Design of Power System Stabilizers Using Hybrid Differential Evolution

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Abstract: - This paper is used to investigate a novel decentralized pole placement design method of lead-lag type power system stabilizers using hybrid differential evolution (HDE). Since the local speed deviations are used as the feedback signals, the stabilizers could be easily implemented. In the design procedures, it wants to place the electromechanical modes within a designated region in the complex variable plane. Participation factors are used to select the sites and number of stabilizers. The HDE method is originally an optimal searching approach. If all electromechanical modes have been moved to the specified region at the convergent steps, the objective function will reach a minimal value. The objective function is chosen to ensure the real parts and/or damping ratios of electromechanical modes. A test power system is used to reveal the goodness of this method. The computation time and convergence characteristic of this approach are better, compared to the differential evolution and genetic algorithm. The coherency measures are also proposed to evaluate the relative behaviors between any pair of generators of the system with and without stabilizers.

Key-Words: - **Power system stabilizer, Electromechanical mode, Pole placement, Hybrid differential evolution, Power system dynamics.**

1 Introduction

The dynamic stability characteristics of a power system are affected by the location of electromechanical modes. It is sufficient that all electromechanical modes are placed in a suitable region in the complex s-plane to ensure damping effects on low frequency oscillations. Power system stabilizers (PSSs) have been widely used to increase the damping ratios of electromechanical modes. Recently, design technology has focused at how to tune parameters of PSSs in order to obtain optimal dynamic stability characteristics. Those methods include the optimization method using eigenvalue analysis [1], genetic design using simulated annealing optimization algorithms [2], probabilistic approach [3], Tabu search algorithm [4], particle-swarm-optimization technique [5], and genetic algorithm [6].

The hybrid differential evolution (HDE) is one of the best evolutionary algorithms for solving non-linear optimization problems [7]-[8]. A lot of works have recoded the HDE applications. It has been applied to the optimal control problem of a bio-process system [9]. Estimating the kinetic model parameters using HDE was presented in other literature [10]. This method was also employed for plant scheduling and planning to solve the decision-making problems of the manufacturing industry [11]. The improved HDE method for distribution systems has been used to reduce power loss and enhance the voltage profile [12]. This method may determine the optimal capacitor location of a radial distribution feeder [13].

The HDE method is applied in this paper to tune the lead-lag type PSSs. Participation factors are used to select and determine the sites and number of stabilizers [14-15]. The local speed feedback scheme is applied, considering the implementation requirement. It is to move all electromechanical modes to a region in the complex variable plane. The objective function is selected to ensure the location of real parts and/or damping ratios of all electromechanical modes. At the end of iterative procedures, if all electromechanical modes have been moved to the designated region, the objective function will converge to zero, which is the minimal value. From the simulation results of a multi-machine power system, the designed PSSs can let the generators have enough damping forces when there are line-tripping disturbances. The computation time and design results are better, compared with that using the differential evolution (DE) and genetic algorithm (GA). From the results of coherency measures, the levels of similarity between any pair of generators of the systems with and without PSSs have also been kept.

2 Hybrid differential evolution

A nonlinear optimization problem can be expressed as

$$\text{Minimize } M(\mathbf{X}) \tag{1}$$

Subject to

$$g_k(\mathbf{X}) \le 0 \qquad k = 1, \ldots, n_g \tag{2}$$

$$h_k(\mathbf{X}) = 0 \qquad k = 1, \ldots, n_h \tag{3}$$

where $M(\mathbf{X})$:objective function of variable vector $\mathbf{X}$,

$$\mathbf{X} = \left[\mathbf{X}_1, \mathbf{X}_2, \ldots, \mathbf{X}_j, \ldots, \mathbf{X}_D\right]^{\mathrm{T}}$$

$g_k(\mathbf{X})$: inequality constraints.

$h_k(\mathbf{X})$: equality constraints.

Differential evolution is a parallel direct search method for minimizing nonlinear and non-differential objective functions. The fitness of an offspring is determined by one-to-one competition with the corresponding parent. The solution procedures are given as follows.

Step 1. Initialization: Several initial populations $\mathbf{X}_i^0, i = 1, 2, \ldots, N_P$ are randomly selected. They should cover the entire search space uniformly. The elements of each individual $\mathbf{X}_i^0$ are given by

$$X_{ji}^0 = X_j^{min} + \rho_i (X_j^{max} - X_j^{min})$$

$$j = 1, 2, \ldots, D \;, i = 1, 2, \ldots, N_P \tag{4}$$

where $\rho_i \in [0,1]$ is a random number, and N_P is the population size. X_j^{min} and X_j^{max} are the lower and upper bounds of the variable X_j, respectively.

Step 2. Mutation operation: At generation G, each mutant vector is generated based on the corresponding present individual $\mathbf{X}_i^G$ by

$$\mathbf{U}_i^{G+1} = \mathbf{X}_i^G + F(\mathbf{X}_{r1}^G - \mathbf{X}_{r2}^G), \; i = 1, 2, \ldots, N_P \tag{5}$$

where $i \ne r1$, $i \ne r2$, and $r1, r2 \in \{1, 2, \ldots N_P\}$. $F \in [0,1]$ is a scalar factor. $\underline{X}_{r1}^G$ and $\underline{X}_{r2}^G$ are two randomly selected individuals.

Step 3. Crossover operation: To extend the diversity of individuals in the next generation, the perturbed individual $\mathbf{U}_i^{G+1} = \left[U_{1i}^{G+1}, U_{2i}^{G+1}, \ldots, U_{ji}^{G+1}, \ldots, U_{Di}^{G+1}\right]^{\mathrm{T}}$ and the present individual $\mathbf{X}_i^G = \left[X_{1i}^G, X_{2i}^G, \ldots, X_{ji}^G, \ldots, X_{Di}^G\right]^{\mathrm{T}}$ are mixed to yield the trial vector

$$\hat{\mathbf{U}}_i^{G+1} = \left[\hat{U}_{1i}^{G+1}, \hat{U}_{2i}^{G+1}, \ldots, \hat{U}_{ji}^{G+1}, \ldots, \hat{U}_{Di}^{G+1}\right]^{\mathrm{T}} \tag{6}$$

where

$$\hat{U}_{ji}^{G+1} = \begin{cases} X_{ji}^G, \textit{if a random number} > C_R \\ U_{ji}^{G+1}, \textit{otherwise} \end{cases}$$

$$j = 1, 2, \ldots, D, \; i = 1, 2, \ldots, N_P \tag{7}$$

where D is also the number of genes. $C_R \in [0,1]$ is the crossover factor and must be set by the user.

Step 4. Evaluation and selection: The parent is replaced by its offspring in the next generation if the fitness of the latter is better. Contrarily, the parent is retained. The first step is one-to-one competition. The next step chooses the best individual, $\mathbf{X}_b^{G+1}$ in the population. That is

$$\mathbf{X}_i^{G+1} = \textit{arg-min}\{M(\mathbf{X}_i^G), M(\hat{\mathbf{U}}_i^{G+1})\}$$

$$i = 1, 2, \ldots, N_P \tag{8}$$

$$\mathbf{X}_b^{G+1} = \textit{arg-min}\{M(\mathbf{X}_i^{G+1})\}, i = 1, 2, \ldots, N_P \tag{9}$$

where *arg-min* means the argument of the minimum.

The above steps are repeated until the maximum iteration number or the desired fitness is obtained. In general, a faster descent usually leads to a local minimum or a premature convergence. Conversely, diversity guarantees a high probability of obtaining the global optimum. The trade-off can be obtained by slightly lowering the scaling factor F and by increasing the population size N_P. However, more computation time is required. The migrant and accelerated operations in HDE are used to overcome the local minimum solution and time consumption. The migrant and accelerating operations are inserted in the differential evolution.

Step 5. Migrant operation if necessary: For increasing search space exploration, a migration operation is introduced to regenerate a diverse population of individuals. The migrant individuals are selected on a "best individual" basis $\mathbf{X}_b^{G+1}$. The j[th] gene of $\mathbf{X}_i$ is regenerated by

$$x_{ji}^{G+1}=\begin{cases} x_{jb}^{G+1}+\rho_1(x_j^{\min}-x_{jb}^{G+1}), & \text{if a ramdom number } \rho_2<\dfrac{x_{jb}^{G+1}-x_j^{\min}}{x_j^{\max}-x_j^{\min}} \\ x_{jb}^{G+1}+\rho_1(x_j^{\max}-x_{jb}^{G+1}), & \text{otherwise} \end{cases} \tag{10}$$

where ρ_1 and ρ_2 are randomly generated numbers uniformly distributed in [0, 1]. The migrant population will not only become a set of newly promising solutions, but also avoid the local minimum trap.

The migrant operation is performed only if a measure fails to match the desired population diversity tolerance. The measure in this study is defined as

$$u=\frac{\left[\sum_{\substack{i=1\\ i\neq b}}^{N_P}\sum_{j=1}^{D}\eta_{ji}\right]}{D(N_P-1)}<\varepsilon_1 \tag{11}$$

where

$$\eta_{ji}=\begin{cases}1, & \text{if } \left|\dfrac{x_{ji}^{G+1}-x_{jb}^{G+1}}{x_{jb}^{G+1}}\right|>\varepsilon_2 \\ 0, & otherwise\end{cases} \tag{12}$$

parameters $\varepsilon_1\in[0,1]$ and $\varepsilon_2\in[0,1]$ express the desired tolerance of the population diversity and the gene diversity with regard to the best individual, respectively. Here η_{ji} is defined as an index of the gene diversity. A zero η_{ji} means that the j[th] gene of the i[th] individual is close to the j[th] gene of the best individual. If the degree of population diversity u is smaller than ε_1, the HDE performs migration to generate a new population to escape the local point. Otherwise, HDE breaks off the migration, which maintains an ordinary search direction.

Step 6. Accelerated operation if necessary: When the fitness in the present generation is no longer improved using the mutation and crossover operations, a descent method is then applied to push the present best individual toward a better point. Thus, the acceleration operation can be expressed as

$$\hat{\mathbf{X}}_b^{G+1}=\begin{cases}\mathbf{X}_b^{G+1}, & \text{if a objective function } M(\mathbf{X}_b^{G+1})<M(\mathbf{X}_b^{G}) \\ \mathbf{X}_b^{G+1}-\alpha\nabla M(\mathbf{X}_b^{G+1}), & \text{otherwise}\end{cases} \tag{13}$$

The gradient of the objective function, $\nabla M(\mathbf{X}_b^{G+1})$, can be approximately calculated with a finite difference. The step size $\alpha\in(0,1]$ is determined according to the decent property. Firstly, α is set to unity. The objective function $M(\hat{\mathbf{X}}_b^{G+1})$ is then compared with $M(\mathbf{X}_b^{G+1})$. If the decent property is achieved, $\hat{\mathbf{X}}_b^{G+1}$ becomes a candidate in the next generation, and is added into this population to replace the worst individual. On the other hand, if the decent requirement fails, the step size is reduced, for example, 0.5 or 0.7. The decent search method is repeated to find the optimal $\hat{\mathbf{X}}_b^{G+1}$, called $\mathbf{X}_b^N$, at the (G+1)[th] generation. This result shows the objective function $M(\mathbf{X}_b^N)$ should be at least equal or smaller than $M(\mathbf{X}_b^{G+1})$.

3 Pole placement design

3.1 Power system description

Determining the parameters of PSSs for an N-generator power system should consider various loading conditions. When considering a linearized time-invariant system, the equations of generator *i* in the two-axis model are expressed by

$$\dot{\mathbf{x}}_i(\mathbf{t})=\mathbf{A}_{ii}\mathbf{x}_i(\mathbf{t})+\sum_{j=1,\,j\neq i}^{N}\mathbf{A}_{ij}\mathbf{x}_j(\mathbf{t})+\mathbf{B}_{ii}\mathbf{u}_i(\mathbf{t}) \qquad i=1,2,\ldots,N \tag{14}$$

where $\mathbf{x}_i(t)=[\Delta E'_{di}\ \ \Delta E'_{qi}\ \ \Delta\omega_i\ \ \Delta\delta_i\ \ \Delta E_{FDi}\ \ \Delta V_{Si}\ ]^T$ is the state vector, $\Delta E'_{di}$ and $\Delta E'_{qi}$ are the d-axis and q-axis transient voltages, respectively, and $\Delta\omega_i$ and $\Delta\delta_i$ are the rotor speed and angle, respectively, ΔE_{FDi} is the field voltage, ΔV_{Si} is the output signal of stabilizing transformer. The diagram of the static excitation system is given in Fig. 1.

3.2 Lead-lag PSS

The conventional lead-lag phase compensation PSS is considered. The local speed deviations are used as the feedback signals. The transfer function is

$$u(s) = K_S \frac{sT_5}{1+sT_5}\left(\frac{(1+sT_1)(1+sT_3)}{(1+sT_2)(1+sT_4)}\right)\Delta\omega(s) \qquad (15)$$

If the washout time constant, T_5, is given, the remaining parameters, K_S, T_1, T_2, T_3, and T_4, are to be determined by the HDE.

3.3 Objective function

The objective function is selected so that all electromechanical modes can be moved to the specified region as shown in Fig. 2. It is required that $\sigma_{i,j} \le \sigma_0$ and $\zeta_{i,j} \ge \zeta_0$, where $\sigma_{i,j}$ and $\zeta_{i,j}$ are the real part and damping ratio of the ith electromechanical mode under the jth operating condition. Then the objective function for an N-generator system is given as

$$M = \sum_{j=1}^{np}\sum_{i=1}^{N}\left(\sigma_0 - \sigma_{i,j}\right)^2 + \sum_{j=1}^{np}\sum_{i=1}^{N}\left(\zeta_0 - \zeta_{i,j}\right)^2 \qquad (16)$$

$$\text{for} \quad \sigma_{i,j} \ge \sigma_0 \quad \text{and} \quad \zeta_{i,j} \le \zeta_0$$

where np is the number of operating points considered simultaneously in the design procedures. The system stability condition is determined by the specified damping constant σ_0 and damping ratio ζ_0. In the design procedure using the HDE, the population size N_P is selected to be 5, the scalar factor F to be 0.01, and the crossover factor C_R to be 0.5.

4 Example: A multi-machine system

Consider the New England power system as shown in Fig. 3 where bus 1 is assumed to be an infinite bus. Generators 2-10 (G2-G10) are equipped with static exciters. The system data are given in [16]. The electromechanical modes of the system are shown in the first column of Table 1. Some damping characteristics of electromechanical modes are poor, especially that of $-0.06 \pm j6.68$ and $-0.10 \pm j3.16$.

The participation factors for sum of $\Delta\delta$ and $\Delta\omega$ of each generator are used to select the sites and number of PSSs [14-15]. The participation factors associated with the electromechanical modes are also given in Table 1. G10 is chosen to install a PSS to enhance the worst damping mode ($-0.06 \pm j6.68$) by using the participation factors. G9 is suitable to install a PSS to improve the mode ($-0.10 \pm j3.16$). The other suitable sites are G2, G4 and G7.

In the designing PSSs of G2, G4, G7, G9, and G10 using DE, GA, and HDE methods, it is selected that $\sigma_0 = -0.5$ and $\zeta_0 = 0.1$. All objective functions have converged as reveled in Fig. 4. If the convergent value of an objective function reaches zero, it means that all electromechanical modes have been moved to the designated region. It is also shown that DE, GA, and HDE take 52, 1002, and 356 iteration steps to converge, respectively. The computation time is evaluated by the CPU time on a Pentium III 2.4 GHz computer as shown in Table 2. It indicates that HDE is faster than GA. Although the DE is the fastest one, it is convergent to a local optimal solution and has a larger convergent objective function value. The electromechanical modes of the system with DE_PSS, GA_PSS, and HDE_PSS under operation condition 1 are tabulated in Table 3.

In the time domain simulations, nonlinear differential equations must be used to examine the damping effects of PSSs. The tripping of line 1-38 is used as a larger disturbance. Simulation results are given in Fig. 5 for generators 2, 4, 7, 9, and 10. The system with the HDE_PSS has better responses.

The coherency measures which are derived from time-domain responses in Fig. 5, are proposed to evaluate the relative behaviors between any pair of generators. The results are given in Table 4 for the system with the PSSs. It can be found that the levels of similarity have been kept. Since the coherency behaviors do not be destroyed, the system should have a higher stability condition.

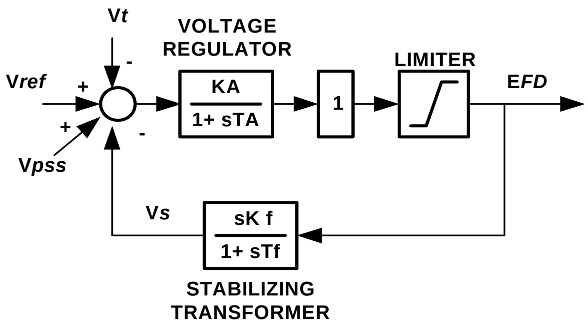


Figure 1. Block diagram of static excitation system

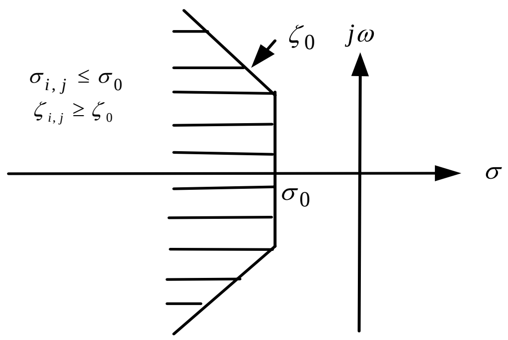


Figure 2. A region where $\sigma_{i,j} \le \sigma_0$ and $\zeta_{i,j} \ge \zeta_0$

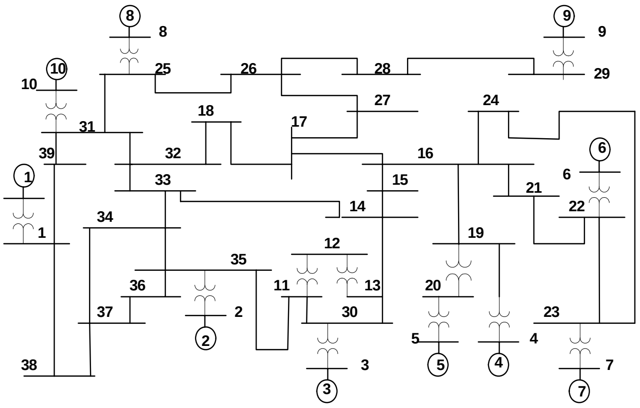


Figure 3. Single line diagram of New England power system

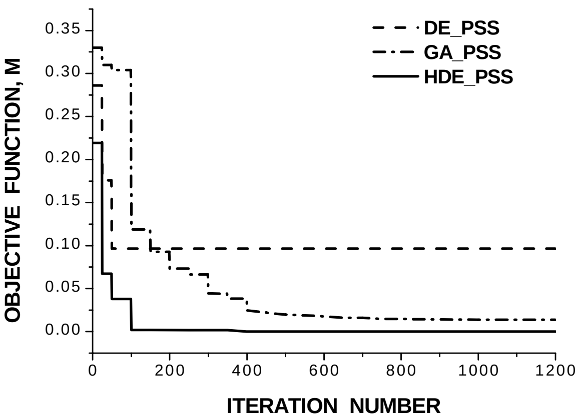
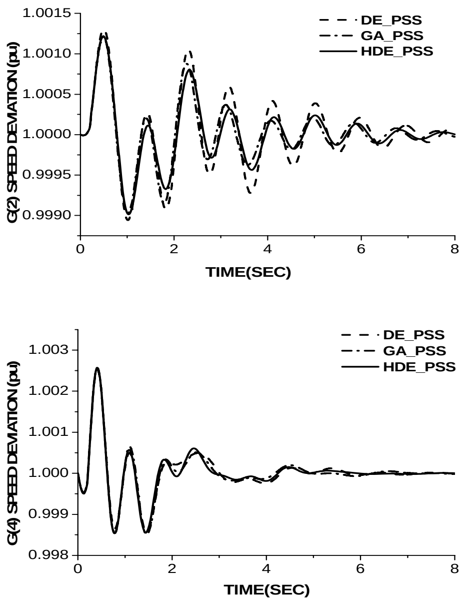


Figure 4. Convergent characteristics of objective functions M using DE, GA, and HDE



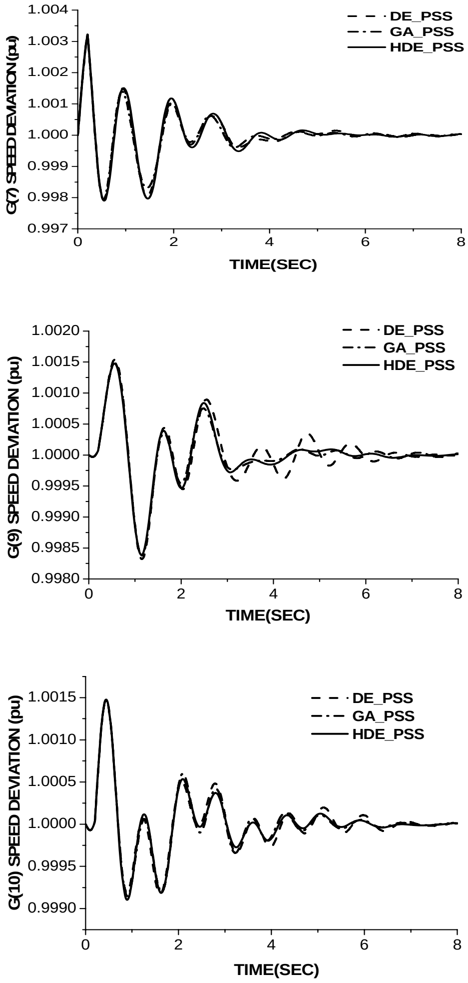


Figure 5. Responses of Generators 2, 4, 7, 9, and 10 subjected to large disturbance

5 Conclusions

A comprehensive decentralized pole assignment method based on HDE has been successfully used in the design of lead-lag phase compensation power system stabilizers. A multi-machine system is used as an example to demonstrate the developed method and reveal the convergent procedures. The participation factors associated with the electromechanical modes are used to select the sites of power system stabilizers. The computation time and the convergent characteristics of the objective function are better, compared with that from GA and DE. The chosen region to assign the electromechanical modes could be relatively important in the design. From the simulation results, the HDE gives a good method in tuning power system stabilizers to improve system dynamic stability. The coherency analysis results reveal that the levels of similarity between any pair of generators have been kept.

Table 1 Participation factors of generator speed and rotor angle of the New England system without PSS

Electromechanical mode (Damping Ratio)	G2	G3	G4	G5	G6	G7	G8	G9	G10
-0.49 ± j 9.48 (0.052)	0.0001	0.0003	-0.1569	-0.0103	0.7312	1.5044	0.0015	0.0001	0
-0.40 ± j 9.21 (0.043)	0.001	0.0039	1.7995	0.1783	0.1135	-0.1609	0.0877	-0.0003	0.0003
-0.42 ± j 8.80 (0.048)	0.0063	0.0121	0.0447	0.0098	0.0483	-0.0033	1.8013	0.043	0.0906
-0.24 ± j 7.99 (0.031)	1.0283	0.9793	0	0.0001	0.0034	0.0005	0	0	0
-0.26 ± j 7.08 (0.038)	0.3021	0.2387	0.0102	0.2378	0.8178	0.4012	-0.0001	0.0249	0.0046
-0.06 ± j 6.68 (0.01)	0.1441	0.1739	-0.0019	0.0559	0.0463	0.028	0.0201	0.0537	1.4916
-0.19 ± j 6.03 (0.032)	0.3921	0.4203	0.0042	0.3931	0.0202	0.0158	0.0077	0.6083	0.1475
-0.20 ± j 5.91 (0.035)	0.0017	0.0006	0.0774	0.821	0.0186	0.0112	0.036	0.9216	0.124
-0.10 ± j 3.166(0.031)	0.1357	0.184	0.2439	0.3564	0.2699	0.2261	0.0881	0.3596	0.1433

Table 2 Comparison of DE, GA, and HDE

DE					GA					HDE				
Objective Function (pu)	N_P	CPU time (sec)	C_R	F	Objective Function (pu)	N_P	CPU time (sec)	P_c	P_m	Objective Function (pu)	N_P	CPU time (sec)	C_R	F
0.09634	5	7.7776	0.5	0.01	0.0138	5	293.4507	0.5	0.01	0.000148	5	76.8322	0.5	0.01

Table 3 Electromechanical modes with PSSs

DE	GA	HDE
Eigenvalue(Damping Ratio)	Eigenvalue(Damping Ratio)	Eigenvalue(Damping Ratio)
-3.19 ± j 7.41 (0.41)	-2.08 ± j 8.57 (0.24)	-2.30 ± j7.64 (0.29)
-1.04 ± j 3.71 (0.27)	-1.28 ± j 4.90 (0.25)	-1.46 ± j7.69 (0.19)
-0.82 ± j 2.38 (0.32)	-1.17 ± j 8.95 (0.13)	-1.28 ± j 8.55 (0.15)
-0.73 ± j 7.52 (0.1)	-1.11 ± j 6.42 (0.17)	-1.28 ± j4.53 (0.27)
-0.43 ± j 7.02 (0.06)	-0.63 ± j 7.35 (0.09)	-1.04 ± j9.34 (0.11)
-0.41 ± j 8.84 (0.05)	-0.59 ± j 8.92 (0.07)	-0.82 ± j 8.946 (0.09)
-0.38 ± j 8.19 (0.05)	-0.58 ± j 6.84 (0.08)	-0.818 ± j 8.95 (0.09)
-0.33 ± j 6.54 (0.05)	-0.57 ± j 9.22 (0.06)	-0.74 ± j7.15 (0.1)
-0.33 ± j 5.95 (0.06)	-0.41 ± j 9.18 (0.04)	-0.68 ± j6.43 (0.11)

Table 4 Coherency measures of the system with PSSs

	G2	G3	G4	G5	G6	G7	G8	G0	G10
G2	1.0000	0.8667	0.6192	0.7747	0.2021	0.3338	0.8151	0.8407	0.8277
G3	0.8667	1.0000	0.6021	0.7707	0.1141	0.2668	0.8393	0.7746	0.8137
G4	0.6192	0.6021	1.0000	0.4529	0.2996	0.4531	0.6950	0.5873	0.7503
G5	0.7747	0.7707	0.4529	1.0000	0	0.1249	0.6509	0.7765	0.6354
G6	0.2021	0.1141	0.2996	0	1.0000	0.8226	0.2191	0.1828	0.2647
G7	0.3338	0.2668	0.4531	0.1249	0.8226	1.0000	0.3649	0.3205	0.4070
G8	0.8151	0.8393	0.6950	0.6509	0.2191	0.3649	1.0000	0.7043	0.9202
G9	0.8407	0.7746	0.5873	0.7765	0.1828	0.3205	0.7043	1.0000	0.7183
G10	0.8277	0.8137	0.7503	0.6354	0.2647	0.4070	0.9202	0.7183	1.0000

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