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Particle swarm optimization and Taguchi algorithm-based power system stabilizer-effect of light loading condition

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ABSTRACT

A robust design of particle swarm optimization (PSO) and Taguchi algorithm-based power system stabilizer (PSS) is presented in this paper. It incorporates a novel concept in which Taguchi and PSO techniques are integrated for stabilization of single machine infinite bus (SMIB). The system tolerates uncertainty and imprecision to a maximum extent. The proposed controller's effectiveness is proved through experiments covering light load condition using MATLAB/Simulink platform. The performance of the system is compared without PSS and with a conventional PSS. The settling time of the optimal PSS is decreased by more than 75% to conventional PSS. The study reveals that the proposed hybrid controller offers enhanced performance with respect to settling time as well as peak overshoot of the system.

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1. INTRODUCTION

With the continuous demand of electrical energy, the complexity of power system is on the raise and there is a strong need to provide stable, secured, reliable and high-quality electric energy to meet the intricated power demand. Power system stability is one of the most important issues in their operations. For a given operating condition, it is the ability to regain the state of equilibrium under external disturbances is bounded with the system variables. This makes the system to remains intact while providing the uninterrupted services. The quality of electric energy supply to the end user depends mainly on the stability of the power system and it is very much essential [1]–[3].

Bayoumi *et al.* [4] have proposed the particle swarm optimization (PSO) technique to tune the parameters associated in dynamics of power system stabilizer (PSS) in power system network. The proposed algorithm has advantages with respect to flexible in design, minimization of overshoot and other control system prominent parameters compare to other conventional control algorithm. Panda and Padhy [5] have designed a controller by transforming it in to an optimization problem and solved using PSO technique. The aim of the proposed technique is to improve the small signal stability issue associated in single machine infinite bus (SMIB) based PSS subjected to disturbance.

Karnik *et al.* [6] presented on how to tune PSS parameters for a stable response of the power system in full operating regime. His calls for an efficient optimization algorithm and they developed a methodology integrating Taguchi design technique with PSO. With this, they were able to determine robust parameters of PSS in a SMIB system by considering variations in operating condition as a noise factor.

Kumara and Srinivasan [7] designed an optimal controller using linear quadratic regulator algorithm based optimal control theory and studied for various operating conditions. It was found that the feedback control signal plays a major role in reducing the low frequency oscillations and hence to improve the stability. Ali and Khosravi [8] have designed the improved particle swarm optimization based PSS for SMIB system by reducing the fitness function. With this proposed technique, the low frequency oscillations can be controlled to a greater extent. Vikal and Surjan [9] have proposed PSO based variable structure control (VSC) method for SMIB system

PSO and Taguchi integrated method are used to construct a PSS and it is more capable of handling uncertainty [10]. Unal and Dean [11] that the Taguchi technique accentuates on quality at the design stage. This calls for a design of product which is intensive and robust. It is an efficient and systematic way of determining optimum configuration of design parameters including performance cost and quality. Kadiman *et al.* [12] has introduced an auto-tuning traditional PSS of proportional integral derivative (PID) structure as an extra controller to dampen low frequency oscillations and improve the system's dynamic performance.

Soliman and Soliman [13] have proposed observer based power system stabilizer to improve the stability using a linear matrix inequality (LMI) condition. Balasubbareddy *et al.* [14] proposed a three different power system stabilizer to enhance the power system stability in SMIB system. Aljarbouh *et al.* [15] has proposed the design of PSS using time-delay neural network for improvement of dynamic stability of the system. In work [16] presented a PID-fuzzy power system stabilizer (PID-FPSS) technique was developed on the basis of a velocity PID controller, and its gains are tuned using the particle swarm optimization technique. The speed deviation, derivative speed deviation, and output power are used as inputs to the fuzzy controller in this stabilizer. Using the PSO algorithm, a coordinated design of PSS and static VAR compensator (SVC) was used to achieve better stability for a multi-machine infinite bus system presented in [17].

Kim and Park [18] proposed the design of PSS not only dampens out LFOs through conventional lead-lag compensation, but also provides additional damping torque based on the magnitude of the perturbation through the use of a synchronous impedance characteristic (SIC). Aribowo *et al.* [19] proposed an intelligent control of PSS, The Archimedes optimization algorithm (AOA) is a metaheuristic method for calculating the force in a fluid as a result of a load in this PSS. Soleymani and Hasanvand [20] have presented the design of PSS using an optimal controller like a genetic algorithm (GA) and PSO to mitigate the low frequency oscillations ans enhanced the small signal stability. Shivakumar *et al.* [21] have proposed firefly optimizer-based controller is compared and analyzed with traditional to improving system stability of multi machine power system. Here PSS is designed through Particle swarm optimization and Taguchi (PSO-Taguchi) technique, comparative study is made between optimal controller and conventional PSS for SMIB system.

2. RESEARCH METHOD

Kennedy and Eberhart were the first to introduce PSO as a novel experiential method in 1995. In socio-cognition human agents and evolutionary calculations, the technique includes social psychology elements. PSO is commonly thought of as a straightforward concept that is simple to implement and computationally efficient. PSO is adaptable and offers a well-balanced mechanism to improve global and local exploration skills, unlike other heuristic methods [22]. An attractive force search method and hybrid PSO are used to enhance system stability through a coordinated structure consisting of a PSS and static synchronous series compensator (SSSC) based dampening controller [23]. Kumara and Srinivasan [24] proposed the comparison and assessment of conventional and optimal coordinated PSS and unified power flow controller (UPFC) damping controller.

2.1. PSS operating condition

In power system network, load is not constant but will vary continuously from minimum to maximum. The operating points of a system is described by terminal of generator, operating conditions and it is represented by terminal voltage (V_t), line reactance (X_l) and real power P, various loading conditions considered in the current study are shown in Table 1. The electromechanical mode eigenvalues for the open loop system are determined using the participation factor approach for different combinations of terminal voltage V_t, real power P, and line reactance X_l.

2.2. Overview of PSO

The nature of fish schooling or avian flocking is predicted by PSO. Every solution in PSO is a bird in the search domain. Particles are the name for these solutions [12]. The fitness function that needs to be optimized determines the fitness values of all these particles. The velocities of the fitness values determine the nature of flight. The present optimum particles lead them through the problem. The i^{th} particle of the population (also known as the swarm) can be represented by a set of D-dimensional vectors = (s_1, s_2, ..., s_D) when the search space is D-dimensional.

The velocity can be represented by another D-dimensional vector $v = (v_1, v_2, \ldots, v_D)$. The previously visited best position (p_{best}) of the i^{th} particle is represented as $P_{best} = (p_1, p_2, \ldots, p_D)$. Let g is the index of the best particle in the swarm (g_{best}). The iteration number is indicated by the superscripts, and the swarm can be represented by (1) and (2):

$$v_i^{k+1} = w^k v_i^k + c_1 r_1^k \left(p_i^k + s_i^k\right) + c_2 r_2^k \left(p_g^k - s_i^k\right) \tag{1}$$

$$s_i^{k+1} = s_i^k + v_i^{k+1} \tag{2}$$

where w is the inertia weight; V_i^{k+1} is velocity of particle i at iteration k+1; V_i^k is velocity of particle i at iteration k; S_i^{k+1} is position of particle i at iteration; k +1S_i^k is position of particle i at iteration k; c_1 is the cognitive parameter; c_2 is the social parameter; c_1 and c_2 are also called as learning factors; r_1 and r_2 are the uniformly distributed random numbers having a range of [0-1]; i =1, 2 . . . N; and N=Swarm size, and $k = 1, 2, \ldots$, is the present iteration.

Figure 1 illustrates the concept of modifying a searching point by PSO in a 2-D space. The inertia weight controls the trade-off among exploitation and exploration. Exploration is the global search facilitated by a large weight while exploitation is the current search area facilitated and fine-tuned by a small weight.

A swift convergence of the procedure and improvement in the local minima depends on proper fine tuning of cognitive and social parameters. The diversity of the population can be maintained by using r_1 and r_2, distributed uniformly in the range of 0 to 1. This procedure is based on g_{best} sociometric principle that interlinks all the members of the swarm to one another, conceptually. Among the entire population, the most desired performance of any member has influence of each particle. Even though PSO is an evolutionary technique, it is unique compared to other evolutionary algorithms (EA) techniques.

Table 1. Operating conditions

Type of Load	P	V_t	X_l
Light Load	0.6	0.95	0.4
Normal Load	0.8	1.0	0.6
Heavy Load	1.0	1.05	0.8

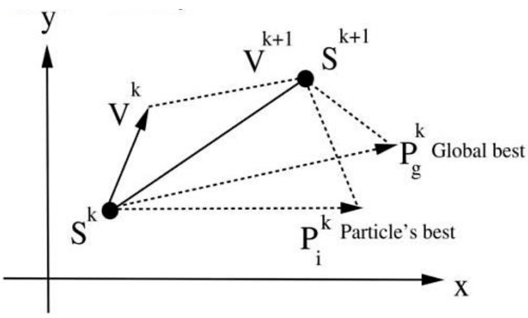

Figure 1. Typical scheme of modifying a search point by PSO in a 2D space

2.3. Overview of Taguchi technique

The Taguchi approach involves the minimization of variation through robust design of tests in a process. The goal of this strategy is to provide a high-quality product at a low cost. The Taguchi technique was created by Genichi Taguchi. His method entails conducting experiments to see how different parameters affect the variance and mean of a process evaluation as well as the performance behavior that characterizes how a process works [6]. Taguchi proposes using orthogonal arrays (OA) to organize the parameters impacting the process and the levels at which they must be adjusted in his simulation experiment design. Unlike the factorial design, this method includes testing pairs of choices rather than all possible combinations. This will ensure that all relevant data is gathered in order to estimate the aspects that have the greatest impact on product quality with the least amount of experimentation. This will help you save money and time. This strategy is best suited for a process with an intermediate number of variables (3 to 50) and few notable interactions between variables.

2.4. Implementation through PSO and Taguchi technique

The simulation steps are potted as below:

- Step 1: In PSS design, the first step is to determine the gain and time constant parameters so as to shift the electro-mechanical eigenvalues to the required reference location, $(\lambda \text{ mech})ref = (\sigma\, ref \pm j\omega\, ref)$. For a given setting of PSS under any operating condition, if the eigenvalues of electromechanical modes are $(\lambda \text{ mech})op = (\sigma\, j\omega)$, the distance measured can be used to represent the objective function of the optimization (J_{op}) given by,

$$J_{op} = \sqrt{(\sigma_{ref}-\sigma)^2+(\omega_{ref}-\omega)^2}$$

Hence, minimization of J_{op} is necessary to tune the PSS subject to the constrained given by,

$K_{pss}, min \le K_{pss} \le K_{pss}, max$;
$T_1, min \le T_1 \le T_1, max$; and
$T_3, min \le T_3 \le T_3, max$;

The minimization of objective function is solved by PSO [6] to determine the PSS parameters.

- Step 2: Selecting orthogonal arrays for noise and control factors. To begin with, noise and control factors of the system under consideration have to be identified in Taguchi optimization procedure. These factors are accounted by choosing a suitable OA that has discrete set of levels defined for every noise and control factors [6]. In an OA, the set of experiments is represented by number of rows. The maximum number of factors which can be analyzed are represented by number of columns [7] indicated in Table 2. An OA basically combines levels of various factors under consideration in a fractional factorial form. All possible combinations of factor levels occur at equal intervals for any pair of columns. This means and implies that the columns of the OA are mutually orthogonal with each other.

Table 2. Orthogonal array

	Level of noise factors		
Entry Number	P	Vt	Xl
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

- Step 3: Computation of S/N ratio. For each entry j $(j = 1, 2 \ldots., N)$ in the control OA, M objective function values $(J_{op},\ op = 1, 2\ 3 \ldots\ M)$ as per noise OA are estimated through simulation and the S/N ratio corresponding to each objective function is computed. When the optimization objective (J_{op}) has to be maximized, the definition of S/N ratio in (4) corresponds to "the bigger the better type". This S/N ratio needs J_{op} to be non-negative. It is noteworthy that with the maximization of S/N ratio, the objective function is maximized. It also ensures minimum drift of the values of the objective function [25] as shown in Figure 2.

$$\frac{S}{N}\ ratio = -10 * log_{10} \left[\frac{1}{M} \sum_{op=1}^{M} J_{op}^2 \right] dB \tag{4}$$

- Step 4: Simulation of SMIB without PSS and obtaining its operating condition at light load
- Step 5: Simulation of SMIB with CPSS and obtaining its operating condition at light load
- Step 6: Simulation of SMIB with PSO PSS and obtaining its operating condition at light load
- Step 7: Effective illustration of PSO PSS in the time domain
- Step 8: Computation of peak overshoots
- Step 9: Computation of settling time.

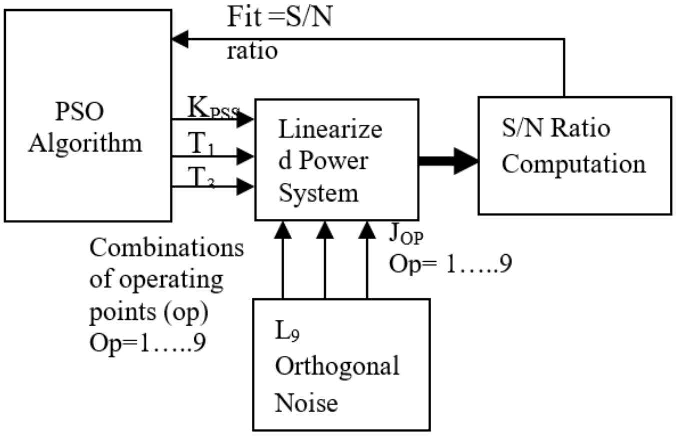

Figure 2. Methodology of Taguchi PSO based PSS design

3. RESULTS AND DISCUSSION

The results of the simulation for the state variable such as rotor angle deviation, slip deviation, q-axis component deviation, and field voltage deviation for the three scenarios of without PSS, PSO PSS, and conventional PSS are reported in this paper. The data from the Figures 3 to 6 are extrapolated to obtain Tables 3, 4 and Figure 7. From this, we understand that for the light load condition the PSO based controller shows enhanced performance with regard to settling time for all the four state variables and stable performance with regard to peak overshoot for slip deviation and rotor angle deviation. The conventional controller provides improved performance in settling time for quadrature axis component deviation and field voltage deviation.

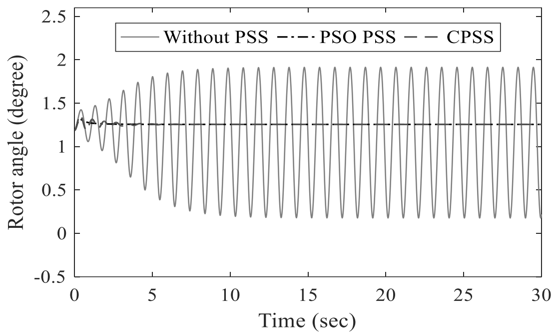

Figure 3. Light load rotor angle deviation response

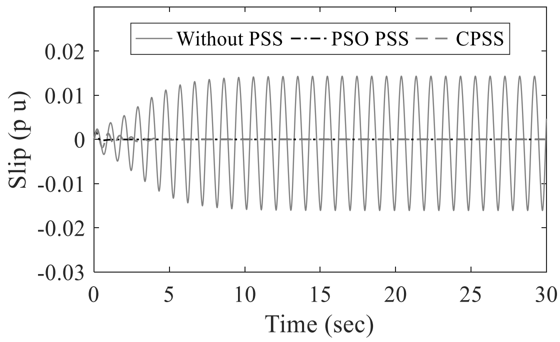

Figure 4. Light load slip deviation response

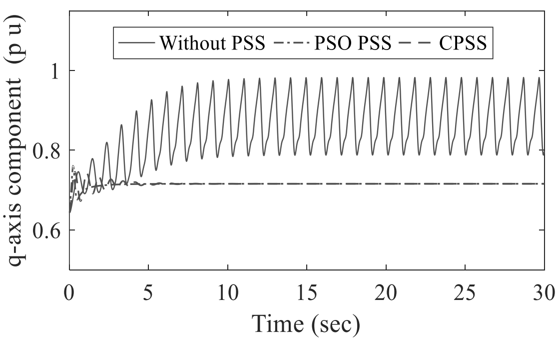

Figure 5. Light load q-axis component deviation response

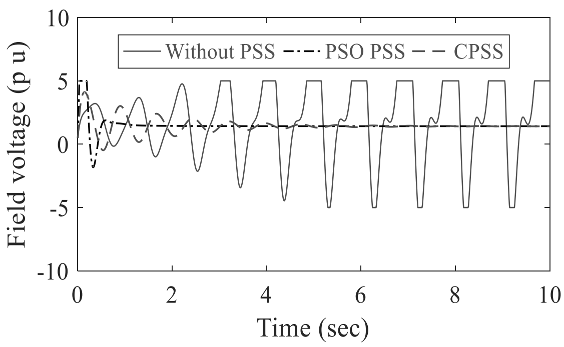

Figure 6. Light load field voltage deviation response

Table 3. Comparison of settling time for light load with different controller

State Variables	Without PSS	CPSS	PSO PSS
$\Delta\delta$	Above 30 s	4 s	1 s
Δs	Above 30 s	5 s	1 s
$\Delta E'_q$	Above 30 s	6 s	1 s
ΔE_{fd}	Above 30 s	7 s	0.5 s

Table 4. Comparisons of peak overshoot for light load with different controller

State Variables	Without PSS	CPSS	PSO PSS
$\Delta\delta$	1.9	1.3	1.1
Δs	0.015	0.002	0.001
$\Delta E'_q$	0.99	0.76	0.77
ΔE_{fd}	5	4	5

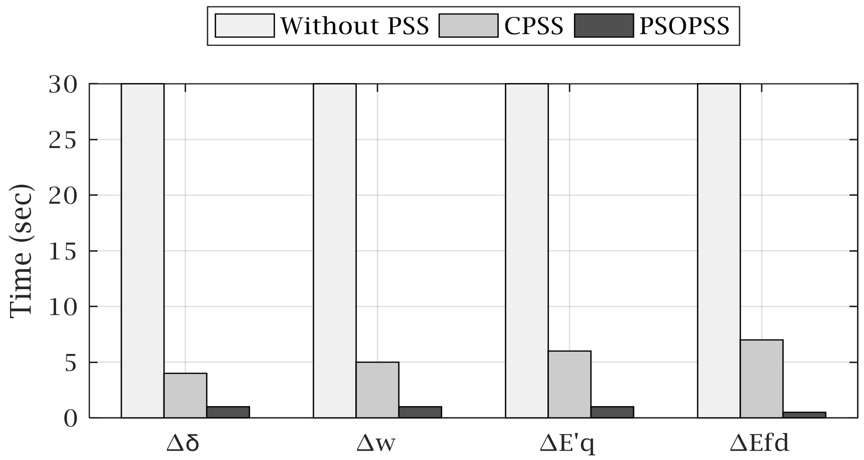

Figure 7. Comparison of settling time for the 4 state variables ($\Delta\delta, \Delta s, \Delta E'_q, \Delta E_{fd}$) with optimal PSO and Taguchi based PSS, conventional and without PSS for light load

4. CONCLUSION

In the present work some important conclusions are drawn with regard to the power system stabilizer integrated with Particle swarm optimization and Taguchi techniques. The System stability of PSO and Taguchi based PSS is enhanced and robust performance in terms peak overshoot with respect to rotor angle deviation ($\Delta\delta$) slip deviation (Δs) quadrature axis component deviation ($\Delta E'_q$) and field voltage deviation (ΔE_{fd}) for light loading conditions. The System stability of PSO and Taguchi based PSS is enhanced and robust performance in terms settling time with respect to rotor angle deviation ($\Delta\delta$) slip deviation (Δs) quadrature axis component deviation ($\Delta E'_q$) and field voltage deviation (ΔE_{fd}) for light loading conditions.

APPENDIX

Synchronous Generator: x_d =1.6; x_q =1.55; x_d' =0.32; $x_{q'}$ =0.4; H=5; ω =377 rad/s.
External network and infinite bus: $x_{transformer}$ =0.1; lRe =0; Xe =0.4(per line); Infinite bus voltage E_b =1.0;
IEEE type DCIA excitation system: K_A=100; T_A =0.0500; T_d' =6 s; $Limits\ on\ VR = \pm 6.0$;
PSS Parameters;

$$CPSS = 20;\ T_W = 2; \mathrm{T}_1 = 0.005; \mathrm{T}_2 = 0.002; \mathrm{T}_3 = 3;\ \mathrm{T}_4 = 5.4;\ Limiter = 0.05\ to\ -0.05$$

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