Identification of optimum site for power system stabiliser applications

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Abstract: The paper presents a modal-based identifying method of the optimum site for power system stabilisers. A recent concept of participation factors is extended by introducing new coupling factors, which enables a direct selection of generators where the application of stabilisers yields maximum improvement of overall system damping characteristics. The performances of the proposed method are studied and compared with those of the previous methods, on the example of the well known ten-machine test system.

1 Introduction

The enhancement of damping of electromechanical oscillations in multimachine power systems by the application of power system stabilisers (PSS) has been the subject of great attention in the past two decades, and is much more significant today when many large and complex power systems frequently operate close to their stability limits. Although extensive research has been carried out into the problem of PSS design (see, for example, the list of References in Reference 1), one very important aspect, i.e. the determination of the most effective combination of generators for PSS application, has been subjected only to rather limited studies [2–5]. Early modal approaches to this problem [2, 3] used the eigenvalue–eigenvector analysis of the power system model to pick out the generators most suitable for the implementation of the stabilising feedback, yielding the maximum improvement of the undamped or poorly damped modes of oscillations. Later, the frequency domain method, based on the concept of coherent groups [4], was proposed for improving the stability of the total system. Although this method was successfully tested [6], it suffers from arbitrariness concerning the selection of a particular site for PSS application within one coherent group, which cannot be overcome without extensive investigations of dynamic performances of stabilised systems under various combinations of the selected generators. Recently, the concept of participation factors was shown to be a valuable and feasible means for resolving this problem [5]; but it is still restricted, like early modal approaches, to the sequential PSS application, which considers the enhancement of damping of just one critical electromechanical mode at a time.

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In this paper the concept of participation factors is extended by introducing new coupling factors, which make possible direct and exact identification of machines where the application of stabilisers ensures maximum improvement of overall system damping characteristics. The proposed method is systematised as an analytical procedure for determining the best locations for stabiliser applications in the multimachine power system. The simplicity and efficiency of the new technique are illustrated on the example of the well known New England test system [4–7].

2 Power system model

The relative influence of a PSS on the different electromechanical modes of oscillations can be determined by using a classical representation of the synchronous machines in the power system model [4]. Accordingly, the state equations of the linearised power system model are expressed in general matrix form by

$$\Delta\dot{x} = A\Delta x + B\Delta u$$
$$\Delta y = C\Delta x \tag{1}$$

where

$$\Delta x = [\Delta\delta^T \,\vdots\, \Delta\omega^T]^T, \quad \Delta u = [\Delta P_m]$$

and

$$A = \left[\begin{array}{c|c} 0 & I \\ \hline -M^{-1}K & -M^{-1}D \end{array}\right] \quad B = \left[\begin{array}{c} 0 \\ \hline M^{-1} \end{array}\right]$$
$$C = [0 \,\vdots\, I]$$

The following notation is used:

$\Delta\omega_i = d\Delta\delta_i/dt$ = deviation of angular velocity of generator i
$\Delta u_i = \Delta P_{mi}$ = deviation of mechanical input power
$M = \mathrm{diag}[M_1, \ldots, M_n]$ = diagonal inertia matrix
$D = \mathrm{diag}[D_1, \ldots, D_n]$ = diagonal damping matrix
$K = \{k_{ij}\}$ = matrix of synchronising coefficients:

$$k_{ij} = \left.\frac{\partial P_{ei}}{\partial \delta_j}\right|_o \quad i, j = 1, 2, \ldots, n$$
$$k_{ij} = E_i E_j[G_{ij} \sin(\delta_{io} - \delta_{jo}) - B_{ij}\cos(\delta_{io} - \delta_{jo})] \quad i \neq j$$
$$k_{ii} = -\sum_{j\neq i} k_{ij}$$

where the term P_{ei} indicates electrical output power of generator i, E_i is the constant voltage magnitude of the ith machine behind transient reactance x'_{di} and $G_{ij} + jB_{ij}$ is the admittance between the internal nodes i and j.

All quantities are in per unit of value, except inertia constants M which are in seconds and angles δ in radians. In the above relations I is an identity matrix and the subscript o denotes the value at the steady-state operating point.

3 Participation and coupling factors

The main criterion for determining optimal location for PSS is the sensitivity of power system electromechanical

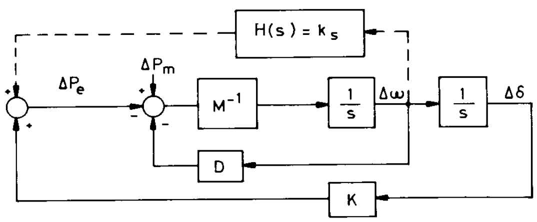

Fig. 1 *Block diagram of power system model (described in eqn. 1) with static PSS inserted*

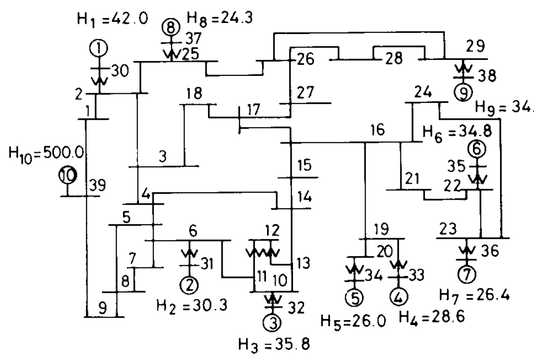

Fig. 2 *Ten-machine power system, $M_i = H_i/\pi f_o$, $f_o = 60$ Hz*

eigenvalues λ_h with respect to stabiliser parameters applied over different machines. Therefore, the higher the sensitivity of critical mode is, the better will be the site for PSS application. The hybrid formulas for the sensitivity of the eigenvalue λ_h in the multivariable system (eqn. 1) to changes in stabiliser gain K_s, when PSS transfer function is $H(s)$, can be derived [7] in the form

$$\frac{\partial \lambda_h}{\partial k_s} = \underset{\sim}{c}_l v_h w_h^T \bar{b}_m \frac{\partial H(\lambda_h)}{\partial k_s} \tag{2}$$

where $\underset{\sim}{c}_l$ and $\bar{b}_m$ are the appropriate row and column of matrices C and B respectively, (eqn. 1), defining the PSS position between lth output and mth input in the multimachine system. Right and left eigenvectors of system matrix v_h and w_h^T, respectively, are normalised so that $w_h^T v_h = 1$.

Assuming the presence of an 'ideal PSS' (i.e. the static stabilising feedback measuring angular velocity and actuating upon accelerating torque, see Fig. 1) the above relation reduces to

$$\frac{\partial \lambda_h}{\partial k_s} = -v_{ih} w_{ih} \frac{1}{M_i} \tag{3}$$

The obtained expression quantifies net influence of the power system structure on the sensitivity of the hth mode to PSS application on the ith machine. The key part of eqn. 3 is the product of the ith entries of the hth right and left eigenvectors, termed the participation factor [8]:

$$p_{ih} = v_{ih} w_{ih} \tag{4}$$

In contrast to eigenvectors, participation factors are dimensionless (scale and unit independent) and generally determine the relative participation of the ith state in building the time response of the hth mode, as well as the relative participation of the hth mode in the ith state at $t = 0$.

As well as the above it is important to note that eigenvectors also provide a quantitative measure of power system mode controllability and observability. The time response of system at eqns. 1, for a zero initial condition $\Delta x_0 = 0$ and a given impulse input vector $\Delta u = \delta(t)\bar{u}$, in the form

$$\Delta x(t) = \sum_h v_h e^{\lambda_h t} w_h^T B\bar{u} \tag{5}$$

shows that value w_{ih}/M_i (where w_{ih} corresponds to the state $\Delta\omega_i$ of the ith machine) measures controllability of the hth mode from the ith input. On the other hand, a free response of the same system when $\Delta u = 0$, in the form

$$\Delta y(t) = \sum_h C v_h e^{\lambda_h t} w_h^T \Delta x_o \tag{6}$$

shows that values v_{jh} measures observability of the hth mode in the state $\Delta\omega_j$, i.e. on the jth machine. From the above it follows directly that the value of $v_{jh} w_{ih}/M_i$ determines how much an ideal PSS applied on the ith machine affects the jth machine motion during the excitation of the hth oscillatory mode. This influence is due to the certain kind of generators coupling, whose appearance is connected with the mutual exchange of energy of oscillations between them. Thus, sequentially defined coupling factor between machines i and j in the particular oscillatory mode h will be

$$C_{ij(h)}^2 = \frac{v_{jh} w_{ih}}{M_i} \frac{v_{ih} w_{jh}}{M_j} = \frac{p_{ih} p_{jh}}{M_i M_j} \tag{7}$$

From the above sequential coupling factor it is evident that the total coupling factor, which weights the influence of stabilisers applied over machines i and j on their dynamic behaviour under simultaneous excitation of all power system modes, can be given by

$$C_{ij}^2 = \sum_h C_{ij(h)}^2 \tag{8}$$

The coupling factor defined in eqn. 8 represents a suitable and reliable base for identification of the most effective combination of generators for PSS application, yielding maximum enhancement of the total system stability.

It is worth noting that the above relations are not restricted by the complexity of the power system model. If the higher-order model of controlled synchronous machine is used, then the transfer function $H(s)$ of an 'ideal PSS' becomes

$$H(s) = PSS_\omega(s) \cdot GEP(s) = k_s \tag{9}$$

where $GEP(s)$ is the plant transfer function [10] whose phase characteristics are nearly identical to those of the closed-loop voltage regulator (AVR), and the gain depends on the generator load and AC system strength. $PSS_\omega(s)$ is the transfer function of a practical speed stabiliser, tuned to compensate the phase lag in $GEP(s)$ over the frequency range of interest. Thus the PSS produces the desired damping component of torque in phase with speed changes during rotor oscillations. Therefore, it can be concluded that the characteristics of the transfer function $GEP(s)$ mainly affect the PSS tuning, rather than the choice of optimum site for its application. However, it must be pointed out that in practice PSS applications are preferred on the machines equipped with static exciters rather than on those fitted with AC exciters, since the

Table 1 : Values of sensitivities p_{ih}/M_i for ten-machine system

mode h	ω_h, rad/s	machine number (i) 1	2	3	4	5	6	7	8	9	10
1	3.90	0.073	0.147	0.184	0.488	$\boxed{1.000}$	0.473	0.459	0.142	0.566	0.166
2	5.97	0.047			0.251	2.297	0.056	0.055	0.122	$\boxed{3.268}$	
3	6.47	0.020	$\boxed{1.724}$	1.535	0.047	1.722	0.065	0.057	0.016	0.801	0.005
4	7.16	0.011	0.846	0.489	0.020	1.155	$\boxed{1.892}$	1.647	0.014	0.126	
5	7.98	0.013	$\boxed{3.159}$	2.526			0.020	0.015	0.018	0.002	
6	8.11	2.096	0.029	0.215	0.004	0.002	0.216	0.160	$\boxed{2.786}$	0.317	0.002
7	9.24	0.019	0.003	0.009	$\boxed{5.421}$	0.687	0.307	0.069	0.064		
8	9.61	1.971							$\boxed{4.335}$	0.004	
9	9.74				0.035		2.067	$\boxed{4.372}$			

latter significantly attenuate the PSS signal, which results in less efficient stabilisation.

4 Results and discussion

Fig. 2 shows the single-line diagram and generator inertias for the well known New England test system [4–7].

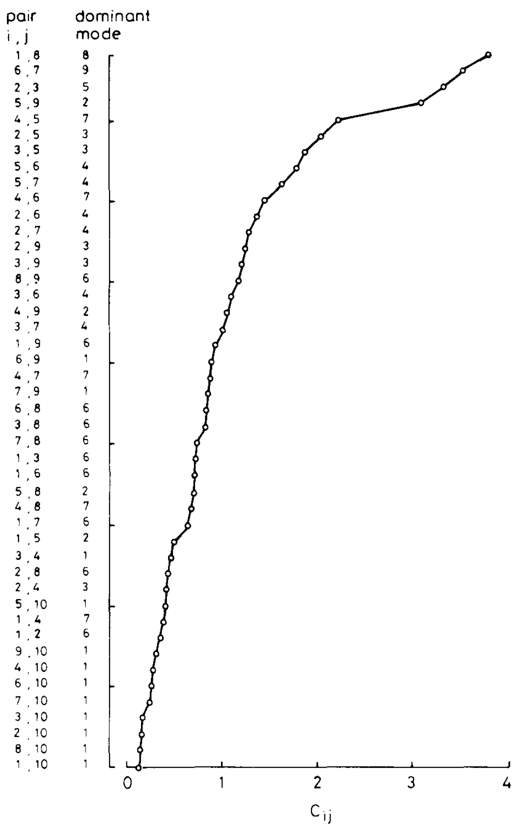

Fig. 3 *Ranked values of coupling factors C_{ij} and dominant modes for ten-machine systems*

The ratios D_i/M_i are specified to be the same for all generators, which results in the uniform damping throughout the system.

For the discussed ten-machine power system values p_{ih}/M_i greater than 10^{-3} are given in Table 1. Inspecting the data in Table 1 it may be recognised that each electromechanical mode has a particular machine where implementation of PSS leads to the maximum improvement of the critical mode damping. This is represented in Table 1 by outlining the highest sensitivities for each mode. Such a property of power system dynamic structure indicates the decoupling between certain parts of the system during the excitation of particular modes, which undoubtedly encourages the decentralised approach to the PSS design [8, 9].

Fig. 3 shows the values of coupling factors for all possible generator pairs in the ten-machine power system, ranked from the largest to the smallest. Each pair is accompanied by its dominant mode h, for which the following condition holds:

$$\max_h \{C_{ij(h)}\} \tag{10}$$

The generator pairs with the strongest dynamic coupling (1, 8), (6, 7), (2, 3) and (5, 9) can be found directly from Fig. 3. Examinations of Fig. 3 indicate that within each of the first three pairs exist strictly local modes 8, 9 and 5, respectively, whereas local mode 2 mostly involves pair (5, 9), although it is not the only pair where this mode appears as dominant. The existence of such (strictly) local modes points out generators which are in the nuclei of larger modal groups. These groups themselves include machines involved by the widespread intersystem modes of oscillations, such as the 1st, 4th and 6th modes in the example. The analysis of dominant modes for generator pairs throughout the ranking table in Fig. 3 identifies modal groups between which the intersystem modes exist. Thus, for example, mode 1 determines oscillations between equivalent machine 10 and the rest of the system; mode 3 mainly exists between generator pairs (2, 3) and (5, 9); etc. This analysis can be confirmed by the simulation studies, as illustrated in Fig. 4 for the 4th mode, when initial disturbance $\Delta x_o = v_h$ in eqn. 6 excites only a selected mode h.

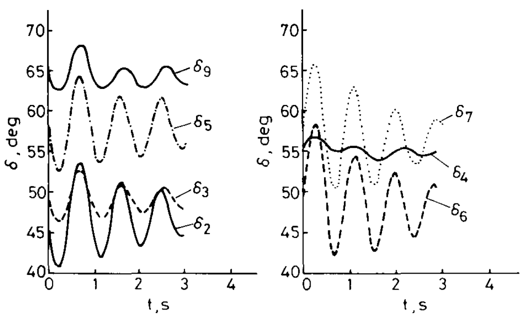

Fig. 4 *Time response of the 4th mode*

In view of the above results, it can be concluded that for improving the stability of the whole system the application of stabilisers is necessary over at least one of the machines from each generator pair identified in Fig. 3 as the most tightly coupled in the system. Given that these generator pairs form nuclei of larger modal groups involved with intersystem oscillations, it is obvious that the ensuring of good local mode damping, through the PSS applications on them, will be to the greatest possible extent beneficial for intersystem mode damping. Hence, the selection of generators to be equipped with PSSs can be done by considering sensitivities in Table 1 for machines only within generator pairs (1, 8), (6, 7), (2, 3) and (5, 9). Regarding the highest total effect on the damping of all electromechanical modes, which has the insertion of PSS on the machines 8, 7, 2 and 5, these generators are identified as desired sites for stabiliser applications. The same result has been verified as optimal in numerous simulation studies during sequential and co-ordinated syntheses of stabilisers in the New England test system [4–7].

Finally, it must be emphasised that the previously identified optimum sites for PSS applications are virtually independent of changes of the power system operating point. However, this is not so with the tuning of practical PSS, which should preferably be adapted to changes in $GEP(s)$ [11] during the variations of power system operating conditions, to maintain full damping effect of the PSS.

5 Conclusion

In this paper a modal-based identifying method of optimum site for power system stabiliser applications is presented. It has been shown that the concept of participation and newly introduced coupling factors yields a physically motivated and computationally efficient procedure for determining the best combination of generators to be equipped with stabilisers. The proposed technique enables fast and reliable identification of generators which are situated in the nuclei of the modal groups, where the application of PSS is necessary for improving overall system stability.

6 References

1 HSU, Y.Y., SHYUE, S.W., and SU, C.C.: 'Low frequency oscillations in longitudinal power systems: Experiences with dynamic stability of Taiwan power system', *IEEE Trans.*, 1987, **PWRS-2,** pp. 92–100

2 ARCIDIACONO, V., FERRARI, E., MARCONATO, R., DOSGHALI, J., and GRANDEZ, D.: 'Evaluation and improvement of electromechanical oscillation damping by means of eigenvalue–eigenvector analysis. Practical results in the Central Peru power system', *IEEE Trans.*, 1980, **PAS-99,** pp. 769–778

3 DEMELLO, F.P., NOLAN, P.J., LASKOWSKI, T.F., and UNDRILL, J.M.: 'Coordinated application of stabilizers in multimachine power systems', *ibid.*, 1980, **PAS-99,** pp. 892–901

4 HIYAMA, T.: 'Coherency-based identification of optimum site for stabiliser applications', *IEE Proc. C, Gen., Trans., & Distrib.*, 1983, **130,** (2), pp. 71–74

5 HSU, Y.Y., and CHEN, C.L.: 'Identification of optimum location for stabiliser applications using participation factors', *ibid.*, 1987, **134,** (3), pp. 238–244

6 LIM, C.M., and ELANGOVAN, S.: 'A new stabilizer design technique for multimachine power systems', *IEEE Trans.*, 1985, **PAS-104,** pp. 2393–2400

7 PAGOLA, F.L., and PEREZ-ARRIAGA, J.I.: 'Design of power system stabilizers using eigenvalue sensitivities and SMA techniques'. Proc. of VIII PSCC, 1984, Helsinki, pp. 997–1001

8 VERGHESE, G.C., PEREZ-ARRIAGA, I.J., and SCHWEPPE, F.C.: 'Selective modal analysis with applications to electric power systems, Part II: The dynamic stability problem', *IEEE Trans.*, 1982, **PAS-101,** pp. 3126–3134

9 LIU, C., ZHOY, S., and FENG, Z.: 'Using decoupled characteristic in the synthesis of stabilizers in multimachine systems', *IEEE Trans.*, 1987, **PWRS-2,** pp. 31–36

10 LARSEN, E.V., and SWAN, D.A.: 'Applying power system stabilizers', *IEEE Trans.*, 1981, **PAS-100,** pp. 3017–3046

11 OSTOJIC, D., DJURIC, M., and MUZDEKA, G.: 'An adaptive power system stabilizer', to be presented at IFAC Symposium on Power Systems, 1988, Brisel