9

Simulations

… in which the effects of two linear dampers and the influence of control signal limitations are studied through time simulations of the twenty-three machine system.

Time simulations are often used to verify linearized models. As the linearized models of the three and twenty-three machine systems used in the previous chapters originate from a simulation model in EUROSTAG such a comparison is not critically important yet interesting. In this chapter, time simulations will demonstrate the effect of dampers in the twenty-three machine test system. As the disturbances that are simulated are small, the linear model should be able to describe the results. This offers a new view of the eigenanalysis results.

Section 4.1 suggested that active loads can be switched on and off to damp electro-mechanical oscillations. In the simulation model this behaviour may be approximated by simply limiting the output of the linear damping controller. While being impossible to incorporate into a linear analysis, the consequences of limitations are conveniently studied through time simulations.

The procedure for running a simulation in EUROSTAG consists of three stages: preprocessing, simulation and postprocessing. During the first stage, the model is defined by entering the components of the power system along with their parameters and an operating point (see Fig. 2.1). To study damping, the system needs to be excited and the appropriate dampers should be activated at certain instants. The sequence of such events are written into a file that is read by the simulator. Once the preparations are done, the simulation can start, either from steady state or from a state saved from an earlier simulation. The simulator writes the results into two files that together with the system description files make it possible to reproduce all variables that have been defined. Fig. 9.1 shows the postprocessing required to view the simulation results graphically or read them into Matlab. All graphs in this chapter are produced in Matlab.

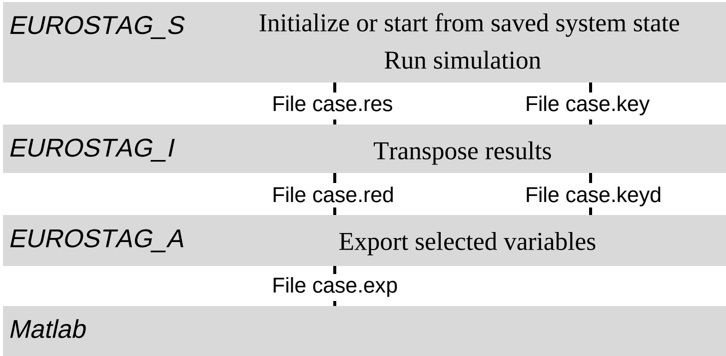

Fig. 9.1 Processing required to analyze results in Matlab. During simulation EUROSTAG_S writes the results to the file case.res. In EUROSTAG_I the results are "transposed" so that the *variables* appear sequentially. EUROSTAG_A features functions for plotting, printing and exporting of any variable to a file that can be read into Matlab.

To study the impact on one mode at a time the modes are selectively excited. This is described and demonstrated in Section 9.1 for each of the three study modes and serves as reference cases with no dampers involved. Section 9.2 gives the results for dampers at the buses N47 and N63 controlled by local bus frequency, while Section 9.3 treats the case with dampers at the buses N47 and N51 controlled by the frequency of the machines A4047_1 and A4051_1 respectively. Section 9.4 briefly studies the effect of limiting the controller output, both symmetrically around zero and asymmetrically to imitate a load that is switched on and off. This is done for a single damper placed at bus N63 and controlled by the local bus frequency. Conclusions are given in Section 9.5.

9.1 Simulating Damping of a Single Mode

In Chapters 5 and 6 it was demonstrated for a single-mode system, that the electro-mechanical mode could be excited by periodically varying an active load using the eigenfrequency of the mode. The same procedure can be used in a multi-mode system, with the difference that the excitation needs to be done at the appropriate place to yield the correct mode shape. This can be checked by comparing the motions of the states with the right eigenvector. If the excitation is properly done, each state will vary sinusoidally with magnitude and phase angle in accordance with the right eigenvector elements as explained in Section 4.2.

In [Eliasson 1990] the machine with the greatest swing energy is excited. The square root of the swing energy for machine i and mode j is,

$$\sqrt{W_{ij}} = M_i^{-1/2}\left|\Phi_j(\Delta\omega_i)\right| \tag{9.1}$$

where M_i is the mass of the machine defined as in (2.21), and $\Delta\omega_i$ is the rotor velocity element for machine i of the j-th right eigenvector. It is pointed out in the discussion of [Eliasson and Hill 1992] that an equivalent energy ranking is obtained directly from the participation factor of the rotor velocity state of machine i in mode j,

$$\sqrt{W_{ij}} = \sqrt{p_{ij}} \tag{9.2}$$

Using (9.1) or (9.2) the machines can thus be ranked after their energy or participation in each of the three modes. Doing this shows that the machines with the greatest swing energy are A4051_1 and A4051_2 for Modes 1 and 2, while A4047_1 and A4047_2 have the most swing energy for Mode 3. The excitation using active power will therefore be done close to these machines, at bus N51 for Modes 1 and 2 and at bus N47 for Mode 3. Excitation for 60 s is found appropriate and is used in all cases. Appendix D describes the damping controllers with excitation facilities.

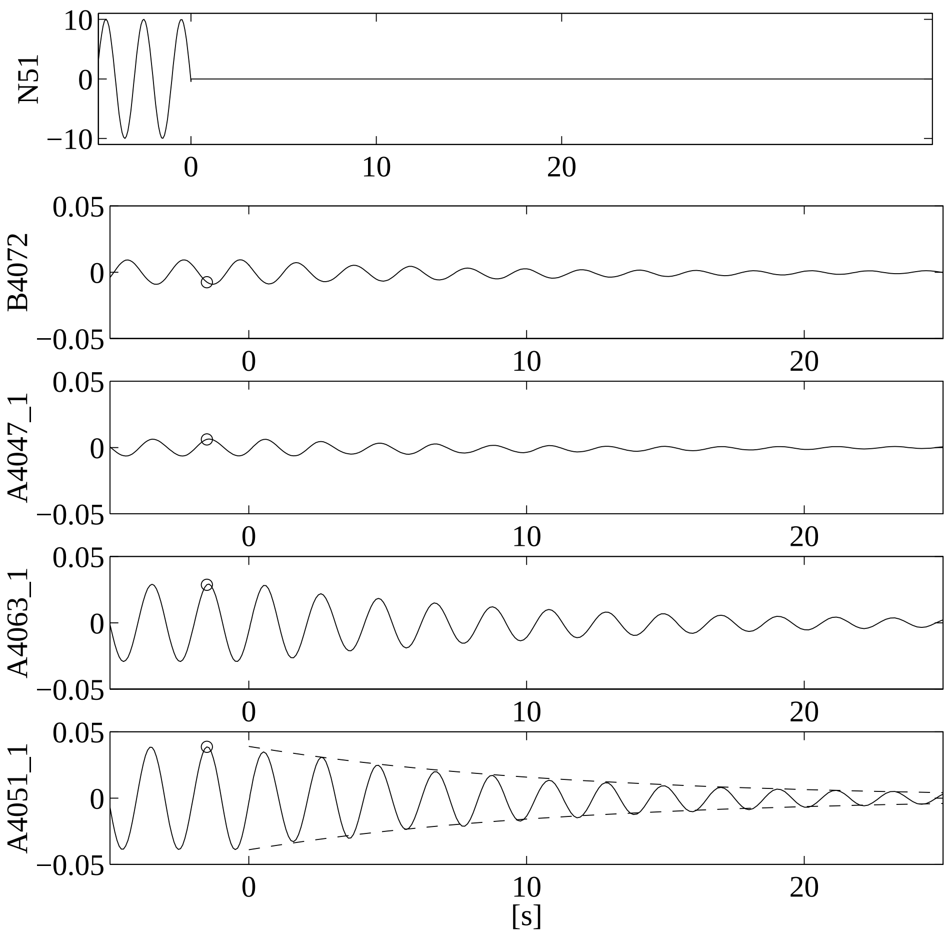

Fig. 9.2 Active power at bus N51 in MW (top) for excitation of Mode 1. Rotor angular frequencies in Hz of the machines B4072, A4047_1, A4063_1 and A4051_1 (below), where the values at one instant are indicated by circles (o). The dashed line is an exponential decay with the time constant 11 s.

The effect of injecting a sinusoidally varying active power with the frequency of Mode 1 (3.09 rad/s according to Table 2.2) at bus N51 is demonstrated in Fig. 9.2 which shows the frequencies of some representative machines. Shortly before time reaches zero the frequency signals are sampled, which is indicated by circles. The sign and magnitude of each signal agrees well with the mode shape for the rotor angles in Fig. 2.9a. When the excitation ceases at time zero, the system performs the free motion of (2.9) with only Mode 1 involved. According to (2.9), the envelope of the free oscillation should be an exponential with a time constant equal to the inverse of the negative real part of the eigenvalue. The prediction is verified by the dashed lines, which illustrate an exponential decay with the time constant 11 s = 1/0.09 s.

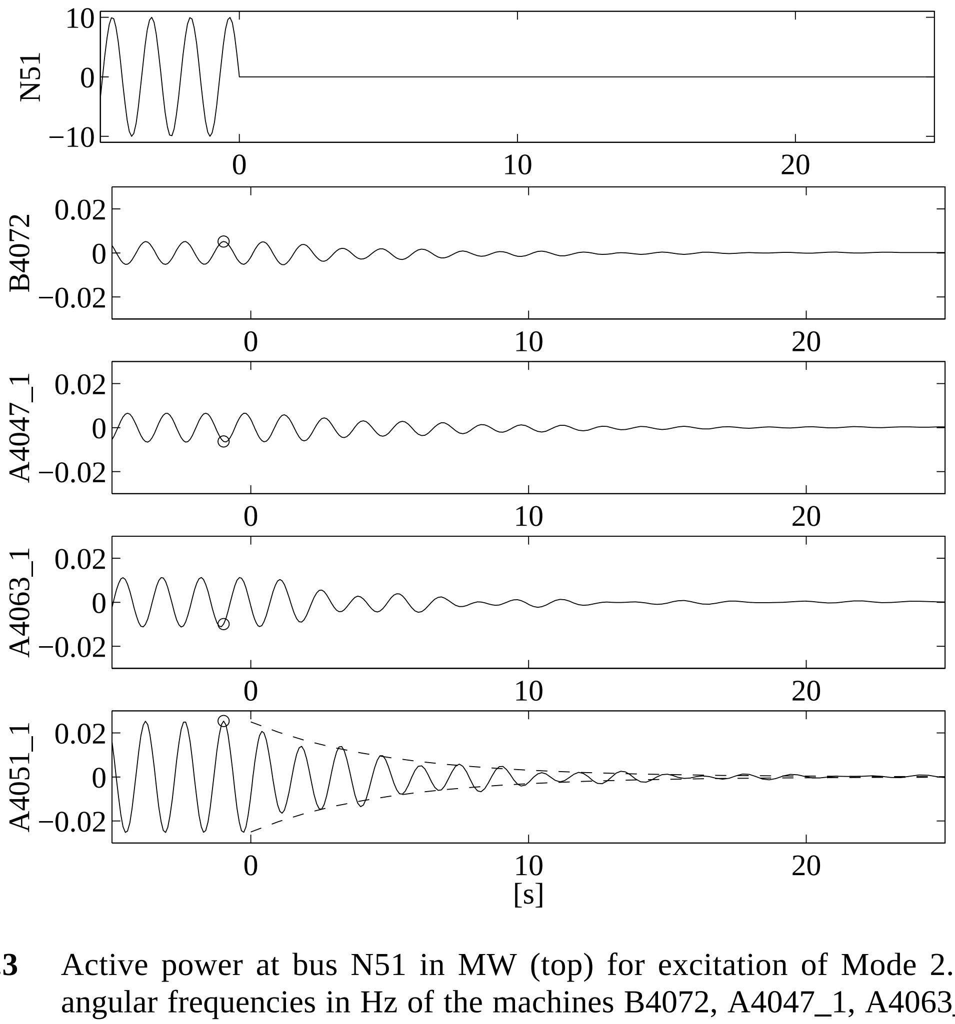

Fig. 9.3 Active power at bus N51 in MW (top) for excitation of Mode 2. Rotor angular frequencies in Hz of the machines B4072, A4047_1, A4063_1 and A4051_1 (below), where the values at one instant are indicated by circles (o). The dashed line is an exponential decay with the time constant 4.8 s.

Table 2.2 shows that the frequency of Mode 2 is 4.47 rad/s. Simply changing the frequency of the excitation to this value yields the results of Fig. 9.3. Sampling the signals shows that the mode shape of Mode 2 has been obtained. Damping in the simulation agrees well with the dashed exponentials based that have a time constant of 4.8 s = 1/0.21 s.

For Mode 3, the most active machines are A4047_1 and A4047_2 and therefore the excitation is done at bus N47. Sinusoidal excitation with the frequency set to 4.64 rad/s yields the results of Fig. 9.4. When the sinusoidal motions are stable, the circles indicate that the machines move according to the mode shape in Fig. 2.9a. The time constant of the exponentials is now 4.5 s = 1/0.22 s.

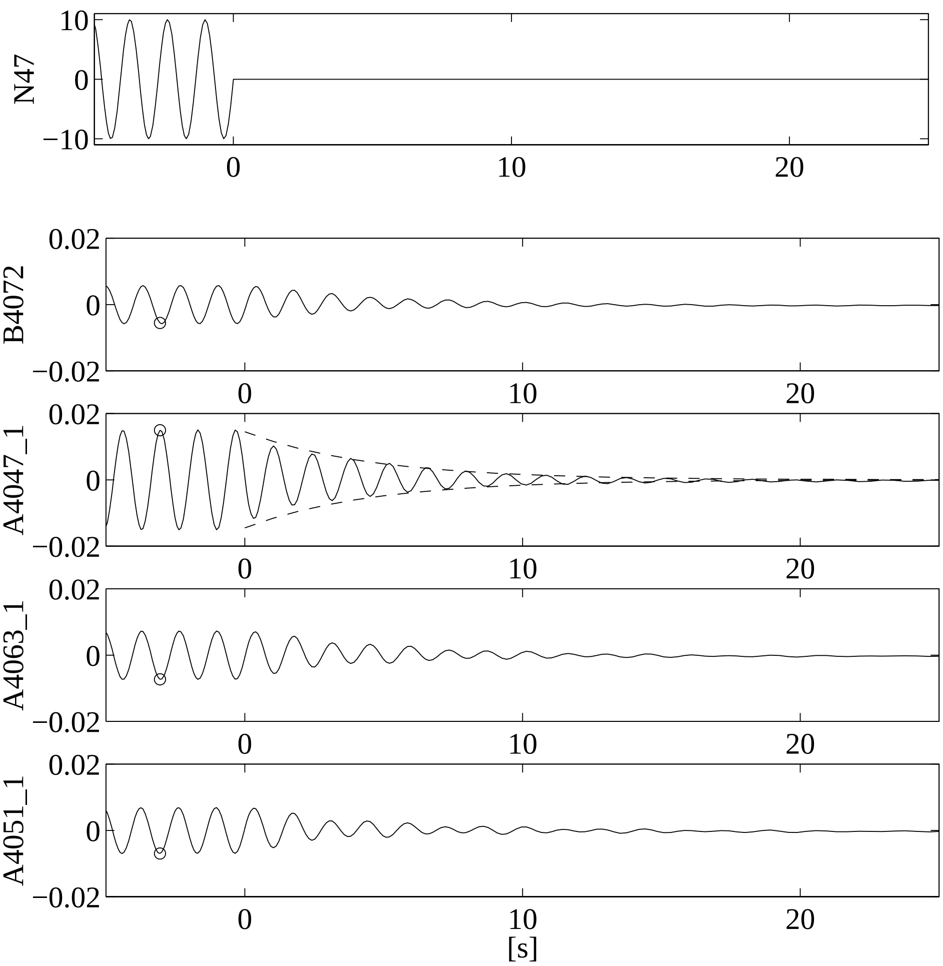

Fig. 9.4 Active power at bus N47 in MW (top) for excitation of Mode 3. Rotor angular frequencies in Hz of the machines B4072, A4047_1, A4063_1 and A4051_1 (below), where the values at one instant are indicated by circles (o). The dashed line is an exponential decay with the time constant 4.5 s.

The magnitude of the excitation is 0.1 p.u. or 10 MW for all three modes. Due the different damping of the modes, the maximum frequency deviations are also different in the three cases.

9.2 Local Bus Frequency

In Chapters 7 and 8 it was shown that active power injection at the buses N47 and N63 controlled in proportion to the local bus frequency can increase damping of the Modes 1, 2 and 3 substantially. This can be demonstrated by simulating the impact of the dampers on the individual modes. The modes are excited as in Section 9.1, but at time zero when the excitation ceases the dampers are activated. This is done by changing the gains of the dampers from zero to the values selected in Chapter 8: 2.8 p.u./(rad/s) for the damper at bus N47 and 4 p.u./(rad/s) for the one at bus N63.

An alternative is to let the damper by active also during excitation. This eliminates the transient associated with damper activation that excites other modes. The behaviour for times less than zero will, on the other hand, be different. The decay then starts at different amplitudes in the cases with and without dampers, which makes comparisons less straightforward.

The results for Modes 1, 2 and 3 are given in Figs 9.5-9.7, which can be compared to the free motion as shown in Figs 9.2-9.4.

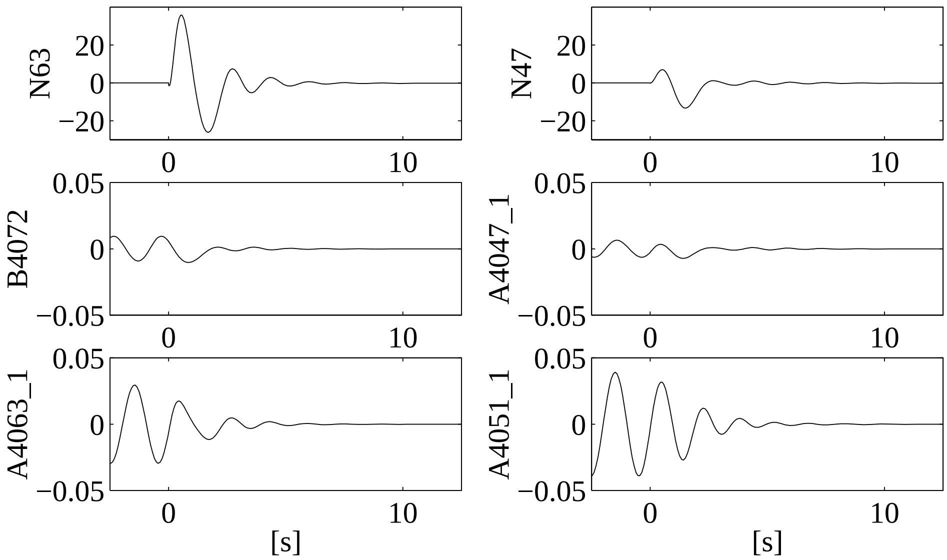

Fig. 9.5 Damping of Mode 1 after 60 s of excitation at bus N51: active power controlled at buses N63 and N47 in MW (top) controlled by local bus frequency. Rotor angular frequencies in Hz of the machines B4072, A4047_1, A4063_1 and A4051_1 (below).

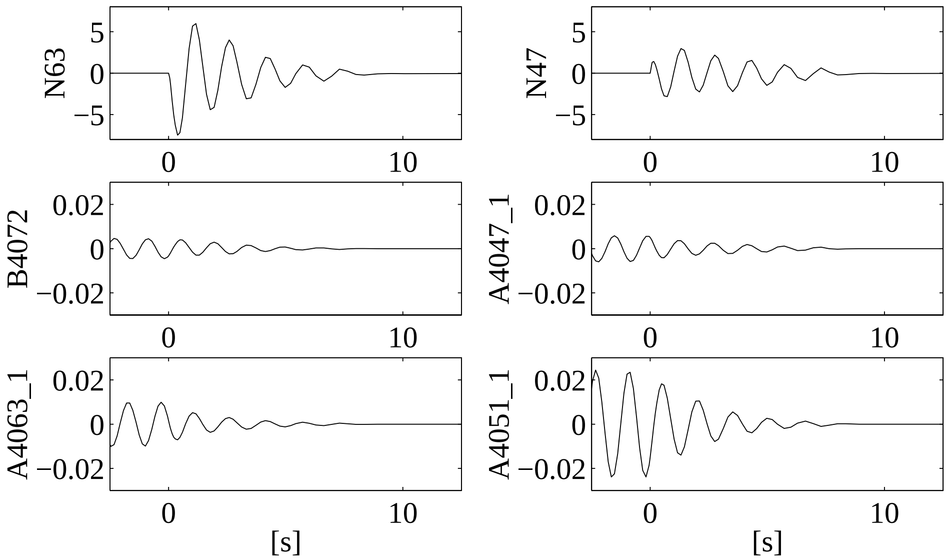

Fig. 9.6 Damping of Mode 2 after 60 s of excitation at bus N51: Active power controlled at buses N63 and N47 in MW (top) controlled by local bus frequency. Rotor angular frequencies in Hz of the machines B4072, A4047_1, A4063_1 and A4051_1 (below).

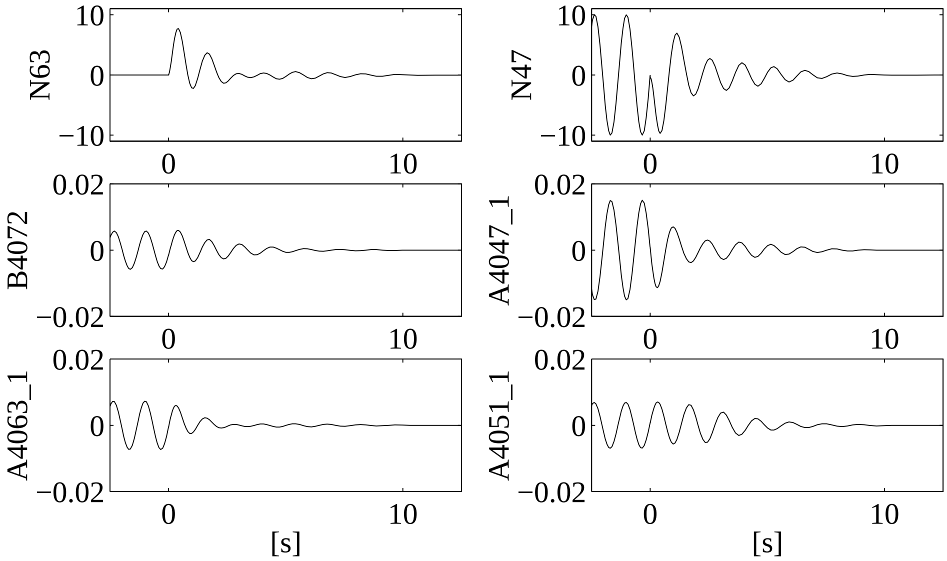

Fig. 9.7 Damping of Mode 3 after 60 s of excitation at bus N47: Active power controlled at buses N63 and N47 in MW (top) controlled by local bus frequency. Rotor angular frequencies in Hz of the machines B4072, A4047_1, A4063_1 and A4051_1 (below).

As the dampers are not restricted in frequency, they transfer some swing energy to other modes when activated. A pure exponential can therefore not be fitted to the envelope of the damped oscillation. The eigenvalues of the modes shown in Fig. 8.13 predict that Mode 1 is damped twice as fast as Modes 2 and 3. This more relative measure agrees well with the simulations.

Note that due to the difference in magnitudes for the oscillations of the four machines, it is difficult to make any statements about which damper is most effective in each case.

Robustness to Changes in Network Topology

The analysis has so far treated the fault case with the double line between the buses N4044-N4045 out of service. For the case when no dampers are involved, the state of this line affects mainly the frequencies of the electro-mechanical modes, as shown by the left part of Fig. 9.8. All expressions for the eigenfrequency of the mechanical systems involve one or more spring coefficients. As the mechanical equivalent to deleting a line is to remove a spring, it is expected that the line influences the frequency of the electro-mechanical modes of the power system.

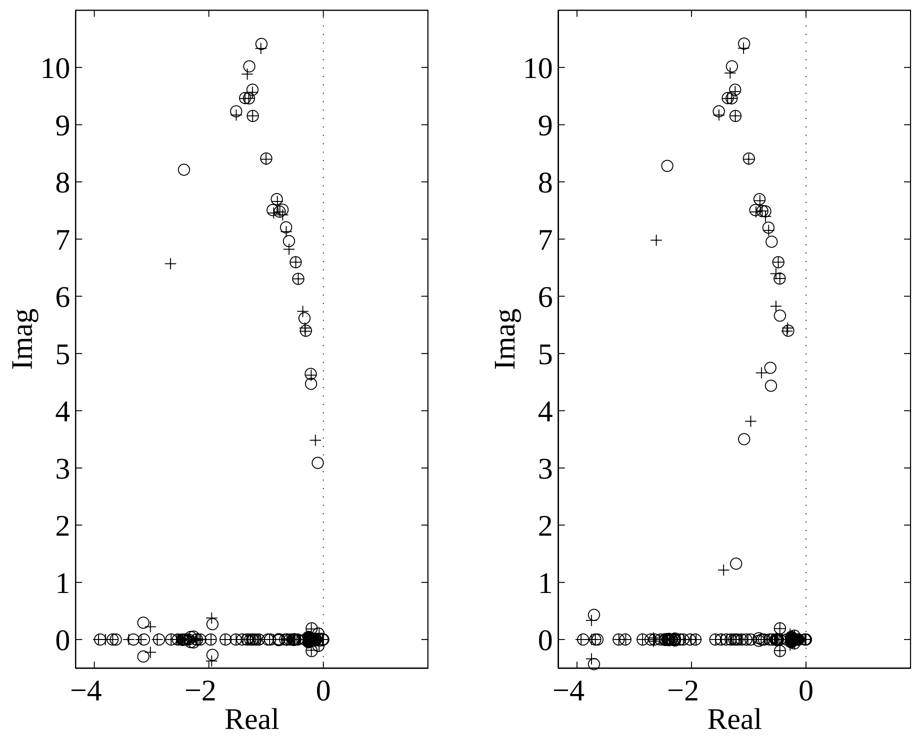

Fig. 9.8 Eigenvalues for line N4044-N4045 in (+) and out (o) of service, when damper gains are zero (left) and take the optimum values (right). Active power controlled by local bus frequency at buses N47 and N63.

The dampers at the buses N47 and N63 are introduced to increase the damping of the electro-mechanical modes. The setting of their gains to 2.8 and 4 p.u./(rad/s) respectively is based on the case with the line N4044-N4045 disconnected. The right part of Fig. 9.8, shows the eigenvalue locations resulting from these gains both when the line is in and out of service. It is evident that the damping of all modes is approximately the same in the two cases.

Changes in the network topology are fairly drastic and it can hardly be expected that the eigenvalue locations should be unaffected. The results given here are very limited, but indicate good robustness properties and show that the essence of the proof in Section 4.3 is maintained also for large gains, where it is not formally valid.

9.3 Closest Machine Frequency

Active power injection at the buses N47 and N51, controlled by the rotor angular velocities of the machines A4047_1 and A4051_1 yield considerable damping to the three selected modes. The effect of the dampers on the modes can be studied through time simulations. The procedure is the same as in the previous section: one mode at a time is excited as in Section 9.1 and the dampers are activated when the excitation ceases at time zero. The gains are those arrived at in Chapter 8: 2.6 p.u./(rad/s) for the damper at bus N47 and 2.4 p.u./(rad/s) for the one at bus N51.

The effect of the dampers on Modes 1, 2 and 3 is shown in Figs 9.9-9.11, and again the free motions of the modes in Figs 9.2-9.4 serve as reference cases.

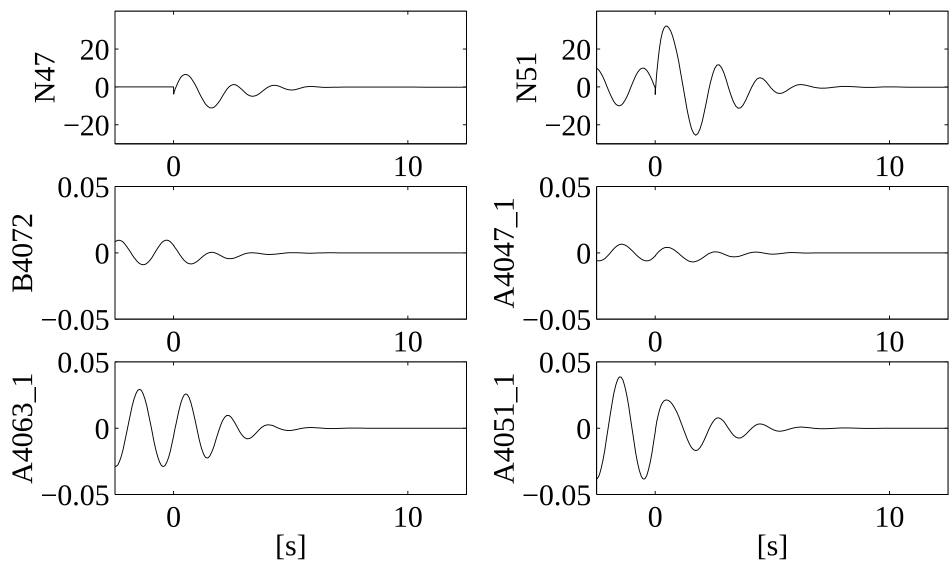

Fig. 9.9 Damping of Mode 1 after 60 s of excitation at bus N51: active power at N47 and N63 in MW (top) controlled by the machine frequency of A4047_1 and A4063_1 respectively. Rotor angular frequencies in Hz of the machines B4072, A4047_1, A4063_1 and A4051_1 (below).

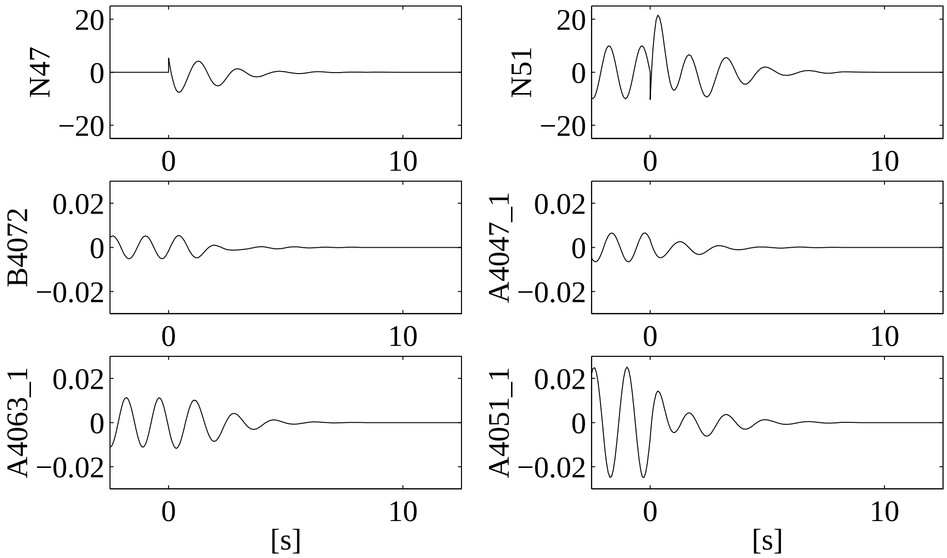

Fig. 9.10 Damping of Mode 2 after 60 s of excitation at bus N51: active power at N47 and N63 in MW (top) controlled by the machine frequency of A4047_1 and A4063_1 respectively. Rotor angular frequencies in Hz of the machines B4072, A4047_1, A4063_1 and A4051_1 (below).

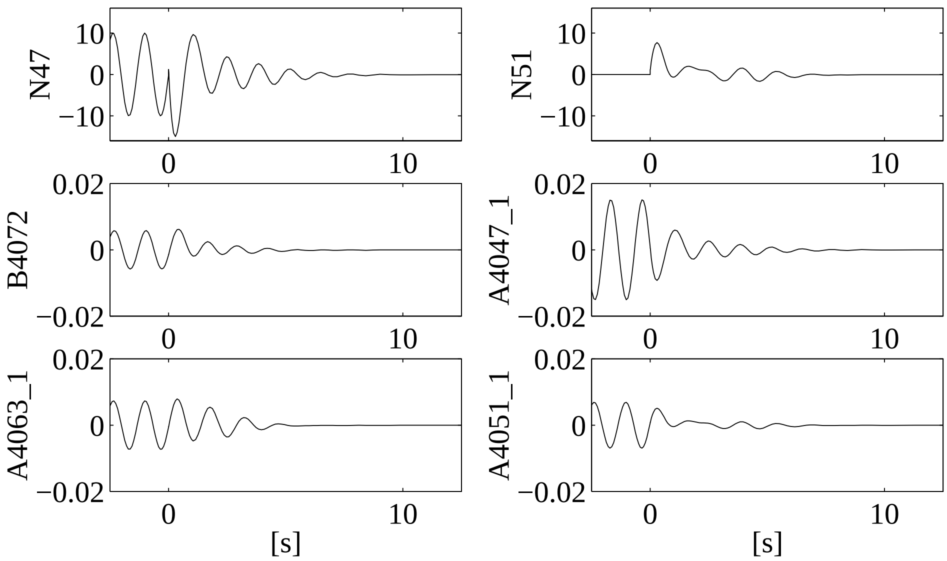

Fig. 9.11 Damping of Mode 3 after 60 s of excitation at bus N47: active power at N47 and N63 in MW (top) controlled by the machine frequency of A4047_1 and A4063_1 respectively. Rotor angular frequencies in Hz of the machines B4072, A4047_1, A4063_1 and A4051_1 (below).

All three modes are damped in roughly the same time. This is expected as the eigenvalues of the three modes have the same real part in Fig. 8.17. The waveforms are similar to the bus frequency case.

Robustness to Changes in Network Topology

The eigenvalue locations for the case with dampers engaged and the line N4044-N4045 in and out of service are shown in the right part of Fig. 9.12. The dampers are beneficial in both cases, but the differences due to the state of the line are greater here than when using bus frequency as feedback signal. The damping of Mode 1 is for example reduced by 50 % when the line is reinserted. No general conclusions can be drawn.

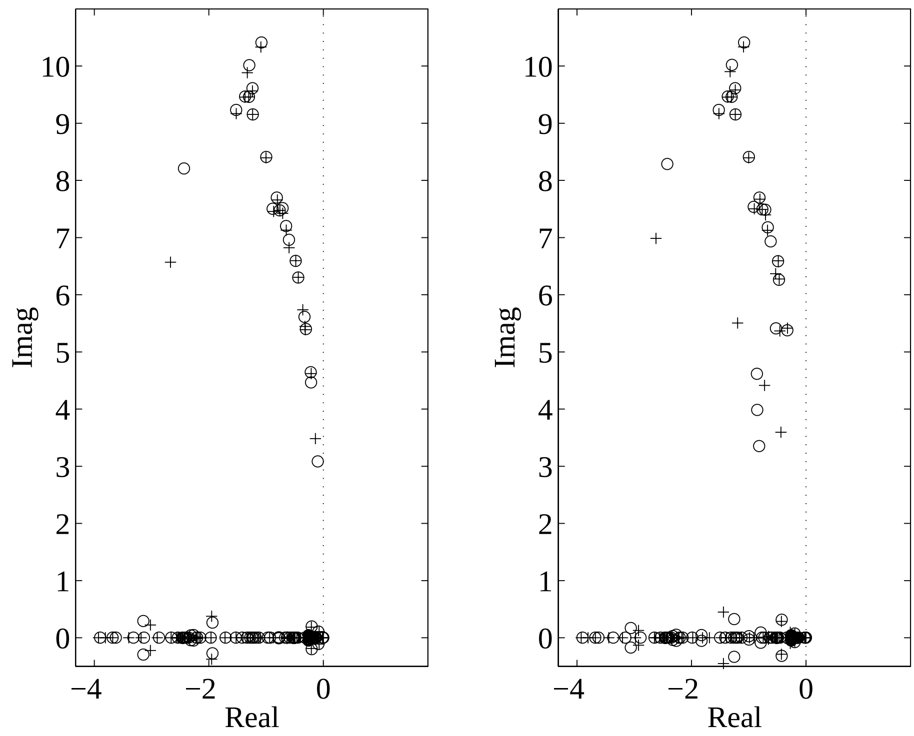

Fig. 9.12 Eigenvalues for line N4044-N4045 in (+) and out (o) of service, when damper gains are zero (left) and take the optimum values (right). Active power at buses N47 and N51 controlled by the machine frequency of A4047_1 and A4063_1 respectively.

9.4 On-off Control

In contrast to linear analysis techniques, time simulation is not restricted to linear control laws. A nonlinear alternative of great practical value is on-off control, which was used in Chapters 5 and 6. Simulation of controllers with relay characteristics may prove difficult. The approximate effect of on-off control may, however, be studied by modifying the linear controller so that its output signal is a sequence of pulses. Limiting the controller output gives a maximum output signal amplitude. The controller is turned off after a certain time to imitate that the on-off controller can only damp the oscillation down to a certain amplitude.

On-off control requires asymmetric limitation of the controller output, and thus gives an offset in the output signal. In order to study the effects of limitation and offset separately, the limitation is first symmetric. Fig. 9.13 shows the damping of Mode 1 using one damper at bus N63 controlled by local bus frequency. The controller has a gain of 4 p.u./(rad/s) and its output is limited to ±1 MW. After five oscillation periods the damper is disengaged.

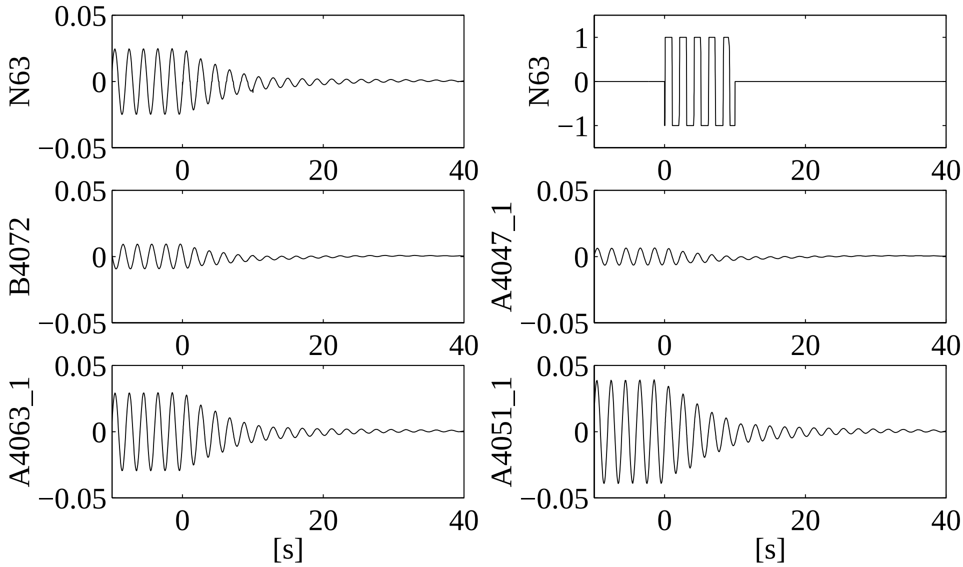

Fig. 9.13 Damping of Mode 1 after excitation at bus N51: Active power at bus N63 controlled by local bus frequency but limited to ± 1 MW. Frequency deviation in Hz at bus N63 (top left) and damper output in MW (top right). Rotor angular frequencies in Hz of the machines B4072, A4047_1, A4063_1 and A4051_1 (below).

The effect of the limited damper is a linear decay of the oscillation. This is very similar to the results in Chapters 5 and 6. The reduction of the control signal magnitude leads to slower damping than with unlimited linear control.

The offset is now added by changing the output limits to 0 and +2 MW, which gives the results of Fig. 9.14.

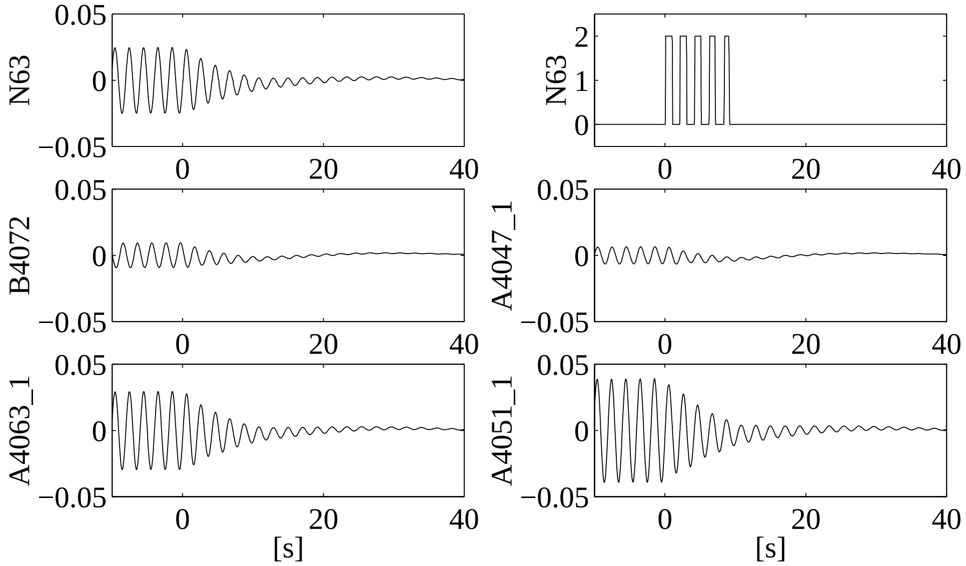

Fig. 9.14 Damping of Mode 1 after excitation at bus N51: Active power at bus N63 controlled by local bus frequency but limited to be between 0 and 2 MW. Frequency deviation in Hz at bus N63 (top left) and damper output in MW (top right). Rotor angular frequencies in Hz of the machines B4072, A4047_1, A4063_1 and A4051_1 (below).

The damping effect on the oscillation is the same as before, but the offset in the control signal excites the rigid body mode leading to a temporary reduction in the frequency of all machines. This is handled by the turbine governors in the system.

The simple study indicates that on-off control is efficient also in a realistic multi-machine system. A real implementation of an on-off controller faces two potential problems. The first one is the direct influence of the switching on the measured signal if this is local bus frequency. This may be solved by additional filtering that can reject the switching disturbances or by instead using machine frequency for feedback. The second problem is the selection of the frequency deviation at which the active load should be switched on. Chapter 5 suggested a test to determine the minimum value of this parameter, called $\Delta\omega_{on}$. It is possible that this test can be used to give one value of $\Delta\omega_{on}$ for each of the different modes. By choosing the largest of these values limit cycles are avoided. The problem is to assure that the final value is valid for all operating points and network configurations that can occur.

On-off control in itself has two properties that need to be considered. One is the possibly detrimental impact on the torsional dynamics of long turbine-generator shafts. This needs further investigation. It is also important to realize that the damping of the system in the linear sense is unaltered: once the oscillation amplitude is small enough it decays as for the uncontrolled system. This motivates the existence of damping systems with continuous action such as PSS or the supplementary controllers of phase controlled power electronics such as HVDC.

9.5 Conclusions

The simulations in this chapter confirm the results arrived at through eigenanalysis in Chapter 8. The individual modes are excited by active power modulation with the mode frequency close to the machine that is most active. The gains arrived at in Chapter 8 provide very good damping of all three study modes both when using local bus frequency and machine frequency for feedback. With the dampers engaged the envelope of the oscillations does not decay as a pure exponential, which indicates the presence of other modes.

Eigenvalue locations are shown for the selected damper gains with the double line N4044-N4045 in service. It is shown that the dampers have a beneficial effect on damping regardless if the line is in or out of service.

The output of a linear damping controller with local bus frequency input is limited to imitate on-off control. It is shown that symmetric limitation of the controller output prolongs the time it takes to damp an oscillation. Asymmetric limitation gives the same damping performance but excites the rigid body mode.