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Optimal Power System Stabilizer Tuning in Multi-machine System via an Improved Differential Evolution

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Abstract: Power system stabilizer (PSS) is one of the most important controllers in modern power systems for damping low frequency oscillations. Many efforts have been dedicated to design the tuning methodologies and allocation techniques to obtain optimal damping behaviors of the system. Traditionally, it is tuned mostly for local damping performance, however, in order to obtain a globally optimal performance, the tuning of PSS needs to be done considering more variables. Furthermore, with the enhancement of system interconnection and the increase of system complexity, new tools are required to achieve global tuning and coordination of PSS to achieve optimal solution in a global meaning.
Differential evolution (DE) is a recognized as a simple and powerful global optimum technique, which can gain fast convergence speed as well as high computational efficiency. However, as many other evolutionary algorithms (EA), the premature of population restricts optimization capacity of DE. In this paper, a modified DE is proposed and applied for optimal PSS tuning of 39-Bus New-England system. New operators are introduced to reduce the probability of getting premature. To investigate the impact of system conditions on PSS tuning, multiple operating points will be studied. Simulation result is compared with standard DE and particle swarm optimization (PSO).

Keywords: Differential evolution, power system stabilizer, modal analysis

1. INTRODUCTION

Low frequency power system oscillations have been one of the major concerns in modern system operation. Plentiful work has been dedicated in power engineering to achieve stable and reliable operation of synchronous generators. One of the important techniques is to provide an efficient excitation system for a synchronous unit. Power system stabilizer (PSS) is developed based on this mind to utilize the control signal in the excitation system [1]. It can provide more damping to the system so that the dynamic response of the system is improved.

The implementation of PSS in power grids to damp electro-mechanical modes needs to select appropriate locations and tune parameter settings properly. So far, many methodologies have been proposed for the allocation of PSS in power system. In [2, 3], the placement of PSS are decided from participation factors regarding to left and right eigenvectors. The concept of root locus is presented in [4] for tuning parameters, however the coordination among parameters are ignored. The optimal control theory is used in [5] via the iterative riccati equation, however, only a part of eigenvalues are considered for the movement to the left side of the complex plane by the pole assignment. Order reduction and pole assignment methodologies are also investigated in [6, 7, 8]. The drawback of the former technique is it might result in approximate solutions, whereas the later one could lead the parameters outside their reasonable range.

Also, optimization techniques are introduced in this field to eliminate the drawbacks above. In [9], the eigenvalue variation is minimized and the parameters are bounded by equality and inequality constraints. It is solved by sensitivity analysis and linear programming. However, since the objective function is evaluated by sensitivity method, a suboptimal solution might be obtained. To overcome this problem, nonlinear programming method without using sensitivity techniques is proposed in [10]. Further improvements are achieved by using artificial intelligent (AI) techniques to tune the PSS parameters [11, 12].

DE is a relatively new member of EA and first proposed by Storn and Price at Berkeley over 1994-1996 [13, 14]. It is an algorithm of population based, steered random search as well as iterative development. Fig. 1 gives a general flowchart of typical EA. DE has the capability of solving optimization problems by minimization process. It employs a nonuniform crossover to guide through the optimization process. The mutation operation with DE is directed by arithmetical combinations which exploit the diversity among randomly chosen vectors, other than perturbing the digits in individuals with small possibility as genetic algorithms (GAs) [15]. These characteristics make DE a precise, fast and robust algorithm. However, like other EA methods, DE is also suffering from the premature behavior, which restricts the DE application.

In this paper, a modified DE is developed to solve PSS tuning in New England 39-bus system. In the proposed DE, new operators are introduced to reduce the probability of getting premature. Simulation result is compared with standard DE and particle swarm optimization (PSO). Furthermore, the impact of system operating conditions on PSS parameters are also investigated. The following content is organized as follows. Section 2 gives a brief review on DE and linearized system model. In Section 3, the modified DE is detailed and the optimization problem is formulated. Simulation is implemented in Section 4 and 5, followed by conclusion.

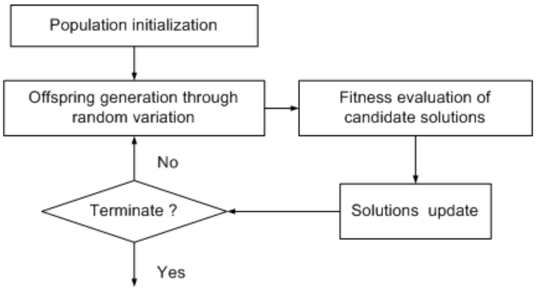

Fig. 1. A general flowchart of EAs.

2. FUNDAMENTALS OF DE AND LINEARIZED SYSTEM FORMULATION

Before detailing the optimization model, some fundamentals of DE and system model is provided below.

2.1 Brief Introduction to DE

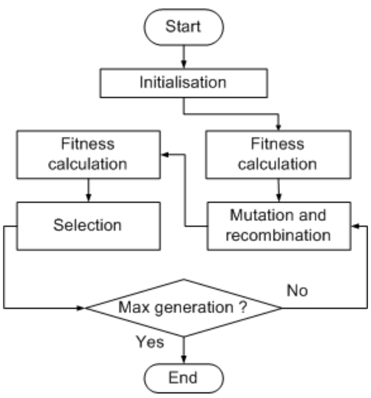

Fig. 2. A typical flowchart of DE.

Similar to other EA, DE depends likewise on initialized population, mutation, crossover and selection to search solution space through iterative progress till the algorithm terminations are met.

Main Operators of DE The realization of DE is basically depending on three operators, mutation, crossover and selection. The introduction of them is followed accordingly.

Mutation This operator is the main operator of DE, which provides the diversification of the algorithm and directs the optimisation process. A typical mutation method is listed below:

$$x'^{G+1}_i = x^G_i + f_1 \cdot \left(x^G_{r1} - x^G_{r2}\right)$$

Here, the x^G_i is the $i - th$ vector to be mutated, $r1$ and $r2$ are randomly chosen indices of vectors from the population, where $r1 \neq r2 \neq i$. G and $G+1$ mean the $G - th$ and $(G+1) - th$ generation. x'^{G+1}_i is the vector after mutation.

Crossover Unlike GAs, crossover in DE is only a complementary procedure to enhance the diversity of the algorithm. The normally used crossover is a discrete method. This discrete approach is employing a constant probability CR to determine if the digit of the newly generated vector is to be recombined. Here, a predefined digit can be specified that means that digit will be recombined compulsorily.

Selection The selection operator in DE is relatively simple. The fitness values of the newly generated population will be computed and compared to the fitness values before mutation and recombination procedures. The vector with better fitness value at a specified position in the population will be preserved whereas the vector with worse fitness value is replaced. The new population generated after selection will be used in the next generation. Fig. 2 illustrates the typical procedure of a DE.

To enhance the optimization capability of DE, the modification of operators is required to increase the diversity and randomness of the algorithm and hence the searching space can be more explored.

2.2 Brief Review of Linearized System Model

In power system analysis, linearized system model analysis can provide valuable insight into the operating behavior. Low frequency oscillations in a system can be assumed linear when it is caused by small disturbances. Under small signal condition, the variations of dynamic variables of the system can be approximated linear as well. Multi-machine system dynamic behavior in frequency span is usually represented by a set of non-linear differential and algebraic (DAE) equations:

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

where f and g are the maps of differential and algebraic equations. h is the function of output equations. The vectors $x \in R^n$, $z \in R^m$, $u \in R^p$ and $y \in R^q$ represent the state variables, algebraic variables, system inputs and outputs respectively. Equations (1) can be linearized as follows:

$$\begin{aligned} \Delta\dot{x} &= \frac{\partial f}{\partial x}\Delta x + \frac{\partial f}{\partial z}\Delta z + \frac{\partial f}{\partial u}\Delta u \\ 0 &= \frac{\partial g}{\partial x}\Delta x + \frac{\partial g}{\partial z}\Delta z + \frac{\partial g}{\partial u}\Delta u\Delta \\ y &= \frac{\partial h}{\partial x}\Delta x + \frac{\partial h}{\partial z}\Delta z + \frac{\partial h}{\partial u}\Delta u \end{aligned} \tag{2}$$

Referring to [16], eliminating the algebraic variable Δz, the system matrices can be obtained:

$$\begin{aligned} \Delta\dot{x} &= A\Delta x + B\Delta u \\ \Delta y &= C\Delta x + D\Delta u \end{aligned} \tag{3}$$

where the expressions of A, B, C, D are listed below:

$$\begin{aligned} A &= \frac{\partial f}{\partial x} - \frac{\partial f}{\partial z}\left(\frac{\partial f}{\partial z}\right)^{-1}\frac{\partial g}{\partial x} \\ B &= \frac{\partial f}{\partial u} - \frac{\partial f}{\partial z}\left(\frac{\partial g}{\partial z}\right)^{-1}\frac{\partial g}{\partial u} \\ C &= \frac{\partial h}{\partial x} - \frac{\partial h}{\partial z}\left(\frac{\partial g}{\partial z}\right)^{-1}\frac{\partial g}{\partial x} \\ D &= \frac{\partial h}{\partial u} - \frac{\partial h}{\partial z}\left(\frac{\partial g}{\partial z}\right)^{-1}\frac{\partial g}{\partial u} \end{aligned} \tag{4}$$

In this paper, only matrix A is addressed to analyze the system oscillation modes. In forming system A matrix, the model of generators is represented by the 4th order model [17], as (5) shows.

$$\begin{aligned} \dot{\delta} &= \omega_o(\omega - 1) \\ \dot{\omega} &= (P_m - P_e - D(\omega - 1))/M \\ \dot{E}_q^{'} &= (E_{fd} - E_q^{'} - (X_d - X_d^{'})I_d)/T_{do}^{'} \\ \dot{E}_d^{'} &= ((X_q - X_q^{'})I_q - E_d^{'})/T_{qo}^{'} \end{aligned} \tag{5}$$

Excitation system for generators is represented by the modified IEEE type I exciter [18]. The formulae are given in the following equations:

$$\begin{aligned} \dot{V}_{ex1} &= (V_g - V_{ex1})/T_R \\ \dot{V}_{ex2} &= \{K_A[V_{ref} + V_{PSS} - V_{ex2} \\ &\quad -\frac{K_F}{T_F}(E_{fd} - V_{ex3})] - V_{ex2}\}/T_A \\ \dot{V}_{ex3} &= (E_{fd} - V_{ex3})/T_F \\ \dot{E}_{fd} &= (V_{ex3} - (K_E + S_E)E_{fd})/T_E \end{aligned} \tag{6}$$

PSS is used in the system to enhance the small signal stability. The formulae are listed below:

$$\begin{aligned} \dot{V}_1 &= \frac{1}{T_w}[-V_1 - K_{pss}\Delta\omega] \\ \dot{V}_2 &= \frac{1}{T_2}[-V_2 + (1 - \frac{T_1}{T_2})V_1 + K_{pss}(1 - \frac{T_1}{T_2})\Delta\omega] \\ \dot{V}_{pss} &= \frac{1}{T_4}[-V_{pss} + (1 - \frac{T_3}{T_4})V_2 + \frac{T_1}{T_2}(1 - \frac{T_3}{T_4})V_1 \\ &\quad + K_{pss}\frac{T_1}{T_2}(1 - \frac{T_3}{T_4})\Delta\omega] \end{aligned} \tag{7}$$

Based on the models above, the system A matrix will be formed by analytical way and accurate Jacobian matrix can be obtained. More details of these model can be found in [17, 18, 19].

3. MODIFIED DE AND OPTIMIZATION PROBLEM FORMULATION

In this section, the first part proposes a modified DE which is to enhance the capability of typical one. Subsequently, the optimization model of system damping enhancement is detailed.

3.1 Modified DE

The proposed DE enhances the main operators of DE and incorporate two other procedures, information exchange and elitism.

Mutation and Crossover The initial population is generated randomly within each variable's bounds. After initialization, the mutation procedure employs the following equation:

$$x'^{G+1}_i = x^G_{opt} + f_1 \cdot \left(x^G_{r1} - x^G_{r2}\right) + f_2 \cdot \left(x^G_{r3} - x^G_{r4}\right) \tag{8}$$

where x_{opt} is the best solution achieved so far. f_1, f_2 are randomly selected from $[0.5, 1.5]$. $r1, r2, r3, r4$ are randomly chosen from population and $r1 \neq r2 \neq r3 \neq r4 \neq i$.

The crossover or recombination procedure employs discrete method with a constant probability CR. A digit of each vector is predefined to be recombined compulsorily. After mutation and crossover, the newly generated vectors build up a trial population.

Information Exchange The information exchange procedure is introduced to DE algorithm to enhance the vectors exploration. Each new vector obtained after mutation and crossover procedures has a probability p to exchange the information with a randomly selected vector from the original population at each generation. Equation (9) gives the detailed operation.

$$\begin{aligned} x_i &= [x_{i0}, x_{i1}, \ldots, x_{im}, \ldots, x_{in}, \ldots, x_{i,D-1}] \\ x_j^{'} &= \left[x_{j0}^{'}, x_{j1}^{'}, \ldots, x_{jm}^{'}, \ldots, x_{jn}^{'}, \ldots, x_{i,D-1}^{'}\right] \\ &\Downarrow \\ x_j^{''} &= \left[x_{j0}^{'}, x_{j1}^{'}, \ldots, x_{im}, \ldots, x_{in}, \ldots, x_{j,D-1}^{'}\right] \end{aligned} \tag{9}$$

Here x_i is a randomly picked vector from the original population at that generation, whereas $x_j^{'}$ is the $j-th$ vector of trial population, $i \neq j$. D is the total dimension of the vector. Indices m and n are also randomly selected. In this operation, the subvector $\left[x_{jm}^{'}, \ldots, x_{jn}^{'}\right]$ in $x_j^{'}$ is replaced by the subvector $[x_{im}, \ldots, x_{in}]$ in x_i.

Selection and Elitism The selection operator employs the same operation as typical DE. To keep the superior solutions attending iterations, elitism scheme is incorporated. The best solution achieved so far will be preserved in the population after selection. The detailed procedure of modified DE is demonstrated in Fig. 3.

3.2 Optimization Problem Formulation

The optimization objective is to maximize the damping of the whole system. The objective function is formulated as:

$$\sum_{i=1}^{n}(1 - c_i\xi_i) \tag{10}$$

where the ξ_i is the damping of unique modes. c_i is the weightiness of each mode, which can be determined by the critical extent of oscillation modes. In this paper, all the unique modes are dealt equally. Since the uncertainties of the objective function value, to keep all the dampings are positive, two conditions are penalized:

1 If there are negative dampings, the weightiness of that damping will be assigned a large constant.

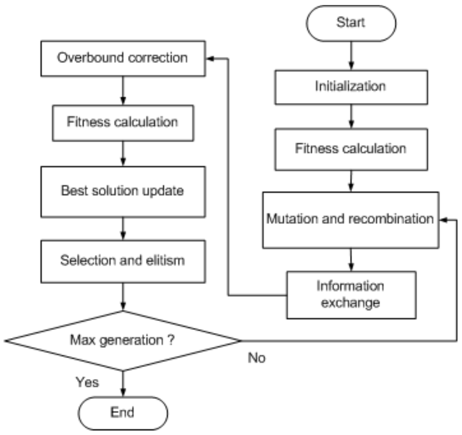

Fig. 3. The procedure of modified DE.

2 If there are zeroth dampings, the portion corresponding to this mode in objective function will be assigned a large constant.

The modified DE will be implemented to solve this optimization problem. In implementation, the algorithm employs 100, 30 as generation and population size respectively. The information exchange possibility is set 20%.

4. CASE STUDIES

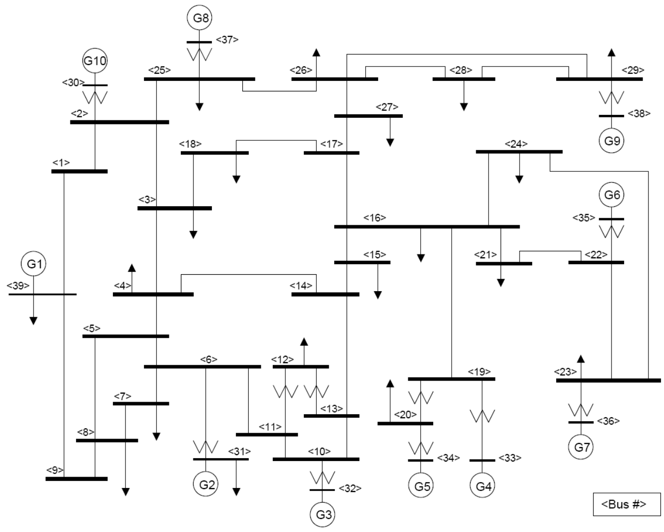

Fig. 4. One line diagram of the New England 39-bus System.

The new England 39-bus system is investigated to verify the feasibility of the method. The one-line diagram of the system is shown in Fig. 4. Among the 10 generators the system contains, the 1th generator represents another connected system and hence the inertia constant of it is very high. The PSS model showing in equation (7) has 6 parameters, i.e. $K_{pss}, T_w, T_1, T_2, T_3, T_4$. In this paper, the washout time constant T_w is taken as a constant and hence there are totally 5 parameters for each PSS to be tuned. The typical range of these 5 parameters is shown in table 1 [17].

Two case studies are developed. In case I, The effect of PSS at each generator location is studied. The parameters of PSS are optimized to achieve the best overall damping condition with the particular PSS location. Since the 1th generator indicates a neighbor system, totally 9 candidate locations of PSS are investigated one by one. This is to check the different impacts of PSS at different locations. In the base case (without PSS installed), there are 8 critical local modes (associated with generator 2-4, 6-10) plus 1 interarea mode (associated with Generator 1, well-damped). The proposed DE is applied to tune the PSS parameters corresponding to each of the generators as shown in Fig. 5. Table 2, 4 summarize the simulation results.

Table 1. The variant ranges of PSS parameters

Range	K_{pss}	T_1	T_2	T_3	T_4
Min	0.10	0.20	0.02	0.20	0.02
Max	50	1.50	0.15	1.50	0.15

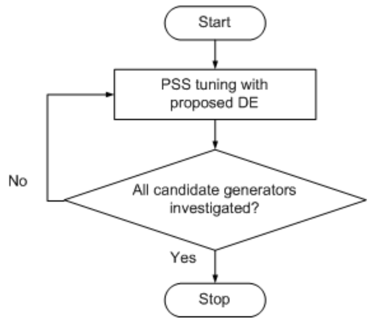

Fig. 5. PSS tuning procedure with proposed DE.

In table 2, the optimal tuning of PSS parameters at each specific generator is given. Table 4 indicates the shifting of the modes after the installation of PSS at each generator as well as the values of objective function. The mode whose damping is bellow 0.05 is considered as critical [19, 20]. With PSS at specific generator, after parameters optimization, the dampings of modes are changed. In table 4, if the mode is significantly improved (damping is over 0.3) or the frequency corresponding to that mode is disappear, the damping value will not be provided in the table. From the table it is clear that although PSS is well-recognized for damping local modes, it might have significant impact on interarea modes as well. Also it can be seen that the PSS installed at generator 2 and 9 has minor influence on the 10th mode. And from the damping value, it can be concluded that the location of PSS at 10th generator is the most effective position, where the dampings of 4 modes are significantly improved.

It can also be seen that the PSS at 2nd, 4th, and 9th generators damps out the local modes associated with those generators, however, the local mode corresponding to 5th generator appears. It indicates that the installation of PSS at certain locations might lead to unexpected behavior in terms of electromechanical oscillations.

In case II, to verify the effectiveness of the proposed algorithm, the parameters of 5 PSSs are tuned in the system. Generator 3rd, 4th, 6th, 9th and 10th are selected as the most influential locations of PSSs. The result of the proposed method will be compared with the standard DE [13] and PSO [21]. The generation and population size of algorithms are unified 200 and 50 respectively. The best

Table 2. Optimal tuning parameters for 1 PSS at each generator

Optimal parameters	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9	Gen 10
K_{pss}	2.81	0.74	1.04	0.29	0.22	0.94	0.13	0.51	0.81
T_1	1.15	1.50	0.48	0.20	1.50	0.72	1.50	0.40	0.76
T_2	0.15	1.50	0.15	0.02	0.15	0.15	0.15	0.15	0.15
T_3	1.27	0.81	0.20	0.77	0.20	0.95	0.20	0.20	0.20
T_4	0.02	0.02	0.02	0.15	0.05	0.02	0.02	0.02	0.02

Table 3. Shifting of the damping of each mode and the best value of objective function

Base case Freq. Damp	Relative Gen	G2 PSS Damp	G3 PSS Damp	G4 PSS Damp	G5 PSS Damp	G6 PSS Damp	G7 PSS Damp	G8 PSS Damp	G9 PSS Damp	G10 PSS Damp
0.6014 0.0738	1st	**0.0881**	**0.0988**	**0.1179**	**0.0715**	**0.1312**	**0.1213**	**0.0817**	**0.1047**	**
1.0107 0.0464	2nd	**	0.0443	**	0.0353	0.0395	0.0395	0.0395	**	0.0412
1.1873 0.0370	3rd	0.0427	**	0.0367	0.0367	0.0379	0.0294	0.0367	0.0367	0.0368
1.3488 0.0368	4th	0.0370	0.0374	**	0.0357	0.0357	0.0392	0.0369	0.0373	0.0381
** **	5th	0.0410	**	0.0442	**	**	**	**	0.0399	**
1.1132 0.0356	6th	**	0.0361	0.0352	0.0322	**	**0.0542**	0.0355	0.0307	0.0388
1.3931 0.0420	7th	0.0420	0.0420	0.0417	0.0420	**0.0632**	**	0.0420	0.0420	0.0421
1.3809 0.0463	8th	0.0463	0.0464	0.0463	0.0463	0.0462	0.0463	**0.1660**	0.0466	**0.0648**
0.9497 0.0433	9th	0.0444	0.0446	0.0489	0.0411	0.0479	0.0467	0.0450	**	0.0469
1.1087 0.0420	10th	0.0038	0.0020	0.0001	0.0000	0.0000	0.0002	0.0000	0.0083	**
	Obj. Func.	11.11	11.48	11.32	11.51	11.46	11.01	11.52	10.95	11.15

** : mode is either significantly damped or eliminated after PSS tuning

Table 4. Comparison of Different Algorithms

Base case Freq. Damp	Relative Generator	Standard DE Damp	PSO Damp	Modified DE Damp
0.6014 0.0738	1st	0.2519	0.1761	0.2950
1.0107 0.0464	2nd	0.0455	0.0754	0.0716
1.1873 0.0370	3rd	0.1424	0.3127	-
1.3488 0.0368	4th	0.1448	0.0314	0.1159
- -	5th	0.0640	0.0754	0.1717
1.1132 0.0356	6th	-	0.1102	0.3146
1.3931 0.0420	7th	0.0974	0.0694	0.0888
1.3809 0.0463	8th	0.0472	0.0471	0.0650
0.9497 0.0433	9th	-	-	-
1.1087 0.0420	10th	-	0.0099	0.2031
	Obj. Func.	10.54	11.29	10.38

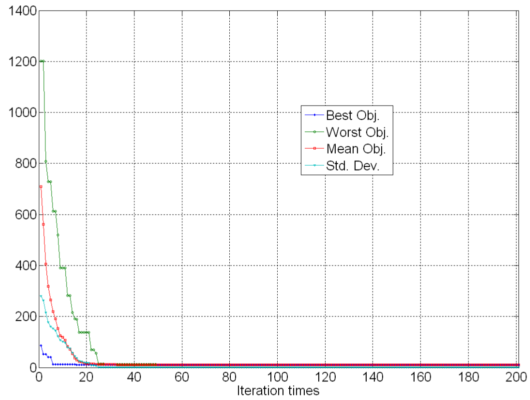

Fig. 6. The iteration procedure of the modified DE.

Table 5. Optimal tuning parameters of 5 PSS at specified generators

	Gen 3	Gen 4	Gen 6	Gen 9	Gen 10
K_{pss}	0.21	0.10	0.28	1.29	0.95
T_1	1.33	1.34	1.44	1.43	0.68
T_2	0.15	0.15	0.15	0.15	0.15
T_3	0.20	0.20	0.20	1.41	0.20
T_4	0.02	0.02	0.02	0.15	0.02

Table 6. Selected operating conditions

operating points	Line Outage
base case	no outage
1	21-22
2	28-29
3	2-3
4	5-6
5	10-11

results of each algorithm in multiple trials are compared in table 4. The optimal parameters of PSSs are listed in table 5.

In table 4, the dampings optimized by standard DE can well damp 8 modes except for mode 2nd and 8th, whereas the result with proposed DE can provide sufficient dampings to all the modes of the system. PSO gives the worst performance with 3 modes not damped.

Fig. 6 demonstrates the variation of the best, best mean, best maximum as well as minimum standard deviation of objective function during the iteration procedure. From the discussion above, it shows that the proposed DE can give fast convergence speed as well as good global optimization capacity.

5. VERIFICATION WITH MULTIPLE OPERATING POINTS

In this section, the proposed DE is applied to optimize the PSS parameters in multiple operating conditions. Here, to check the parameters variance of PSS in different operation conditions, 6 operating points are selected, as shown in table 6. The selection of outage lines is based on the assumption that the lines which are closer to generators and have larger flows will impact more on system stability, and hence affect PSS parameters. To ensure the optimum of the parameters, the best result of 10 trials for each condition is chosen.

Fig. 7 illustrates the mean and standard deviation of the parameters of PSS in selected 6 operating conditions. Regarding to parameter K_{PSS}, it can be seen that generator 2 has the highest standard deviation while the lowest variation appears at the 3rd generator. Large variation of T_1 and T_3 is found at 2nd, 3rd, 5th and 2nd, 4th, 5th, 7th generators respectively. The variance of T_2 and T_4 is relatively low at all the generators. It can be concluded that the parameters of PSS at generator 2 has the highest sensitivity with respect to different operating conditions.

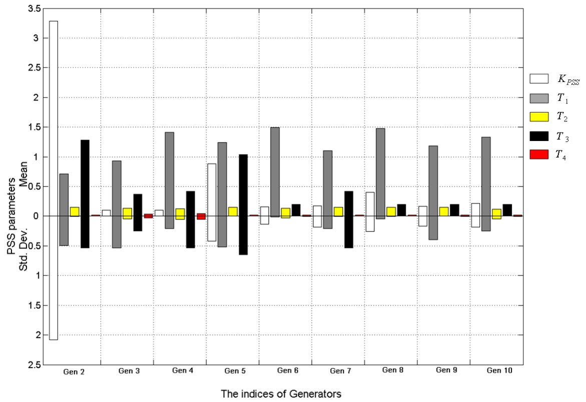

Fig. 7. Statistics of the PSS parameter variance of each generator for 6 operating conditions.

6. CONCLUSION

PSS is one of the most important controllers in damping small disturbances. In this paper, the influences of PSSs at different generators are fully investigated. The result shows that the impact of PSS is not only limited to damp a particular local mode, but may also significantly improve the dampings of other local and interarea modes. A modified DE is proposed in this paper for tuning PSS parameters to damp oscillatory modes and verified with standard DE and PSO. In addition, the impact of system conditions on PSS parameters are also studied. The result will be help in determining the most critical PSS parameters for system dampings when system condition is shifted.

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