DPS configurations should be investigated from an economical point of view where the degree of reliability and the penetration of renewals should be considered as well as the balance between cost and functionality in each power unit of the DPS. This could then be compared with the possible extended values of the DPS at a specific location.

Eventually, after verifying the DPS structure by additional simulation and experimental studies, it is essential to find a suitable site for field tests, either in an existing control area or by building and construction a new test control area with appropriate power units that could be interconnected to an existing network, more or less as shown in Figure 2.10 that was the origin idea for this work.

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Appendix A

Model Library

Models are important for almost all engineering activities. They are used in design and analysis of new and existing systems and they are an increasingly important ingredient in all static and, above all, dynamic systems. Requirements on increased productivity and quality make the systems more complex which means increasing engineering effort in design. At the same time there are demands for shorter development time to a lower cost. Tools that increase the engineering efficiency are therefore essential.

The model libraries for this work are developed in the simulation tool Dymola [Dymola, 2004]. Dymola is an integrated simulation environment (SE) for developing models in the Modelica language [Modelica, 2002]. Dymola is an object-oriented SE for modeling transient physical systems that has good support for interconnecting other object-oriented languages such as C++, which is well exploit in these libraries [Freiseisen, *et al.*, 2003] [Remelhe, 2003] [Svarstad, 2001] [Al-Agtash, *et al.*, 2000]. The libraries developed are here summarized.

- *SignalFlow*; includes information system models applicable at all control levels. This is based on active communication nodes and flows that interact with the software module library.

- *ControlFlow*; includes process control models and ranges from sensors, actuators to flow chart blocks and regulator blocks for local control.

- *PowerElectronics*; includes several types of converters and some machines.

- *RenewablePowerSystems*; include several sub libraries for wind power, solar power, storage and loads.

- *PowerFlow*, is mainly used for verifying the EMS structure and the network operation of various DPSs. Most of the models are simplified and interconnected to the C++ module library.

All main libraries have, in principal, the same structure and include five sub library levels.

- *dBase*; include partial model classes to construct the framework of the other model levels.

- *dComponent*; include model classes of well-defined and limited equipment used at power plants (energy processes), e.g. solar panel, wind turbine rotor.

- *dUnit*; includes model classes of well-defined and limited equipment used at power plants, solar power units or wind power (wind turbine)

- *dSystem*; include entire systems as a power plant system, e.g. several interconnected wind turbine units.

- *dValidations*; include test benches for the different model levels to be validated.

Some libraries has an additional dControl sub library including model classes regarding specific control intended only for this explicit library. This library utilizes the main library "ControlFlow".

A.1 Base structure

The "dbase" library structure is the same for each main library and is shown in Figure A.1 a, which is the foundation for every higher level model class.

The dBase library contains the dConnector, dInterface, dIcon, dRecord, and dFunction library. The usage of these base libraries is illustrated by an example as shown in Figure A.1 b.

a) dBase library   b) model class inheritance
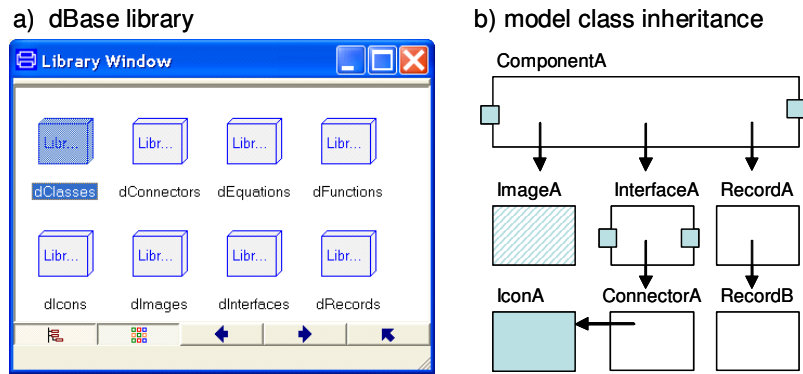
Figure A.1: a) Base structure included in all sub libraries; b) model class inheritance hierarchy.

The sub library dConnector contains several connector (terminal) types that are defined by the following Modelica semantics:

connector connectorA (example)
    Real   voltage;
    flow   current;
end connectorA;

The model interfaces, within the dInterface sublibrary, are composed of icons and connectors as below where the interfaceA has two connectors.

partial model InterfaceA (example)
  extends dIcons.IconA;
  dConnectors.ConnectorA connectorA;
  dConnectors.ConnectorA connectorB;
  Real voltageA = connectorA.voltage;
  Real currentA = connectorA.current;
  Real voltageB = connectorB.voltage;
  Real currentB = connectorB.current;
end InterfaceA;

The model component class is composed of imageA, interfaceA, and recordA, which is the framework for all components and units.

model componentA (example)
  extends dImage.ImageA;

```
   extends dRecords.RecordA;
   extends dInterface.InterfaceA;
   Real      value;
   // specific component or unit equations
   value = dFunctions.getValue();
      ………………
end component A;
```

The advantages of this multilevel inheritance are several. The library developer may choose various ways of structuring a library that may be easily updated or modified. For example, if changing an icon or parameter in a record, this is made in one single place, which propagates to all affected component and unit classes throughout the library structures.

A.2 SignalFlow

This "SignalFlow" library is interconnected with a C++ class library whit the objective to simplify the signal exchange in large simulation models based on modular designs. This corresponds to the signal flow for real applications by representing common networks as models with general interfaces.
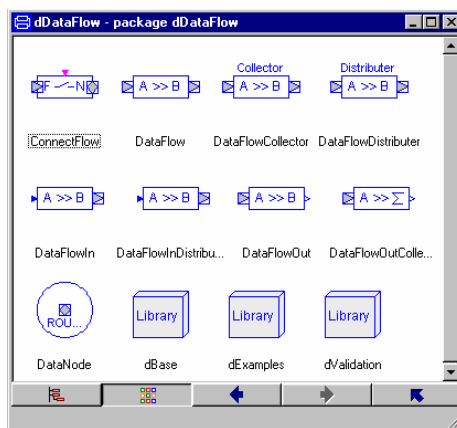
Figure A.2: The SignalFlow library.

The library enables automatic configurations during simulation using dynamic vectors and has additionally functions for exchanging several types of signals in both continuous and discrete mode. The SignalFlow

library is shown in Figure A.2 and mainly contains the following component models:

- The *SignalNode* (SN, SNode) model manage all in and out coming signal interfaces initiated by the SignalFlows

- The *SignalFlow* (SF, SFlow) model represents the signal configuration between the SNodes.

- The *SignalFlowOut* (SFO, SFlowOut) model has a standard Modelica output terminal to interconnect with other library models.

- The *SignalFlowIn* (SFI, SFlowIn) model has a standard Modelica input terminal that supplies the signal system with signals.

- The *SignalFlowDistributer* (SFD) model is similar to the SFlowIn but initiates an automatic search for SFlowOut models that are configured according to a predefined SType.

The main component models are constructed by several sub libraries within the Base library. The sublibrary dConnector contains two connector (terminal) types that are defined by the following Modelica semantics:

```
connector SignalNodePort
    Real   signalNode;
    flow   signalLine;
end  SignalNodePort;
```

The second connector "SignalFlowPort" is identical except for the icon, which is a triangle instead of a quadrangle as in the "SignalNodeConnector" case. The model interfaces, within the dInterface sublibrary, are composed as below where the node and flow have one two connectors respectively.

```
partial model SignalNodeInterface
  extends dIcons.SignalNodeIcon;
  dConnectors.SignalNodePort nodePort;
  Real nodeS  = nodePort.signalNode;
  Real lineS    = nodePort.signalLine;
end SignalNodeInterface;
partial model SignalFlowInterface
  extends dIcons.SignalFlowIcon;
```

```
    dConnectors.SignalFlowPort flowPortA;
    dConnectors.SignalFlowPort flowPortB;
    Real nodeA  = flowPortA.signalNode;
    Real lineA   = flowPortA.signalLine;
    Real nodeB = flowPortB.signalNode;
    Real lineB   = flowPortB.signalLine;
end SignalFlowInterface;
```

The user interface assigning the SNode parameters are shown in Figure 5 where the node type can be used to force the node to be of storage type. The node identity is normally automatically assigned but could also be forced to a specific value, and the last parameter determines if the node should be continuously or discrete. The SNode in the SignalFlow library is initiated and automatic assigned an identity by the zNodeInit function.
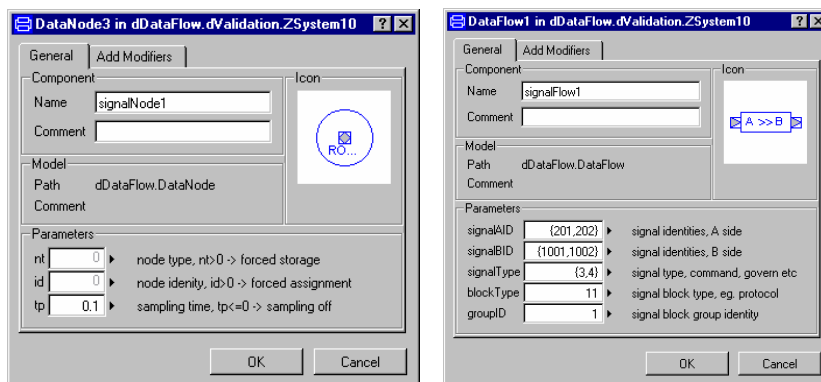
Figure A.3. User interface for assigning the parameters of the SignalNode (left) model and the SignalFlow model (right).

The function argument is a configuration vector (cv) where all predefined parameters are placed. Dependent on whether the SNode should be discrete (sampled) or continuous the variable nodeD or nodeC is assigned. When initiated the node updates every time interval according to the SE and extended equations are only one technique solving the discrete or continuous options. The SNodes are always initiated at simulation start and during simulation the only input is the "lineS" that is one of the arguments in the zNodeUpdate function. As the "lineS", per Modelica-definition, is declared as a "flow", all connected SFlow models are summarized in this variable enabling the node to examine which lines that is active.

```
model SignalNode
  extends dRecords.SignalNodeRecord;
  extends dInterfaces.SignalNodeInterface;
protected
  Real nodeID(start=0.0);
  Real nodeC(start=0.0);    // continuous
  Real nodeD(start=0.0);    // discrete
  Boolean sampleTrigger;
equation
  when initial() then
    nodeID = dFunctions.zNodeInit(cv, cvSize);
    reinit(nodeC, nodeID);
  end when;
  sampleTrigger = if samplingON then
        booleanPulse1.outPort.signal[1] else false;
  when sampleTrigger then
    nodeD = dFunctions.zNodeUpdate(nodeID,
            lineS,  time);
  end when;

  der(nodeC) = if samplingON then 0.0 else
              nodeID – dFunctions.zNode_
              Update(nodeID, lineS, time);
  nodeS = if samplingON then pre(nodeD)
          else nodeC;
end SignalNode;
```

By definition, the SFlow model has always a flow of signals from A to B as shown by the icon and in the "SignalFlowInterface" declaration where the two terminals are denoted A and B. The SFlow model is initiated as soon as the variables "nodeA" and "nodeB" are positive. The initiating function, zFlowInit, then automatically returns the line identities lineAID and lineBID. In normal operation the SFlow only checks that the line is correct for transmitting. If a failure occurs on the line, the ""lineA" and "lineB" are assign to an error code. When the line is restored the initiating process once again is performed.

```
SignalFlow
  extends dRecords.SignalFlowRecord;
  extends dInterfaces.SignalFlowInterface;
  Real flowID(start=0);
```

```
   Real lineAID(start=0);
   Real lineBID(start=0);
equation
   when (nodeA*nodeB > 0) then
      flowID = dFunctions.zFlowInit(nodeA, nodeB,
                  cv, cvSize, signalType, sTypeSize,
                  signalAID, sAIDSize, signalBID,
                  sBIDSize);
      lineAID = dFunctions.zTryConnectFlowOut(flowID,
                   nodeA, time);
      lineBID = dFunctions.zTryConnectFlowIn(flowID,
                    nodeB, lineAID, time );
   end when;
   lineA = dFunctions.zFlowUpdate(flowID, nodeA,
          lineAID, nodeB, lineBID, time);
   lineB = dFunctions.zFlowUpdate(flowID, nodeB,
           lineBID, nodeA, lineAID, time);
end SignalFlow;
```

In the SignalFlowOut model the lineB is not used and in the SignalFlowIn model the lineA is not used. They are replaced by the "value" variable that is connected to the standard Modelica Input or Output connectors.

```
   ---------------------------------------------SignalFlowOut ---
   lineA = zFlowUpdate(flowID, nodeA, lineAID);
   for index in 1:sTypeSize loop
     value[index] = zFlowGet(nodeA, lineA, index);
   end for;
   ---------------------------------------------SignalFlowIn ----
   lineB2 = zFlowUpdate(flowID, nodeB, lineBID,…);
   lineB  = zFlowSet(nodeB, lineB2, value, valueSize);
```

In the zFlowInit function, the argument is equivalent to the "SignalFlowRecord" that corresponds to the signal classification in Figure A.3.

Verification

The "SignalFlow" library is verified by using all the components in several connections as shown in Figure A.4. At the left hand, there are two identical areas with internal control using the signal facilities. The

SGIdentities are assigned 1 respective 2 that in this case also represents the two units. Unit 1 is not connected until 0.3 second after simulation start for testing of components added during simulation. Each unit has a SNode (SN) corresponding either to a communication intermediate storage area or a complete database for the unit where a number of signals are selected. All SNodes are assigned to 10 Hz sample rate.
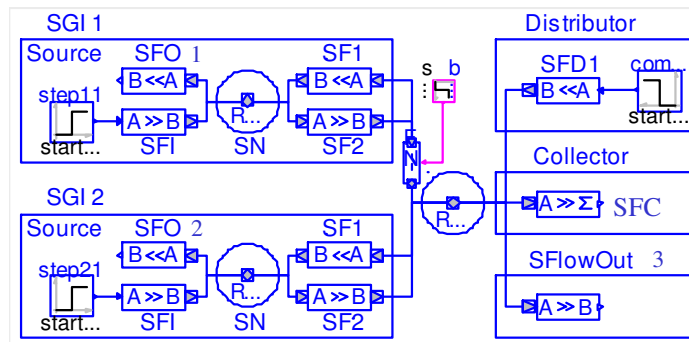
Figure A.4. Signal system setup for validation of several different signal exchange possibilities.

The signals are distributed to the SFlowOut (SFO1, SFO2) models of respective unit, which is shown in the upper graph in Figure A.5, where the initiating for configuration requires 3 samples. At this point, the SFlowOut2 is in operation state and updates the signal to the value 1.0. The SFlowOut1 should have been operated in the same manner but is not connected until time equal to 0.3 second, which then takes another 2 samples to be configured before turning to operating state. At 0.8 second, the two signals are directly increased to verify that there is no delay time in operation state.

This example shows that the SNodes can handle altered configuration during simulation with only a few samples of delay and that the signals are distributed to the intended units. Moreover, in the other signal flow direction, the sources of unit 1 and 2 are constant 1.0 respectively 2.0. The SFlowOut3 are configured by SIdentities to connect these to signals. In the middle graph, Figure A.5, this is also shown by first being delayed 3 samples before operating the signal from unit 2 and then additionally 2 samples for unit 1 due to the afterward connection at 0.3 second. Assigning the SBTypes and STypes configures the SFCollector in the third case. The

bottom graph is the same as in the previous case. The value 1-3 corresponds to the sum, max and min functions, which are correct at 0.5 second, where the sum is equal 1+2=3, max=2 and min =1.
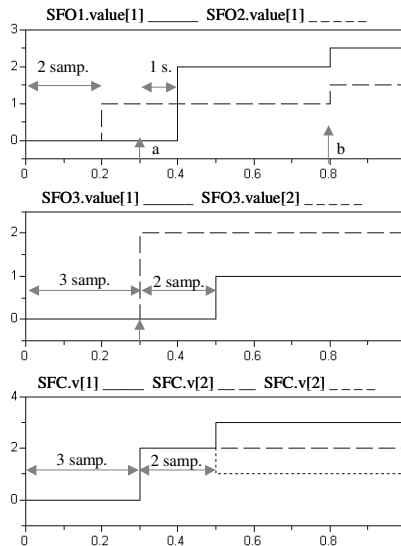
Figure A.5: Simulation results for the validation model.

However, this example is configured with a small number of SNode and SFlow models that imply that few samples are needed for the configuration state. Consequently, in more complex system models the configuration sample delay increases but not necessary in time, depending on the sampling rate.

A.3 ControlFlow

The "controlFlow" library includes different hardware and software regarding control systems as sensors, control units etc. The library distinguishes between discrete and continuous control by sequential control blocks and continuous regulatory control blocks.

The main purpose of the library is to provide other libraries with control system blocks and reusable functions. The first sub library "dBlocks" include several levels of function blocks as shown in d). These are exemplified in the later described wind power plant model structure as for most of the model classes in this library. Sub library b) include an extended

version of the Petri Net library in Modelica to manage several new interconnections and functions. This is utilized in most of the sequential control blocks in the control software. At field level, several input and output blocks have been developed. The sensors can be chosen to be filtered by parameter settings and have also internal control of its status, which is used to inform higher level control units.
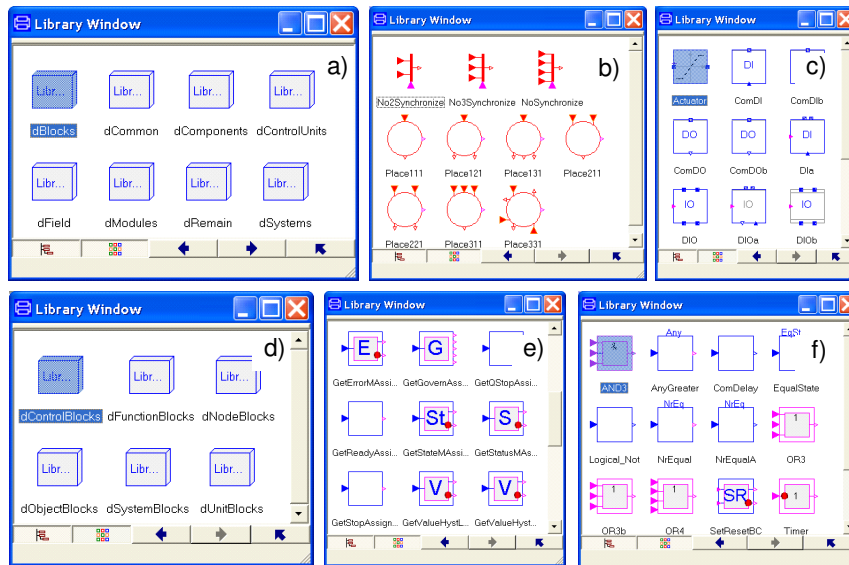
Figure A.6: ControlFlow library overview.

The sub library in e), include signal managing block according to the operational communication interface (OCI) that determines the validity of each used signal before entering a function block. Sub library f) include various standard logic block used throughout the control structure to check logical conditions and some also include memories (states) as for the SR-block, e.g. not to lose information in case of communication failure. Another sub library includes communication equipment model classes that are interconnected to the SignalFlow library, which is the nerve throughout the control systems, especially when distributed as in this case.

The "ControlFlow" library includes sub libraries and numerous model classes not treated here, where several are described later in the Appendix.

A.4 PowerElectronics

The "PowerElectronics" library primary includes different types of converters and the electrical equipment needed to verify them. In Figure A.7 (a), an overview of some of the included sub libraries is shown. The sub library dConverters (c) includes DC/DC and AC/DC converters for different time scales. A more sophisticated converter library is developed in [Karlsson, 2002] which ranges in micro- to milliseconds.

The most used converter is the simplified DC/DC type that partly is based on research from [Carlsson, 1999] and has excluded the modulation and switching parts. This model is used in the range of seconds for power flow analysis and is more thoroughly described in the "PowerFlow" library.
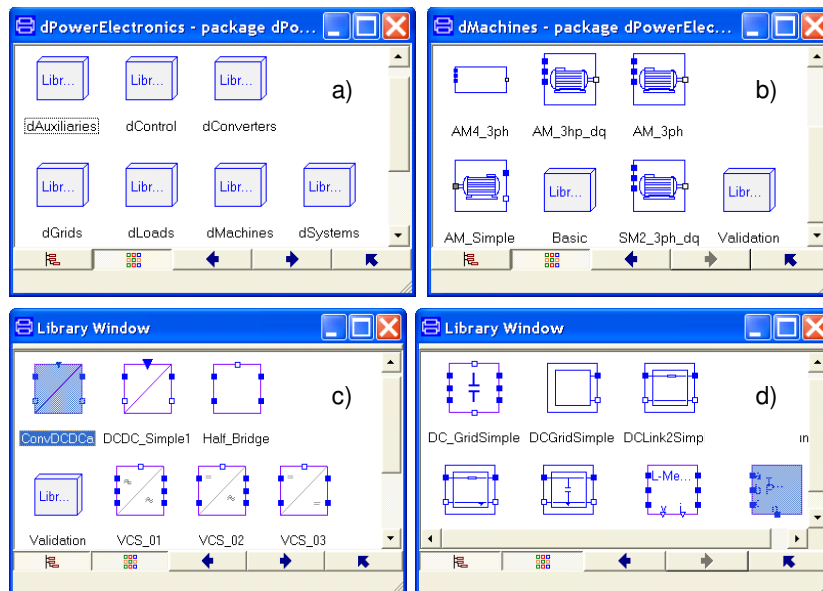
Figure A.7: PowerElectronic library overview.

Various simplified grid and transmission models are found in the dGrids library (d) and some machine types (b) are developed and used as almost any generation unit include generators for electricity conversion. The sub library dControl include different control blocks to control the converter types and their applications.

The electrical connectors adopted (terminals connecting model classes) are using the standard connecters provided by the Modelica Electrical library in Dymola. Several developed components in the PowerElectronics are based on the already existing Modelica library. The basic purpose is to have model classes that can be used by other libraries and this is made by using uniformed interfaces.

The "PowerElectronics" library utilizes the previous described libraries dBase, SignalFlow and ControlFlow. Specific developed control blocks that are not considered general are placed in the locally sub library dControl that include different types of DSP blocks.

A.5 RenewablePowerSystems

The "RenewablePowerSystem" library includes several self-contained libraries as the SolarPower-, WindPower-, Storage- and Load Libraries as shown in Figure A.8 (a). Each of them are structure as previous described in Appendix A.1 that includes the dBase, dComponent, dUnit, dSystem an dValidate sub libraries.
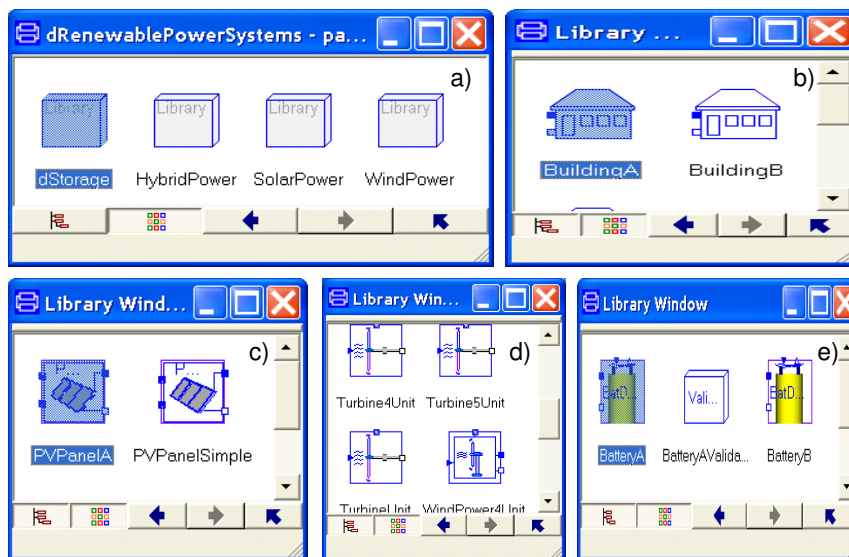
Figure A.8: RenewablePowerSystems library overview.

The Load library (b) includes several types of load which are embedded in the building model. The overall building energy consumption is based on temperature balances and some statistic data.

The other consumptions are represented by statistic curves which depend of the time in terms of the hour on a particular day and actual month. The losses of temperature in the building and the hot water for the showers take effect from a hot water tank. The hot water tank model is heated by an electric heater controller that keeps the temperature between a predefined interval. The heater plus direct current use in the building are together building up a load that affects the DC- net. Several test benches have been made to validate the model classes and some system models have been analyzed, which are described in following sections.

A. 5.1 Solar power model

The solar power library includes some solar panels where one is shown in Figure A.9. The photovoltaic panel (PV) test bench model includes the PV Panels model and the weather model class.
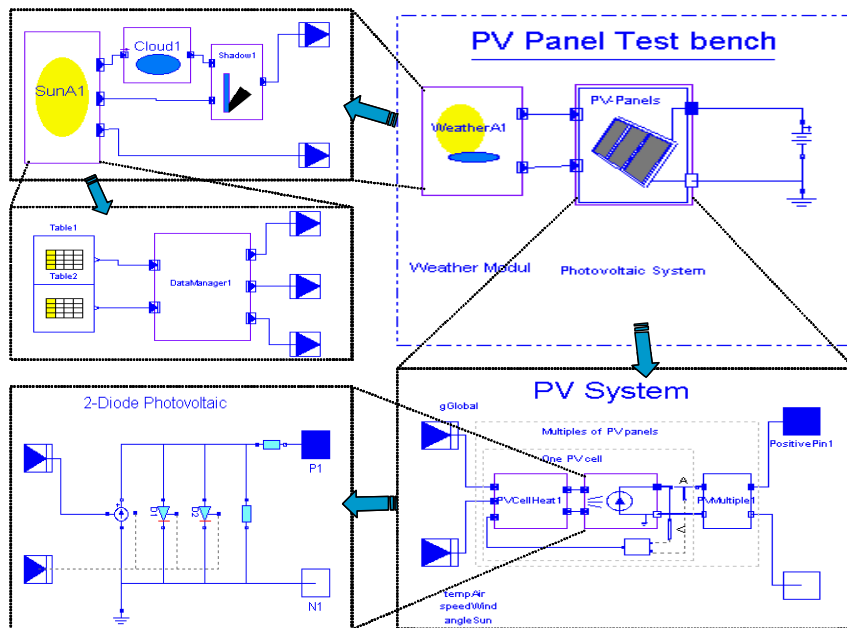
Figure A.9: Solar power test bench model structure.

The weather model includes separate model classes for solar irradiations and different types of shading classes, one for clouds and one for physical objects affecting the PV panels. The SunA1 model includes Modelica models, Table 1 and 2, that reads weather data from specific files. The data include wind speed and directions, direct and indirect solar irradiation, solar angle vertical and horizontal due the movement of the sun, and temperature. The data management class contains several adjustment possibilities be parameters depending on the data provided, timeframes, data conversions etc.

The PV system model include three classes, the PVCellHeat, Electrical PV and PVMultiple classes. The PVCellHeat determines the actual current and temperature affected by the electrical circuit. The electrical circuit is based on the classical two diode model. The parallel resistor corresponds the leakage resistance of the semiconductor and the series resistance corresponds to the sum of the metalisation resistance and resistance in the semiconductor.
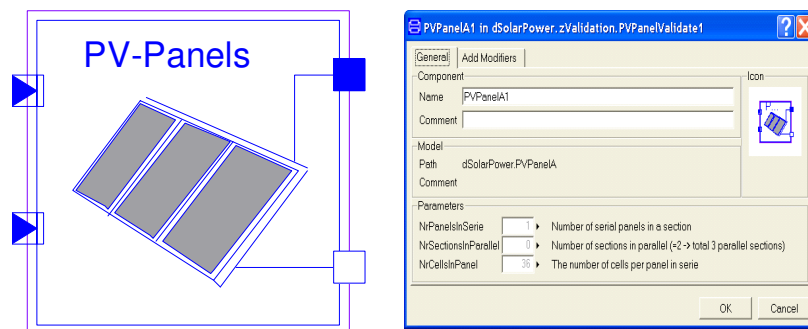
Figure A.10: Solar power model class.

The PV multiple model includes algorithms enabling the user to choose the serial and parallel configuration of the PV system, which affects the possible voltage and current level. The possible parameter settings and the solar power model class are shown in Figure A.10.

A test bench for testing the controllability of a solar power system is shown in Figure A11. The maximum power production is achieved be a maximum power point tracker (MPPT) that includes an algorithm for continuously searching the power maximum depending on solar irradiations.
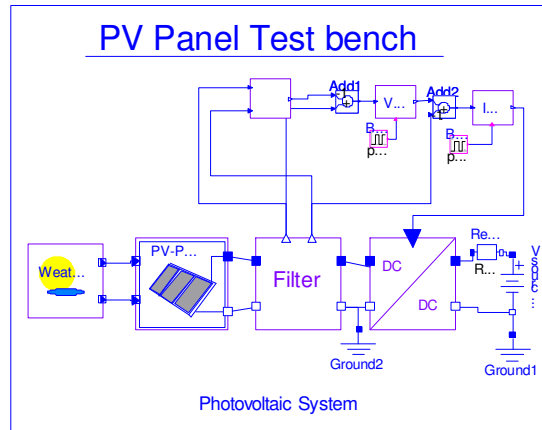
Figure A.11: MPPT test bench.

The conventional MMPT algorithm is here further developed be an algorithm that senses small changes in the irradiations and injects a small disturbance (signalMPPTc1.trigger) in the control algorithm that more easily finds the new point of maximum shown in the left graph in Figure A12.
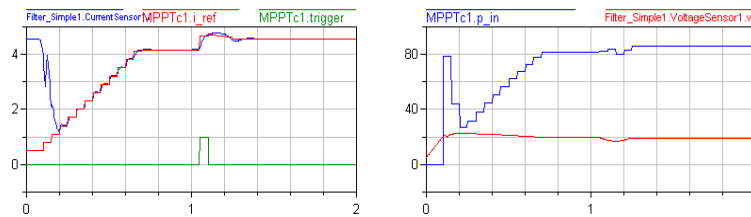
Figure A.12: MPPT tracking results.

The right Figure shows the time for reaching the maximum power production level at a certain irradiation level, which may be considerably improved.

A.5.2 Wind power model - modular unit structure

A system for local power generation and distribution has been investigated. The overall system with its comparably long time constants consists of wind power plant connected to the transmission network supplying power

to a load. The intention of the investigation is to study a wind power plant consisting of only two wind turbines connected to a load via an internal DC-network according to Figure A.13.
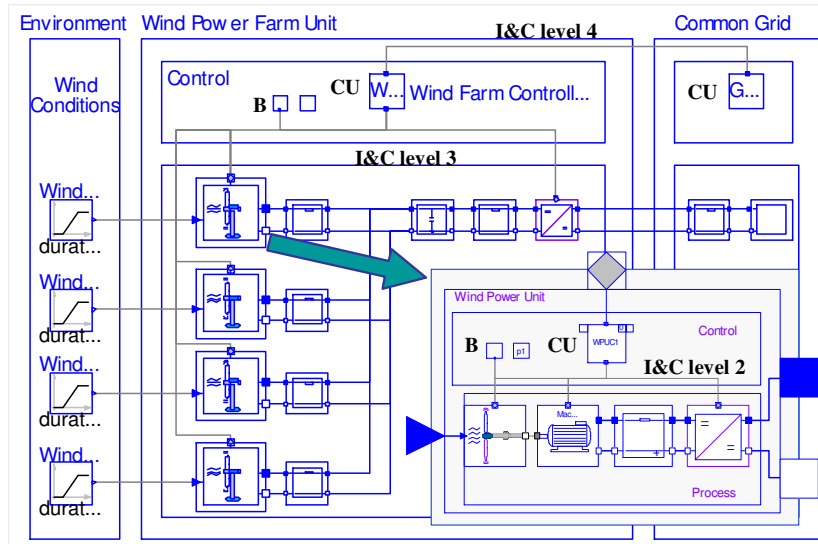
Figure A.13: System overview of a distributed power generation system based on wind turbine units.

The wind turbines are constructed with variable-pitch. They are directly connected to induction generators. The generators are connected to an internal DC-network via converters. The internal DC-network is connection to the HVDC transmission network via converter based substations.

The information and control (I&C) system structure is divided in four levels.

- The overall EMS-wind power plant control, I&C level 4, which handles the communication between the wind power plant unit and external transmission systems.

- The internal system operation level between the EMS-WPP and the wind turbine controllers, I&C level 3, which has a supervisory manoeuvre task such coordinating start/stop and control modes of the wind turbine.

- The wind turbine controller, I&C level 2, which have a supervisory manoeuvre task such as internal start/stop and execute control mode commands aimed for the individual wind turbine. The wind turbine includes several separately controlled units that are internally coordinated to perform its task.

- The internal units of the wind turbine have their own control units, e.g. the machine controller has an observer estimating the stator flux and rotation velocity. The machine controller calculates the reference currents to the converter controller. The AC/DC-converter controller makes sure that the generator slows down the turbine with a counteract torque, i.e. speed controller. The distribution of power to the common transmission network is managed by the DC/DC-controller. The system model have a structure and parameter setting-up for easy up scaling. At this level, I&C level 2, the control units are directly connected to the field level receiving input signals from the sensors and distributing control signals to actuators.

All the models start out from the overview model, Figure A.13. The wind turbine and generator models belongs to the long time scale (>0.1s), and generates reference values to the other system. For analysis of the system in the short time scale (<0.1s), the internal DC distribution network is thoroughly modeled together with the converters in the work described in [Karlsson, 2002]. The idea is to control the power transfer between the converters in such a way that the DC distribution network voltage is controlled to a constant level. In this model, the DC network is considered as purely capacitive, which represents the energy storage needed at the converter DC side.

The wind turbine unit model is shown in Figure A.14, which include four individual units consisting equipment and control parts. This exemplifies the modularization of power units that have enabled separate test benches for each unit to be verified before assembled unit by unit. In this model primarily the information and control structure has been studied. One of the outputs of this model is the reference value to the converter and generator control.

The input to the model consists of an adjustable ramp, representing the wind speed, rising from 1 to 10 m/s during 1 second. The rotor unit model is basically build-up out of an efficiency curve, which has a maximum output at a certain tip speed of the rotor, and converts part of the available

wind energy into mechanical power according to classical equations. Here the air density, swept area, power coefficient, and rotor speed wind speed, are included variables that determine the torque of the shaft. This torque can be controlled by adjusting the pith angle of the rotor blades. Furthermore, a brake component is included in the rotor model, which sole purpose is to fix the shaft at emergency situations or when manually stopped.
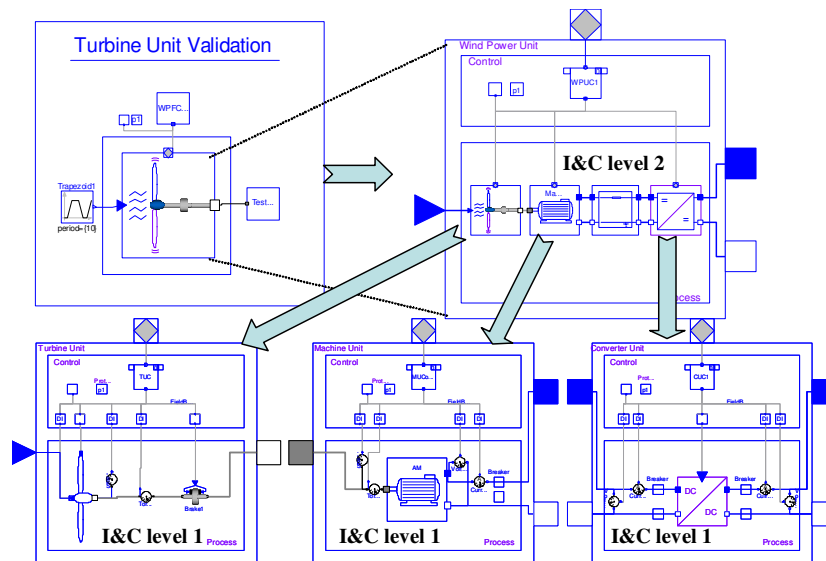
Figure A.14: Wind turbine unit model overview.

Several generator unit models are included in the library where one only consists of moment of inertia and a transformation from mechanical to electrical domain. Another includes a full three phase induction generator. Both have been investigated. The converter unit model includes the DC/DC converter circuit, sensors and output equipment controlling the converter, and a control unit.

The wind turbine controller, I&C level 2, manages the start and stop of the wind turbine by releasing the break due to proper wind and release of emergency switch. The controller produces a given reference current value, provided there is enough wind, to the DC/DC converter. When the wind turbine reaches the rated output power, the pitch controller adjusts the blades to maintain the power output even though the wind increases.

This simulation results show how the wind power controller manages the turbine when the wind goes from standstill to full power. In Figure A.15 the brake (Brake1.locked) releases when the wind reach above 3 m/s. The rotor velocity (Turbine1.w) increases linearly up to 4 rad/s, then the pitch-controller adjust the blades (Turbine1.beta) to constant velocity (power).
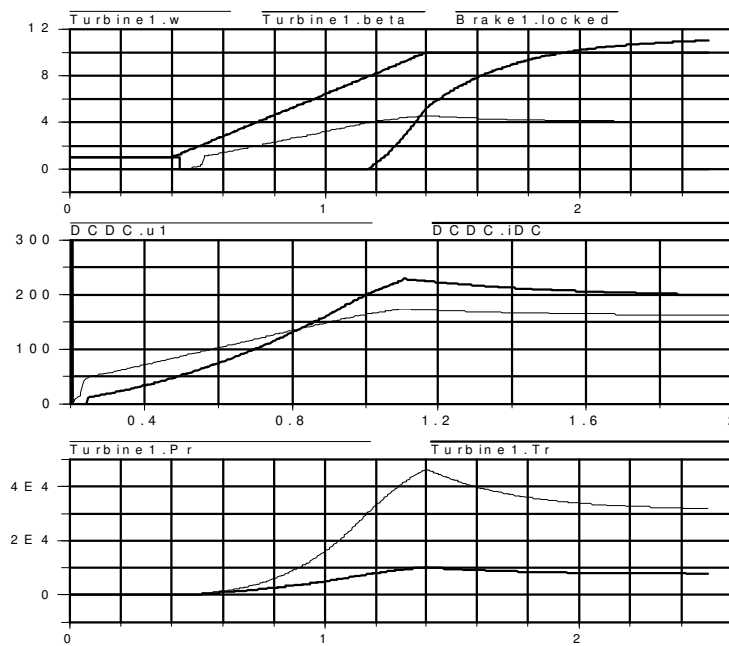
Figure A.15: Angular velocity (rad/s) control of the wind turbine (top graph); Voltage and current at the converter (middle graph); Power output (kW) and torque (Nm) (bottom graph).

The power (Turbine1.Pr) of the wind turbine exceeds the rated output power due to a control error and the moment of inertia, Figure A.15. The power output reach to the expected level after about one second. A drawback of this design, i.e. without gear, is the high torque (Turbine1.Tr), which requires a generator with a high number pole pairs. The output current (DCDC.iDC) through the converter reaches steady state after about one second as for the input voltage (DCDC.u1). The electrical output power corresponds to the mechanical power at the turbine rotor except for the losses.

The same model has been used except for that the simple generator has been exchanged to a three phase induction generator. The generated output current reference is open due to the absent machine-controller. The purpose of this simulation is to find operating point and how to control the generator. The input wind speed (Turbine1.Vw) starts at 5 m/s and takes a step to 8 m/s after 0.5 seconds, Figure A.16.
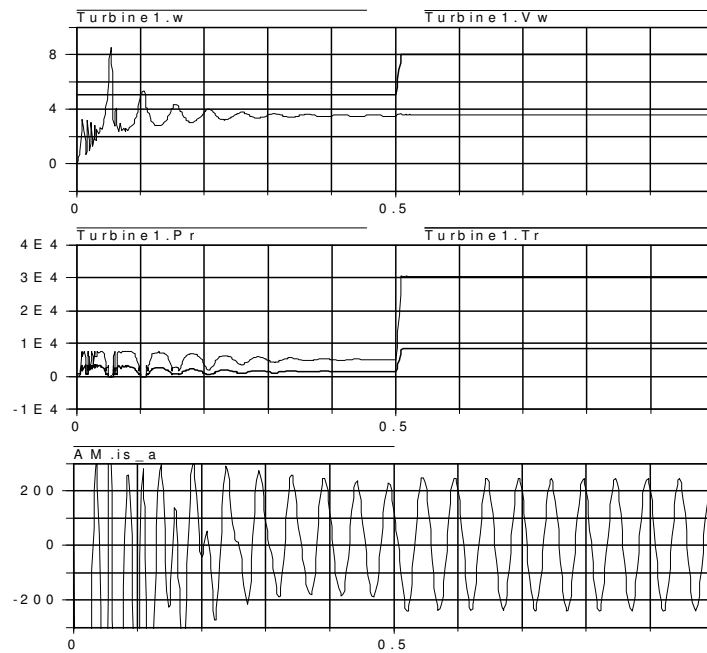
Figure A.16: Wind speed (m/s) and Angular velocity (rad/s) (top graph); Turbine rotor power (Nm/s) and torque (Nm) (middle graph); generator stator current (bottom graph).

The rotor velocity (Turbine1.w) is constant 3.8 (rad/s) due to the direct network connection of the generator, and the number of pole pairs of the induction generator is 72 and the grid frequency is 20 Hz for this simulation. In this case the wind thrust increases the torque (Turbine1.Tr), Figure A.16, at the turbine rotor, which is undesirable. A proper coupling with a converter will avoid this problem. The excitation of the generator takes about 0.3 seconds after that the current (AM.is_a) is approximately 200 ampere until the sudden wind disturbance at 0.5 seconds where the current distinctly increases.

A.5.3 Wind power model – information and control structure

The information and control (I&C) structure for the entire WPP is quite extensive and the structure is here partly described. Independent each I&C level, the control system structure include at least one control unit (CU) and the communication system. The hierarchy of a single power unit is almost always vertical. Viewing inside one unit gives a general description of these levels as they are very much alike independent I&C level.
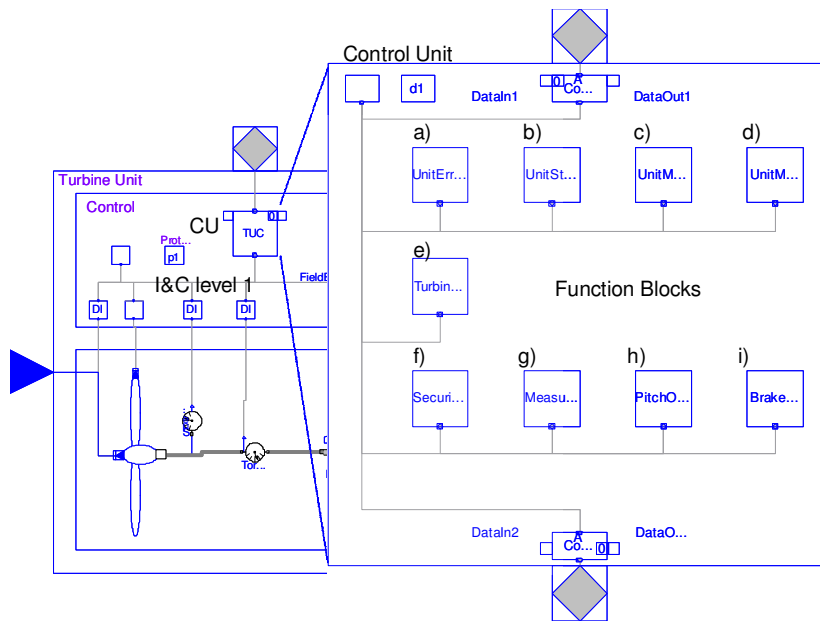
Figure A.17: Control software block structure of the rotor model unit.

The rotor model class (turbine unit model in Figure A.17) is at field level and include the turbine unit control block (TUC), several sensors and actuators. The field level communication utilizes the SignalFlow library that makes the communication system general and enables unlimited interconnections of control system equipment. Inside the control unit (TUC), corresponding a computer processing unit, several function blocks are included that interconnects the software applications communicate by the internal communication network (intercommunication). The intercommunication network is also based on the SignalFlow library. At the top and bottom of each CU are the communication terminals, the upper

connected to I&C level 2 and the bottom to I&C level 1, which functions as interfaces with condensed data to the external communication networks. The function blocks a-d represent the upper interface towards I&C level 2 where the management of the interface signals are done. These blocks include the Unit Error (a), UnitStatus (b), UnitMeasurement (c), and UnitManagment (d), which manage all communication between the higher and lower level. The Turbine Function block (e) includes the sequential control coordinating the object blocks, security, measurement, pitch and brake. The object blocks, at this level, include the software interaction with the physical process.
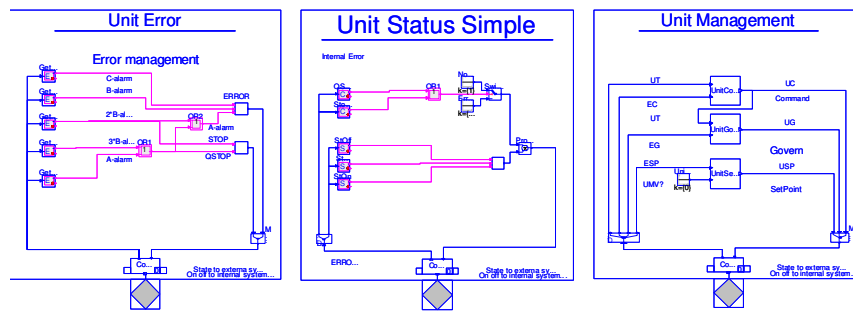
Figure A.18: Signal management block overview; (left) Unit Error block; (centre) Unit Status block of; (right) Unit Command, Govern and Set point block.

Viewing inside the signal management blocks a, b and d (Figure A.17) as shown in Figure A.18, the unit error collects all adequate error signals from every function block in the control unit. The error signals are categorized in A, B and C errors that are managed in this block. The Unit Error block determines the total error degree of the unit and takes action from out of that. The block includes several logical model classes, as shown in the left Figure A.18, for this management and the result are transmitted both to upper levels and the operation of the unit itself. For example, an A error witch is the highest priority affects the Unit Management block that shut down the unit. The Unit Status block continuously supervises the status of the unit and transmits the signal to next I&C level, shown in the centre and right blocks of Figure A.18. The Unit Management block handles the command, govern and set point signals for the unit. Each of these signals has similar logical blocks structure as the error and status signals embedded in respective management blocks.

The signal flow is from left to right in all function blocks and at each side the individual signals are treated by the signal assignments blocks. For example, the input signals in the unit Error block are selected by the Get Error Assignment block and after signal processing the output error signals are assign by the Error Assignment block as shown in Figure A.19.
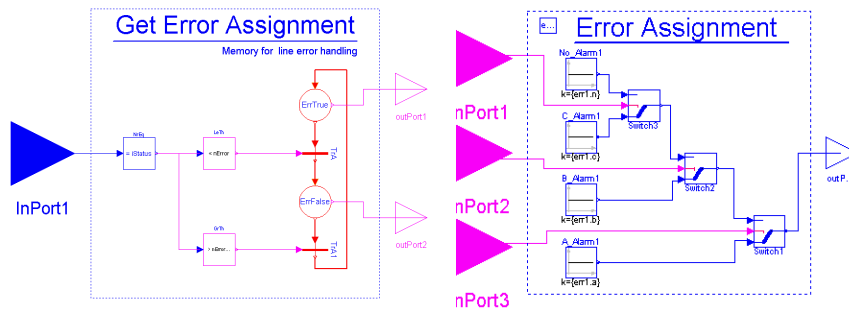
Figure A.19: Control software block structure of the rotor model unit.

The Turbine Control Function block in Figure A.17 (e) is enlarged in Figure A.20, which is based on sequential control.
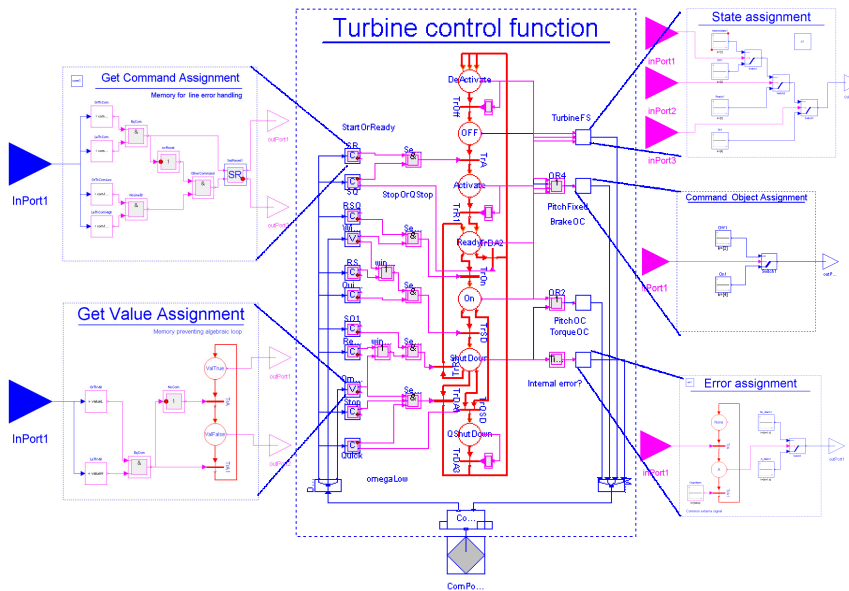
Figure A.20: Control software block structure of the rotor model unit.

 The input signals from the right side are managed by the assignment blocks. The Get Command Assignment block collects and checks the validly of the command signal (off, ready, start, etc) and the Get Value Assignment block collect a measurement or calculated value. The value is then compared with either a high or low limit level or both, which assign a logical output to true or false. All the values and command signals are filtered via logical function blocks that sets conditions for the sequential column in the middle to move from one state to another.

Figure A.21: Control software block structure of the rotor model unit.

The right side of the sequential column combines several states to individual output signals for the lower level object blocks. For example, the Pitch Object block is activated only in the state "on" and "shutdown". The Error assignment block at this level checks the sequential flow by measure the time in some of the states. If some conditions are fulfilled and the time limit is exceeded, the error from this function block is activated and transmitted to the Unit Error block (a).

At object block level, the pitch control function is shown in Figure A.21. This block is divided in a logical and control part. The logical part check the predefined conditions, among them the command signal, and releases the control part if fulfilled. The control part then starts to control the rotor blades according to the Govern signal and set points.

The Govern block is enlarged to the right and shows the different switches that activates the control loop. The feedback in this block checks different positions of the blade angle depending on the control mode and the state of the unit. The Get Regulation Assignment block checks the assignment of the govern signal and sets the logical output terminal.

A.5.3 Hybrid power system model A

A local hybrid power system has been investigated where the configuration include one wind power unit, one solar power unit, one battery storage unit and one building load unit interconnected via an internal DC network as shown in Figure A.22. The system is set to be autonomous, able to deliver 10 kW in peak load and approximately 20.000 kWh per year that represents the average consumption in a Swedish household.
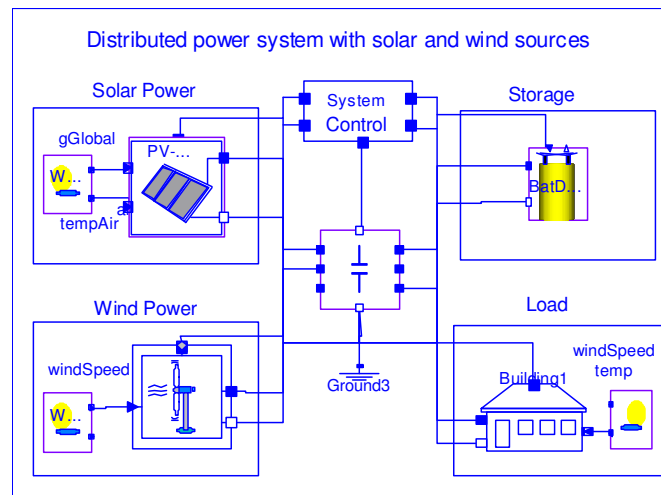
Figure A.22: Hybrid power system based on solar, power and storage units supplying a building.

The weather model is based on statistics from the Swedish Metrology and Hydrology Institute (SMHI, 1994). The year 1994 is the base for the study and all parameters are updated hourly. The parameters of interest are direct solar intensity, indirect solar intensity, temperature and wind speed. In order to study the reflection and other phenomena that are related to the site, the model takes consideration of the angel between the array and the direction of the sun. The site for the study is Lund in Sweden.

The photovoltaic array consists of a number of photovoltaic arrays. The mathematical model is based on the two diode model. The parameters that mainly affect the performance of the solar cell are solar intensity and the temperature of the cell. The solar intensity is corrected for reflection and temperature is calculated though energy balances throughout the surface.
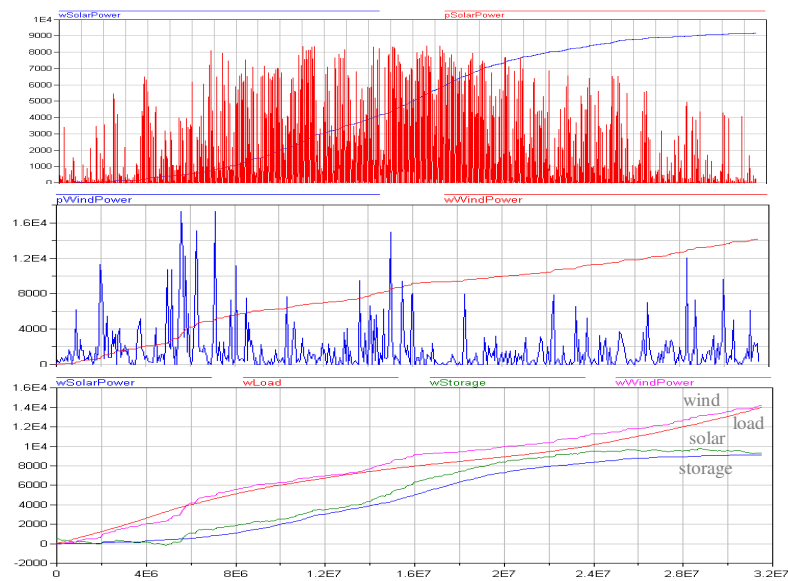
Figure A.23: Hybrid power system based on solar, power and storage units supplying a building.

The battery bank uses only the linear part of the battery characteristic, which means than only 0.2-0.8 parts of the possible charging amount is used. The load is represented by a building, which is based on temperature balances and some statistic data. The other consumptions are represented by statistic curves, which depend of the time in terms of the hour on a particular day and month. The losses of temperature in the building and the hot water for the showers take effect from a hot water tank. The hot water tank is heated by an electric heater in a way that the temperature stays between 60 and 70 degrees Celsius.

The operation and control is performed by the system control model that coordinates the power units by a rather simple strategy. The battery unit mange the primary voltage control of the DC network and the wind and

solar power unit generate at maximum as long as the battery and building are able to consume the production. The battery strives to have a state of charge at about 50 percent enabling the unit to balance the power up and down depending on production and consumption.

A simulation over one year with real weather data for production and synthetic date for the consumption has been made. In Figure A.23 the upper graph show the power and energy from the wind power unit and the centre graph show corresponding for the solar power. The bottom graph shows the energy over the year for respective power unit. The fluctuation by solar power and wind power cause a large demand of the storage as illustrated. The solar and wind production over the year is clearly much more than needed but not in correlation with the need for load consumption, which require the storage to balance the production over the year. The storage size, in this case, is dimensioned to always manage the power surplus, which is very uneconomic. However, the result shows that the storage size will be considerable independent of system configuration.
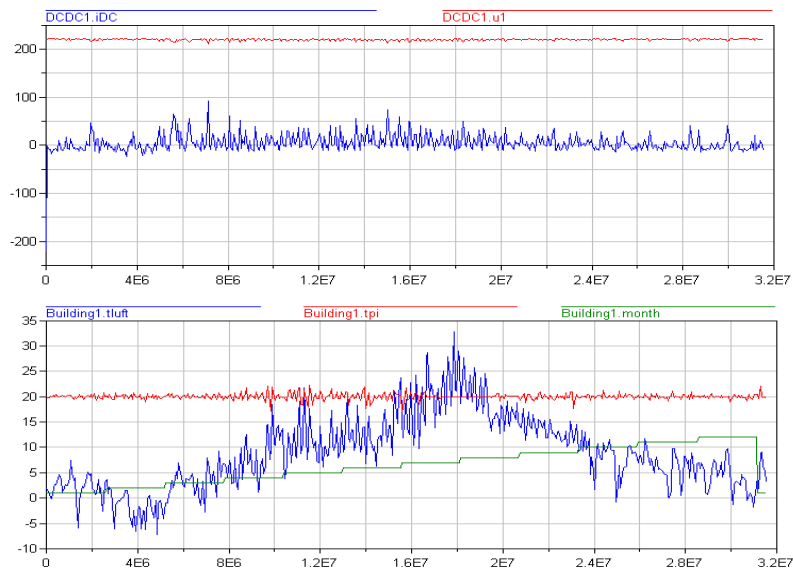
Figure A.24: Hybrid power system based on solar, power and storage units supplying a building.

In the upper graph in Figure A.24, the consumption is shown where the DC voltage level is constant and the current fluctuates according to the loads of

the building. The lower graph shows the variations of the outside temperature and the inside temperature where that is approximately 20 degree Celsius over the year.

A.5.3 Hybrid power system model B

This hybrid power system is based on the same model as in A.5.2 except wind power model is exchanged to an additional storage unit based on hydrogen. The storage includes an electrolyser, fuel cell and storage of hydrogen gas. The system model consequently has two storages, operation as one fast and one slow. The only generation unit is here the solar power unit.

The electrolyser convert electrical energy into chemical energy in form of hydrogen gas and the fuel cell convert the gas back again. This conversion is due to the impossibility to store electrical power and hydrogen being a good energy carrier. That due to the high energy density and that hydrogen is easy to convert back and forward. The gas flows are air and hydrogen gas. The hydrogen from the electrolyser is stored in a tank and supplies the fuel cell via a valve. To supply the fuel cell with oxygen, air, a compressor is needed. The cell temperature is calculated from an energy balance with gas flows in and out and the heat released from the reaction. The pressure in the tank is then updated continuously. The limit of the tank is 150 m^3 and 30 bars.

The system operate similar to the other system with the DC- network in the centre and but gets its primary generation only from the photovoltaic array when the sun is shining and the system has a load to support. The aim is always to support the building with its needs. If the production from the solar power is larger than the consumption of the load, the electrolyser produces hydrogen gas which is stored in the tank. If there is a shortage of power on the DC- network, the fuel cell produces what is needed by consuming gas from the tank and air from a compressor. To meet the fast variations in demand or production a battery bank assists the DC- network with both load and production.

Dimensioning of the components has been done in two ways. The first part sets the dimension on the fuel cell and the battery and these sizes are due to the fast variety in load. When the fuel cell is to slow to supply the fast load demand, the battery size needed is determined. The parameters affecting

the sizes of other components are the energy requirements and the portion of flows between the gas tank and direct consumption from the sun cell.

The response time for the fuel cell and the electrolyser affect the dimensioning of the battery. In Figure A.25 (a), the curves show the power from the fuel cell, the set point for fuel cell, the power of the battery supporting the load due to the slowness in the fuel cell, and the actual load.
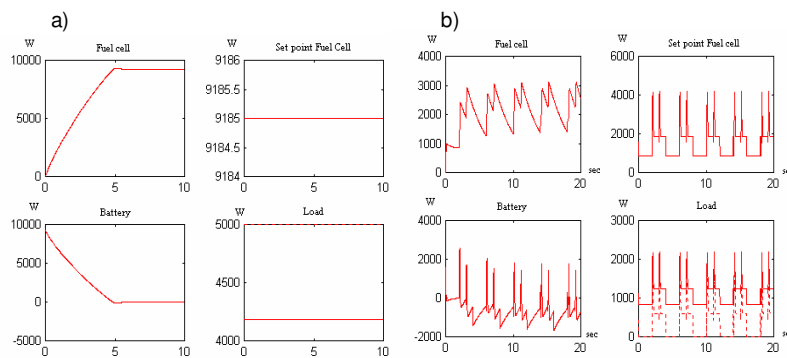
Figure A.25: a) Start-up conditions for the fuel cell; b) Storage systems load sharing when using a drilling machine as load.

The battery is affected by the time constants of the fuel cell. The accumulated energy that is supported by the battery is approximately three times greater with a time constant of four seconds compared to one second. In order to study the fast variations in load, some start up conditions and variations in load have been studied. In Figure A.25 (b), the curves consist of: Fuel Cell - effect from the fuel cell, set point fuel cell, battery - the effect that the battery support the load due to the slowness in the fuel cell, load - the load that in all cases consist of consuming, dotted line and supporting power to the fuel cell due to the compressor, continuous line. The two figures below shows how the use of the battery is affected by the time constants of the fuel cell. In order to study how the system reacts on fast variations in load, a drilling machine that is repeatedly started and stopped is represented as the load. Regarding the yearly energy consumption of the household, one third comes directly from the photovoltaic array and the remains taken from the storage tank, which caused an even large storage than in the system with wind power, which is expected.

A.6 PowerFlow

The "PowerFlow" library consists of simplified model classes regarding the physical equipment of the power system. The physical power units are based on the libraries in Appendix A.1-A.5 and are extended with a dynamic and flexible information and functional structure. The control and communication part is much larger in comparison with the other model classes. The model unit are structured to resemble the real power system as much as possible to make reliable simulations. At top level, the information flow is horizontal along the power lines and vertical inside the power units.
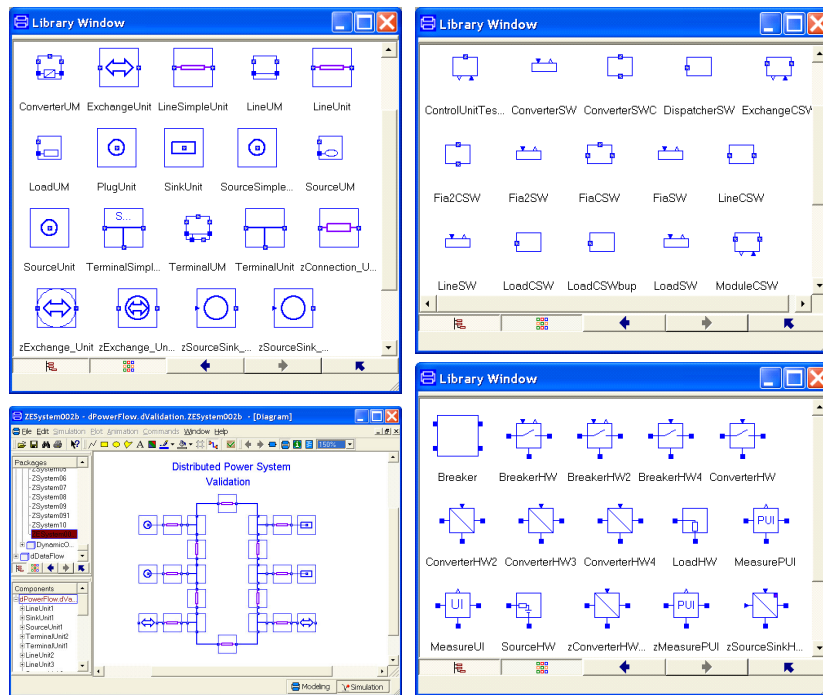
Figure A.26: PowerFlow library overview.

In order to manage large system models, it is preferable to have a good overview of the system making the simulation simple with few blocks on the screen. In order to keep it simple, all of the different units have been made as different modules that are used to build up a power system.

The library is built on the same principles as the others and the main part of the units included are shown in the upper left corner of Figure A.26. These power units are structured to be connected in a simple and easy manner as shown in the system example in the lower left corner, like building blocks. The building blocks have simple rules for interconnections.

The structure of the dComponnet sub library differs slightly as this is divided in a dSoftware and dHardware library as shown in the right side of Figure A.26. The software (SW) part includes the modules (advanced functions) and the information system interconnection. The hardware (HW) part includes the simplified physical model classes.

An example of on a model test benches for a smaller system is shown in Figure A.27 that includes several power units. The system shows some of the different types of power units that are used in this work except for the exchange unit. But this is added similar as the others. With a structure like this, it is easy to have a good overview of the system and new units can be added easily.
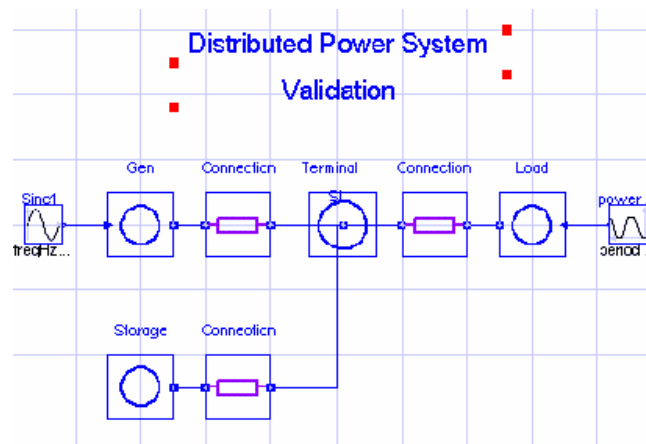
Figure A.27: Figure of a small DPS in a simulation environment.

The generation unit, load unit, storage unit and terminal unit are active and correspond to power nodes. The three connection units are passive and resemble power lines or cables and are classified as power flows. The rules for connecting the different power units are that a power flow must always be connected to a power node and parallel connection can only be done via terminal units.

This means that each generation or load unit has to be connected via a connection unit before it is attached to a terminal unit. The connection unit adds some power line parameters into the system and can represent everything from a small connection to a high capacity power line. The terminal units function as the hart of each DPS system. This is the link to the automated operating programs, production management (PM) module, where all the command signals are collected and distributed. Without any connection to this module the unit will not get any permission to start.

Power unit description

All of the power units are properly built and classified to maintain balance in the system. This part of the chapter will describe the main structure of each power unit used in the simulations.

Every power unit used in the model has to be given a certain group identity number otherwise the PM module is not able to separate the power units from each other.

The generation unit

A generation unit is a resource only capable of generating power. In reality this could be a wind power plant, water solar power plant, etc. The same model used to simulate a generator is also used to simulate a load unit. The generation unit is shown in Figure A.28, where the software and hardware division is clearly illustrated. To inform the system control that this is a generator, some initial settings are made. This is done in the parameter window of the model class. In this box is the group identity number for the unit and the nominal power chosen.

Furthermore, parameters regarding nominal power, maximum power rate and nominal voltage level are assigned here for the unit. The left side connector port provides the actual power of the generator at a certain point of time. This is placed out side the generator model enabling the user to choose waveform properties. The right part of Figure A.28 shows the inside of the model class. The model class is mainly divided in three parts corresponding the three blocks in the middle of the Figure.

The top block includes the production exchange module and the communication to interconnect the production management module. The production exchange block verify and authorizes all of the command

signals coming from that production management blocks. The hart of this block, the power flow control block, is discussed later in this Appendix. When the command signals are verified they are transmitted down to the control level.
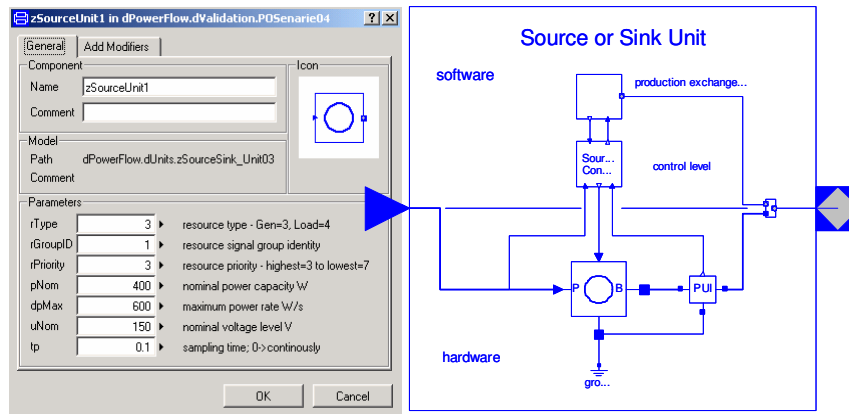
Figure A.28: Source and sink unit overview.

The control block in the centre of the figure manages the information from the level above and calculates a set point for the converter that is situated below. This control block returns information according to the OCI. The physical model class of the source is simple and could be describe as a pump that pumps power into the system. The output, the thick line, from the source is the power line including the voltage and currents variables. The small block named PUI measures the power, voltage and current in the point where it is placed. The connection point (terminal) in the very right in the generator model combines the information channel from the upper part of the model and the power line from the lower part of the model. The line out from the generation unit is then a combination of a power line and an information line.

The load unit

The load unit model is the same as for the generation unit. The only thing that differs is that the initial parameter should be set as for a load unit and the maximal capacity value must be a negative value.

The storage unit

This power unit differs slightly from the other two mentioned above. As the power unit represents a storage, the unit has bi-directional power flow since it must be able to charge and discharge. An additional function for estimating the energy stored is included and the initial values are focused on the performance of the unit.

The model class is shown in Figure A.29 where all the energy stored in the unit is stored in a capacitor. The voltage level over the capacitor will increase or decrease depending on if the capacitor is charging or discharging, where the energy level is estimated. Otherwise, the major structure is very similar to the structure of the generator and the load. The communication block is exactly the same as in the previous units and will not be commented any further in this part.
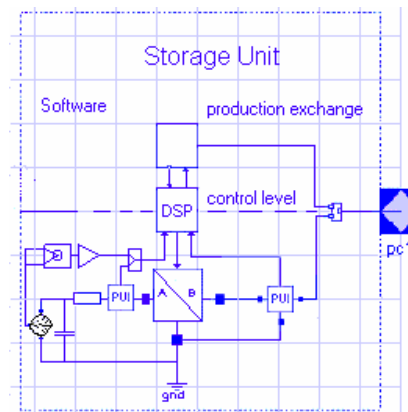
Figure A.29: Storage unit overview.

The control part is a little bit different in comparison to the generator and the load. The set point that distributed from the control block is assign in between –1 and 1, which enables the converter to control the power in both directions.

The converter model itself is acting as a pump that is capable of pumping power in both directions. The power level to be controlled depends on the set point and the maximal power of the unit that can deliver or receive, and the actual mode of operation.

The exchange unit

This unit is similar to the storage unit since it has a bi-directional power flow. The main differences are that the unit not store energy and is connected in between two different DPSs, representing a controllable electric interface. The exchange unit is shown in Figure A.30, where it is obvious that the communication block is equipped with another communication port enabling information management from two DPSs. As the exchange unit is an interface between two equally entities, the unit is independent of which side it is interconnected. The unit only keep track on its own two sides of interconnection, side A and B, implying on equally treatments. The unit itself has the last outpost in deciding commands for controlling the power depending on local strategy. However as long as the communication is working and the signal received is properly, the unit adapt to its environmental requests.
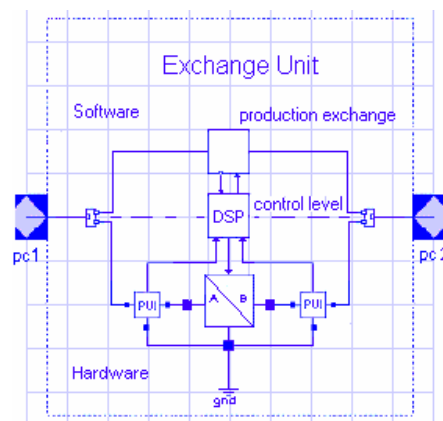
Figure A.30: Exchange unit overview.

The converter model used for the storage unit is the same as for the storage unit. The converter model functions as a controllable actuator that can be fully open (+1), closed (0), and fully reversed (-1).   Dependent on power flow direction the measurement (PUI) is from the left or right side of the converter.

The connection unit

The connection unit represent a transmission line or cable in the power system. The unit separate the output conductor on the different generation

and load units from each other and includes a more realistic model by adding line characteristics to the system, as shown in Figure A.31.

From that figure it is clearly shown that the communication line and the power line is going side by side between the different units. But before it is possible to add the line characteristics, the power line has to be separated from the communication line.
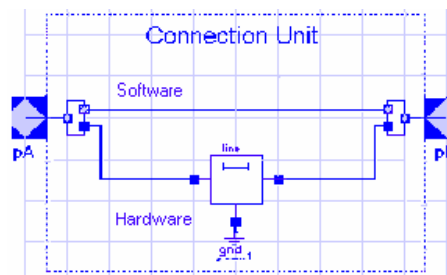
Figure A.31: Connection unit overview.

All of the line parameters, such as resistance per meter, capacitance per meter, reactance per meter and length of the cable, is set in the in the block in the centre of the Figure that is an origin Modelica model class. The line is general and can be divided in several segments. When the characteristics have been added, the two lines are attached to each other again to be transmitted to the next unit.

The terminal unit

The terminal unit is the core unit of the DPS. It is this module that every unit in the DPS has to be connected to in order to be a part of the system operation and control. The terminal unit is shown in Figure A.32.

In the simulation model the terminal unit has a very simple layout. First of all the power line and communication line is separated from each other. The power line is connected to a capacitor that keeps a stable voltage level in that point and a conductor.
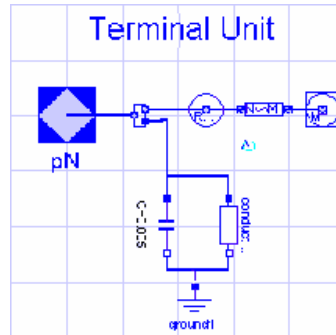
Figure A.32: Terminal unit overview.

The communication line is connected to the three blocks that is connection to the entire operation and control program structure. These three blocks are disused later in this Appendix.

Interconnections and Interactions

All of the operation and control algorithms and information system programs are developed in C++ code. This code is linked to the simulation model via the signal management structure described in the SignalFlow library. The production management (PM) and production exchange (PE) modules are embedded in the model classes referred to power node control blocks and power flow control blocks.

Power flow control block

The power flow control block is placed in the communication block in the top of each generation, storage, exchange and load unit. When a signal enters the communication block it is directly connected to the power flow control block, which links the signals to the production exchange module program, as shown in Figure A.33.

Two types of communication blocks are used. The first one is used for the generators, loads and storages and the other one is used for the exchange unit. The component within the dashed line in the centre of the figure is forming the power flow control block and all of the connections are connected to this module.
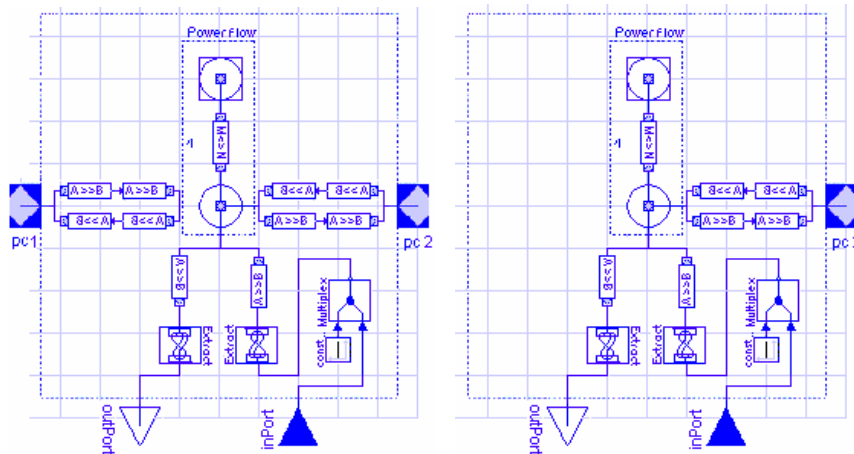
Figure A.33: Communication blocks for the power units where the right one is in the exchange unit and the left on is for the others.

The program for the power flow control block can connect an unlimited amount of connections, so there is no need for adjustment when new connections for the exchange unit are made. The connections in the very right in the pictures belong to the power node control block. The reason to why they are placed here is that there is no fix number of connections connected to the power node. If they are placed in the unit, a new set of connections will be added when a new unit is added.

The power node control block

The power node control block is placed in the terminal unit and looks much like the power flow. It is also working in a very similar way as the power flow. The only difference is that the program is linked to the production management program. As discussed before, there is no connection blocks placed in the terminal unit. They are instead placed in each power unit to make it easier to connect and disconnect new units.

A.7 Modelica - C++ communication

The basic Modelica structure for connecting communication nodes (SNode) and communication flows (SFlows) is shown in Figure A.34 (a). The structure prevents algebraic loops, which is easily caused with a high

degree of control levels in a SE. Even if the SE can handle this, as in the Dymola case, it might become a complicated problem in large system models. The SNodes have a state (node) corresponding to capacitors (voltage) summarizing the variables from the SFlow models. The SFlow assigns the lineA and lineB, identities, corresponding to currents in the electrical case.
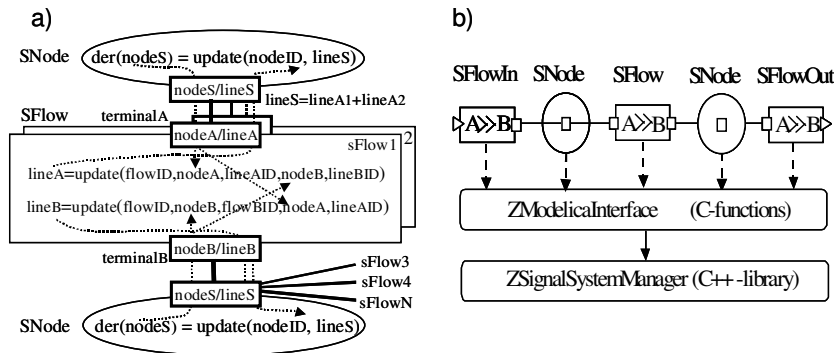
Figure A.34: a) Terminal assignments between SNodes and SFlows; b) Modelica and C++ interconnection.

The line identities are then identified by using a "modulo 2" function both when assigning and decoding the identities, e.g. if four SFlows are connected and the identities of them are 2, 4, 8 and 16 with the sum of 30, it is easy for the SNode to decode the SFlows to determine both if a new SFlow has to be configured and if a line is broken. Each node can be connected to numerous signal flows where the SNode assigns the terminal variable "nodeS" and the line identities are summarized in the terminal variable "lineS" of the node. In the SFlow, the lineA and lineB are separated enabling the responsible node to change the line identity if needed. In case of disconnecting one SFlow model, it is not likely that the identities will be the same in a dynamic environment. There is also a cross coupling between the nodes by the arguments in the update function, which uses the corresponding node identities in order to avoid losing the equation tail in the SE. The SE initiating process automatically assigns all identities of the SNode and SFlow models.

The Modelica models in the SignalFlow library have several functions for interacting the with C++ library. All included functions are similarity declared as here exemplified for the "zNodeUpdate" function.

```
function zNodeUpdate
  annotation (Library={"Libcore"});
  input Real nodeID;
  input Real flowSum;
  output Real y
external "C" y = zNodeUpdate(nodeID, flowSum);
end zNodeUpdate;
```

The "Libcore" assignment is the actual C++ library that is linked to the SE by the "Libcore.lib" file, which is placed under the "dymola\bin\lib" directory. Each SNode and SFlow model creates a separate object in the C++ layer where the Modelica-layer models use function calls to the ModelicaInterface and method calls to the C++ library, as shown in Figure 9. The header declarations for the "ZModelicaInterface.h", enables method calls from the C++ implementation, as shown below. By using the "ZModelicaInterface.cpp", the Modelica function calls are translated to method calls from the "ZSignalSystemManager" class where all methods can be found in each step interfacing the C++ library.

```
// --- ZModelicaInterface.h ---
#ifndef ZMODELICAINTERFACE_H
#define ZMODELICAINTERFACE_H

#include "ModelicaUtilities.h"
#include "ZSignalSystemManager.h"

#ifdef __cplusplus
extern "C" {
#endif
double zNodeInit(int cv[], int cvSize);
double zNodeUpdate(double nodeID, ….);
………. remaining functions

#ifdef __cplusplus
}
#endif
#endif  // end
```

The description of the specification is here exemplified, where the remaining functions are declared as the two presented.

```
// --- ZModelicaInterface.cpp ---
#include "ZModelicaInterface.h"

ZSignalSystemManager   sys;  // C++ class

double zNodeInit(int cv[], int cvSize)      {
   return sys.nodeInit(cv, cvSize);
);
double zNodeUpdate(double nodeID,...)  {
   return sys.nodeUpdate(nodeID, ….);
}
………. remaining functions
// end
```

The "ZSignalSystemManager" class is the actual interface between the Modelica-layer that manages all the ZSignalNode and ZSignalFlow objects using dynamic vectors as is briefly shown here. The JVector class is a dynamic vector (DV) equivalent to the CVector class in the C++ standard library except for some modifications making a smooth conversion to the JAVA environment. The dynamic properties in the library are based on the DV that is used for pointing out all needed objects for the specific application. There are facilities in Modelica allowing to declare void*-pointers and external objects by defining a partial class "ExternalObject" with constructor and destructor functions that would make the ZSignalSystemManager excessive. However, this is not used in this version but might be implemented in the next.

```
typedef JVector<ZSignalNode*> ZSignalNodeVector;
typedef JVector<ZSignalFlow*>  ZSignalFlowVector;

typedef JVector<ZProductionManagement*> ZProductionManagementVector;
typedef JVector<ZProductionExchange*> ZProductionExchangeVector;

class ZSignalSystemManager
{
private:
   ZSignalNodeVector* m_nodeVector;
   int m_nodeCounter;

   ZSignalFlowVector* m_flowVector;
   int m_flowCounter;
```

```
    ZProductionManagementVector* m_productionVector;
    int m_productionManagementCounter;

    ZProductionExchangeVector* m_exchangeVector;
    int m_productionExchangeCounter;

    ZOutFileHandler *outfile;

public :
    ZSignalSystemManager();
    ~ZSignalSystemManager();

    //*********** Signal Node  ********************************
    int nodeInit(int cv[], int cvSize);
    int nodeUpdate(int node, double flowSum, double time);
    int nodeSet(int node, double value[], int valueSize, double timeStamp);
    int nodeGet(int node, int index, double timeStamp);

    //*********** Signal Flow ********************************
    int flowInit(int nodeA, int nodeB, int cv[], int cvSize,int sType[],
                                                    int sTypeSize);
    int flowUpdate(int flow, int nodeA, int dataFlowA, int nodeB, int
                                            dataFlowB, double time);
    int tryConnectFlow(int node, int flow, double time);
    int tryConnectFlowIn(int flow, int node, int dataFlowA, double time);
    int tryConnectFlowOut(int flow, int node, double time);
    int tryConnectFlowBuff(int flow, int node, double v[], int vSize);
    int flowSet(int node, int dataFlow, double* value,int valueSize,
                                                    double time);
    double flowGet(int node, int dataFlow, int index, double timeStamp);

    //*********** Production Management  ***********************
    int PMConnect(int flow, int node, int nodeB, int rm ,double time);
    int PMInit(double cv[], int cvSize);
    int PMSet(int objectID, double value[], int valueSize,
                                                double timeStamp);
    int PMUpdate(int objectID, double timeStamp);
    double PMGet(int objectID, int index, double timeStamp);
```

```
//*********** Production Exchange **************************
int PEConnect(int flow, int node, int nodeB, int rm ,double time);
int PEInit(int cv[], int cvSize);
int PESet(int objectID, double value[], int valueSize, double timeStamp);
int PEUpdate(int objectID, double timeStamp);
double PEGet(int objectID, int index, double timeStamp);

//********** Output Manager ****************************
void outputManager(const char* text,int type);

}; // end ZSignalSystemManager
```

Appendix B

Module library

The module library is implemented in a C++ class library that is connected and implementation both to the simulation environment and the experimental set-up.

B.1 Module structure

Using the C++ class libraries, a designer can describe components at a broad range of abstraction levels [Svarstad, *et al.*, 2001] [Al-Agtash, *et al*, 2000], which result from the ability to perform signal and control modification separately.
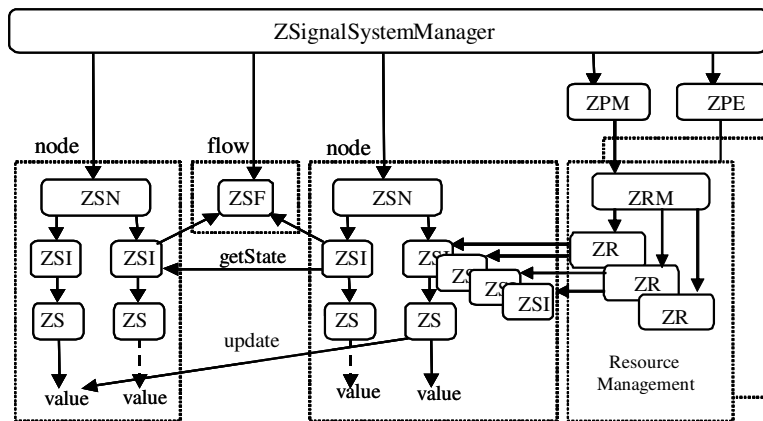
Figure B.1: C++ structure.

There are different levels of abstraction at which C++ can be used for the signal management system as shown in Figure B.1. The C++ library mainly includes the following classes:

- The *ZSignalNode* (ZSN) class is responsible for searching and joining together every signal in each connected input and output data interface. The class is receptive to changes of new interconnections and continuously controls all connections for not being defected.

- The *ZSignalInterface* (ZSI) manages a pre-defined number of signals in a block that, for example, could correspond to a protocol. This object could be of several types such as inputs and outputs for communication but also parameters for configurations and specifications.

- The *ZSignal* (ZS) class is the object containing the particular value of the signal and its configuration. It could also be a reference pointing at another ZSignal class.

- The *ZSignalFlow* (ZSF) class is the actual configuration of the signals between two DNodes including the needed types and identities.

- The *ZResource* (ZR) is the actual recourses in the system and is using the ZSignalInterfaces to communicate with the rest of the system.

- The *ZResourceManager* (ZRM) class is responsible to keep track of all the resources and make sure that the every resource operates as intended.

- The *ZProductionManagement* (ZPM) class is the coordination module in the system and decides what command signals each resource should have be collecting and distributing the signals included in the OCI.

- The *ZProductionExchange* (ZPE) class is the last check that each resource will not get any command signals that is beyond the unit limits.

The main functioning of this structure is described in [Svensson and Karlsson, 2003].

B.2 Modules

The complete code for the C++ library includes several hundreds of pages and is here only described by the class headers.

The ZSignalNode class --

class ZSignalNode {

private:
  ZIntegerVector*   m_cv;
  ZSignalInterfaceVector* m_iv;
  ZSignalInterfaceVector* m_ov;
  int   m_state;
  bool   m_change; m_storage;

public:
  static int m_signalNodeCounter; // object counter
  // constructor and destructor
  ZSignalNode(int cv[], int cv_size);
  ~ZSignalNode(void);
  // --------- configuration functions ------------------------
  int   verifyInInterface(int cv[], int cv_size);
  int   addInInterface(ZSignalFlow* flow, doub. time);
  void removeInInterface(int iID);
  // corresponding functions for OutInterface
  void tryConfiguration(void);
  void configureAllSignals(void
  void verifyAllSignals(void);
  void findSignalByID(ZSignalInterface* di);
  void findSignalByType(ZSignalInterface* di);
  void findSignalByBlock(ZSignalInterface* di);
  // ----------- operational functions ----------------------
  void   update(int nodeID, double ntime);
  void   setValues(interfaceID, dou* value, int size);
  double getValue(int interfaceID, int index);
  // ----------- error and information functions ----------
  void checkConfiguration(int cv[], int cv_size);
}; // end ZSignalNode

The ZSignalInterface class --

class ZSignalInterface {

private:
 // Internal variables
 ZIntegerVector* m_cv;
 ZSignalFlow*   m_flow; // configuration

```
ZSignalVector*   m_sv;
ZSignalInterface* m_siConnected;
Int               m_state
bool              m_active, m_change;
bool              m_storage, m_destination;
```

public:
```
static int m_signalInterfaceCounter; // object counter
// constructor and destructor
ZSignalInterface(int cv[], int cv_size, ZSFlow* flow);
virtual ~ZSignalInterface();
// ---------- configuration functions ---------------------------
int       getSize(void);     // number of signals
int       getType( void );  // interface type
int       getStorageType(void), getState(void);
void      setState(int state);
int       getGroupID(void);
ZSignal*  getSignalRefByIndex( int index );
ZSignal*  getSignalRefByID( int id );
ZSignal*  getSignalRefByType( int type );
void      connect(ZSignalInterface* di);
void      tryConfiguration(void);
void      verifyConfiguration(void);
void      addSignalElement(ZSignal* sObject);
void      removeAllSignalElements(void);
bool      change( void );
// -------  operational functions -------------------------------
void      update(void);
void      setValues(double* value, int valueSize);
double    getValue(int index);
double    getSum(void), getMax( void ), getMin( void );
// -------  check functions ( throwable) ----------------------
void      checkConfiguration(int cv[], int cv_size);
}; // end ZSignalInterface
```

The ZSignal class --

class ZSignal {

private:
```
int       m_signalID,  m_signalType;
int       m_blockType, m_groupID;
```

```
 double    m_value;
 double*   m_valueRef;
 bool      m_refOK, m_storage;
```

public:
```
 ZSignal( int bid, int id, int type, bool storage );
 virtual ~ZSignal();
 // --------- configuration functions -----------------
 void      setValueRef(double* value);
 double*   getValueRef(void);
 bool      refOK(void);
 bool      active(void);
 int       getGroupID(void);
 int       getBIockType(void);
 int       getSignalType(void);
 int       getSignalID(void);
 // ----------operational functions --------------------
 void      update(void);
 void      setValue(double value);
 double    getValue(void);
 // --------- check functions (throwable) -----------
 void      checkConfiguration();
}; // end ZSignal
```

The resource class --

```
typedef JVector<int> ZIntegerVector;
typedef JVector<ZDataInterface*> ZDataInterfaceVector;
```

class ZResource {

private:
```
 // resource internal configuration
 int    m_type;                    // resource type
 int    m_id;                      // resource identity
 int    m_groupID;                 // signal group identity
 ZDataInterfaceVector* m_div;      // vector with all interface references
 ZDataInterface*  m_di;            // temporary interface
 ZIntegerVector*  m_bt;       // integer vector with requested block types
 int              m_btSize;
 ZIntegerVector*  m_bti;      // integer vector with actual block type indexes
 ZIntegerVector*  m_bts;      // integer vector with actual block type sizes
```

public:
ZResource(int groupID, ZIntegerVector* bt);
virtual ~ZResource();
 // ***** Internal resource administration *******
 void   setID(int id);
 int   getID(void);
 void   setType(int type);
 int   getType(void);
 void   setGroupID(int groupID);
 int   getGroupID(void);
 int   getInterfaceSize(void);

 // ***** configuration ***********
 bool   verifyInterfaceRef(ZDataInterface* interfaceRef);
 bool   replaceInterfaceRef(ZDataInterface* interfaceRef);
 void   addInterfaceRef(ZDataInterface* interfaceRef);
 ZDataInterface* getInterfaceRef(int bType, int bNr);
 ZDataInterface* getInterfaceRef(int iIndex);
 void   bt_initVectors(void);
 void   bt_resetVectors(void);
 void   bt_updateVectors(void);
 int   bt_getIndexB(int bType); // returns index for blockType
 int   bt_getIndex(int bType);   // returns index for blockType
 int   bt_getIndex(int bType, int bNr); // returns blockType
 int   bt_getNr(int bType);

 // ***** operation **************
 bool   inOperation(void);
 void   setValue(int bType, int bIndex, double value);
 void   setValue(int bType, int bNr, int bIndex, double value);
 double   getValue(int bType, int bIndex);
 double   getValue(int bType, int bNr, int bIndex);
}; #endif

The resource manager class --

typedef JVector<ZResource*> ZResourceVector;
typedef JVector<int> ZIntegerVector;

class ZResourceManager {

private:

```
// configuration
  int    m_group;        // group identity
  int    m_bid;          // the block type, if used within a specific block
  int    m_id;           // resource manager identity
  int    m_type;          // resource type
  bool   m_refOK;
  int                    m_nodeID;
  ZDataNode*             m_nodeRef;  // connected dataNode
  ZDataFlow*             m_flow;
  ZResourceVector*       m_rv;        // Resource vector
  ZIntegerVector*  m_bt;            // block type vector
public:
  enum{RMC_VECSIZE  = 4};         // configuration vector size
  enum{RMI_ID       = 0};         // resource manager identity
  enum{RMI_TYPE     = 1};         // resource manager type
  enum{RMI_BT1      = 2};         // block type in (interface)
  enum{RMI_BT2      = 3};         // block type out

  static int m_resourceManagerCounter;

  ZResourceManager( int id, int type, int nodeID);
  ZResourceManager(int cv[], int cv_size, ZDataFlow* flow);
  virtual ~ZResourceManager();

  bool   tryConnectInterfaceRef(ZDataInterface* interfaceRef);
  void   addResource(ZResource* resource);
  void   addResource(ZDataInterface* interfaceRef);
  void   removeResource(int resourceID);
  void   tryRemoveResource(ZDataInterface* interfaceRef);
  int    verifyResource(int resourceID); //check if it already exists
  int    findResource(ZDataInterface* interfaceRef); //returns resource id
  int    findInterfaceInResource(ZDataInterface* interfaceRef);
  void   setInterfaceRef(int rIndex, ZDataInterface* interfaceRef);
  void   setInterfaceRef(ZDataInterface* interfaceRef);
  bool   verifyInterfaceRef(int rIndex, ZDataInterface* interfaceRef);
  bool   checkInterfaceRef(ZDataInterface* interfaceRef);
  void   checkConfiguration(void);
  void   verifyResources(void);
  void   check_vIndex(int vIndex);
  bool   getResourceChange(void);
```

```
    void      setResourceChange(void);
    int       getBlockType(int vIndex);
I  int       getBlockIndex(int vIndex);
// function used by other objects
    void      setValue(int rIndex, int bType,int bIndex, double value);
    void      setValue(int rIndex, int bType, int bNr, int bIndex, double value);
   double  getValue(int rIndex, int bType, int bIndex);
   double  getValue(int rIndex, int bType, int bNr, int bIndex);
    int       bt_getNr(int rIndex, int bType);
    int       bt_getIndex(int rIndex, int bType, int bNr); // returns blockType
    void      setValue(int rIndex, int vIndex, double value);
    void      setValues(int vIndex, double* value, int valueSize);
   double   getValue(int rIndex, int vIndex);
   double* getValues(int vIndex);
   double   getSumValue(int vIndex);
    int       getResourceSize(void);
    void      setValue(double value);
   double   getValue(void);
    void      setValueRef(double* value);
   double* getValueRef(void);
   bool      refOK(void);
   // internal functions for the Resource Manager
    void      setID(int id);
    int       getID(void);
    void      setType(int type);
    int       getType(void);
}; #endif
```

The production management class ---

class ZProductionManagement {

private:
```
  double SPgen;
  double loadSP;
  double storSP;
  double exchSP;
  bool lowVoltage;
  bool enablePowerGeneratingUnits;
  //---------- constructors -------------------------------
  ZProductionManagement(double cv[], int cvSize);
```

public:
```
void       setValue(int index, double value);
void       setValues(double* value, int valueSize);
double    getValue(int index);
double    getValue(int ind, int index[], int value[], int size);

void        setAttribute(int rID, int index, double value);
            // "rID" and "index" starts with 1
double    getAttributeSum(int index);
double    getAttributeSum(int rType, int cStatus, int gStatus, int index);
double    getValueSum(int target, ZIntegerVector* targets);
double    getResourceValue(int rID, int index);
void        getResourceNr(void);   // number of each resource type
int          getResourceID(int index[], int value[], int size);
int          getResourceByCondition(int index[], int value[], int size);
ZIntegerVector* getResourcesByCondition(int index[], int value[], int size);
int          getResourceNrByCondition(int index[], int value[], int size);
double    findMinValue(int target, int targetRef, int index[], int value[], int size);
double    findMaxValue(int target, int targetRef, int index[], int value[], int size);
double    turnOnSetpointAsCondition(int condIndex[],
                            int condValue[], double powerToBeIncresed);
double    turnOffSetpointAsCondition(int condIndex[], int condValue[],
                                    double powerToBeDecresed);
double    shutOffUnits(int condIndex[], int condValue[],
                                    double powerToBeDecresed );
double    turnOnUnits(int condIndex[], int condValue[],
                                    double powerToBeIncresed );

double    findLargestByCondition(int rType, int cStatus, int gStatus,
                                                int index );
double    findSmallestByCondition(int rType, int cStatus, int gStatus,
                                                int index );
void        analysePowerCapacity(void);
void        securityUpdateSequence(void);
void        decidePowerSetpoints(void);
void        calculatePowerCapacity(void);
void        pGenerationCapacity(void);
void        pLoadCapacity(void);
void        pStorageCapacity(void);
void        pExchangeCapacity(void);
```

```
 void       analyzePowerCapacity(void);
 void       updateSecurity(void);
 void       loadManagement(void);
 void       genManagement(void);
 void       storManagement(void);
 void       exchManagement(void);
 void       update(double timeStamp);
}; //end ZProductionManagement
```

The production exchange class --

class ZProductionExchange {

private:
```
 ZString* m_objName;
 ZResourceManager* m_rm;
 bool   m_rmOK;
 bool   m_simOK;
```

public:
```
 //---------- constructors --------------------------
 ZProductionExchange(int cv[], int cvSize);

 //----------- operational functions ----------------------------
 void       setValue(int index, double value);
 void       setValues(double* value, int valueSize);
 void       unitSecurityUpdate(void);
 void       update(double timeStamp);
}; //end ZProductionExchange
```

Appendix C

Communication set–up system

An automated power system is very much depending on a well-defined communication system. Disturbances can occur at any time and has to be managed immediately. It is important that the power units within the DPS have a well working communication system enabling fast coordination and cooperation. The bandwidth of the communication network is crucial in making the system dynamic, and special consideration has been taken for this reason. This work includes different types of information paths that have to be solved before a fully automated DPS could be set up in the laboratory environment. The included communication paths are:

- *Converter-PC communication*: This communication link is used between the control computer of the converter and control application in the PC. The connection enables the usage of the developed software applications in PC enviroment to operate and control the converter. The communication is managed by a program in Matlab.

- *PC-PC communication*: The different converters have to be controlled by a computer. Since the production management program has to know what every converter is doing, all of the computers have to be able to communicate with each other.

- *Matlab - C++ communication*: The communication between all of the different units is done by Matlab but the control program is written in C++. Therefore it is necessary to find a way to use C++ files from Matlab.

- *Matlab-Matlab communication*: this is used when the production management and production exchange program are handled from the same computer. In this case it is unnecessary to use the external

communication when it can be done with internal communication within the computer.

The laboratory tests on the different communication paths are here further described.

C.1 Converter – PC communication

The communication between the PC and converter is managed by using the dSpace program. DSpace works as an interface between the PC and the converter and interacts with the Simulink program that controls the converter. DSpace is also used to directly change set points and different variables that may be changed after the download to the DSP card is done. It is also possible to use dSpace to supervise certain values and signals to receive information from the converter during operation.

A common way to communicate with the converter is to use the control desk program in dSpace. In this environment it is possible to configure your own control system. This has been done to test the control signals; command, govern and set point. In return, the DC-voltage, DC-current and the power have been shown during operation. The control desk program is a helpful tool in order to test the individual converter stations before interconnection to the superior automated functions.

The connection from the converter stations to superior functions requires the possibilities to change the variables from another program written in a high-level programming language. The Matlab library "MLIB" is used, which function as an interface between dSPACE and Matlab. Enabling the MLIB requires a predefined search path to the variables needed for information exchange. This is done using the following code.

mlib('SelectBoard','DS1104');

variables   = {'Model Root/Superior \ncontrol/Command/Value';...

var_desc   = mlib(' GetTrcVar ', variables);

After the establishment of the search path, the values are changed by the following function calls separately depending on writing or reading.

mlib('Write',var_desc,'Data', {The variables that have been initiated});

mlib('Read', var_desc);

The constant "var_desk" is a number informing the converter where to find the variables that have been traced, and has to be used both when writing and reading. The tracing part only needs to be done once, and it takes about 0.3 seconds to perform and the reading and writing part takes less then 0.001 seconds.

C.2 PC – PC communication

The individual converter stations are attached to one computer each. Since the converters should exchange information between each other, this communication is done via the computers. The TCP/IP is used for in the local network that connects all of the computers. The PC to PC communication program used is written in Matlab. The Matlab library manages the tcp/ip communication from Matlab. The main file is written in C++ and the library includes several small m-file programs that use the C++ file. The files applied from the library of m-files were:

- tcpip_open;   opens a new tcpip connection.
- tcpip_close;   closes an open tcpip connection.
- tcpip_sendvar;   sends matlab variable.
- tcpip_getvar;   gets matlab variable.
- tcpip_servsocket;   creates a socket to a port, waiting for connections
- tcpip_listen;   checks/gets connection to tcpip_servsocket
- tcpip_status;   returns status of open connection

The communication bandwidth is important and several performance tests have been conducted were three is presented. The first test was made to check the m-files themselves and their performance. The tests where conducted using only two computers, one to open the connection and to send and the other one to receive, as shown in Figure B.1 (a).
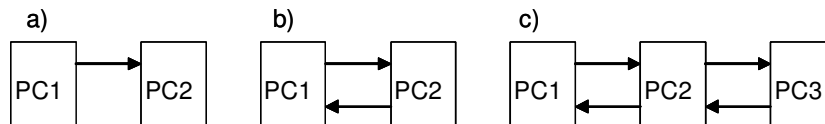
Figure B.1: a) unidirectional performance test; b) bi-directional performance test; c) multi computer performance test.

The message size included one constant, which were sent 300 times to get reliable results. The time needed for every message to reach its destination was saved in a vector to be analyzed. The most important m-files used in this experiment for PC 1 were tcpip_open to open a new connection and tcpip_sendvar to send the package. The most important m-files for PC 2 were tcpip_listen to check if someone is trying to send something to the computer and tcpip_sendvar to receive what has been sent. The most relevant results to show from these tests are the maximum, minimum and the average time it took for one message to reach its destination. These times are shown in Table B.1. The average time and the shortest time from Table B.1 are quite similar. It means that most of the messages are being sent at full rate, and that a few of them took slightly longer to reach their destination. These longer times can be explained with the fact that the tests are done on a communication network that is used by more computers than the one used in this test.

<div align="center">Table B.1</div>

T average	15,6 milliseconds
T max	32 milliseconds
T min	15 milliseconds

The second test was conducted to check how long time it took to send one package from one computer to another and then be sent back again to the first one as shown in Figure B.1 (b). This test was also repeated 300 times in order to get reliable results. The result of the test is shown in Table B.2 and shows the minimum, maximum and the average time for one message to go both ways.

<div align="center">Table B.2</div>

T average	32,5 milliseconds
T max	344 milliseconds
T min	31,0 milliseconds

The average and minimum time are about twice as large in comparison to the previous performance test, which was expected since the package has to

go two ways instead of just one. But the maximal time to send one message was longer then expected.

The third test conducted included three computers as shown in Figure B.1 (c) where PC 2 sends its message to PC 1 and waits for the answer. When the answer has arrived it sends a new message to PC 3 and waits for the answer, and so on. PC 1 and PC 3 have the same program and their only tasks are to wait for a signal from PC 2 and, when the signal arrives, to respond. The performance for this system is shown in table B.3. From Table B.3 it is possible to see that the results for the computers are quite similar to the results in test 2, showing that the packages do not collide with each other.

Table B.3.

	Computer 1	Computer 2	Computer 3
T average (ms)	79,1	39,4	79,2
T max (ms)	94	62	94
Tmin (ms)	78	31	78

The results for PC 1 and PC 3 are also sufficient; their times are quite fast and there is not a large gap between the minimum and the maximum results. This method is the one used for further investigations and verifications of the automated functions developed in the work.

C.3 Matlab – C++ communication

The DSpace application controls the converters and uses Matlab / Simulink as a base program for its controlling technique. It is also from Matlab that the communication between the converter and the computer is taking place. But the major control programs that are processing all the data and making the system work dynamically and efficiently are written in C++ code.

The Matlab programs are linked to the C++ programs according to Figure B.2. To execute the code from Matlab an interface class in C++ had to be developed. That interface class points at the functions that Matlab is using.

All of the C++ code had to be made as a .dll file to make it possible for Matlab to compile it.

There are mainly two different C++ classes that Matlab are able to communicate with. Therefore two different .dll files have to be created. The first one linked to the production management class. This class manage all the automation functions and to this class all the production exchange classes are connected.
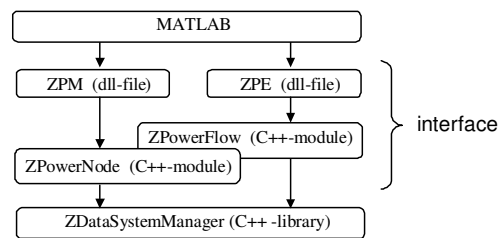
Figure B.2: Matlab and C++ interconnection.

The second one is linked to the exchange class. This class has to be used in every computer that controls a converter station. This due to that the control signals have to be processed by this class before being forwarded to the converter.

C.4 Matlab – Matlab communication

This communication link is only used when there are two Matlab programs running on the same time on one computer. This communication is not controlled in any way, so both of the Matlab programs read and write to the storages files as fast as possible. There are two files that are used for the communication. One file is only used for communication from the production management part to inform the production management part. The other file is used by the production exchange part to inform the production management of its status. Each file is in other words used for a one-way communication link.

The files that are used are the standard functions "fwrite" and "fread". These functions write and read data from a file on the computer. But before these functions can be used, the file used must be opened for read or write access. This is to prevent the file from being read and written to at the same time. The opening process is done with the fopen-function.

C.5 Matlab

The complete system is controlled from Matlab in the laboratory tests. Matlab manages the communication between the computer stations and between the computer station and the converter as shown in Figure B.3.

The converter is controlled through the dSpace interface program. In order for dSpace to work as requested, a control program made in Simulink has to be downloaded to dSpace.

The large boxes in Figure B.3 represent the different computers in the system. Computer 1 in the left side of the Figure is the one managing the coordination of the power system.
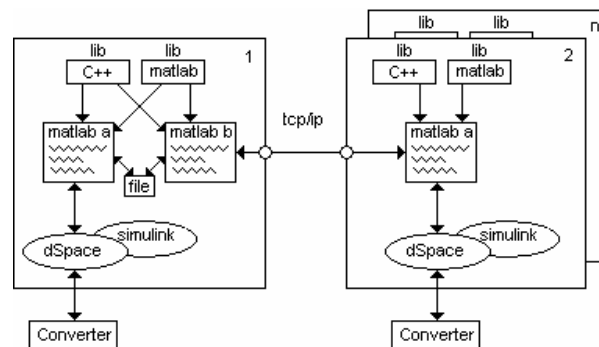
Figure B.3: Schematic picture of the communication paths in the DPS.

The best way to change variables and to get feedback signals from the process while it is running is to use Matlab. The Matlab program "a", in Figure B.3, is therefore continuously checking some values from the converter and updating others. The information managed is linked to the production exchange management (PE) program in the C++ library. This program also receives the information from the production management (PM) program. The result from this class is transmitted to the converter and back to the PM program via the PE. This is done by using a function library with both C++ and Matlab classes.

Another Matlab program "b", which is managing the automation and coordination part, runs in parallel. This program controls the other application programs. From this program all the information to the converter is transmitted, via a local file on the computer. It is linked to the

production management class (also in the C++ library) and it is from this program the Matlab program gets the information that is distributed to the other units. Other computers, i.e. computer "2" to computer "n" from Figure B.3, are able to connect by using the TCP/IP protocols. These computers do however only need to have the exchange program running, since the automated coordination program part is executed at computer 1.

Appendix D

System capability diagram
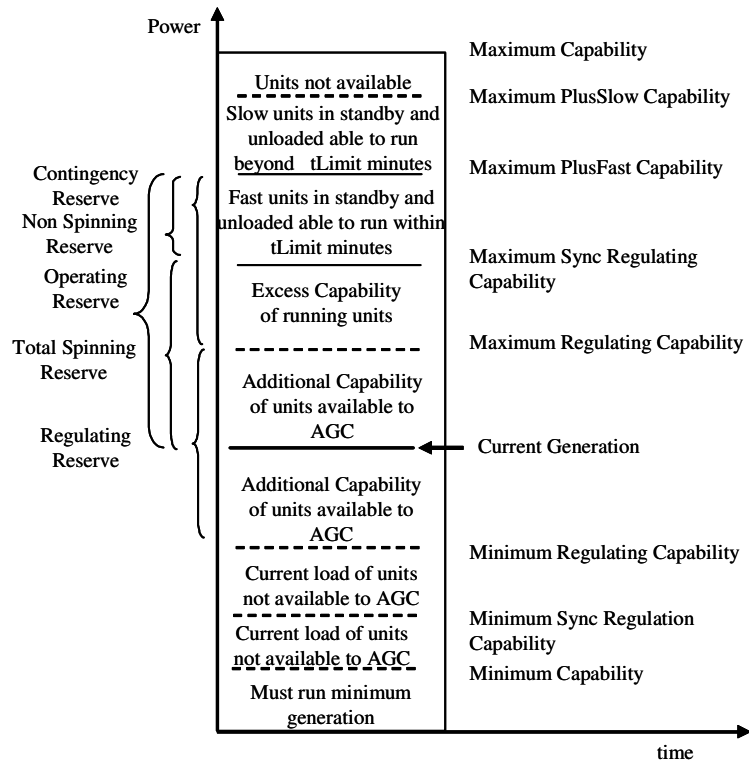
Appendix E

Control flow schemes

E.1 Primary control sequence

Primary control sequence

```
Get rNumber = number
of units that can operate
in primary control.
```

| rNumber = 0 | (rNumber =1) && (power demand <= 0.9* pMax) | rNumber >=2 |

no.   yes.

```
Raise Regulating
reserve is small?
```
yes.   no.

```
Any sink unit connected ?
```
no.   yes.

```
Activate primary
source unit
```

To the power set point decision part.

E.2 Secondary control algorithm

abs(new setpoint – actual setpoint) > LIM	

yes+	no	yes-
PowerToBeIncreased > 0		PowerToBeDecreased > 0
Check for generators with highest priority		Check for generators with lowest priority
Try to increase generators in ON state to fulfill the setpoint.		Try to decrease generators in Pcontrol to fulfill the setpoint.
PowerToBeIncreased > 0		PowerToBeDecreased > 0
yes	no	yes
Try to turn on generators in Ready stage to fulfill the setpoint.		Try to decrease generators in Pmax mode to fulfill the setpoint.
PowerToBeIncreased >0		PowerToBeDecreased > 0
Try to turn generators in Ready stage to prepare to fulfill the setpoint.		Try to turn generators in Pmin mode off in order to fulfill the setpoint.
PowerToBeIncreased > 0		PowerToBeDecreased > 0
yes	no	yes
Decrease priority level		Increase priority level

End

E.3 System set point assignment procedure

```
                    │
                    ▼
        ┌──────────────────────┐   yes    ┌────────────────────────┐
        │  GenOK & LoadOK      ├─────────▶│ Try to set the setpoint │
        └──────────┬───────────┘          │ for the loads as high   │
                   │ no                    │ as the demand for the   │
                   │                       │ loads                   │
                   │                       └────────────┬───────────┘
                   ▼                                    │
        ┌──────────────────────┐   yes    ┌─────────────▼──────────┐
        │ GenOK & StorOK &     ├─────────▶│ SPstorage = – (PmaxGen │
        │ Storage not full &   │          │ – pmaxLoad)            │
        │ PmaxGen > (pmaxLoad  │          │ SPGen += –SPstorage    │
        └──────────┬───────────┘          └─────────────┬──────────┘
                   │ no                                  │
                   ▼                                     │
        ┌──────────────────────┐   yes    ┌──────────────▼─────────┐
        │ GenOK & ExchOK &     ├─────────▶│ SPexchange = – (PmaxGen│
        │ PmaxGen > pmaxload+  │          │ – pmaxLoad +pminStor)  │
        │ PminStor)            │          │ SPGen += –SPexchange   │
        └──────────┬───────────┘          └──────────────┬─────────┘
                   │ no                                   │
                   ▼                                      │
        ┌──────────────────────┐   yes    ┌───────────────▼────────┐
        │ ExchOK & LoadOK &    ├─────────▶│ SPexch = PmaxLoad      │
        │ PmaxLoad > pmaxGen   │          │ –pmaxGen               │
        └──────────┬───────────┘          └───────────────┬────────┘
                   │ no                                    │
                   ▼                                       │
        ┌──────────────────────┐   yes    ┌────────────────▼───────┐
        │ StorOK & LoadOK &    ├─────────▶│ Spstorage = PmaxLoad – │
        │ Storage not empty &  │          │ pmaxGen –pmaxExch      │
        │ PmaxLoad > (pmaxGen  │          └────────────────┬───────┘
        │ + PmaxExch)          │                           │
        └──────────┬───────────┘                           │
                   │                                        │
                   ▼                                        │
        ┌──────────────────────────────────────────────────▼───────┐
        │ SPload = The generation sum of all of the remain units    │
        └──────────────────────┬───────────────────────────────────┘
                               │
                               ▼
```