Parameter optimization of power system stabilizer via Salp Swarm algorithm

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2 authors:

Serdar Ekinci
Batman Üniversitesi

Baran Hekimoğlu
Batman Üniversitesi

Parameter Optimization of Power System Stabilizer via Salp Swarm Algorithm

Serdar Ekinci
Department of Computer Engineering
Batman University
Batman, Turkey
e-mail: ekinciser@yahoo.com

Baran Hekimoğlu
Department of Electrical and Electronics Engineering
Batman University
Batman, Turkey
e-mail: baran.hekimoglu@batman.edu.tr

***Abstract*—A novel application of a very recent heuristic-based method, namely Salp Swarm Algorithm (SSA) is presented here for tuning of power system stabilizer (PSS) in a multi-machine power system. The tuning problem of PSS parameters is expressed as an optimization problem and the SSA method is utilized for searching the optimal parameters. The efficacy of the SSA-based PSS design was successfully tested on a well-known 3-machine, 9-bus power system. The results are comparatively evaluated with the other results obtained by the Tabu Search (TS) and the Biogeography-Based Optimization (BBO) methods. From the eigenvalue analysis and nonlinear simulation results it is confirmed that for damping oscillations, the performance of the proposed SSA approach in this study is better than that obtained by other intelligent techniques (TS and BBO).**

Keywords-biogeography-based optimization; power system stabilizer; salp swarm algorithm; tabu search; parameter optimization

I. INTRODUCTION

A power system exhibits usually electromechanical oscillations because of disturbances due to short circuits and variations in operating point. These frequency oscillations must be damped to a desired limit; otherwise the growing amplitude of these oscillations will cause instability [1]. The power system stabilizers (PSSs) are the most commonly utilized device for solving oscillatory stability problems. Therefore, PSSs have long been seen as an efficient way of making the damping of electromechanical oscillations in electrical power systems better [2].

The classical PSS designs are based on the linear control theory, in which the power system model is linearized around a nominal operating point. The construction and parameters of the PSS are defined to give the best performance at this point. But, usually power systems have a nonlinear nature and the operating conditions can continuously vary over a wide range. Thus, the classical PSS with fixed parameters may not give optimum performance inside of the entire operating range. Furthermore, the power system configuration varies over time, which requires adjusting the parameters of the PSS to maintain the desired performance. Other control techniques, such as pole placement, pole shifting, feedback linearization, and self-tuning regulators have also been studied for the design of PSSs. However, these techniques need intense calculations with longer computer processing time [3].

Recently, intelligent optimization methods have been used for PSS parameter optimization. Although Simulated Annealing (SA) in [4] is proposed to optimize the PSS, this technique may fail when it is trapped into one of the local optima. Tabu Search (TS) is another heuristic method that is proposed in [5] to design PSS. This method may seem to be efficient for the design problem however, due to the large number of parameters that should be optimized and the use of highly epistatic objective functions its efficiency is reduced. It is also a time-consuming method. Genetic algorithm (GA) in [6]-[7] is developed for optimal design of PSS. However, depending on the size of the system under study, this optimization method requires a very long run time. Besides, the premature convergence of GA poses a major problem. Particle swarm optimization (PSO) in [8]-[9] is proposed for the design of the PSS parameters at different operating conditions. Nevertheless, the performance of the original PSO highly affected by its parameters, and it often suffers from the problem of being trapped into the local optima and having a premature convergence. A relatively fresher evolutionary algorithm, called Biogeography-Based Optimization (BBO) for the design of the PSS parameters is shown in [10]. Migration and mutation operators are utilized by the classical BBO algorithm as its concentration and diversification strategies, respectively. Frequently, however, the mutation operator corrupts the quality of the solutions. Other methods are listed in [11]-[18] for PSS parameter optimization. In order to overcome all drawbacks of above mentioned methods, an SSA based PSS is proposed in this study.

SSA is a population-based heuristic optimization technique proposed by Mirjalili et al. [19], which mathematically models and mimics navigating and foraging behavior of salps in oceans. Because, SSA algorithm has only one main controlling parameter, it is simple and easy to implement. The adaptive mechanism of SSA allows it to avoid local solutions and eventually finds an accurate estimation of the best solution obtained during optimization. This makes the SSA algorithm being capable of solving optimization problems with hard and unidentified search spaces [19]. Taking into account the effectiveness of this algorithm, it is implemented in this study for the optimal tuning of PSS parameters. To the authors' best knowledge,

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this novel application is used for the first time for solving power system stability analysis problem.

In this study a novel design method is proposed to improve the stability of a multi-machine power system using PSS in which parameters are tuned by the SSA algorithm. To confirm the efficacy of algorithm, the stability performances are performed and compared to other approaches based on the original TS and BBO. The eigenvalue analysis and nonlinear time domain simulations are executed on the 3-machine, 9-bus electric power system. The analysis results demonstrate that the presented method achieves the expected performance for damping the low frequency oscillations and enhances the system dynamic stability under a severe disturbance.

II. Salp Swarm Algorithm (SSA)

The mathematical model of swarming behavior of salp chains starts with dividing the population in two groups, namely the leader and the follower. The leader salp is always at the front of the salp chain to guide the swarm and the rest follows it and each other [19]. In the search space, there is a food source as each swarm is targeting at and is called *TF*. The location updating equation for the leader salp with respect to the target food is given as in

$$x_j^1 = \begin{cases} TF_j + c_1\left(c_2\left(ub_j - lb_j\right) + lb_j\right) & c_3 \geq 0 \\ TF_j - c_1\left(c_2\left(ub_j - lb_j\right) + lb_j\right) & c_3 < 0 \end{cases} \quad (1)$$

here, x_j^1 represents the location of the leader salp in the j-th dimension, TF_j represents the location of the target food the j-th dimension, c_1, c_2, and c_3 are random numbers, ub_j and lb_j are upper and lower bounds in the j-th dimension, respectively. The coefficient c_1 is balancing the exploration and exploitation phases of the algorithm. Therefore, it is considered as the most important parameter of the SSA and given as in

$$c_1 = 2e^{-\left(\frac{4m}{M}\right)^2} \quad (2)$$

here, m represents the current iteration, and M represents the total number of iterations, which is chosen as 100 in this paper. Both random numbers c_2, and c_3 are homogeneously produced in the range of [0, 1]. To update the location of each follower salp with respect to the one that it follows is given in (3)

$$x_j^i = \frac{1}{2}\left(x_j^i + x_j^{i-1}\right), \quad \forall i \geq 2 \quad (3)$$

Equation (3) shows that each salp follows its leader to form a salp chain. Here, x_j^i represent the location of the i-th follower salp in j-th dimension. The initial locations of all salps are randomly formed as in other swarm based optimization algorithms [19].

III. Problem Statement

A. Power System Model with PSS Structure

Nonlinear dynamic equations of each machine can be summarized as in [20] as follows

$$\dot{\delta}_i = \omega_s(\omega_i - 1) \quad (4)$$

$$\dot{\omega}_i = (P_{mi} - E'_{qi} - (x_{qi} - x'_{di})i_{di}i_{qi} - D_i(\omega - 1)) / M_i \quad (5)$$

$$\dot{E}'_{qi} = (E_{fdi} - E'_{qi} - (x_{di} - x'_{di})i_{di}) / T'_{doi} \quad (6)$$

$$\dot{E}_{fdi} = (-E_{fdi} + K_{ai}(V_{ref,i} - V_i + V_{pss,i})) / T_{ai} \quad (7)$$

The principal purpose of a PSS is to generate an supplementary stabilizing signal for damping out the generator rotor oscillations through the excitation system [2]. A commonly utilized classical lead-lag PSS structure is given by

$$V_{pss} = K_P \frac{sT_w}{1 + sT_w}\left[\frac{1 + sT_1}{1 + sT_2}\frac{1 + sT_3}{1 + sT_4}\right]\Delta\omega \quad (8)$$

This structure consists of a control gain K_P, a washout filter with a time constant T_w, two lead-lag blocks for phase compensation with time constants T_1-T_4 with a limiter as illustrated in Fig. 1. The PSS output signal V_{pss} is a voltage that is going to be added to the generator exciter input [21]. In general, the generator speed deviation $\Delta\omega$ is utilized as the PSS input signal.

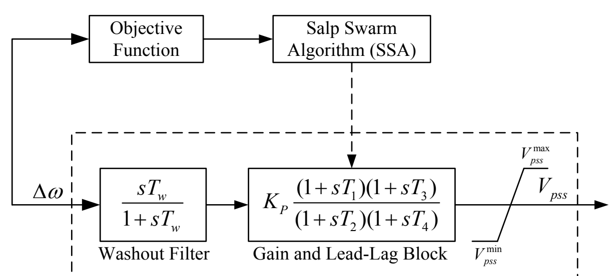

Figure 1. PSS structure.

B. Linearized System Model

Typically, the linearized incremental models around an equilibrium point are utilized in PSS designs [20]. By the linearization of the power system equations, as stated in [20], and by the addition of PSS equations, the linearized power system model yields the state equation as follows

$$\Delta\dot{x} = \mathbf{A}\Delta x + \mathbf{B}\Delta u \quad (9)$$

where, **A** is the state variables matrix and **B** is the input matrix. The vector Δx is the state variable vector and Δu is the input variable vector. In this work, $\Delta x = [\Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta E_{fd}]^T$ and Δu are the output signals of PSS.

C. *Objective Function and PSS Tuning using SSA*

The Integral of Time multiple Absolute Error (ITAE) of speed deviations is selected as the objective function in here and is formulated as in

$$J_{ITAE} = \int_0^{t_{sim}} t(|\,\omega_2 - \omega_1\,| + |\,\omega_3 - \omega_1\,|)\, dt \qquad (10)$$

By optimizing J_{ITAE}, the sum of speed deviations in each generator speed response is being minimized. The optimal tuning of PSS parameters problem is formulated as the following constrained optimization problem, where the constraints are the PSS parameters' boundaries. Minimizing J_{ITAE} depends on the following constraints

$$0.1 = K_P^{\min} \le K_P \le K_P^{\max} = 100 \qquad (11)$$

$$0.01 = T_i^{\min} \le T_i \le T_i^{\max} = 1 \ \ ; \ i = 1,2,3,4 \qquad (12)$$

The washout time constant T_w is commonly fixed and its value is equal to 10 s [3]. Considering the objective function given in (10), the presented approach implements SSA algorithm for solving this optimization problem and seek for an optimal set of PSS parameters (K_P and T_1–T_4). The computational flow chart of the SSA technique is given in Fig. 2.

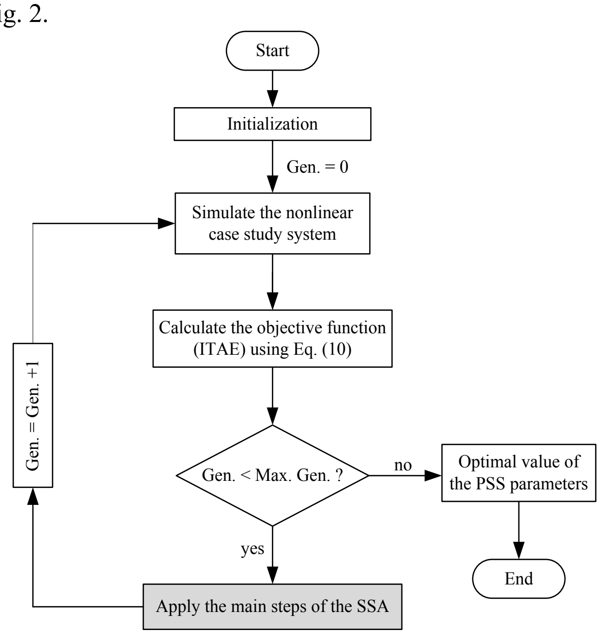

Figure 2. Flowchart of the proposed SSA based PSS design.

IV. Results and Simulations

A. *Test System and Implementation of SSA to PSS Design*

The well-known Western System Coordinated Council (WSCC) 3-machine 9-bus power system is considered to show the performance of the proposed algorithm, in this study. This system is also used in [1] and [2], as it have been widely used in the literature. Fig. 3 illustrates the test system's single line diagram. According to participation factor analysis the placement of PSS is only required in the second generator [18].

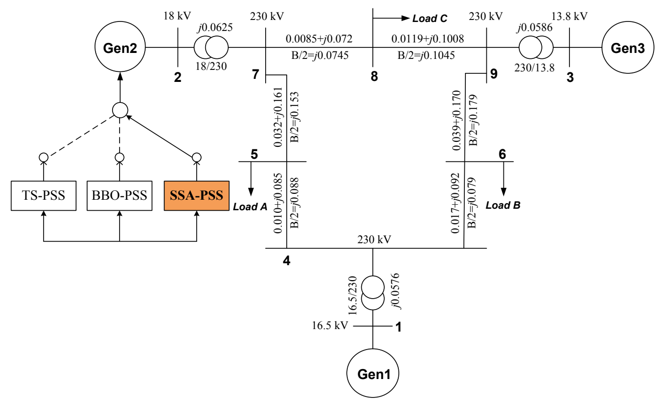

Figure 3. WSCC three-machine nine-bus system.

There are 5 parameters to be optimized for a 3-machine 9-bus test system, in this study. For resolving the optimization problem and examining the optimal set of stabilizers parameters, the SSA was carried out in MATLAB software. It is significant to underline that SSA has run a number of times and later the optimal set of PSS parameters is selected. The optimization of PSS parameters is executed via the assessment of the objective function as yielded by (10) and the last values of the optimized PSS parameters utilized TS, BBO (see [22]-[23] for more details about the problem solution for TS and BBO) and the proposed SSA methods are given in Table I.

TABLE I. Optimized PSS Parameters Using Three Algorithms

Algorithm	K_P	T_1	T_2	T_3	T_4
TS	36.4731	0.4822	0.0100	1.0000	0.7594
BBO	10.1792	0.9390	0.5898	0.6637	0.0240
SSA	23.0722	0.6775	0.7014	0.3433	0.0537

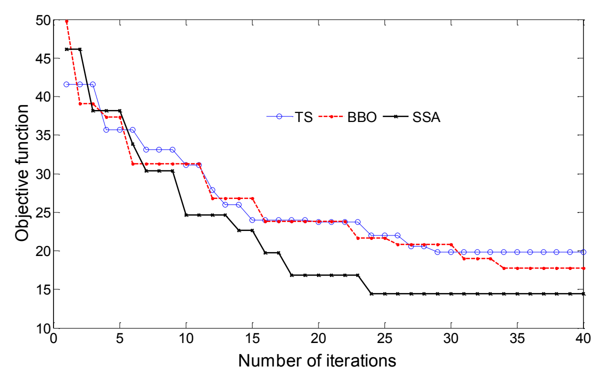

Figure 4. Convergence of J_{ITAE}.

The convergence characteristics of TS, BBO and SSA methods are shown in Fig. 4. From the convergence plot, the SSA technique has better convergence rate (24 iterations) than TS (29 iterations) and BBO (34 iterations).

B. *Eigenvalue Analysis*

Table II shows the system electromechanical modes and damping ratios of both cases, without PSS and with the optimized PSS (TS-PSS, BBO-PSS and SSA-PSS), respectively. From the table, it is seen that the system is poorly damped ($\zeta_{\min} = 4.85\%$) when PSS is not installed. Furthermore, the proposed stabilizer SSA-PSS outperforms the TS-PSS and BBO-PSS and it has the best damping ($\zeta_{\min} = 29.24\%$).

TABLE II. EIGENVALUES AND DAMPING RATIOS OF ELECTROMECHANICAL MODES

System Property	Eigenvalues	Damping Ratio
Without PSS	$-0.3831 \pm 7.8846i$	0.0485
	$-1.3738 \pm 11.7499i$	0.1161
TS-PSS	$-1.3989 \pm 13.5594i$	0.3658
	$-2.4122 \pm 10.3084i$	0.2278
BBO-PSS	$-2.9824 \pm 10.5724i$	0.2714
	$-2.3538 \pm 5.1882i$	0.4131
SSA-PSS	$-3.2545 \pm 10.6419i$	**0.2924**
	$-2.3779 \pm 5.1490i$	0.4192

C. *Nonlinear Simulation Results*

In this study, the efficacy of the presented SSA-based PSS has been studied via comprehensive non-linear time domain simulation studies under a large disturbance. A three phase fault at $t = 2\ s$ on bus 9 at the end of line 8-9 is considered [24] as a representative of large disturbance. The fault persists for 150 ms (9-cycle) and took out without line tripping, and the original system is fixed. The system's behavior is evaluated for 10 s. The system power angles and speed deviations of G2 and G3 with respect to G1 are depicted in Figs. 5-8.

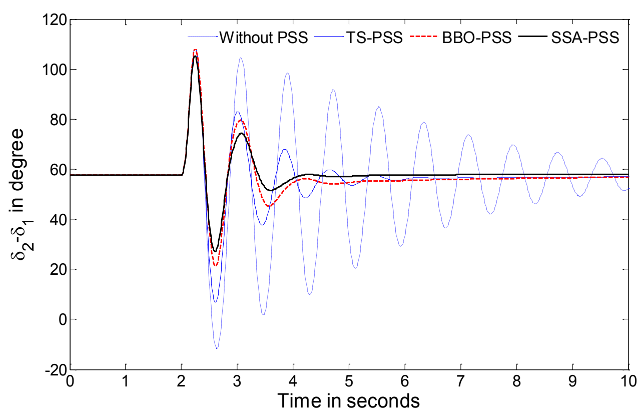

Figure 5. Power angle response of G2 (relative to G1) for large disturbance.

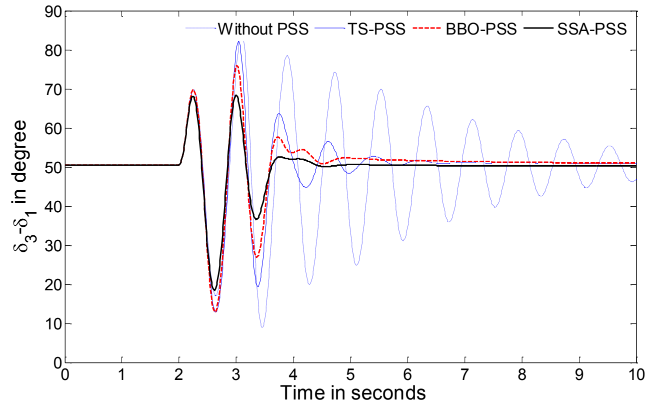

Figure 6. Power angle response of G3 (relative to G1) for large disturbance.

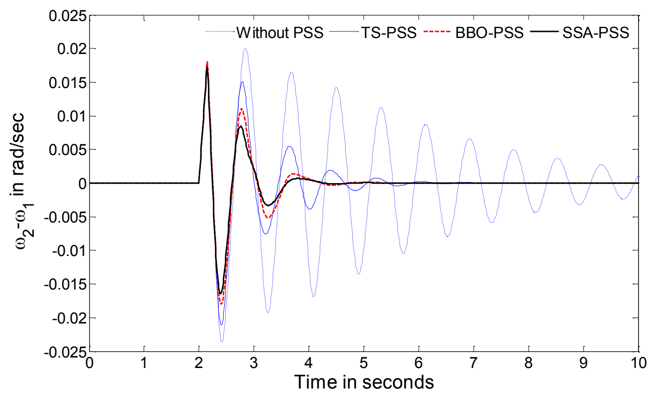

Figure 7. Speed deviation response of G2 (relative to G1) for large disturbance.

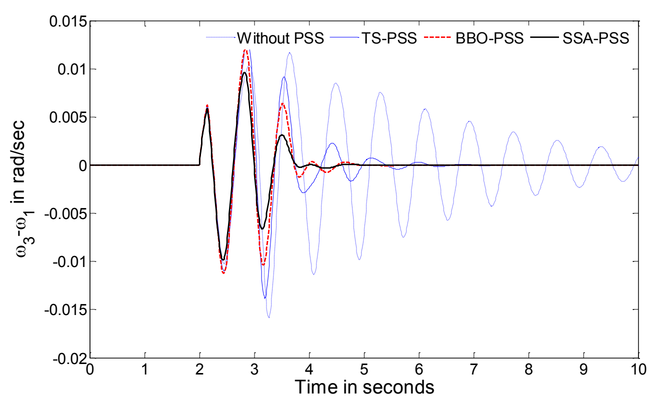

Figure 8. Speed deviation response of G3 (relative to G1) for large disturbance.

From the figures, it is obvious that the power system oscillations are unsatisfactorily damped without stabilizer, yet the system is stable. With the application of TS-PSS and BBO-PSS the stability of the system is preserved and power system oscillations are suppressed efficiently. It is also clear from these figures that, both the overshoot and settling time obtained by the SSA technique are better when compared to the other two methods.

V. CONCLUSIONS

A novel approach called salp swarm algorithm (SSA) is proposed in this study, for optimally designing PSS parameters to damp the small signal oscillations in power system network. It is worth to mention that there is no such study that has been proposed in the literature before. For the design problem of the PSS parameters, a parameter-restrained, time domain-based objective function is used to make power system's dynamic performance better. Then, SSA is successfully applied to seek for optimal parameters. The performance of the presented controller is tested on a multi-machine power system and compared with TS and BBO methods. It was observed from eigenvalue analysis and nonlinear time-domain simulation results that the SSA-PSS significantly suppressed the electromechanical low frequency oscillations of the power angle and rotor speed better than TS-PSS and BBO-PSS.

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