10

Conclusions

… in which the results of the thesis are reviewed and some continuations of the work are suggested.

All results indicate that active power is efficient for damping of electro-mechanical oscillations. The work presented here provides thorough understanding of the fundamental limitations associated with active power controlled by a frequency signal. This is outlined in Section 10.1 together with the experience gained from the different models and methods that are used. One possible implementation of the studied damping systems relies on the use of controlled active loads in the low voltage network. It would give the desired modulation of active power in the transmission system, but also a variation in reactive power. A closer investigation of the extent and the effects of this reactive variation, is one of the most important topics for future research suggested in Section 10.2.

10.1 Summary of Results

The exploration of active power controlled by different signals has provided knowledge about the controllers themselves, but also insights in the dynamics of the power systems. This is summarized below together with observations more related to the used models and methods.

Linear Control of Active Power

The suggested linear damping controllers influence the system in a way that can be well understood. This is mostly done by studying the mechanical inter-area mode equivalent. Provided the gains are small the dampers have a positive effect on damping of the modes that are affected while others are left practically unaltered. This applies for all the tested locations and was predicted for the local bus frequency case by the proof in Chapter 4.

The impedance matching concept explains the limitation in maximum obtainable damping as well as the possible reduction in damping when a second damper is introduced.

In the twenty-three machine system, the use of two dampers gives good damping of the three selected modes for the case when the line N4044-N4045 is out of service. The fact that eigenvalue locations are not altered much by reinserting the line, indicates a certain amount of robustness against structural changes in the network.

On-off Control of Active Power

The field test verifies the results in Chapter 5, that on-off control of active power can be used for damping of electro-mechanical oscillations. It also shows that estimated mode frequency as described in Chapter 4 is practically useful and needs only one-phase measurements of three variables. Furthermore the test illustrates how little active power that needs to be controlled.

Models

The mechanical equivalents used along with the power system models provide analytical expressions for eigenvalues and zeroes as well as measures of mode controllability and mode observability. The spring-mass systems are linear which makes it straightforward to write down the equations, whereas the pendulum equivalent needs linearization. The pendulum, on the other hand, is easier to visualize as it moves in one direction and extends in another.

The use of numerical multi-machine models demonstrates that the results obtained for the inter-area mode equivalent are valid also in a large power system model. When properties specific to meshed networks are of central importance, the one-dimensional inter-area mode equivalent is not valid and is replaced by the three machine system.

By introducing an electric equivalent to the inter-area mode, it is shown that the swing energy and its dissipation correspond to reactive and active power. This naturally leads to the interpretation that tuning a damper for maximum damping is equivalent to impedance matching.

Methods

The analysis makes extensive use of the eigenvectors of DAE models. It is evident that the algebraic part of these eigenvectors contain useful information related to the network. This is exemplified in Chapters 3 and 4 by the measures of active power mode controllability and phase angle mode observability at all buses. For the studied power systems these can be illustrated as bending modes of flexible structures.

Root locus plots are used to study damping for large gains. By comparing eigenvalue sensitivities against root locus plots it is clear that the directional information of the sensitivities is accurate. The sensitivity magnitude, on the other hand, says little about how far the eigenvalue will move. By comparing root locus plots it is shown that modes may change identities when their eigenvalues are close to each other.

The linearized multi-machine power system models are generated by the power system simulator EUROSTAG. This guarantees the consistency between the models used for linear analysis and time simulations, which is demonstrated.

10.2 Future Research

The use of controlled active distribution loads for damping is realistic, but implicitly also includes modulation of reactive power. The main challenge in the continued work is to manage this reactive component. Alternatively, if active power can be controlled at the transmission level, the suggested control laws can be used but need further refinement. In any case the robustness of the resulting control system should be thoroughly investigated.

Impact of Reactive Power

Whereas the possibilities to control active power at the transmission level are limited, they are better at the distribution level. The field test indicates that generators connected to the distribution network can be damped by controlling nearby loads. Their impact on oscillations in the transmission system is less obvious due to the reactive losses in distribution system lines, cable and transformers. Switching an active distribution load will cause a variation in both active and reactive power delivered by the transmission system. The study of this phenomenon can be divided into two parts: one dealing with characterization of the reactive component and one that considers its effect on the system. The latter is done by extending the mode controllability analysis in Chapter 3 to reactive power.

	Bus	Mode 1	Mode 2	Mode 3
P	N47	$0.096e^{j105°}$	$0.021e^{j32°}$	$0.145e^{-j42°}$
Q	N47	$0.005e^{-j152°}$	$0.028e^{-j94°}$	$0.101e^{j145°}$
P	N51	$0.318e^{j101°}$	$0.224e^{-j64°}$	$0.044e^{-j43°}$
Q	N51	$0.224e^{-j69°}$	$0.083e^{j128°}$	$0.026e^{j150°}$
P	N63	$0.381e^{j106°}$	$0.228e^{j119°}$	$0.142e^{j135°}$
Q	N63	$0.201e^{-j65°}$	$0.177e^{-j57°}$	$0.090e^{-j40°}$

Table 10.1 Mode controllability of active (P) and reactive (Q) power respectively.

The mode controllabilities of active and reactive power at some buses in the twenty-three machine system are given in Table 10.1. These preliminary results show that the reactive power mode controllability has a lower magnitude and opposite phase as compared to the active power mode controllability. The influence of the controlled active power on the modes is thus reduced by the reactive component. This indicates that the proposed control laws will be less effective. It can, however, be beneficial for other purposes: at buses where the total controllability of all modes is very small the switching of large amounts of load will not affect the electro-mechanical dynamics. This can be used in special trading situations where the possibility of temporarily making power available is valuable.

To analyse the impact of reactive power the model needs to represent voltage dynamics. This disqualifies all the analytical models presented in Chapter 2. The proper treatment of reactive power requires more complicated models, where the numerical models used throughout this work are good candidates. The work done on the use of SVCs for damping also points out the importance of realistic load models. An important topic is consequently appropriate modelling of controlled low voltage loads.

Control of Active Power

A continued analysis of using controlled active power at the transmission level, should consider possible implementations. The use of a district heating boiler has already been mentioned. One alternative is to use controlled distribution loads in combination with an SVC at the transmission level. In this case the active power drawn by the loads is used for damping, while the associated modulation of reactive power is compensated for by the SVC. Industrial use of DC or charging stations for electric vehicles may introduce power electronic converters. If they are self commutated they can contribute to reactive compensation at a lower voltage level when their active power consumption is modulated for damping.

The robustness of the proposed control laws deserves a comprehensive treatment. This is even more important when reactive power modulation is involved as its properties vary much with different loading situations.

The linear controllers will benefit from further work on filtering. A simple improvement is to include washout filters, so that they do not respond to offsets in system frequency. The frequency is the same at any point in a radial distribution network as at the point in the transmission network where it is connected. If appropriate filtering can be provided the local bus frequency may thus be determined anywhere in the distribution network.

On-off control can use local bus frequency if the signal could be processed so that it is not disturbed by the switching actions. The procedure for selecting the relay threshold described in Chapter 5 can perhaps be adapted to multi-mode systems. The use of dynamic braking resistors must consider the impact on the fatigue life of turbine-generator shafts [Kundur 1994 p. 1106]. The corresponding effect of transmission loads that are switched to damp oscillations must be investigated. The problem may be eliminated by the fact that the rating of these loads is considerably less than that of a braking resistor.

When a realistic implementation has been designed, it would be interesting to see what influence it has on the scenario of January 1st 1997 described in Fig. 1.2.