STABILIZATION OF MULTIMODAL ELECTROMECHANICAL OSCILLATIONS BY COORDINATED APPLICATION OF POWER SYSTEM STABILIZERS

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Abstract - This paper presents a hybrid methodology which utilizes modal sensitivity and frequency domain analysis to coordinate power system stabilizers in multimachine systems. The proposed approach permits robust stabilization of multimodal electromechanical oscillations by the minimal number of coordinated stabilizers. A spectral monitoring technique is used for the fast examination of performances of coordinated stabilizers in the non-linear power system.

Keywords: *Electromechanical oscillations, spectral analysis, eigenvalue control, power system stabilizers*

INTRODUCTION

The poor damping of electromechanical oscillations is symptomatic of intrinsic weaknesses in the power system. In some interconnections the situation is worsened by the growth of inter-utility wheeling, which is dictated by the economical constraints in modern power systems. These factors combine to bring the typical operating states closer than ever to the system stability limits and to make the damping of electromechanical oscillations a recurrent problem in several power systems [1-3]. Since the introduction of new control systems to the uncertain and multivariable environment of complex power systems is a slow process, which incurs a variety of risks, the full utilization of existing power system stabilizers (PSSs) is essential for the enhancement of overall system stability on the present level of system development [4]. A feasible approach to achieve this goal is to coordinate the local stabilizers and to ensure their robustness during multimodal electromechanical oscillations, which follow the changes and disturbances in system conditions.

Early modal approaches to the coordinated design of PSSs [5,6] used the eigenanalysis of the power system model to pick out generators most suitable for the implementation of the stabilizing feedback, yielding the maximum improvement of the damping of critical oscillatory modes. Later, several state space methods have been proposed which treat the PSS design as a decentralized eigenvalue assignment problem [7-10]. Although these methods, based on the eigenvalue sensitivities, successfully handle the dimensionality of the problem, they suffer from arbitrariness concerning the selection of assigned values for the controlled modes and mode shapes in a large power system. Because of that, a PSS designed in this manner may perform unsatisfactorily when the system conditions change from the operating point considered in the design procedure. Recently, frequency domain methods were shown to be capable of handling the coordinated tuning of PSS parameters in multimachine power systems [11,12]. However, an arbitrary pairing between PSSs and oscillatory modes, as well as uncertain convergence properties of the design algorithms are drawbacks of these methods. Finally, both state space and frequency domain methods lack an insight into the non-linear response of stabilized system, which must be analyzed to ensure a good PSS design.

This paper describes a hybrid methodology for the determination of PSS parameters in multimachine power systems. The proposed approach combines the accuracy of multivariable state space techniques and the robustness of frequency domain methods. The modal sensitivity analysis of detailed system model is used to identify the nuclei of system modal groups where the application of stabilizers affects the largest number of oscillatory modes. The same sensitivity information is used to maximize the PSS damping effects on local as well as inter-area modes. This is achieved through the coordinated compensation of system phase characteristics on the critical range of resonant frequencies. The result is a robust stabilization of multimodal electromechanical oscillations by the minimal number of coordinated PSSs. For the monitoring of non-linear system response, a spectral technique is proposed which provides an insight into the time-frequency distribution of energy of electromechanical oscillations. This monitoring technique is used for the fast examination of the damping efficiency and robustness of coordinated stabilizers in the well known 10-machine test system.

PROBLEM STATEMENT AND OVERALL APPROACH

A power system is permanently subjected to both predictable and unpredictable disturbances, which constantly change the system operating conditions. The system trajectory during these changes is characterized by band-limited electromechanical oscillations (between 0 and 2.5 Hz), which are described by non-linear swing equations

$$\begin{aligned} \Delta\dot{\omega}_i &= -d_i\Delta\omega_i + P_{ai}(t)/M_i \\ \Delta\dot{\delta}_i &= \omega_B\Delta\omega_i \qquad i=1,2,..,n \quad . \end{aligned} \tag{1}$$

In the swing equation of the ith generator $\Delta\delta_i$ is the rotor angle deviation (radians); $\Delta\omega_i$ is the speed deviation relative to a synchronous reference frame (p.u.); P_{ai} is the accelerating power (imbalance between mechanical and electrical power) (p.u.); M_i is the inertia constant (seconds); d_i is the ratio of natural damping coefficient (D_i in p.u.) to inertia constant M_i; ω_B is the synchronous angular frequency (rad/s).

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The electromechanical oscillations of an n-machine system are composed of (n-1) inter-unit oscillatory modes and one system mode which describes the motion of the system center of inertia versus the synchronous reference frame. Particular excitation of an electromechanical oscillatory mode leads to the mutual exchange of energy of oscillations between two groups of generators swinging in opposite directions. For a strictly *local mode*, these two groups are practically only two machines, whereas an *inter-area mode* involves two modal groups which contain several machines. The generators in the inter-area modal groups are dynamically coupled through the local modes. The most tightly coupled generator pairs form the nuclei of inter-area modal groups, which are optimal sites for the monitoring and stabilization of multimodal electromechanical oscillations [13,14]. Although redundancy of controllers is often required in large power systems, the nuclei of inter-area modal groups at least should have a priority for the application of power system stabilizers.

Time-Frequency Distribution of Energy of Electromechanical Oscillations

A classical tool for the spectral analysis of non-linear electromechanical oscillations is the Fourier transform. The Fourier analysis allows the decomposition of a signal into individual frequency components and establishes the relative intensity of each component. However, the standard spectral analysis does not reveal *when* particular oscillatory modes occurred. The time-dependent frequency changes in the electromechanical oscillations can be analyzed by using the short-time Fourier transform (STFT) or spectrogram, which is an efficient method for the study of non-stationary signals [15]. The STFT associates with each instant of time the Fourier transform of the signal in the neighborhood of that instant. This neighborhood represents a short-time window in which the signal is more or less stationary. In practice, the spectrogram of non-stationary electromechanical oscillations can be computed by using the discrete Fourier transform (DFT), [14],

$$\hat{S}_i(k\Delta f) = \frac{2M_i\omega_B}{N^2}\left|\sum_{n=0}^{N-1}\Delta\omega_i(n\Delta T)\exp(-j2\pi kn/N)\right|^2 \qquad (2)$$

$$k=0,1,\ldots,N/2 \quad .$$

The above expression is a DFT spectral estimate of the excess kinetic energy built up in the ith machine rotor during the period $N\Delta T$. Also, ΔT is the sampling interval of the data sequence of length N, while Δf is the frequency sampling rate ($\Delta f=1/N\Delta T$).

The accumulation of excess kinetic energy by the ith machine rotor (2) is caused by the imbalance between mechanical and electrical power, $P_{ai}(t)$ in (1). This imbalance is inherent to an ac power system and varies from low levels during normal changes of system operating conditions, to relatively large levels in the case of major disturbances such as faults. The electromechanical oscillations represent the exchange of the excess kinetic energy between generator rotors, via the interconnection network. Therefore, the sequential computation of (2) gives a time-varying spectra, which shows the time-frequency distribution of energy of electromechanical oscillations. The time-frequency distribution completely describes the *dispersion* and *dissipation* of the disturbance energy [16]. The dispersion of disturbance energy over the system resonant frequencies is due to the different phase velocities of oscillatory modes, which are initially excited by the disturbance in the non-linear system. On the other side, the damping of these oscillatory modes is caused by the dissipation of the disturbance energy. Both phenomena are frequency dependent and have different characteristics for local and inter-area modes. The coordinated stabilization of multimodal oscillations has to reduce the dispersion of disturbance energy to the frequencies of inter-area oscillatory modes and to increase the damping of all modes. The sequential spectral monitoring of excess kinetic energy (2) provides necessary information about these effects of stabilizers in multimachine power systems.

Sensitivity of Electromechanical Oscillatory Modes

Consider a linearized model of n-machine power system described by

$$\dot{\Delta x}_i = A_{ii}\Delta x_i + \sum_{j\neq i} A_{ij}\Delta x_j + b_i\Delta u_{si} \qquad (3)$$

$$i,j = 1,2,\ldots,n \; .$$

The matrices and vectors in (3) can be identified from Fig.1, which shows a linearized model of the ith generator in a multimachine power system [17]. The transfer functions $W_{ai}(s)$ and $W_{gi}(s)$ in Fig.1 represent arbitrary complex excitation and turbine-governor subsystems, respectively.

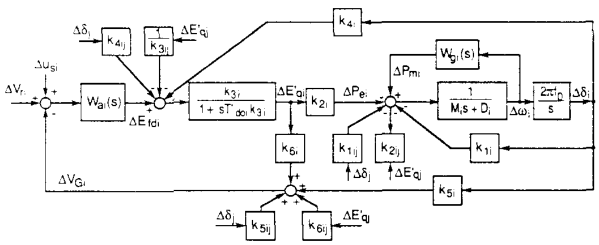

Fig.1 Linearized model of the ith generator as a part of multimachine power system

If a feedback stabilizer, which has a transfer function $W_{si}(s)$, is inserted in the system (3), then the sensitivity of the open-loop eigenvalue λ_h to changes in the stabilizer parameter k_{si} can be computed by using a hybrid formula, [9],

$$\frac{\partial\lambda_h}{\partial k_{si}} = R_{hi}\frac{\partial W_{si}(\lambda_h)}{\partial k_{si}} \qquad (4)$$

where

$$R_{hi} = w_h^T b_i c_i^T v_h \qquad . \qquad (5)$$

In the above expression v_h and w_h are right and left eigenvectors of the system matrix $A = \{A_{ij}\}$, respectively, which are normalized so that $w_h^T v_h = 1.0$. Also, b_i and c_i are the appropriate vectors which define the stabilizer position on the ith machine. The open-loop residue R_{hi} (5) determines the effect of stabilizer location on the hth mode, i.e. the sensitivity of the eigenvalue λ_h to the insertion of the static stabilizing feedback k_{si} on the ith machine. Assuming the application of a practical PSS

$$\Delta u_{si} = W_{si}(s)\,\Delta\omega_i \qquad , \qquad (6)$$

where

$$W_{si}(s) = k_{si}L_i(s) \quad , \quad L_i(s) = \left[\frac{1 + a_i\tau_i s}{1 + \tau_i s} \right]^{n_i} ,$$

the expression (4) reduces to

$$\frac{\partial \lambda_h}{\partial k_{si}} = R_{hi}L_i(\lambda_h) \quad . \tag{7}$$

The main function of the practical PSS (6) is to produce the damping component of the torque in phase with speed changes during rotor oscillations. This means that the PSS transfer function $L_i(s)$ has to compensate the phase lag of R_{hi} on the frequency of corresponding electromechanical mode ($\lambda_h = \sigma_h + j\omega_h$), as it is shown in Fig.2.

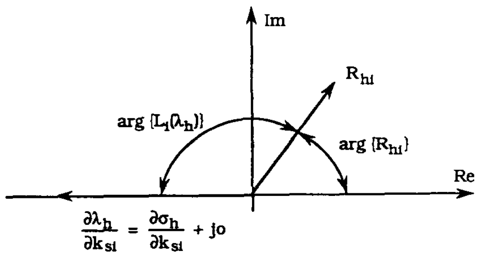

Fig.2 Ideal stabilization of the hth oscillatory mode by the ith PSS

The desired compensation of the hth mode (Fig.2) can be obtained by the sequential tuning of the ith PSS transfer function

$$\phi_{mi} = \frac{\pi - \arg\{R_{hi}\}}{n_i} ,$$

$$a_i = \frac{1 + \sin \phi_{mi}}{1 - \sin \phi_{mi}} , \tag{8}$$

$$\tau_i = 1/(\omega_h\sqrt{a_i}) .$$

The maximum phase lead of a feasible PSS transfer function, ϕ_{mi} in (8), has to be smaller than 1 rad. Thus, the number of lead-lag pairs, n_i, for a typical PSS is between 1 and 4.

In a multimachine power system, the phase lag of residue ($\arg\{R_{hi}\}$) may vary from few degrees to more than 180°. Therefore, a sequentially tuned stabilizer (8), while improving the damping of λ_h , may introduce a negative damping on the other frequencies of electromechanical oscillations. This is observable as the rotation of phasors $R_{si}L_i(\lambda_s)$ ($s \neq h$) to the first or fourth quadrant of the complex plane in Fig.2. From this point of view, it is a convenient property of a power system that the application of PSS on one machine significantly affects a small number of oscillatory modes. However, the optimal utilization of stabilizers calls for the application of PSSs on generators situated in the nuclei of inter-area modal groups, where the stabilizers affect the largest number of oscillatory modes. In this case, the coordinated tuning of stabilizers contributes the most to the enhancement of overall system stability.

COORDINATED TUNING OF POWER SYSTEM STABILIZERS

The coordination of stabilizers in a multimachine power system has two steps. The first step is the initialization of PSS transfer functions (6), which has to ensure a robust stabilization of multimodal electromechanical oscillations. This means that all electromechanical eigenvalues, which are affected by the application of PSSs, have to shift toward left in the complex s-plane. In the second step, the final tuning of selected PSS parameters is used to optimize the system dynamic performances through the eigenvalue control of local oscillatory modes. The objective of the coordinated eigenvalue assignment in the nuclei of inter-area modal groups is to maximize the enhancement of damping of multimodal electromechanical oscillations with the minimal number of PSSs.

Initialization of PSS Transfer Function

Assume that the residues R_{si} and R_{li} (5) have the largest and the smallest phase lag ($\arg\{R_{hi}\}$), respectively, for the application of PSS on the ith machine. If the ith machine belongs to the nucleus of an inter-area modal group, then the electromechanical eigenvalues $\lambda_s = \sigma_s + j\omega_s$ and $\lambda_l = \sigma_l + j\omega_l$ correspond to the appropriate inter-area and local mode, respectively. Since, typically, $\omega_s < \omega_l$ and $|R_{si}| < |R_{li}|$, the coordinated PSS can stabilize the dominant local mode (λ_l), while providing the highest possible contribution to the damping of less controllable inter-area mode (λ_s). In order to do that, the ith PSS has to have the maximum phase lead on the frequency ω_l and to compensate accurately the phase lag of R_{si} on the frequency ω_s. The above conditions are satisfied if

$$\arg\{L_i(\lambda_l)\} = n_i\phi_{mi} , \tag{9}$$

$$\arg\{L_i(\lambda_s)\} = \pi - \arg\{R_{si}\} . \tag{10}$$

With respect to the phase characteristics of $L_i(s)$ (6), the (9) and (10) can be expressed as

$$\tau_i = 1/(\omega_l\sqrt{a_i}) , \tag{11}$$

$$\frac{(a_i - 1)\tau_i\omega_s}{1 + a_i(\tau_i\omega_s)^2} = \operatorname{tg} \phi_s , \tag{12}$$

where

$$\operatorname{tg} \phi_s = \frac{\pi - \arg\{R_{si}\}}{n_i} .$$

Since the natural damping of an inter-area oscillatory mode (σ_s) is very small, the approximation $\lambda_s \simeq j\omega_s$ has been used in (12). By solving (11) and (12) for the unknown parameter a_i, the following expression can be found

$$a_i = (C_{ls} + \sqrt{1 + C_{ls}^2})^2 , \tag{13}$$

where

$$C_{ls} = \frac{\omega_l^2 + \omega_s^2}{2\omega_l\omega_s} \operatorname{tg} \phi_s .$$

It is obvious that the parameters of coordinated PSS (11) and (13) reduce to the parameters of sequentially tuned PSS (8) if $\omega_l = \omega_s$.

Assignment of Electromechanical Eigenvalues in the Frequency Domain

In the frequency domain, the closed-loop model of an n-machine power system (Fig.1) is described by 2n complex algebraic equations, which can be written in matrix form as

$$\begin{bmatrix} D_3(s) & D_2(s) \\ D_1(s) & K_2 \end{bmatrix}\begin{bmatrix} \Delta\delta(s) \\ \Delta E'_q(s) \end{bmatrix} = 0 \quad . \qquad (14)$$

The real submatrix K_2 comprises the coefficients of linearization k_{2ij} $(i,j=1,2,\ldots,n)$, while complex submatrices are defined as follows

$$d_{ii}^{(1)} = k_{1ii} + \frac{s}{\omega_B}\left[M_i s + D_i - W_{gi}(s)\right] \quad , \qquad (15)$$

$$d_{ij}^{(1)} = k_{1ij} \qquad (i\neq j) \quad , \qquad (16)$$

$$d_{ii}^{(2)} = 1/k_{3ii} + k_{6ii}W_{ai}(s) + sT'_{d0i} \quad , \qquad (17)$$

$$d_{ij}^{(2)} = 1/k_{3ij} + k_{6ij}W_{ai}(s) \qquad (i\neq j) \quad . \qquad (18)$$

$$d_{ii}^{(3)} = k_{4ii} + k_{5ii}W_{ai}(s) - sW_{ai}(s)W_{si}(s)/\omega_B \quad , \qquad (19)$$

$$d_{ij}^{(3)} = k_{4ij} + k_{5ij}W_{ai}(s) \qquad (i\neq j) \quad . \qquad (20)$$

It is important to note that the ith PSS transfer function, $W_{si}(s)$, appears *only* in the term $d_{ii}^{(3)}$ (19). This favorable property of practical PSS (6) stems from the use of $\Delta\omega_i$ for the ith PSS input signal. This fact, however, does not imply a loss of generality, since the equivalent rotor speed deviation ($\Delta\omega_{ei}$) can be derived for different realizations of PSS input signal [4].

The frequency response of an arbitrary complex n-machine system (Fig.1) is determined by (14). If the desired resonance frequency of (14) is λ_z, then the kth PSS transfer function $W_{sk}(s)$ can be used to assign an appropriate electromechanical eigenvalue of system matrix (3) to the λ_z position in the complex s-plane. After the substitution of $s=\lambda_z$ and permutation of rows and columns in (14), the following expression can be found

$$\begin{bmatrix} d_{kk}^{(3)}(\lambda_z) & c_k^T(\lambda_z) \\ b_k(\lambda_z) & F_k(\lambda_z) \end{bmatrix}\begin{bmatrix} \Delta\delta_k(\lambda_z) \\ f_k(\lambda_z) \end{bmatrix} = 0 \quad . \qquad (21)$$

From (19) and (21), the desired transfer function of the kth PSS at the complex frequency λ_z is

$$W_{sk}(\lambda_z) = \frac{\omega_B}{\lambda_z W_{ak}(\lambda_z)}\left[k_{4kk} - g_k + k_{5kk}W_{ak}(\lambda_z)\right] \qquad (22)$$

where

$$g_k = c_k^T(\lambda_z)F_k^{-1}(\lambda_z)b_k(\lambda_z) \quad .$$

The vector $f_k(\lambda_z) = -F_k^{-1}(\lambda_z)b_k(\lambda_z)$ represents a part of the right eigenvector which corresponds to λ_z and is normalized such that $\Delta\delta_k(\lambda_z)=1.0$. Therefore, an efficient eigenvalue assignment by the kth PSS is ensured if $|\Delta\delta_i(\lambda_z)| < 1.0$ $(i=1,2,\ldots,n\ ,\ i\neq k)$. This condition is satisfied if λ_z is the dominant local mode of the kth generator in the nucleus of an inter-area modal group.

Since (22) can be rewritten as

$$WR_k + jWI_k = (1 + \tau_k\lambda_z)\left[W_{sk}(\lambda_z)\right]^{(1/n_k)} \quad , \qquad (23)$$

the parameters k_{sk} and a_k, which determine the desired amplitude and phase lead of $W_{sk}(s)$ (6) at the frequency $\lambda_z=\alpha_z+j\beta_z$, are

$$a_k = \frac{WI_k}{(\beta_z WR_k - \alpha_z WI_k)\tau_k} \quad , \qquad (24)$$

$$k_{sk} = \left(\frac{WI_k}{a_k\tau_k\beta_k} \right)^{n_k} \quad . \qquad (25)$$

The proposed procedure for the coordinated stabilization of an n-machine power system is summarized in the following steps:

1.step Identify the dominant local (λ_l) and inter-area (λ_s) modes for all nuclei of system modal groups (m) by using residues R_{hi} (5);

2.step Initialize m PSS transfer functions (m<n) by using (11-13);

3.step Set the desired damping (α_{zk}) and frequency (β_{zk}) for local oscillatory modes (k=1,2,..,m)

4.step Compute parameters a_k and k_{sk} (k=1,2,...,m) by using (22-25);

5.step If the change of any PSS parameter in the previous step is higher than the prespecified tolerance ε repeat the step 4, otherwise compute the system eigenvalues and stop.

NUMERICAL EXAMPLE

To illustrate the proposed approach, an example of a 39-bus 10-generator system has been selected. Figure 3 shows the one-line diagram of the test system

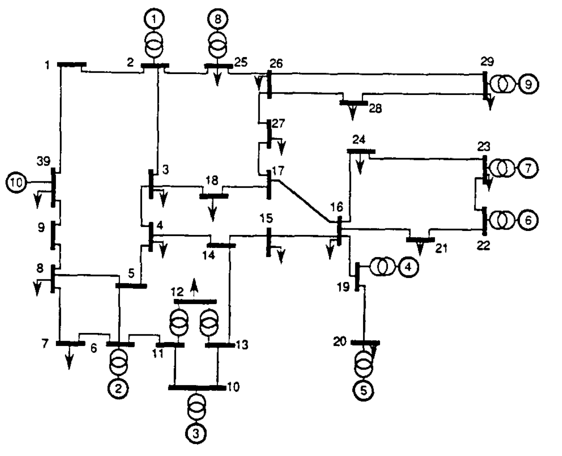

Fig.3 Ten-machine test system

[18]. The study system has nine electromechanical oscillatory modes, which characterize the local and inter-area oscillations. Although the overlapping between modes prevents the exact representation of system modal structure, the origins of electromechanical modes can be traced on the modal graph shown in Fig.4 [14]. Since the generator pairs (1,8), (2,3), (5,9) and (6,7) are the nuclei of inter-area modal groups in Fig.4, generators 8, 3, 9 and 7 were selected for the application of power system stabilizers. The sensitivities of open-loop electromechanical eigenvalues to static PSS ($R_{hi}=\partial\lambda_h/\partial k_{si}$) on these generators are shown in Fig.5.

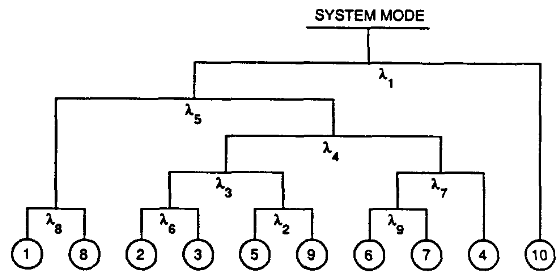

Fig.4 Modal structure of ten-machine system

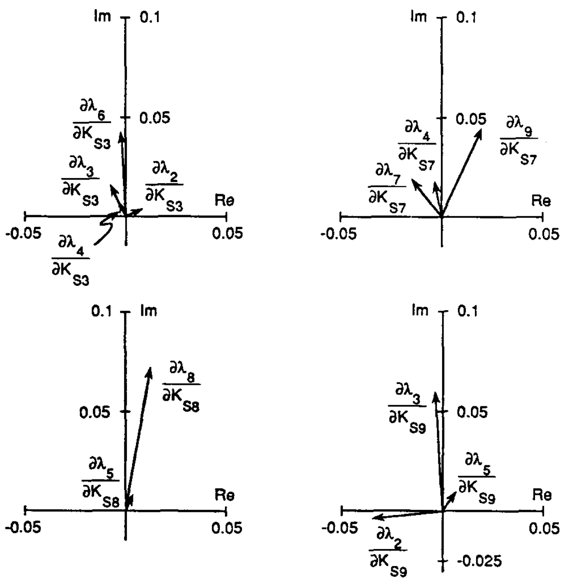

Fig.5 Residues ($R_{hi}=\partial\lambda_h/\partial k_{si}$) of electromechanical modes for the application of PSS in the nuclei of inter-area modal groups. The sensitivities which have the magnitude smaller than 0.01 are omitted.

The coordinated initialization of PSS transfer functions is shown in Table 1. The selection of dominant local (λ_l) and inter-area modes (λ_s)for each stabilizer is done on the basis of residues in Fig.5. It is worth noting that λ_2 is not a typical local mode, although it is closely related to the oscillations between generators 5 and 9. Thus, the PSS transfer function on the machine 9 is initialized with respect to λ_3. The mode λ_3 is chosen because its residue $R_{39}=\partial\lambda_3/\partial k_{s9}$ has the largest magnitude and the medial phase lag on the machine 9 (Fig.5).

Table 1 Initialization of PSS transfer functions

generator	local mode	inter-area mode	PSS parameters n	a	τ
3	λ_6	λ_3	2	3.40	0.075
7	λ_9	λ_4	2	4.80	0.054
8	λ_8	λ_5	2	8.35	0.040
9	λ_3	λ_3	2	5.30	0.060

Note: The same number of lead-lag pairs (n=2) for all PSS is primarily because the same first order exciter model has been used for all generators

The final tuning of PSS parameters k_{si} and a_i is shown in Fig.6. The robust initialization of PSS transfer functions (Table 1) ensures the fast placement of local electromechanical eigenvalues to the assigned positions in the complex s-plane. In Fig.6 the adopted values for α_z are between -1.0 and 2.5 s^{-1}. Also the tolerated deviation of controlled mode frequency (β_z) around its natural value was ∓5%. The selected range of damping is usually achievable for local oscillatory modes if the controlled mode frequency is kept around its natural value. However, it has been found that the separation of local resonant frequencies (which might be very close in a power system) improves the convergence of the eigenvalue control algorithm. Therefore, the originally close frequencies of λ_8 and λ_9 (Table 2) have been separated by the coordination of PSSs in the test system.

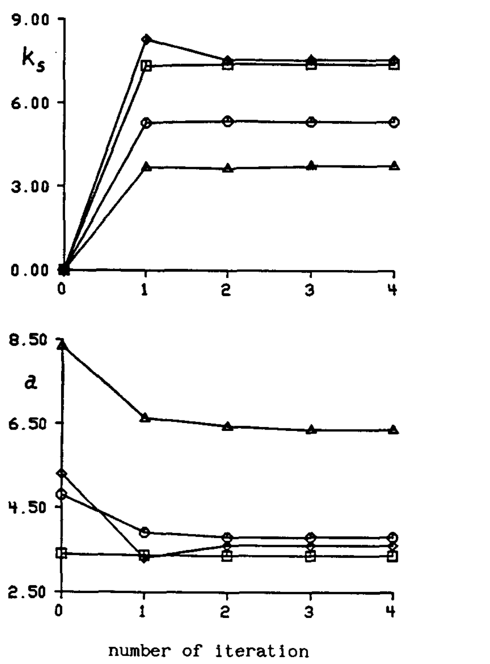

Fig.6 Coordinated tuning of PSS parameters k_{si} and a_i in ten-machine power system (ε = 0.01)
□ - generator 3, ○ - generator 7,
△ - generator 8, ◇ - generator 9.

Table 2 Electromechanical eigenvalues of ten-machine power system

mode	before stabilization	after stabilization
λ_1	+0.150 + j3.851	-0.054 + j3.784
$*\lambda_2$	+0.241 + j6.024	-1.000 + j6.000
λ_3	+0.268 + j6.267	-0.065 + j6.136
λ_4	+0.001 + j6.697	-0.138 + j6.827
λ_5	+0.056 + j7.116	-0.131 + j7.182
$*\lambda_6$	-0.065 + j7.213	-2.500 + j7.300
λ_7	-0.311 + j8.340	-0.384 + j8.364
$*\lambda_8$	-0.258 + j8.467	-2.000 + j8.000
$*\lambda_9$	-0.346 + j8.481	-2.000 + j8.500

Note: The controlled eigenvalues are marked with *

Table 2 shows the results of the coordinated application of PSSs in the nuclei of system modal groups. Due to the optimal selection of PSS sites and coordinated tuning of PSS transfer functions, only four stabilizers are able to stabilize five unstable oscillatory modes. Moreover, the effects of such a stabilization are remarkably positive on all frequencies of electromechanical oscillatory modes, which ensures the enhancement of damping of multimodal electromechanical oscillations in the non-linear power system. From this point of view, it is worth noting that the gains in Fig.6 are relatively small, which is important for the efficiency of stabilization of power system dynamics during the major disturbances.

The results obtained in the frequency domain and the robustness of coordinated stabilizers have been tested by the time-domain simulations of the detailed non-linear power system model with a 5-order machine model [18]. Figure 7 shows the oscillations of active power on the tie-line 15-16, following the three-phase short-circuit fault near bus 10, which is cleared after 100ms by opening the line 10-13. When the stabilizer on machine 3 is switched off, the system is unstable, because of the negative damping of mode λ_3. In this case the fastest growth of the excess kinetic energy occurs on the generator 5, which is dynamically coupled with generator 3 through the mode λ_3 (Fig.4). Figure 8 shows the time-frequency distribution of the excess kinetic energy of the generator 5 after the fault, when the PSS on generator 3 is switched off. The increase of the excess kinetic energy of generator 5 on the frequency of mode λ_3 is accompanied by the accumulation of the excess kinetic energy at 0 rad/s

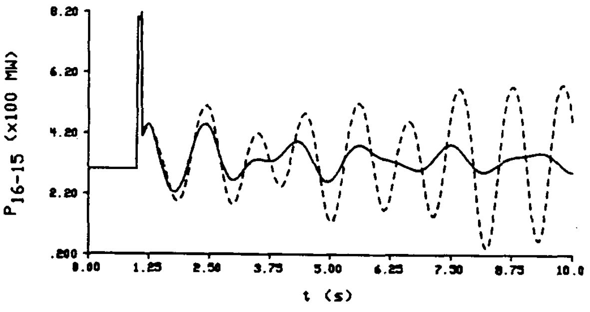

Fig.7 Oscillations of active power on the line 15-16
———— PSS on generators 3, 7, 8 and 9
- - - - - - PSS on generators 7, 8 and 9

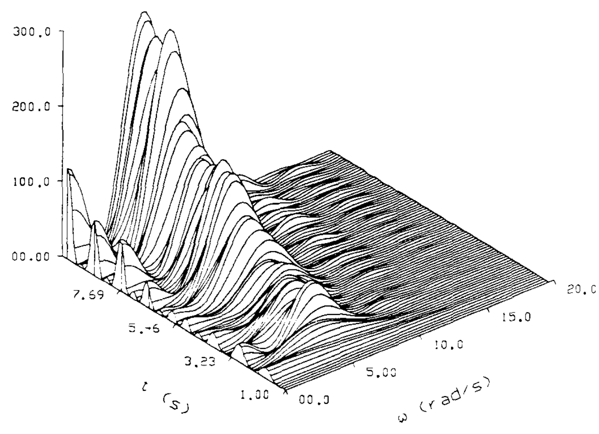

Fig.8 Spectral monitoring of excess kinetic energy on generator 5 (PSS on generators 7, 8 and 9)

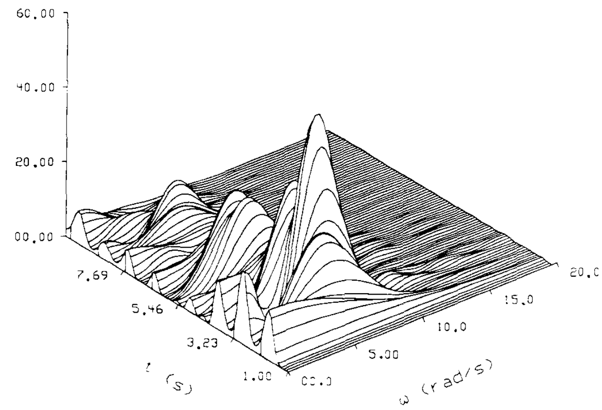

Fig.9 Spectral monitoring of excess kinetic energy on generator 5 (PSS on generators 3, 7, 8 and 9)

(Fig.8). When this aperiodic component of the excess kinetic energy exceeds the system potential energy margin, generator 5 looses its synchronism. However, if generator 3 is equipped with the previously designed PSS, generator 5 remains stable after the fault, as it is shown in Fig.9. The comparison between system responses in Figures 7, 8 and 9 exemplifies the importance of the coordinated stabilization of all nuclei of system modal groups for the enhancement of overall system stability.

The robustness of decentralized stabilizers is particularly vulnerable to changes of network configuration in the radial parts of system. Figure 10 shows the time-frequency distribution of the excess kinetic energy of the generator 9 after the three-phase short-circuit fault near bus 26, which lasts for 100ms. The fault is followed by the doubling of line impedance between buses 25 and 26, which further reduces naturally weak synchronizing and damping torques on the generator 9. Fortunately, the robustness of coordinated stabilizers is sufficient to overwhelm these unfavorable effects and to ensure a stable transient process in the post-fault system (Fig.10). However, the maintenance of full damping effects of PSSs during the large variations of system operating conditions is not possible without the implementation of adaptive stabilizers.

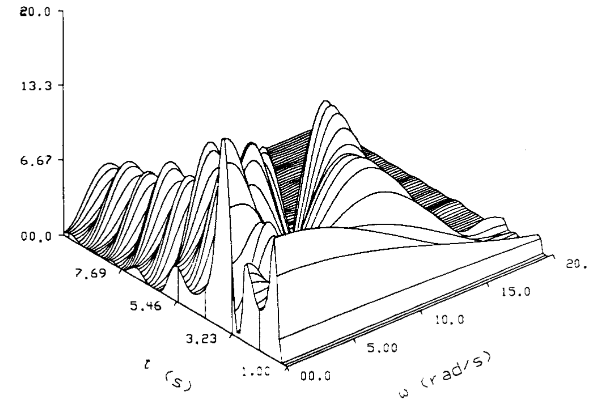

Fig.10 Spectral monitoring of excess kinetic energy on generator 9 (PSS on generators 3, 7, 8 and 9)

CONCLUSION

This paper presents a hybrid methodology for the coordinated design of stabilizers in multimachine power systems. The proposed technique combines the modal sensitivity analysis of complex power systems and two frequency domain methods for the coordinated tuning of PSS parameters. The first method is proposed for the robust initialization of PSS transfer functions, which are applied on generators located in the nuclei of inter-area modal groups. The second method enables the final tuning of PSS parameters through the eigenvalue assignment of dominant local modes in the nuclei of inter-area modal groups. The result of the proposed control strategy is the minimal number of coordinated stabilizers which are able to robustly stabilize multimodal electromechanical oscillations. The coordinated stabilizers improve the damping of all oscillatory modes and enhance the overall system stability after major disturbances. The monitoring of system dynamic performances is based on a signal processing technique, which provides an insight into the time-frequency distribution of energy of non-linear electromechanical oscillations. The proposed monitoring technique is a feasible analytic tool for the on-line examination of PSS performances during the changes in system operating conditions.

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