Control of a Multi-terminal VSC-HVDC system

A general Control System structure

Evripidis Karatsivos

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Department of Measurement Technology and Industrial Electrical Engineering

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Department of Measurement Technology and Industrial Electrical Engineering
Faculty of Engineering
Lund University
Box 118
221 00 LUND
SWEDEN

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Abstract

Environmental impact and security of supply has fuelled a shift in the power mix of power systems today. Traditionally used fossil fuel gives more and more space to the development of renewables in an effort to comply with strict international standards regarding CO_2 emissions and secure energy supply. Wide geographical spread of renewable resources indicates that HVDC technology is most suitable for transmitting power from the isolated points of generation to the points of consumption. This is also supported by the fact that the most advanced among renewable technologies is wind power technology which tends to expand offshore where higher wind potential is available and projects are more immune to public opposition. Integration of renewables and their upgraded role in the power system together with the ambition of an integrated energy market trigger visions of a highly controllable and reliable, continent-wide DC grid based on multi-terminal HVDC technology.

Recent developments in converter technology make this vision realistic. Voltage Source Converter (VSC) technology shows great controllability facilitating the connection to the AC system compared to Current Source Converter (CSC) technology. VSC-HVDC technology is suitable for multi-terminal system arrangements but several issues need to be investigated before this becomes reality. While the development of large multi-terminal VSC-HVDC depends on the functionality of a fast and reliable DC breaker, such component may not be indispensable for the development of smaller systems. Nevertheless, concerns exist for the development of smaller, regional multi-terminal VSC-HVDC systems, especially if they are expected to expand and interconnect to form a larger DC grid in the future. Lack of field experience is a source of concern but most importantly, lack of standardization and absence of a control system to perform the coordinated operation of the multi-terminal VSC-HVDC system.

The focus of this thesis is the control system that will allow automated and coordinated operation of a multi-terminal VSC-HVDC system. It is perceived that the control system can contribute in the standardization in

software level with the intention to allow uniform interfacing with equipment coming from different suppliers. The transition from small, regional multi-terminal VSC-HVDC systems to a large DC grid will most likely happen gradually expanding and interconnecting the individual, small multi-terminal systems to form a larger system where coordinated operation is considered necessary. A well designed control system already in this stage can contribute in keeping up with this evolution assuring at the same time safe system operation both in normal conditions and under disturbances. The intention is to describe the structure and features of such system and provide an implementation that can be validated by simulations.

In this thesis the structure and features of an overall control system for a multi-terminal VSC-HVDC system are described. Following this outline an implementation is proposed that is validated through simulations on mainly 3-terminal VSC-HVDC systems. Uniform interfacing is used and a minimum necessary data set is suggested. The expandability of the proposed control system is tested as well as its behaviour in normal operation and operation under disturbances, such as communication loss events and AC faults.

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Lund, 9 July 2013
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Contents

Chapter 1

Introduction

The debate over DC or AC technology existed since the beginning of use of electricity. The first developed power systems used DC technology developed by Edison. Experience with DC technology, at that time, made its disadvantages clear quite soon. Due to resistive losses the transmission range of DC power was very limited. Tesla then suggested the use of AC technology and came up with the 3-phase power system that is in use today. The use of 3-phases instead of one made the power output stable enough to compete with DC technology. The main advantage of AC technology though, was its key component; the transformer. The use of transformers allowed the conversion of voltage to high levels. In this way the current in the conductor was reduced leading to less losses and allowing much longer transmission range. The "war of currents" was virtually over with the AC technology as the winner, and it would remain like this without any major challenge for about a century.

AC technology dominated the power systems and kept developing to lead to today's highly reliable power systems that energize industry and daily life. High dependency of society on electricity and its ever growing demand of power, stretch the AC power system's capacity to serve its purpose. The power system is today called to satisfy increased power demand, coming from a versatile power mix, fulfilling strict requirements on efficiency and reliability and under a free market regime.

The model of centralized power generation alone is not sustainable anymore since it depends on fossil fuels and carries all their implications, environmental impact and security of supply issues. Renewable energy sources, with wind power standing out, appear then on the scene promising to enable sustainable power generation and resolve security of supply issues. However, integration of renewables challenges directly the structure of the power system. Their wide geographical distribution not only complicates their connection to the existing power system but also requires transmission of large amounts of power over long distances to bring the power from the point of generation to the point of consumption. This becomes even more imperative as wind power, the most developed among renewables, expands offshore.

Recent developments in semiconductor converters and HVDC technology put DC back on the scene promising low loss and long range transmission and control flexibility. Since the 1980's thyristor based HVDC technology has been used for bulk transfer of power over long distances offering low power losses. However, thyristor based HVDC, or CSC-HVDC, requires connection to strong grids on both sides to control reactive power. This makes it unsuitable for wind power integration, since wind power plants (WPPs) are in principle weak grids. The advent of transistor based HVDC technology, based on Voltage Source Converters (VSCs), responded to this issue. VSC-HVDC technology handles active and reactive power separately making the connection to a weak grid possible.

Point-to-point VSC-HVDC connections answer the question of isolated WPPs connection to the existing power system or power transmission from one point of the power system to another, distant one. However, the geographical expansion of WPPs and the higher power demand in multiple consumption areas might require a multiple input-multiple output arrangement for power transmission. In such arrangements, the use of point-to-point connections could be the solution but it would be a costly one and redundancy would be an issue. Instead, multi-terminal VSC-HVDC arrangements are more attractive, both economically and in terms of functionality and reliability.

Multi-terminal VSC-HVDC systems promise to contribute to the integration of renewables, handle long range bulk power transmission and integrate markets on European level. Ideas already exist about the so-called SuperGrid, a DC grid transferring power from hydro plants in north Europe or solar plants in North Africa to the consumers.

So, is this a new "war of currents"? AC and DC technologies are not going into war again anytime soon, it will most likely be a peaceful coexistence. It is not difficult to come to such a conclusion. AC is a well proven technology, most of the expertise today in power systems revolves around

AC technology and most importantly nearly all the existing infrastructure is based on AC technology. On the other hand, DC technology promises to compensate for the disadvantages of AC technology but it is still at an early stage of development. Considering the cost of DC technology today it becomes obvious that it will be used at transmission level, at least in the beginning. It simply wouldn't be a good idea to replace AC technology with DC technology overnight; definitely not from an economical point of view and neither from a technical point of view.

1.1 Motivation

The controllability of the VSCs is established both on converter level and on system level when it comes to point-to-point connections. Experience on VSC-HVDC systems today lies solely with two-terminal, point-to-point connections. In this type of connections the coordination of the terminals is simple and follows the guidelines of CSC-HVDC systems, while in case of emergency they are allowed to shut down. There is no field experience though when it comes to multi-terminal VSC-HVDC systems. A multi-terminal VSC-HVDC system will cover a wide area and handle large amounts of power, thus its coordinated operation is necessary both to monitor and to coordinate the different terminals. In case of emergencies strict restrictions will most likely apply to avoid large disturbances inflicted to the adjacent AC systems and prevent the HVDC system from shutting down.

The evolution of multi-terminal VSC-HVDC systems will most likely be that regional systems will start being built that will later be expanded and interconnected to form the DC grid. This follows the experience of the AC system evolution and also the existing experience on VSC-HVDC systems and the lack of standardization for this type of systems. In this sense the control system that will coordinate the operation of the multi-terminal VSC-HVDC system shall be designed to be able to follow the evolution of such system.

Most research efforts have been concentrated on coordinated DC voltage control which is a fundamental condition for the operation of a multi-terminal VSC-HVDC system. It is perceived though, that there is a gap of knowledge regarding the control system that will put coordinated DC voltage control in context and automate system operation in a standardized manner to facilitate its expansion. The motivation for this project is to investigate what the role of an overlying control system can be in standardization, reliability and expansion of a multi-terminal VSC-HVDC system.

A system of such scale and with such fast dynamics will require automatic adjustment of setpoints and control modes especially in case of emergencies. Coordinated DC voltage control contributes much in the stabilization of the system during rapid power flow changes but it does not necessarily keep the system close to its optimal operation. Quick readjustment of setpoints is important especially during disturbances and if used appropriately can limit the propagation of disturbances to adjacent systems or direct it to the ones that can best handle it. One major obstacle towards coordinated operation is the lack of standardization. Lack of standardization, in the scope of this work, does not concern hardware standardization but interface standardization. In the course of development of multi-terminal VSC-HVDC systems it is reasonable that different suppliers will be involved. In the lack of standardization, different suppliers will have different interfacing requirements and different expected outcome for the operation of their equipment. The interaction of such versatile mix of equipment under one control system will be an issue for system coordination and operation. Also as VSC-HVDC technology advances and multi-terminal systems become more complex new requirements might exist. The control system under discussion must then be designed in a way that it is able to incorporate new requirements without affecting its operation.

If an overlying control system is considered required then what structure should it have? How can this structure be used to promote the expandability of multi-terminal VSC-HVDC systems? If this control system is going to operate on equipment that complies with different standards, how is it going to communicate and could the communication be standardized? How dependent will it be on communications and how can they be used to coordinate the response of the system at specific disturbances?

The lack of answers in most of the above questions is the motivation of this project which intends to provide some of them with the ambition to outline the structure of future control systems for multi-terminal VSC-HVDC systems.

1.2 Objectives

The main objective of this work is to describe an overall control system structure for the coordinated operation of a multi-terminal VSC-HVDC system in order to guide the design of future systems.

The intention is to describe the general features of this control system and then to provide suggestions as to how it can be implemented. In the course of this work, the different features and functionalities of the control system are divided in different control levels and specified in order to lead to an implementation that can be validated through simulations. The aim is a functional control system that can successfully coordinate the operation of a given system both in normal operation and under disturbances. In addition, the suggested control system is intended to be flexible and expandable both in terms of functionality and in terms of number of terminals. General coordination functions shall handle the coordinated function of the system without limiting its expandability. DC breakers are not considered in this work and thus DC faults are considered to be disturbances that will shut down the system. Other disturbances should be considered though, such as AC faults and communication loss events, that the control system must be able to overcome quickly and without interruption of operation.

A multi-terminal VSC-HVDC system that interacts with different types of connected systems, using equipment by different suppliers needs to establish a form of communication with the different involved systems. The intention is to propose a uniform pattern of interfacing between the different systems. Uniform interfacing must be general and thus include a minimum necessary data set that can easily be followed by the different suppliers if not already partly implemented. To keep up with future increase of complexity of multi-terminal systems the objective is that the minimum necessary data for interfacing is dynamic and thus adaptable to different requirements for different systems.

The implementation of the control system structure must prove through simulations its ability to easily integrate additional terminals, regardless of their type and assure reliable operation both during normal conditions and under disturbances.

1.3 Outline of the Thesis

Chapter 2 gives a view on the developments that lead VSC-HVDC technology to be considered as a competitive solution for future integration of renewables and bulk power exchange. It also attempts to present what is today's standpoint regarding experience on VSC-HVDC technology and what the visions and the challenges for its development are.

Chapter 3 presents the basics of Voltage Source Converters together with their control scheme. Their operation is then discussed in a two-terminal system and in a multi-terminal system.

Chapter 4 describes the structure and general features of the suggested control system distributed in its different control levels. The role of the uniform interface is also described there and some concerns that need to be taken into account when this system is implemented.

Chapter 5 contains the detailed description of the implementation of the control system used in this work. It also contains the description of the models used to validate the control system.

Chapter 6 contains the simulation scenarios used to validate the proposed control system on the described model. The results of these simulations are presented and a discussion follows as to what extent the control system corresponds to its expected behaviour.

Chapter 7 presents the main conclusions drawn from this work following the rationale developed throughout its course and mainly based on the simulation results obtained in Chapter 6.

Chapter 8 discusses points of interest and further development that could be a natural continuation of this work

1.4 Contributions

The main contribution of this work is to show that a general control system can be designed and that it can facilitate the operation of a multi-terminal VSC-HVDC system.

The basic characteristics of such a control system are described and an implementation is suggested, proving its feasibility and functionality through simulations. A standardized interface to the overall control system is suggested that can dynamically be adjusted in different requirements depending on each individual system.

The structure of this control system can function as a platform changing the implementation of one or more control levels without affecting communications among them or the operation of the entire system as long as requirements on interfacing and expected operation of each control level are fulfilled.

Specific methods are followed to prevent system failure due to communication loss events or AC faults. Key role in this plays the use of general coordination functions in the overall control system and the form of the uniform interface.

In addition a verification model of a multi-terminal system is built in Dymola. A control panel is provided in the model allowing easy modification of the entire model simply changing few parameters. In this way the model can be used to investigate different scenarios either by changing parameters or components.

1.5 Publications

[1] E. Karatsivos, J. Svensson, O. Samuelsson, (2011). Control System Structure of Multi-terminal VSC-HVDC Transmission System, Presented at: *10th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, Aarhus, Denmark, 25-26 October 2011

[2] E. Karatsivos, J. Svensson, O. Samuelsson, (2013). Coordination of a Multi-terminal VSC-HVDC System with a General Control System, Submitted for: *7th IET international conference on Power Electronics, Machines and Drives*, Manchester, UK, 8-10 April 2014

Chapter 2

Renewables, a step towards DC grids

Renewable energy sources play an important role in electricity generation today and are expected to obtain an even more important position in the power mix of future power systems. Renewables pose as an alternative to fossil fuel in terms of reducing the environmental impact and improving security of supply. Renewable energy technology has greatly improved over the last years and the wide geographical spread of renewable energy sources make them an available and efficient solution to many countries.

However, their wide geographical spread brings up issues of transmitting power from the points of generation to the points of consumption. AC transmission technology is one approach to this issue but developments in HVDC technology and the long distances usually involved suggest that a DC solution may be more preferable. This coincides with the concept of a European-wide integrated energy market which will most likely require transmission of bulk power across the continent framing HVDC technology as a strong candidate to take this task. An overlying DC grid on the top of the AC system would then be a likely solution. However, this suggests a massively multi-terminal HVDC system for which not much field experience exists today.

It is a realistic assumption that such a wide DC grid will not occur at once but by connecting smaller multi-terminal HVDC systems, as was the case in the development of the AC system. In this aspect, the integration of renewables can function as an experience gaining field. HVDC technology can be used to tackle the issue of long distances for offshore wind power plants and connect one or more of them to one or more points onshore, building in this way multi-terminal HVDC systems. Following the plans for wind power expansion in the North Sea, these multi-terminal HVDC systems can later be connected to form a DC grid in the North Sea and offer at the same time the necessary know-how for a European-wide DC grid.

2.1 Background

For many years electricity has been produced almost exclusively by fossil fuel rising issues like environmental impact and security of supply due to political reasons. It was then European policy that promoted research and development of renewables. Through the course of development renewable sources of energy have been questioned for their cost and their ability to provide reliable supply of electricity. Despite all defiance research and industry proved renewables to be a promising solution reducing costs and improving efficiency. Wind power technology stands out as one of the most competitive renewable technologies. Most research efforts have been focused on wind power due to its availability. Wind power is attractive because its potential is more widespread geographically than that of solar power. Wide geographical distribution of wind potential largely promoted research and development of wind power but also raised the issue of transmitting this power from dispersed locations of production to locations of consumption.

Onshore wind power deployment started with units of low capacity that were relatively easy to connect to the existing grid. It soon became obvious that as the wind power technology advanced providing higher capacity wind turbines and the necessary know-how, the future of wind power lies on the deployment of larger clusters to further reduce costs. Two new issues rose, the first one had to do with the price of land needed for such deployment and also the severe opposition encountered by the local communities while the second was more technical regarding the high penetration of wind power into the power system.

The direction was clear and pointing offshore. Offshore wind power projects were less vulnerable to public opposition and could be connected directly to the transmission system with little or no enhancement. Going offshore meant that higher and more constant wind potential was now available for harvesting, shorter or no delays could be imposed due to public opposition and easier deployment of larger clusters was possible due to connection with the transmission network. The first small offshore wind power plants (WPPs) started being built close to the shore with two objectives. Firstly, to show the feasibility of the concept and secondly to point out the coming challenges as higher capacity WPPs would expand further offshore. Since the first offshore WPPs were of low capacity and close to the shore, AC transmission technology proved to be sufficient to connect them to the onshore grid.

Since the ambition is that the WPPs expand larger and further offshore an important issue rising is the transmission of the produced power to the shore. Larger offshore WPPs mean higher penetration in the power system which gives wind power a new role. The role of wind power is not supplementary to the power production anymore. Wind power should be able to produce bulk power and support the system when needed instead of shutting down. Further offshore deployment means longer distances for the produced power to reach the onshore grid. AC technology is sufficient for WPPs close to the shore but for longer distances substations in the middle of the sea would be needed to support voltage.

Long distances and harsh environment may require a new approach for the transmission system. Since the invention of power electronics, HVDC technology provides a promising solution for efficient power transmission over long distances. On one hand there is the well proven HVAC transmission technology that has been widely used and therefore developed since the beginning of use of electricity. That was due to the fact that DC voltage could not be high enough for long distance power transmission and voltage had to be supported within very short distance due to resistive losses. With the use of transformers AC technology did not suffer from the same problem. Nevertheless AC voltage had to be supported also but within longer distances. Even though resistive losses were not significant with the high AC voltage, the AC nature of the system had to charge and discharge the cables in every cycle resulting in reactive losses and less efficient cable capacity usage. Building and maintaining a substation where needed to support the AC voltage is not a problem for a system onshore, but when it comes to an offshore system this would mean that a platform out in the sea would have to be built to host the substation and scheduled maintenance would be dependent on the weather conditions. Therefore an HVDC solution that would be able to transmit power directly to shore with lower losses appears attractive. Power electronics allowed DC power to be manipulated to higher voltage levels and allowed efficient power transmission. Through the course of time power electronics have been developed and tested on field providing nowadays complete power transmission solutions. Conventional Current Source Converter (CSC) HVDC technology is widely used today in different parts of the world to transfer bulk power over long distances from one point to another with high reliability.

In an early stage of offshore wind power expansion there is the option to use point-to-point conventional HVDC connections to connect the individual WPPs separately to the shore. CSC-HVDC technology is well proven through its utilization in onshore applications, where the large footprint of its substations is not a problem and the connection to strong grids on both sides is assured. Large footprint and requirement for strong grid connection are the two main obstacles for which CSC-HVDC technology cannot be used for interconnection of offshore WPPs. A WPP is in principle a weak grid therefore unsuitable to be connected with conventional HVDC technology and also going offshore imposes space limitations for the substations so large-footprint substations are not preferable. In this sense a later HVDC technology is preferable for offshore WPP interconnection. The Voltage Source Converter (VSC) HVDC technology is based on transistor devices and provides small-footprint substations that make it suitable for offshore applications. The key feature of VSC-HVDC technology for weak grid connection is that it allows independent control of active and reactive power [1-3]. While a change in active power with CSC-HVDC technology imposes a respective change in reactive power thus requiring a strong grid to be connected to that to sustain the voltage, with VSC-HVDC technology reactive power control is independent from active power control and thus no strong grid connection is required. First field implementations by Siemens and ABB [4] showed the feasibility of such connections. Even though VSC-HVDC technology offers low-loss transmission solutions reducing operational costs, its investment costs are relatively high due to the cost of its terminals. In this way using point-to-point connections for interconnecting the individual WPPs would require a large number of terminals thus increasing the total cost. The reliability of point-to-point connections would also be proportional to cost, since connections should be multiple to provide redundancy. It then becomes obvious that point-to-point connections can be practical but maybe not the most efficient way to interconnect WPPs [5]. The real potential of VSC-HVDC technology can be utilized when multi-terminal VSC-HVDC arrangements can be implemented. In a multi-terminal arrangement multiple terminals are connected to a DC system, in its most fundamental form, clustering in this way production and consumption units. A multi-terminal VSC-HVDC transmission system is a stand-alone transmission system that once energized can be used to energize other connected systems, supply loads, support weak grids or transmit power [6]. Since in this case the discussion is about offshore wind power systems connected to the shore, at least one of the terminals will be connected to the on shore strong grid that could be the one used to energize such a system. Of course, other possibilities exist depending on the capacity of the connected wind power systems and the control methods used for their operation. Multi-terminal arrangements can increase reliability of the transmission system providing redundancy of connections between the different terminals based upon the ability of the VSC-HVDC technology to provide bi-directional power flows on the same line.

In this work, early stage of offshore wind power deployment is referred to high capacity wind power plants clustered together in one multi-terminal VSC-HVDC transmission system with at least one connection to the shore. The layout of the considered system is radial at this stage so that it can form meshes in a later stage of deployment. In the same cluster, production units and loads of different types can be present. The idea is that this radial cluster will form the basic cell of the later stage of deployment when many such clusters will be connected to each other to form a larger offshore DC grid. In terms of technological advancements this separation seems reasonable since the existing experience does not permit the direct jump to the later stage of deployment. Also equipment that will be needed at the later stage of deployment such as the DC breaker and the necessary protection schemes are still in early stage of development. In the absence of the DC breaker the capacity of each cluster must be limited so that it can be acceptable by the served grid to be shut down for some time in case of emergency. The limit of capacity and off line time can vary according to the control system and operation applied.

2.2 VSC-HVDC projects

Multi-terminal HVDC arrangements have long concerned researchers and acting companies in the field. This research effort resulted in the establishment of the first multi-terminal HVDC system in 1990 in Quebec-New England, Canada. The existing HVDC line of 690MW was extended north over a distance of 1100km to connect a new 2250MW terminal and also to the south over a distance of 214km to connect an 1800MW terminal. Later, in 1992 a new 2138MW terminal was integrated in the multi-terminal system. The established operation voltage level is ±450kV. The second multi-terminal HVDC system will be commissioned in India in 2014-2015. The North East- Agra link will be the first multi-terminal UHVDC system and will have four terminals with a capacity of 6000MW, the largest HVDC transmission ever built. The operating voltage will be ±800kV and the length of the overhead DC line will be 1728km. At the same time point-to-point HVDC links have been installed all over the world. Experience showed that multi-terminal HVDC systems using CSC-HVDC technology appear to have important difficulties when it comes to implementation.

Both installed multi-terminal HVDC systems are designed for fixed power flow, their control system complexity is significantly high and they impose high requirements on the connected systems regarding stiffness.

Table 2. 1: Summary of existing and scheduled VSC-HVDC projects [4], [7-9]

Project name	Comission year	Power rating	AC voltage	DC voltage	Length of DC cables	Topology	Semiconductors
Hellsjön, Sweden	1997	3MW ±3MVAr	10kV (both ends)	±10kV	10km Overhead lines	2-level	IGBTs (series connected)
Gotland HVDC Light, Sweden	1999	50MW -50 to +50 MVAr	80kV (both ends)	±80 kV	2x70km Submarine cable	2-level	IGBTs (series connected)
Eagle Pass, USA	2000	36MW ±36MVAr	138kV (both sides)	±15,9 kV	Back-to-back HVDC Light station	3-level NPC	IGBTs (series connected)
Tjaereborg. Denmark	2000	8MVA 7,2MW -3 to +4MVAr	10,5kV (both sides)	±9 kV	2x4,3k, Submarine cable	2-level	IGBTs (series connected)
Terrenova Interconnection (Directlink), Australia	2000	180MW -165 to +90MVAr	110kV-Bungalora 132kV-Mullumbinby	±80 kV	6x59km Underground cable	2-level	IGBTs (series connected)
MurrayLink, Australia	2002	220MW -150 to +140MVAr	132kV-Berri 220kV-Red Cliffs	±150 kV	2x180km Underground cable	3-level ANPC	IGBTs (series connected)
CrossSound, USA	2002	330MW ±150MVAr	345kV-New Heaven 138kV-Shoreham	±150 kV	2x40km Submarine cable	3-level ANPC	IGBTs (series connected)
Troll A offshore, Norway	2005	84MW -20 to +24 MVAr	132kV-Kollsnes 56kV-Troll	±60 kV	4x70km Submarine cable	2-level	IGBTs (series connected)
Estlink, Estonia-Finland	2006	350MW ±125MVAr	330kV-Estonia 400kV Finland	±150 kV	2x31km Underground cable 2x74km Submarine cable	2-level	IGBTs (series connected)
NORD E.ON 1, Germany	2009	400MW	380kV-Diele 170kV-Borkum 2	±150 kV	2x75km Underground cable 2x128km Submarine cable	-	IGBTs (series connected)
Caprivi Link, Namimbia	2009	300MW	330kV-Zambezi 400kV-Gerus	350 kV	970km Overhead lines	-	IGBTs (series connected)
Valhall offshore, Norway	2009	78MW	300kV-Lista 11kV-Valhall	150 kV	292km Submarine coaxial cable	2-level	IGBTs (series connected)
Trans Bay Cable, USA	2010	400MW, ±170MVAr	230kV/138kV, 60Hz	±200kV	85km	Multi-level	IGBTs
East West Interconnector, Ireland- UK	2012	500MW	400kV	±200kV	186km	-	IGBTs?
INELFE, France-Spain	2013	2x1000MW	400kV, 50Hz	±320kV	60km	Modular multi-level	IGBTs
HVDC PLUS link HelWin1, Germany	2013	576MW	155kV to 250kV	259kV	85km	-	-
HVDC PLUS link BorWin2, Germany	2013	800MW	155kV/300kV/400 kV	300kV	200km	-	-
DolWin1, Germany	2013	800MW	155kV/380kV	±320kV	75km	-	IGBTs?
Skagerrak HVDC Interconnections	2014	700MW	400kV	500kV	140km	-	IGBTs?
NordBalt, Sweden-Lithuania	2015	700MW	400kV/330kV	±300kV	400km	-	IGBTs?

Even though there is no practical experience of multi-terminal systems using VSC-HVDC technology, VSC-HVDC technology has been used to overcome CSC-HVDC technology disadvantages for point-to-point connections of many different grids, including weak grids. The small footprint of a VSC-HVDC substation makes its installation on offshore platforms possible which greatly facilitates the integration of offshore wind power plants.

The experience gained by the implementations mentioned in Table 2.1 showed that VSC-HVDC technology is able to provide power flow flexibility, simpler control, independent active and reactive power control, ability to connect any kind of system and black start capability [10]. All these features are necessary for the formation of small, at first, and then large multi-terminal HVDC systems that will greatly facilitate energy trading among nations and integration of renewables.

2.3 Visions and Challenges

The potential of bulk energy transfer over long distances, that the HVDC technology offered, triggered the interest of researchers for a highly interconnected European-wide power system given the benefits of the interconnected AC power system. As the deregulation of the electricity market advanced and renewable power technology developed, taking an important role in power production, different plans started appearing regarding the future of the power system on a continental level [11]. The deregulated market and the distributed production resulting by the use of renewables require a flexible system that is able to transfer large amounts of power across the continent if necessary. Making use of the HVDC technology, ABB already in the 1990s presented its vision of the future highly interconnected, European-wide power system shown in Figure 2-1. In such system bulk power transmission was based on the HVDC technology and much of its power production would be based on wind, solar and hydro power dispersed around the continent.

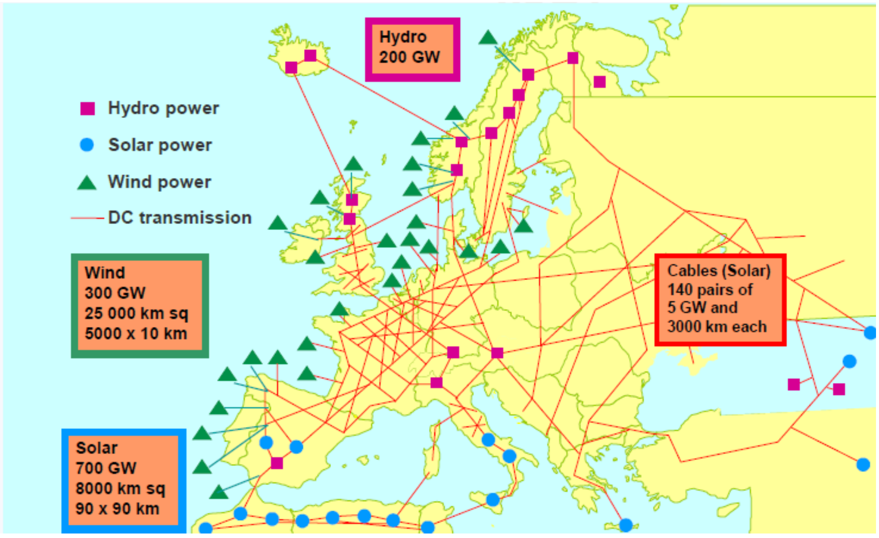

Figure 2-1: ABB's vision from the 1990s

It was clear since then that the future power system would not replace the already existing AC system since it would be as costly as inefficient to replace an already established and operational system for a new one that was not proven yet. The DC system would be a new layer on the top of the AC system and used for bulk power transmission across the continent. The vision of the overlying DC grid has been limited for many years by the weaknesses of CSC-HVDC technology concerning power flow flexibility and strong grid connection requirements. A DC grid would form nodes and meshes to be effective, pointing to a massively multi-terminal arrangement. It can be claimed that even if ABB's vision was encouraged by the commission of the world's first multi-terminal CSC-HVDC system in Canada, it soon became obvious that CSC-HVDC technology could not reach the power flow and grid connection flexibility required to form multi-terminal systems that would make the DC grid vision reality. It was then the rise of VSC-HVDC technology that gave solution to most of CSC-HVDC technology weaknesses and gave a new boost to the vision of the SuperGrid. Even though VSC-HVDC technology is still not mature, it promises the adequate flexibility to form multi-terminal systems and ultimately the SuperGrid. SuperGrid in the form of an overlying system [12] was again within reach and a number of new visions for it appeared. In 2008 [13], a larger suggested system appeared. As shown in Figure 2-2, it extends to northern Africa and includes Russia in a system that is divided in 19 different areas in an effort to integrate solar power produced in Africa and natural gas power produced in Russia.

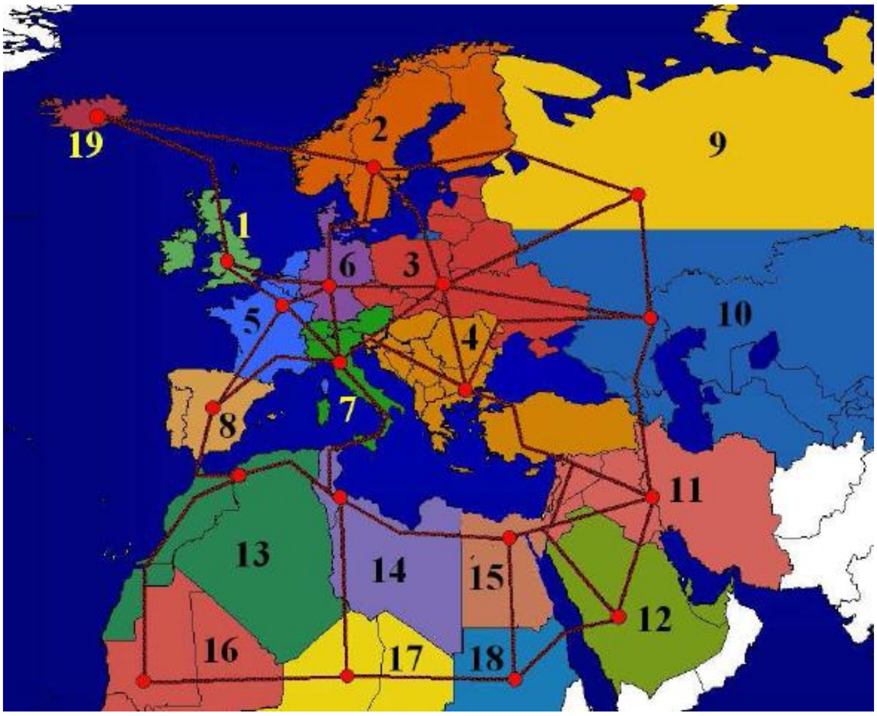

Figure 2-2: G.Czisch vision from 2008 [13]

In the same rationale, Figure 2-3 shows the DESERTEC vision that was presented in 2009 [14].

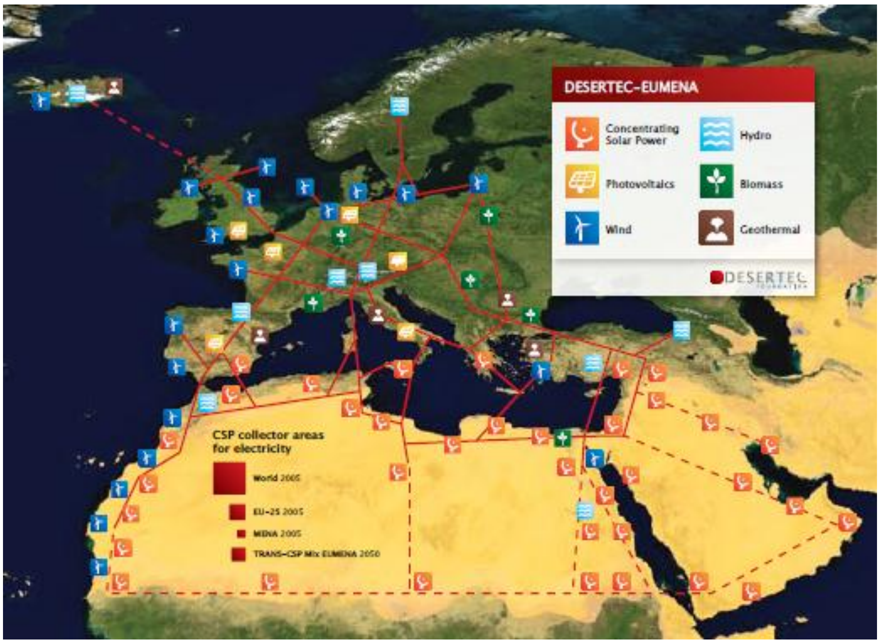

Figure 2-3: DESERTEC vision from 2009 [14]

Of course all the above are visions regarding the final shape of the system. The AC system experience shows that the interconnected system will not occur at once. As for the AC system, smaller cells of the DC system will be developed first and will ultimately be interconnected to form a larger system. In this sense, smaller multi-terminal systems have been proposed with focus on interconnectors between nations and offshore wind power integration. The North Sea is a location shared by many nations and featuring high wind power potential, thus it was reasonable that it is in the focus [15-16]. Many plans have been constituted around the North Sea in an effort to integrate in a DC grid power exchange, in the form of interconnectors between nations, power production, in the form of wind power plants and power consumption, in the form of electricity supplied oilrigs [17-20]. The fact that already all of the above exist in the North Sea makes its selection even more reasonable. In this sense, the plan in Figure 2-4 was presented in [21] with focus on the North Sea.

Figure 2-4: Airtricity vision from 2009 [21]

In the same context, EWEA presented its own vision about the North Sea in 2009 [22].

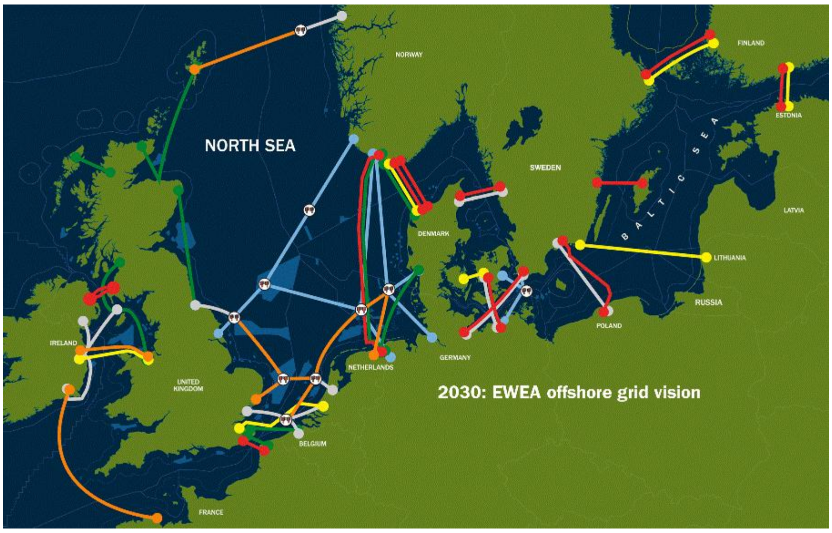

Figure 2-5: EWEA vision from 2009 [22]

EWEA’s vision, shown in Figure 2-5, took into account the existing links in the region and presented what a possible development could be.

The above presented visions regarding the SuperGrid capture the ambitions for the future power system following the recent developments in DC technology and the benefits it offers. It should be kept in mind though, that there are major challenges that lay ahead. VSC-HVDC technology has not reached yet the field experience of the mature CSC-HVDC technology and only recently it started being used for point-to-point connections. Nevertheless, VSC-HVDC connections in place grow in numbers and this poses a significant issue if they are to be connected in one system at some point. Standardization is a concern for the future [23] and only recently action is taken [24]. So far, the different VSC-HVDC links are tailor-made systems optimized to minimize losses but no significant consideration seems to have been taken for their future integration in one system. Standardization in voltage levels and operation routines combined with modularity both in hardware and software will be a defining factor in the facilitation of the expansion from point-to-point connections, to multi-terminal systems, to SuperGrid. Especially if it is considered that one can safely guess that the Supergrid will not be built by one supplier, it becomes obvious that standardization must be a combined effort by TSOs and acting companies in the field. Coordinated control is also something that needs to be considered already now since it can provide guidelines for the design of the present systems for their easy integration. Protection is also an issue of great importance that only recently seems to have made some progress. The main obstacle in terms of protection has been the lack of an acting device, the DC breaker. The DC breaker was a device that puzzled researchers for almost a century. Even though there have been several approaches [25], it is only recently that there is a first answer [26]. The DC breaker is the device that can allow the formation of large, meshed, multi-terminal VSC-HVDC systems and thus allow the next step towards the SuperGrid.

2.4 The Need of a Control System Structure

In this work the development of multi-terminal VSC-HVDC systems is considered in two stages. The early stage of development considers the formation of small multi-terminal systems that integrate in the same system production and consumption. Both production and consumption can come from weak grids in the form of wind power plants and oil rigs.

In the early stage of development the multi-terminal system is radial and no DC breakers are considered. In the latter stage of development, the system becomes massively multi-terminal in a meshed arrangement where DC breakers are indispensable. The focus is in offshore systems and this division is made in accordance to the existing plans for offshore development of wind power and multi-terminal HVDC systems in the North and Baltic Sea.

The scope of this work is to investigate multi-terminal HVDC systems in their early stage of development with the intention to make a contribution in the development of a general control system structure that will be valid at this stage of development of multi-terminal HVDC systems and outline the control system structure of the latter stage of multi-terminal HVDC development. Such a control system structure shall be highly oriented towards modularity and expandability and thus, it shall be able to accommodate different types of connected systems and equipment from different suppliers. The ambition is to point out the main features that are necessary for such a control system structure for reliable operation during both normal and emergency conditions. The proposed control system is then to be implemented and simulated on selected scenarios to verify its efficiency. Possible improvements and future work is later discussed.

Chapter 3

System Operation and Control

There are certain analogies in the operation of an AC system and a DC system from which useful information can be deducted for the operation of a multi-terminal VSC-HVDC system.

In an AC system the indicator of power balance is frequency and for this reason it is the focus of primary control to keep frequency between strict margins. Changes in power influence the frequency of the system. Whether they are caused by generation or load loss or because of the scheduled, hourly power flow changes within the system, they create deviations in the frequency of the system. This is because the kinetic energy of the generators is used to balance the power changes in the system; primary control is then responsible to balance the system at its nominal frequency eliminating stationary errors.

Many generators operate in parallel in an AC system and each one of them has different operating costs and rating limitations. Frequency droop is used then to allow the different generators share the load. In combination with an economic dispatcher, frequency droop can be manipulated to impose load sharing to the different generators according to their operating costs and rating limitations targeting in this way to an economic optimal and yet safe operation of the system. The economic optimal operation in the Scandinavian countries including Estonia and Lithuania is defined on an hourly schedule that occurs from the day-ahead and intraday Nord Pool spot markets.

In a DC system the indicator of power balance is the DC voltage. Even though DC voltage will have different values at the different substations it can be used as the power balance indicator. While a substation in a multi-terminal VSC-HVDC system may operate in different control modes, every control action is ultimately translated to changes in current that directly affect the power balance and consequently the DC voltage. Since there is no kinetic energy involved in this system the effect on the DC voltage is immediate and thus its primary control has to be fast to keep the DC voltage within strict limits. The DC system is expected to operate in combination with the AC system, thus its power flows are scheduled on an hourly basis as for the AC system. Power flow changes will then happen every hour and the different substations will have to operate in parallel to achieve them.

In the same manner as in the AC system, DC voltage droop control can be used to make the different substations share load while collectively supporting voltage regulation. In a multi-terminal VSC-HVDC system different substations may have different ratings and different available power at each point in time. This means that a dispatcher is necessary in a higher control layer to play the role of secondary control and adjust setpoints for DC voltage droop controllers in the system.

A substation in a multi-terminal VSC-HVDC system may have several types of controllers apart from the DC voltage droop controller. This has to do with the type of functionality that is necessary in the system and the type of system each substation connects to the DC system. In any case, a wide range of controllers at each substation provides a wider range of control possibilities for the overall control system of the DC system.

To better understand today's approach in the operation of multi-terminal VSC-HVDC systems and their benefits and limitations, it is necessary to take a step back and look at the principle of operation of such a system and the development of its control. The heart of this system is its converter; focusing on its characteristics and limitations as well as the operation of 2-terminal systems, better understanding is reached regarding the operation and requirements for a multi-terminal system.

3.1 Voltage Source Converter Principle of Control

The principle of operation of the three-phase VSCs used in HVDC systems can be tracked down to the combination of simpler converter arrangements. Switch mode converters are DC/DC power converters that utilize fully controllable semiconductor switching devices to manipulate the voltage level of the transmitted power. The most fundamental forms of switch mode converters are the boost and buck converter [27], shown in Figure 3-1.

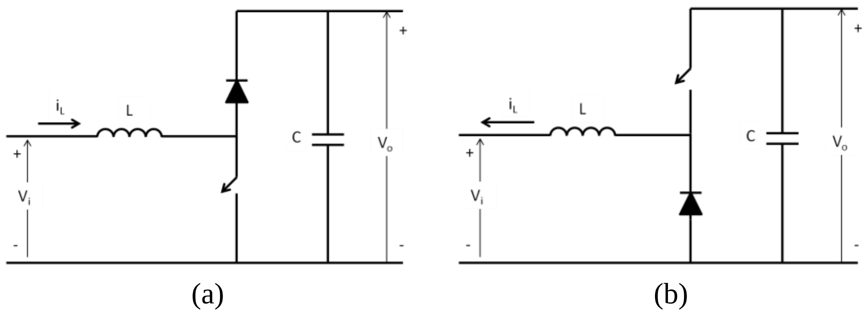

Figure 3-1: Boost (a) and buck (b) DC-DC converters

Both boost and buck converters have an inductance, a capacitance, a diode and a switch as their main elements. The arrangement of those elements defines the functionality and direction of power flow in each topology. In this sense both boost and buck converters are unidirectional. Each of the topologies provides two paths for the current depending on whether the switch is on or off. By comparing a sawtooth waveform with a control signal as shown in Figure 3-2, the time each topology's switch is on, the duty cycle, is determined and the output voltage is manipulated to the desired level. The entire operation of switch mode converters is based on the dynamics of the inductance and the capacitance used. Turning the switch on and off changes the stored magnetic energy in the inductance which tries to keep the current unchanged. Since the inductance is not infinite, variations will appear on the current which will result in variations in voltage. The capacitor supplies then the necessary current to stabilize the voltage. The result is that the capacitor keeps the voltage around the desired value as long as power is provided to the output. The duty cycles of the switches may be implemented using Pulse Width Modulation (PWM).

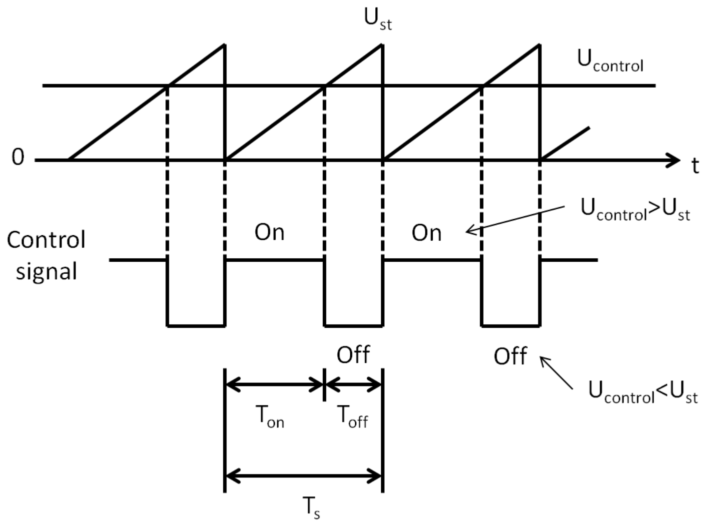

Figure 3-2: PWM example for buck converter

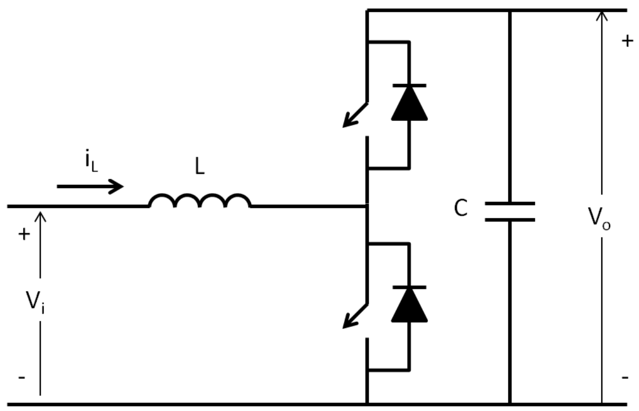

Figure 3-3: Half-bridge converter

When boost and buck converters are combined in one topology, the half-bridge converter results (Figure 3-3). This topology is bidirectional and it requires that the voltage at the output (V_o) is higher than the voltage at the input (V_i). The direction of the current defines whether the boost or the buck converter is active. The bi-directionality of the half bridge converter allows for an AC voltage connection at the input as long as it is lower than that of the output. The half-bridge converter though can only operate in two UI quadrants. For four-quadrant operation two half-bridge converters can be combined to form the full-bridge converter (Figure 3-4). The full-bridge converter allows power exchange between a single phase system and a DC link.

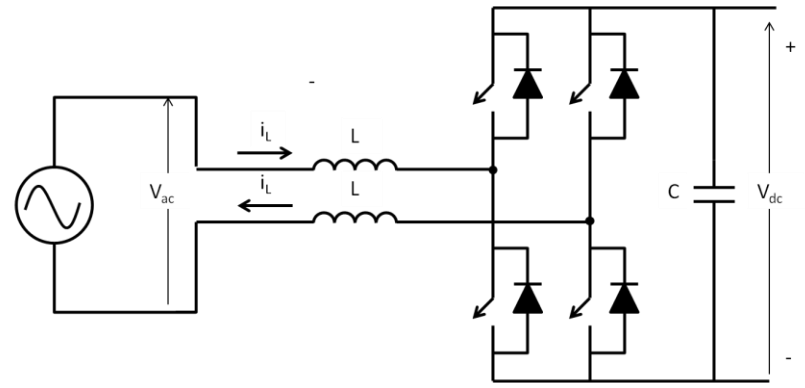

Figure 3-4: Full-bridge converter

To form a three-phase converter three half-bridge converters must be combined (Figure 3-5). The three-phase converter allows interaction between three-phase systems and a DC link and is the core of the HVDC system.

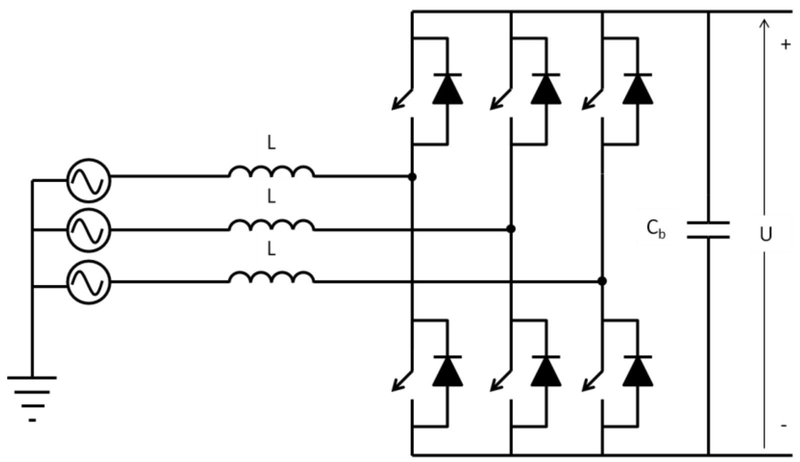

Figure 3-5: Three-phase converter

PWM is extended to be used for 3-phase VSCs and different variations have been developed to deal with harmonic elimination and over-modulation. The simplest PWM method remains the sinusoidal PWM where a sinusoidal waveform for each phase is compared to the same carrier, high frequency triangular waveform to create the switching signals for the semiconductor devices.

It is important at this point to understand what the 3-phase VSC needs for its operation and what the outcome of its operation is. Since it consists of half-bridge converters it requires that the DC voltage is higher than the AC voltage. A PWM modulator is then necessary to drive its switches. This results in the creation of an AC voltage vector at the AC side of the converter. The AC voltage created, since it is produced by switching, is a rectangular waveform. This means that it carries a fundamental frequency and amplitude but harmonics are also present. Adequate selection of PWM method and filters modify the harmonic content seen by the grid so that power quality requirements are fulfilled. The fundamental frequency and amplitude of the produced AC voltage is the main product of use resulting by the operation of the 3-phase VSC, driven by the PWM modulator. Since the fundamental frequency, amplitude and angle of the produced AC voltage can be defined accurately the current flow on the inductance can be controlled with the same accuracy taking into account the voltage vector on the other edge of the inductance. For example, connection to an active AC grid assumes that there is an AC voltage vector with constant frequency and amplitude, while connection to a passive AC grid assumes an AC voltage that is completely defined by the AC voltage vector produced by the converter. By controlling the output AC voltage vector of the converter, the current of the inductance can be controlled taking into account the voltage drop across the inductance and the AC voltage vector on the other edge of the inductance.

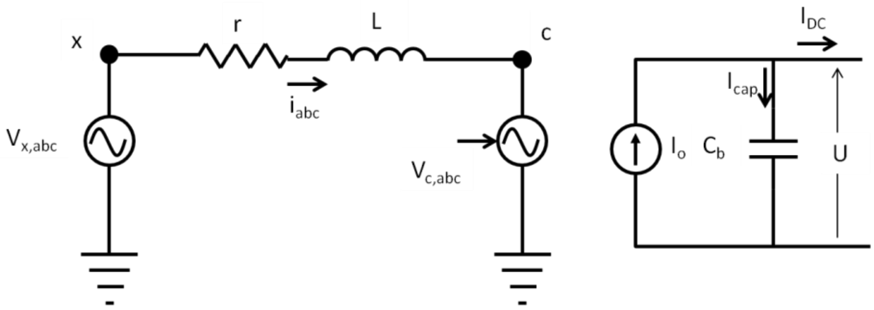

Figure 3-6: Single phase depiction of VSC

$$V_{x,abc} - V_{c,abc} = r \cdot i_{abc} + L \cdot \frac{di_{abc}}{dt} \qquad \text{Eq. 3.1}$$

Equation (3.1) corresponds to Figure 3-6 and clearly shows that the only element that can be adjusted to control the current is the difference between the converter voltage and the grid voltage at the Point of Common Coupling (PCC) which is fixed for strong AC grids and variating with power for weak AC grids. Equation (3.1) is the fundamental equation for the connection of a VSC to an AC grid, and summarizes the core of its controllability. The question then is why is it important to control the current, how a control scheme can be defined to perform the control and under which criteria. Current control offers accurate control over the exchanged power at the PCC. Since the voltage is fixed at the grid voltage, current defines the power going into or out of the PCC. Much of the control scheme can be transferred by motor control theory and adjusted to the needs of the system under discussion. The criteria of control depend on the expected functionality of the system. Current control allows control over the exchanged power between the AC and the DC system. The objective of this control might be different according to the desired operation of the system at the time. Examples of desired operation of such a system can be the accurate exchange of power, the control of the DC voltage or control of the AC voltage or frequency when the connected AC grid is weak or passive.

3.2 Control Scheme

As mentioned, the control scheme of the VSC has its origin in motor control. Switch mode DC/DC converters, single phase VSCs and three phase VSCs are attractive for motor control because they can manipulate the terminal voltage of the motor, thus controlling its speed. Directly controlling the input voltage alone of a motor is not the most efficient way to control its speed though. Speed is sustained by controlling the torque of the motor but torque is generated by the magnetic flux in the motor which is, in turn, generated by the current through its windings. The VSC is then called to provide the electrical power to be transformed into mechanical power by manipulating the input voltage so that an adequate current flows that will create the correct magnetic flux to produce the torque that will sustain the speed of the motor at the desired level. A cascade control structure is revealed in this sense, placing current control at the inner control loop. The adequacy of the cascade control approach is supported by the presence of different time constants in the system. While current can change almost instantly, and torque follows the change in current, the speed of the motor changes much more slowly due to the inertia of the rotor. Cascade control allows the separation of the different time constants. To simplify the control even further, since flux and voltage are rotating vectors, the control is made not in the stationary abc frame but in the rotating d-q frame. The controlled variables are then DC rather than AC quantities, which makes control with no control error easier.

As in motor control, a grid connected VSC is responsible for the power transfer between the AC system and the DC system. Thus, the control structure can be directly transferred with the inner current control loop not changing much [28], [29]. The outer control loop in the case of the motor described above controlled the speed. In the grid connected VSC different outer control loops might be present to control different variables, all of which are translated to current references and through the inner current control to voltage references for the PWM modulator. The d-q frame is applicable in the grid connected VSC also since rotating voltage vectors are to be manipulated.

Inner current control loop

The inner current control loop is based on a pair of P controllers to separately control the active and reactive components of the current. It receives current references from the outer control loops that converts to voltage references for the PWM modulator. Since the control is made in the d-q frame while the required voltage references are in the abc frame transformation is needed from the d-q frame to the abc frame, thus a phase lock loop (PLL) is necessary to keep synchronization.

The control equation for the inner current controller is derived by equation (3.1) and the power balance between the AC and the DC side of the converter. Applying the Clark transformation [30] at equation (3.1),

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = k \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \qquad \text{Eq. 3.2}$$

Equation (3.3) is obtained.

$$V_{x,\alpha\beta} - V_{c,\alpha\beta} = r \cdot i_{\alpha\beta} + L \cdot \frac{di_{\alpha\beta}}{dt} \qquad \text{Eq. 3.3}$$

Before equation (3.1) is expressed in the d-q frame, Park's transformation must be applied.

$$\left.\begin{aligned} V_{x,\alpha\beta} &= V_{x,dq} \cdot e^{j\omega t} \\ V_{c,\alpha\beta} &= V_{c,dq} \cdot e^{j\omega t} \\ i_{\alpha\beta} &= i_{dq} \cdot e^{j\omega t} \end{aligned}\right\} \qquad \text{Eq. 3.4}$$

Equation (3.1) is then expressed in the d-q frame in the following form.

$$\begin{aligned} V_{x,dq} \cdot e^{j\omega t} - V_{c,dq} \cdot e^{j\omega t} &= r \cdot i_{dq} \cdot e^{j\omega t} + L \cdot \frac{d\left(i_{dq} \cdot e^{j\omega t}\right)}{dt} \\ &= r \cdot i_{dq} \cdot e^{j\omega t} + j \cdot \omega \cdot L \cdot i_{dq} \cdot e^{j\omega t} + e^{j\omega t} \cdot L \cdot \frac{di_{dq}}{dt} \end{aligned} \qquad \text{Eq. 3.5}$$

Which can be rewritten as:

$$V_{x,dq} - V_{c,dq} = r \cdot i_{dq} + j \cdot \omega \cdot L \cdot i_{dq} + L \cdot \frac{di_{dq}}{dt} \qquad \text{Eq. 3.6}$$

Equation (3.6) can be rearranged in the following form,

$$\left.\begin{aligned} L\frac{di_d}{dt} &= V_{xd} - V_{cd} - r \cdot i_d - \omega \cdot L \cdot i_q \\ L\frac{di_q}{dt} &= V_{xq} - V_{cq} - r \cdot i_{dq} - \omega \cdot L \cdot i_d \end{aligned}\right\} \qquad \text{Eq. 3.7}$$

Expressing the apparent power at PCC in the d-q frame, the following expression is obtained.

$$\begin{aligned} S &= \frac{3}{2} \cdot V_{x,dq} \cdot i_{dq}^{*} = \frac{3}{2} \cdot \left(V_{xd} + j \cdot V_{xq}\right) \cdot \left(i_d - j \cdot i_q\right) \\ &= \frac{3}{2} \cdot \left[\left(V_{xd} \cdot i_d + V_{xq} \cdot i_q\right) + j\left(V_{xd} \cdot i_d - V_{xq} \cdot i_q\right)\right] \end{aligned} \qquad \text{Eq. 3.8}$$

At steady state operation, and neglecting any losses, active power on the AC side is equal to the active power on the DC side.

$$\begin{gathered} P_c^{'} = P_c \\ \frac{3}{2} \cdot \left(V_{xd} \cdot i_d + V_{xq} \cdot i_q\right) = U \cdot I_{DC} \end{gathered} \qquad \text{Eq. 3.9}$$

Full decoupling between the active and reactive current components can be achieved by implementing the control in the d-q frame. The AC voltage vector at PCC is placed on the d axis of the frame which rotates at its rotational speed. Voltage at PCC can be expressed:

$$\left.\begin{aligned} V_{xq} &= 0 \\ V_{xq} &= V_x \end{aligned}\right\} \qquad \text{Eq. 3.10}$$

This makes the expression of active and reactive power as follows:

$$\left.\begin{aligned} P_c^{'} &= \frac{3}{2} \cdot V_{xd} \cdot i_d \\ Q_{dq} &= -\frac{3}{2} \cdot V_{xd} \cdot i_q \end{aligned}\right\} \qquad \text{Eq. 3.11}$$

Based on equation (3.11) and the differential equation (3.7), the inner current controller is designed (Figure 3-7).

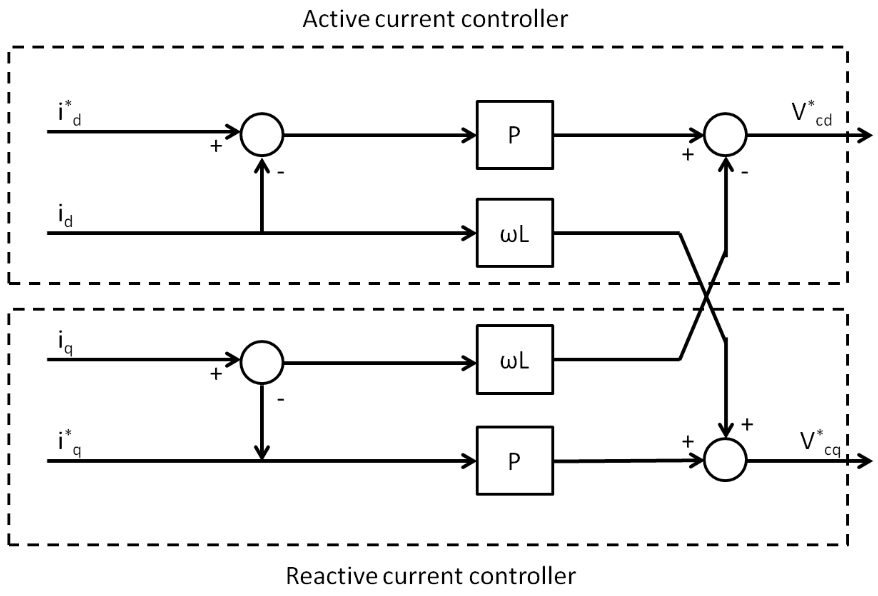

Figure 3-7: Inner current controller

The gains of the P controllers are selected to offer stiff control and feed-forward terms are used to cancel the cross-coupling between d axis and q axis.

The basis is now set for independent control of active and reactive power. The active current component manipulates active power according to the references received by the outer controllers, whether it is to control the active power exchange or the DC voltage. The reactive current component manipulates the reactive power on the AC side to control the exact amount of reactive power the AC system requires or to control the AC voltage on the AC side when a weak AC grid is connected. The functionality is selected by the outer controllers.

Outer control loops

Different outer control loops can be used to provide references for the active and reactive current. The outer controller set defines the control mode set of the converter. Each outer controller controls a different variable according to its control objective and translates it in current reference. Since accuracy is required at this level PI controllers are used.

Active power control

One of the most basic controllers is the Active power controller (Figure 3-8). Following the previous analysis and according to equation (3.11), active power depends only on the active component of the current (i_d) and the d component of the voltage at PCC. Since the voltage at PCC is considered to have small variations, its contribution to the calculation of active power can be considered constant. In this sense, the active power controller can produce an i_d reference to be fed directly to the inner current controller.

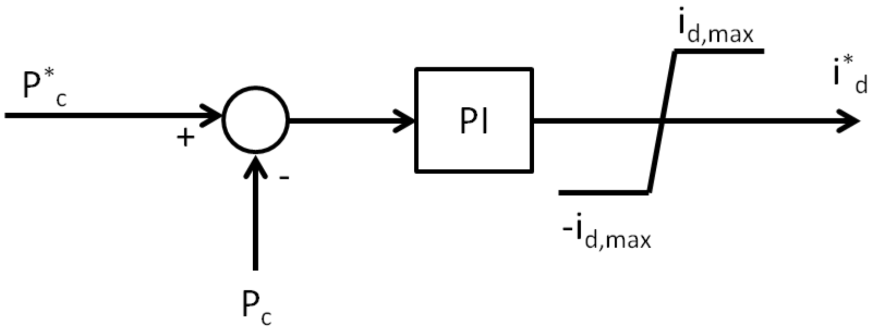

Figure 3-8: Active power controller

The anti-wind up limiter of the PI controller limits the id reference at the rated amplitude of the single phase current.

$$i_{max} = i_N \qquad \text{Eq. 3.12}$$

Reactive power control

Following the same rationale as for the active power controller and according to equation (3.11) reactive power can be considered a function of the reactive component of the current (i_q) only. The reactive power controller, shown in Figure 3-9, produces the current reference for the reactive component of the inner current controller.

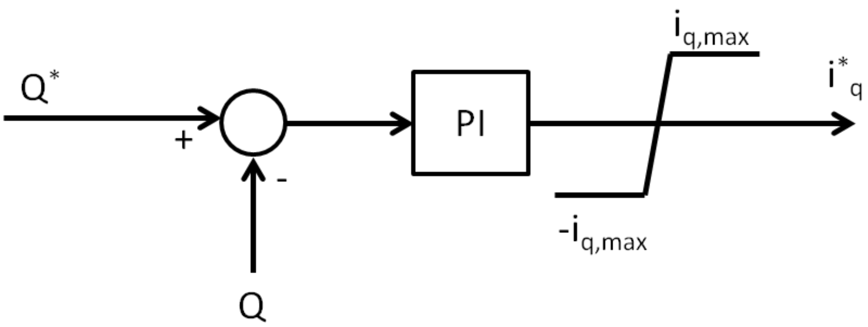

Figure 3-9: Reactive power controller

An anti-windup limiter is also present in this controller but, since priority is given to active power exchange, its limit is defined according to the rated amplitude of single phase current and the id reference.

$$i_{q,max} = \sqrt{{i_N}^2 - {i_N^*}^2} \quad \text{Eq. 3.13}$$

AC voltage control

When a weak grid is connected to the VSC its voltage needs to be regulated. A weak grid is a grid whose voltage at PCC suffers large variations as the power flow changes.

Kirchhoff's voltage law on the inductance gives:

$$\widehat{V_x} - \widehat{V_s} = (r + j \cdot \omega \cdot L) \cdot \widehat{\iota_s} \quad \text{Eq. 3.14}$$

The current can be expressed as:

$$\widehat{\iota_s} = \left(\frac{S}{V_x}\right)^* = \left(\frac{P + j \cdot Q}{V_x}\right)^* = \left(\frac{P - j \cdot Q}{V_x}\right) \qquad \text{Eq. 3.15}$$

And then the following expression can be obtained:

$$\begin{aligned}\widehat{V_x} &= \widehat{V_c} + (r + j \cdot \omega \cdot L) \cdot \widehat{\iota_s} \\ &= \widehat{V_c} + (r + j \cdot \omega \cdot L) \cdot \left(\frac{P - j \cdot Q}{V_x}\right) \\ &= \widehat{V_c} + \left(\frac{P \cdot r + Q \cdot \omega \cdot L}{V_x}\right) + j \cdot \left(\frac{P \cdot \omega \cdot L - Q \cdot r}{V_x}\right)\end{aligned} \qquad \text{Eq. 3.16}$$

Which, since the voltage variation at PCC on the imaginary axis is negligible, gives:

$$\widehat{V_x} = \widehat{V_c} + \left(\frac{P \cdot r + Q \cdot \omega \cdot L}{V_x}\right) \qquad \text{Eq. 3.17}$$

In equation (3.17) the only available parameter to control is Q, since P is already separately controlled. This can be expressed as follows.

$$\Delta V_x = \frac{\omega \cdot L}{V_x} \cdot \Delta Q \qquad \text{Eq. 3.18}$$

The AC voltage controller is then an extension of the reactive power controller and is presented in Figure 3-10.

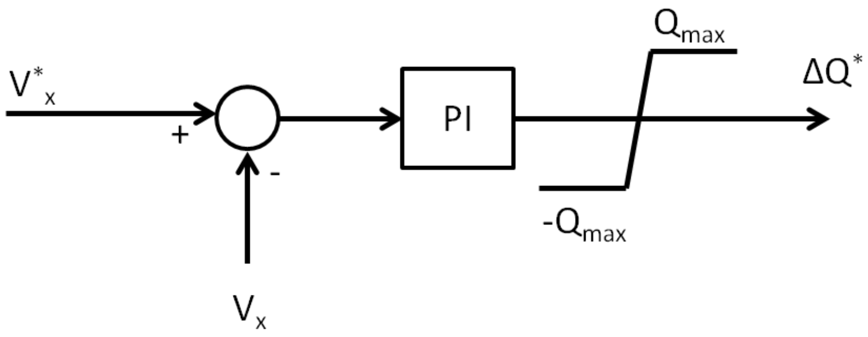

Figure 3-10: AC voltage controller

Frequency control

Another functionality the VSC can offer to the connected AC system is to support its frequency. Frequency in an AC system is an indicator of power balance and power regulation that is sensitive to frequency variations is possible by the VSC. Frequency control can be achieved with an additional input to the Active power controller (Figure 3-11).

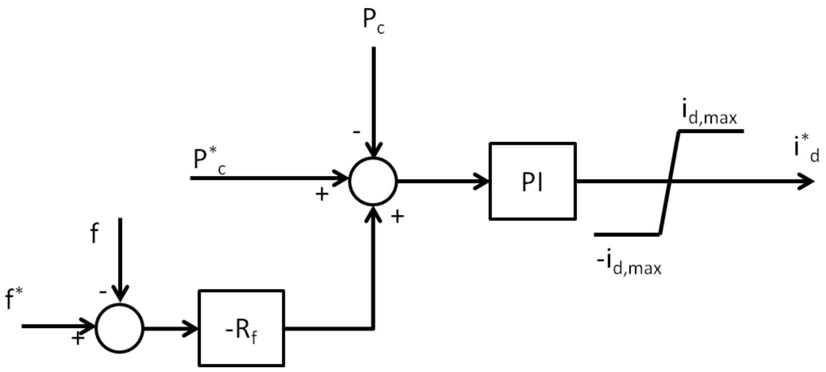

Figure 3-11: Frequency droop controller

A frequency droop slope can be implemented as in the case of a generator. It can be implemented as a factor operating on the error of the frequency before it is added to the error of active power. In this way the active power reference becomes sensitive to frequency variations and its sensitivity can be adjusted by adjusting the value of this factor. When the steady-state error of the controller is zero, its input can be described by:

$$(P_c^* - P_c) - R_f(f^* - f) = 0 \qquad \text{Eq. 3.19}$$

This leads to power injection in the DC system by the VSC terminal that is expressed by:

$$P_c = P_c^* - R_f(f^* - f) \qquad \text{Eq. 3.20}$$

DC voltage control

DC voltage on a DC link resembles the frequency in an AC system. It reflects the power balance in the DC link and is, thus, necessary to be kept constant within narrow margins, as frequency in an AC system. Another reason for large DC voltage variations not to be allowed is that they directly affect the losses of the system. Since there are only resistive losses in the DC link, the lower the voltage, the higher the current and the higher the losses. Hence, the most adequate controller for the DC voltage is a PI controller derived by the input-output power balance of the VSC (Figure 3-12).

$$\begin{gathered} P_c' - P_c - P_{cap} - P_{Loss} = 0 \\ \frac{3}{2} \cdot V_{xd} \cdot i_d - P_c - P_{Loss} - U \cdot i_{cap} = 0 \end{gathered} \qquad \text{Eq. 3.21}$$

Solving for i_{cap}:

$$i_{cap} = \frac{3 \cdot V_{xd} \cdot i_d}{2 \cdot U} - \frac{P_c + P_{Loss}}{U} \qquad \text{Eq. 3.22}$$

This can also be expressed as:

$$i_{cap} = C_b \frac{dU}{dt} \qquad \text{Eq. 3.23}$$

Combining equation (3.20) and equation (3.21) the following expression occurs:

$$\begin{aligned} \frac{dU}{dt} &= \frac{1}{C_b} \cdot \left(\frac{3 \cdot V_{xd} \cdot i_d}{2 \cdot U} - \frac{P_c + P_{Loss}}{U} \right) \\ &= \frac{3 \cdot V_{xd} \cdot i_d}{2 \cdot C_b \cdot U} \cdot \left(i_d - \frac{2 \cdot P_L}{3 \cdot V_{xd}} \right) \end{aligned} \qquad \text{Eq. 3.24}$$

Equation (3.22) shows that the active component of the current (i_d) can be used to regulate the DC voltage. Power losses can be compensated by feed-forward, although the integral part of the controller will handle it anyway.

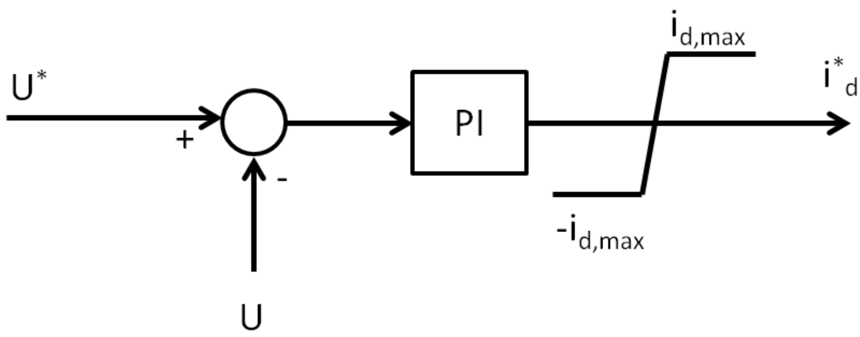

Figure 3-12: DC voltage controller

DC voltage controller will maintain the DC voltage constant on the reference value with as little variations as possible, as long the required current is within the safe limits of the converter.

It should be mentioned at the end of this section that, in this work, guidelines for controller tuning can be found in [31]. However, the final tuning was made through trial and error.

3.3 System Operation

Now that the main functionality of a VSC is explained, its operation will be considered from a system perspective. The fundamental operation targeted for VSCs is power transmission over long distances. The simplest system configuration consists of two VSC terminals at the two edges of a DC cable, together with any equipment required for filtering.

Two-terminal system

On a 2-terminal system, as in Figure 3-13, the power can be of fixed direction or bi-directional, depending on the control modes implemented on each terminal.

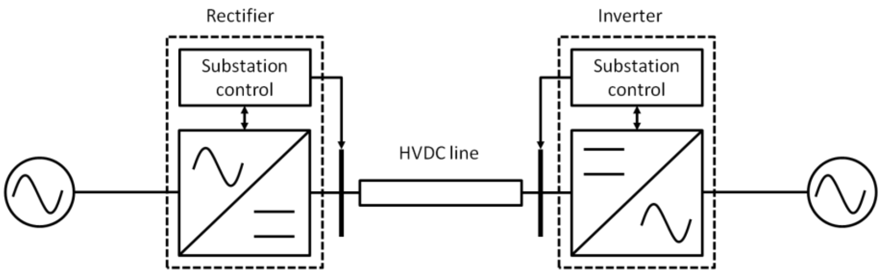

Figure 3-13: Two-terminal system

In the case that both VSC terminals are connected to strong grids, no special functionality is required. One of the terminals functions as a rectifier while the other functions as an inverter. The fundamental condition for any power exchange over a DC link is that the DC voltage is kept constant within strict limits. Thus, one of the terminals must control the DC voltage using its DC voltage controller. The remaining terminal can then operate at Active power control regulating the active power going into or out of the DC link. The recommended operation is that the rectifier operates at DC voltage control and the inverter at Active power control. In this way the power flow is controlled by the inverter minimizing overvoltage risks. If the inverter was to operate at DC voltage control and the rectifier at Active power control, the operation of the link would still be viable but a potential malfunction of the DC voltage controlling inverter could lead to overvoltage since the rectifier would keep injecting power in the DC link. Other combinations of control modes in the two terminals are the operation of both terminals at Active power control which is not viable since the fundamental condition of a stable DC voltage is not assured, and operation of both terminals at DC voltage control which is not viable since no power setpoints can be implemented and a minor disturbance on the DC voltage could lead the two competing DC voltage controllers to destabilize the system.

If not both VSC terminals are connected to strong grids, they need to play a different role implementing special control modes as long as one of them controls the DC voltage. In the case of weak grid connection the AC voltage must be supported or in the case of passive load connection frequency needs to be supported by the VSC terminal. The most adequate control mode combination needs then to be considered.

Multi-terminal system

In a multi-terminal system, as in Figure 3-14, any type of system might be connected to the different terminals. In addition, a large multi-terminal system consisting of different types of connected systems might encounter various emergencies. Thus, its VSC terminals must feature a full controller set despite each one’s connected system.

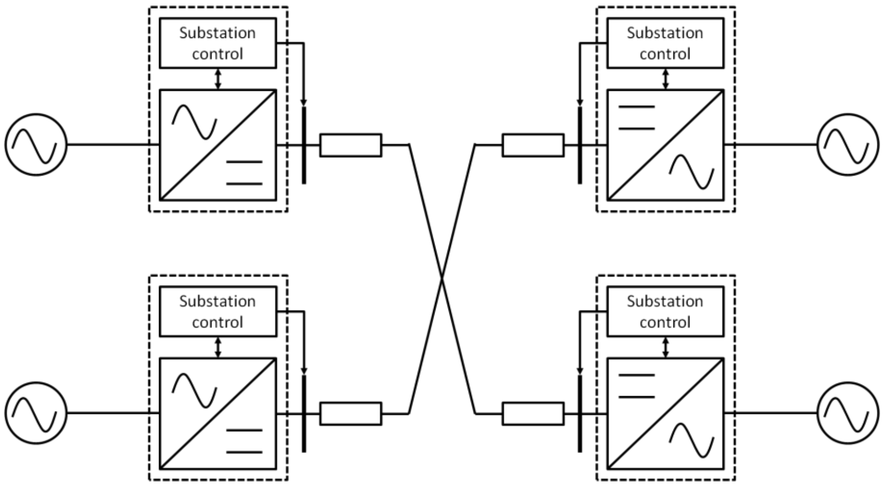

Figure 3-14: Multi-terminal system

However, the main issue in a multi-terminal system is DC voltage control, both in normal operation and during emergencies. DC voltage control performed by one terminal in the multi-terminal system is an option, deriving directly by the 2-terminal system operation. It is though, not a desirable operation since it raises reliability issues at the event of DC voltage regulating converter failure. Also, in normal operation the DC voltage regulating converter (slack converter) is not able to share load while operating other terminals in DC voltage control at the same time, may lead to competing controllers, even when operated at different setpoints, which may de-stabilize the system. Even in this case fast communications are necessary to coordinate the setpoint distribution to the different terminals. A coordinated approach is necessary to the control of DC voltage in a multi-terminal system to avoid converter overloading, controller competition and instability in case of slack converter failure. Coordination of control modes and setpoints allows the control of the power flow in a multi-terminal system in different ways.

Coordinated DC voltage control

Coordinated DC voltage control first addressed the issue of safety during converter failure. As mentioned above, fast communications are necessary to reassign DC voltage regulation to a new terminal in case of slack converter failure. The voltage margin control method is designed to address the reliability issues occurring by the regulation of the DC voltage by a single slack converter in a multi-terminal system [19], [32]. To avoid the uncertainty in the DC voltage regulation when the slack converter is close to its capacity limits or when it suffers a failure and prevent dependency on fast communications, the voltage margin control method duplicates the slack converter functionality to other converters that can take over the DC voltage control in a master-slave configuration. Master converter operates in DC voltage control mode at the nominal DC voltage and is designed to turn to Active power control mode when its capacity is close to its limits. One of the slave converters, then, clamps the DC voltage at another voltage level and follows the same behavior; when its capacity is close to the limits it turns to Active power control and the next slave converter takes over the voltage regulation. Different slave converters are designed to clamp the voltage at higher and lower values in a cascade manner that creates a safety margin for the DC voltage both for higher and lower values from the nominal. Although the voltage margin control method increases the overall reliability of the system several issues persist. There is still only one converter controlling the DC voltage at a time which puts a lot of stress on it. The abrupt transition from one voltage level to another puts extra stress on the system. To avoid voltage regulation by more than one converters at a time the voltage margins of the slave converters must be large enough which could lead to unwanted oscillations and uncertain behavior of the system.

AC system operation offers some lessons to tackle these problems in the operation of a DC system. In the AC system frequency is the indicator of power balance. Frequency droop is used to coordinate the operation of the different generators in the system making them sensitive to power changes in the system. The slope of the frequency droop characteristic defines the sensitivity of each generator and the load distribution among them. Frequency is a universal characteristic within an AC control area, it is something that the different generators throughout the control area sense and react upon at the same time.

The equivalent magnitude in a DC system is the DC voltage. Although DC voltage is the indicator of power balance in the DC system, the locally measured DC voltage is not the same at all terminals. In this sense a DC voltage-power sensitive controller can be designed for each terminal in the system but different voltage setpoints are necessary for each terminal taking into account voltage drops over the transmission line due to current power flows, leaving the optimization to an overall control system. The DC voltage-power sensitive controllers or DC droop controllers are able to share load or power injection in the DC system while contributing collectively in the DC voltage regulation and in this way participate in the implementation of a control strategy for the system [33-37]. As shown in Figure 3-15, the DC droop controller can be implemented as an additional input to an active power controller with an adjusting factor operating on the output of a P-controller. The adjusting factor is the equivalent of the slope of the frequency droop characteristic and adjusts the sensitivity of the active power controller at changes in the voltage.

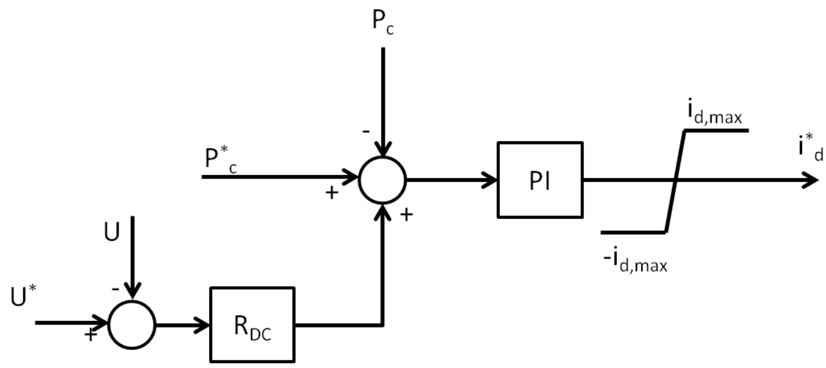

Figure 3-15: DC droop controller

When the steady-state error of the controller is zero, its input can be described by:

$$(P_c^* - P_c) + R_{DC}(U^* - U) = 0 \qquad \text{Eq. 3.25}$$

This leads to power injection in the DC system by the VSC terminal that is expressed by:

$$P_c = P_c^* + R_{DC}(U^* - U) \qquad \text{Eq. 3.26}$$

DC droop control overcomes the disadvantages of the voltage margin control method by providing possibility of load and power injection sharing to the different terminals, shared responsibility on the regulation of the voltage and smooth response of the rest of the terminals when one is suffering a failure. The disadvantage is that there is no longer PI-control on the DC voltage meaning that there is no guarantee of steady-state error elimination. Since steady-state errors are not eliminated an overall system is necessary to adjust the voltage setpoints at each terminal in real time to avoid operation away of nominal voltage or out of the limits.

Coordinated operation

The preferred control mode in a multi-terminal system is DC droop control and since voltage is safely regulated the focus is now on the selection and implementation of adequate voltage and power setpoints for the different terminals to keep the operation of the system as close as possible to the nominal DC voltage. As mentioned above, this requires an additional control level as depicted in Figure 3-16. An overall control system that has the full picture of the system and takes into account the current power flows in it. The overall control system must be in position to monitor the different terminals before it is able to take action to coordinate them distributing voltage and power setpoints to the different terminals in the system. Monitoring and coordination require an interface for data exchange between the overall system and the different terminals. Functionality overlapping should also be avoided between the different parts of the control system. For this reason a well-defined structure is required to separate the entire control system including the overall control system in different control levels with their respective domains of responsibility. After having addressed the issue of reliable operation during normal or abnormal conditions, the control system must also focus on the expandability of the multi-terminal system. The structure of the control system must be such that it enables the integration of new terminals without major modifications. To achieve this, the interface between the overall control system and the different terminals can play a vital role. Standardization of the interface between the overall control system and the different terminals can facilitate the implementation of the logic of the control system in a way that allows easy integration of new terminals.

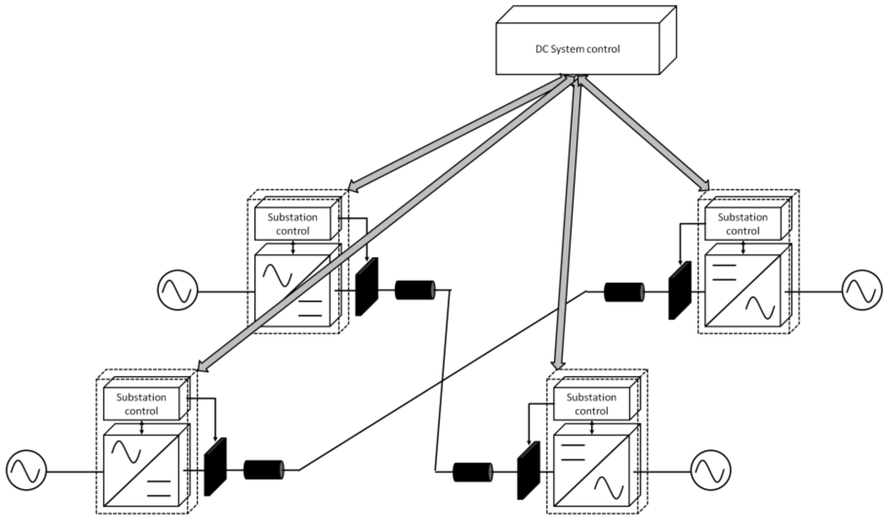

Figure 3-16: Coordinated operation

In this work an attempt is made to outline the structure of such a system and an implementation is later on tested to prove its efficiency. The control modes discussed above form the control level closest to the converter and are considered the basic functionality of the control system, thus the focus is on its structure and coordination functionality taking into account reliability and expandability of the multi-terminal system.

Chapter 4

Control System Structure

To achieve the coordinated function of the multi-terminal VSC-HVDC system an overall control system is required. This could be an additional layer to the already existing control system for 2-terminal systems. In this case the overall control layer would have to adjust to the requirements of the existing control system in each case, limiting in this way its future expandability. An alternative is to reconsider the entire control system establishing some necessary principles that it should comprise, both structurally and operationally, to allow modularity in its structure and facilitate its future expandability. If the control system is looked upon as a whole, there is a range of functionalities it should support; from operational tasks at its bottom layer to coordination tasks at its top layers. These tasks can be performed by different control levels that can be designed in accordance to the fundamental principles of the control system not to obstruct modularity or expandability of the system. Well defined responsibilities of each control level in combination with appropriate interfacing can decouple the implementation of each control level from its operation. In this way, automated functions that may be included in the required functionality of each control level is independent of the implementation approach as long as the required functionality is followed. Since multi-terminal VSC-HVDC systems are expected to grow larger, it is desirable that the control system accounts for this. The interconnection of multi-terminal VSC-HVDC systems to form larger ones will create common points among neighboring systems. The common points may be shared substations and then control priority issues over the shared substations may rise. A flat structure together with a priority system may be the answer so it is desirable that the control system is flat structure compatible by design.

4.1 Control System Structure Overview

As already mentioned the different tasks of the control system can be distributed in the different control levels. The proposed control system structure consists of three control levels related to the perceived entities in the system; the converter control level, the substation control level and the DC system control level, as depicted in Figure 4-1.

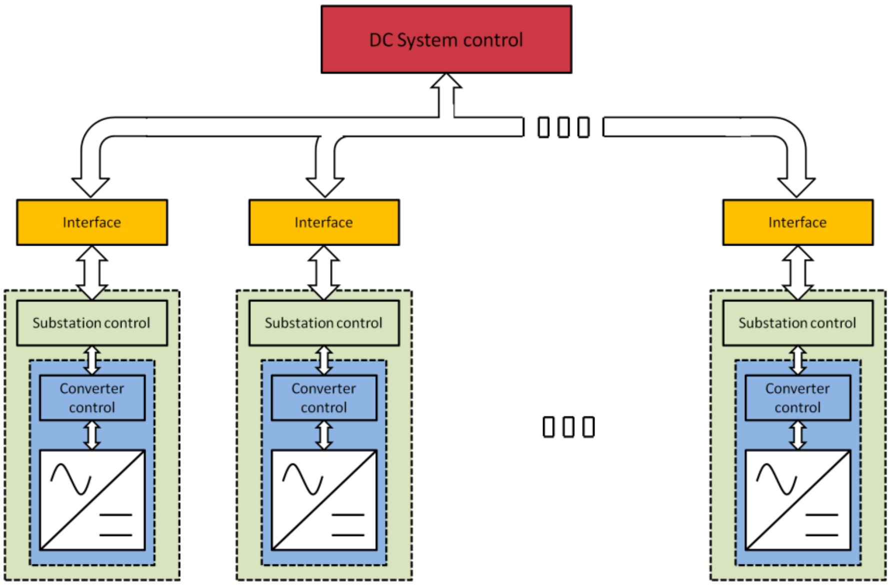

Figure 4-1: Control System structure

The different control levels are responsible to perform the different operational and coordination tasks necessary for the operation of the system. As mentioned, the design of the control system, both structurally and operationally, shall be based on some necessary principles to facilitate modularity in its structure and facilitate its future expandability. These are some general features that need to be considered through the design process.

Modularity

As further expansion of HVDC systems is expected both in size and capacity, future transmission systems should be flexible in order to integrate more terminals both in numbers and diversity. This pushes the expectations of such systems further than multi-terminal arrangements. It is now required that these systems are also able to expand easily to integrate diverse types of systems, from high capacity wind power plants to oilrigs, without any major modification in their control system. Of course a first step towards that direction is the standardization and modularity of the hardware equipment to be used. Once the modularity of hardware is established, the control system should have the appropriate structure to integrate new terminals. For this reason it is necessary that direct interaction between the individual terminals is avoided. This interaction should only take place through the overall control system, giving in this way the overall control system the flexibility to coordinate terminals that have no “awareness” of the rest of the system. The individual terminals will only be aware of their own local status and safety, meaning that measurements will be obtained from both sides of the terminal to achieve a certain objective that has been assigned to them by the overall control system and also to keep their components within the limits of safe operation. The individual terminals obtain in this way their “distributed intelligence” that grants them with a certain degree of autonomy, while at the same time the “brain” of the system, the overall control, is released from operational duties and is left to deal with the coordination of the different terminals. What is needed for the overall control system to support such modularity is to minimize its input data. This means that the overall control system will handle a minimum necessary data set that will provide all the necessary information for the coordination of the different terminals such as the number of the connected terminals, the type of the connected systems, the instantaneous power demand and offer of each of the terminals and a kind of prioritization regarding importance, capacity and stiffness of the systems in case of emergency. This assures that the system is coordinated to remain in a stable operation under both normal and emergency conditions while at the same time each individual connected system is operated according to its properties. Having standard local controllers with a predefined range of embedded control modes, the information of the type of the connected system to the overall control system might exclude some operation modes in order to secure stable operation. For example a passive connected network cannot be assigned to support the DC voltage. The overall control system will also deal with data regarding agreements between the involved parts in order to formulate an operation strategy.

Uniform Interfacing

Since the substation is the common point between the multi-terminal HVDC system and the connected system, the uniform interface aims to decouple the different interfacing requirements of the different connected systems with the multi-terminal HVDC system in two levels. First, since the information of the type of the connected system is included in the interface, the control mode set used by the connecting substation does not have to be modified. The control system of the multi-terminal HVDC system is able to exclude control modes in the respective substations according to the properties of the connected system, enabling in this way the use of a standard control mode set for all substations. Secondly, since the information the substation itself exchanges with the overall control is limited to a necessary minimum data set, the equipment supplier of the substation is irrelevant as long as the exchanged data set is respected and the expected functionality is followed.

In this way the transmission DC System Control can gather information by all connected systems and schedule the coming power flows to satisfy power demands and existing agreements between the involved parts. Important information that the interface should also provide to the transmission system is the information of the type of the connected system. By introducing this information in the interface, the freedom of operating individual systems by a standard interface is given. Instead of adjusting the interface to the particular system, the system declares itself as being of one type so that the transmission system knows how to operate it. By having this information the transmission system excludes operation modes or favor some of them in the expense of others choosing from a range of operation modes of a standard terminal controller where all the functionalities are defined. Information regarding capacity and stiffness of each connected system will make possible for the transmission system to prioritize accordingly systems of the same type in order to optimize operation both under normal conditions and under emergencies.

Having this information the overall control system is in position to directly intervene in the control of the substations when an emergency occurs or simply supervise them during normal operation after having defined a frame of operation for them regarding allowed control modes according to the connected system.

Flat Structure Compatibility

As discussed earlier, further expansion of multi-terminal HVDC systems is expected that may lead to the integration of regional multi-terminal VSC-HVDC systems to a large DC grid. Since the DC grid will probably be formed by the interconnection of the different individual early stage multi-terminal HVDC systems, it is important to start considering already how this integration can be facilitated on the control system level. The early stage multi-terminal HVDC systems can be considered the "cells", the building blocks, from which the integrated DC system will occur. The "cells" can be radial, in their most basic form, or meshed systems depending on whether DC breakers are considered at the early stage of development. In any case, the different "cells" define their own control area that will later on be interconnected with others through shared substations. The shared substation then needs to be bi-directionally controllable since it will interface with two overall control systems of the respective control areas. This raises the question of control priority among the involved overall control systems. Technically, there should be no priority, both overall control systems must have equal rights on the operation of the shared substation and the substation itself must have the freedom to select which overall system commands to follow only when its safety is at risk. In this case, prioritization information in the interface of the concerning shared substation can help implementing predefined agreements between the involved parts for normal and emergency operation and define the desirable hierarchy among the involved systems. For this to be possible in the future, the control system for the early stage multi-terminal HVDC systems must have this orientation and be designed compatible with flat structure. Eliminating hierarchical structures in the design of the control system will enable the implementation of hierarchy among the different control areas of the integrated DC grid using the prioritization in the shared substations according to the requirements of the adjacent control areas. In one sentence the message is, instead of tailored control system design to implement hierarchy among adjacent systems, flat structure compatible control system design that allows prioritization to tailor desirable hierarchies at request.

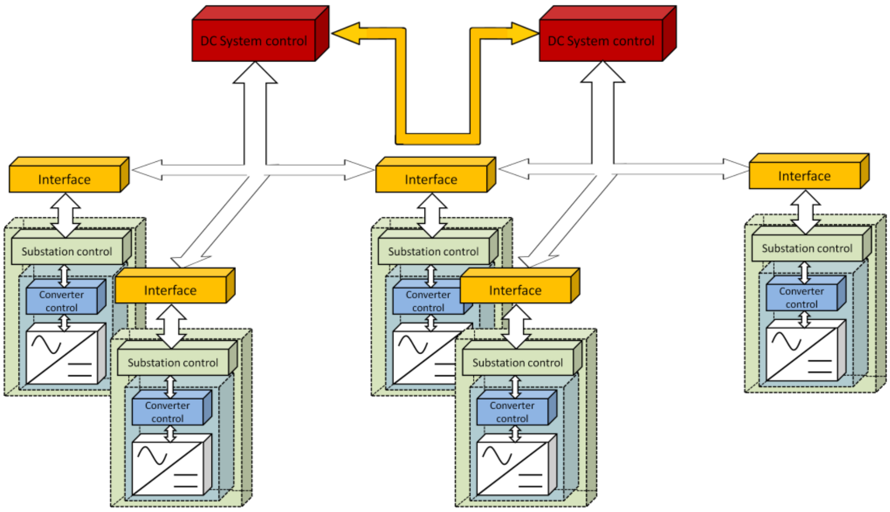

Figure 4-2: Flat structure demonstration

As depicted in Figure 4-2, flat structure compatibility requires that the shared substations can be bi-directionally controlled. This means, that the shared substations receive commands in their interface by both overall control systems and implement the commands of the overall control system with the current highest priority. Since the substation is shared between the two systems, so is its interface; meaning that the two overall control systems can exchange information directly. There is no need for operational information to be exchanged between the two overall control systems. Although, since one of the two overall control systems at a time operates the substation, they can exchange requests over the priority to control the substation due to some condition. An example of this operation could be that the first overall control system currently operates the shared substation. In a hypothetical condition the second overall control system decides that it needs to take control over the shared substation to resolve a situation. In this case, it has to send a request to the first overall control system for this operation. If the first overall control system thinks that it can manage itself without controlling the shared substation it will grant priority to the second overall control system to operate the shared substation. An obvious case in which the first overall control system would not grant priority to the second is if the shared substation was the one that controlled its DC voltage. To avoid these situations it is always the overall control system that currently operates the shared substation that decides whether to grant priority to another system over the shared substation and it is not possible that an overall control system arbitrarily assumes control over a shared substation at any time and without previous consultation.

Automated Functions

Unlike scheduled power flows that are scheduled in advance according to an operation strategy following existing agreements and predicted power demands, emergency situations happen randomly and have to be dealt with very quickly. A multi-terminal VSC-HVDC system has the ability of rearranging its power flows very quickly but modularity dictates no interaction between individual terminals and large disturbances cannot be handled locally, they have to be handled by the overall control system. Local terminal controllers will try to protect their own components in this kind of situation which will reach their limits unless a change in the total power flow in the DC system is done in an effort to stabilize the system. The overall control system is then supposed to take action in order to rearrange the power flows in the system to regain stability. One important condition is the fast detection of a disturbance whether it is internal or external to the HVDC system. And then the coming issue is what the time span available to take action is. This time span is significantly reduced when the discussion is about interconnected nations where a disturbance could propagate to disturb the operation of neighboring national grids. It becomes obvious that human operators, although they are efficient in scheduling power flows ahead, could not handle an emergency in that short time span. Disturbances could though be handled by automated functions embedded in the overall control system of the transmission system. The combination of automated functions operating under predefined conditions with the fast controllability of a VSC-HVDC system could give an almost immediate, yet controlled, response upon the detection of a disturbance. Important issues that rise are how automated functions can become general to fit the modularity of the system and how much system resources should be deducted to support the stability of an external system not to affect the others.

Regarding the first issue, in order for the automated functions to be as general as possible, they should be activated and function according to specific events that might happen in any terminal after the detection of a disturbance. There should not be any emergency scenario involving specific terminals. After the detection of a disturbance, automated functions should be activated to coordinate terminals with specific characteristics, regarding type, capacity and current status that can be found in the information obtained by the overall control system through the uniform interfaces. The concept is to divide disturbances into smaller scale events that will trigger different automated functions to provide step-wise adjustable approach to any disturbance. So instead of giving an overall response to a major disturbance that is limited to predefined scenarios, the aim is to provide automated functions that will attack a disturbance step by step so that it is possible to reconsider the status of the system after every step and rearrange strategy if needed.

Regarding the second issue of how much system resources should be deducted to support the stability of an external system; this should be part of the agreement between the involved parts. Each part should agree beforehand how much and what kind of support should be expected in case of emergency. The quality and quantity of the services for each part should be included in the partners' agreements.

Coordination Functions

The coordination of the different terminals in the system is the most important responsibility of the system. Since the safe operation of each terminal is managed in the Substation and Converter Control levels, coordination is left for the DC System Control level. Substation and Converter Control levels must be restricted to their local authority to sustain the modularity of the system. Then, DC System Control level that receives information from all the terminals is the most adequate to coordinate them to operate as a system.

Coordination is performed by different coordination functions that are spread in the different stages of system operation. The basic coordination functions can be classified as:

- Start up function
- Schedule management function

- Emergency function

Coordination action is necessary in all stages of the operation of system, although it may differ according to the desired result. The startup stage of the system operation is a preparation stage. The system needs to energize the DC link before any power exchange is possible. Having multiple terminals connecting various systems, means that startup needs to be a coordinated procedure. In multi-terminal VSC-HVDC system the connected AC system might range from strong national grids, to weak grids such as WPPs and passive loads such as oilrigs. To initiate the startup procedure, the Control System needs to first identify the connected AC systems, and then decide which of them will be used to charge the DC link. The Control System will involve all available active grids in the process stressing them according to their capability unless otherwise defined in agreements between the involved parts. Coordination action at this stage involves selection of the terminals to be utilized and distribution of the respective voltage setpoints.

When the DC link is charged the system is ready to perform the scheduled power flows. Coordination for the DC System Control level in this stage consists in managing the schedule delivered to it. The schedule holds information regarding control modes and voltage and power levels for the different terminals to define the requested power flows in the system. DC System Control level manages the timing of the implemented power flows and divides the schedule in parts according to the concerning terminal in the system in order to distribute those parts of the schedule to the respective terminals. As a preventive measure, DC System Control distributes to the different terminals in the system schedule ahead of time to anticipate potential communication loss events. At the same time DC System Control receives feedback by the terminals regarding their operation status. This is to validate the implementation of the requested power flows and intervene in case of fault.

When a fault happens, in this case an AC 3-phase fault is considered, the terminal that suffers it acts to protect its equipment. This makes the terminal inaccessible for the DC System Control. Nevertheless, DC System Control is informed about the fault and is called to take action to reschedule the power flow in the system. Rescheduling might happen according to different criteria, for example power demand matching. DC

System Control will first identify the power flow in the system before the fault and then try to match the remaining power demand in the system. If the remaining power production in the system is enough to match the power demand, DC System Control will distribute new power setpoints to the remaining terminals to match it. In case the power demand is higher than the available power production, the power setpoints are calculated so that maximum power is provided to the consuming terminals in an effort to support demand in the best possible way. In the case of the AC 3-phase fault, the local preventive action of the Substation Control level to prevent equipment damage is followed by the corrective coordination action of the DC System Control level to reschedule the power flows in the system to limit the propagation of the disturbance to the adjacent systems.

Having these basic principles in mind the control levels can be defined together with their responsibilities.

4.2 Control Levels

The functionalities of the control system are distributed in its different levels and range from terminal coordination and substation safety to converter control. If expandability is the target, modularity is the tool. To achieve modularity the control system focuses on explicitly defining the responsibilities of each control level and the interfaces between each other. In this way each control level has a very specific domain of responsibility and through uniform interfacing it is made possible that the actual implementation of each control level is not relevant to the operation of the control system as long as it responds to its duties and exchanges the necessary data as defined by the interface. In practice, this means that different suppliers of hardware or software equipment can operate under the same roof as long as they comply with this minimum interface data and functionality set.

This can prove quite useful in a field with no standardization at present. Even if standardization was in place, one can safely guess that not all multi-terminal VSC-HVDC systems will be built by the same supplier. The case will most likely be that even for the same system, equipment will come from different suppliers. Then a control system structure is necessary to accommodate the different approaches in the substation control of the different suppliers and achieve their coordinated operation.

In an effort to systematically classify the different system functionalities in distinct responsibility domains, the proposed control system is structured in three levels, as shown in Figure 4-1:

- DC System Control level
- Substation Control level
- Converter Control level

This fundamental hierarchical structure represents a top-to-bottom classification of the control levels included in the control system. The lower a control level is in the hierarchy the narrower is its responsibility domain. In principle, each control level follows the commands received by its superior but this holds as long as each level’s safety is not breached. In other words, each control level must follow the received commands but has the freedom to decide for itself and act to protect the equipment that is responsible for when it comes to security margins and then inform its superior. This is possible due to the bi-directional data flow and handshaking operations between the different control levels.

It is important to mention at this point that an important feature of the proposed control system does not appear in the above classification since it is functionality is not to process or produce data for any other control level. The uniform interface is responsible for performing the data transfer between DC System Control level and Substation Control level in a uniform and modular way. It does not appear in the classification above since it is not another control level but it will be described in this section since it is a defining feature of the proposed control system and as important as the system structure itself.

DC System Control level

DC System Control level plays the role of the supervisory control of the system. It gathers information from the entire system through the uniform interfaces to coordinate the different terminals to perform the necessary actions. It receives the schedule to be implemented, distributes it to the different substations and constantly monitors the system for fault signals that require its intervention. Automated functions allow DC System

Control to quickly intervene when necessary and perform emergency power flow rescheduling. General search functions allow it to address the different terminals within its domain of responsibility according to their characteristics, without using any predefined naming. This makes the integration of new terminals easy since no modification in the control system is required to include them in the control procedures.

The operation of DC System Control is divided in different stages through which it proceeds according to the feedback it receives by the Substation Control level. During initialization DC System Control recognizes the system. The assumed topology is radial at this first stage of development and DC System Control reads how many terminals are connected to the system. After an error check DC System Control sets the error-free terminals ready for operation. From the ready to operate terminals a selection of one terminal or a group of terminals is made to charge the DC system. The selected terminals are then commanded to charge the DC link and DC System Control waits for feedback regarding the DC link voltage. When the DC link is charged to the right level, DC System Control moves into normal operation.

In normal operation DC System Control receives the required power flow schedule as an input and distributes it to the different substations. It is important to note at this point the difference in the operation of DC System Control in comparison to prior-to-normal operation. Before the normal operation stage DC System Control delivers commands and setpoints directly to the different substations (Operational management) while during the normal operation stage DC System Control delivers the schedule to the different substations instead (Schedule management). Operational management is used in general for out-of-normal operation whether this has to do with the preparation of the system for normal operation or with the operation of the system under disturbances. Operational management assumes proper function of communications and it is preferred because it can readjust setpoints dynamically to influence the power flows in the system under close supervision. Schedule management on the other hand is used during the normal operation of the system. It assumes that the system operates far from extremities and substations are given the freedom to take care of themselves following the given schedule. This makes the system immune to communication loss events for a time interval that can be defined according to the requirements of the system. Even in this case, DC System Control retains its supervisory role and Operational management will override Schedule management upon a perceived emergency.

A severe disturbance in the AC side can shut down the respective substation. When this happens a power imbalance is instantly created in the DC system. During such disturbance, DC System Control assumes the direct control of the terminals and imposes Operational management over Schedule management. DC System Control must then act as quickly as possible to limit the consequences of the disturbance, firstly in the DC system and secondly their expansion to adjacent AC systems. Since DC System Control directly operates on the remaining substations the actions it can take range from appropriate control mode selection to power flow rescheduling which can take place according to predefined criteria. It is important to mention at this point that DC System Control loses control over the faulted substation in the sense that the substation itself prioritizes its own decisions to protect itself. The only way for the faulted substation to return under the control of DC System Control is that the fault to which it responded is removed or DC System Control creates power flows that do not violate the faulted substation’s safety margins using the remaining substations.

In all, DC System Control can be a gentle supervisor or an aggressive guard of the system’s operation. It will try to create the necessary conditions for the different substations to operate as independently as possible and to protect them from possible mishaps but it will intervene aggressively in their operation when the system’s operation is in jeopardy. Its access to data from all substations of the system allows it to have a complete image of the system at all times, and its direct access to the controls of each substation gives it the chance to directly affect this image of the system when necessary.

Substation Control level

The Substation Control level consists of all the Substation Control Objects (SCOs) that correspond to the different terminals. Each SCO receives its individual identity by which it is known to the DC System Control level and is responsible for the safe operation of the terminal it operates. The SCOs receive direct commands or schedule commands by the DC System

Control level through the uniform interface. The commands are interpreted and arranged in a way the lower control level of Converter Control can recognize. The SCOs also receive data in the form of measurements from the Converter Control level that they use for their operation. A selection of this data is also placed in the uniform interface to be forwarded to the DC System Control level. The SCOs can be directly operated for out-of-normal operation or operate independently according to the schedule they receive by their DC System Control level. In any case, the first priority of any SCO is to protect the substation equipment, for this reason in case of safety margins breach the SCO will circumvent any control request in an effort to protect the respective equipment. When this happens an error signal is sent to DC System Control level so that the DC System Control level does not expect the specific SCO to follow any requested command. This may lead to the need for emergency rescheduling by the DC System Control level which will force the rest of the SCOs to accept direct control to balance the system.

The SCOs are expected to interface in a common way with the DC System Control level for which the uniform interface is responsible. For this to have any meaning, the SCOs must support a range of control modes regardless of the way they actually implement them and have the expected effect on the physical system when these control modes are used. The range of the supported control modes can be wider than the range of the control modes that each of the adjacent AC systems can support. In this case the information of the type of the connected AC system in the uniform interface will allow the DC System Control to exclude a part of the control mode range for specific terminals. For example, a terminal connecting a passive load cannot be operated at DC voltage control but in no case can the DC voltage control mode be totally excluded by the control mode set of the control system.

The control of the converter is decoupled in the d-q frame. The SCOs do not handle the control of the converter directly, but they have to provide the next control level with the right signals to do it. The SCOs are responsible for interpreting the control requests they receive, in separate control signals for the d and q axis. The control modes supported or at least requested by the SCOs have to be present in the next control level as well. The SCOs then, according to the requested control mode creates the respective control signals that activate the right set of controllers in the next control level and provide them with the right setpoints for their operation. The suggested control mode set in this work contains:

- DC droop voltage control
- DC voltage control
- Active power control
- Reactive power control
- AC voltage control

The control mode set up can of course be wider, but these control modes are considered adequate at this point of this work.

For the sake of modularity, the different SCOs in a system are not allowed to interact directly. If direct communications were to be established between the different SCOs, the integration of new terminals would turn a complicated task. For data to be exchanged between specific substations, their individual interfacing needs should be matched leading to special interfaces for each of this type of communication connection. This means that for any new terminal addition all these communication connections would have to be reconsidered. The data exchange and their paths would also become complicated and detecting a communication failure would be cumbersome, let alone handling it. For all the above reasons the proposed control system structure does not allow the individual terminal SCOs to communicate with each other, interfacing is allowed with DC System Control level only that is the sole responsible for the coordination of system operation.

Converter Control level

The Converter Control level is the lower control level and the closest to the converter in this control system structure. It consists of the different Converter Control Objects (CCOs) that correspond to the different terminals in the system. Each CCO contains the necessary controller set for its converter to perform the expected operation of the terminal according to the type of AC system it connects to the DC system. All measurements that are gathered by the physical system and end up to DC System Control level through the Substation Control level are first collected in Converter Control level. This happens because it is in the Converter Control level that the continuous control of the converter takes place. The different P and PI controllers forming the controller set of the different CCOs need real measurements to operate apart from the setpoints received by the Substation Control level. Also fast current changing faults in the AC side need to be dealt with as soon as possible when they happen and intervention is not needed by any higher control level since the first priority again here is to preserve component safety.

The standard CCO contains an inner current control loop which receives its setpoints by a set of outer control loop controllers, as shown in Figure 4-2. While the inner current control loop is indispensable in this kind of implementation, the controllers of the outer control loop can vary to match the expected functionality of each terminal. As mentioned in Substation Control level section the suggested outer loop controller set in this work contains a DC droop voltage controller, a DC voltage controller, an Active power controller, a Reactive power controller and an AC voltage controller. Although it would be possible to have different controller sets for the different terminals, the controller sets of all terminals are selected to be identical in this work. Not all controllers are used in all terminals and for this a controller that is not used gets disabled saving simulation time since no integrator operates on any uncontrolled variable.

Converter Control level is the most dependent control level of the three since it needs a continuous supply of control commands and setpoints. It communicates only with its directly superior control level, the Substation Control level, and if its communications fail it keeps implementing the last received control request. Although, communication failure at this level is not considered a real threat since both the SCO and the CCO will be accommodated in the substation and will not be exposed to the possibly harsh environmental conditions. The only freedom of self-management the CCO has is during faults on the AC side. It is considered that in this case if the CCO was to follow the requested operation safety margins would be breached leading to equipment damage taking down the substation for a long period of time. Instead, CCO detects high currents and responds according to the type of the detected AC fault circumventing any control requests from higher control levels.

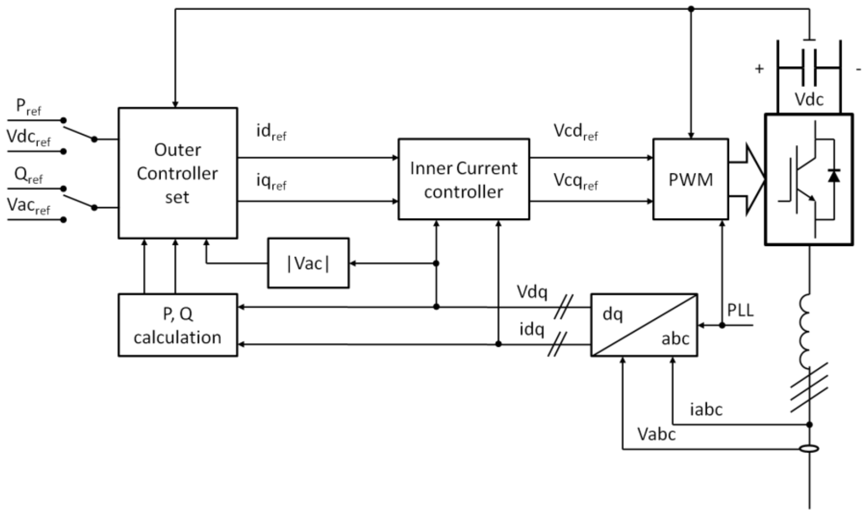

Figure 4-3: Controller configuration

Uniform Interface

As mentioned earlier the uniform interface is not yet another control level, it is considered though a defining feature of the proposed control system structure and thus its functionality will be described in this section. The uniform interface is the means of communication between the different SCOs and the DC System Control level. It establishes a common pattern for the communication of the different terminals with the DC System Control level and decouples the control of the individual substation from the control of all the substations as a system. In this way, the DC System Control level deals only with the available data on the uniform interface without having to go into detail in the operation of the individual substations and consequently the implementation of their control. The uniform interface filters the information provided to the DC System Control level by the different SCOs isolating it from the details of their operation but offering at the same time all the necessary information for the DC System Control level to fulfill its coordination duties.

For the uniform interface to function it is assumed that all the SCOs comply with its data arrangement and that each control operation on the Substation Control level has the expected effect on the physical system despite of its implementation. The challenge then is to define the required data set to assure uniform compliance. The data set of the uniform interface is preferred to be the minimum necessary. The reason for this is to facilitate the operation of DC System Control level; the less data it has to consider the faster its operation will be. In this sense, the data set should focus on measurements of universal value to the system and also status updates, meaning updates on the control modes statuses of the different substations. Apart from updating the DC System Control level about the status of the respective SCO, it should of course be able to transfer commands from the DC System Control level to the different SCOs. From the above discussion, it becomes obvious that the uniform interface needs to support bi-directional flow of data carrying information both regarding the status of the SCO it connects to the DC System Control level and regarding control commands that are requested by the DC System Control level.

Following the above rationale, it is considered that a minimum data set for the uniform interface is necessary to contain the following signal groups:

- Control signals
- Status signals
- Measurement signals
- Error signals

Control signals should contain the requested control modes for the respective SCO together with the necessary setpoints.

Status signals should function as handshake signals confirming the implementation of the requested control commands by the SCO.

Measurement signals carry all the necessary measurement information from the SCO to the DC System Control level.

Error signals inform the DC System Control level about present emergency conditions in the respective SCO.

Although an effort is made to identify the necessary interface signals by functionality, the detailed data set remains under discussion. The detailed data set used in this work is presented in Chapter 5 but it should be kept in mind that the uniform interface is based on dynamic data sets, meaning that the data set used can be adjusted to include additional necessary data or discard excessive data according to the needs of each individual system. In all, the uniform interface adds much to the modularity, and consequently to the expandability, of the system both by allowing different types of substation control implementation to interface with the DC System Control and by offering the flexibility to the designer to adjust the necessary data set to the individual systems.

Summary

In this section the structure of the proposed control system was described together with the basic principles it is based upon. Its control levels were described with their distinct functionalities and domains of responsibilities, having the uniform interface as a defining feature. The distributed "intelligence" in the Substation Control level makes the different substations more autonomous in their operation on one hand and on the other relieves the operation of the DC System Control level releasing it from operational duties and leaving it with the coordination operation only. At the same time the uniform interface allows different types of substation control implementations to be used under the same DC System Control. The latter is the best motivation for the clear distinction of functionalities between the different control levels intended in the proposed control system structure.

As mentioned above, the proposed control system structure intends to be considered as control system platform meaning that the different parts of it should be seen as "components" that can be changed or modified. For this to be possible there are of course some guidelines that must be followed, for the Converter Control level to be implemented with different controller sets, they should be supported by the Substation Control level and for the Substation Control level to be implemented in different ways it should comply with the uniform interface data set and correspond to its expected functionality. Even the DC System Control level could be implemented in a different way as long as it keeps its fundamental functionalities and complies with the uniform interface data set. This shows that the clear distinction of functionalities between the different control levels is vital and offers the necessary flexibility to the control system towards modularity and expandability for achieving its long-term objective of flat control system structure that is necessary for its later stage of development.

Chapter 5

Implementation

In the previous chapter a three-level control system structure was described together with the general features it should comprise for the operation and coordination of a multi-terminal VSC-HVDC system. In this chapter the implementation of the structure of the control system as well as the implementation of its distinct control levels is presented. This implementation will later be used to operate a multi-terminal VSC-HVDC system whose model is also discussed in this chapter.

As shown in Figure 5-1, the implementation of the control system extends in two different domains that interact with each other; C++ where most parts of the control system are developed and Dymola that is the simulation tool where the system model is developed. The different parts of the control system that appear in Figure 5-1 will be explained through this chapter.

The chapter is structured in three sections where the implementation of the control system structure, the interaction between the different domains, the implementation of the different control levels and the system model are described in detail.

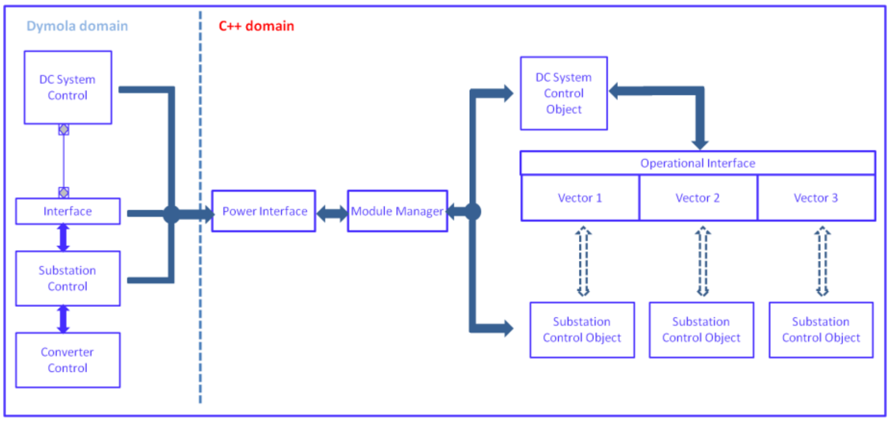

Figure 5-1: Interaction between Dymola and C++ domain

5.1 Control System Structure Implementation

The programming language that was selected for the implementation of the control system is C++. The motive behind the selection of C++ was the intention to develop a control system that can be easily transferred to other simulation tools for validation and even directly to a real system since C++ is a language used on industrial level. Most importantly C++ allows dynamic management of different numbers of terminals with different sizes of data sets.

The idea is to standardize the necessary data exchange between the control system and the physical system and also between the different levels of the control system itself by defining a minimum yet general enough data set to cover most possible situations such system might encounter. In this way the data process and data transfer procedure are separated allowing the independent implementation and future development of the different control levels. Even this minimum data set can be adjusted for future requirements since it is based on dynamic vectors.

The basis for this implementation is described in [38]. The implementation of the control system structure can be presented by describing in detail its fundamental elements.

Operational Interface

The Operational Interface is the point of communication between the different connected terminals and the overall Control System. It is, in this sense, the point of communication between the DC System Control level and the Substation Control level. Every Substation Control object (SCO) outputs there all information related to its operation including measurements, hand-shaking signals and system type information and acquires from the Operational Interface operation commands or schedule assigned to it by the DC System Control level. The DC System Control in its turn receives all the information regarding the connected SCOs from the Operational Interface that are necessary for the system analysis before it outputs there all the commands addressing each individual SCO. It should be pointed out at this point that the DC System Control has two possibilities of controlling the different SCOs; it can either control them directly by placing commands on the interface and monitoring each SCO's operation by the feedback it provides, or by placing a schedule in the interface that the SCOs are expected to follow. From the DC System Control perspective these two constitute clearly two distinct cases. At direct control, DC System Control uses the output Operational Vector to directly provide control commands to the different SCOs, while at indirect control it uses the Schedule Vector to output an expected schedule operation to each SCO. From the SCO perspective the cases are also different; however the SCO provides its feedback through the Operational Vector always. This means that regardless of the way a control command was handed to the SCO, directly or indirectly, it will update DC System Control in the same way, by updating the handshake signals in the Operational Vector.

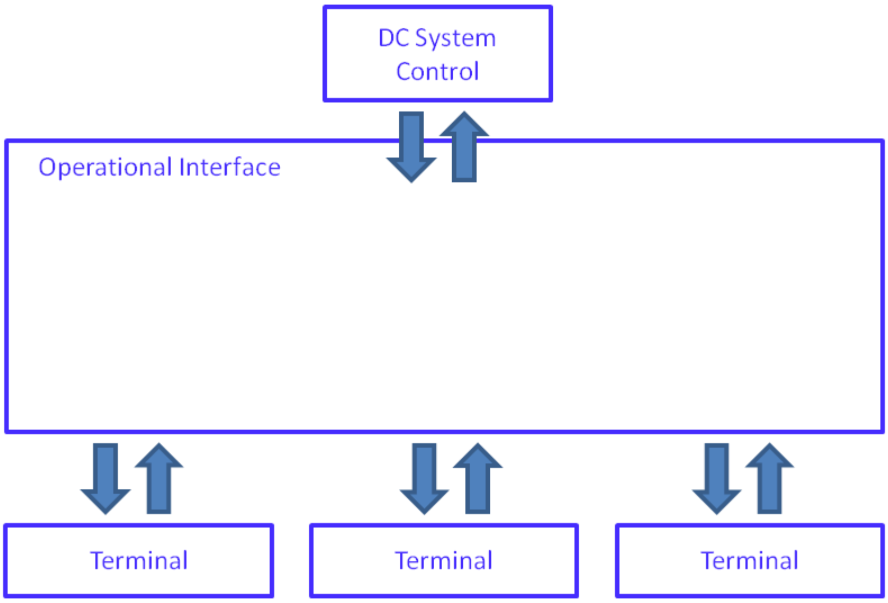

Figure 5-2: Operational interface, the tank paradigm

Let’s take a step back at this point and discuss what Operational and Schedule Vectors are and how they are implemented in the Operational Interface.

The Operational Interface could be parallelized with an open tank, as depicted in Figure 5-2, where from one side the DC System Control injects commands and extracts information related to the status and operation of all SCOs. While on the other, each SCO injects information about its status and operation and extracts commands. The paradigm of the tank though has an important weakness, the information of each SCO could be mixed and the DC System Control could get the wrong image for a specific SCO and thus direct the wrong commands to it. To avoid this, compartments must be added to the tank (Figure 5-3).

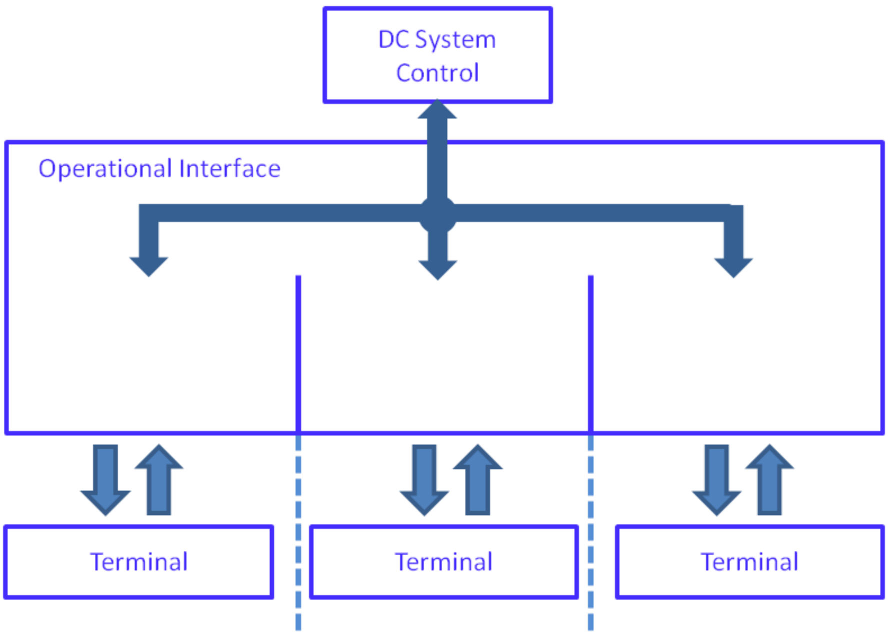

Figure 5-3: Operational interface, tank compartments

The compartments in the tank visualize the domain of each SCO in the Operational Interface. The Operational Vector together with the Schedule Vector that correspond to each SCO constitute the different compartments in the Operational Interface tank (Figure 5-4). Each SCO is assigned with its own set of Operational and Schedule Vector where it deposits its data and from where it extracts the DC System Control's commands or schedule addressed to it. In this way, the DC System Control knows where to look for information for a specific SCO and each SCO knows where to look for commands. The compartment tank is also an easy way to illustrate the access rights of each Control System level. The Substation Control objects (SCO) have access only to their own compartment (Operational and Schedule Vector), they do not have the full image of the system and thus they operate towards their own security following the instructions given to them by the DC System Control level. On the other hand, the DC System Control level receives information by all the connected SCOs in order to have the full image of the system and thus coordinate the operation of all terminals by distributing the required commands to each one of them.

The Operational Vectors themselves consist of an input/output vector set. The input or the output vector contains data that can be both updates and handshakes depending on their direction. For instance when a control command is directed from the DC System Control to a SCO then it is considered as an update while when it is directed from a SCO to the DC System Control it is considered as a handshake. Handshakes are used to confirm that the data transfer has been successful and inform the counterparts about each other's status. While the Operational Vector is bi-directional, allowing both input and output, the Schedule Vector is unidirectional allowing the flow of information from DC System Control to SCO only. This is reasonable since the data of the schedule is product of prior planning. However, this data becomes of operational value upon implementation and thus the feedback is provided to DC System Control by the SCO through the Operational Vector.

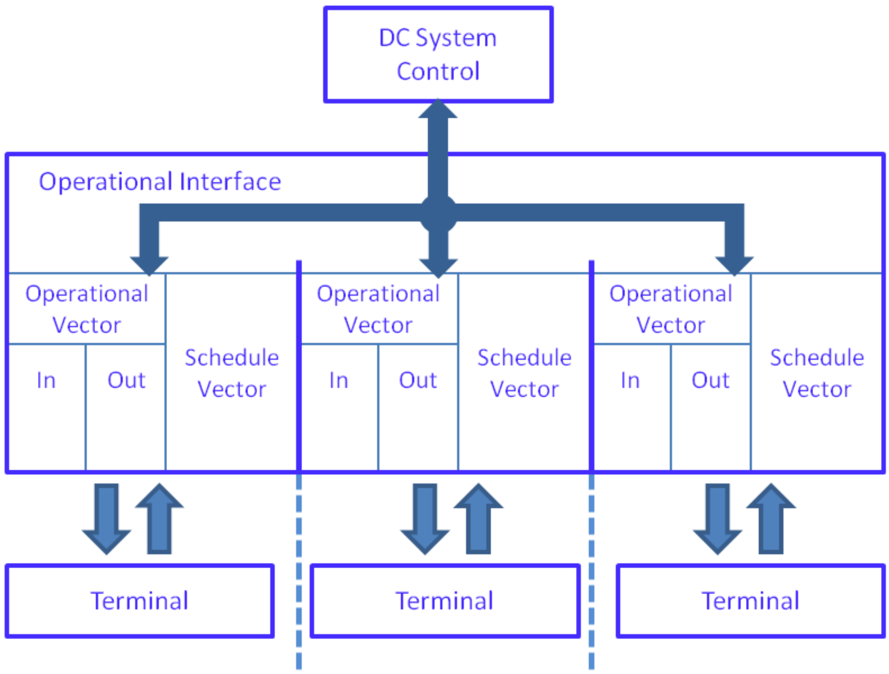

Figure 5-4: Operational interface contents

It is important to be noticed that maintaining such a structure for the data exchange is fundamental for the easy expandability of the system. The data are pooled together, sorted and directed to their destination without requiring one physical input/output node between the DC System Control and each SCO. As it will be discussed later on, the sorting of data is handled by an identity system which is also based on a dynamically managed structure. The combination of the dynamically managed identity system and the dynamic Operational and Schedule Vectors provides the flexibility to add as many SCOs as necessary and implement more complex data sets without interfering with the implementation of the DC System Control.

Apart from the structure of the Operational Interface, it is important to take a look at the data set itself that is used for the implementation of the Control System. While the individual signals may change within each signal group, it is important that the signal functionality groups are kept similar to what is suggested in the IEC 61850 standard [39-42].

Table 5-1: Operational Vector signal configuration

	Signals	Functionality
	OVI_NOT_USED	Not used signal to match C++ and Dymola indices
	OVI_TRANSACTION	Not used currently
Control Signals	OVI_COMMAND	Status of Terminal (ON, OFF, Stand by)
	OVI_GOVERN	Control mode
	OVI_SPVDC	DC voltage setpoint
	OVI_SPP	Active power setpoint
	OVI_SPVAC	AC voltage setpoint
	OVI_SPQ	Reactive power setpoint
Status Signals	OVI_RES_TYPE	Connected system type
	OVI_T_STATUS	Transaction status
	OVI_D_STATUS	Direction status
	OVI_C_STATUS	Command status
	OVI_G_STATUS	Govern status
Measurement Signals	OVI_E_CUR	Current level of energy
	OVI_P_MAX	Maximum current power capability
	OVI_UDC_CUR	Current DC voltage level
	OVI_P_CUR	Current level of active power
	OVI_UAC_CUR	Current AC voltage level
	OVI_Q_CUR	Current level of reactive power
Error Signal	OVI_ERROR	Error signal

Table 5-1 shows the data set of an Operational Vector, it is the information that is collected in the DC System Control level and the Substation Control level and exchanged between them. This data set is considered here the minimum necessary to operate a range of different connected systems since it includes control, status, measurements and error signals including a type of connected system signal that informs the DC System Control level of the type of the connected system to be operated. As mentioned above, this is considered a necessary minimum but it is based on dynamic vectors meaning that it can be expanded to include more information if necessary or be adjusted to special cases.

The data set of the Schedule Vector can be smaller since it does not need to include feedback signals regarding statuses, measurements and handshakes. Table 5-2 shows that the Schedule Vector contains only the control signals and information regarding the implementation of the schedule itself, such as initiation time, duration and addressed substation identities.

Table 5-2: Schedule Vector signal configuration

	Signals	Functionality
Timing signals	RSCH_RES_ID	Target resource
	RSCH_START_TIME	Schedule implementation start time
	RSCH_INTERVAL_DUR	Schedule interval duration
	RSCH_INTERVAL_NUM	Expected schedule intervals
Control signals	RSCH_COMMAND	Status of Terminal (ON, OFF, Stand by)
	RSCH_GOVERN	Control mode
	RSCH_SPVDC	DC voltage setpoint
	RSCH_SPP	Active power setpoint
	RSCH_SPVAC	AC voltage setpoint
	RSCH_SPQ	Reactive power setpoint

Module Manager-Resource Manager

The different control levels of the Control System are implemented as classes in C++ so that many objects of the same class can be present in the same model. Module Manager helps distinguishing between the different objects of the same or different class. It provides a set of simple functions through which each object can call its respective class, managing in this way the access rights to the Operational Interface of each object in the model. The functions are called by the different objects (resources) in the model through the Power Interface whose role will be discussed in a later section. The main functionality of these functions is to transfer operational or schedule data but since the call is made by specific objects the respective classes are also called to perform the calculation of the necessary output data.

All types of objects are connected to Module Manager through Power Interface to be redirected to the corresponding class. Within Module Manager each object is classified according to module type (moduleType) according to its position in hierarchy. The top hierarchy module (DC System Control) creates a dynamic vector (Resource Vector) that is managed by the Resource Manager and in which the identities (resourceID) of the different Substation Control Objects are held. An Operational-Schedule Vector set corresponds to each resourceID that represents a Substation Control Object and is obtained upon initialization, as shown in Figure 5-5. This is to assure that the access rights to the Operational Interface of each object correspond to its position in hierarchy. In this way, the DC System Control object can access the entire Operational Interface, while the different Substation Control Objects access their respective Operational-Schedule Vector sets in the Operation Interface through Dymola.

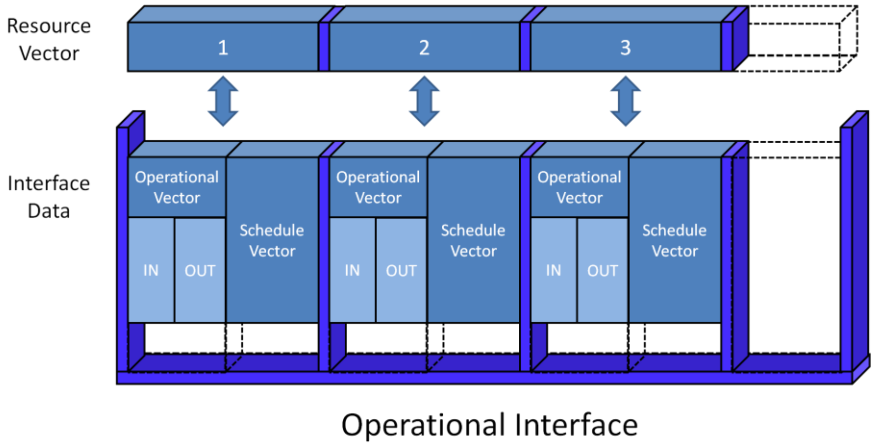

Figure 5-5: Resource Vector- Operational interface depiction

The meaning of dynamic Resource Vector is that it will be adjusted to the number of objects in the system and it will create a new Operational-Schedule Vector set for each new Substation Control moduleType object.

The respective DC System Control moduleType object will then automatically gain access to it.

As mentioned above the function set provided by Module Manager is simple and built to trigger only the more complex parts of the code.

mInit (moduleType, cv[], cvSize)

- Arguments

- moduleType: As mentioned above, moduleType defines the type of each object as DC System Control, Substation Control or Converter Control classifying accordingly each object in hierarchical order.

- Cv[]: Cv stands for configuration vector. It can host information that the operator considers important for each object. The Control System itself expects to receive some information by the cv[] such as limits regarding maximum power, power ramping or current. The size of the expected interface must also be defined in cv[] as well as the type of the connected system (resourceType). In the physical system a substation might connect to the DC system different types of systems, such as wind power plants, loads or onshore grids. For this reason the Substation Control object handling each substation unit must have the information of the type of the system that the substation unit connects to the DC system. In this way the DC System Control is aware of the available power mix in the system so that it can consider it in scheduling. In the same way each Substation Control object can have a better image of what safe operation is according to the connected system.

- cvSize: It contains the information of the size of cv[]. This information is important and has to be included because it makes cv[] adjustable to the requirements of each system.

- Functionality

  It can easily be conducted by the analysis of the arguments of the mInit function that its purpose is to initialize the respective object.

Every time it is called using a specific moduleType a new resourceID is saved in the Resource Vector of the corresponding moduleType. At the same time Module Manager creates a new object by calling the constructor of the respective class. At the end of this procedure a new object will be created and given a resourceID which is also saved in the respective Resource Vector.

Cv[] is also provided by mInit as a set of information for the newly created object that will accompany it after initialization also. Cv[] is a source of fundamental information about each object that can be accessed at any time.

mUpdate (moduleType, objectID, timeStamp)

➢ Arguments

- moduleType: Same as in mInit.

- objectID: ObjectID refers to resourceID, the unique identity of each object. This argument is used here since the mUpdate function is supposed to be executed on the specific object that calls for it. ModuleType places the object in hierarchy and accordingly, Module Manager points the object to a specific class, then objectID helps executing the update function within the class for this specific object that will provide it with access rights over the respective Operational-Schedule Vector set in the Operational Interface.

- timeStamp: TimeStamp is the time within the simulation tool. Even if it has no relation with the navigation of the C++ program in its own structure, it is a useful piece of information when time dependent events affect the operation of the different classes. Especially when Dymola is the simulation tool, it is used to force Dymola to execute update and this is because timeStamp will always change from sample to sample. Dymola might not execute a function again if its arguments have not changed, by including timeStamp it is guaranteed that the function will be executed even for the same objectID.

- Functionality

Update means recalculate here. It will use the input Operational or Schedule Vector/s available, recalculate and fill the output Operational Vector/s. Depending on the implementation of the mUpdate function for each class the inputs and outputs might not be updated within the mUpdate function, in such case mUpdate must be preceded by a mSet function and followed by a mGet function to make sure that mUpdate operates on the latest data obtained by the system and outputs its data to the system. As for the case of mInit, moduleType defines the position of the object in hierarchy while objectID distinguishes it from other objects of the same moduleType. Especially for mUpdate this will define which Operational or Schedule Vector/s are available for it, since a DC System Control object can receive input and provide output to all connected Substation Control objects while Substation Control objects can only interact with the Operational Vector that is assigned to them.

mSet (moduleType, objectID, vectorType, value [], timeStamp)

- Arguments

- moduleType: Same as in previous functions.
- objectID: Same as in previous functions.
- vectorType: The vectorType argument defines whether the function will operate on the input Operational Vector, the output Operational Vector or the Schedule Vector of the above specified object. VectorType can define 4 types of vectors, input Operational Vector, output Operational Vector, Schedule Vector and configuration vector. Although the mSet function can only operate on the Operational Vector. More specifically, the reasonable operation of mSet function is on the input Operational Vector.

- value []: Value [] is a vector of data provided as an argument to be transferred from the Dymola connector to the input Operational Vector.

- timeStamp: Same as in previous functions.

➢ Functionality

The mSet function is used to receive inputs from Dymola domain and transfer it to C++ domain. For any calculation to be made in C++, information needs to be input by the physical system and mSet provides the way to do so. Value [] is copied in the input Operational Vector and thus must be arranged accordingly beforehand, while moduleType and objectID locate the exact Operational Vector to be changed within the Operational Interface.

mGet (moduleType, objectID, vectorType, index, value, timeStamp)

➢ Arguments

- moduleType: Same as in previous functions.

- objectID: Same as in previous functions.

- vectorType: Same as in mSet. For mGet function though the reasonable operation is on the output Operational Vector or the Schedule Vector.

- index: For mGet, instead of providing the data to be transferred in the form of a vector, the data is provided element by element and this is the reason why it is necessary to specify in which position of the output Operational or Schedule Vector each element must be placed. As it can easily be guessed, for a data set to be copied to the output Operational or Schedule Vector, mGet must be within a “for” loop running all of the respective vector’s elements. Although it might appear to have no particular meaning, this procedure provides the possibility to randomly access and change any element in the Operational Vector. This is necessary because there are objects that only need to change few elements of the

Operational or Schedule Vector and not the entire vector. On the other hand the important information in the output Operational or Schedule Vector is commands and control signals which are mainly digital and there is no need to update them if there is no change. On the input Operational Vector which is manipulated by the mSet function the most important information is measurements. The measurements reach the Control System in digital form but since they derive from analog signals they change very often thus making their update in every sample a necessity.

- value: Value is what is to be transferred to the index specified position of the output Operational Vector.

- timeStamp: Same in previous functions.

➢ Functionality

The functionality of mGet is to extract the output Operational or Schedule Vector of the moduleType and objectID indicated object to the respective Dymola connector. This is done in an element by element mode which makes imperative the use of a “for” loop together with mGet if the entire output Operational or Schedule Vector is to be copied to the Dymola connector. But in this way it provides the possibility of selectively output specific elements of the Operational Vector to substitute the previous values without altering the rest. The role of mGet is as important as the role of mSet and mUpdate since there would be no value in inputting data to C++ domain and making any calculations there if there was no way to output the results of these calculations to the system.

Module Manager provides the infrastructure for the interaction between the different objects within the system. It applies a systematic classification of each object according to type (moduleType), and thus position in hierarchy which defines its access rights in the Operational Interface, and identity (resourceID) which distinguishes each object from other objects of the same type. It also consists of a simple function set that can be called by the different objects in the system through the Power Interface that will be discussed later on. The main principle of operation for the function set for any object that uses it could be described in three steps, update inputs (mSet), calculate (mUpdate) and update outputs (mGet). It is important to mention that the implementation of each function might change from class to class. Arguments like moduleType and objectID are present in almost all functions and their sole role is to allow Module Manager to choose the right implementation according to the object that is calling for them.

Power Interface

Power Interface is mentioned here to avoid confusion with Uniform Interface. Power interface does not have to do with the interfacing between the different control levels of the control system described above. It serves as the link between C++ code and the outer world, in this case Dymola. Power Interface contains a function set like the one of Module Manager, only this time all the functions are defined as external and they only call the functions of Module Manager. In this way, Power Interface allows internal functions to be called from outside the program indirectly. This "buffer" stage is important so that external users of the program do not interfere with C++ indices that the program uses to keep track of its objects. Power interface takes care of any index mismatch between C++ and Dymola assuring that indices match and there is no index out of boundaries. As in C++, in Dymola the functions of Power Interface must have copies that are defined as external "C" functions and then be imported in the correspondent Dymola class before they can be used.

5.2 Control Levels Implementation

The Control System is divided in three hierarchical levels and thus its implementation in C++ follows the same structure. In the C++, each level of the Control System is implemented as a separate class. In this way many objects of the same class can be created in a system with Module Manager keeping track of each one of them. The hierarchy in the Control System is reflected in the access rights to the Operational Interface that each class is given through its implementation. As will be shown later, the access rights of each class is something programmed within each class constituting in this way the Operational Interface as the common data node for every class and thus for every object. Each class has the right to manipulate the Operational Interface as a whole or parts of it (Operational-Schedule Vectors).

DC System Control

DC System Control level is supposed to have a clear image of the system as an entity in order to be able to make decisions for the coordination of the different terminals and act towards this goal by distributing control commands. To do so the DC System Control class has access to all input and output Operational and Schedule Vectors within the Operational Interface. In this way, DC System Control receives information by all connected terminals in order to determine the status of the system and then according to this manipulate the outputs heading to each terminal or distribute schedule information to achieve the current control objectives.

The main idea is to implement the DC System Control level as a state machine with the different states representing different stages in the operation of the system. The intention is to represent the system as accurately as possible through the different states and for this reason different conditions have been used to determine the current state of the system and also the transitions between the states. Consequently, the operation of DC System Control class is divided in updating the conditions from incoming measurements, updating the state according to the conditions and updating the outputs according to state. It is important to mention here that there is no need to update the inputs in DC System Control class since this is taken care of by the uniform interfaces connecting the different terminals. The functionality of the uniform interface will be discussed later on.

In an effort to make the operation of the DC System Control general, automated search functions have been used to handle the different terminals according to their properties avoiding a direct reference to their identity. Since the ambition is that the number of terminals should be allowed to change, DC System Control must be adaptable. Thus, having a resource vector that might vary in size it is not recommendable to use direct references to the identities of the different objects in the system. Instead, it is preferable to have some search function that will go through the resource vector and find the object with the desired set of properties. The function will then return the identity of the object for further utilization. If direct identity references were to be used, the addition of a new terminal in the system would imply the modification of the code of DC System Control class or its de facto exclusion from the operation of the system. Automated search functions are used through the different parts of the DC System Control.

- Conditions

  If DC System Control is to be implemented as a state machine the determination of the current state at each point of operation as well as the transition between the different states is of vital importance. Of course these conditions have to be related to external inputs for the DC System Control to be connected to the reality of the physical system. The different conditions are in the form of logical flags that represent a specific situation in the physical system. Their state (true or false) is determined by searching a specific group of resources or all of the resources or one specific resource for specific properties. The inputs for the different conditions come from the input Operational Vectors to DC System Control by the different connected Substation Control objects. This means that the signals that are taken into account to determine the system's state are measurements and handshake signals, thus reflecting the real situation of the system both in terms of measured quantities and control signals.

  As mentioned above, the flags used are related both to measurements from the physical system and handshake signals reflecting the control status of the respective terminal or group of terminals. Table 5-3 lists the status flags.

Table 5-3: Status flags

Flags	Interpretation
Internal Voltage	DC Voltage measured for at the charging terminal is above preset limit
Full Stop	All terminals are at Command signal OFF
Idle	All terminals are at Command signal READY
Power Off	No power flow in the DC system
Generation-Load Units	Presence of both generation and load units in the system for sustainable operation
Active Units	At least one terminal at Command signal ON
Active Error	Presence of error in one of the active units

The list of flags can of course be expanded and include more detailed information about the system. Although, it should be kept in mind that the flags must fit the general perception of the Control System, in the sense that they should be grouping different terminals' properties. It is perceived here that the above mentioned set of flags is adequate to move through the different states for the system used in this implementation.

After their determination, the different flags are grouped together to form the conditions for state determination and transition from one state to another which will be presented together with the different states.

- States

The operation of the Control System has been divided in different states which are presented in Figure 5-6. This is to facilitate decision making according to the stage of operation of the physical system. It is also an effort towards the minimization of the data that needs to be monitored in every stage of operation as well as towards the minimization of chances of misinterpretation of the real status of the system at any time. Every state in the state machine is derived according to the previous state in combination with specific conditions of interest. The state machine is designed to return to safe state in case of error or uncertainty, if the error is severe the system will shut down and start again otherwise the problem will be addressed through the emergency state. If no solution is found in the emergency state then the system will once again have to shut down and restart.

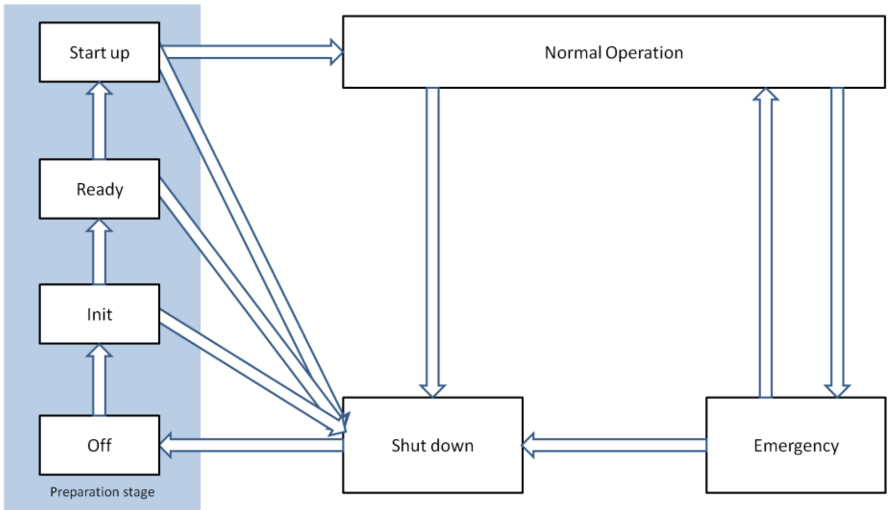

Figure 5-6: DC System Control level as a state machine

- OFF

All terminals are off, no power exchange

The system is assumed to start in this state where all terminals are at Command signal OFF and there is no power exchange between the different terminals. This, in terms of the above mentioned flags would be interpreted as:

Full Stop = True

The condition for transition to the next state is a timer expiration and an external operator signal. The external operator signal must be activated for the system to restart its operation automatically. If for some reason the operation of the system must be discontinued the timer will give some time to the operator to deactivate the external signal

Timer OFF = True

Operator signal = True

From OFF state and given that the conditions for transition hold the system will proceed to the next state.

- INIT

Terminal availability check, all error free terminals are set to 'ready' (stand by).

The conditions for the system to be in this state are that it has previously been in OFF state, Timer OFF has expired and the Operator signal remained true.

For the system to proceed to the next state, first, error free generation and load units must be identified in the system and then at least one of them must be at Command signal READY. All error free terminals must be at Command signal READY and some of them must be generation units while others must be load units. The reason why there must be error free terminals in the system is quite straight-forward since no operation can start without them. The error free terminals must be at READY, standing by for operation. Generation and load units must be among the READY error free terminals to justify sustainable operation. In terms of flags this would be interpreted as:

Generation-Load Units = True

Idle = True

Error Free = True

From INIT state and given that the conditions for transition hold the system will proceed to the next state.

- READY

One or more 'ready' terminals are selected to charge the DC link.

If the system is at this state, it means that there are both error free generation and load units standing by for operation.

The functionality of this state is to select one or more of the generation units to charge the DC link so that any power exchange can take place. Charging the DC link is a shared responsibility among all READY active terminals operating at DC droop control. It is obvious that no passive connected network can participate in this procedure. More criteria can be added for this operation to include prioritized terminals for this purpose and implement potential agreements between the involved parts. For instance, DC voltage control could be used for a specific terminal to charge the DC link, if existing agreements dictate so. To signal this to the rest of the system a flag turns true that shows that there are active units now in the system. Since the DC link is not charged yet, no power exchange can exist among the connected terminals and thus, this flag indicates that the system is taking action, requesting different terminal to get active in preparing the normal operation of the system. In terms of flags this would be interpreted as:

Active Units = True

When this flag becomes true, the system automatically proceeds to the next state.

- START UP

One or more terminals are charging the DC link, wait until DC link is charged.

When the system enters this state, there are already one or more terminals charging the DC link. What is necessary at this point is to monitor the DC link voltage and when its lower limit is reached the system can proceed to the next state. When the DC link is charged the internal voltage flag becomes true. If the active units continue being error free the transition to next state is signaled.

Internal Voltage = True

Active Error = False

When Internal Voltage is true and if there is no error in the active terminals the system is ready to begin power exchange between the different terminals, thus schedule implementation can start.

- NORMAL OPERATION

Schedule is implemented.

When the system arrives at this state it is ready to start the implementation of the required schedule. All conditions are present to begin the normal operation of the system, the DC link is charged and error free generation and load units are present in the system.

As mentioned in earlier sections, DC System Control can either control the different substations directly through the Operational Vectors or indirectly through the Schedule Vectors. Up to this state DC System Control operates the different substations directly, assigning control commands and setpoints in an effort to coordinate their operation to prepare the system for schedule implementation. When the system enters this state the control becomes indirect. Schedule is an input to DC System Control, which has to divide it and distribute it to the concerning substations. DC System Control instead of controlling the different substations through the Operational Vectors, it distributes the schedule to the different substations through the Schedule Vectors. Each substation receives the schedule it needs to implement for the coming two intervals by DC System Control. The schedule itself contains the information about the duration of its intervals and the starting time. In this way, both DC System and Substation Control know when to shift the schedule interval under implementation and the pending one. The operation of DC System Control is to read and send the schedule interval to the corresponding substation. DC System Control is always looking at one schedule interval ahead of the one that is implemented. As shown in Figure 5-7, every time a schedule interval expires, DC System Control reads and distributes the next. In the Substation Control there are two positions for the schedule intervals, one holding the schedule interval under implementation and the other holding the pending schedule interval. When a schedule interval expires, Substation Control has to discard the implemented interval and shift the interval in pending position to implementation position. In this way, the transition from one interval to another is made and also the pending interval position is freed to receive the next interval that DC System Control sends. Timing information in the schedule is important to achieve the synchronization of operations in DC System and Substation Control and avoid data collision or loss.

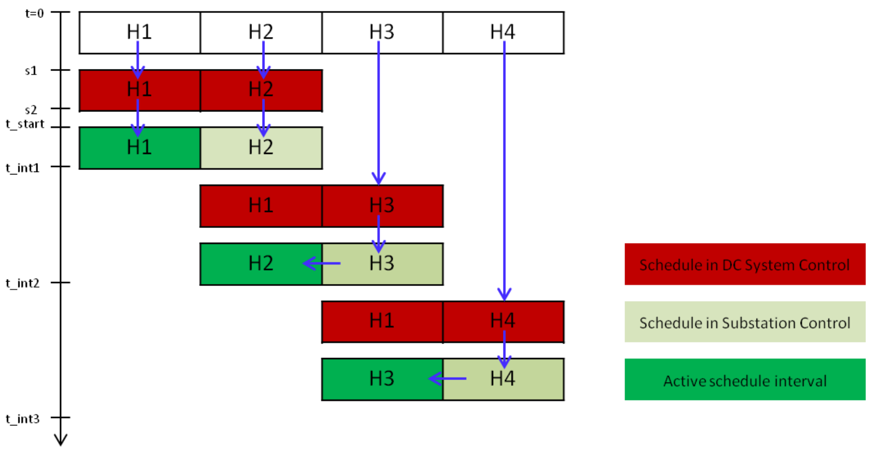

Figure 5-7: Schedule distribution implementation

The advantage of distributing the schedule to the different substations is that DC System Control is released from operational duties and can focus on its supervisory role, on one hand. On the other hand, having the substations aware of their expected operation makes the system less vulnerable to communication loss. In this implementation the substations are aware of two schedule intervals which means that if the interval lasts for one hour, as it is today, the system has at least one hour to recover from a communication loss event before it enters uncertain operation. This offers the flexibility to offer a time window for reaction against communication loss. It also shows a limitation for the reaction time. Since the available reaction time is bound to the duration of the schedule interval, if this duration is to change in the future, available reaction time will be affected and might become unacceptable. To raise this limitation, consideration is taken in this implementation so that the number of before-hand known intervals to the substation can be arbitrarily defined (Figure 5-8). This means that if the requirement for available reaction time against communication loss in the system is one hour, if the duration of schedule intervals is decreased to 15 minutes, the number of before-hand know intervals can be increased to 5 to match the requirement.

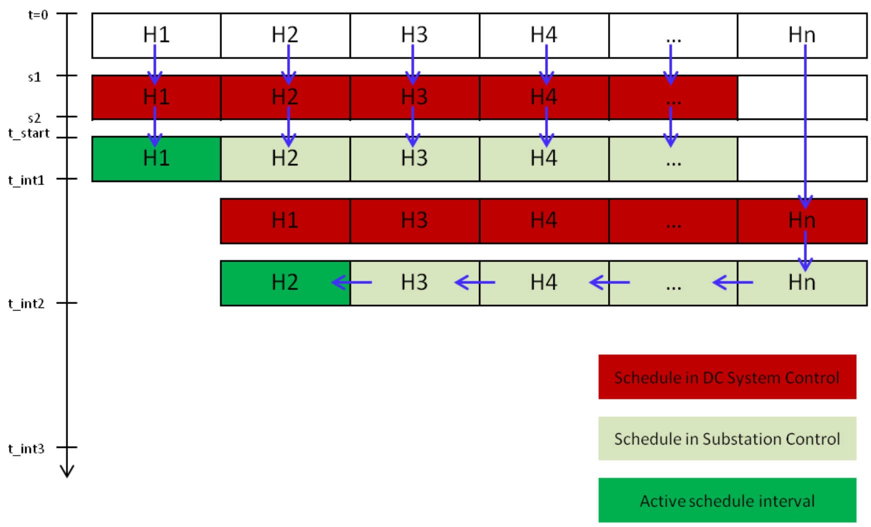

Figure 5-8: Schedule distribution in the general case

The system leaves the NORMAL OPERATION state when a shut down request is received or an emergency takes place. It should be mentioned at this point that, since the schedule is distributed to the different substations, communication loss does not constitute an emergency. The system is expected to continue its operation unaffected by a communication loss event and communication loss events are assumed not to last longer than a schedule interval.

- SHUT DOWN

All terminals are turned off.

The system enters this state when there is an end of operation request by the schedule under implementation or a severe error in normal operation or an unresolved issue in emergency operation.

After this state the system will return to OFF state when all power exchange has stopped between the different terminals and the DC link voltage is at zero. In terms of flags this would be interpreted as:

Full Stop = True

After shutting down the system will return to its initial state and try to start again unless a different operator signal is provided.

- EMERGENCY

One or more terminals have sent an error signal. There is at least one error-free terminal in operation.

Emergency condition is considered an external disturbance to the system. Since communication loss is not considered an emergency in this implementation and DC breakers are absent so that a DC fault must be handled by the AC protection systems, emergency conditions that this system can handle are AC disturbances affecting the operation of the HVDC system. The AC disturbances that this system deals with are 3-phase AC faults that are considered to be the most severe.

When a 3-phase fault happens in the AC side of each of the terminals, after it takes action automatically to protect its equipment, it will send an error signal to DC System Control. DC

System Control enters EMERGENCY state when an error signal is detected.

If no error-free terminal remains in the system, DC System Control will proceed to SHUT DOWN, otherwise it will try to coordinate the remaining terminal so that the system remains operational until the error is removed and return to NORMAL OPERATION is possible.

It is important to mention here that all different states are protected by a timer. This is to certify that the system will never get stuck in any state. In case the respective timer has expired in any state the system will go to SHUT DOWN state to stop any operation and start again.

➢ Outputs

Each state has its own duties during operation. The different flags signify the transitions between the different states and then in every state different actions are taken that eventually affect the flags. In a way flags resemble sensors while states resemble actuators. A state reflects a set of conditions in the system and thus has to perform the necessary tasks according to the conditions of the system.

- OFF

At OFF state there is no power flow within the DC system and the DC link voltage is zero. All the terminals are then turned into STOP Command signal to prepare them for the new start up operation. This state accesses all Operational Vectors and changes their output Command signal to STOP. This signal returns as a handshake signal in the input Operational Vector of every terminal after the command has been implemented and updates the respective flags in the system. The updated flags will then signal the transition to next state.

- INIT

At INIT state all terminals are at STOP Command signal. The system in this state will first perform an availability check in all terminals. This in practice means that the system will go through all Operational Vectors and search for errors at the OVI_ERROR position of the vector. Then, among the error free terminals it will search for generation and load units. It will search in all Operational Vectors at OVI_RES_TYPE position for generation and load units. It will acquire their identities and separate them in two vectors, one holding the identities of generation units and the other holding the identities of load units. At the end it will go through all the stored identities in both vectors and access their respective output Operational Vectors to change their Command signal from STOP to READY. In this way INIT state sets all the error free units at stand by given that there are both generation and load units. The commands will get distributed to the different terminals and handshake signals will occur to update the respective flags. The updated flags will allow the transition to the next state.

- READY

When the system enters in READY state there are stand by units in the system waiting for operation. The task that READY state performs is that among the stand by units it chooses one or more to charge the DC link. It is obvious that the selected unit must be a generation unit and not a load unit. READY state uses the identity vector filled in INIT state that holds the identities of generation units. The selected units will then be commanded to start operation in DC droop control mode at a specific setpoint. For this to take place, the respective output Operational Vectors are accessed and changed in several positions so that command signals, control mode signals and setpoints are set to the correct values. In the same manner as before the affected signals will be transferred to the terminals where handshake signal will occur to update the respective flags and signal transition to next state.

- START UP

When the system enters the START UP state there are one or more terminals charging the DC link. START UP state does not change any control signal since its task is to simply monitor the DC link voltage. The DC link voltage changes due to action taken in the previous state and the respective flag is updated independently of the state. It seems that READY and START UP states could be one but if this was the case unnecessary identical changes would happen in the different Operational Vectors wasting computing resources. In this sense START UP is an idle state where the system waits for the actions taken in READY state to affect the physical system.

- NORMAL OPERATION

  In this state the DC link is already charged, one or more terminals are set to DC droop control holding the DC voltage and other terminals are at stand by for operation. The system is then ready to input the required schedule and start implementing it. In NORMAL OPERATION the direct control of the substations by DC System Control ceases. Operational Vectors are not used to transfer control commands anymore, instead, Schedule Vectors distribute schedule intervals to the substations where they are interpreted in control commands. DC System Control updates the schedule interval and supervises the entire system according to data it receives by the Operational Vectors in case it needs to intervene to resolve an emergency. It is important to mention here that every terminal is called in the schedule with an externally given identity which is not necessarily the same as the one the Resource Vector holds. For this reason a special function is used to relate the externally given identities which are unknown to the Control System to the internally given identities of the different objects that are classified in the Resource Vector.

- SHUT DOWN

  At SHUT DOWN state all terminals receive the command to stop operation, which in terms of signals is changing the value of OVI_COMMAND to COMMAND_STOP**.**

- EMERGENCY

  An emergency is detected by the error signal in the uniform interface. When an error signal is received, DC System Control moves to the EMERGENCY state. It is assumed then that the faulted substation has already taken action to protect its equipment and that it will not allow DC System Control to operate it until the error is removed. Since the normal control mode of the substations is DC droop, there is no concern about DC voltage collapsing. DC System Control will then have to reschedule the power setpoints of the remaining error-free terminals to minimize disturbance propagation to adjacent systems. Figure 5-9 presents the logic implemented.

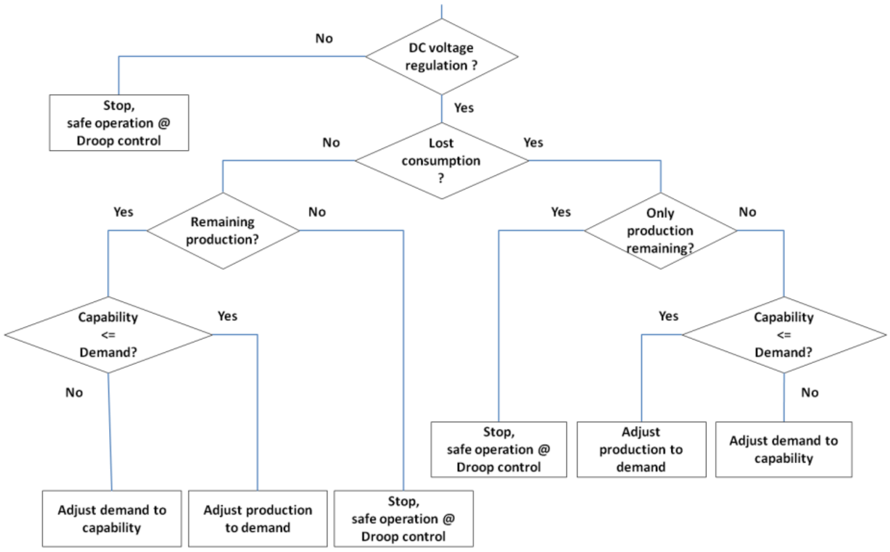

Figure 5-9: Rescheduling after 3-phase fault

The objective of DC System Control when it enters EMERGENCY state is to determine new power setpoints for the error-free terminals. Since the fault can happen at any time, DC System Control will have to figure out what the power flows were at the system before the fault happened so that it can readjust them. Before it can make any change, it needs to be certain that the DC voltage is regulated by at least one of the error-free terminals over which it has control. For this reason, the first thing DC System Control does upon entering EMERGENCY state is to search for voltage regulating terminals. This takes place with the help of search functions that perform conditional searches in all terminals looking for specific properties. For example, when DC System Control searches for voltage regulation, the search function is given the search objective of DC droop or DC voltage control and search criteria of error-free terminal. The search function will then go through the Resource Vector, search one by one all terminals according to their identity in the Resource Vector and return the identities of the terminals that fulfill the specified criteria. After voltage regulation is confirmed by DC System Control, it will proceed to specify whether the faulted terminal was producing or consuming power. In a 3-terminal system, a consuming faulted terminal shows that there is at least one producing terminal left in the system. If there is only one producing terminal left in the system, it means that it was the one feeding the other two which means that it can keep feeding the remaining consuming terminal with no problem. DC System Control will then adjust the producing terminal's output to the new demand of the system after the consumption loss. In the case that both the remaining terminals are producing, the only demand in the system was the faulted terminal's demand. Since the faulted terminal cannot absorb any power the demand in the system is zero and thus the output of the two producing terminal must be set to zero as well. Power flows are adjusted in a similar way when the faulted terminal was producing power. If the remaining terminals are both consuming, since there is no power production in the system their power setpoints will be set to zero. If there is one remaining producing terminal its output will be adjusted to the demand if it is within its capability, otherwise demand will be adjusted at its maximum power output.

The intention of DC System Control at this state is not to preserve DC voltage, since this is taken care of by DC droop. Its intention is to make sure no other terminal will trip because of the automatic loss sharing imposed by DC droop which will disregard the maximum capabilities of the terminals to balance the DC voltage. By adjusting the power setpoints DC System Control prevents DC droop from forcing another terminal out of its limits in an effort to distribute the power deficit and preserve DC voltage.

It is important to mention at this point that for DC System Control to achieve this quick adjustment it assumes Operational control over the terminal directly manipulating control modes and setpoints. Anyway the schedule has no practical value at this point since the system is not the same. If the timeline of actions is considered, one can observe that the primary objective when a fault happens is first of all, to protect equipment that will allow continuation of operation when the fault is removes. Then, DC droop is used to preserve DC voltage so that the rest of the terminal can continue their operation which will be adjusted. Finally, DC System Control readjusts the power setpoints of the remaining terminals to avoid cascade tripping.

Substation Control

Substation Control level is implemented as a separate class in C++ to assure the safe operation of the different substations in the system following the control commands or the schedule delivered to them by DC System Control level. Since it is implemented as a class, there will be one object (SCO) of this class for each substation in the system. Each SCO is an independent unit responsible for the safe operation of its respective substation. Since the SCOs have only local authority, they are not in the position to be aware of the entire system, thus coordination is needed and provided to them by DC System Control. An Operational-Schedule Vector set is assigned to each SCO at initialization. The SCOs are connected to DC System Control through the uniform interfaces and to their respective Converter Control level that will be discussed in a later section.

The duty of a SCO is to follow the operation instructions provided to it by DC System Control. Its first priority though is to protect its equipment. For this reason it will only follow instructions as long as it operates within safe limits. When, for example, a 3-phase fault happens on the AC side of the substation and its current suddenly rises, it will control the converter towards keeping the current within its safe operation limits regardless of any control requests by DC System Control. At the same time it will generate an error signal so that DC System Control is aware that it can no longer control the specific SCO. DC System Control will then have to try to reschedule the power flows in the system to first, prevent other substations from tripping due to changed power flows and secondly, to try to relieve the faulted substation.

The SCOs can be directly or indirectly controlled by DC System Control. When in normal operation, the SCO receives the schedule it has to implement through the Schedule Vector, while during start up or emergency and as long as it is not under direct threat of safety limits breach DC System Control assumes direct control over the SCO through the Operational Vector. The SCO interprets the condensed information contained in the uniform interface that connects it to DC System Control to the signals that are necessary for Converter Control. It also receives the measurements obtained by Converter Control and arranges them in the uniform interface for DC System Control to receive them. All measurements from both sides of the substation are obtained at Converter Control level since it is the one performing the continuous control of the converter. They are then forwarded to the respective SCO where they are sorted and placed in the right order in the interface for DC System Control. Since Substation Control translates DC System Control's control commands for Converter Control, it is important that all three "speak the same language", meaning that control modes requested by DC System Control must be recognized by Substation Control and supported by Converter Control.

It becomes clear at this point that Substation Control plays the role of the "bridge" between the continuous control of the converter performed by Converter Control and the overall coordination performed by DC System Control. It is responsible for the safe operation of the substation as a unit and it is responsible for preparing the interfacing with DC System Control. Substation Control could be implemented in other ways as long as it follows the interfacing pattern of the uniform interface and Converter Control can also be implemented in different ways as long as it is able to communicate with Substation Control and fulfill its duties. The point here is that since Substation Control and Converter Control only have local authority, their implementation is indifferent to DC System Control as long as they are able to communicate with each other, the interfacing rules with DC System Control are followed and they fulfill their expected functionality. This means that different equipment suppliers can operate under the same DC System Control as long as the uniform interfacing pattern is followed. Also, since substations are delivered as units, communication between Substation Control and Converter Control is up to the supplier to be determined without influencing the operation of DC System Control.

Converter Control

Converter Control level is the one closest to the converter, it comes with a controller set that is considered to be the necessary minimum. Figure 5-10 shows its implementation in Dymola that performs the continuous control using PI controllers.

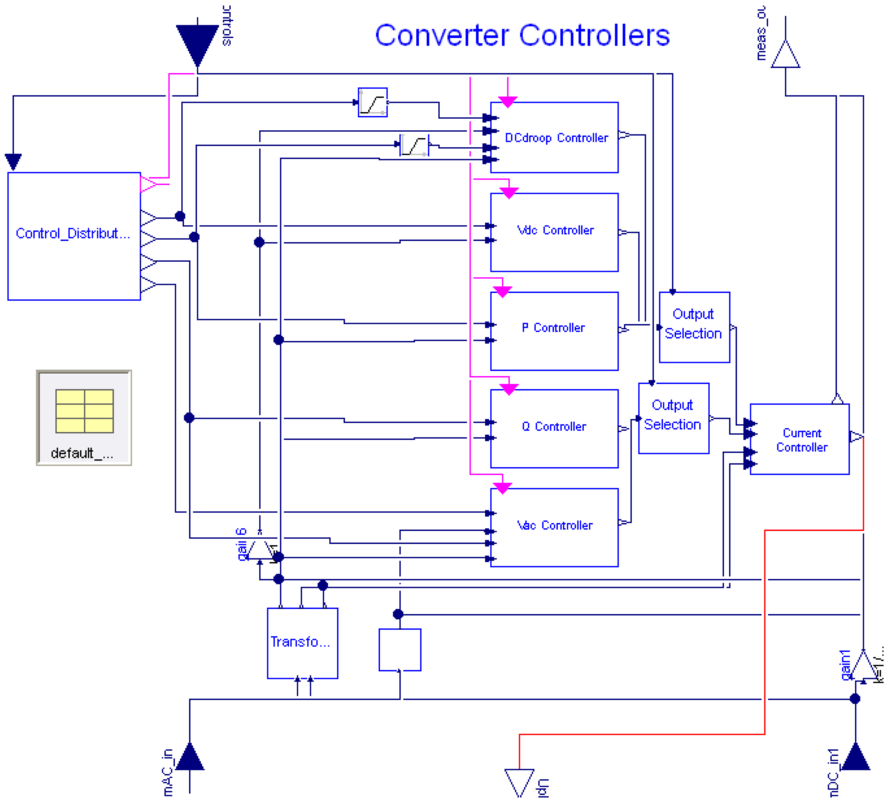

Figure 5-10: Converter Control level implementation

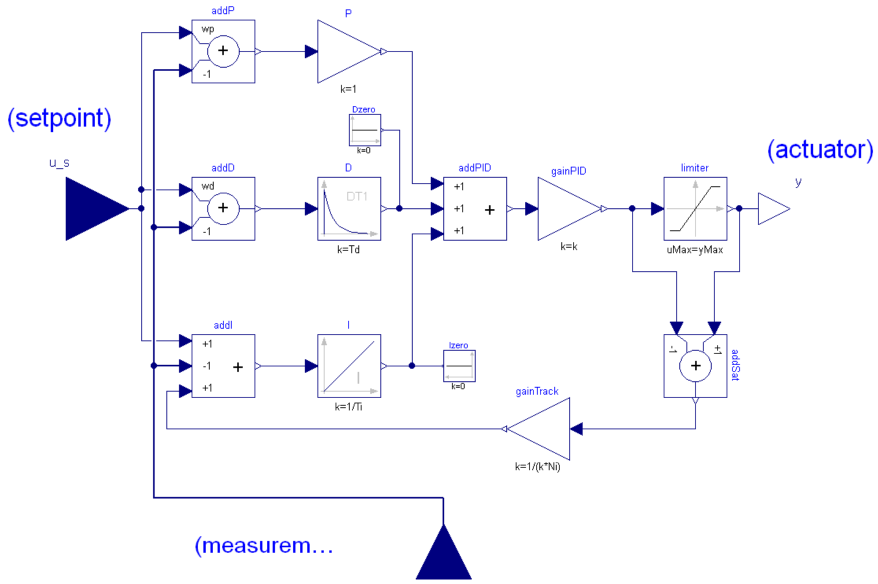

Figure 5-11: Internal structure of PI controller

To take advantage of the possibility of independent active and reactive power control that the VSC technology offers, the control is decoupled and made in the d-q frame. It consists of an inner loop where the current is controlled by a set of P controllers, one for d and one for q axis, and outer loops of PI controllers, shown in Figure 5-11, that can control active power and DC voltage separately or in droop mode, as shown in Figure 5-12, in the d axis and reactive power and AC voltage in the q axis.

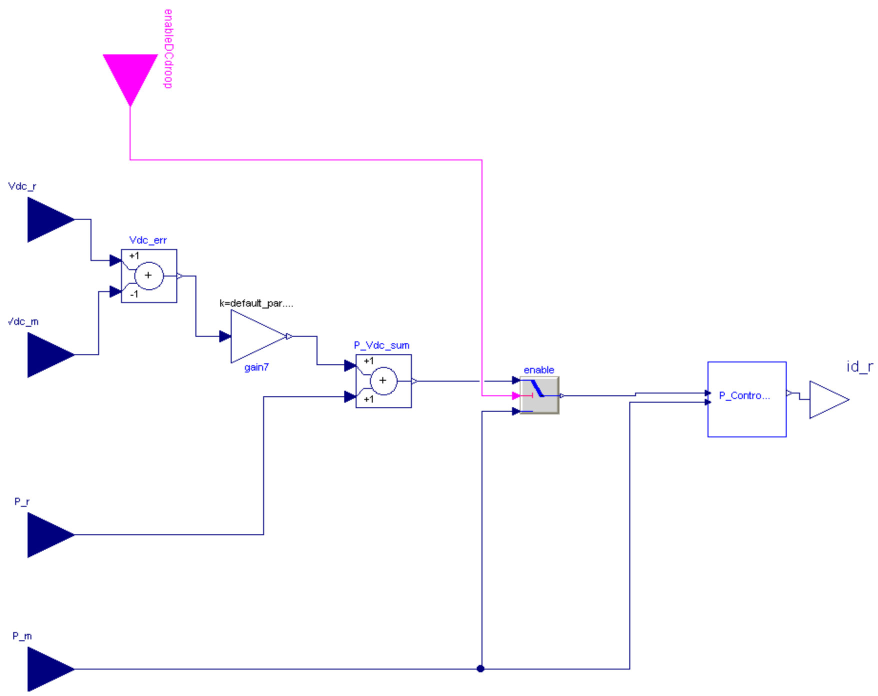

Figure 5-12: Internal structure of DC droop controller

The suggested controller set consists of the following controllers, as can be seen in Figure 5-10:

- DC droop controller
- DC voltage controller
- Active power (P) controller
- Reactive power (Q) controller
- AC voltage controller

Converter Control contains other blocks also, such as the transformation from abc quantities to d-q quantities where measured active and reactive power are also estimated according to measurements of voltage and current. Control Distribution is the block that receives the requested control modes and setpoints by Substation Control and then distributes it to the respective controllers. Setpoints are classified in d axis setpoints and q axis setpoints in Control Distribution and are thus sent to all d axis controllers and q axis controllers respectively. To avoid confusion among the different controllers, Control Distribution also controls an enable signal for each controller. In this way it enables the controllers that must operate at each time while the rest are disabled. Simulation time is also saved in this way since the integral parts of the controllers would consume a lot of computing power if they were to operate on a false setpoint that they do not actually control.

Measurements from the system are collected in this level and converted to per unit according to the parameters defined for the system. The per unit values are used by the different controllers in this level and then forwarded to Substation control and from there to DC System Control.

5.3 Physical System Model

The control system of a multi-terminal VSC-HVDC system, which is the focus of this work, was discussed in detail up to this point. It was first described conceptually as an abstract structure with the properties it must feature and then its proposed implementation was described in detail regarding all the tasks it needs to perform and the manner they are distributed in the different control levels, the responsibility domains of the different control levels and the way they interface among each other. It is now time to test the functionality of the proposed system. For this reason a system model is necessary.

Before defining an adequate model for the control system to be tested, it needs to be considered what the objectives of this test are, what is to verify concerning the control system. Test objectives can be classified in two categories, structural and operational. Structural test objectives are related to the modularity and expandability of the control system. Operational test objectives are related to the efficiency of the implementation of the different control levels to operate the multi-terminal system safely. The test objectives will influence the definition of the adequate physical system model as well as the selected simulation scenarios.

In the context of structural test objective the control system is tested for its ability to integrate additional terminals. This tests the correct propagation of signals through the uniform interface, and confirms the expandability of the control system with no required modification at its code. For this category of test objectives there is no need for a detailed model since what is to be tested is the correct flow of information through the different control levels and the functionality of the uniform interface to assure the modularity of the control system and thus its expandability.

In the context of operational test objectives the control system is tested for its ability to implement the requested power flows by the schedule. Stable operation and smooth transition from one power flow to another are required. The control system is also put through abnormal conditions such as communication loss and 3-phase faults on the AC side in an effort to investigate the effect of those disturbances in the stability of the system. For this category, power flows and voltage changes need to be closely followed thus a more detailed model is necessary.

In both cases the intention is to validate the functionality of the proposed control system and since no optimal operation is considered at this point, the modeled physical system does not need to be complex. A 3-terminal VSC-HVDC system will be considered in two different levels of detail following the needs of the two test objective categories and the actual timeline of the development of the proposed control system.

Test model

As discussed above to test the structural properties of the system there is no need for a complex model. The intention at this point is to validate the correct propagation of signals from one control level to another and prove the functionality of the uniform interface. Accurate power flows and realistic ratings are not critical at this point, what matters is to track the different control signals and confirm that they are correct and reach their target. Following the timeline of development of the proposed control system, this simple model was built for a quick confirmation of the control system structure before too much effort was put on programming the different control levels. At this stage, the simple model also helped in defining a minimum necessary data set for the uniform interface. It should be mentioned at this point that after the structure is validated the content of the different parts can be changed. This means that the implementation of the different control levels can be changed as well as the content of the uniform interface. In this sense the content of the control system and the uniform interfaces tested at this point are not at their final version but the structure remains unchanged.

Going into the details of this model, as mentioned above it is a 3-terminal model shown in Figure 5-13. To simplify it as much as possible it consists of 3 DC-DC converters each connected to the DC network on one side and fed by a DC voltage sources on the other side.

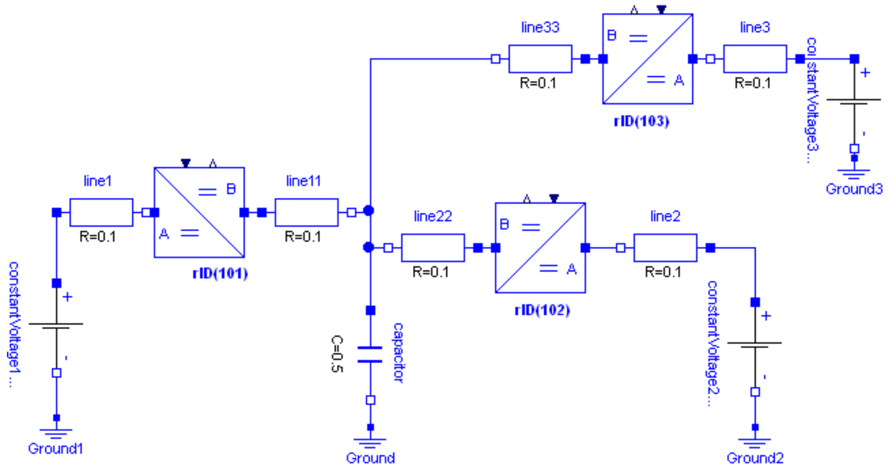

Figure 5-13: Three-terminal test model configuration

In the substation block there is the converter model and the Converter Control level in a simplified version together with the connectors to the Substation Control level. The Converter Control level is implemented here by a DC voltage controller and a Power controller together with a basic control signals’ distribution logic.

The substation block receives a control mode command together with a setpoint and a direction signal which tells the converter which side to control. These signals are sent by the Substation Control level and are used by the Converter Control level inside the substation block to create a current reference. The converter is implemented as a controlled current source shown in Figure 5-14, thus there is no need for cascade control since the current reference is reached instantly.

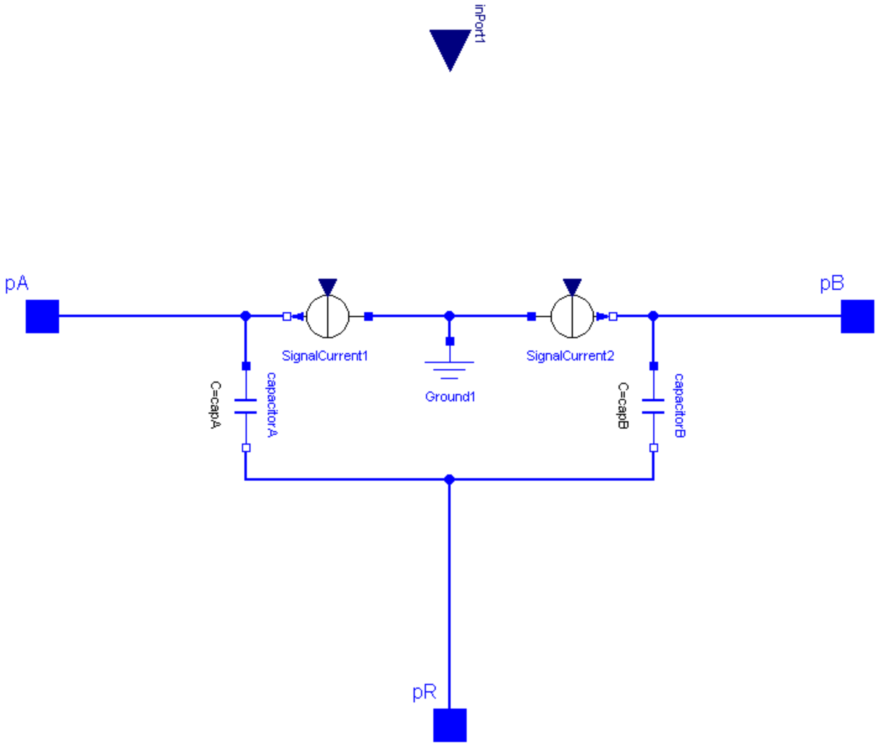

Figure 5-14: Converter model for test model

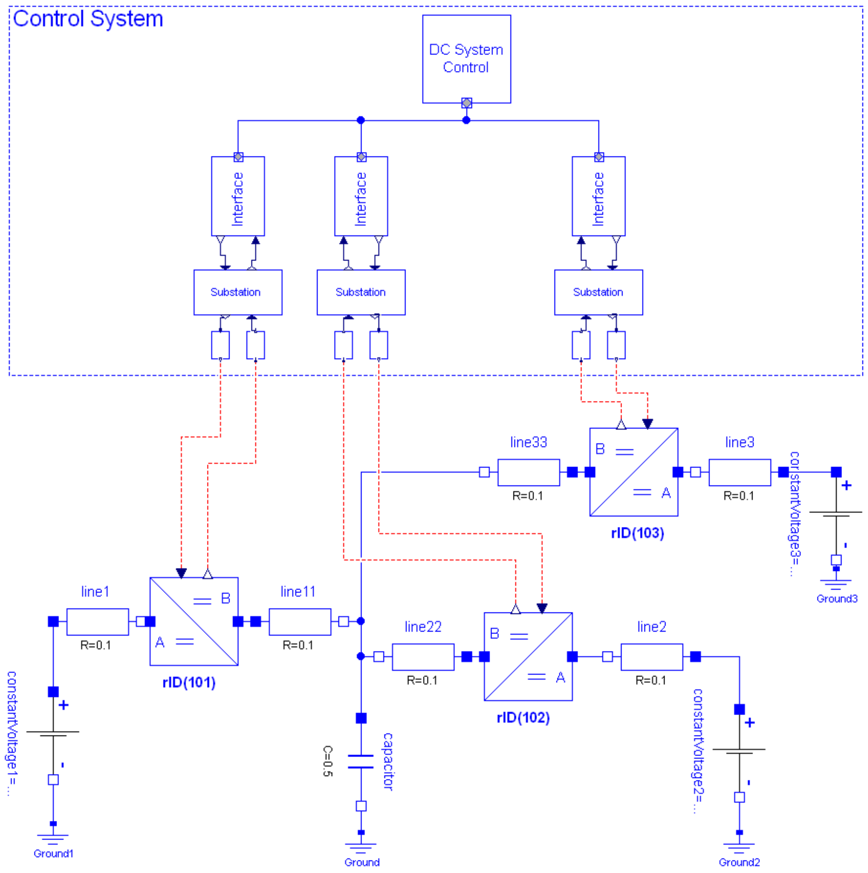

Figure 5-15: Complete configuration for test model including control system

In Figure 5-15 the Control System is included in the model. The different substations are connected to their respective SCO and then through their uniform interfaces to the DC System Control. The blocks that appear as parts of the Control System are implemented in C++ and connected to the Dymola model through shared external functions.

At this point, DC System Control is programmed to identify the different connected substations in the system and coordinate them for a start up procedure. It puts its commands on the uniform interfaces from where the SCOs receive the information and simply transfer the commands to the CCOs within the different substation blocks in the system. What is to be tested is whether all the terminals are identified by DC System Control with use of the uniform interfaces and how the different control signals are distributed to the different terminals during this simple start up procedure. The fundamental functionality of the uniform interface is tested and the flow of signals among the different control levels. Adding a fourth terminal to the system, as in Figure 5-16, will test the role of the uniform interface in system modularity.

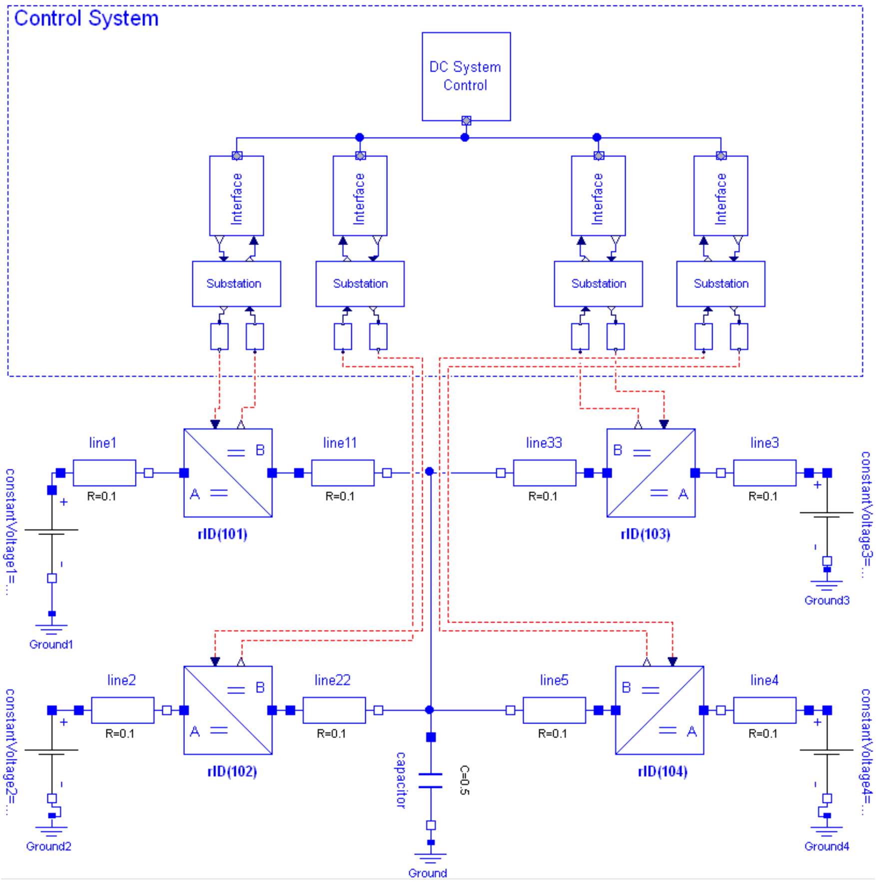

Figure 5-16: Configuration expansion, one additional terminal

For this test to be successful, the DC System Control must immediately identify the new terminal and be able to include it in its operation together with the existing terminals. The implementation code of DC System

Control shall not change to include the new terminal- connecting the new terminal through the uniform interface must be enough for the operation of the new terminal within the existing system. This will prove the structural functionality of the uniform interface and the benefits it offers in terms of modularity and consequently of expandability. The data set within the uniform interface and the ability of the Control System to operate the different terminals according to their properties and achieve their coordination will also prove adequate.

Verification model

The verification model is used to validate the operational test objectives of the system. It is thus necessary that this model can follow closely the intended power flows within the system. The first thing that becomes obvious then is that there needs to be a shift from the very simplified version of a full DC model to an AC-DC model. The detailed model features a 3-terminal VSC-HVDC system connected to three adjacent AC systems. The focus at this point is to implement and present a full version of the proposed control system. In this sense the implementation of the control system now moves away from its simplistic version for the test model above to follow the control system implementation as described in Section 5.1. All control levels are fully developed and implemented within distinct blocks in Dymola and are clearly separated from the converter model. The expected outcome by the use of this model is to validate that the proposed control system correctly implements the different requested power flows in the system and performs smooth transitions from one to another. The proposed control system must also be able to overcome communication loss events and quickly react to 3-phase AC faults to avoid disturbance in the DC system. Since after a 3-phase AC fault the power flow in the DC system is disturbed, the proposed control system must perform rescheduling according to predefined criteria distributing new power setpoints to the different terminals.

As mentioned above, this model consists of three terminals connected to a DC network on the DC side, and AC voltage sources on the AC side. Each terminal is built in a block called “Substation Unit” that contains the converter model together with the respective CCO, SCO, Uniform Interface and the connector to DC System Control. The different parts of the model will be described separately first, and will then be put together to form the modeled system. It should be mentioned at this point that the most of the standard components in the developed model belong to the Spot Library for power systems in Dymola.

The three AC systems included in the model are identical and consist of an AC voltage source, and a line to connect to the Substation Unit.

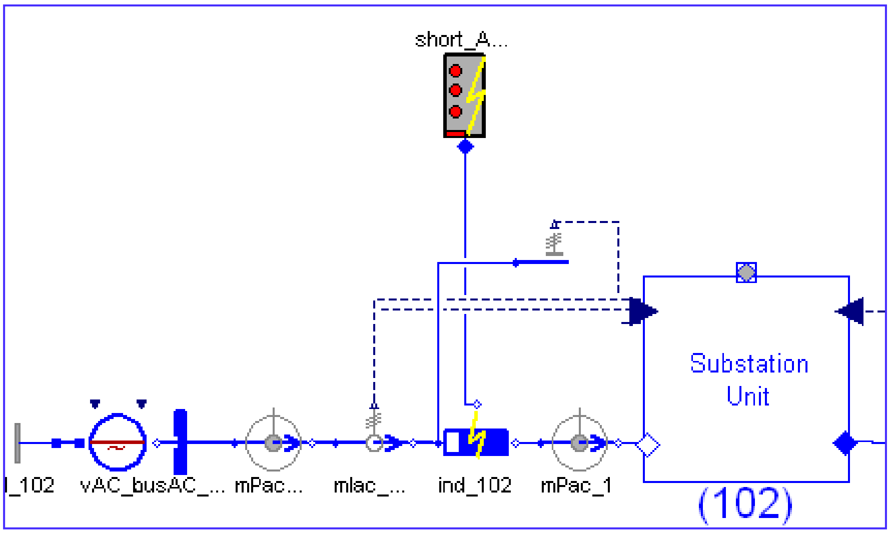

Figure 5-17: AC system implementation

As shown in Figure 5-17 there are other components present in the model that serve for collecting the measurements that are fed to the Substation Unit. Some of the measurement components are used to provide measurements for the operation of the Substation Unit while others are only used for monitoring active power and provide plots for the user. It should be pointed out that the line model used is customized to be used in combination with the 3-phase fault component which can be used to impose a disturbance in the system upon request. All three AC systems used in this model include the 3-phase fault component meaning that a 3-phase fault can be implemented at any moment of the operation of the system at any AC side.

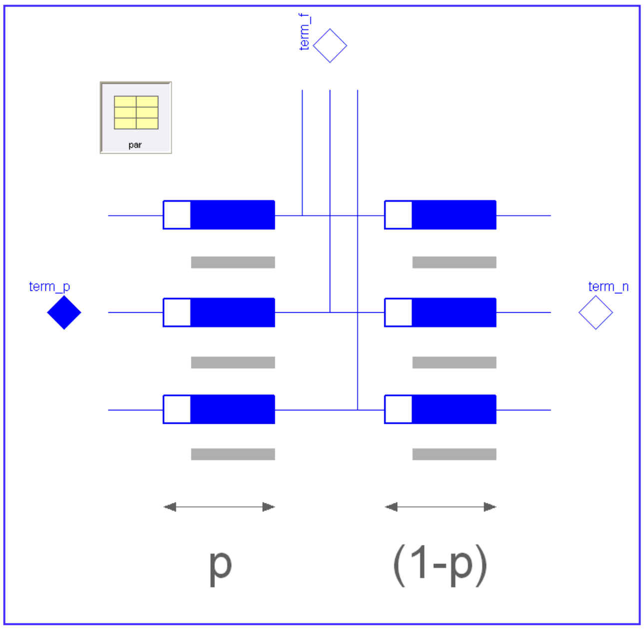

Figure 5-18: Three phase line model with three phase fault capability

The faulted line model looks as in Figure5-18; even if there is only one connector at each side it is a 3-phase line model with an extra connector to impose a fault. At this point it is important to notice the table-like component at the left top of Figure5-18. It is a “Record of parameters” and appears often in this model. All the parameters within the block correspond to the parameters defined in the record and the record allows their definition from the outside of the block. In this way it is possible to have a “Control panel” on the top layer of the model where all the parameters are defined and grouped and from where they propagate to their right positions. The use of such “Control panel” adds to the flexibility of the model since it becomes easy to significantly change the model by adjusting the respective parameters. The “Control panel” will be described in detail later.

Moving on with the description of the DC system used in the model; it is a radial connection, as mentioned above, that consists of two DC cables, 100km and 300km respectively, with a node in the middle where a third system is connected.

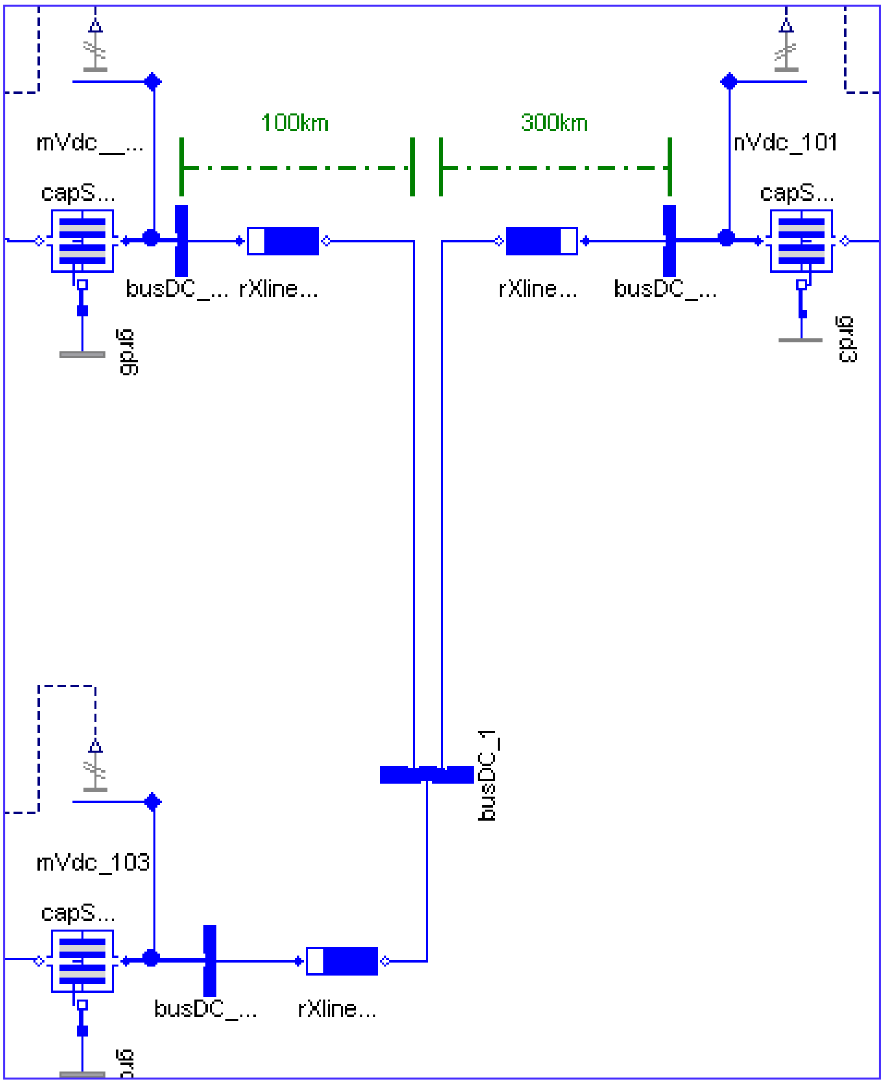

Figure 5-19: DC system model

The system is bipolar which is not obvious from Figure5-19, but will become obvious when the capacitor system and cable models are presented. Starting with the capacitor system model, it looks as shown in Figure5-20.

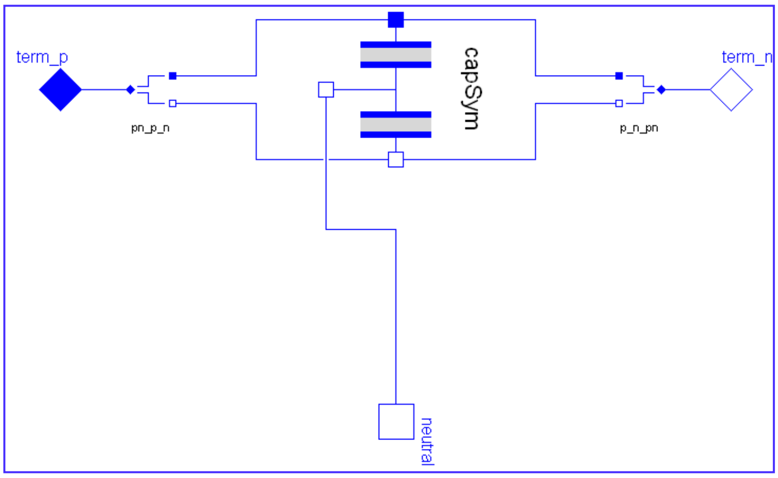

Figure 5-20: Capacitor configuration

It is a symmetric capacitor system with a ground connection in the middle, which means that the voltage is symmetric around zero. As mentioned before, the system is bipolar and this is obvious in Figure5-20. The two external connectors of the capacitor system model are split in two connectors inside the model, one positive and one negative. The cable model, shown in Figure 5-21, uses the same connectors which are split in positive and negative in the implementation code.

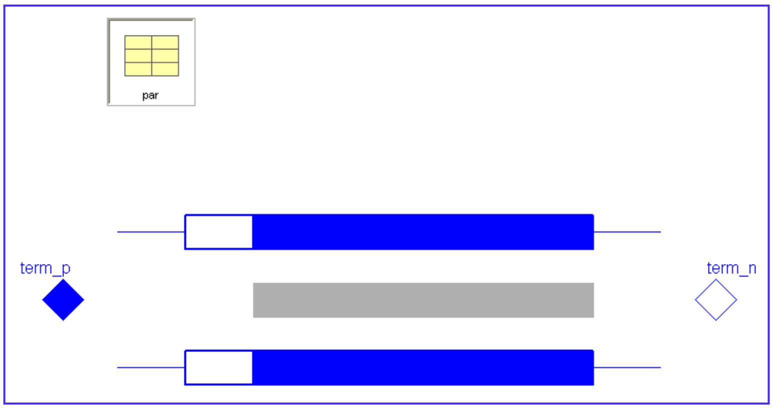

Figure 5-21: DC cable model

The record of parameters should be noticed in this model also. As claimed before this type of component will appear in all components that are subject to potential parameter change.

Now that the AC systems and the DC system used in the model are presented, and before the entire system is put together, let's have a look at the component that connects the AC and DC domains. This component is the "Substation Unit".

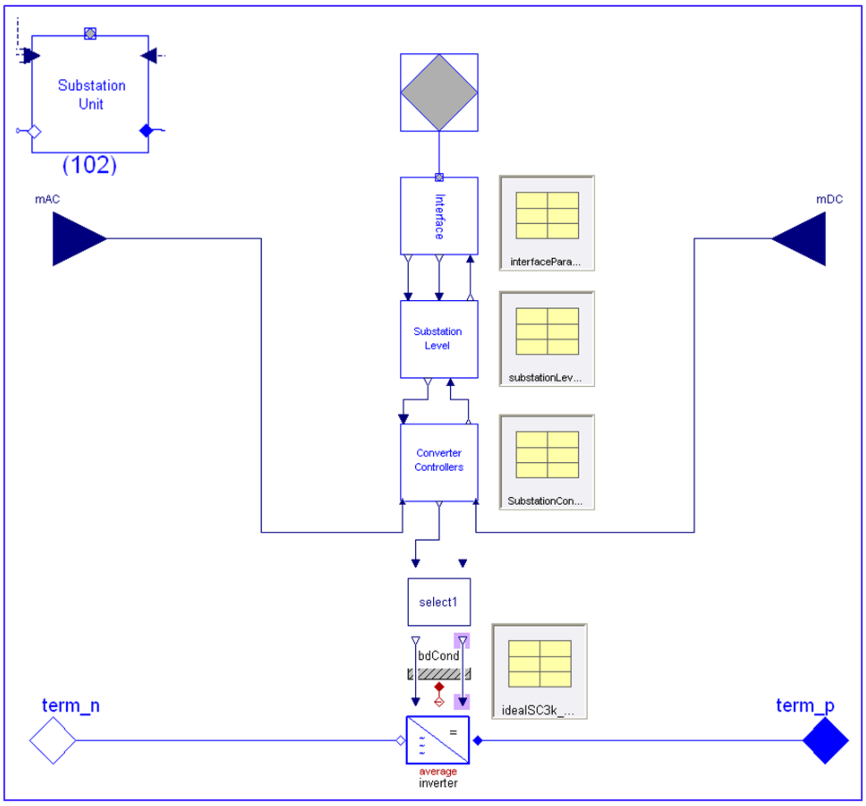

Figure 5-22: Substation Unit structure

Substation Unit is the component that carries two of the control system levels, the uniform interface and the converter itself. Substation Unit is intended to be seen as complete component that integrates the "hardware" models, the implemented control logic and the interface. It should be regarded a unit ready to connect and operate. In other words the structure of the Substation Unit is the best possible depiction of the control system structure and its connection to the physical system.

In Figure5-22 the internal structure of the Substation Unit is shown. Starting from the bottom, the converter model can be seen connected to the external electrical connectors. The connector at the AC side is the same as in the fault line that was presented earlier and splits in three connectors, one for each phase. The connector on the DC side is the same as the ones used in the capacitor system model and splits in two, one positive and one negative. The converter model used here is an average converter model which is considered to be detailed enough for the purposes of this model. Select unit drives the converter according to the voltage references it receives from the Converter Controllers. The Converter Controllers block features the Converter Control level of the control system.

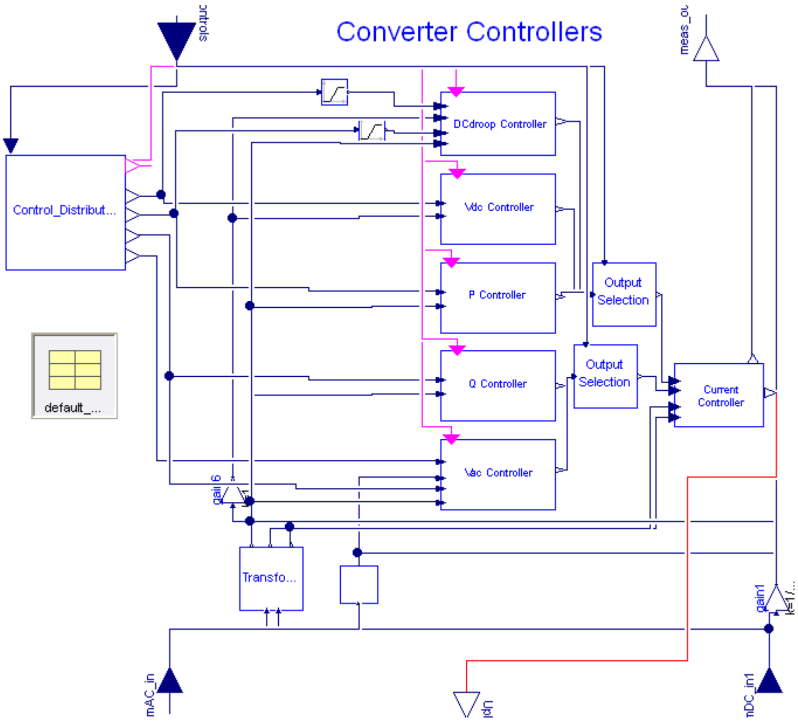

Figure 5-23: Converter Control implementation in Dymola

The Converter Controllers block, shown in Figure 5-23, contains the controller set used to control the converter. Measurements from the outside of the Substation unit end up in this block, where they are transformed to the d-q frame and their per unit values are calculated. They are then used by the different controllers and fed to the upper level. The Converter Controllers block also receives the necessary control signals and setpoints by the Substation Control level which go through the Control Distribution block and are directed to the respective controllers. Enable signals prevent non-operating PI controllers from integrating variables they do not control saving simulation time in this way. All controllers send their output to the Current Controller where the current reference is transformed to a voltage reference to be sent to the Select unit and then to the converter. The control implemented here is standard, it is performed in d-q frame and then a cascade arrangement is used. Outer PI controllers operate on the controlled variables to produce a current reference, the current reference is then sent to the inner Current Controller to produce the voltage reference required by the converter. The d-q frame allows decoupled control while the controller set allows different combinations of control modes for the substation. The used controller set contains a DC droop controller, a DC voltage controller and an Active power controller for d axis and a Reactive power controller and an AC voltage controller for the q axis.

Moving upwards, the Converter Controllers block communicates with the Substation Control block. The Substation Control simply uses external C++ functions which means that it is essentially implemented in C++ as mentioned earlier. Substation Control block interprets the received control signals for the Converter Controllers block and receives the measurements obtained there to monitor the operation of the converter and create the necessary error signals when necessary. It also sorts the information received by the Converter Controllers block and places it in the interface to be read by DC System Control. On its top side the Substation Control block has two inputs and one output. The two inputs correspond to the Operational and the Schedule Vectors which are the two ways DC System Control can operate each substation and their functionality was explained in Section 5.1. The output contains all the measurements that need to be known to DC System Control. They are made available to DC System Control by being placed in the uniform interface in the required order. Substation Control also outputs in the uniform interface information regarding errors and its control status that are useful for the coordination operation performed by DC System Control.

Moving again upwards, the next block is the Uniform Interface. The Uniform Interface is also implemented in C++, thus the Interface block in Dymola simply calls external C++ functions. The functionality of the Uniform interface is to provide a common interfacing pattern for the different substations and tag each Operational-Schedule Vector set with the user-defined identity of each substation. As mentioned in Section 5.1, each substation receives an identity at initialization. This identity is automatically generated in the C++ code and helps DC System Control to address and operate the different terminals of the system. The automatically generated identity though is not known to the user neither to the incoming schedule. The user needs to define an identity for each substation by which each substation is referred in the provided schedule. This identity is defined in the configuration vector of the Uniform Interface but is not related to the internal identity system. An internal function in DC System Control corresponds then the user-defined identity to the automatically generated identity within the C++ code. It is important that the user does not have the right to interfere with the internal identity system for double definitions to be avoided but it is also important that the user has a way to refer to the different substations when necessary. The Uniform Interface offers this possibility as an independent identity system that is later used internally within DC System Control. Operational and Schedule commands reach the output of the Uniform Interface and are then sent to the Substation Control block while Operational feedback reaches the interface from the Substation Control block and becomes then available to DC System Control. Above the Interface block there is only the connector to the DC System Control.

The intention is to present a complete Substation Unit that includes apart from the converter, all which is necessary for its continuous control, monitoring and interfacing with the overall control system. Thus, the Substation Unit is an operation-ready unit needing only the electrical and communications connection.

The records of parameters mentioned above are an indispensable feature for the configuration of the Substation Unit. There is one record for each block in the Substation Unit and the parameters defined in them range from vector sizes, resource identities and maximum power capabilities for the Interface and Substation Control to controller gains, base quantities for the per unit system and converter characteristics for the Converter Controllers block and the converter model, all of which are adjustable on the top layer of the model for easy modification of the model.

The most important parts of the system have been described separately and with their combination the full model is formed as it is presented in Figure5-24.

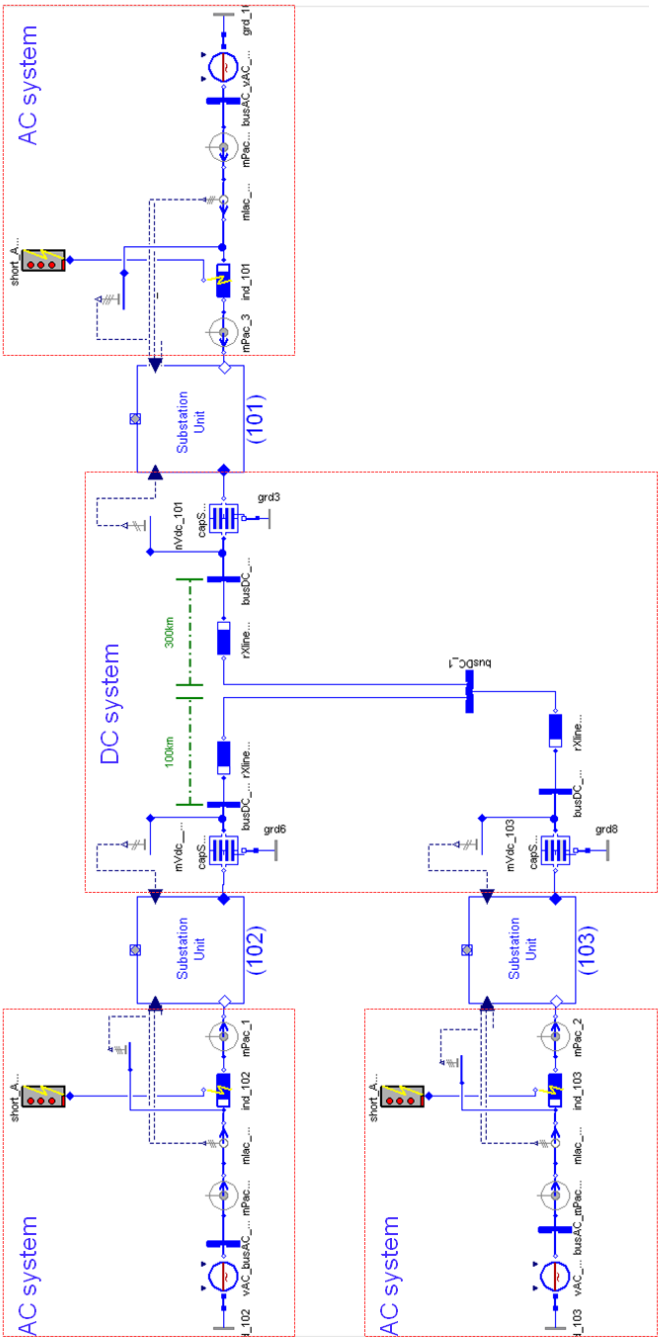

Figure 5-24: Full configuration, no coordination control

Figure5-24 shows the model of the used 3-terminal VSC-HVDC system but the overall control is not added yet. The system in this form contains three operation-ready terminals and the components needed to create 3-phase AC faults. To complete the coordinated 3-terminal system, DC System Control needs to be added together with the necessary components to create the communication loss events. The complete system appears in Figure5-25.

DC System Control has been added in Figure5-25, together with the necessary communication lines and the necessary components to create the communication loss events upon request. DC System Control is implemented in C++ as described in Section 5.1, thus the DC System Control block operates on external C++ functions. It should be noticed that DC System Control comes with an extra input and an extra output on the side. These are to control the schedule input. The schedule is a table that contains the scheduled power flows for the system, in terms of power setpoints, voltage levels and control modes, divided in hours and each hour is transferred to DC System Control upon request. The schedule is read by DC System Control and distributed to the different terminals.

Now that the system is complete and able to perform all the previously defined tests regarding power flows implementation, handling of communication loss events and 3-phase AC faults, what remains to be defined are the different parameters of the model. As mentioned above this takes place on the top layer of the model with the help of the “Control panel” which uses the functionality of records of parameters to propagate the defined parameters to the right position, in the right layer of the model. Control panel groups a number of records of parameters that each corresponds to a specific component for each substation unit and its AC line. Common parameters of the system like DC cable capacity and converter settings are separate records and are used commonly. The benefit that the Control panel offers is that different sets of parameters can be saved and using the same model substantially different systems can be tested simply by replacing the records in the Control panel.

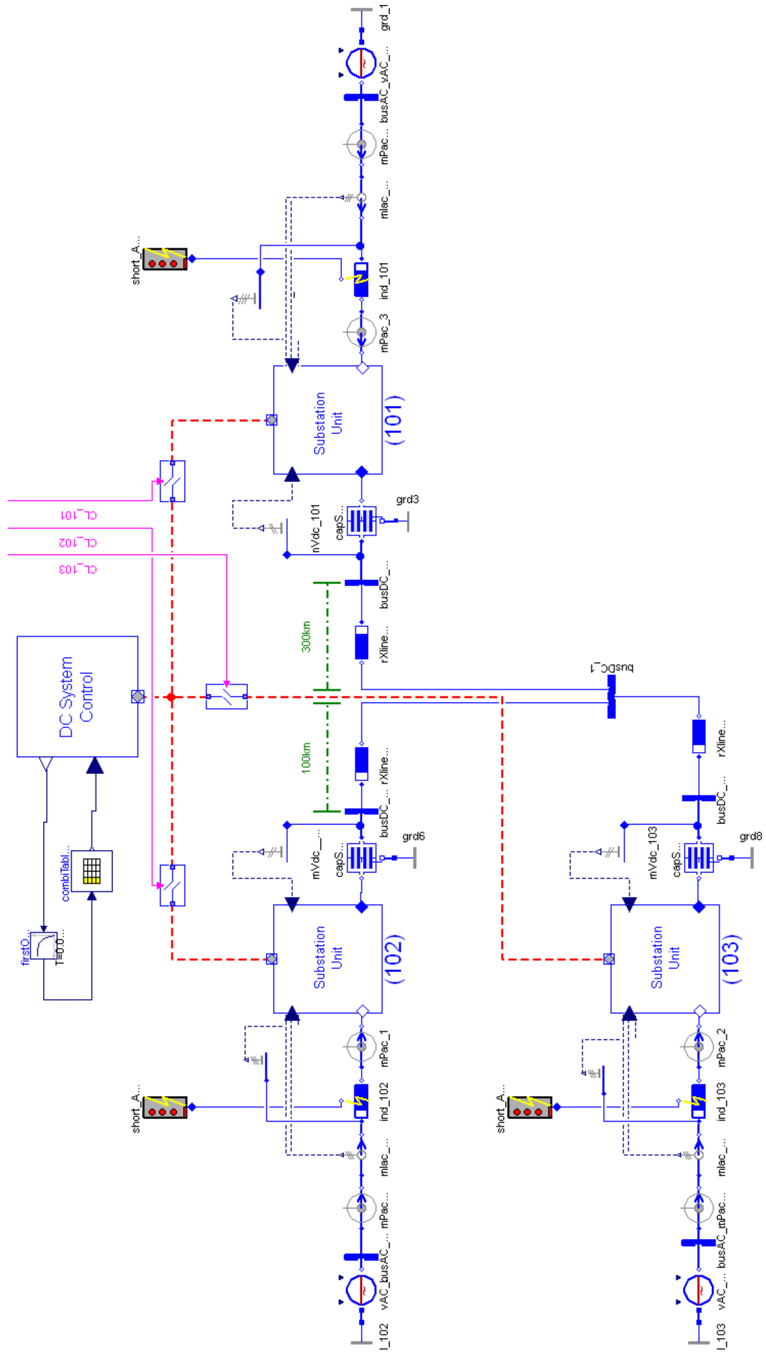

Figure 5-25: Full configuration, DC System Control included

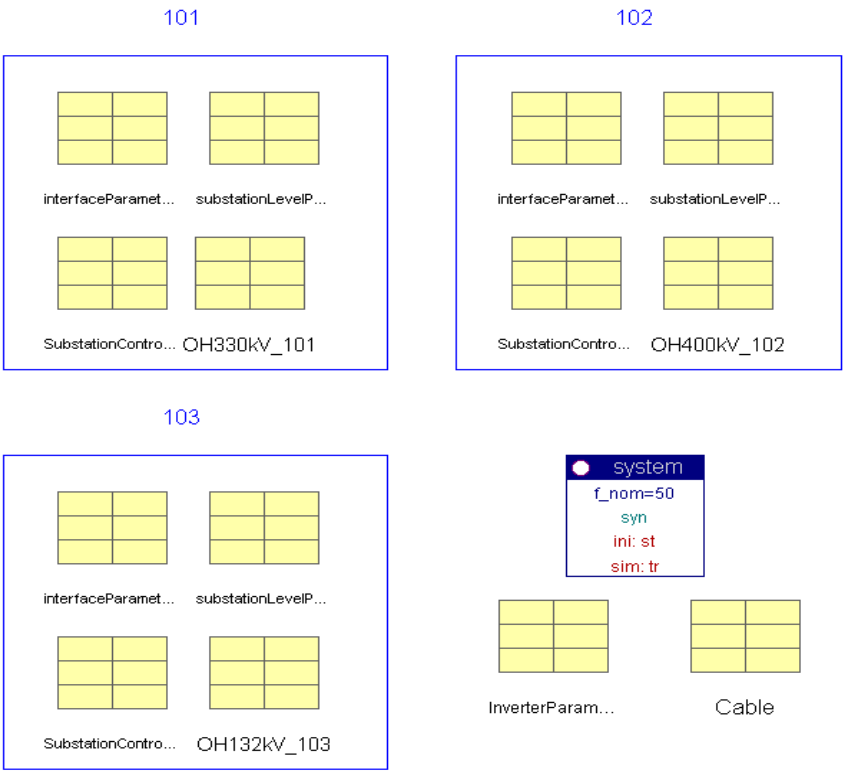

Figure 5-26: Control panel

As shown in Figure5-26 the records of parameters are grouped according to terminal but separated according to component. This provides the flexibility to replace the parameters of one terminal or of one of the components of a terminal. From the Control panel the ratings of the system used in the simulations can be summarized in Table 5-4 below.

Table 5-4: System ratings

Resource Identity	**Power Rating**	**Nominal Voltage**
101	700MW	AC 330kV
102	700MW	AC 400kV
103	700MW	AC 132kV
DC Cable	700MW	DC +/-400kV

The model is now set up to provide all the functionality required to examine the previously defined test objectives. In addition, special consideration has been taken regarding the structure and flexibility of the model in order to be reusable. The model is structured to be easily changed to test different functionalities on different levels of detail.

Chapter 6

Simulation and Verification

Test objectives have been divided in two categories in the previous section. From this division an inventory of two models occurred, each to validate one category of test objectives. The two models were described in detail in the previous section and since the tools are in place for test objective validation, the simulation scenarios will be described in this section, through which the models will validate the structural and operational features of the system. The results of the simulations for each of the two models will be presented and discussed in this section also.

6.1 Structural Features

Simulation Scenarios

As discussed in the previous section the structural test objectives are related to the structural features of the proposed control system structure and have to do first, with the correct propagation of control signals through the different control levels and the uniform interfaces and second, with its modularity and consequently its expandability. In this context, the proposed control system will first be tested on a 3-terminal system during a simple startup procedure to assure right propagation of control signals and adequate coordination of the different terminals. Then, an additional terminal will be added making the previous setup a 4-terminal system. The additional terminal will be connected directly to the control system through a uniform interface. This is to test the ability of the control system to easily integrate new terminals. The control system is expected to recognize and operate the new terminal without any change in its code. This is an important feature and once validated it will show the modularity of the system obtained by the common interfacing pattern defined by the uniform interface and the flexibility of the overall control system to identify the physical system and operate it accordingly.

Since the order of presentation of the test objectives follows the actual timeline of development of this control system structure, it should be mentioned that these tests took place early in the development of the proposed control system structure and thus the contents of the different control levels and the uniform interface are slightly different than their final versions. The implementation differences are not important in the different control levels for the validation of the structural features, although it is important to mention the difference in the uniform interface data set to be possible to follow the results later on. The uniform interface data set was described in Section 5.1 in Table 5-1 and Table 5-2. Table 5-1 presents the Operational Vector signal configuration and Table 5-2 presents the Schedule Vector signal configuration. As described in Section 5.1, the Operational Vector is used by DC System Control during off-normal operation, while the Schedule Vector is used during normal operation. Since in this case the control system will only be tested for a startup procedure, the Schedule Vector will not be used and thus is not included in the uniform interface. The signal configuration for the Operational Vector is also different to correspond to the different model. Since the converters of this model are DC/DC converters the control direction must be defined. Table 6-1 presents the full signal configuration of the Operational Vector for this model.

Table 6-1: Operational Vector signal configuration for test model

	Signals	Functionality
	OVI_NOT_USED	Not used signal to match C++ and Dymola indices
	OVI_TRANSACTION	Not used currently
Control Signals	OVI_COMMAND	Status of Terminal (ON, OFF, Stand by)
	OVI_GOVERN	Control mode
	OVI_DIRECTION	Direction of power flow
	OVI_SETPOINT1	Target setpoint
	OVI_SETPOINT2	Ramp setpoint
Status Signals	OVI_RES_TYPE	Connected system type
	OVI_T_STATUS	Transaction status
	OVI_D_STATUS	Direction status
	OVI_C_STATUS	Command status
	OVI_G_STATUS	Govern status
Measurement signals	OVI_E_CUR	Current level of energy
	OVI_P_MAX	Maximum current power capability
	OVI_P_CUR	Current level of power
	OVI_P_RATE_CUR	Current rate level of power
	OVI_U_CUR	Current level of DC voltage
	OVI_I_CUR	Current level of current (dependent on direction)
	OVI_U_EXT_CUR	Current level of AC voltage
Error signal	OVI_ERROR	Error signal

In this signal configuration, OVI_COMMAND has the same functionality as described in Section 5.1, OVI_GOVERN is limited to two control modes in total, Voltage control and Power control, and OVI_DIRECTION specifies which side of the converter is to be controlled.

Going into the details of the simulation scenario to be implemented in this section, as mentioned earlier, the control system will be tested on a start up procedure for a 3-terminal system in the beginning. The control system is expected to go through the different states of its state machine until the DC link is charged. This includes the initialization of the system, the selection of one terminal to charge the DC link and the advance to the normal operation state when the DC link is charged. During initialization the different objects are created in the control system and then classified in the Module Manager according to their corresponding class and their place in hierarchy. Their configuration vectors are also read by the DC System Control where information regarding their type, external id and maximum power capacity is included. At the same time their Operational Vectors are created and one is corresponded to each SCO. When the different objects in the system are initialized, an availability check takes place and all error free terminals are set to READY (stand-by mode) and sorted in generating, consuming or exchange terminals. This happens so that DC System Control can make the selection of the terminal that will be given the duty to charge the DC link. In this implementation the generating or exchange terminal with the highest power capacity is selected to charge the DC link. It is expected then, that DC System Control will go through the different states until the DC link is charged. During this process the generating or exchange terminal of highest capacity will be set to START on Voltage control to charge the DC link while the rest of the terminals will remain at stand-by (READY). When the DC link is charged DC System Control proceeds to normal operation state and the rest of the terminals are set to START to begin normal operation. This test will validate the correct circulation of data among the different control levels since control signals generated in the DC System Control must reach the converters to perform the charging operation while measurements obtained in the Converter Control level must reach the DC System Control level which will monitor them to decide the transitions between its different states.

In the second part of the simulations for structural features validation, the same operation takes place but this time an additional terminal is added to expand the previous system to a 4-terminal system. The stages of operation of DC System Control are the same as for the previous case. The intention here is to test the ability of DC System Control to integrate in its operation an additional terminal without any modification in its implementation code. The additional terminal is connected through the uniform interface directly to the communication node where the rest of the existing terminals are connected. The newly added terminal is intentionally defined as the exchange terminal, bi-directional power flow capable, with the highest power capacity so that it is given an active role in charging the DC link by DC System Control. The desirable outcome of this simulation is that the additional terminal is identified and operated by DC System Control directly. This result will validate the role of the uniform interface in providing a modular interfacing system that allows the expansion of the system, on one hand. On the other hand, it will validate the general nature of DC System Control and its ability to operate different numbers of terminals without being limited by their type or external, user-defined, identities.

Results

Since the focus for this set of simulations is to validate the correct circulation of data, the ratings of the system are insignificant and thus very low. The target DC voltage is only 100V and the focus is on the different states the system goes through to reach it. Figure 6-1 shows the 3-terminal system used for this simulation together with the identity of each terminal (rIDs). Before discussing the results of the simulation it is useful to provide an explanation for the signals that appear. The different states of DC System Control are presented together with the command and govern signals distributed to the different terminals according to the state DC System Control is in. The meaning of these signals has been discussed in previous sections and only the numbering is provided at this point in Table 6-2.

Table 6-2: Signal interpretation

Signals	Value	Interpretation
States	1	OFF
	2	INIT
	3	READY
	4	START UP
	5	NORMAL OPERATION
Command	2	STOP
	3	READY
	4	START
Govern	4	POWER CONTROL
	5	VOLTAGE CONTROL

3-terminal system

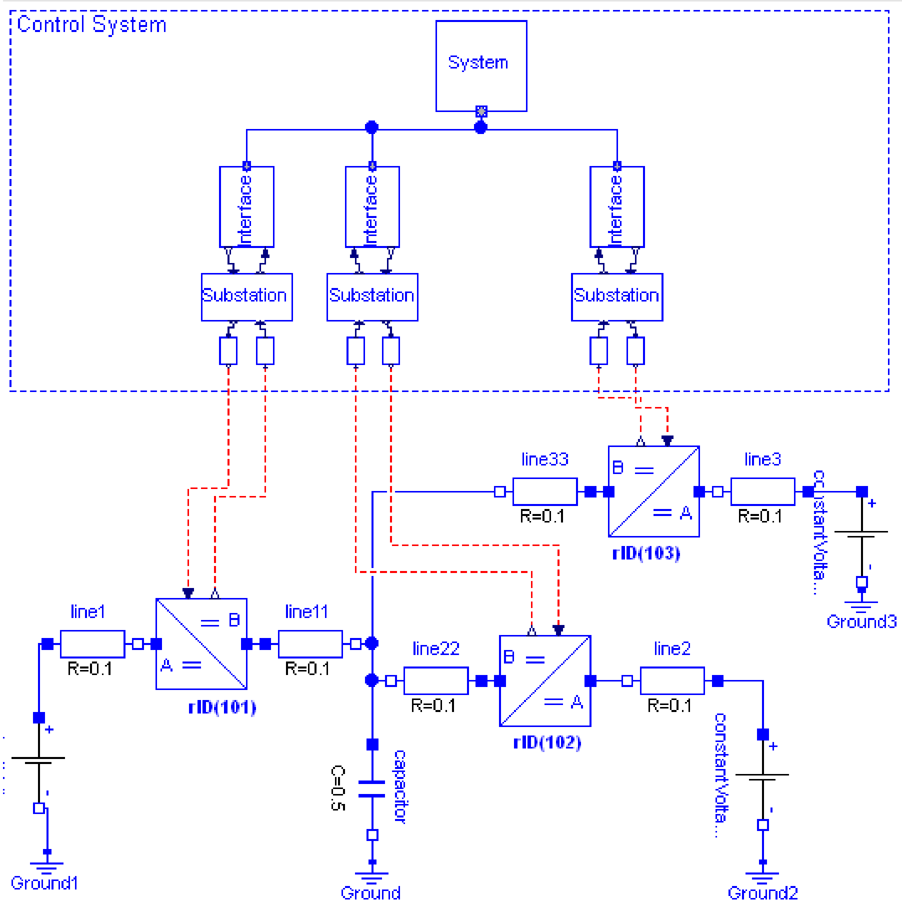

Figure 6-1: Test model for 3-terminal system

In this configuration the terminals connect to the DC system three different types of systems. A generation unit is connected through rID(101), an exchange unit is connected through rID(102) and a load unit is connected through rID(103). As mentioned earlier, after the initialization DC System Control will go through the different terminals to find the generation or exchange unit of highest power capacity to charge the DC link. In this sense rID(103) is excluded as a load unit. The selection will be among rID(101) and rID(102). It is defined in this case that the exchange unit connected by rID(102) has the highest power capacity and is thus expected to be selected to charge the DC link. The identities and system types for each system are defined in the configuration vector of each interface while their power capacities are specified in the configuration vector of the SCOs. Selection of terminals according to prediction means that DC System Control gained access to this information for each terminal and was able to make the selection according to the logic implemented. It should be mentioned that this logic holds for this set of simulations and can and will be changed later on. It is though adequate to show the correct circulation of data among the different control levels and the uniform interfaces.

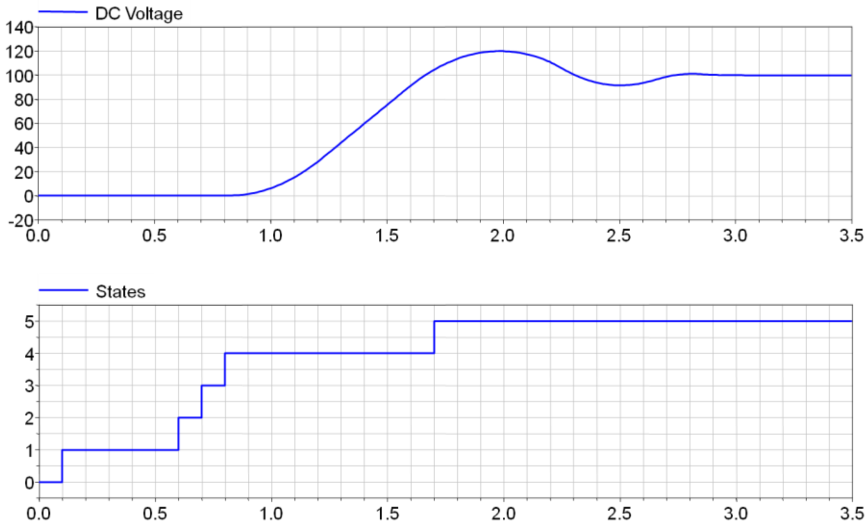

Figure 6-2: DC Voltage and DC System Control states for 3-terminal system

In Figure 6-2 the DC voltage and the different states of DC System Control are presented. DC System Control moves through all the preparation stages before it enters the start up state. DC System Control stays at OFF (1) state for a predefined time interval before it moves to INIT (2). This delay is provided so that human operator intervention can be applied if necessary. When the timer expires DC System Control moves to INIT (2) where all the connected terminals in the system are checked for errors. The error free terminals are then set to READY command and stand by for operation. DC System Control moves to READY (3) state where one terminal is selected to charge the DC link according to the earlier mentioned criteria. It should be noticed that since it is at READY (3) state that a terminal in assigned for the first time to operate in voltage control, it is then that the voltage starts rising as the DC link charges. When a terminal is set to Voltage control, DC System Control moves to START UP (4) state where it monitors the DC voltage waiting to reach the target value. After the target value is reached DC System Control moves to NORMAL OPERATION (5) state. Already from Figure 6-2 it can be concluded that the signals in the Operational Interface circulate correctly since the measurement of the DC voltage was successfully delivered to DC System Control for the transition from START UP (4) state to NORMAL OPERATION (5) state.

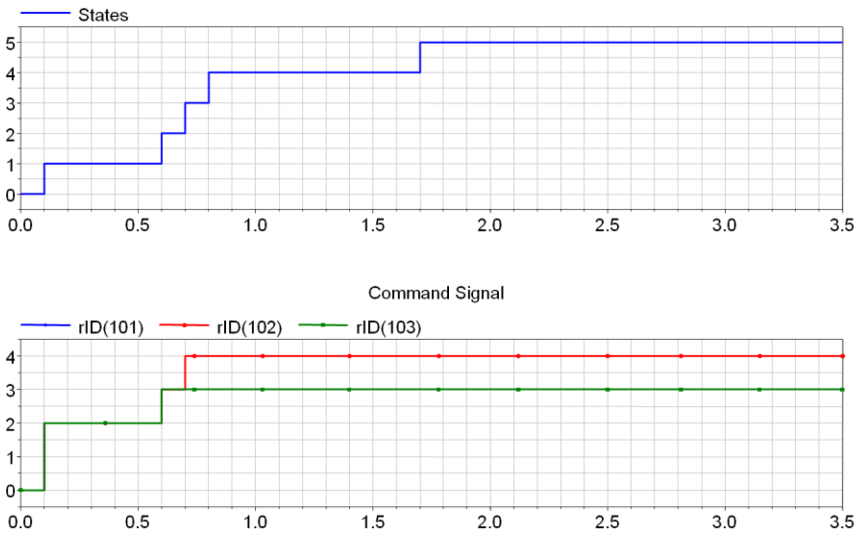

Figure 6-3: States and Command Signal for 3-terminal system

Figure 6-3 shows the changes in the Command signals according to the state of DC System Control. All terminals are at STOP (2) command when DC System Control is at OFF state. At INIT and since there is no error in any of the terminals they are all set to READY (3) command and stand by for operation. At this point it is confirmed that DC System Control gained access to the configuration vector of both the uniform interfaces and the different SCOs since it is able to select the expected terminal to charge the DC link. As mentioned earlier rID(102) is the exchange terminal of highest power capacity and is the one that was expected to be selected according to the logic of DC System Control as long as it has access to all the necessary information. As expected, rID(102) is set to START (4) command as DC System Control enters READY state while the rest of the terminals remain at READY (3) command. Since a terminal is charging the DC link now, DC System Control moves to START UP state in the next sample.

At this point the correct flow of information among the different control level and through the uniform interface is validated. Measurements reached DC System Control and DC System Control identified the connected terminal and distributed commands according to its logic.

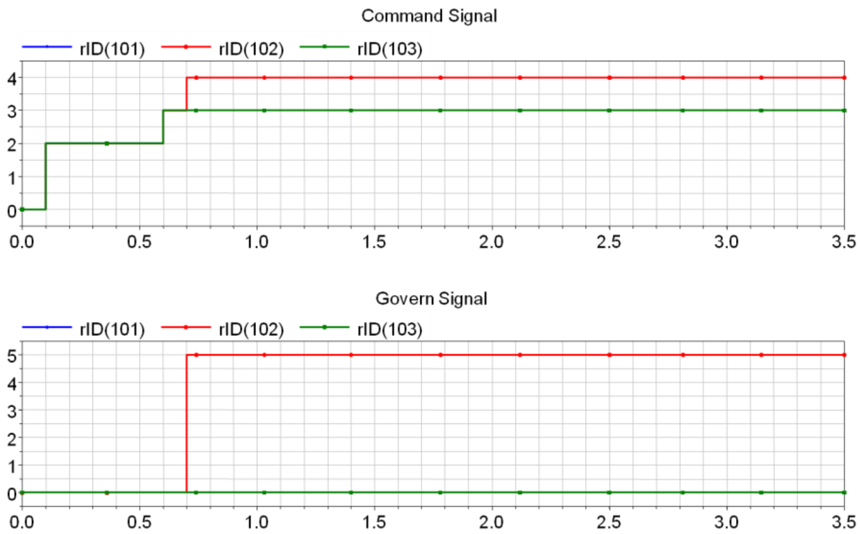

Figure 6-4: Command and Govern Signal for 3-terminal system

As a last step, Figure 6-4 confirms that the selected terminal not only received the expected command to start operation but the control mode selected by its Govern signal is correct. Terminal rID(102) was selected to charge the DC link and for this reason it received a Voltage control request by DC System Control.

A simple start up procedure for a 3-terminal system is implemented in this simulation to test the correct circulation of information among the different control levels and through the uniform interface. The simulation results confirm the correct exchange of data among the DC System Control and the different SCOs through the uniform interface. DC System Control is able to identify the system that consists of different types of connected systems, prepare and coordinate the operation of the different terminals to perform the operation of charging the DC link. This is possible due to the use of the uniform interface that defines a common interfacing pattern between the different terminals and DC System Control and due to the flexibility of DC System Control to handle terminals according to their properties and without referring to a specific system arrangement.

4-terminal system

So far, the correct circulation of data across the different levels of the control system is validated. It is now time to test the ability of DC System Control to incorporate and operate additional terminals without modification in its code. To do so, an additional terminal is added to the existing system and the same simple start up procedure is followed. No modification in the code of DC System Control is made since the new terminal is connected to DC System Control via the uniform interface.

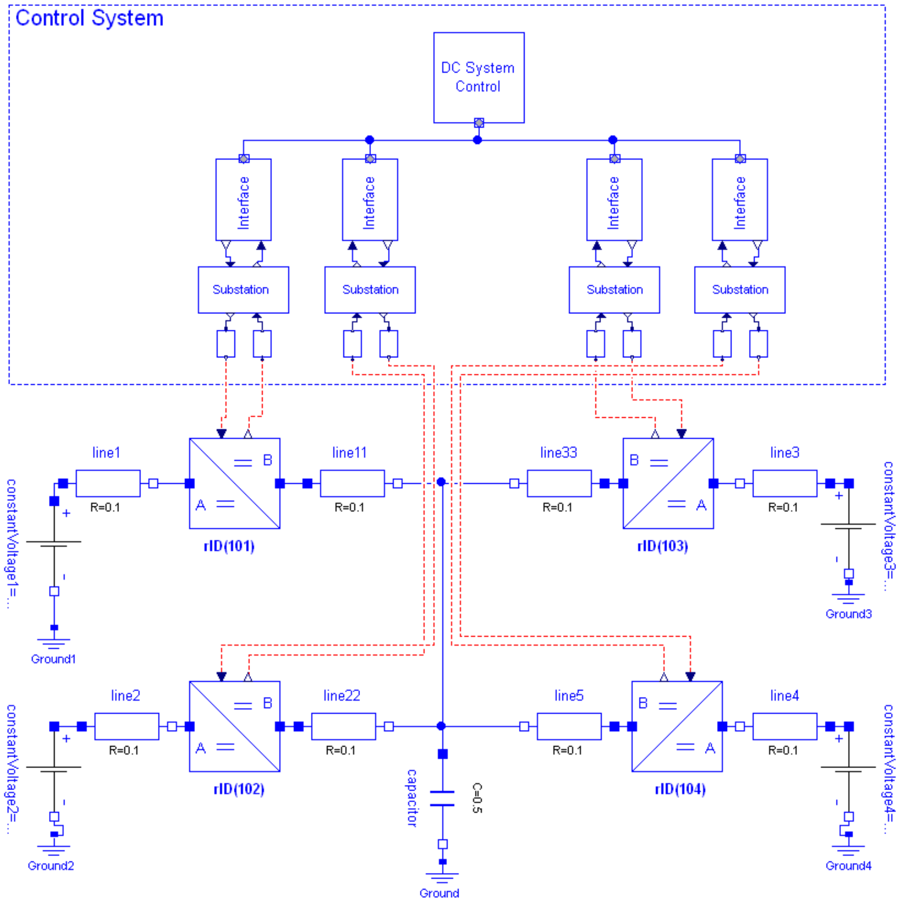

Figure 6-5: Test model for 4-terminal system

Figure 6-5 shows the new 4-terminal system. Terminal rID(104) is intentionally selected to be the exchange unit of highest power capacity in the system. According to DC System Control's logic it should then be the one to be selected to charge the DC link. The intention is that the additional terminal has an active role in the 4-terminal system not only to validate its identification by DC System Control but also its integration in the system's operation.

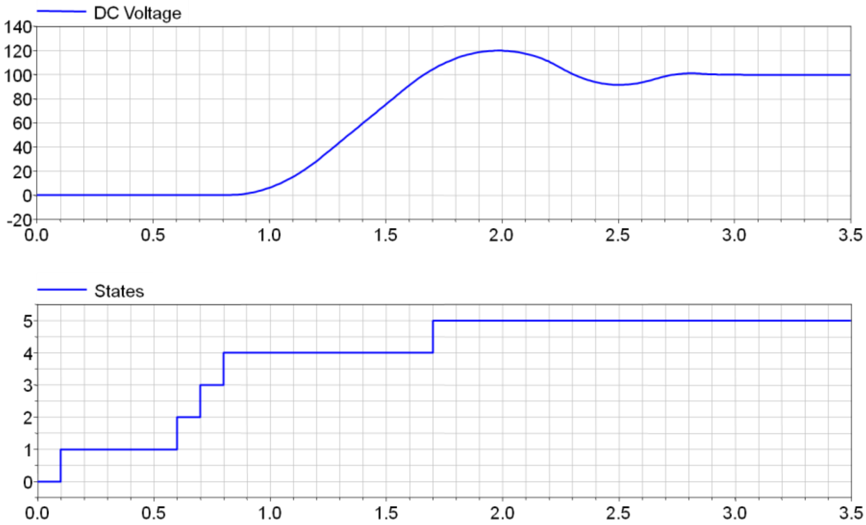

Figure 6-6: DC Voltage and DC System Control states of 4-terminal system

Figure 6-6 shows, as in the previous case, the DC voltage as DC System Control moves through its states. Figure 6-2 and Figure 6-6 look the same and this is an indicator that the additional terminal, at least, did not change the overall operation of the system. From Figure 6-6 it is not possible to conclude whether the new terminal is actually identified by DC System Control or if it is possible to be operated by DC System Control. This will be confirmed by the command and govern signals it receives by DC System Control.

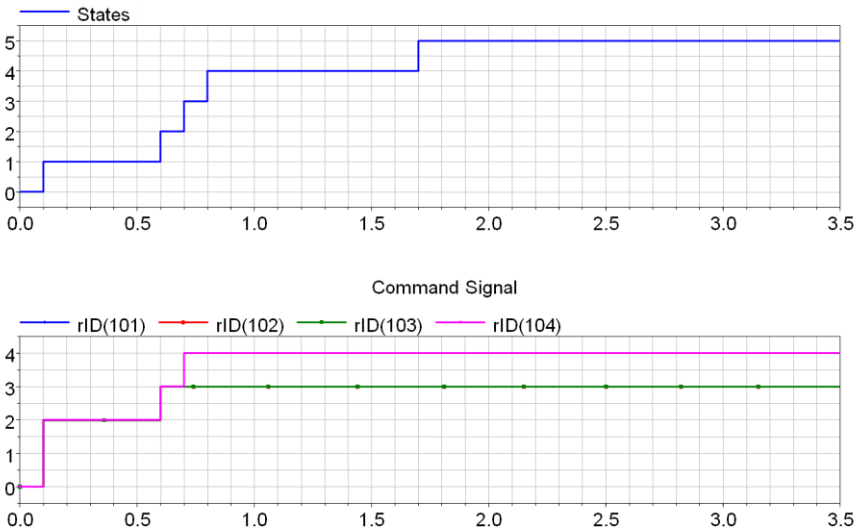

Figure 6-7: States and Command Signal for 4-terminal system

In Figure 6-7 it becomes clear that DC System Control has identified terminal rID(104) and operates it according to its logic. Since terminal rID(104) is the one with highest capacity it is selected to charge the DC link, as expected. When DC System Control enters the READY state rID(104) is selected to start operation. It can be seen that terminal rID(104) is identified by DC System Control already at state OFF where terminal rID(104) obtains OFF command. If it had not been identified its command signal would remain at zero. Terminal rID(104) follows the operation of the existing terminals until READY state is reached. At this state DC System Control selects it to charge the DC link.

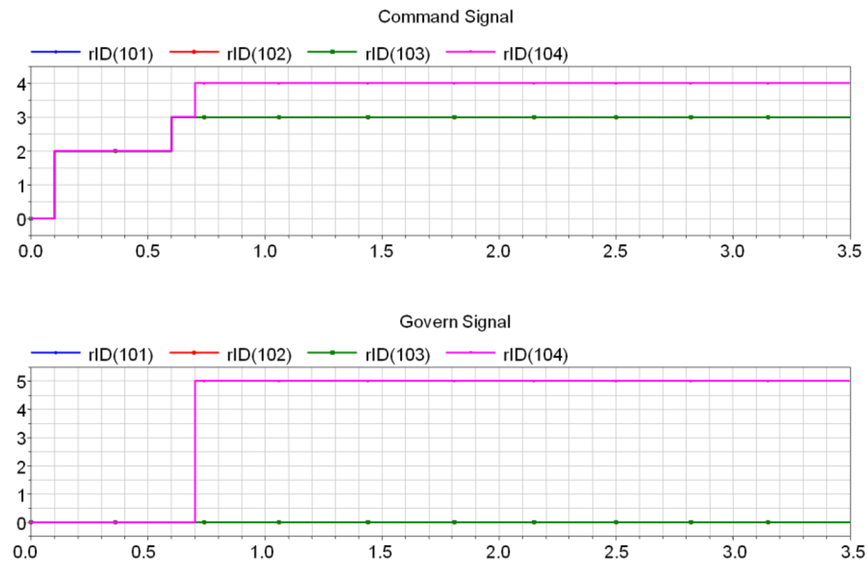

Figure 6-8: Command and Govern Signal for 4-terminal system

Terminal rID(104) is identified and integrated in the operation of the system and Figure 6-8 confirms that it is correctly operated also. DC System Control is at START UP state waiting for the DC voltage to reach its target value, thus rID(104) is set to operate at Voltage control.

In this simulation a 4-terminal system is tested through the same start up procedure as the 3-terminal system previously discussed. The intention at this point is to prove the flexibility of the DC System Control to identify and operate an additional terminal. Uniform interface provides the interfacing pattern which is common for all terminals and recognized by DC System Control. In this way, DC System Control gains access to new terminals as it does for already existing terminals. Once the new terminal is identified by DC System Control, it needs to be integrated in its operation. This is possible due to the flexible nature of DC System Control. DC System Control obtains access to all necessary information regarding all connected terminals through the uniform interfaces but it is its job to handle this information in way that allows it to deal with different numbers of terminals in the system. DC System Control is implemented in a way that allows it to access each terminal according to its properties and not any predefined name or identity. An example of this is the selection of the terminal to charge the DC link. DC System Control will search and find the terminal with highest capacity among the generating or exchange terminals. The number of terminals in the search is irrelevant, thus newly connected terminals can be part of it.

The set of tests in this section confirmed the structural features of the proposed control system. Circulation of data is essential especially for an abstract control system structure where objects can be added virtually at any time. The identity system implemented through Resource Manager keeps track of the direction of data and the access rights of each object while the uniform interface provides a common interfacing pattern so that DC System Control is released from interfacing concerns with each individual terminal and can focus on managing their properties. Simulation results show that data travelling upwards or downwards in the hierarchy of the control system successfully finds its target and makes the identification and coordination of the system possible. The use of the uniform interface in combination with the flexible implementation of DC System Control allows new terminals to be easily integrated in the operation of the system. The uniform interface assures that the additional terminal is identified by DC System Control and takes responsibility of its interfacing with it. Then, DC System Control handles the connected terminals, existing or new, in a general way addressing them according to their properties and regardless of external identities or names. In this way the additional terminal is not only identified by DC System Control but also integrated in its operation automatically.

6.2 Operational Features

Simulation Scenarios

In this set of simulations the operational features of the proposed control system are to be validated. As mentioned in Section 5.2, the operational features are related to the adequate implementation of requested power flows according to a schedule. Since in this case the focus is on the accurate implementation of the requested power flows, the verification model is necessary to follow closely power and voltage levels in the system. The proposed control system is implemented at its final form, with all its control levels and the uniform interface implemented as described in Section 5.1. The model used is the one depicted in Figure 5.23.

The 3-terminal system initially implements a given schedule of power flows to confirm accurate power levels according to request. Then, specific disturbances are imposed to the system to investigate their impact on its operation. First, a number of communication loss events are imposed to investigate the sensitivity of the system on communication failure. Communication loss events are anticipated by schedule distribution by DC System Control to the different substations

Then, 3-phase faults are successively imposed on the AC sides of the terminals. This is to test the reaction of the DC droop to fast power changes and let DC System Control reschedule the power flows in the system according to its criteria. The intention of DC System Control in such case is to suppress the propagation of the disturbance from the DC system to the adjacent AC systems or direct the disturbance in one direction rather than letting it diffuse in all directions. The criterion selected for rescheduling in this implementation is matching the demand if possible. In the case of a 3-phase fault DC System Control enters its emergency state, recalculates the power setpoints for the different terminals and obtains direct control over them.

It should be reminded at this point that the model for this set of simulations features a full controller set even though DC droop is the preferred control mode throughout the main part of its operation. DC droop is able to perform the requested power flows keeping the DC voltage within a +/- 5% margin of its nominal value. At the same time, DC droop allows the different terminals to share the responsibility of sustaining the DC voltage which assures no large voltage variations from one terminal to another while being the first line of defense against events that disturb it. The ratings of the 3-terminal system are as described in Table 5.4 which is presented again here in Table 6-3.

Table 6-3: System ratings

Resource Identity	**Power Rating**	**Nominal Voltage**
101	700MW	AC 330kV
102	700MW	AC 400kV
103	700MW	AC 132kV
DC Cable	700MW	DC +/-400kV

The startup procedure used in the previous section was a simple approach and was used to verify the correct circulation of data. For this set of simulations the procedure has changed and since DC droop is available in the controller set, all available terminals contribute in charging the DC link before normal operation starts. The startup procedure is not the focus at this point and for this reason it will be omitted in favor of the power flow implementation during normal and disturbed operation of the system.

Results

The starting point of this set of simulations is the implementation of a schedule of requested power flows to validate that the proposed control system can implement them accurately on the 3-terminal system of Figure 5-25. The schedule of power flows is the base scenario used in this set of simulations and is the one presented in Table 6-4. Power is expressed in p.u. and the base power is the rated power as showed in Table 6-3. Positive power signifies direction towards the DC system while negative power signifies direction out of the DC system.

Table 6-4: Base scenario, required schedule

	Resource ID	**Schedule interval**					
		#1	#2	#3	#4	#5	#6
Base Scenario	101	1	-0.5	-0.5	-0.4	-0.4	-0.4
	102	-1	0.25	-0.5	-0.6	0.4	0
	103	0	0.25	1	1	0	0.4

Table 6-4 presents the Base Scenario, a schedule of requested power flows that will be used throughout this entire set of simulations and on which different disturbances will later on be imposed. The schedule of Base Scenario is divided in schedule intervals to realize the hour-to-hour power flow changes in the system. Schedule implementation starts at t_s=0.3s and the duration of each interval is t_{int}=0.5s. The duration of the schedule intervals is considered to be of minor importance is since the interest is in the transitions between the different intervals. The schedule consists of six intervals in total and for each one of them there is a value of expected active power at each terminal. Each terminal is labeled with an identity that is used in the schedule so that the control system is aware of which part of the schedule refers to which terminal and is able to perform the schedule distribution. The results presented below refer to the normal operation where DC System Control is at its NORMAL OPERATION state.

The scheduled power flows are selected so that a range of transitions is investigated. Terminals have to operate at low or high capacity, reverse their power flows or readjust them according to schedule. DC droop, which the preferred control mode, must be able to allow any power flow in the DC link, keeping at the same time the DC voltage within the +/-5% margin that is used as the requirement here.

It should also be mentioned that the results presented below were obtained using the DC droop control mode for all the terminals. The rest of the controllers form an inventory of available controllers for the DC System Control to use if necessary. Reactive power is controlled to zero throughout the simulations.

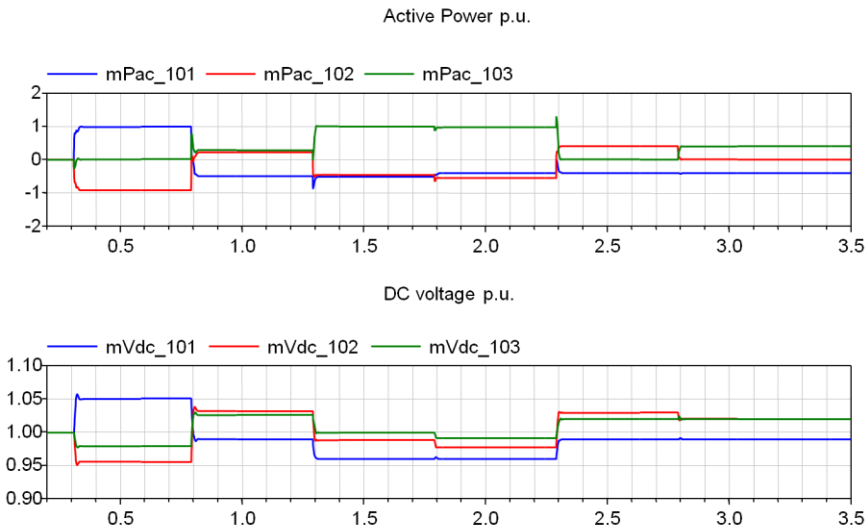

Figure 6-9: Base scenario, Active power and DC voltage

Figure 6-9 presents the results of the implementation of the schedule in Base Scenario. DC System Control splits the schedule in parts according to related terminal and then distributes the schedule to the respective terminal for the current interval and the interval to come. The SCOs then use this information to adjust their power setpoints. Following the power flow implementation interval by interval, the resulting power flows follow the pattern required by the schedule. During interval 1, terminal 101 feeds terminal 102 with 1p.u. of power that corresponds to 700MW while terminal 103 does not supply or consume power. In interval 2, terminal 101 reverses its power flow to consume 350MW which are supplied equally by terminal 102 and terminal 103, which has also reversed its power flow to supply power now. Interval 3 features the increase in power supply by terminal 103 to 700MW that are equally consumed by terminal 101 and terminal 102. Interval 4 shows the possibility to distribute the injected power to the DC link at will. While in interval 3 terminals 101 and 102 were sharing the 700MW injected by terminal 103 equally, they now share the 700MW at a 60/40 ratio. Then for the interval 5 and 6, terminal 101 consumes 420MW which are supplied by terminal 102 in the beginning and then by terminal 103.

The smooth transitions are to be observed in Figure 6-9 both in power and voltage. Power setpoints for the different terminals are accurately reached and follow the requests of the schedule. DC voltage is kept within +/-5% of the nominal for all power setpoints, even when terminal operate at full capacity or when large power transitions take place from one interval to another.

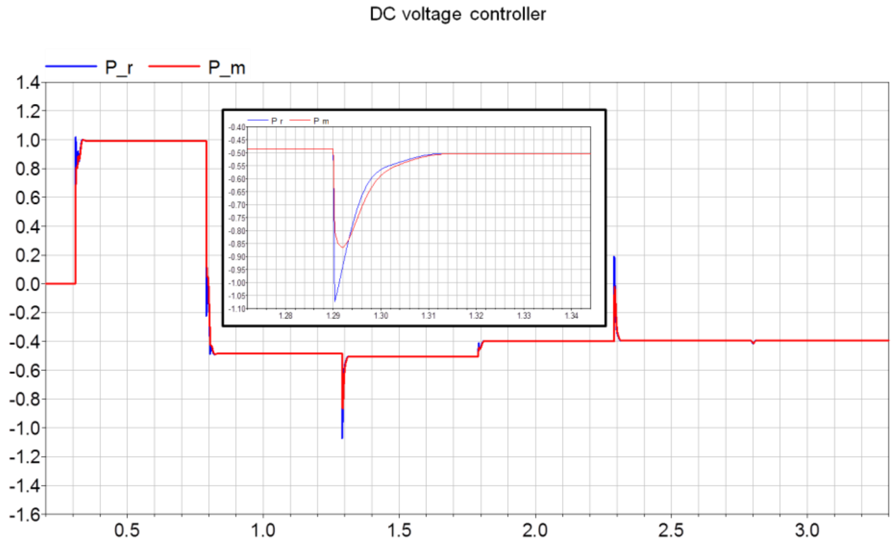

Figure 6-10: Base scenario, DC droop controller detail

In Figure 6-10 the operation of one of the DC droop controller is displayed. The measured signal follows closely the reference and this is clearer at the zoomed detail.

Table 6-5: Single communication loss event during schedule

	Resource ID	**Schedule interval**					
		#1	#2	#3	#4	#5	#6
Scenario 1	101	1	-0.5	-0.5	-0.4	-0.4	-0.4
	102	-1	0.25	-0.5	-0.6	0.4	0
	103	0	0.25	1	1	0	0.4

Table 6-5 shows Scenario 1, during which the same schedule as in Base Scenario is implemented but a communication loss event happens during a part of interval 1 and 2 for terminal 101. Scenario 1 intends to investigate the behaviour of the system when communication is lost for a time period with one of the terminals in the system. It should be reminded at this point that the control system deals with communication loss events by distributing the schedule to the different terminals in the system. This can be considered as a preventive action, before communication loss happens all the terminals in the system are aware of what their operation should be for the coming interval. The system is expected to be unaffected by the communication loss event, since during the intervals DC System Control does not interact with the terminals.

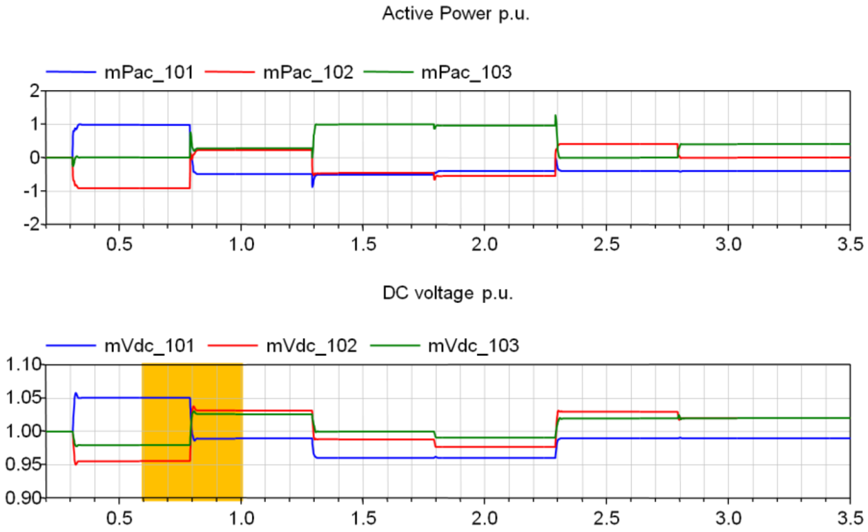

Figure 6-11: Single communication loss event, Active power and DC voltage

Comparing Figure 6-9 and Figure 6-11 shows that the operation of the system under communication loss of terminal 101 is indeed unaffected. The time duration of the communication loss event is marked with light orange colour and this is the only indicator that something has changed. An error signal is generated in DC System Control when a communication loss event happens in some terminal and this is to signify that DC System Control has no longer access to the respective terminal. Nevertheless, the isolated terminal is aware of what it is expected to do during the interval and thus DC System Control remains in normal operation, distributing the schedule to the rest of the terminals and monitoring the overall operation. As long as the duration of the communication loss events are within specific time limits they do not represent an emergency for the system.

Table 6-6: Multiple communication loss events during schedule

Scenario 2	Resource ID	Schedule interval					
		#1	#2	#3	#4	#5	#6
	101	1	-0.5	-0.5	-0.4	-0.4	-0.4
	102	-1	0.25	-0.5	-0.6	0.4	0
	103	0	0.25	1	1	0	0.4

Scenario 2, presented in Table 6-6, is an extension of Scenario 1 featuring simultaneous communication loss events in all three terminals. No big change is expected in the operation of the system for this scenario either. The operation of one terminal under no communications with DC System Control is now extended to all three terminals. As mentioned before, DC System Control distributes the schedule to all of the terminals that know their expected operation.

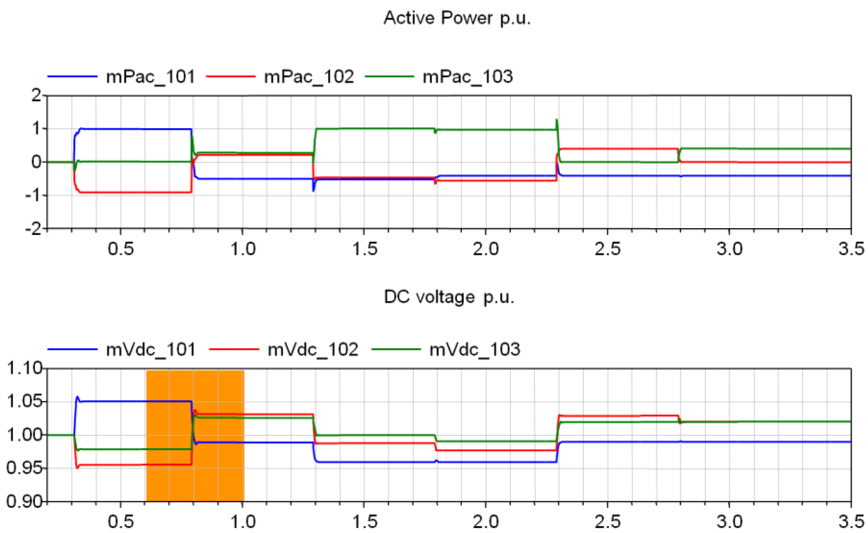

Figure 6-12: Multiple communication loss events, Active power and DC voltage

As for Scenario 1, power and voltage do not show any change in the operation of the system. Figure 6-12 shows that the system performs in the way it would without any communication loss events. Scenario 2 results show that schedule distribution can make the system immune to communication loss events. It does not matter how many of the terminals are temporarily out of communication, the operation of the system will continue as required by the schedule they are all aware of.

There are of course some weaknesses in this implementation. DC System Control is always one schedule interval ahead of the physical system and loads this interval to each terminal at the transition between the intervals. In this way each terminal is aware of the current schedule interval it needs to implement and the coming interval but it receives a new schedule interval at the expiration of the current interval. This means that there are two occasions of uncertainty; one is if the communication loss happens at the time of expiration of the current interval when the new interval is expected to be loaded to the terminal. In this case the schedule interval might not reach its target and the terminal then will be aware only of its current interval. The second case has to do with the duration of the communication loss event. Since each terminal is aware of the schedule at the current interval and one interval ahead, if the communication loss lasts longer than two schedule intervals (2 hours today) the system enters into uncertainty since the terminals wait for instructions and DC System Control cannot provide them. For the second case there is the possibility to extend the number of known schedule intervals to the terminals increasing in this way the time for reaction against the communication loss event. Of course this might not eradicate the problem, but it offers the possibility to adjust the available reaction time against communication loss according to system requirements. In any case there will be such requirement that should not be exceeded. Operation under communication loss is a possibility but it is not a desired operation since it gravely limits the ability of DC System Control to monitor the system. It should only be considered as a transitional stage to restore communications without interrupting the operation of the entire system.

Table 6-7: Successive 3-phase faults during schedule, no rescheduling

	Resource ID	Schedule interval					
		#1	#2	#3	#4	#5	#6
Scenario 3	101	1	-0.5	-0.5	-0.4	-0.4	-0.4
	102	-1	0.25	-0.5	-0.6	0.4	0
	103	0	0.25	1	1	0	0.4

Table 6-8: Successive 3-phase faults during schedule, after rescheduling

	Resource ID	Schedule interval					
		#1	#2	#3	#4	#5	#6
Scenario 3	101	1	-0.5	-0.5	0	0	0
	102	-1	0.25	-0.5	-0.6	0	0
	103	0	0.25	1	0.6	0	0

For Scenario 3 the disturbances imposed to the system are consecutive 3-phase faults in the AC sides of the substations. In Table 6-7 the power setpoints according to the schedule appear. When the faults are first imposed the DC droop makes the terminals share the power imbalance without changing their setpoints. Then DC System Control takes direct control over the remaining terminal and adjusts their setpoints as shown in Table 6-8 in an effort to balance the power in the system. The criterion upon which DC System Control operates is to match the power demand directing the power balancing to the producing terminal as long as it is within its capacity. The rescheduling logic appears in Figure 5-9. This logic is a suggestion for the current implementation that can be changed and its intention is to show the difference between DC droop functionality and the direct intervention of DC System Control in coordination of the system.

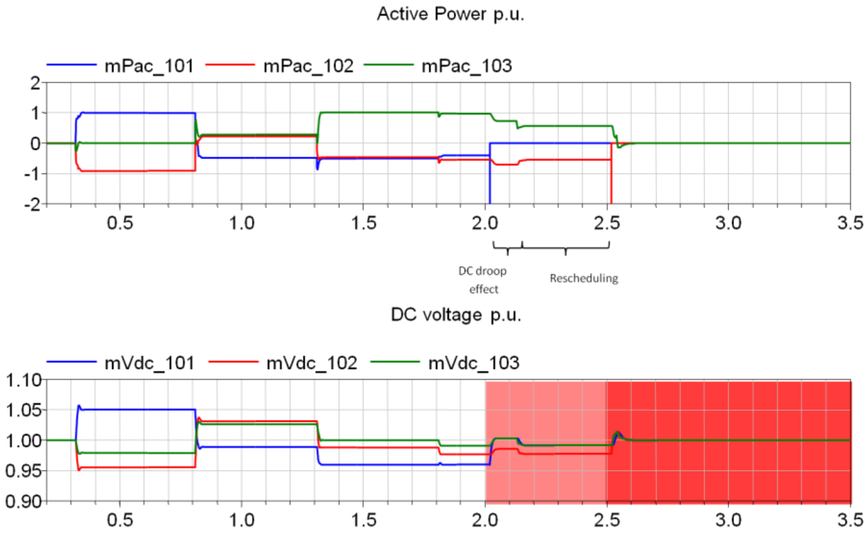

Figure 6-13: Successive 3-phase faults, Active power and DC voltage

Figure 6-13 presents active power and DC voltage on the different terminals. The first 3-phase fault is imposed on the AC side of terminal 101 at 2s. The overcurrent is sensed in terminal 101 leading to control override in an effort to protect the equipment. Indeed, power becomes zero at terminal 101. This leads to a power imbalance which is taken care of the DC droop which assures that the voltage is kept within reasonable values. This is where the functionality of DC droop can be seen. If terminal 101 was in DC voltage control and no other terminal was controlling the voltage. Disabling terminal 101 due to the 3-phase fault would have severe consequences for the DC voltage. DC voltage would drop very quickly and a much faster control system would be necessary to have a chance to deal with it. DC droop assures the sustainable operation of the remaining terminals even if they are a bit off their setpoints. It also gives time to DC System Control to reschedule the power flow in the system. When DC System Control has rescheduled new setpoints are distributed to the remaining terminals after which terminal 103 returns to its expected consumption and terminal 102 reduces its production since terminal 101 cannot consume any power anymore. At this point DC System Control has entered its EMERGENCY state and assumed direct control over the remaining terminals. After half a second at 2.5s a new 3-phase fault is imposed on terminal 102 this time. After this fault there is no remaining consumption in the system. DC droop already leads terminal 103 to zero power output before its setpoint is adjusted. Then DC System Control performs the rescheduling adjusting its power setpoint to zero. DC System Control's operation does not contribute much in this case since consumption is already zero. Nevertheless, DC System Control brings the system in a "stand-by" condition where the power exchange is zero but the DC voltage is at its nominal value, meaning that as the faults are cleared the system is ready to resume its operation.

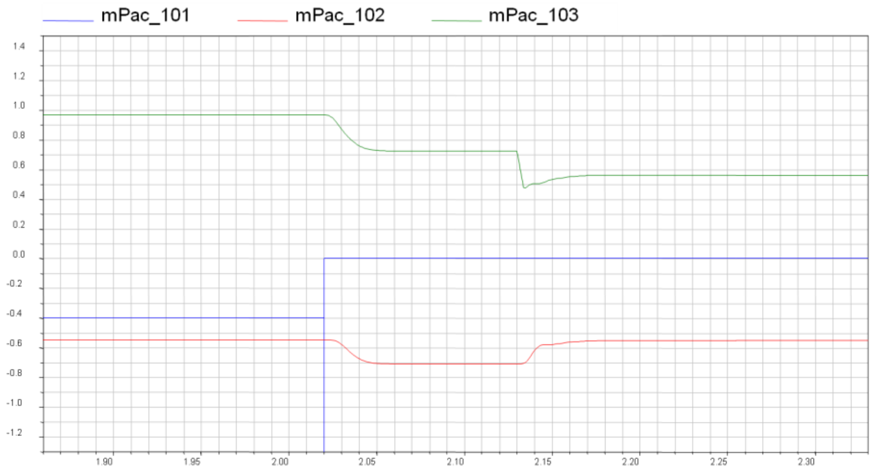

Figure 6-14: Successive 3-phase faults, DC droop action and rescheduling detail

Figure 6-14 shows the details of the difference in operation between DC droop and DC System Control rescheduling after the first 3-phase fault.

To handle the 3-phase faults, DC System Control relies on DC droop and its ability to monitor the system though measurements and control signals it receives from the different terminals, all of which reach DC System Control through communications. A well designed DC droop controller will assure that the system will not be in danger when 3-phase faults happen and it is independent of communications. DC droop will then protect the system from extremities but it will let the disturbances happening on one side to propagate to the DC system and from there to the adjacent AC systems. This is where DC System Control comes and, with rescheduling, it tries to direct the disturbance to the AC system that can deal with it more easily. As mentioned before this happens according to specific criteria that can be changed. However, the rescheduling operation of DC System Control assumes continuous monitoring and direct control of the terminals in the system. A question rising then is what happens if 3-phase faults are combined with communication loss events. At this point the proposed control system can only deal with this combination through DC droop control but it cannot perform any rescheduling.

Chapter 7

Conclusions

In this work the operation and expansion of multi-terminal VSC-HVDC system were discussed. The drivers that lead to the concept of multi-terminal VSC-HVDC system were presented and related to the development of renewables. The technological advancements that made such a system realistic and the obstacles hampering its development were discussed, pointing out standardization and expandability as the main obstacles. The developments of the DC breaker brought the vision of a European-wide DC grid one step closer but, since such a grid will most likely be developed by the integration of smaller multi-terminal HVDC systems, standardization and expandability are crucial both in hardware equipment and in control system. Standard system operation and control were discussed pointing out DC droop as the probably most efficient way to operate a multi-terminal VSC-HVDC system.

A control system structure was proposed to accommodate the standard control methods for a multi-terminal VSC-HVDC system in a structure that provides the general features necessary to allow modularity of the control system to facilitate standardization and thus expandability of the system. The proposed control system is structured in three control levels with their distinct responsibilities. One of the most important features is the uniform interface which provides a common interfacing pattern between different types of substations and adjacent systems with the overall control system. The uniform interface decouples the implementation of the overall control system from the implementation of substation control as long as the interfacing pattern is respected by both sides and the expected functionality is fulfilled. Another important general feature is the automated functions. Since the proposed control system is expected to be autonomous and require minimum or no human intervention, it should be able to respond to emergency situations automatically, both saving reaction time which is valuable due to the fast dynamics of the system and sustaining its autonomous operation even under disturbances. The automated functions must fit in the general sense of the proposed control system structure whose main orientation is modularity. Modularity in the control system is essential for the system to be easily expandable. New terminals must be able to be integrated in the system without any modification in its implementation code. For every uniform interface the overall control system creates a resource object that represents the actual connected substation. All the information that needs to be exchanged then between the actual substation and the overall control system is exchanged via the uniform interface. Automated functions must also support this modular functionality and be able to include in their operation any additional terminal that might be connected to the system. Automated functions as the coordination operation of the overall control system must be based on treating the different terminals according to their properties, without using any external, concrete naming system. The ambition is that all these general features will lead to a flat control system structure. The control system itself should not impose any hierarchy among the different connected terminals or systems so that hierarchies can be defined externally by using the prioritization system available in the proposed control system. The flat control system structure will be particularly useful in the later stage of development of even larger multi-terminal VSC-HVDC systems when small system will be connected to form a larger system. Hierarchy among the different systems should then be a planning procedure that can be implemented according to requirements.

The proposed control system structure was then implemented, for the largest part in C++ and partially in Dymola. C++ is essential since an object oriented approach is necessary to allow modularity in the control system. A detailed description of this implementation follows and some test objectives are defined for the control system. Test objectives are divided in structural and operational. Structural objectives aim to show the structural features of the proposed control system; that is, correct functionality of the uniform interface, correct propagation of signals through the different control levels and the uniform interface, correct operation of different types of adjacent systems through the uniform interface and expandability of the system with an additional terminal that must be integrated in the overall control system operation simply by connecting through the uniform interface. Operational objectives aim to show the accurate operation of the system during normal and abnormal conditions; that is, accurate operation for a given power flow schedule and smooth transitions from one power flow to another and handling of disturbances like communication loss events and 3-phase faults on the AC sides of the system.

The defined test objectives indicated the necessary models to validate them. For the structural test objectives a test model was developed without much concern about its ratings since what was to be tested with it was the correct propagation of signals and easy expandability of the system. For the operational objectives a verification model was developed. In this case the model was expected to keep track of power and voltage levels accurately. Thus, a model with realistic ratings was developed and a schedule was implemented on it. This schedule was used as the base scenario on which different sets of disturbances were tested.

Some conclusions can be drawn looking at the results of the two sets of simulations. Structurally the control system functioned as expected. The implemented labeling identity system that was used by the uniform interface kept right track of the signals in the system which reached their target every time. The information of the type of the connected system in the uniform interface prevented DC System Control from making wrong decisions. This is obvious in the selection of the unit to charge the DC link, no load unit was selected for that, it was excluded because DC System Control had this information. The data set of the uniform interface was flexible too, since it was changed between the two simulations sets. Most importantly from a structural point of view, the additional terminal was connected through the uniform interface and immediately identified and operated by DC System Control. The general search functions in DC System Control help it operate on the properties of the different terminal that become known to it through the uniform interfaces. In this way the number of connected terminals is irrelevant to the operation of DC System Control.

Operationally, the proposed control system was able to accommodate a different implementation of the Substation and Converter control levels, with a different data set for the uniform interface and expanded DC

System Control functionalities and operate the system successfully. A given schedule functioned as the base scenario which was implemented accurately providing smooth transitions from one power flow to another. In this set of simulations the two different ways of control of DC System Control were also tested side by side. Indirect control, or Schedule Management, was used during the normal operation of the system distributing the schedule to the individual substations. This gave the different substations a higher degree of autonomy and let DC System Control perform the overall monitoring. The practice of Schedule Management left the system unaffected when communication loss events happened. Since all the substations were aware of their expected operation for the current schedule interval and the interval to come, substations performed the transition in power flows from one interval to another in an uncoordinated way but successfully. Even though Schedule Management prevented the consequences of communication loss, it raised some issues also. Having the substations knowing the schedule intervals to come prolongs the reaction time the system has to recover from communication losses, but it links the duration of reaction time to the duration of the intervals. Today, the schedule interval is one hour long, although there are discussions about reducing it to half an hour or even 15 minutes to achieve better power resolution. In this case the benefit of distributing the schedule interval to come would be insignificant since instead of gaining one more hour, the gain would only be extra 15 minutes greatly reducing the chances of the system to overcome a communication loss event. It is possible though in the proposed control system to increase the number of before-hand known schedule intervals. Then, the reaction time is decoupled from the duration of the schedule interval, since according to the duration of the schedule interval and the number of before-hand known intervals the available reaction time can be adjusted according to the requirements of the system. In any case, communication loss is a severe disturbance to the system. DC System Control not only cannot control the substation out of communication but it cannot receive any feedback from it either. In this sense DC System Control is “blind” towards the substation out of communication and it has to monitor closely the rest of the substations to intervene if necessary. It becomes even worse if all terminals are out of communication. In this case DC System Control has no authority over the system which operates in an uncoordinated manner. If another disturbance happens at this time, DC System Control will be unable to deal with it.

Communication loss in this sense is a potentially very severe disturbance and prolonged operation under communication loss must be avoided.

When it comes to 3-phase faults, the proposed control system responds in different levels. First, the Converter Control level in the faulted terminal prevents equipment damage by circumventing any control request and controlling the converter to zero power output. At the same time an error signal is sent to DC System Control. The rest of the terminals immediately see the power imbalance created by the faulted terminal shutdown. DC droop balances the power in the DC system by distributing the lost power to the remaining terminals. In this way, power setpoints are not accurately followed and the disturbance diffuses in the adjacent systems. DC System Control then intervenes; it assumes direct control of the remaining terminals and readjusts their power setpoints. Operational Management overrides Schedule Management in this case. Anyway, since one of the terminals is not operational the schedule cannot be implemented. The priority is to maintain the operation of the remaining terminals and limit the propagation of the disturbance to the adjacent systems. This test proves the necessity of DC droop control in the primary control of the system. DC droop kept the DC voltage at reasonable levels. If DC voltage control was used instead and the disabled terminal was the one controlling the DC voltage the disturbance on the DC voltage would be so severe that DC System Control would not have the time to reverse the situation. This test also shows that DC System Control can identify emergencies in the system and be used to facilitate the operation of the system even in emergency conditions. As mentioned before the rescheduling logic implemented here aims at matching the power demand in the system which means that it is assumed that the remaining producing terminal is able to cover the power mismatch created by the shutdown of the faulted terminal not to reduce the power delivered to the consuming terminal. This logic can be changed or expanded to match the requirements of each system; new criteria can be implemented according to the characteristics of each adjacent system or prioritization according to agreements between the involved parts. Three phase faults were tested in this work since they are considered to be the most severe AC faults. It is assumed that different types of AC faults will require different treatment and different detection mechanism. A faulted terminal might not need to be shut down then, creating new scenarios for the rescheduling procedure since part of the capacity of the faulted terminal might be available.

In all, the proposed control system showed adequate behavior according to the requirements set in the beginning. It was able to operate a 3-terminal system accurately and deal with communication loss events and 3-phase faults. It also proved the value of the uniform interfacing when connecting different types of adjacent systems and when additional terminals are to be integrated. The proposed control system structure also showed its flexibility in accepting different implementations of its different parts. Throughout the tests, Substation and Converter control level implementation was changed and DC System Control level implementation was expanded to include further functionality. The data set of the uniform interface was also changed, adjusted and expanded from one set of simulations to another. The proposed control system structure seems to be adequate to play the role of the control system platform mentioned in the beginning of this work, and the proposed control system implementation seems adequate to be the basis on which a general control system can be developed.

Chapter 8

Future Work

In the scope of this work a general control system structure was proposed with the intention to contribute against the lack of standardization in today's plans for multi-terminal VSC-HVDC systems and promote their expandability through modularity and uniform interfacing. The control system structure and implementation were described in detail and its functionality was validated through simulations on, mainly, 3-terminal systems. Although 3-terminal systems are adequate to prove the control system structure and main functionality, they remain the simplest form of a multi-terminal system. It seems as a natural continuation of this project that the proposed control system is tested on more complex multi-terminal arrangements featuring more terminals and in meshes with consideration of DC breakers. Due to the fast dynamics of a multi-terminal VSC-HVDC system automated functions are imperative, thus the operation of DC breakers must be integrated in the functionality of the control system and system's topology identification after DC breakers' operation must be performed by the control system in a very short span of time. Power flow calculation methods must also be considered and fit both the modularity of the system and the requirements for the aftermath of DC breakers' operation.

As mentioned earlier 3-phase faults are considered to be the most severe and this is the reason why they have been investigated in this work, but under no circumstances are enough to cover all cases. Different types of AC faults must be investigated both in terms of fault detection and counteraction. Experience in AC power systems have a lot to teach regarding the behavior and effect of AC faults but how to integrate the counter-measures required in the proposed control system to minimize their effect on the DC system and the substation equipment is a point of further investigation. In addition, if DC breakers are considered, DC faults must be addressed also. The proposed control system must take responsibility to deal with DC faults as well since the tools for that are considered. New general algorithms might be necessary to deal with all a wide range of electrical faults both of AC and DC nature. An important type of fault of no electrical nature is communication loss as discussed in this work. Schedule distribution has been suggested to anticipate this type of events but, as mentioned, operating under communication loss is an uncoordinated operation and a minor disturbance might have more serious consequences. In this sense, ahead in time schedule distribution is a temporary solution but how far ahead is too far? As discussed earlier the arbitrary number of schedule intervals that can be distributed before-hand can determine the available reaction time for the system to recover from communication loss events. The question rising is how long should the system be allowed to operate in an uncoordinated way before the risk for the rest of the system becomes too high. Investigating combined disturbances will also be of great interest. The behavior of a system that suffers different types of faults under communication loss is an issue to be addressed and criteria for the rescheduling of the power flows of the remaining healthy terminals must be developed.

Another interesting point for further investigation is the parallel operation of many systems. Since the integrated large DC grid will be formed by several multi-terminal systems that will probably form their own control area, the parallel operation and interfacing of many systems is necessary. This might later on call for another, higher level of overall control to coordinate the different areas.

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