

Research Article

Comparative Study of Popular Objective Functions for Damping Power System Oscillations in Multimachine System

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Received 24 February 2014; Accepted 19 March 2014; Published 6 April 2014

Academic Editors: N. Barsoum, P. Vasant, and G.-W. Weber

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Power oscillation damping controller is designed in linearized model with heuristic optimization techniques. Selection of the objective function is very crucial for damping controller design by optimization algorithms. In this research, comparative analysis has been carried out to evaluate the effectiveness of popular objective functions used in power system oscillation damping. Two-stage lead-lag damping controller by means of power system stabilizers is optimized using differential search algorithm for different objective functions. Linearized model simulations are performed to compare the dominant mode's performance and then the nonlinear model is continued to evaluate the damping performance over power system oscillations. All the simulations are conducted in two-area four-machine power system to bring a detailed analysis. Investigated results proved that multiobjective D-shaped function is an effective objective function in terms of moving unstable and lightly damped electromechanical modes into stable region. Thus, D-shape function ultimately improves overall system damping and concurrently enhances power system reliability.

1. Introduction

Reliability and security of multimachine power system are achieved through numerous controllers. Design of robust damping controllers for the interconnected power system is very sensitive in order to suppress oscillations [1]. Power system oscillation is very harmful to the overall interconnected system. Therefore, proper and adequate damping is required to prevent damages caused by oscillations [1]. Damping power system oscillations are performed by means of power system stabilizers (PSSs) installed in the generator's excitation system and flexible AC transmission system (FACTS) devices installed in transmission line for fast acting damping performance [2–4]. The damping performance by PSS and FACTS depends on proper selection of its controller parameters [3]. The design of PSS and FACTS controllers usually is achieved in the linearized model by minimizing or maximizing an objective function using metaheuristic

optimization algorithms [5–9]. Improving damping performance has been proposed by many superior metaheuristic algorithms using inconsistent objective functions [5, 9–13]. However, metaheuristic algorithms are used to minimize or maximize an objective function that correspond optimized parameters under several system operating conditions [11, 14]. Therefore, selection of objective function may influence the overall controller optimization problem and that consequently affects existing system reliability.

In the last few years, many approaches to formulate the objective functions have been used in the damping controller design problem. That may be categorized into two types: (i) single objective functions and (ii) multiobjective functions. Application of single objective functions is presented either in terms of damping factors or damping ratios of electromechanical modes. In many literatures, the worst damping factor (largest value) has been selected and then the aim of optimization was set to minimize it [5–8]. On

the other hand, damping ratio is also important to limit the overshoot of oscillations which ultimately improves damping performance of controllers. Therefore, the lowest damping ratio has been determined and controller parameters were optimized in such a way to maximize it in [9]. However, system damping depends on the performance of dominant electromechanical modes rather than a single mode only. So, a single objective function known as comprehensive damping index (CDI) has been proposed in [10] that includes dominant modes. As both of the damping factor and damping ratio contribute to enhance damping performance, significance of multiobjective functions is realized in numerous researches [11–19]. In multiobjective techniques, the formulation to place electromechanical modes into a D-shaped region is very popular. However, different approaches have been applied to form D-shaped stability area. In [11, 14–18], a technique to form D-shaped stability zone is discussed based on the expected damping factor and ratio for dominant modes. In that objective function, only selected dominant modes are considered into optimization that do not have expected damping factor or damping ratio. Another approach to set up D-shaped region has been claimed in [12, 19] by the algebraic sum of the worst damping factor and ratio. Moreover, a different arrangement is reported in [13] in order to form D-shaped sector.

Application of the objective function with different formulations has been proposed for the design of robust damping controllers. As an objective function formulation is quite sensitive to damping controller parameter optimization, it is very significant to evaluate their comparative performance under a common base. Therefore, this research comes forward to conduct a comparative and comprehensive investigation to evaluate the existing objective functions for damping controller design in multimachine power system. Popular objective functions are considered to use with a metaheuristic optimization algorithm under a base setting. Later on, the analysis is extended to assess performances in linearized model and nonlinear model of the power system.

2. Power System and Damping Controller

Two-area four-machine power system shown in Figure 1 is a benchmark system to study power system oscillations [1, 2]. The performance of local and interarea modes of oscillations can be observed easily in this system [2]. Therefore, it is adopted to design damping controllers by means of PSSs. The overall system has 13 buses, two load areas, and four synchronous generators equipped with similar components. The excitation system is the IEEE type ST1 exciter. The detail system data are taken from [2].

A PSS is added with each synchronous generator to provide an additional damping torque if system tempts to become unstable for oscillations. All PSSs are conventional PSS (CPSS) which consists of two-stage lead-lag compensation blocks with one gain and one washout block. The rotor speed deviation ($\Delta\omega$) is the input of PSS. IEEE type ST1 excitation system with PSS is presented in Figure 2, where T_w is the washout time constant and it is set to 10 s for all PSSs.

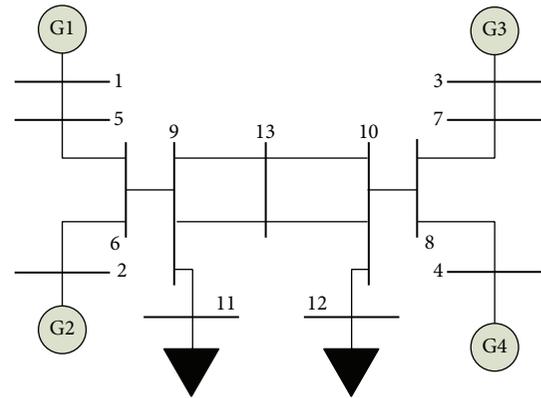


FIGURE 1: Single line diagram of two-area four-machine power system.

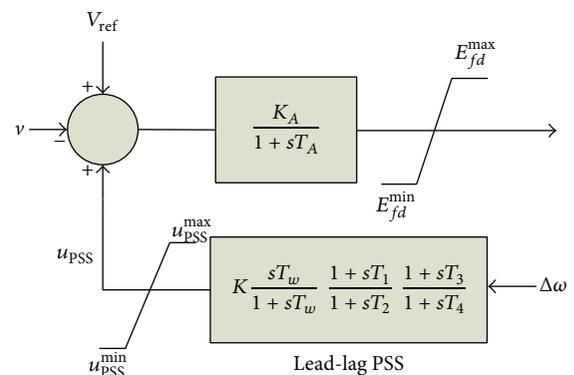


FIGURE 2: IEEE type ST1 excitation system with power system stabilizer.

On the other hand, optimizing parameters are gain constant (K) and lead-lag time constants (T_1 , T_2 , T_3 , and T_4).

The entire systems are modelled based on linear-time-invariant (LTI) state-space (SS) theory around an operating point from a set of nonlinear differential equations. The linearized system model is represented in terms of the state matrix (A), input matrix (B), output matrix (C), and feed-forward matrix (D) shown in

$$\begin{aligned} \dot{x} &= A \cdot x + B \cdot u, \\ y &= C \cdot x + D \cdot u, \end{aligned} \quad (1)$$

where x is the vector of state variables and u is the vector of input variables. The eigenvalues determined from state matrix A reflect the overall system stability. Therefore, objective functions are formulated to move eigenvalue forcefully from unstable region (right side of s -plane) to stable region (left side of s -plane). The key properties of an eigenvalue ($\lambda = \sigma \pm j\omega$) are damping factor (σ) and the damping ratio (ζ) that are determined from

$$\begin{aligned} \sigma_i &= \text{real}(\lambda_i), \\ \zeta_i &= -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}, \end{aligned} \quad (2)$$

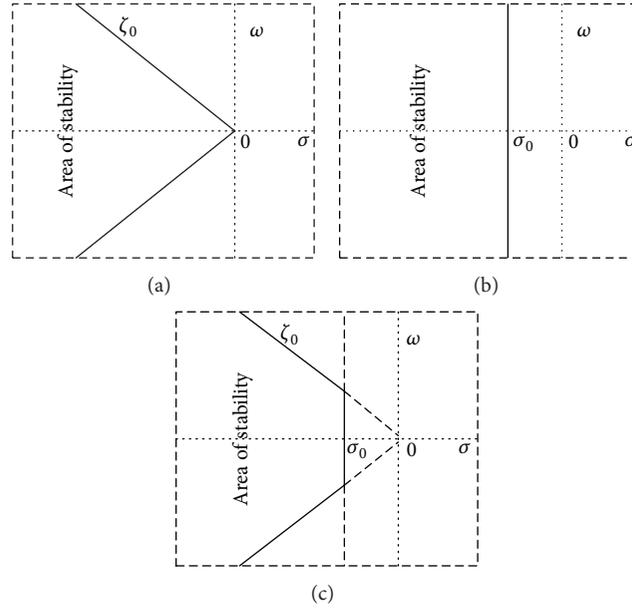


FIGURE 3: Stability regions defined by different objective functions in s-plane.

where $i = 1, 2, 3, \dots, n$ and n is the total number of eigenvalues in the power system. The objective functions are maximized or minimized in order to achieve system stability under constraints of damping controller parameters shown

$$\begin{aligned}
 K_{\min} &\leq K \leq K_{\max}, \\
 T_{1,\min} &\leq T_1 \leq T_{1,\max}, \\
 T_{2,\min} &\leq T_2 \leq T_{2,\max}, \\
 T_{3,\min} &\leq T_3 \leq T_{3,\max}, \\
 T_{4,\min} &\leq T_4 \leq T_{4,\max}.
 \end{aligned}
 \tag{3}$$

3. Objective Functions

The main purpose of objective function formulation is to shift eigenvalues from unstable region to stable region shown in Figure 3 to achieve sufficient damping over power system oscillations. The popular objective functions are described in (4)–(8).

3.1. Single Objective Functions. These types of objective functions are formulated by focusing one property of eigenvalues (either σ or ζ) that partially ensure system stability for total j operating points. From research paper [5–8], the objective function is constructed to improve only damping factor shown in (4). In this case, the objective function J_1 is set to minimize

$$J_1 = \max \{ \text{real}(\lambda_{ij}) \}.
 \tag{4}$$

Damping ratio is a measure of damping oscillations. In [9], the eigenvalue with poorest damping ratio is selected to maximize J_2 shown in

$$J_2 = \min(\zeta_{ij}).
 \tag{5}$$

In other literature [10], CDI is considered as the objective function that considered all dominant modes to achieve maximum damping ratios instead of one mode only. CDI is described by (6). Here, J_3 is minimized in order to optimize controller parameters.

$$J_3 = \sum_{i=1}^n (1 - \zeta_{ij}).
 \tag{6}$$

3.2. Multiobjective Functions. Different approaches are adopted to move eigenvalues into D-shaped stability regions. Multiobjective functions in (7) [11, 14–18] and in (8) [12, 19] are reported to minimize (J_4) and maximize (J_5), respectively, in order to achieve D-shaped stability criteria:

$$J_4 = \sum_{j=1}^{np} \sum_{\sigma_{ij} \geq \sigma_0} (\sigma_0 - \sigma_{ij})^2 + a \cdot \sum_{j=1}^{np} \sum_{\zeta_{ij} \leq \zeta_0} (\zeta_0 - \zeta_{ij})^2,
 \tag{7}$$

$$J_5 = -\max(\sigma_{ij}) + \min(\zeta_{ij}).
 \tag{8}$$

4. Differential Search Algorithm

Differential search algorithm (DSA), as a metaheuristic optimization algorithm, is selected to assess the objective functions (4)–(8) for improving damping performances by multimachine PSSs. Tuning the parameters of PSSs damping

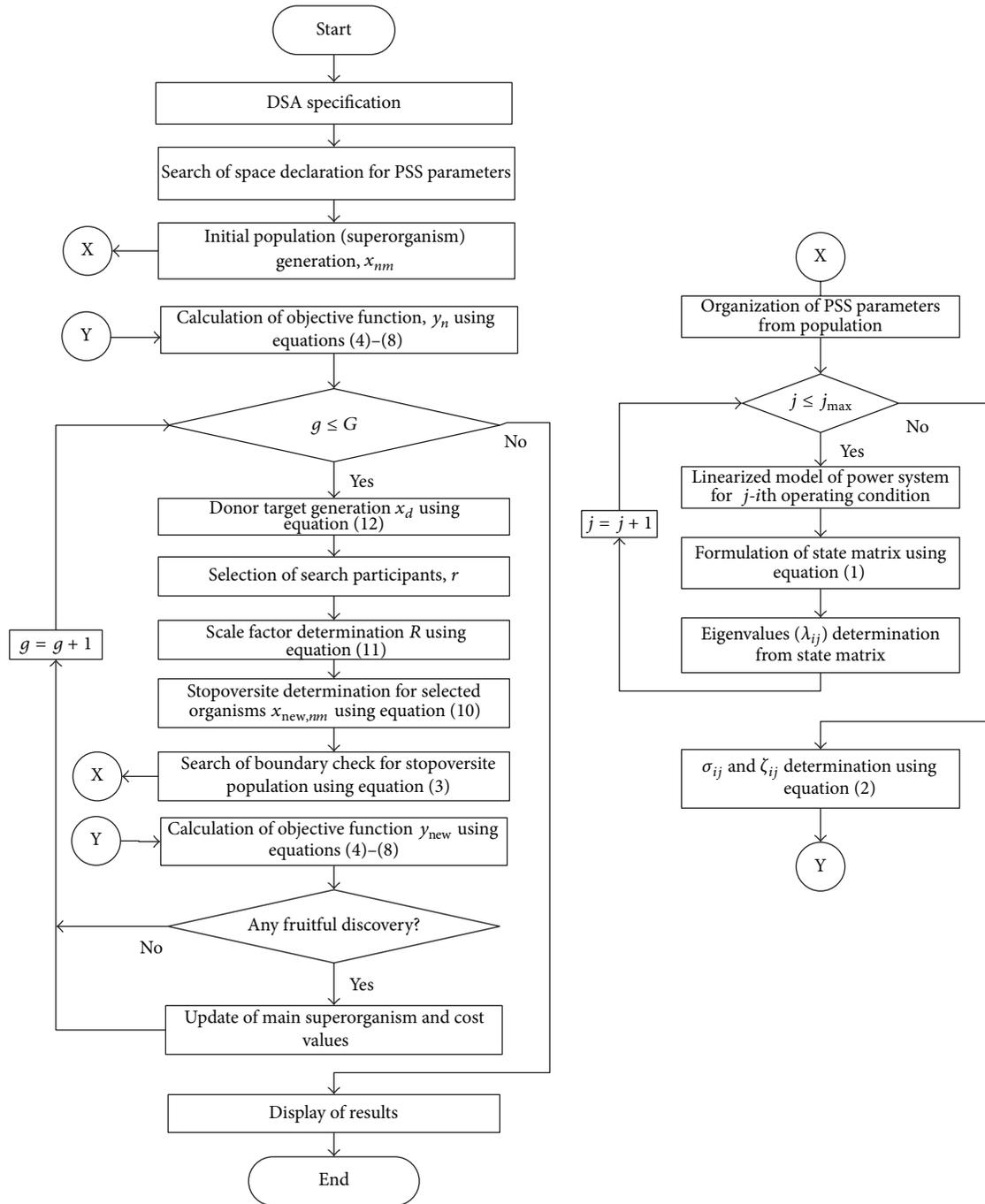


FIGURE 4: Flow chart of PSS parameters optimization with different objective functions using DSA.

controllers is a multimodal optimization problem and DSA is recommended specially to solve this type of problem [20]. In DSA, the initial population of organisms is generated using (9) and their movements are characterized by (10):

$$x_{nm} = low_m + (up_m - low_m) \cdot rand, \quad (9)$$

$$x_{new, nm} = x_{nm} + R \cdot (x_d - x_{nm}), \quad (10)$$

where x_{nm} is the initial population and low_m and up_m are the lower and upper constraint vectors of PSS parameters,

respectively. The scale factor R is generated using a gamma random function as shown in

$$R = randg \cdot [2 \cdot rand] \cdot (rand - rand), \quad (11)$$

where $randg$ and $rand$ are the gamma random function and uniformly distributed pseudorandom number, respectively. In DSA, donors are considered to be located in fruitful area. Therefore, generated populations are moved towards the

TABLE 1: System operating conditions considered in damping controller design.

Case	Operating points	Faults at bus	Between buses
1	Base case (all line in services)		
2	Three phase fault	9	9 and 13
3	Line to line fault	13	13 and 10

location of donors and donors are made up by reshuffling the original populations as shown in

$$x_d = (x_{nm})_{\text{random_reshuffling}} \quad (12)$$

For a fair comparison, the simulation settings of DSA are kept the same for each objective function. The simulation settings are mentioned in the appendix. To understand the overall procedures of this research, the step by step works are depicted in flow chart diagram shown in Figure 4. Interested authors are referred to the original paper of this optimization algorithm in [20].

5. Results and Discussion

In order to evaluate the effectiveness of selected objective functions in (4)–(8), simulations are performed in linearized model and nonlinear model of the power system. The linear model simulations are performed using DSA technique to minimize or maximize the objective functions that concurrently bring unstable and poorly damped electromechanical modes into stable region. The common base setting for optimization simulations using DSA is the same (mentioned in the appendix) for all objective functions. All the simulations are performed on a desktop computer with 3.14 GHz processor and 4 GB DDR3 RAM. The system operating points are considered as mentioned in Table 1. The test system has four PSSs and total 20 parameters are to be optimized.

Simulations for each objective function have been performed 10 times and data are recorded. Then the best one (according to the objective function value) is selected for comparison. The same process is executed for all five objective functions. The best optimized parameters of four PSSs are listed in Table 2. From the best optimized value, the major dominant modes are determined as shown in Table 3 with corresponding damping ratios and frequencies. Sensitive modes are highlighted (bold) for easy understanding.

For objective function J_1 , although dominant modes have achieved expected damping ratios, (0.15) it may lead to system instability. The reason is its interarea mode's damping factor, which is below expected value (-1.5). In addition, the frequency of interarea modes is very low; therefore it is enough to show poor damping. For remaining objective functions, it is noticeable that dominant modes for only J_4 are achieved expecting damping factor and damping ratio. Moreover, J_4 has no modes with very low frequency. The improvement is based on the damping factors and damping ratios. Single objective functions J_1 , J_2 , and J_3 do not have both expected values, which is a sign of poor damping performance. Whereas multiobjective functions J_4 , J_5 have

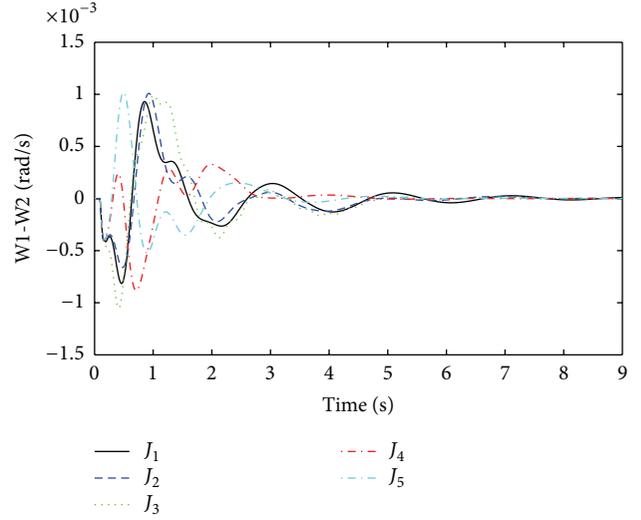


FIGURE 5: Local mode of oscillations between G1 and G2 (W1-W2) for three-phase fault at bus 9.

better performance compared with single objective functions. Even though J_5 do not have expected damping factor for its low frequency mode, which may lead to poor damping.

The objective functions performances are assessed further in nonlinear time domain simulations by comparing damping performance. In order to check the robustness of damping controller, it is important to evaluate damping performances under considered (Table 1) and not considered operating points during linear model optimization. As a considered operating condition, three-phase fault near bus 9 (between lines 9 to 13) and, as a not considered operating point, three-phase fault near bus 13 (between lines 13–9) are executed individually. For both conditions, faults are applied for 100 ms duration and cleared by opening remote end of the faulted line at 150 ms. After that the system is operating in only one tie line and oscillations between generators to generators start growing. Optimized PSSs sense the oscillations and provide damping to suppress it. The quality of a good damping controller is measured on how fast the settling time is achieved and how smoothly the overshoot it can handle to avoid major damages by oscillations. Figures 5 and 6 are the responses of local mode and interarea mode oscillations obtained for fault at bus 9. In Figure 5, it is observed that only J_4 has lower overshoot and very fast settling time than others. For interarea mode of oscillations in Figure 6, J_4 and J_5 have almost the same settling time except high overshoot for J_5 .

Rotor oscillation responses for the fault at bus 13 are obtained as shown in Figures 7, 8, 9, and 10. From Figures 7–10, it is observed that single objective functions J_1 and J_2 have very poor settling times and overshoot than other. Objective function CDI has quite a satisfactory damping performance except in Figure 7. For J_4 , the best settling times are achieved in all modes and the overshoot values are also quite reasonable. Multiobjective function J_5 has damping performance just like single objective functions J_1 , J_2 . Thus, from Figures 7–10, the time domain simulations are used to

TABLE 2: Best optimized parameters for each objective function using DSA.

Objective functions	K	T_1	T_2	T_3	T_4	
J_1	PSS1	5.1903	1.1099	0.2358	1.6706	1.3299
	PSS2	7.2073	1.1549	1.2313	0.7452	1.5635
	PSS3	6.3461	0.8985	0.5746	0.8453	0.3337
	PSS4	10.7097	0.0906	0.7335	1.4030	1.6083
J_2	PSS1	5.0422	0.9573	1.8312	1.6562	0.2857
	PSS2	29.3894	0.2130	1.7013	0.0165	1.9849
	PSS3	21.8602	0.2569	0.1395	1.3798	1.1226
	PSS4	25.9223	0.0634	1.7467	0.9554	0.8587
J_3	PSS1	15.0137	1.3111	1.0455	0.4944	0.0597
	PSS2	40.2497	0.2833	1.8740	0.5664	1.9577
	PSS3	31.1375	0.7925	0.9937	0.1303	0.0108
	PSS4	22.8605	0.2659	1.6025	1.0201	1.6150
J_4	PSS1	25.5890	1.3868	0.9446	0.0788	0.7359
	PSS2	3.10292	0.7043	0.7753	1.3975	0.1023
	PSS3	12.5965	0.0191	0.5753	1.1611	0.4992
	PSS4	16.5014	0.6357	0.3429	1.0108	0.9893
J_5	PSS1	33.794	0.0411	1.9849	0.7937	1.1574
	PSS2	31.8907	0.3248	0.0561	0.3886	1.8845
	PSS3	28.9673	1.1705	0.7381	0.1170	0.0134
	PSS4	35.8091	1.1773	0.8512	0.0769	0.6321

TABLE 3: Comparative improvement in dominant modes for different objective functions.

Objective functions	Dominant modes eigenvalues	Damping ratio (ζ)	Frequency (ω)
J_1	-0.7180 - 3.8405i	0.1838	0.6112
	-2.0831 - 10.7434i	0.1904	1.7099
	-3.2354 - 17.3224i	0.1836	2.7570
J_2	-0.7376 + 4.0867i	0.1776	0.6504
	-2.2613 + 12.3786i	0.1797	1.9701
	-3.0685 + 17.0267i	0.1774	2.7099
J_3	-1.6484 - 4.8225i	0.3234	0.7675
	-2.6479 + 18.0621i	0.1451	2.8747
	-0.7421 + 18.5663i	0.0399	2.9549
J_4	-2.7588 - 11.0712i	0.2418	1.7620
	-4.4346 + 13.9203i	0.3035	2.2155
	-2.7934 + 17.2958i	0.1594	2.7527
J_5	-1.2487 - 3.3262i	0.3515	0.5294
	-2.5901 - 6.5999i	0.3653	1.0504
	-3.8229 - 16.0199i	0.2321	2.5496

validate the optimization performance in order to check the system stability for the three-phase fault at bus 13.

6. Conclusion

In this research, comparative analyses of different objective functions used for power system oscillation damping controller design have been performed. Damping power

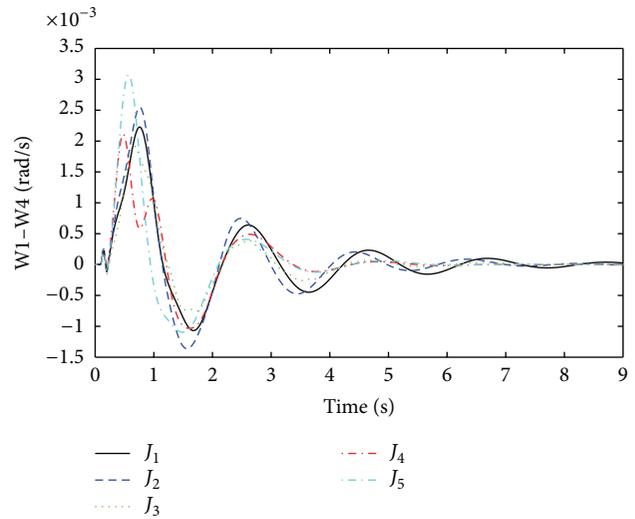


FIGURE 6: Interarea mode of oscillations between G1 and G4 (W1-W4) for three-phase fault at bus 9.

system oscillations by optimal tuning of PSS is approached. Metaheuristic algorithm DSA is kept the same in settings for all objective functions. Simulations for each objective function are conducted 10 times and best results are selected for comparison. The comparisons are performed in terms of dominant eigenvalues (damping factor, damping ratio) and the damping performance in nonlinear time domain simulations. The comparative results show that the multiobjective D-shaped stability function is a more efficient objective function than that of others. The performance of damping

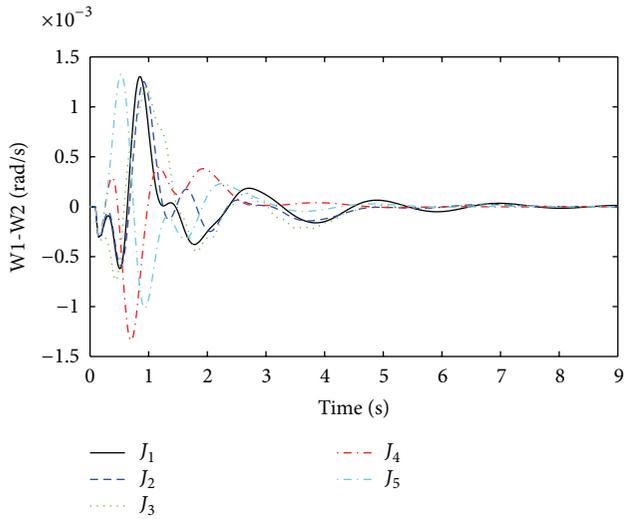


FIGURE 7: Local mode of oscillations between G1 and G2 (W1-W2) for three-phase fault at bus 13.

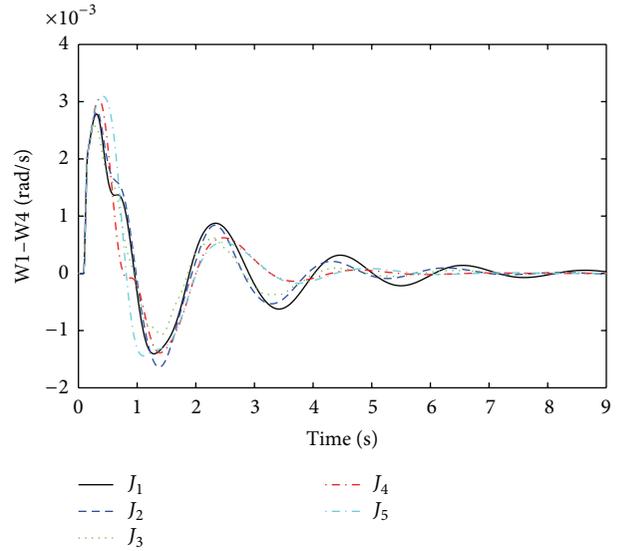


FIGURE 9: Interarea mode of oscillations between G1 and G4 (W1-W4) for three-phase fault at bus 13.

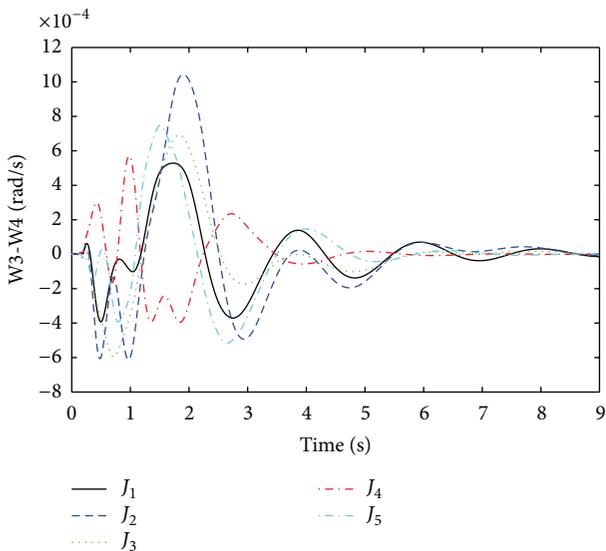


FIGURE 8: Local mode of oscillations between G3 and G4 (W3-W4) for three-phase fault at bus 13.

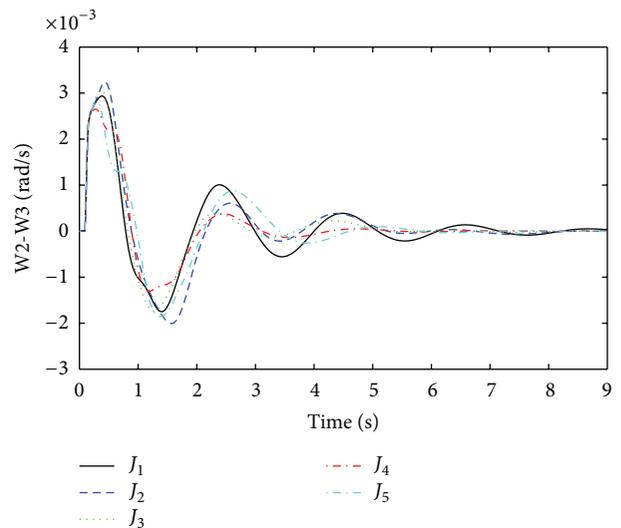


FIGURE 10: Interarea mode of oscillations between G2 and G3 (W2-W3) for three-phase fault at bus 13.

oscillation is further verified in nonlinear time domain simulations. Therefore, problem formulation into D-shaped objective function is recommended in order to design robust damping controller. Further researches should be conducted to develop more efficient objective functions reflecting better performance of damping controllers. Formulation of new and improved objective functions should be challenged based on more extensive comparative analysis with existing uses.

Appendix

Simulation settings of DSA: DSA control parameter, $P1 = P2 = 0.3 \times \text{rand}$, population size, $n = 40$; problem dimension, $m = 20$, and epoch size = 300.

Objective functions settings: expected damping factor, $\sigma_0 = -1.5$, expected damping ratio, $\zeta_0 = 0.15$.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

The authors are grateful to Universiti Kebangsaan Malaysia for supporting this research financially under Grants DIP-2012-03 and 06-01-02-SF1060.

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