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Study on Oscillation Damping Effects of Power System Stabilizer with Eigenvalue Analysis Method for the Stability of Power Systems

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1. Introduction

With the increasing of the scale and the complexity of the interconnected power networks, the problems on the various potential power oscillations, which have the nervous damage against the system stability and the security operation, have been drawn more and more attention (Kunder, 1994; Anderson & Fouad, 2003; Bikash & Balarko, 2005). Power system oscillations were first reported in northern American power network in 1964 during a trial interconnection of the Northwest Power Pool and the Southwest Power Pool (Schleif et al., 1966). Up to now, generally speaking, power oscillations could be divided into three kinds of types, that is, local mode, inter-area mode, and global mode. Local oscillations lie in the upper part of that range and consist of the oscillation of a single generator or a group of generators against the rest of the system. In contrast, inter-area oscillations and global oscillations are in the lower part of the frequency range and comprise the oscillations among groups of generators. As a classic oscillation mode, there are relative mature technologies and devices such as kinds of power system stabilizers equipped as a part of the additional excitation system of machine unit to provide the efficient damping ratio to suppress the local oscillation. Nevertheless, as for the inter-area and the global oscillation mode, the classic stabilizer cannot play an important role to damp such oscillation very well. The leaded result is that the line power transmitted from one area to another will form the instable oscillation with the unease attenuation characteristic.

As a result, if there is no the effective solution to suppress these power system oscillations, the instability could lead the machine unit cut even the networks breakout. Nowadays, severe consequences have been coursed by large-scale blackouts, such as blackouts in the USA, Europe and many other countries in recent years. Moreover, blackouts not only lead to financial losses, but also lead to potential dangers to society and humanity. So it is necessary to pay attention to keep the stability and security of the electrical power systems. Up to now, many authors are trying to develop new methods to enhance the various types of

hand, the power system stabilizer, using the speed signal ($\Delta\omega$) as input signal, will have a positive damping torque component ΔM_{p2} . So, the synthesis torque with positive synchronous torque and the damping torque can enhance the capacity of the damping oscillation. Fig.2.2 shows the structure diagram of power system stabilizer (PSS).

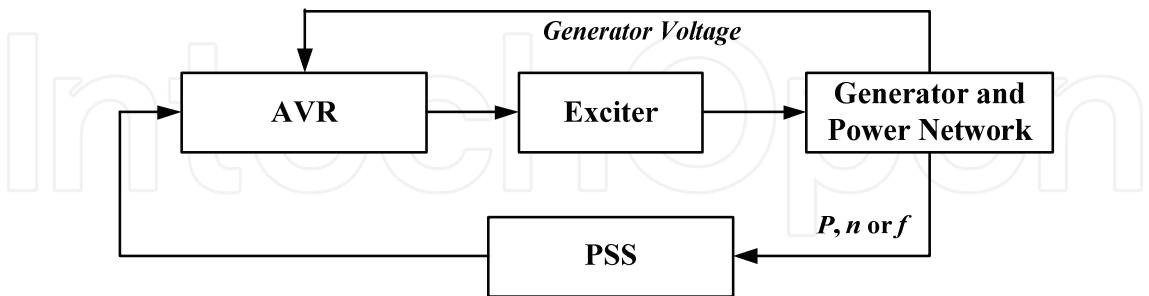


Fig. 2.2. The structure diagram of power system stabilizer(PSS)

2.2 Structure Types (IEEE Power Engineering Society (1992))

Power system stabilizers (PSS) are added to excitation systems to enhance the damping of power system during low frequency oscillation. For the potential power oscillation problem in the interconnected power networks, the power system stabilizers solution is usually selected as the relative practical method, which can provide the additional oscillations damping enhancement through excitation control of the synchronous machines.

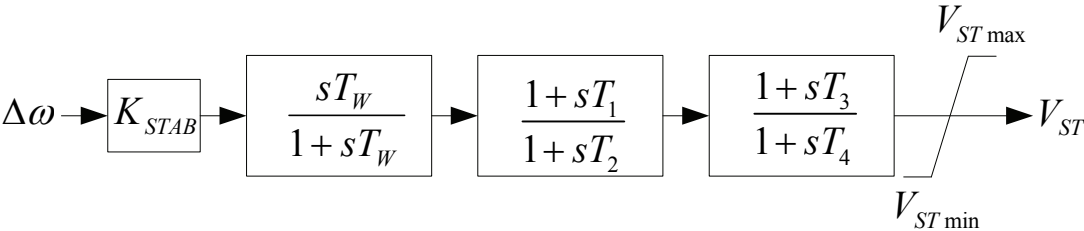


Fig. 2.3. General power system stabilizer model

Fig.2.3 shows the general power system stabilizer model with a single input, and from which, it can be seen that as for the additional damping control of the excitation system of the synchronous machines, basically the general input signal is the rotor speed deviation. The damping amount is mostly determined by the gain K_{STAB} , and the following sub-block has the high-pass filtering function to ensure the stabilizer has the relative better response effect on the speed deviation. There are also two first-order lead-lag transfer functions to compensate the phase lag between the excitation model and the synchronous machine. Fig2.4 shows the power system stabilizer mode with dual-input singles, which is designed by using combinations of power and speed or frequency as stabilizing singles. From it, it can be seen this model can be used to represent two distinct types of dual-input stabilizer implementations. One hand, as for electrical power input stabilizers in the frequency range of system oscillations, they can use the speed or frequency input for the generation of an equivalent mechanical power signal, to make the total signal insensitive to mechanical power change. On the other hand, by combining the speed /frequency and electrical power,

they can use the speed directly (i.e., without phase-lead compensation) and add a signal proportional to electrical power to achieve the desired stabilizing signal shaping.

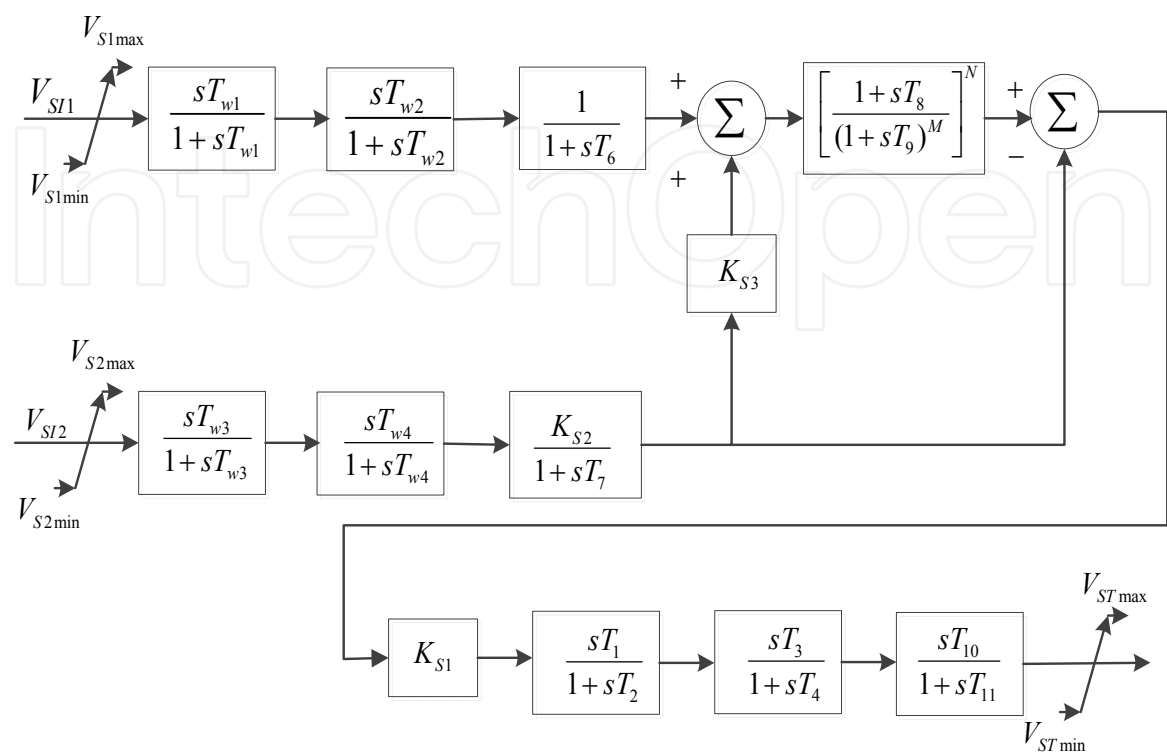


Fig. 2.4. Power system models with dual inputs

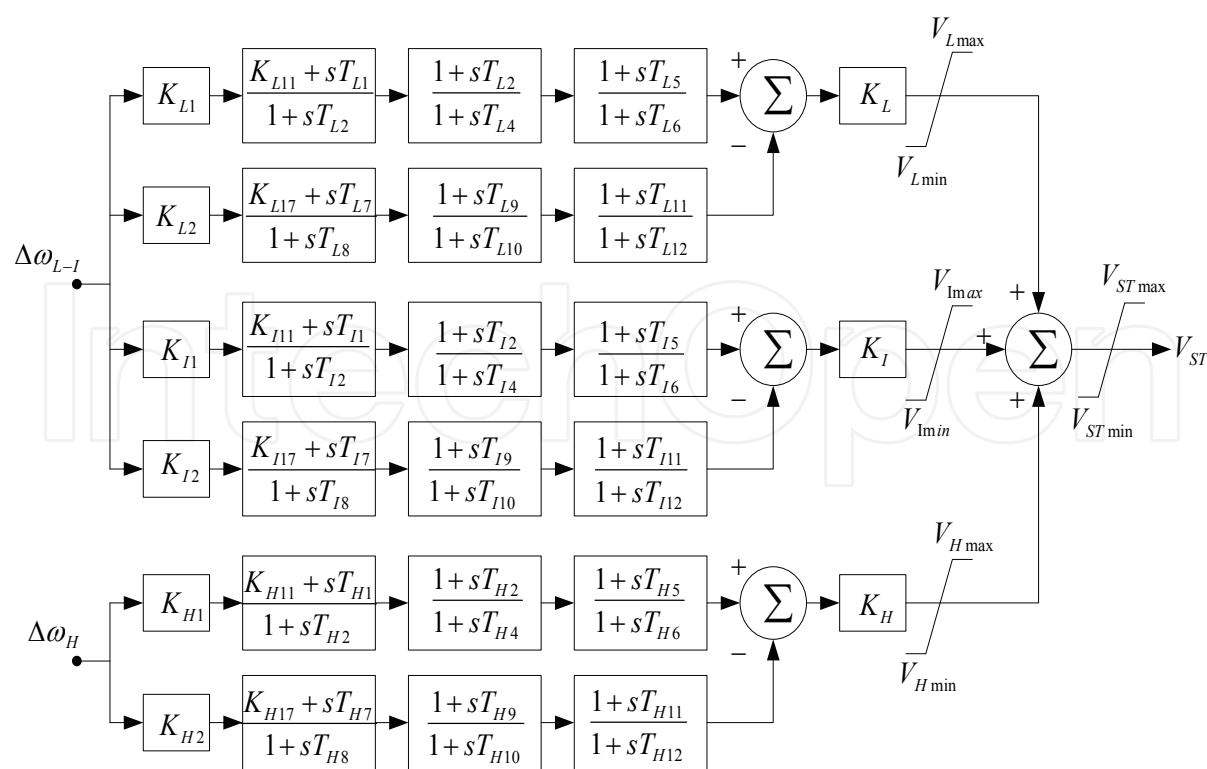


Fig. 2.5. Multi-band power system stabilizer model

Although the conventional stabilizer model has a certain damping effect on the active power oscillation, the action on the special oscillation such as inter-area or global oscillation cannot be considered very well. To solve such oscillation problems, various methods have been provided with the special consideration of the inter-area or global oscillation. Here, the multi-band power system stabilize shown in Fig.2.5 is studied in detail to the inter-area oscillation environment.

In essence, the standardized multi-band power system stabilizer is the multi-structure of the general stabilizer with three kinds of frequency bands action function to consider the mostly potential power system oscillations. In that case, the measured input signal, which has been transferred through high-pass filter sub-block, can be used by the related gain, phase compensation block, and limiter to generate the special output control signal for the local oscillation damping mode. Similarly, the measured input signal, and the related transfer function blocks are used to damp the impossible inter-area and global power oscillation.

3. Eigenvalue Analysis Method

3.1 Small Signal Modelling

The behaviour of a normal power system can be described by a set of first order nonlinear ordinary differential equations and a group of nonlinear algebraic equations. It can be written in the following form by using vector-matrix notation:

$$\begin{aligned}\dot{x} &= f(x, w, u) \\ 0 &= g(x, w, u) \\ y &= h(x, w, u)\end{aligned}\tag{1}$$

In which, x is vector of state variables, such as rotor angle and speed of generators. The column vector w is the vector of bus voltages. u, y is the input and output vector of variables respectively.

Although power system is a nonlinear, it can be linearized by small signal stability at a certain operating point. (x_0, w_0, u_0) is supposed to be a equilibrium point of this power system, then based on direct feedback, it can be expressed as the following standard form (Zhang et al., 2006):

$$\begin{cases} \Delta\dot{x} = A\Delta x + B\Delta u \\ \Delta y = C\Delta x + D\Delta u \end{cases}\tag{2}$$

where Δx , Δy , and Δu express state, output, and input vector, respectively; A , B , C , and D expresses the state, control or input, output, and feed forward matrices, respectively.

3.2 Damping Ratio and Linear Frequency

The eigenvalues λ of A matrices can be obtained by solving the root of the following characteristic equation:

$$\det(\lambda I - A) = 0\tag{3}$$

As for any obtained eigenvalues $\lambda_i = \sigma_i \pm j\omega_i$, the damping ratio ρ and oscillation frequency f can be defined as follows:

$$\rho_i = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \quad (5)$$

$$f_i = -\frac{\omega_i}{2\pi} \quad (6)$$

The above parameters ρ_i and ω_i can be used to evaluate the damping effects of the power system stabilizers on the power oscillation. It is obvious that the higher damping ratio and the lower oscillation frequency, the better damping effects to enhance the stability of the power system, so as for the solution with power system stabilizers to damp the power oscillation, the best scheme is that install the power system stabilizer for every machine in the power networks, in that case, it can inevitably obtain the best damping effects. Nevertheless, such installation scheme must increase the investment cost, which may be not the economical solution scheme. So, with the precondition of demand damping effects within the specific limits, the optimal arrangement for stabilizers in the areas and the machines of the power networks could be valuably performed with the consideration of economical factor, which will be discussed in the case study.

3.3 Participation Factor

if λ_i is an eigenvalue of A , v_i and w_i are non zero column and row vectors respectively such that the following relations hold:

$$Av_i = \lambda_i v_i, \quad i = 1, 2, \dots, n \quad (7)$$

$$w_i A = \lambda_i w_i, \quad i = 1, 2, \dots, n \quad (8)$$

where, the vectors v_i and w_i are known as right and left eigenvectors of matrix A . And they are henceforth considered normalised such that

$$w_i \cdot v_i = 1 \quad (9)$$

Then the participation factor p_{ki} (the k th state variable x_k in the i th eigenvalue λ_i) can be given as

$$p_{ki} = |v_{ik}| |w_{ki}| \quad (10)$$

where w_{ki} and v_{ki} are the i th elements of w_k and v_k , respectively.

4. Cases Study

4.1 Four-Machine Two-Area Test System

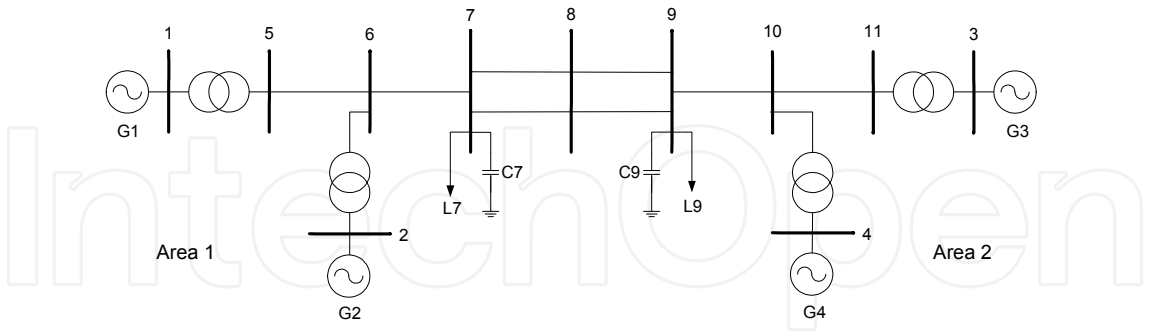
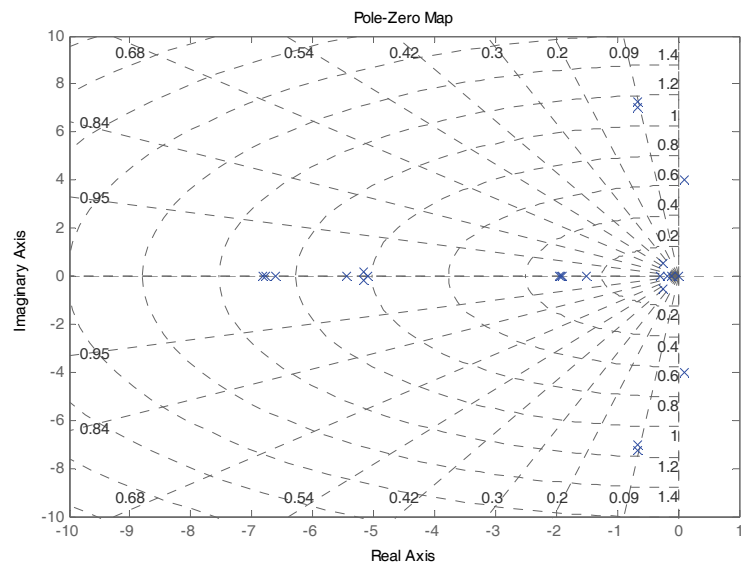
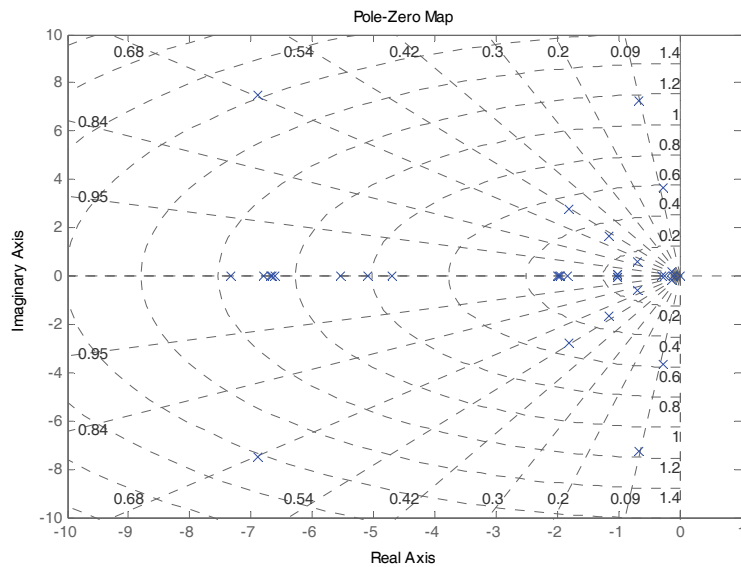


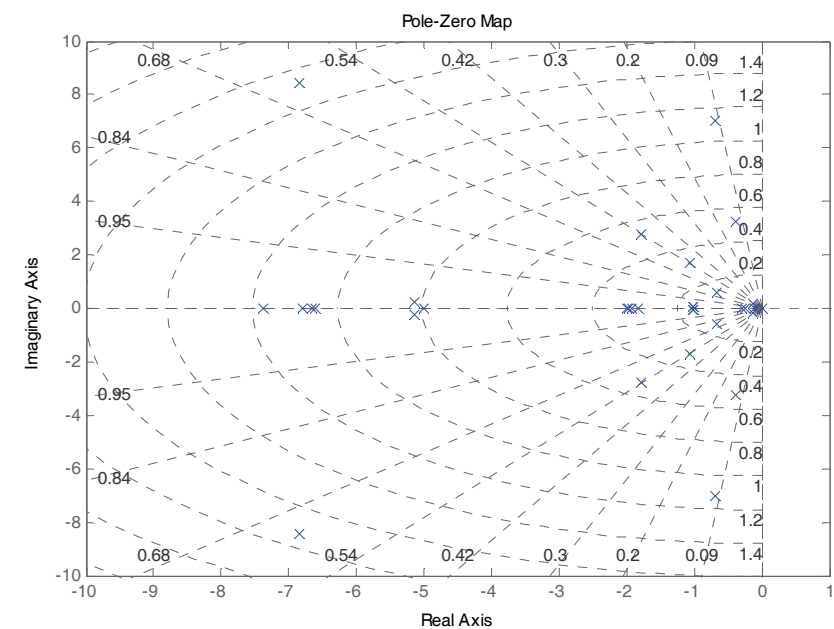
Fig. 4.1. Two-area test system



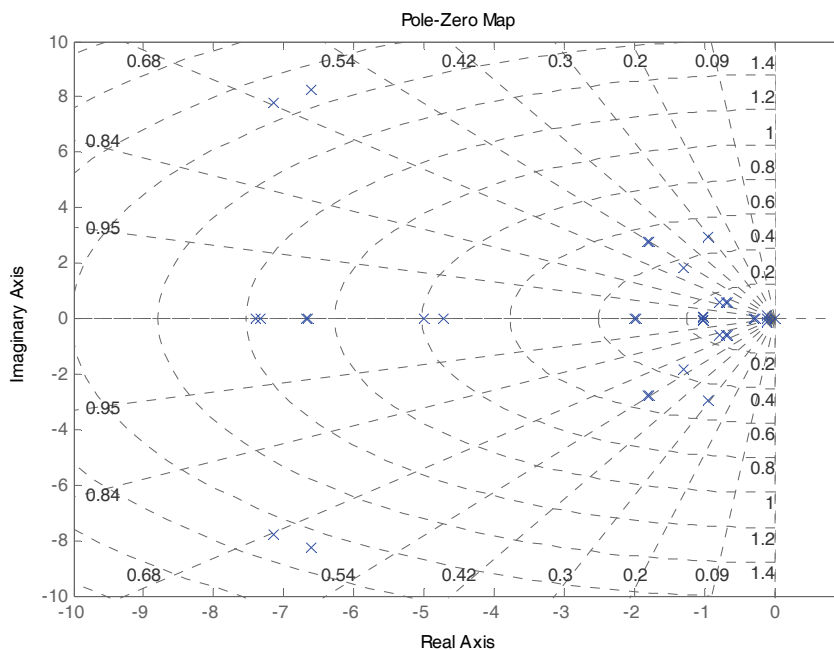
(a)



(b)



(c)



(d)

Fig. 4.2. Dominant eigenvalues of the two-area test system, (a) no stabilizer; (b) with stabilizers in area-1; (c) with stabilizers in area-2; (d) with stabilizers in both areas.

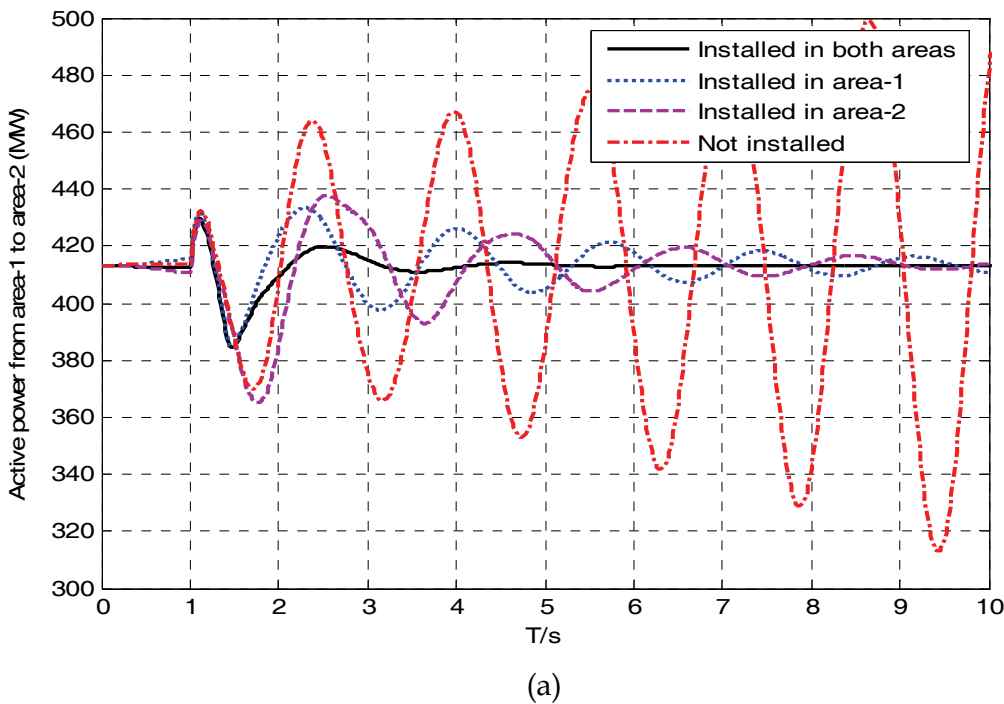
Fig. 4.1 shows the two-area benchmark power system(Kunder,1994) for inter-area oscillation studies. From this, it can be seen that there are two machines in each area, and two-parallel 220km transmission lines are used to interconnect the both areas. In order to discuss the impacts of different stabilizer arrangement on the power oscillation damping, as for the area arrangement scheme, the following tests have been performed: (a) install stabilizers in both areas; (b) install stabilizers in area-1; (c) install stabilizers in area-2; (d) not install stabilizers.

As for the machine arrangement scheme, the following tests have been performed: (a) install stabilizers for G1~G4; (b) install stabilizers for G1 and G3; (c) install stabilizer for G1; (d) no machine installed stabilizer.

It is worth to remark that such testes mentioned above are achieved by small disturbance for the G1's reference voltage step from 1.0pu to 1.02pu with the duration time of 0.2s. In the corresponding situations, the small signal stability for the inter-area oscillation has been analyzed in detail with the eigenvalues analysis method.

Fig. 4.2 shows dominant eigenvalues analysis results for the two-area test system with different area stabilizer arrangement. From Fig. 4.2(a), it can be seen that as for the open-loop system without any installed stabilizer, there is some instability for the inter-area mode. By installing the stabilizers in area-1, the inter-area oscillation mode has been suppressed, and meanwhile the local mode in area-1 between G1 and G2 is also enhanced greatly shown in Fig.4.2 (b). Such similar damping effect shown in Fig.4.2 (c) is also achieved by installing stabilizers in area-2. If we stall the stabilizers in both area-1 and -2, both the inter-area mode and two local modes can be obtained the high damping ratio and lower oscillation frequency shown in Fig. 4.2(d).

In order to represent the related oscillation effects, the time domain for the test system has been performed. Fig. 4.3 shows the simulation results on the line power flow from area 1 to area 2. From this, it can be found that the arrangement on stabilizer installation for every machine in both areas has the best damping effects on inter-area oscillation, which is in unison with the above dominant eigenvalues analysis results. If there is no any stabilizer for machine in both areas, the inter-area oscillation cannot be avoided. The other arrangement schemes exists a certain difference. By comparative analysis, it can be found that the arrangement scheme on installing the stabilizer for G1 in area-1 and G3 in area-2 is the relative optimal solution to damp the inter-area oscillation between area-1 and 2.



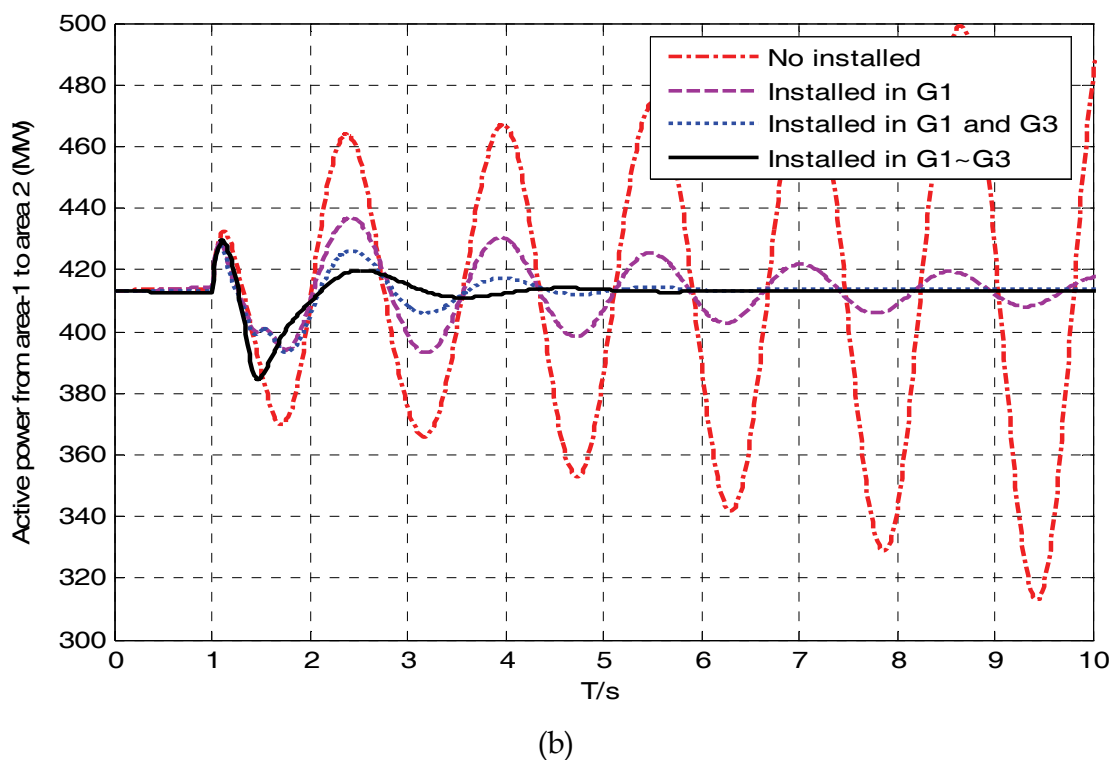


Fig. 4.3. Oscillation damping effects of installed stabilizers, (a) different areas; (b) different machines

4.2 Sixteen-Machine Five-Area Test System

In order to indicate the stabilization effects of multi-PSSs for large-scale power system, the 16-machine 5-area test system (Rogers, 2000) shown in Fig.4.4 is simulated in this section. This is in fact the simplified New England and New York interconnected system. The first nine machines (G1-G9) and the second four machines (G10-G13) are belonged to the New England Test System (NETS) and the New York Power System (NYPS), respectively. In addition, there are other three machines (G14-G16) used as the dynamical equivalent of the three neighbour areas connected with NYPS area. It should be remarked that all the machines are described by the sixth-order dynamical model.

The eigenvalue analysis mentioned in the above Section 3 has been performed on the linearized system model of the multi-machine test system without any PSS. The calculated dominate oscillation modes are shown in Table 4.1. From this, it can be seen that as for the system without PSSs, there are kinds of low frequency oscillations (LFOs) with the very weak damping ratios, which is disadvantage to the normal operation of the multi-machine test system.

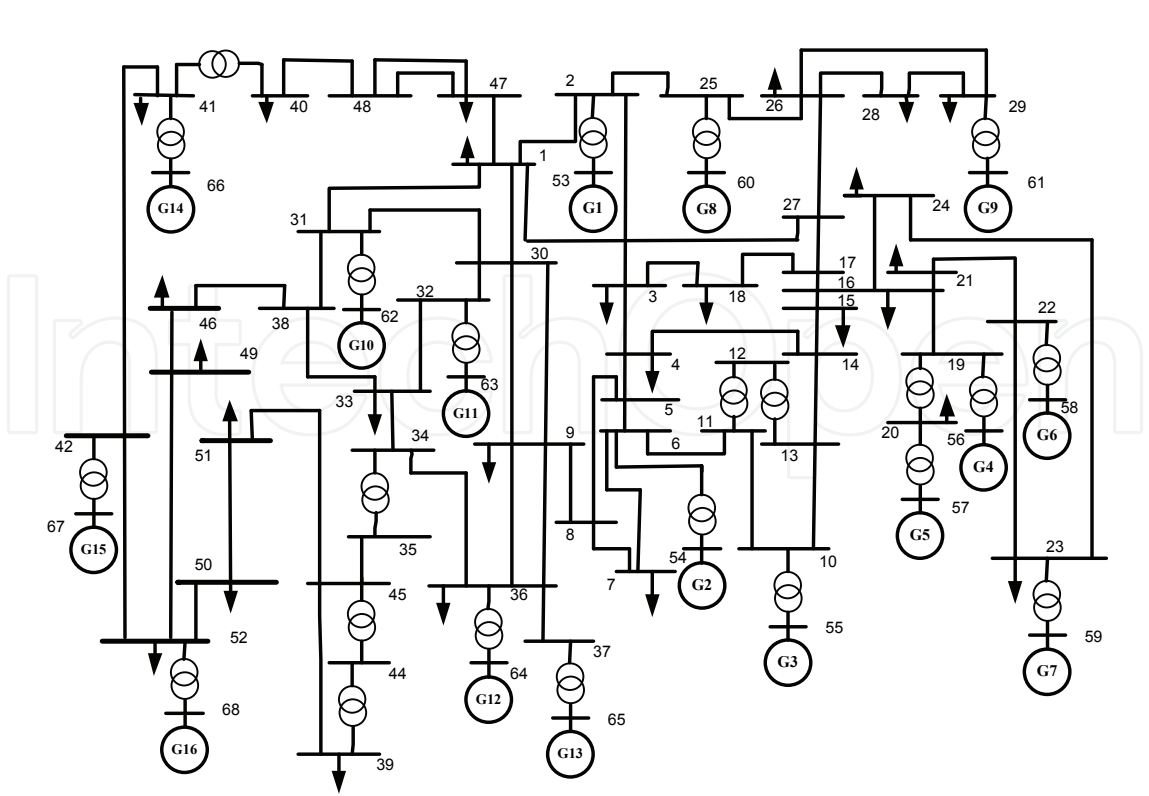


Fig. 4.4. The 16-machine 5-area test system

| Mode | Eigenvalues | Frequency (Hz) | Damping Ratio |
|------|----------------------|----------------|---------------|
| 1 | $-0.064 \pm 2.756i$ | 0.439 | 0.023 |
| 2 | $-0.032 \pm 3.590i$ | 0.571 | 0.009 |
| 3 | $-0.003 \pm 4.408i$ | 0.702 | 0.001 |
| 4 | $-0.131 \pm 5.170i$ | 0.823 | 0.025 |
| 5 | $0.408 \pm 7.673i$ | 1.221 | -0.053 |
| 6 | $0.240 \pm 7.722i$ | 1.229 | -0.031 |
| 7 | $0.647 \pm 7.790i$ | 1.240 | -0.083 |
| 8 | $-0.157 \pm 8.357i$ | 1.330 | 0.019 |
| 9 | $0.291 \pm 8.462i$ | 1.347 | -0.034 |
| 10 | $0.477 \pm 8.615i$ | 1.371 | -0.055 |
| 11 | $0.167 \pm 8.690i$ | 1.383 | -0.019 |
| 12 | $-0.116 \pm 10.095i$ | 1.607 | 0.012 |
| 13 | $0.092 \pm 10.188i$ | 1.621 | -0.009 |
| 14 | $-0.383 \pm 10.207i$ | 1.625 | 0.037 |
| 15 | $0.516 \pm 12.543i$ | 1.996 | -0.041 |

Table 4.1. Dominant oscillation modes (without PSS)

Furthermore, according to the calculation results shown in Table 4.2 about the participation factor of each machine to the corresponding operation mode, it can be observed that under the normal operation condition, the system mainly has four inter-area oscillation modes and eleven local oscillation modes. Combined to Table 4.1, we can obviously obtain the common results about the LFO characteristics. That is to say, as for the inter-area modes, the oscillation frequency is less 1.0Hz, and as for the low-frequency local modes, the oscillation frequency is between 1.0Hz and 2.0Hz.

| Mode | Participation factor (from G1 to G16) | Oscillation mode |
|------|---|---------------------------------------|
| 1 | 0.0147,0.0110,0.0137,0.0127,0.0130,0.0167,0.0120,0.0093,0.0142,0.0049,0.0046,0.0253,0.1400,0.0848,0.1006,0.0366 | G1-G9 vs G10-G16 |
| 2 | 0.0022,0.0012,0.0017,0.0021,0.0023,0.0029,0.0020,0.0014,0.0024,0.0001,0.0000,0.0001,0.0002,0.2065,0.0063,0.2730 | G1,G4-G9,G14 vs G2,G3,G10-G13,G15,G16 |
| 3 | 0.0309,0.0141,0.0214,0.0383,0.0461,0.0546,0.0366,0.0191,0.0392,0.0000,0.0006,0.0205,0.1746,0.0029,0.0003,0.0056 | G1,G4-G8 vs G2,G3,G9-G16 |
| 4 | 0.0000,0.0000,0.0000,0.0001,0.0001,0.0001,0.0001,0.0000,0.0000,0.0000,0.0000,0.0003,0.0029,0.1322,0.3144,0.0498 | G1-G9,G12,G13,G15 vs G10,G11,G14,G16 |
| 5 | 0.0001,0.0059,0.0038,0.0037,0.0048,0.0102,0.0039,0.0008,0.0140,0.0013,0.0006,0.4178,0.0681,0.0000,0.0000,0.0001 | Local oscillation mode |
| 6 | 0.0176,0.0979,0.0734,0.0429,0.0565,0.1126,0.0381,0.0040,0.0758,0.0103,0.0010,0.0422,0.0017,0.0001,0.0000,0.0000 | Local Oscillation mode |
| 7 | 0.0123,0.0898,0.0728,0.0015,0.0014,0.0038,0.0029,0.0111,0.3152,0.0000,0.0000,0.0019,0.0004,0.0000,0.0000,0.0000 | Local Oscillation mode |
| 8 | 0.0055,0.0005,0.0007,0.0167,0.2878,0.1593,0.0536,0.0031,0.0005,0.0019,0.0001,0.0001,0.0001,0.0000,0.0000,0.0000 | Local Oscillation mode |
| 9 | 0.1377,0.0427,0.0108,0.0007,0.0023,0.0102,0.0082,0.0783,0.0166,0.1799,0.0043,0.0077,0.0013,0.0002,0.0000,0.0002 | Local Oscillation mode |
| 10 | 0.0027,0.1864,0.2582,0.0001,0.0002,0.0015,0.0007,0.0014,0.0006,0.0018,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000 | Local Oscillation mode |
| 11 | 0.1213,0.0008,0.0035,0.0001,0.0004,0.0084,0.0012,0.0710,0.0047,0.2569,0.0032,0.0029,0.0021,0.0001,0.0000,0.0002 | Local Oscillation mode |
| 12 | 0.0025,0.0001,0.0005,0.1471,0.0727,0.1056,0.1381,0.0007,0.0003,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000 | Local Oscillation mode |
| 13 | 0.0001,0.0000,0.0000,0.1957,0.0345,0.0365,0.1852,0.0001,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000 | Local Oscillation mode |
| 14 | 0.1793,0.0000,0.0001,0.0001,0.0001,0.0002,0.0001,0.3086,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000 | Local Oscillation mode |
| 15 | 0.0007,0.0002,0.0001,0.0001,0.0000,0.0000,0.0000,0.0002,0.0000,0.0100,0.4323,0.0021,0.0043,0.0001,0.0000,0.0002 | Local Oscillation mode |

Table 4.2. Participation factor and oscillation modes

To describe the existing oscillation modes vividly, the angle eigenvectors for mode 1-8 have been drawn as shown in Figure 4.5 and 4.6. By comparing there two figures, we can obviously find the difference between inter-area mode and local mode. In practice, with the demand of competitive power markets and the large-scale transmission and distribution of electric energy, more and more regional electric networks are interconnected to gradually form the relative bigger scale electric power systems. In that case, the dynamic performance changes more complex, which lead to various instability problems such as voltage instability, power oscillations, and so on. Especial for the inter-area oscillation mode, it could be the typical LFO modes existing in the modern power system, which should be considered carefully. Generally, as for the typical common selection for stabilization of power system, PSS can provide a certain damping for the LFO mode especial for the local mode. Also, as for the inter-area oscillation damping, the multi-band PSS mentioned in the above section should be a better alternative.

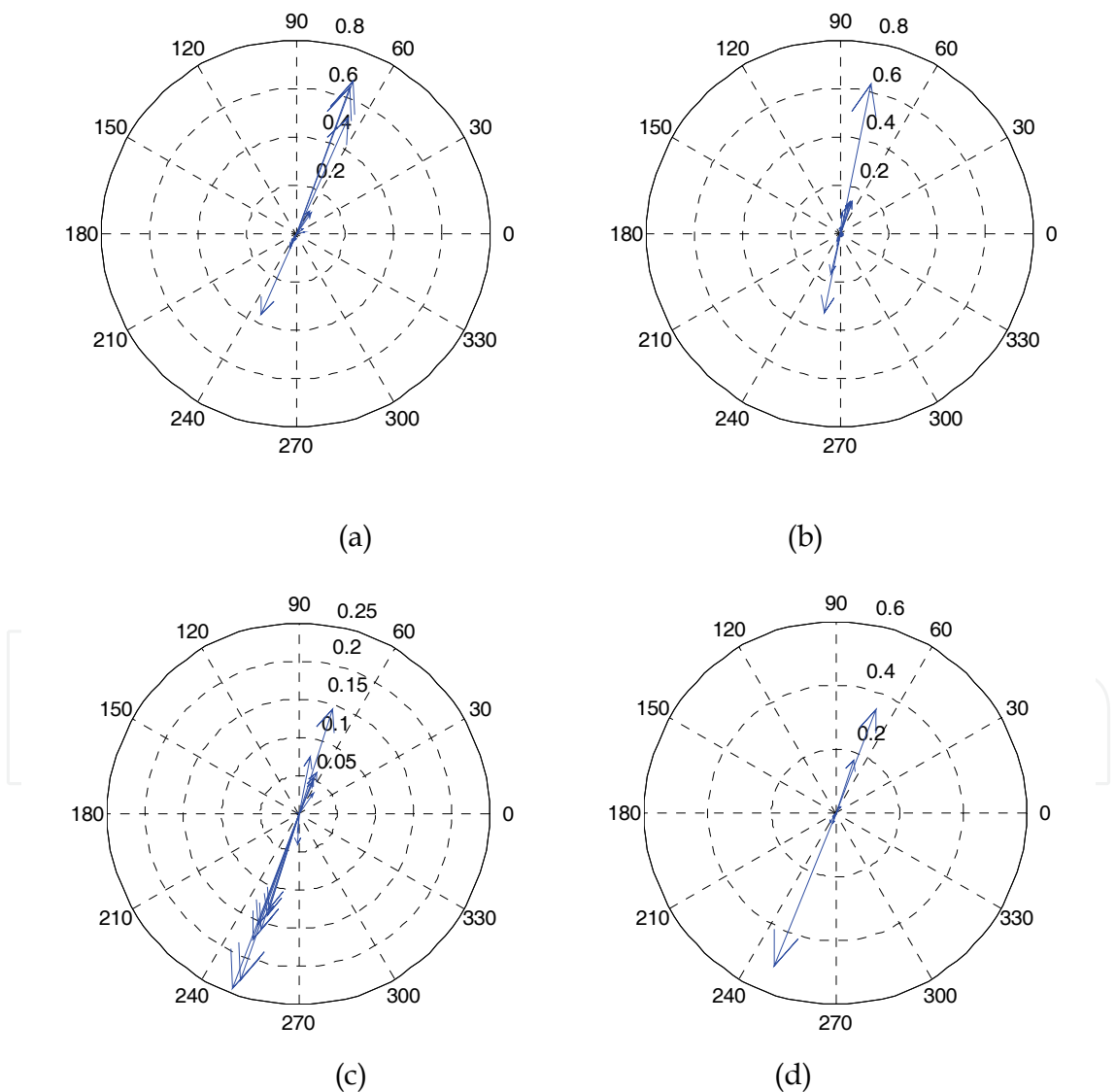


Fig. 4.5. Inter-area oscillation modes. (a) mode-1, (b) mode-2, (c) mode-3, (d) mode-4

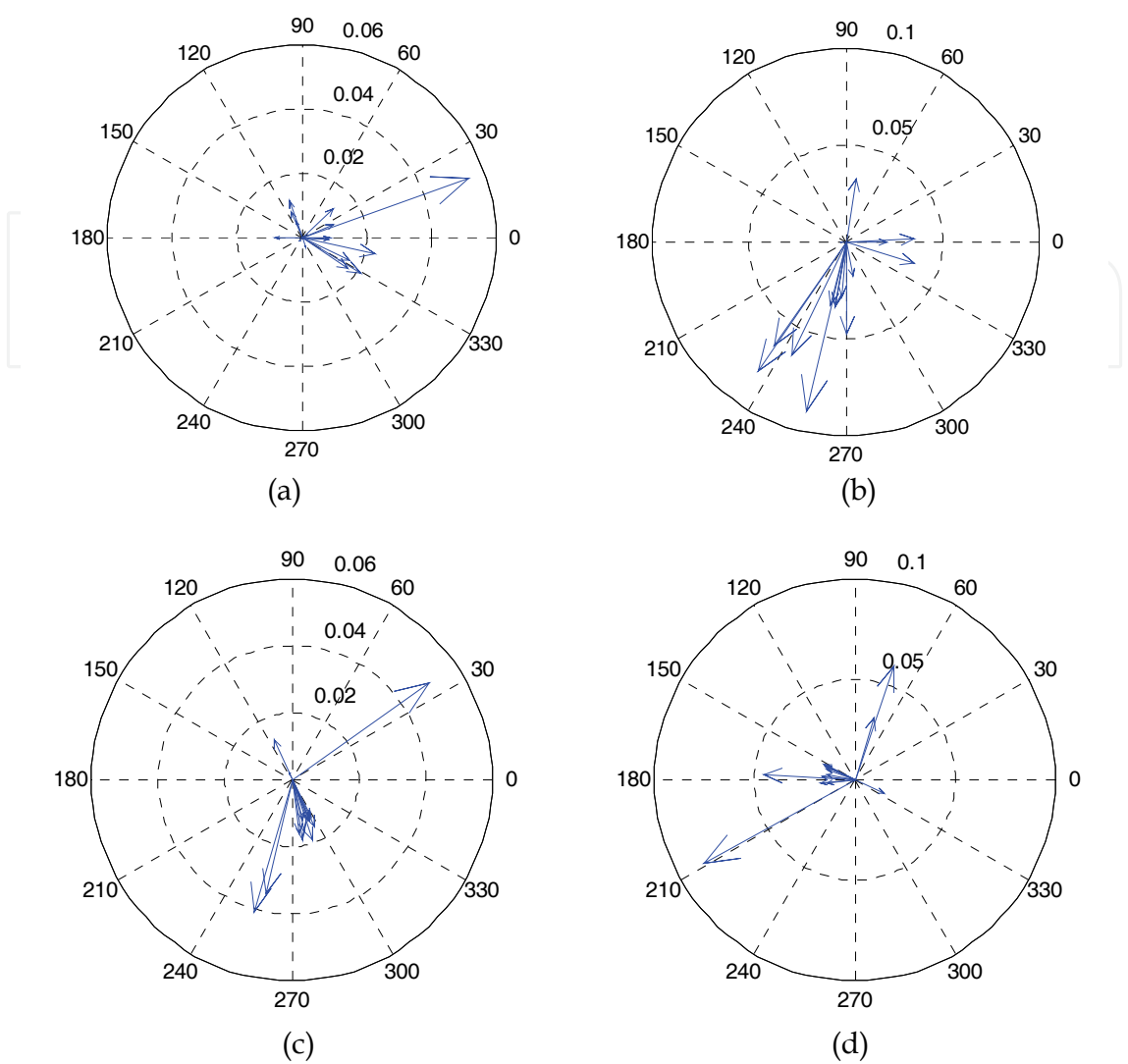


Fig. 4.6. Local oscillation modes. (a) mode-5, (b) mode-6, (c) mode-7, (d) mode-8

In order to reveal the stabilizing effects of the general PSS on the LFO modes, the PSS with the classical structure shown in Figure 2.3 has been installed to each machine in the multi-machine test system. As for the lead-lag time constants for the phase lag compensation, they can be determined using the method given in (Kunder, 1994; Rogers, 2000). The eigenvalues analysis for the linearized model of the multi-machine test system with 16-PSSs has been performed. The calculated dominate oscillation modes are shown in Table 4.3. By comparing with Table 4.1, it can be seen that with the implement of PSSs installation, the damping ratios for both the inter-area and the local modes are greater than 0.1, which indicates the very well stabilization effects of PSS on LFO mode.

| Mode | Eigenvalues | Frequency (Hz) | Damping Ratio |
|------|---------------------|----------------|---------------|
| 1 | $-0.598 \pm 2.667i$ | 0.424 | 0.219 |
| 2 | $-0.690 \pm 3.489i$ | 0.555 | 0.194 |
| 3 | $-0.676 \pm 4.209i$ | 0.670 | 0.159 |

| | | | |
|----|----------------------|-------|-------|
| 4 | $-0.674 \pm 5.037i$ | 0.802 | 0.133 |
| 5 | $-1.205 \pm 7.434i$ | 1.183 | 0.160 |
| 6 | $-1.494 \pm 7.543i$ | 1.201 | 0.194 |
| 7 | $-1.560 \pm 8.152i$ | 1.297 | 0.188 |
| 8 | $-1.810 \pm 8.337i$ | 1.327 | 0.212 |
| 9 | $-1.738 \pm 8.540i$ | 1.359 | 0.199 |
| 10 | $-1.271 \pm 8.622i$ | 1.372 | 0.146 |
| 11 | $-2.767 \pm 8.879i$ | 1.413 | 0.297 |
| 12 | $-1.724 \pm 11.114i$ | 1.769 | 0.153 |
| 13 | $-2.913 \pm 11.414i$ | 1.817 | 0.247 |
| 14 | $-3.024 \pm 11.822i$ | 1.882 | 0.248 |
| 15 | $-2.056 \pm 12.353i$ | 1.966 | 0.164 |

Table 4.3. Dominant oscillation modes (with PSS)

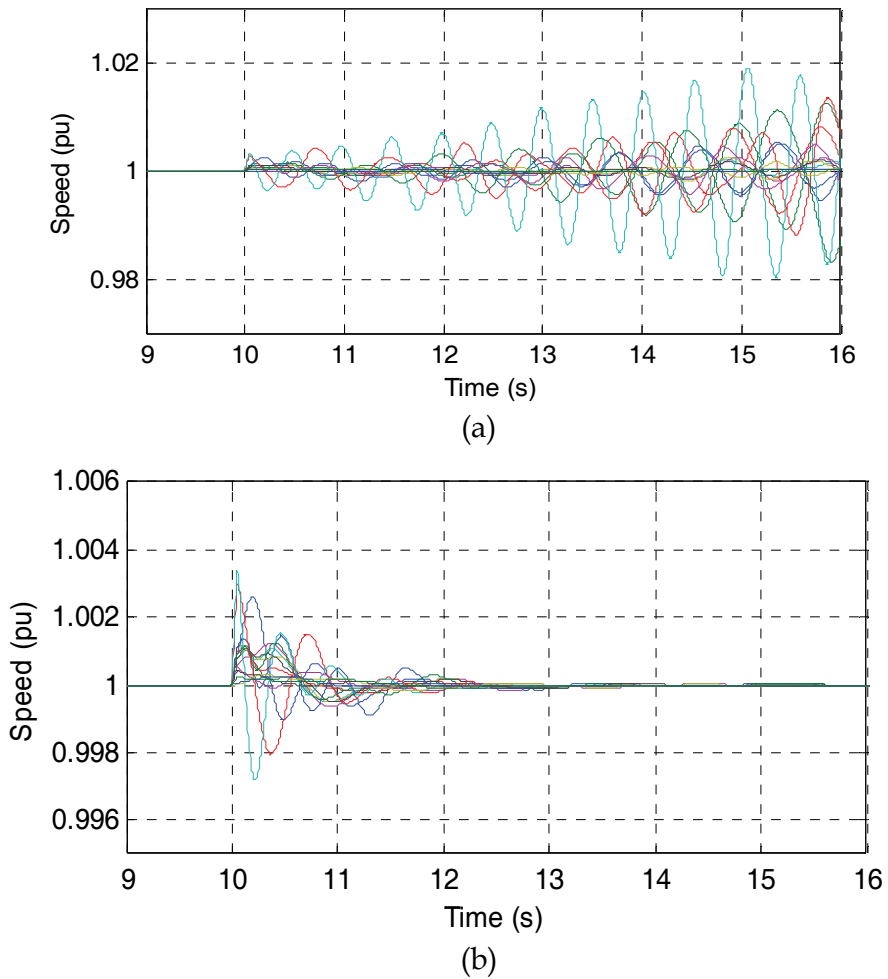
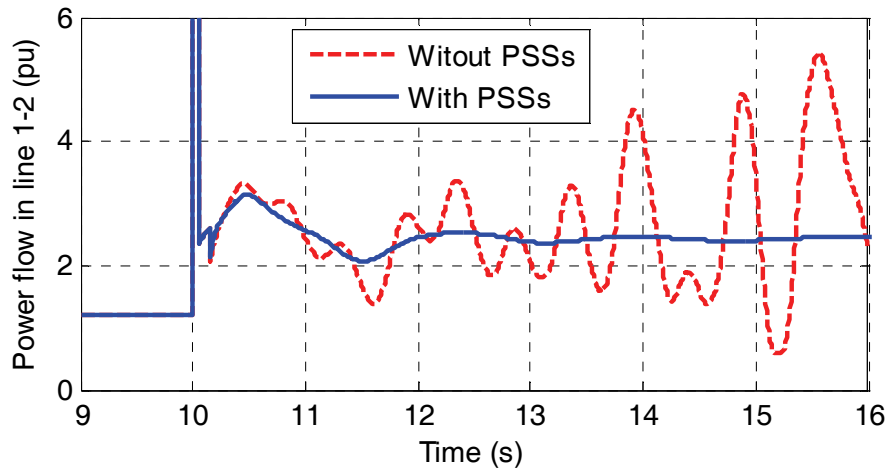
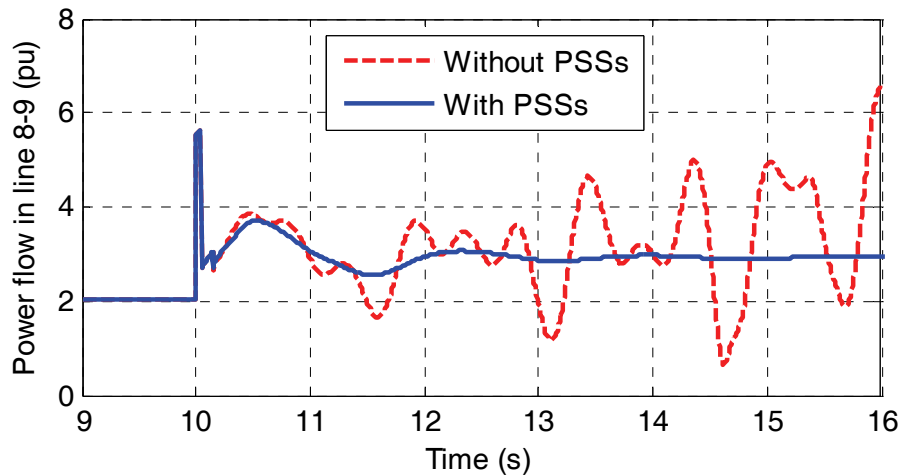


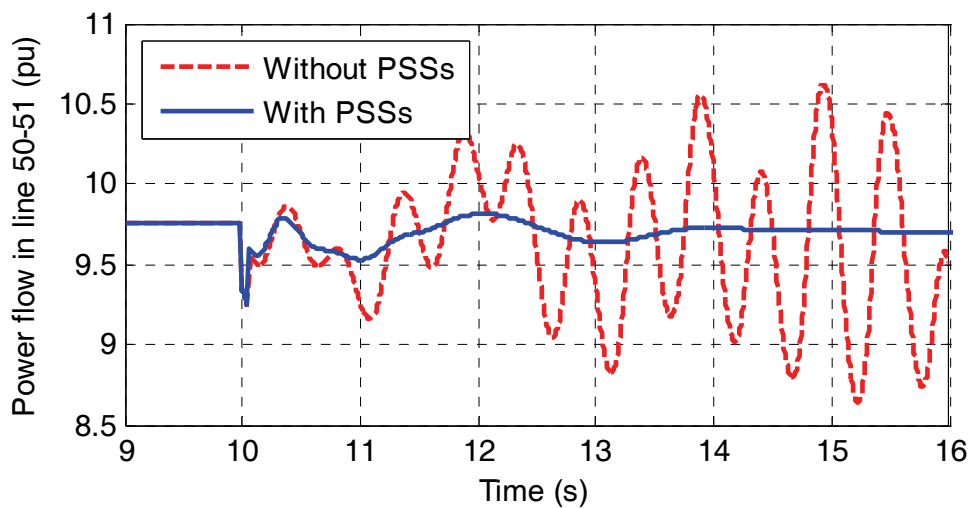
Fig. 4.7. Dynamic response of speed of G1-G16 to a line-to-ground fault. (a) without PSSs, (b) with PSSs.



(a)



(b)



(c)

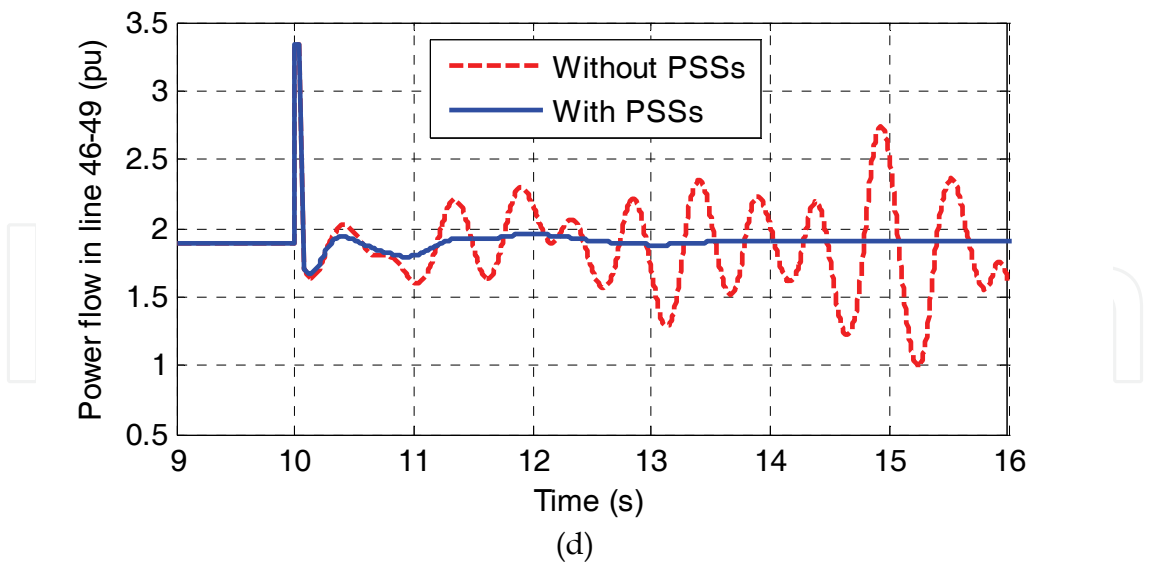


Fig. 4.8. Dynamic response of power flow in the interconnected backbone lines. (a) line 1-2, (b) line 8-9, (c) line 50-51, (d) line 46-49.

In order to evaluate the stabilization performance of PSSs on the LFO modes, the nonlinear simulation on the multi-machine test system has been performed by setting the line-to-ground fault nearby Bus-1. The fault starts from 10.0-s and continuous 50-ms. Figure 4.7 and 4.8 show the dynamic responses of the test system for such large disturbance. From Figure 4.7, it can be seen that the system without PSSs exists the serious power oscillations, which is directly reflected by the instability of machine speed shown in Figure 4.7(a). However, with the implement of PSSs, such oscillations are damped very well, which can be shown in Figure 4.7(b).

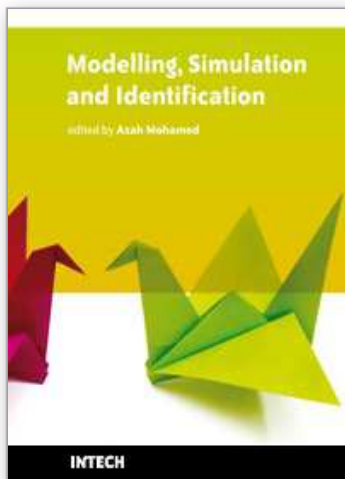
Furthermore, as for the multi-machine test system with five areas, the power flow in the backbone lines, which play an important role on the network interconnection, can be obtained as shown in Figure 4.8. From this, it can be seen that, the installation of PSSs can improve the system dynamic performance very well, and all the backbone lines can transmit the power stably.

5. Conclusion

This paper presents the power system stabilizer with the consideration of local, inter-area, and global mode to damp the potential power oscillation. Based on this, the eigenvalues analysis method has been introduced to analyze the damping effects of various arrangement schemes of such stabilizer. The case study on the typical 4-machines 2-area test system and 16-machines 5-areas shows that although the best arrangement scheme that install the stabilizer for every machine and area can obtain the best oscillation damping effect, it is not the economical solution scheme especial to the large power networks, and the scheme that arrange stabilizer for one area one machine is the optimal arrangement with the consideration of economical factor. This paper has a certain meaning to the optimal stabilizer arrangement for power networks, and the future researches on the arrangement rules with evolutionary algorithm and the coordinated FACTS device to obtain the better power oscillation damping effects could be concerned and performed.

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