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Introduction

… in which the problem of electro-mechanical oscillations and conventional means for damping are briefly reviewed followed by an overview of the thesis and its main contributions.

In their early years electric power systems did not reach far from the generating station. Since then power systems have been inter-connected to cover first regions and later nations. Today they extend over entire continents and contain a huge number of components that together serve to supply electric energy to the customers. The aim is to maintain the voltage and the frequency at their nominal values. To improve reliability both design and operation of power systems involve safety margins to the cost of some profit. Much effort today is spent on control and supervision that can reduce these margins, which also has environmental aspects. This thesis focuses on electro-mechanical oscillations, which reduce line transfer capacity if they are not sufficiently damped. The control of electric loads that draw active power is suggested as means for improved damping.

The nature of electro-mechanical oscillations is outlined in Section 1.1, followed by a brief review of the most important sources of damping in Section 1.2. The use of electric loads is motivated in Section 1.3. The organization of the thesis is described in Section 1.4 and its main contributions are mentioned in Section 1.5.

1.1 Electro-Mechanical Oscillations

The problem treated in this thesis is damping of *electro-mechanical oscillations* in power systems. During such oscillations, *mechanical* kinetic energy is exchanged between synchronous generators as *electric* power flows through the network. The oscillations can be seen in many variables, where the rotor velocities of the generators and the power flows in the network are the most important. The rotor velocity variation causes strain to mechanical parts in the power plant and should be limited. The power flow oscillations may amount to the entire rating of a power line. As they are superimposed on the stationary line flow, they limit the transfer capacity by requiring increased safety margins. Given certain conditions torsional dynamics of the turbine-generator shaft can interact with for example the network, leading to *subsynchronous oscillations*. Such oscillations are not considered in this work.

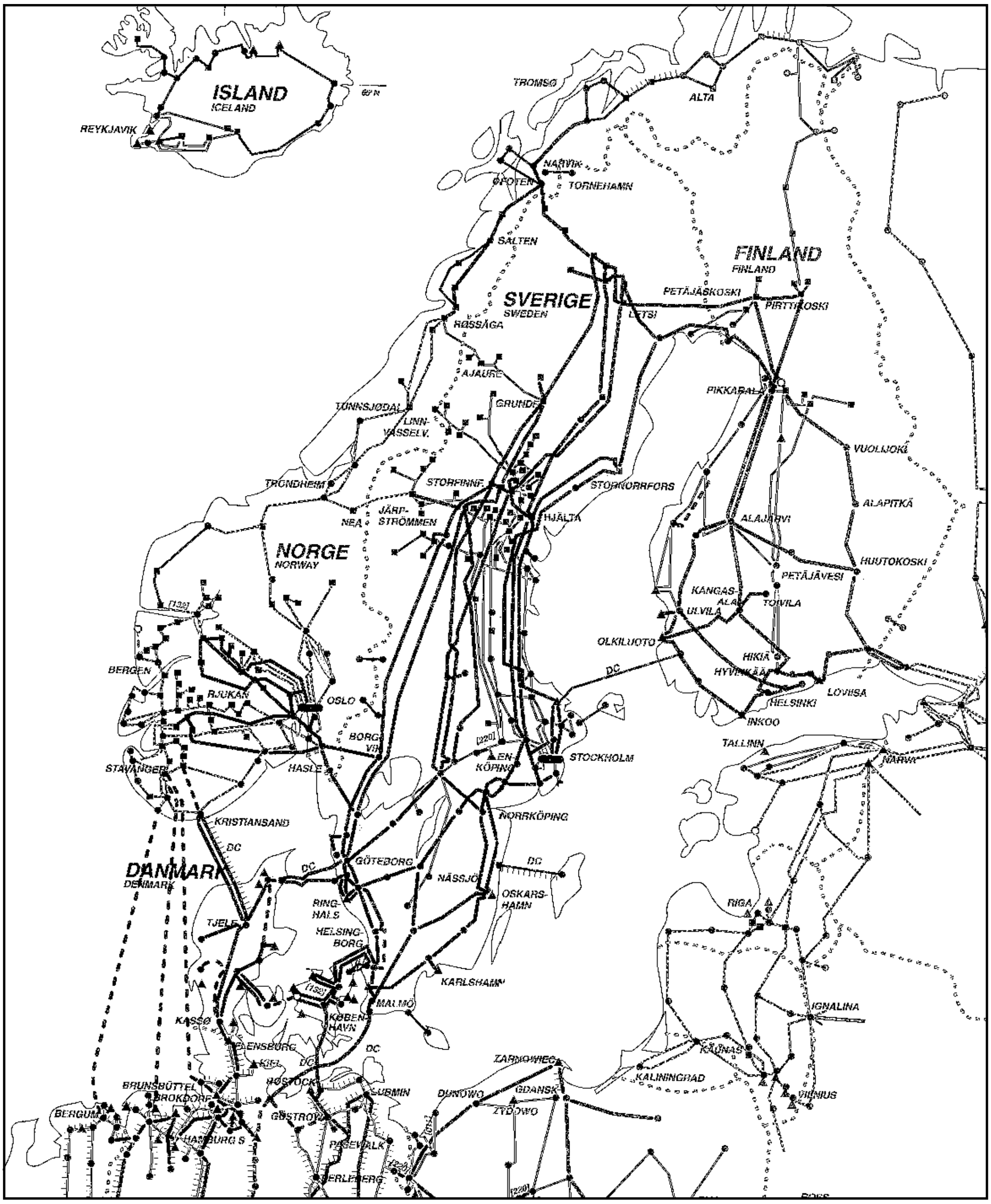

Fig. 1.1 The Nordic high voltage network – the Nordel system – in 1996.

The term *synchronous* generator stems from the fact that this electrical machine is *synchronized* to the network. This makes the shaft speed connected to the frequency of the voltage in the network. At any point in the network the mains frequency is thus determined by the rotor velocity of nearby generators. A consequence worth to mention is that electro-mechanical oscillations can be detected in the mains frequency as a variation around the nominal 50 or 60 Hz.

Studying the damping of electro-mechanical oscillations is generally referred to as *small disturbance stability analysis*, which makes linear mathematical models valid. By formulating such a model of the power system the electro-mechanical dynamics can conveniently be decoupled into a number of *modes*. A mode can be thought of as a resonance and is identified by its combination of oscillation frequency, damping and *mode shape*.

The mode shape indicates which generators that are active and how they swing against each other. There are *local modes* where one generator swings against the rest of the system typically with a frequency of 1-2 Hz. For *inter-area modes* the generators in a large area swing together against one or more other areas at a frequency of 0.1-1 Hz. Examples of such areas in the Nordic power system shown in Fig. 1.1 are: the Danish island Zealand (Sjælland); Finland; southern Norway; southern Sweden and northern Sweden.

In the linear model the mode oscillation is described as a sinusoid with an exponential decay. The time constant of this exponential is a simple but convenient measure of damping. Inter-area modes in general exhibit low damping, meaning a time constant of more than ten seconds. If damping is negative even a small perturbation may excite a growing oscillation.

While damping of local modes can be referred to a single machine and its controls, inter-area mode damping is more related to system properties such as network configuration and power flows. Interconnecting two power systems improves reliability of the power supply, but also introduces a new inter-area mode. If the rating of the tie-line is not sufficient as compared to the power flows associated with the mode, the damping of the mode will be low. The influence of line loading on damping is of current interest as environmental issues make it more difficult to reinforce existing power lines to meet the increasing demand of electric power.

New trading agreements, due to the deregulation of the electricity market and new system inter-connections, give new loading situations. If these have not been analyzed, they can cause problems. This was the case at the disturbance in Sweden on January 1st 1997. In contrast to the normal situation, Denmark this day exported electric energy to Norway via Sweden: A bus-bar fault near Gothenburg (Göteborg) unexpectedly caused tripping of several lines important transmission lines, so that two units of the nuclear power station Ringhals (see Fig. 1.1) to be radially connected to the main grid. As the connecting lines are weak this led to an oscillation with increasing amplitude. After ten seconds the two units were tripped and the system settled down. Fig. 1.2 shows recordings of the power flow of a central line along with voltage and frequency at a point near Helsingborg.

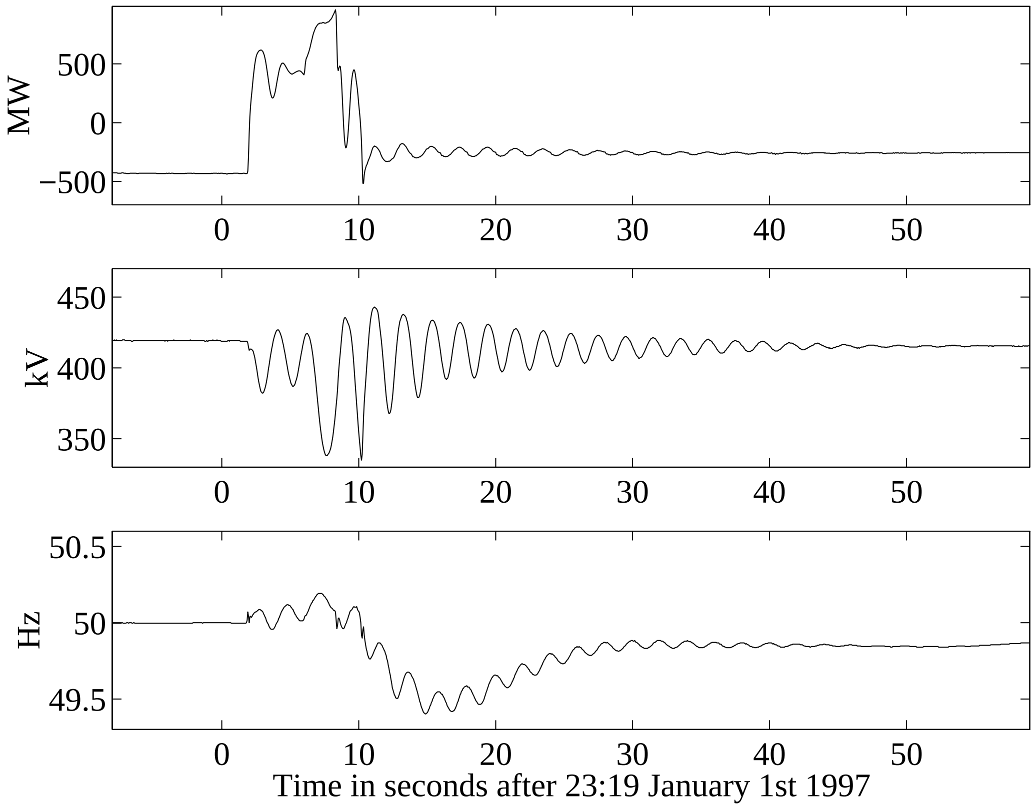

Fig. 1.2 Recordings from the event in southern Sweden on January 1st, 1997: The power flow (top) is reversed when the lines are disconnected. This excites an undamped oscillation that is seen in the voltage (middle) and the frequency (bottom). Several switching actions are performed before the Ringhals units are tripped at 23:19:08. The maximum deviation in mains frequency, here 0.6 Hz, is considered large.

The morning papers treated the press releases about the event as financial news. Terms such as electro-mechanical oscillations or damping were not mentioned.

1.2 Sources of Supplementary Damping

As the damping of electro-mechanical power system dynamics inherently is low, sources of supplementary damping are sought for. The individual generator is equipped with a *PSS* (power system stabilizer) and *damper windings*. Systems based on high power electronic equipment is known as *FACTS* (Flexible AC Transmission System [Hingorani 1988]). Such devices have received much attention during the last five years. They are mostly located on tie-lines and influence the electro-mechanical oscillations through the power flow P on the line,

$$P = \frac{V_1 V_2}{X} \sin\left(\theta_1 - \theta_2\right) \tag{1.1}$$

where X is the line reactance and V_1, V_2, θ_1 and θ_2 are the magnitudes and phase angles of the voltages at each end of the line. Different types of FACTS devices affect P by manipulating different variables or parameters. All FACTS devices have a high bandwidth which is advantageous. Their main drawback is the need for sophisticated protection that often requires more ground space and is more complex than the compensator itself [Jönsson 1996]. *HVDC* (High Voltage Direct Current) links can also be used for damping purposes. As several FACTS and HVDC controllers may be involved to damp a mode it is very important to assure that they do not counteract each other.

In the following the characteristics of the most common sources of supplementary damping are briefly reviewed. Their operating principles are described as well as their advantages and drawbacks.

Power System Stabilizer

All new synchronous generators are equipped with a PSS, which is the most widely spread damping controller. It is a low-cost add-on device to the Automatic Voltage Regulator (AVR) of the generator and operates by adding a signal to the voltage reference signal. High AVR gain gives good voltage control and increases the possibilities of keeping the generator synchronized at large disturbances, but contributes negatively to damping [de Mello and Concordia 1969]. This conflict is mostly solved by limiting the PSS output to ±5 % of the AVR setpoint. The trade-off can be solved more elaborately by integrating the AVR and the PSS and use a design that simultaneously takes voltage control and damping into account [Akke 1989], [Heniche et al 1995].

The PSS classically uses shaft speed, active power output or bus frequency as input [Larsen and Swann 1981]. The stabilizer itself mainly consists of two lead-lag filters. These are used to compensate for the phase lag introduced by the AVR and the field circuit of the generator. Other filter sections are usually added to reduce the impact on torsional dynamics of the generator, and to prevent voltage errors due to a frequency offset. The lead-lag filters are tuned so that speed oscillations give a damping torque on the rotor. By varying the terminal voltage the PSS affects the power flow from the generator, which efficiently damps local modes.

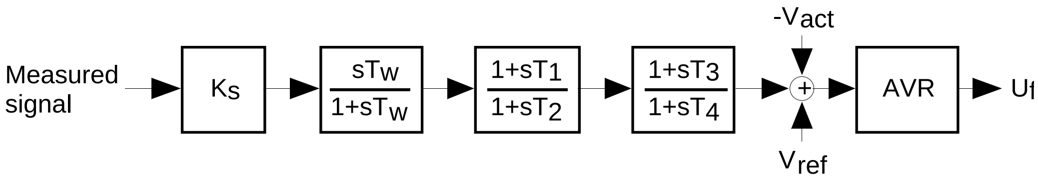

Fig. 1.3 Block diagram of conventional power system stabilizer. Ks is the stabilizer gain, while Tw and T1-T4 are the parameters of washout and lead-lag filteres respectively. The PSS output is added to the difference between reference (V_{ref}) and actual value (V_{act}) of the terminal voltage.

A difficulty of PSS tuning, except for the trade-off with voltage regulation, is that the dynamics that should be compensated by the lead-lag filters vary with the operating point and the network reactances [Larsen and Swann 1981].

The effect of PSS on inter-area modes differs from that on local modes in two ways. Firstly the achievable damping of inter-area modes is less than that of local modes. Secondly inter-area modes are affected mainly through modulation of voltage sensitive loads. This makes assumptions on load characterstics critical both for investigations and for field tuning [Eliasson and Hill 1992], [Klein et al 1992]. Damping of both local and inter-area modes requires suitable phase compensation over a wider frequency range, which may be difficult to achieve.

Static Var Compensator

The Static Var Compensator (SVC) is a reactive shunt device, that uses its reactive capability to alter the bus voltage, which enables a regulated voltage support. An SVC for continuous control contains a thyristor switched capacitor bank in parallel with a bank of phase angle controlled reactors and is connected to the transmission voltage level via a transformer.

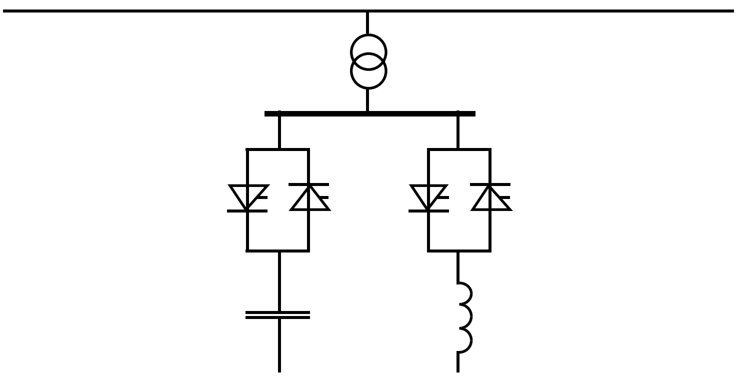

Fig. 1.4 One-line diagram of static var compensator.

The SVC influences electro-mechanical oscillations like the PSS: it both changes the line transfer (by controlling V in (1.1)) and modulates voltage sensitive loads [Ölvegård et al 1981]. Depending on which of these effects that dominate, the SVC is placed either at the midpoint of a long transmission line or near a load centre.

To avoid telemetering of measurements, the damping controller of an SVC should use local signals such as time derivative of bus voltage [Gronquist et al 1995], [Smed and Andersson 1993], active power flow or line current magnitude [CIGRÉ 1996].

For a fixed controller with active power flow as input, the resulting damping is proportional to the line transfer, which means that a reversal of the power flow direction gives negative damping. This has been a practical problem at the SVC installed at Hasle in Norway, between the capital Oslo and the Swedish border. The damping controller is designed to damp oscillations between southern Norway and Denmark (Zealand), when power is exported from Norway. After some incidents when the SVC caused sustained oscillations, the damping controller is now disengaged whenever power flows into Norway at this connection [CIGRÉ 1996].

The GTO (Gate Turn-Off thyristor) based ASVC (Advanced SVC) can replace an SVC. The main difference is that the maximum reactive power output of the SVC is proportional to the square of the bus voltage, while that of the ASVC is constant down to very low voltages [Larsen et al 1992]. This property motivates the term STATCON (Static Condenser).

Controllable Series Capacitor

The Controllable Series Capacitor (CSC) is connected in series with long transmission lines as in Fig. 1.5. In the first place its presence is motivated by the need to effectively shorten the line electrically, which increases the power transfer capability.

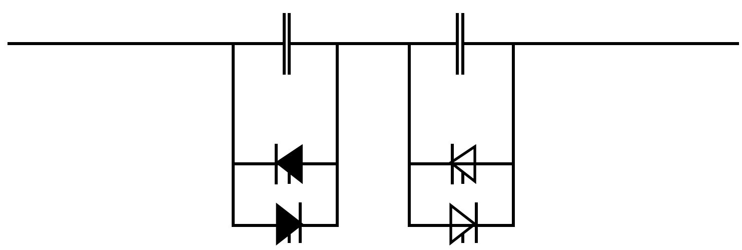

Fig. 1.5 One-line diagram of controllable series capacitor. The filled thyristors are conducting, which makes it possible to both increase and decrease the capacitance.

A CSC affects electro-mechanical oscillations by modulating the transfer reactance of a line, such as X in (1.1). The impact of this control action increases with line loading [Noroozian and Andersson 1994], which is a desirable property. The CSC is more effective than the SVC for damping purposes [Ängquist et al 1993], [Noroozian and Andersson 1994], which is explained by how they are connected: the series device affects the entire line flow; the shunt device only changes a part [Gronquist et al 1995].

While fixed series capacitors are common, only a few CSCs are currently in operation. An important reason is the constructional difficulties with a main circuit on line potential. The voltage rating of a CSC is typically a fraction of the normal voltage drop over the line where it is installed. As this is far less than the voltage resulting from a three-phase short-circuit on the line, protection circuits that by-pass the compensator are critically important.

Due to the low number of CSCs in operation no statements about the measurements *commonly* used by damping controllers can be made. Just like in the SVC case it is advantageous if the signals are locally available. [Gronquist et al 1995] suggests the use of line voltage drop and its time derivative. In [Larsen et al 1995], the mean frequency in remote areas are synthesized from local measurements of voltage and current, while [Chen et al 1995] settles for active and reactive line flow.

High Voltage Direct Current Link

In a High Voltage Direct Current (HVDC) link the AC voltage is rectified; transmitted as DC; and converted back to AC. The absence of reactive transmission losses makes HVDC the preferred technique for connections with submarine cables longer than 30 km and for overhead lines longer than 600 km [Kundur 1994]. The DC transmission also provides an asynchronous connection between two power systems, which is of particular value when the systems have different frequencies such as 50 and 60 Hz. Fig. 1.1 shows a number of submarine DC cables that connect the Nordel and the UCPTE systems of Scandinavia and western Europe respectively. The connection between the Swedish mainland and the island Gotland was the World's first HVDC link. It has a length of 90 km and was installed in 1954.

An HVDC link is controlled at the rectifier and the inverter through their firing angles and through the tap changer of the transformer at each converter station. The control system operates in a number of control modes, where certain variables are held constant. The control has several objectives, which makes the resulting control system fairly involved. The ability to directly affect power flow makes HVDC links very powerful for damping of electro-mechanical oscillations. The Fenno-Skan link connects eastern Sweden and southwestern Finland and has a damping controller whose output is limited to 50 MW. It has a great impact on the mode where machines in southwestern Norway swing against machines in southern Finland [Smed 1993].

The active power modulation is typically controlled by the frequency at the converter station(s) [Smed 1993], [Jones 1996], the frequency of a nearby generator [Eliasson and Hill 1992], [Jones 1996] or a line flow [Kundur 1994], [Jones 1996].

Since the converters are line commutated, a reactive power consumption is associated with the active power flows. The dependence between the modulations of active and reactive power is governed by the control mode. It may either support the active power modulation or counteract it [Smed 1993].

Evolving Technologies

The technologies described above are in operation today, but new power electronic devices with a potential for damping of electro-mechanical oscillations are constantly suggested [Hingorani 1993]. The Universal Power Flow Controller (UPFC) currently receives considerable attention [Bian et al 1996]. The Phase Angle Regulator (PAR) [Iravani et al 1994] and the Superconducting Magnetic Energy Storage (SMES) [Hauer and Boenig 1987] have been considered for some time, but neither seem to be in commercial use yet.

1.3 Controlling Active Loads for Damping

By lending a small fraction of the rating to a damping controller, actuators that primarily are installed for other purposes contribute to damping. The effectiveness is mainly determined by the ability to modulate the flows of active power in the network. With this in mind the loads of the power system are potentially interesting: their joint rating is large and turning them on and off certainly has impact on the power flows.

From a power system control point of view, however, loads are not controllable and are thus regarded as disturbances rather than as actuators. This situation is currently changing as systems for two-way customer-utility communication are installed as part of DSM (Demand Side Management) programs. Via the control outputs of *intelligent electricity meters* that communicate with the utility, the utility can remotely control *selected* loads within customer premises in a nondisturbing manner. The resulting *direct load control* systems are mainly used for *load management* actions such as *peak shaving* (reduction of power peaks).

Control of active power has a powerful influence on electro-mechanical oscillations, which is demonstrated by the Fenno-Skan HVDC link mentioned above (see also cover page). This would motivate the use of controlled active loads to improve damping, but all active loads can not be used for this. Loads with an internal energy storage may, however, be interrupted with little inconvenience for the customer. Thermal loads such as domestic water heaters, stoves and district heating boilers are therefore well suited for fast load control. If future electric vehicles are charged from the electric mains, they are also adequate.

Loads have previously been used for damping by placing an SVC at a load area and modulating the voltage [CIGRÉ 1996]. A similar voltage induced change in load is obtained through tap changer control. As long as the tap changers are mechanical the resulting variation, however, is too slow for damping of electro-mechanical oscillations.

Low voltage loads draw their power from the transmission network through the lines, cables and transformers of the distribution network. These components give rise to reactive losses that vary with the loading level. Turning a purely active low voltage load on and off will therefore modulate both active and reactive power at the point in the transmission network where the radial distribution network is connected.

In this thesis the reactive component is not considered. Oscillations in the transmission network are assumed to be damped by controlled active transmission loads, while oscillating machines in the distribution are damped by low voltage loads. An interesting transmission load is the district heating boiler previously mentioned. In southern Sweden a number of such boilers exist today. The two largest ones are connected to the subtransmission network and their ratings are 100 MW and 70 MW, which can be compared to the 50 MW limit of the damping controller on the Fenno-Skan HVDC link. In order to be used for damping, a part of their rated power needs to be modulated with a bandwidth of a few Hz. This is realistic with currently available techniques, but has not been implemented.

1.4 Outline of the Thesis

In Chapter 2, modal analysis of linearized differential-algebraic models is outlined. It also presents the three power system models that are studied in the thesis and the mechanical equivalents that are used for qualitative understanding and interpretations. Chapter 3 shows where active power modulation is most effective in each test system. In Chapter 4, three measurement signals are introduced and their efficacy in the two multi-machine test systems is quantified. Chapters 5 and 6 demonstrate damping of electro-mechanical oscillations by on-off control. Methods for analysis of the nonlinear controller are provided in Chapter 5, while the field test of a practical implementation is described in Chapter 6. Chapter 7 explores the impact of one linear damping controller on a mechanical equivalent and on the two multi-machine test system. The use of two linear damping controllers is treated in Chapter 8. In Chapter 9 the efficiency of two damping controllers is demonstrated through time simulations of the large test system. Conclusions and suggestions for future work are given in Chapter 10.

1.5 Objectives and Contributions of the Thesis

The thesis treats the use of controlled active power at one or more locations in a power system to increase damping of electro-mechanical modes. The focus is on structural aspects of interaction and of sensor and actuator placement. The main objective is to explore the fundamental possibilities and limitations of the resulting damping system, and to relate them to the structure of the power system. A second objective is to give insight into the complex power system dynamics by providing simplifications and interpretations.

The contributions can be referred to modelling, to control of active power using different measurement signals and to practical experience gained at the field test.

Modelling

Numeric linearized differential-algebraic models of three power systems with one, three and twenty-three generators are used for the analysis. The two latter are generated by the power system simulator EUROSTAG and exemplifies the practical use of large models. A number of analytic models with the same differential-algebraic structure are also given. One of them is a simple linearized multi-machine model, that makes it possible to analytically investigate the impact of controlled active power on electro-mechanical dynamics.

Analytical mechanical equivalents to local and inter-area modes in power systems are included to proved intuitive and qualitative understanding. The spring-mass inter-area mode equivalent and the multi-machine power systems are treated in parallel. It is shown that the individual electro-mechanical modes of the multi-machine power systems behave like the mechanical inter-area mode equivalent. A pendulum equivalent to a local mode is shown to provide easily understandable information regarding suitable locations of actuator and sensor. The mechanical nature of electro-mechanical power systems modes is further exploited by visualizing the mode shape of network related variables like the bending-modes of flexible mechanical structures.

Control

Local bus frequency and machine frequency are used as measurement signals, which leads to a modest need for telemetering. The efficiency of using active power for control (mode controllability) and of using local phase angle or frequency as measurement (mode observability) are shown to have the same geographical variation in the mechanical power system equivalents. The same thing is proved to hold for a general system represented by the analytical multi-machine model. An extension of the proof shows that *all modes* will initially be better damped when the gain, relating the active power to the local bus frequency, is increased from zero.

Numerical investigations show that the damping is improved at small gains but also that it is limited. This applies both when using local bus frequency and machine frequency to control the active power. For large gains the eigenvalues of the electro-mechanical modes move towards resonant transfer zeroes with low damping. The zeroes occur in all the studied systems and their locations relative to the open loop eigenvalues can be predicted by the spring-mass inter-area mode equivalent.

It is pointed out that the swing energy and its dissipation correspond to reactive and active power defined at the swing frequency. This leads to the conclusion that tuning a viscous damper in a spring-mass system for maximum damping is equivalent to *impedance matching*. A numerical comparison shows that the gain obtained through impedance matching deviates slightly from the point of maximum absolute damping. The introduction of a second damper may not increase the maximum obtainable damping. This is explained as a case of impedance matching where the second damper disturbs the first damper rather than supports it.

Field Test

A field test at a small hydro power station demonstrates damping by on-off control of a load. It gives practical experience of the required signal processing. The results are also valuable for communicating the idea of load control for damping purposes.