Design of Modified Maiden Power System Stabilizer Using Cuckoo Search Algorithm

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Abstract This article presents an improved maiden power system stabilizer (PSS) for enhancement of small signal stability of a power system. The free coefficients of proposed PSS are determined using optimization technique with the cuckoo search algorithms (CS-PSS). The performance of the CS-PSS is validated on single-machine infinite-bus power and extended to a multi-machine power system. These results are compared to the newly introduced maiden PSS structure and found superior in terms of settling time and performance indices.

Keywords Power System Stabilizer, Single-machine infinite-bus power system, Two-area Four-machine Ten-bus Power System, Cuckoo Search Algorithm, Maiden PSS

1 Introduction

The energy issue is one of the important challenges in modern scenario. It consists of the power generation, transmission and distribution of the energy to the end users. The resulting network is a large and complex in sense of analysis and operation. On occurrence of sudden load changes and faults on the system, results to small signal oscillations in the range of 0.2 Hz to 3.0 Hz. These oscillations tend to die-out automatically, but some of these may persist for a longer time causing power transfer impossible over the weak transmission lines [1].

In early phase of 1960s, the fast acting, high-gain automatic voltage regulators (AVR) were applied to the generator excitation system which in-turn invites the problem of low frequency electromechanical oscillations in the power system. The device connected to generator excitation to control the oscillations were termed as power system stabilizer. It adds a stabilizing signal to AVR for modulating the generator excitation such as to create an electric torque component in phase with rotor speed deviation, which increases the generator damping [2].

These stabilizers were designed to make system oscillation free with different structural designs and/or control tech-

niques. The early development of PSS were lead-lag and were called as conventional power system stabilizer. Similar to CPSS; a Proportional-Integral-Derivative (PID) controller may be connected to modulate the signal of the AVR to damp-out the small signal oscillations. The conventional tuning method of the PID gains is based on as Zeigler/Nichol's method, gain-phase margin method, Cohen/Coon pole placement, gain scheduling and minimum variance methods. Recently, a new PSS structure is proposed in [3], as similar to CPSS and PID based PSS. However, these methods suffer from some limitations as (a) extensive methods to set gains, (b) difficulty to deal with gains for a large, complex and non-linear power system, and (c) poor performance in a closed loop because of changing conditions [4, 5].

The design of power system stabilizer is explored using fuzzy logic controller [6, 7]. It have been considered for multi-machine models of power system in [8, 9]. The role of membership function in the design of PSS is examined in [10] and with different de-fuzzification methods in [11]. The robust fuzzy PSS is presented in [12]. The role of membership function based on linguistic variables are examined in [13].

To mitigate the shortcomings of these conventional methods much optimization based algorithms have been proposed. The methods available in literature are as Tabu search [14], Evolutionary algorithm [15], the Differential Evolution (DE) algorithm [16], Simulated Annealing [17], Genetic Algorithm [18], particle swarm optimization [19], an iterative linear matrix inequalities algorithm [20], Combinatorial Discrete and Continuous Action Reinforcement Learning Automata (CDCARLA) [21], Bacteria Foraging Optimization (BFO) Algorithm [22], Bat Algorithm (BA) as in [23, 24, 25, 26, 27], Harmony Search algorithm (HSA) as in [28, 29, 5], Fire fly algorithm (FFA) [30] and other than the optimization, some artificial intelligence based, techniques such as type-1 Fuzzy logic based PSS [31, 29, 28, 32, 33], Interval type-2 Fuzzy logic based PSS [34, 35, 36], ANN [37] etc. are ready for use in the design of PSS.

The above optimization methods work well but fail with the objective function as highly epistatic with a large number of parameters. To such objective function, these methods

may give degraded results with a large computational burden.

Meta-heuristic algorithms possess two important characteristics like intensification (or exploitation) and diversification (or exploration) is considered as upper-level methods for the optimization. Genetic algorithm [38, 39] and particle swarm optimization [40, 19, 41] are the typical types of meta-heuristic algorithms for global optimization in the design of a power system stabilizer.

Yang and Deb in 2009 [42], have introduced a promising nature -inspired metaheuristic algorithm called as Cuckoo search (CS) and extended to engineering optimization in [43] and multi-objective optimization in [44, 45, 46]. Civicioglu and Besdok (2013) [47], have introduced a conceptual comparison of cuckoo search with differential evolution (DE), particle swarm optimization (PSO), artificial bee colony (ABC) and suggested that differential evolution and cuckoo search algorithms provide more improved results than ABC and PSO. Gandomi et al. (2013) [48], provided a more extensive comparison study for solving various sets of structural optimization problems and concluded that cuckoo search obtained improved results than other algorithms such as PSO and genetic algorithms (GA). Among the diverse applications, an interesting performance enhancement has been obtained by using cuckoo search in reliability optimization problems in [49].

The main concern of this article is to evaluate and modify the maiden PSS structure proposed in [3]. The maiden PSS structure is modified with the knowledge of modern control theory as required for system to be stable resulting addition of non-zero in the numerator part of the compensator. The free elements of such modified maiden PSS are optimized using CSA (PSS: Proposed) and compared to the maiden PSS (PSS: Falehi) by connecting both controllers to SMIB and multi-machine power system.

In the organization of paper, the problem is formulated in section 2. The Cuckoo search algorithm which is used to optimize the PSS controller parameters is introduced in section 3. The performance analysis is carried out in section 4, for single-machine infinite-bus power system and multi-machine power system model. Lastly the analysis is concluded in section 5, followed by appendix and references.

2 Problem Formulation

The general representation of a power system using non-linear differential equations can be given by

$$\dot{X} = f(X, U) \quad (1)$$

Where, X and U represents the vector of state variables and the vector of input variables. As in [29], the power system stabilizers can be designed by use of the linearized incremental models of power system around an operating point. The system representation based on differential equations and used data is given in [23]. The state equations of a power system can be written as

$$\Delta \dot{X} = A \Delta X + B U \quad (2)$$

2.1 SMIB power system

The schematic diagram of the single-machine connected to an infinite-bus (SMIB) through a transmission line is shown in Fig 1. It includes the generator, AVR and excitation system, PSS, transmission line and the infinite-bus. The infinite-bus system is the representation of a large interconnected power system which is generally represented by the Thevenins equivalent.

Figure 1. The schematic representation of SMIB system

Figure 2. Representation of Heffron-Phillip model of SMIB power system

The excitation system and the AVR system are connected to the generator as in Fig. 1. The deviation in the generator speed is sensed and applied as input to PSS. The output of the PSS is applied to excitation system to modulate the signal. To operate power system in synchronism an adequate damping torque is required. The excitation with AVR system unable to meet requirement of an adequate damping, therefore, to provide extra damping using subsidiary excitation control the PSS have been developed as in [31, 1]. The linearized model of SMIB was the result of a first serious investigation by DeMello and Concordia in 1969 [50]. In system representation by Eqn. 2, A is the system matrix with order as 4×4 and is given by $\delta f / \delta X$, while B is the input matrix with order 4×1 and is given by $\delta f / \delta U$. The order of state vector is 4×1 , the order of is 1×1 . Here, the well known

Heffron-Phillip linearized model and the connection to FPSS with scaling factors is shown in Fig. 2 [16].

2.2 Two-area four-machine power system

The schematic diagram of the four-machine ten-bus power system is shown as in Fig. 3. The analysis of the system can be carried out by simultaneous solution of equations consisting of synchronous machines with excitation systems, prime movers, dynamic and static loads, transmission line network, and other devices like static VAR and HVDC converters based compensators. The dynamics of generator rotors, prime movers, excitation, and other related devices are being represented by differential equations. Thus, the complete multi-machine model consists of large numbers of ordinary differential equations (ODE) and algebraic equations [28, 29]. These are linearized about an operating point (nominal) to derive a linear model for the small signal oscillatory behaviour of power systems. The range of variation in operating point can generate a set of linear models corresponding to each operating point/condition.

Figure 3. Representation of line diagram for four-machine ten-bus power system

Figure 4. Representation of Heffron-Phillip model for multi-machine configuration of power system

The state equations of a power system, consisting N number of generators and N_{pss} number of power system stabilizers can be written as in Eqn. 2. Where, A is the system matrix with order as $4N \times 4N$ (16×16) & is given by $\delta f / \delta X$,

while B is the input matrix with order $4N \times N_{pss}$ (16×4) and is given by $\delta f / \delta U$. The order of state vector is $4N \times 1$ (16×1), the order of is $N_{pss} \times 1$ (4×1). Here, the well known Heffron-Phillip linearized model is used to represent the large multimachine power system as in Fig. 4 [29].

2.3 PSS proposed in Falehi [3] and Proposed

The general requirement of a power system stabilizer to compensate the developed phase lag in between excitation input and air-gap torque, therefore, a phase compensator block is needed. In 2013 [3], Falehi have proposed a new structure of PSS as in Fig. 5, but it larks with the provision of proper phase compensation in compensation block. Therefore, in Fig. 6, proper phase compensation is introduced by non-zero in the phase compensation block. Derivative and integral blocks are kept same as in Falehi PSS [3]. In case of Falehi PSS, there are four parameters (T_c , A_c , K_i , K_d) to be optimized by cuckoo search algorithm, while these are five (T_p , T_c , A_c , K_i , K_d) in the proposed new PSS structure as in Fig. 6.

Figure 5. PSS structure as in [3]

Figure 6. Proposed PSS structure

2.4 Objective function

To increase the system damping to electromechanical modes, of the power system model five different objective functions are considered. The problem constraints are as the parameters of the controllers connected to the power system. The unknown parameter bounds are considered as in Eqn. 3 - 7.

$$T_p^{\min} \leq T_p \leq T_p^{\max} \quad (3)$$

$$T_c^{\min} \leq T_c \leq T_c^{\max} \quad (4)$$

$$A_c^{\min} \leq A_c \leq A_c^{\max} \quad (5)$$

$$K_i^{\min} \leq K_i \leq K_i^{\max} \quad (6)$$

$$K_d^{\min} \leq K_d \leq K_d^{\max} \quad (7)$$

Typical ranges of the optimized parameters are $0.1 \leq T_p \leq 1.5$, $10 \leq T_c \leq 30$, $10 \leq A_c \leq 20$, $0.01 \leq K_i \leq 0.5$, $200 \leq K_d \leq 300$, respectively. The above parameters of

the controller are determined by HS algorithm under the one objective function as describe following.

$$J|_{SMIB} = \int_{t=0}^{t=T_{sim}} |\Delta\omega(t)|^2 dt \quad (8)$$

$$J|_{MM} = \int_{t=0}^{t=T_{sim}} \sum_{i=1}^4 |\Delta\omega_i(t)|^2 dt \quad (9)$$

3 Cuckoo Search Algorithm

The application of CS algorithm in the field of optimization has received appreciable attention. It has been modified time to time according to problem requirements. It have been modified to deal with multi-objective problems by Yang and Deb [44] and proposed a modified CS algorithm by Walton et al. in [51].

As the Cuckoos lay their eggs in the nest of other birds and respective host birds take care of the cuckoos chicks [52]. It is mainly inspired by the obligate brood parasitism of cuckoos by laying their eggs in the nests of other host birds. The infringing cuckoos are in direct contest with the host birds. The host bird discovers the eggs of other birds and may throw these out of nest or may construct another nest elsewhere. The Parasitic cuckoos generally selects a nest in which the host bird just laid its own eggs [52]. The Cuckoo eggs generally hatch somewhat earlier than their host eggs [53]. As soon as, cuckoo chick is hatched starts to evict y blindly propelling the eggs out of the nest to reduce the share of food. Cuckoo chick starts to mimic the voice call of host chicks to gain more opportunity of feeding [52, 54].

An algorithm provides a set of output variables on application of input variables. An optimization algorithm generates/produces a new set of solution x^{t+1} to a given problem from a given solution x^t at time t or iteration.

$$x^{t+1} = A\{x^t, p(t)\} \quad (10)$$

Where, the new solution vector x^{t+1} is nonlinearly mapped through A to given d-dimensional vector x^t . Let the variables of the problem are k and are represented as $p(t) = p_1, p_2, \dots, p_k$ which may be time dependent and can be tuned by A . Let an optimization problem is S with states as ψ then according to pre-define criterion D , the optimal solution x_{os} selects the desired states as ϕ as in Eqn. 11.

$$S(\psi) \xrightarrow{A(t)} S\{\phi(x_{os})\} \quad (11)$$

Thus, the final found/converged state ϕ represents to an optimal solution of the problem of interest. Here, the system states are selected in the design space by running the optimization algorithm A . Thus, the performance of the algorithm is depended /controlled by the initial solution $x^{t=0}$, the parameters p , and stopping criterion.

3.1 Procedural steps

The Cuckoo search algorithm is based on the brood parasitism of some cuckoos such as the *ani* and *Guira* and is

enhanced by use of Levy flights [55], not just by simple isotropic random walks. The Cuckoos are special birds not only because of the beautiful sounds but also because of their aggressive reproduction strategy. Cuckoos engage the obligate brood parasitism by laying their eggs in the nests of other host birds. The *ani* and *Guira* as the species of cuckoos used to lay their eggs in other birds nests and they may remove others eggs to increase the *hatching probability* of their own eggs. It is necessary to make assumptions as followings:

Assumptions

- At a time each cuckoo lays one egg and dumps it in a randomly selected nest
- The nests with high-quality eggs are selected and being carried over to the next generations
- The available number of nests (of hosts) is kept fixed (as n), and the probability of cuckoo egg detection by the host bird is fixed as $P_a \in [1, 0]$. As above, the host bird may get rid of the egg or may even abandon the nest to build a new nest i.e a fraction P_a of the n host nests that are replaced by new nests [52].

Further, as an implementation, it should be assumed that the solution refers to an egg in a nest, and each cuckoo can lay only one egg. Thus, there is no distinction between cuckoo, egg or nest because as each nest consists one egg which corresponds to one cuckoo. CS algorithm uses a combination of a local random walk (for local search) and the global random walk (for global search) and is controlled by a switching parameter P_a .

Local random walk: Let two different solutions selected by random permutation are as x_j^t and x_k^t , Heaviside function as $H(P_a - \epsilon)$, random number drawn from a uniform distribution as ϵ , and with step size as s . Then, the local random walk can be represented as.

$$x_i^{t+1} = x_i^t + \alpha s \otimes H(P_a - \epsilon) \otimes (x_j^t - x_k^t) \quad (12)$$

Here, $\alpha > 0$ is the step size related to the scales of the problem of interests. It is generally selected as $\alpha = 0$. The product $\otimes$ means entry-wise walk during multiplications.

Global random walk: The global random walk is carried out by using Levy flights in which the step-lengths are distributed according to a heavy-tailed probability distribution [52]. On completion of large number of steps the random walk tends to a stable distribution as compared to its origin. The final solution can be represented by Eqn. 13 as following.

$$x_i^{t+1} = x_i^t + \alpha L(s, \lambda) \quad (13)$$

$$L(s, \lambda) = \frac{\lambda \Gamma(\lambda) \sin(\pi\lambda/2)}{\pi} \frac{1}{s^{1+\lambda}} \quad (14)$$

The Eqn. 13 is the stochastic representation for a random walk. The random walk is a Markov chain; whose next location directly depends on the current location and the transition probability. An appropriate value of new solutions generated by randomization and their locations should be far enough from the best solution (current) to make sure not be trapped in a local optimum [53, 42]. The local search exists about to 1/4 of the search time (with $P_a = 0.25$), while global search exists for 3/4 of the total search time.

Lévy distribution: Lévy flights are characterized by infinite mean and variance therefore, CS can explore the search space more efficiently as compared to standard Gaussian process. Thus, CS guaranteed global convergence and highly efficient [53, 56, 57].

In Lévy flight the step-lengths are distributed according to the probability distribution as in Eqn. 15, which provides a random walk while the random step length is drawn from a Lévy distribution for $1 \leq \lambda \leq 3$ [53].

$$Levy(u) = t^{-\lambda} \quad (15)$$

Improved cuckoo search: As above the α introduced in the CS is to find locally improved solutions, while P_a and λ to find global solution. In tuning of solution vectors; the parameters P_a and α plays a vital role. In original CS, P_a and α are kept fixed and cannot be altered during new generations, therefore, the number of iterations kept large to get optimal solutions. With large value of P_a and small value of α , the convergence speed is high but unable to find required solutions. To mitigate the problem of adjusting the value of P_a and α , these are considered as variables in improved CS. The values of P_a and α must be large enough to make capable the algorithm to increase the diversity of solution vectors during early generations and decreased in final generations to result in a better fine-tuning of solution vectors. Thus, P_a and α are dynamically changed with the number of generation and expressed in Eqn. 16 - Eqn. 18, where NI and gn are the number of total iterations and the current iteration, respectively [52].

$$P_a^{gn} = P_{a,max} - \frac{P_{a,max} - P_{a,min}}{NI} gn \quad (16)$$

$$\alpha(gn) = \alpha_{max} \times e^{(c.gn)} \quad (17)$$

$$c = \frac{Ln(\alpha_{min}/\alpha_{max})}{NI} \quad (18)$$

The performance of the algorithm may deteriorate by an increase in the maximum value of α as in [52], therefore, the suitable values are $0.005 \leq P_a \leq 1.0$ and $0.05 \leq \alpha \leq 0.5$. The considered values of P_a and α are 0.25 and 0.25, respectively. The Cuckoo Search is shown in Algorithm 1.

4 System response and discussion

4.1 SMIB power system

4.1.1 Controller parameter optimization

In order to assess effectiveness, the proposed CS-PSS algorithm is programmed in MATLAB R2011b environment and executed on Intel (R) Core (TM) - 2 Duo CPU T6400 2.00 GHz with 3 GB RAM, 32-bit operating system. The parameters of the algorithm used for simulation are: $n = 25$, $P_a = 0.25$ and Iteration as 200 as in Algorithm 1. The plant (SMIB power system) operating at nominal operating condition (where in $X_e = 0.4p.u.$ and $P = 1.0p.u.$) is considered for optimal tuning of PSS parameters as proposed in [28]; subjected to the ISE minimization based objective function with the parametric bounds such as $0.1 \leq T_p \leq 1.5$,

Algorithm 1 Cuckoo search algorithm for tuning parameters of conventional power system stabilizer

- 1: **procedure** OBJECTIVE FUNCTION $F(X)$, $X = (X_1, X_2, \dots, X_d)^T$ (minimization of objective function; where X_d is the number of free Coefficients of CPSS)
- 2: Initialize a population of a host nest, x_i , ($i = 1, 2, \dots, n$); selected as $n = 25$, lower and upper bound are defined in vector
- 3: **for** $i = 1 : n$, $nest(i,:) = L_b + (U_b - L_b) \cdot rand(size(L_b))$ **do**
- 4: **end for**
- 5: **while** $iter < Maximumgenerations$ **do**
- 6: Get a cuckoo (say i) randomly & generate a new solution by levy flights as in Eqn. 15. Evaluate its quality / fitness F_i , Choose a nest among n (say j) randomly.
- 7: **if** $F_i < F_j$ **then**
- 8: Replacing j by the new solution i.e. replacing with minimum function value.
- 9: **end if**
- 10: Abandon a fraction (P_a) of worse nests and generate ($P_a \in [0, 1]$, as 0.25 in Eqns. 16 - 18 new solutions at new location by Levy flights (as in Eqn. 15)
- 11: keep the best solutions(bestnest) i.e. nests with quality solutions rank the solutions and find the current best (f_{min});
- 12: $iter = iter + 1$; (update iteration counter)
- 13: $Fcs(iter, :) = f_{min}$; save Fcs.mat {to plot fitness function or value at each iteration[200 × 1] as in Fig. 8 - Fig. 9}
- 14: $Pcs(iter, :) = bestnest$; save Pcs.mat {Parameters or value at each iteration}
- 15: **end while**
- 16: post process results(f_{min} , bestnest) and visualization
- 17: **end procedure**

$10 \leq T_c \leq 30$, $10 \leq A_c \leq 20$, $0.01 \leq K_i \leq 0.5$ and $200 \leq K_d \leq 300$. The scheme of optimization is shown in Fig. 7 and the performance of cuckoo search in terms of fitness function variation is shown in Figs. 8 - 9. The optimized parameters for both PSSs (Falehi PSS and Proposed PSS) at nominal operating condition are enlisted in Table 1. The fitness function value at 200th iteration for Falehi PSS and proposed PSS are as 8.352×10^{-4} and 7.053×10^{-4} , respectively.

Figure 7. Scheme of parameter optimization using cuckoo search algorithm for PSS: Falehi [3] and PSS: Proposed

Table 1. Optimized parameters using cuckoo search algorithm for PSS (Proposed) and PSS (Falehi) [3]

Structure	T_p	T_c	A_c	K_i	K_d
PSS: Proposed	0.3991	22.9353	16.0501	0.0027	300
PSS: Falehi [3]	-	14.5637	10	0.0187	200

Figure 8. Performance of cuckoo search algorithm in parameter optimization for Falehi PSS Structure [3] in SMIB system **Figure 10.** Plot of SMIB response with PSS structure proposed as in [3] and proposed PSS structure for speed deviation **Figure 9.** Performance of cuckoo search algorithm in parameter optimization for proposed PSS Structure in SMIB system **Figure 11.** Plot of SMIB response with PSS structure proposed as in [3] and proposed PSS structure for control signal

4.1.2 Performance analysis

The considered power system is subjected to fault at 5 seconds (persists up to 0.1 second i.e. cleared at 5.1 seconds) and the performance of both PSS structures in terms of generator speed, control voltage, voltage behind transient reactance, air-gap electric torque, power angle and terminal voltage is compared in Fig. 10 - 15. It is clear that the system behaviour without PSS is unstable, while it is being stabilized using either PSS structure. The recorded settling time with PSS [3] is 15.1 seconds and with PSS (Proposed is 8.2 seconds) as shown in Fig. 10, results heavy performance improvement with proposed PSS. The other signal variations with proposed PSS structure, such as control voltage, voltage behind transient reactance, air-gap electric torque, power angle and terminal voltage shown in Fig. 11 - Fig. 15, respectively are also settled to steady state appreciably earlier than that with PSS structure as in [3].

Figure 12. Plot of SMIB response with PSS structure proposed as in [3] and proposed PSS structure for internal voltage

Figure 13. Plot of SMIB response with PSS structure proposed as in [3] and proposed PSS structure for electric torque

Figure 16. Performance of cuckoo search algorithm in parameter optimization for Falehi PSS Structure [3] in Two-Area System

Figure 14. Plot of SMIB response with PSS structure proposed as in [3] and proposed PSS structure for change in angle

Figure 17. Performance of cuckoo search algorithm in parameter optimization for proposed PSS Structure in Two-Area System

Figure 15. Plot of SMIB response with PSS structure proposed as in [3] and proposed PSS structure for terminal voltage

4.2 Two-area four-machine ten-bus power system

4.2.1 Controller parameter optimization

Considering same parameters of CS algorithm as in preceding section and the actuating data for line diagram in Fig. 3 as in [29, 28] equipped with four controllers to four generators are optimized. The performance of CSA in terms of fitness function (J for multi-machine) variation is recorded as in Fig. 16 and Fig. 17. The fitness function value at the 200th iteration with PSS structure as in [3] is 0.2271 and with the PSS (proposed) is 0.0511.

The higher value of fitness function with PSS [3] represents its premature optimization at 20th iteration and onwards. The optimized parameters with both controllers are

enlisted in Table 2. The speed signal for all four generators (Gen-1 to 4) without PSS, with PSS [3] and with PSS (Proposed) is recorded in Fig. 18 - Fig. 21, respectively. It is clear from these figures that all generators without PSS show unstable behaviour and response with both PSSs as stable. As a comparison the settling time with both PSS structure is recorded in Table 3 and is clear that the performance with proposed PSS is very encouraging because settling to steady state quite earlier. The 5th column of Table 3 represents the percentage improvement (about 86 to 88).

Figure 18. Speed response of two-area power system without PSS, with PSS structure as in [3] and with PSS (Proposed) for Generator-1

It is very clear from above time domain analysis that the performance with proposed PSS outperform the PSS by Falehi, but to have more clearer quantitative analysis three

Table 2. Cuckoo search based optimized parameters for (a) PSS: Falehi [3] and (b) PSS: Proposed

Controller	Genrs	Controller Parameters				
		T_p	T_c	A_c	K_i	K_d
PSS: Proposed	Gen-1	0.10	10.00	10.71	0.28	295.82
	Gen-2	0.31	10.01	10.24	0.06	296.44
	Gen-3	0.11	12.28	19.76	0.50	200.00
	Gen-4	1.01	10.00	10.25	0.50	289.79
PSS: Falehi	Gen-1	-	30.00	10.00	0.49	200.00
	Gen-2	-	20.40	10.00	0.50	299.99
	Gen-3	-	30.00	10.00	0.50	200.01
	Gen-4	-	30.00	10.00	0.50	200.07

Table 3. Settling time in seconds for speed response of system without PSS, with PSS: Falehi [3] and with PSS: Proposed

Generator	Without PSS	PSS:Falehi [3]	PSS: Proposed	Improved (%)
Gen-1	Unstable	84.83	10.92	87.13
Gen-2	Unstable	95.32	11.32	88.12
Gen-3	Unstable	71.88	8.461	88.23
Gen-4	Unstable	71.60	9.407	86.86

Figure 19. Speed response of two-area power system without PSS, with PSS structure as in [3] and with PSS (Proposed) for Generator-2 **Figure 21.** Speed response of two-area power system without PSS, with PSS structure as in [3] and with PSS (Proposed) for Generator-4 **Figure 20.** Speed response of two-area power system without PSS, with PSS structure as in [3] and with PSS (Proposed) for Generator-3

- ITAE: Integral of the Time-Weighted Absolute Error

$$ITAE = \int_0^{T_{sim}} t |\Delta\omega(t)| dt \quad (19)$$

- ISE: Integral Square Error

$$ISE = \int_0^{T_{sim}} |\Delta\omega(t)|^2 dt \quad (20)$$

- IAE: Integral of the Absolute Error

$$IAE = \int_0^{T_{sim}} |\Delta\omega(t)| dt \quad (21)$$

where, T_{sim} is the simulation time of the system considered as 100 seconds. It is found that the least value for all PI's associated to PSS (proposed) resulting to guarantee the better performance as against PSS by Falehi.

types of performance indices (PIs) are introduced as in Eqn. 19 - Eqn. 21 and evaluated as in Table 4.

Table 4. Performance indices (ITAE, IAE and ISE) for speed response with (a) PSS: Falehi [3] and (b) PSS: Proposed

Genr.	ITAE		IAE		ISE	
	Falehi	Prop.	Falehi	Prop.	Falehi	Prop.
G-1	0.7128	0.0092	0.0326	0.0034	3.0848E-05	4.1870E-06
G-2	0.7221	0.0088	0.0326	0.0032	3.0204E-05	3.8272E-06
G-3	0.7018	0.0112	0.034	0.0053	4.5987E-05	1.9542E-05
G-4	0.5384	0.0120	0.0272	0.0047	3.0717E-05	1.4110E-05

5 Conclusion

In this paper a new structure of power system stabilizer to improve small signal stability is introduced. The application of this PSS is applied to single-machine infinite-bus power system and two-area four-machine ten-bus power system and, moreover, the performance is compared to the newly introduced PSS structure in [3] and without PSS. It is established that the performance with proposed PSS is highly encouraging and found better as compared to PSS by Falehi. The results are incorporated in terms of settling time and performance indices (ITAE, IAE and ISE) found as least with proposed PSS as compared to PSS structure in [3].

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