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DAMPING POWER SYSTEM OSCILLATION USING ELITIST DIFFERENTIAL SEARCH ALGORITHM IN MULTI MACHINE POWER SYSTEM

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ABSTRACT

In this paper, damping power system oscillations is presented using the Elitist differential search algorithm (Elitist-DSA) in a multi-machine system. The tuning of power system stabilizers (PSSs) are presumed as the complex optimization problem for the security of power system. The linearized model of power system is transformed into a multimodal objective function and proposed algorithm is applied to search the best solution. Simulations are conducted in linear and non-linear models of power system to verify the robustness of proposed algorithm. Detailed comparative studies are conducted to compare the performance of Elitist-DSA based PSSs with the tuned PSSs using bacteria foraging optimization algorithm (BFOA) and particle swarm optimization (PSO) in terms of statistical analyses, improvement of eigenvalues and system damping over oscillations. The findings show the presented Elitist-DSA technique is far superior as compared to BFOA and PSO in terms of quality solution of multi-machine PSSs optimization. Thus, the proposed technique is efficient for the safety of multi-machine power system against unwanted power system oscillations.

Keywords: *Power System Oscillations, Elitist Differential Search Algorithm (Elitist-DSA), Power System Stabilizer (PSS), Multi Machine Power System, Power System Stability.*

1. INTRODUCTION

Power system oscillation is an immense threat for the safety of entire interconnected power system. System security is deteriorated significantly by the presence of growing oscillations. Oscillation in interconnected power system is a complex phenomenon which is usually originated because of faults and load changes [1]. The oscillations eventually may keep growing to lead complete system collapse if none damping control is undertaken [2]. However, in order to suppress growing oscillations, the damping scheme by means of power system stabilizers (PSSs) have been applied mainly to enhance system dynamic stability [3]. PSS is an auxiliary control device installed on synchronous generators that can manage the stability by providing an additional control signal to excitation system. Usually, the input signal of PSS is the rotor speed of generator. In addition, the fixed lead-lag structure of conventional PSS (CPSS) is widely used PSS structure recommended by major power utilities to carry out an extensive overall power system dynamic performance [4]. Research showed that fine tuning of CPSS parameters can significantly improve system damping over different modes of oscillations. Thus, the stability of power system is enhanced dramatically.

Over the past years, many metaheuristic algorithms were applied widely to solve the complex optimization problem of PSS parameters tuning. For example, bio-inspired algorithms such as genetic algorithm (GA), BAT algorithm, bacterial foraging optimization algorithm (BFOA) and particle swarm optimization (PSO) have been employed to optimize PSS parameters [5-9].

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However, most of these algorithms have many disadvantages such as local minima stagnation, difficulties in control parameters selection, poor convergence, etc. Therefore, the optimal tuning of PSS parameters is generally not ensured in case of multi-machine power system where lots of parameters are required to be optimized. Thus, the system overall stability is not secured because of many pitfalls of optimization algorithms.

In this research, Elitist-DSA algorithm is proposed for optimal tuning of multi-machine PSSs. The tuning of multi-machine PSSs are transformed into a complex optimization problem (cost function) using linear time invariant (LTI) model of power system. After that, the formulated cost function was minimized using the proposed Elitist-DSA technique for optimum design of PSSs that concurrently improving damping over oscillations. Consequently, the system safety is ensured from unwanted incidents [10-12]. Later on, the performance of proposed technique is investigated through eigenvalues and non-linear time domain simulation in terms of system damping over oscillations. Although, the test system taken in this research is a medium sized test power system. The sufficient damping by the damping controllers is the main objective of this research using an efficient optimization technique.

2. MULTI MACHINE POWER SYSTEM

In this research, 2 areas 4 machines system is considered as the multi machine test power system to optimize PSSs using Elitist-DSA. The test system is displayed as a single line diagram in the Figure 1. This is a benchmark multi machine power system to study multimode oscillations inherited in interconnected system [16]. The system consists of two generation area and two load area interconnected between bus 9 and bus 10 through double circuit tie lines. There are two synchronous generators in each area rated at 900 MVA, 20 kV. Each generator is linked via transformer to the 230 kV power line. The entire system is quite heavily loaded (at Bus 11, 976MW and 100MVAr; at Bus 12, 1765MW and 100MVAr) and area 1 is transferring 400MW to area 2. The turbines, governor and excitation systems are identical in all generators. Excitation system contains static exciter equipped with generic PSS. Detailed dynamic properties and data about bus, line, exciter, turbine, governors, loads, and machines are adopted from [14]. Each generator of multi machine system is modeled by six first-order nonlinear ordinary differential equations. This test system shows the basic electromechanical oscillations inherent in multi machine interconnected power system. In this system, generators are tempted to oscillate against other generators for different modes of oscillations after subjected to disturbances. Local mode and inter-area mode of oscillations are due to the generators of same area (G1-G2 and G3-G4) and the generators for other areas (G1-G4 and G2-G3), respectively.

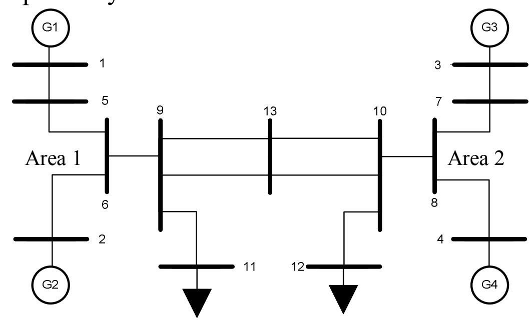

Figure 1: 2 areas 4 machines power system.

3. POWER SYSTEM STABILIZER

A PSS is an additional control devices installed at excitation system of a synchronous generator. The main purpose of PSS is to maintain power system stability by damping electromechanical oscillations providing additional control signal to the input of excitation system. Local stabilizing signal such as generator terminal frequency, rotor angle deviation, rotor speed can be taken as input signal to PSS. In this case, the rotor speed of the synchronous machine is taken as PSS input.

The well-known generic structure of the PSS taken in this research is shown in the Figure 2. It is composed of a gain block; a washout block and two stages lead-lag blocks. Gain block estimate the amount of damping, washout block acts as a high pass filter and the lead lag block determine the phase lead or lag required to compensate between exciter input and the generator electrical torque.

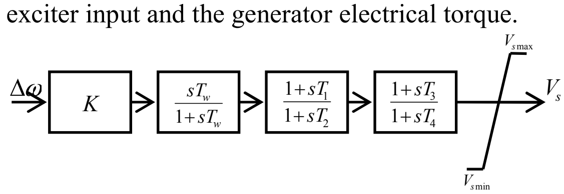

Figure 2: Lead-Lag Structure of Power System Stabilizer.

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4. POWER SYSTEM MODEL

The dynamics of a power system can be represented by a set of non-linear ordinary differential equations (ODE).

$$\dot{x} = f(x,u) \quad y = g(x,u) \qquad (1)$$

where x is the state vector, and u is the input vector.

For system simplification, linear time invariant (LTI) system theory can be applied to streamline non-linear equations into state space (SS) model forming a set of coupled first order linear differential equations.

$$\dot{x} = Ax + Bu \quad y = Cx + Du \qquad (2)$$

where, A, B, C and D are the state matrix, input matrix, output matrix, and feed-forward matrix. Later, LTI state space model is characterized in frequency domain which simplify to analyses of the dynamic behavior of power system around an operating point. In the analysis, the stability is determined by observing eigenvalues ($\lambda_i = \sigma_i \pm i\omega_i$) of matrix A. The system damping factors and damping ratios are determined from the real (σ_i) and imaginary part (ω_i) of eigenvalues as follow-

$$\text{Damping factor, } \sigma_i = real(\lambda_i) \qquad (3)$$

$$\text{Damping ratio, } \zeta_i = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \qquad (4)$$

where i = 1, 2, 3. . . i and i is the total number of eigenvalues of the system.

5. COST FUNCTION

To achieve fast and sufficient damping over growing oscillation due to disturbance in the power system, the eigenvalue based multi-objective cost function (shown in Equation 5) involving damping factors and damping ratios of poorly and unstable electromechanical modes is preferred [15].

$$f = \sum_{j=1}^{np} \sum_{\sigma_{ij} \ge \sigma_0} (\sigma_0 - \sigma_{ij})^2 + a \sum_{j=1}^{np} \sum_{\zeta_{ij} \le \zeta_0} (\zeta_0 - \zeta_{ij})^2 \qquad (5)$$

where, a is the weight factor and j = 1, 2, 3… np and np is the number of operating points considered during PSS design. This multi-objective cost function ensure system stability by forcing electromechanical modes to be placed into a D-shaped region due to multiple system operating points. If the expected damping factor and damping ratio are σ_0 and ζ_0 respectively then the D-shaped region for stability is formed imposing the condition $\sigma_{i,j} \le \sigma_0$ and $\zeta_{i,j} \ge \zeta_0$ as displayed in the Figure 3.

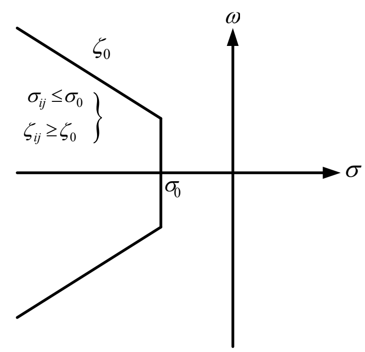

Figure 3: System stability criteria defined by D-shaped region in S-plane.

In that case, the requirements $\sigma_{i,j} \le \sigma_0$ and $\zeta_{i,j} \ge \zeta_0$ represent the damping factor and damping ratio for i-th eigenvalue of j-th operating condition respectively. Therefore, the design problem of PSSs can be formulated to minimize the cost function, f subject to:

$$K_{\min} \le K \le K_{\max}$$
$$T_{1,\min} \le T_1 \le T_{1,\max}$$
$$T_{2,\min} \le T_2 \le T_{2,\max}$$
$$T_{3,\min} \le T_3 \le T_{3,\max}$$
$$T_{4,\min} \le T_4 \le T_{4,\max}$$

The final value of cost function will become zero [15] if all electromechanical modes move into the D-shaped stability zone.

6. ELITIST DIFFERENTIAL SEARCH ALGORITHM AND IMPLEMENTATION

Elitist-DSA is a nature inspired meta-heuristic optimization algorithm developed by Civicioglu [16-17], and it is described as an effective technique for multimodal optimization solution. The concept behind its development is the seasonal migration of different species of nature for the search of fruitful living. This means discovering

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better stopover sites during the movement of organisms. In this algorithm, the individual search organisms together form a bigger population known as superorganism.

Elitist-DSA is a special version of DSA optimization technique in which strategic movement of superorganism is evolved towards to the best solution. In the standard DSA techniques, search direction is towards the donor which are made up by reshuffling of original superorganism. As the search direction of superorganism in Elitist-DSA toward its best solution every time they discover stopover sites, the convergence rate is superior compared to standard DSA. The best solution is assumed to be in fertile area always. During their movement for stopover site discovery, some randomly chosen locations are checked whether they meet their transitory criteria or not. If any location is appropriate for their lays over temporarily during the journey, the individual of the superorganism ($x_{\text{superorganism}}$) that revealed the stopover, right away settle in that location and carry on their journey from that location. The search speed is influenced by the scale factor in the population. The scale factor is defined by Equation 6.

$$\text{Scale factor, } R = 1/randg\,(1{,}0.5) \qquad (6)$$

where, *randg* is the gamma random number generator.

The successful migration of the superorganism depends on the mechanism of stopover sites. In Elitist-DSA, the best organism (individual) in the superorganism (population) is considered to be in the most fruitful area and therefore, search target of the population is redirected towards it (as defined by Equation 7). The discovery of stopover sites ($x_{stopover}$) is then determined using the Equation 8.

$$\text{Search direction, } Dir_{\text{search}} = \min(x_{\text{superorganism}}) \quad (7)$$

$$x_{\text{stopover}} = x_{\text{superorgaism}} + R \cdot (Dir_{\text{search}} - x_{\text{superorgaism}}) \quad (8)$$

It is worth to mention that some randomly selected participants involve in the search of stopoversite discovery and they are considered to discover global minima point of the problem. In Elitist-DSA, exploration and exploitation concept are used simultaneously to escape local minima stagnation and to narrow down the search space for actual optimal solution, respectively. This algorithm has only two control parameters and both of them are stochastic variables. Both parameters are used to randomize the selection process of search participants. As they don't have any direct influence over organism's movement, the initial selection of them does not affect the solution at all. Therefore, Elitist-DSA is recommended to solve complex multimodal optimization problems. Interested reader are referred to download the original source code of Elitist-DSA in [18]. In this paper, Elitist-DSA is applied to tune parameters of PSSs for its robust performance over different modes of power system oscillations. The implementation flowchart of Elitist-DSA based PSS design is depicted in the Figure 4.

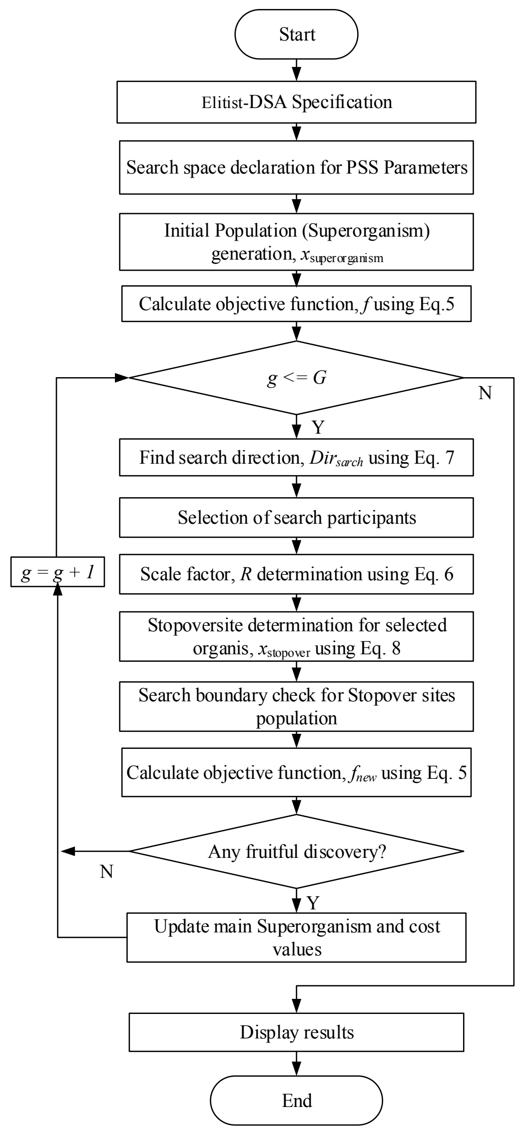

Figure 4: Flowchart for Elitist-DSA based PSS design.

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7. RESULTS AND DISCUSSIONS

In this research, results obtained from linear and non-linear simulations are analyzed extensively. In order to evaluate the robustness of Elitist-DSA in minimizing cost function, statistical analysis is very important to summarize and compare the cost values obtained using Elitist-DSA with other two algorithms, BFOA and PSO. Therefore, optimization is carried out 20 times for each algorithms in linear model of 2-area power system. All the data are recorded during optimization simulation for PSSs tuning. The optimization settings used for Elitist-DSA, BFOA and PSO are mentioned in Appendix. The weight factor, a (in the Equation 5) was set to 10 [15]. The expected damping factor and damping ratios were selected to -1.5 and 0.2 respectively. The settings for optimization algorithms are given in Appendix section. In majority of preceding literatures, T_1 and T_3 were typically considered variables to be optimized [15]. For this research, T_2 and T_4 were included in the optimization to extend complexity of optimization problem. There are four PSSs in 2 areas 4 machines power system and for each generator, the number of optimizing parameters are five (K, T_1, T_2, T_3, and T_4). The time constant T_w was set to 10s. Therefore, total 20 parameters were optimized in search problem using proposed DSA technique. The search boundary limits are listed in Table 1.

Table 1: Boundaries of search space

Parameters	K	T_1	T_2	T_3	T_4
Minimum	0.01	0.01	0.01	0.01	0.01
Maximum	100	2	2	2	2

The data for 20 time simulations has been plotted as a box plot using MATLAB. The box and whisker plots for Elitist-DSA, BFOA and PSO are shown in the Figure 5. In the box plot, least, 25% quartile, median, 75% quartile and greatest data points are much lower for Elitist-DSA compared with BFOA and PSO. Moreover the best cost value for Elitist-DSA is almost near to the final goal compared with BFOA and PSO. From the box plots, it is clearly visible that the cost data span of Elitist-DSA is much narrower over all four quartiles compared to BFOA and PSO. These certainly indicates that the Elitist-DSA is very prominent in finding the solution without getting stuck in convergence stagnation (local minima traps).

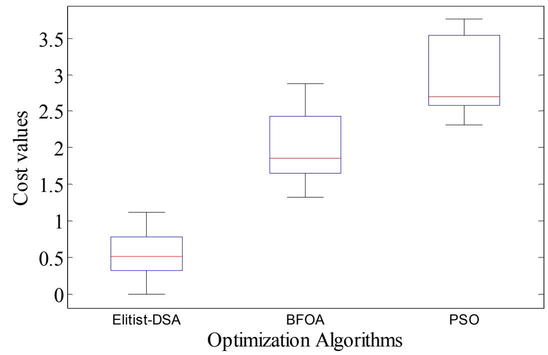

Figure 5: Box and whisker plots drawn from 25 individual simulations for Elitist-DSA, BFOA and PSO.

The linear model simulation is based on the system eigenvalues obtained from state-space model. The optimization relocates unstable and lightly damped system eigenvalues to stable region of complex-s plane. The improvement of eigenvalues are summarized in Table 2 for Elitist-DSA, BFOA and PSO techniques. The unexpected results are highlighted in bold style. It is obvious that poorly damped and unstable modes are found when system is operated without PSSs. The addition of optimized PSSs increases system stability by enhancing electromechanical modes. Moreover, it is evident that Elitist-DSA based optimization can significantly improve poorly and unstable eigenvalues than BFOA and PSO based optimization. For considered operating conditions, the damping factors and damping ratios for Elitist-DSA based design are much improved compared to BFOA and PSO based design. Thus, it is just another acquiescence to accept Elitist-DSA for PSSs optimization.

Table 2: Dominant eigenvalues and damping ratios achieved from best optimization solution

	Eigenvalues	Damping Ratio
Without PSSs	**0.0535** ± 3.9936i	**-0.0134**
	-0.5016 ± 7.2742i	**0.0688**
	-0.4829 ± 7.3229i	**0.0658**
Elitist-DSA-PSSs	-2.8902 ± 11.4771i	0.2442
	-2.7267 ± 12.0288i	0.2211
	-2.7697 ± 17.2172i	0.1588
BFOA-PSSs	-1.9226 ± 10.2429i	0.1845
	-1.7955 ± 14.7454i	**0.1209**
	-2.7082 ± 16.7595i	0.1595
PSO-PSSs	**-0.5159** ± 8.1294i	**0.0633**
	-1.3993 ± 15.7444i	**0.0885**
	-3.0836 ± 15.5436i	0.1946

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The non-linear model of test system are executed using the optimized parameters. A three-phase fault is created to one tie circuit between bus 10 and 13 near at bus 10 of 2-area power system shown in the Figure 1. The fault is applied at 100ms of simulation time (9s) for 150ms. After that the system is operating with one tie line only and oscillations grow in the system. Figure 6 and Figure 7 are the damping responses over different modes of oscillations, respectively. The system is totally unstable without PSSs because of the three-phase faults. However, the installation of PSSs after optimization bring back the stability for all optimization techniques as shown in Figures 6-7. From both figures, as compared to BFOA-based and PSO-based designed PSSs, Elitist-DSA based designed PSSs have significantly reduced overshoots and settling times for different modes of oscillations. Thus, system stability is improved notably in a disturbed system using Elitist-DSA based designed PSSs.

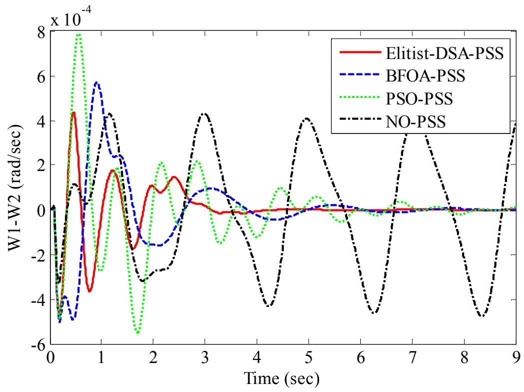

Figure 6: Local mode between G1 and G2 (W1-W2)

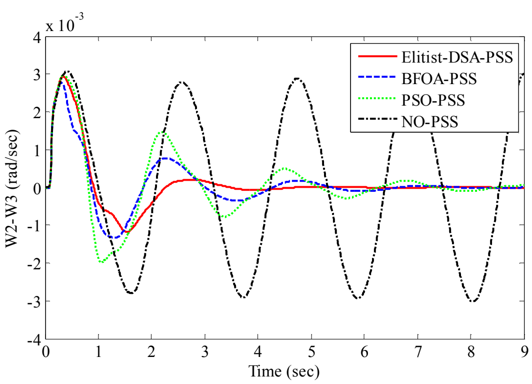

Figure 7: Inter-area mode between G2 and G3 (W2-W3)

8. CONCLUSION

This paper proposes Elitist-DSA for damping power system oscillations by tuning of multi-machine PSSs. The stability problem of multi-machine power system is formulated into a complex multimodal optimization problem using LTI spate-space model. Implementation of Elitist-DSA is for improving damping over different modes of oscillations. The performance of Elitist-DSA is compared against with BFOA and PSO techniques in linear and non-linear models of simulations. To verify the performance of the proposed optimization algorithm, comparative analyses are carried out in terms of boxplots, eigenvalues, and damping oscillations. According to the analyses conducted in this research, the performance of Elitist-DSA is remarkable as compared to BFOA and PSO techniques. The eigenvalues are more stable in the proposed design, which indicates efficient search techniques of the proposed optimization algorithm. In the time domain simulation, enough damping is achieved to stabilize system from disturbances and its consequence incidents. Therefore, the presented Elitist-DSA optimization technique has potential to solve complex design problem of coordinated PSSs and to protect the multi-machine power system.

APPENDIX:

Optimization algorithm settings:

(a) Elitist-DSA Settings: dimension size, D = 20; population size, N = 50; generation, G = 350; control parameters, P1 = P2 = 0.3×*rand*.

(b) BFOA Settings: dimension size, D = 20; population size, N = 50; chemotactic steps, N_c = 70; reproduction steps, N_{re} = 5; elimination-dispersal steps, N_{ed} = 5; p_{ed} = 0.25; C=0.05; m_{ar}= 0.1; w_{at} = 0.2; w_{re} = 10.

(c) PSO Settings: dimension size, D = 20; population size, N = 50; generation, G = 350; cognitive constant, C_1 = 2; social constant, C_2 = 2; w_{min}=0.4; w_{max}=0.9.

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