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Optimal design and tuning of novel fractional order PID power system stabilizer using a new metaheuristic Bat algorithm

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Bat algorithm (BA);
FireFly algorithm (FFA);
Single Machine Infinite Bus (SMIB) power system

Abstract This paper proposes a novel robust power system stabilizer (PSS), based on hybridization of fractional order PID controller ($PI^{\lambda}D^{\mu}$) and PSS for optimal stabilizer (FOPID-PSS) for the first time, using a new metaheuristic optimization Bat algorithm (BA) inspired by the echolocation behavior to improve power system stability. The problem of FOPID-PSS design is transformed as an optimization problem based on performance indices (PI), including Integral Absolute Error (IAE), Integral Squared Error (ISE), Integral of the Time-Weighted Absolute Error (ITAE) and Integral of Time multiplied by the Squared Error (ITSE), where, BA is employed to obtain the optimal stabilizer parameters. In order to examine the robustness of FOPID-PSS, it has been tested on a Single Machine Infinite Bus (SMIB) power system under different disturbances and operating conditions. The performance of the system with FOPID-PSS controller is compared with a PID-PSS and PSS. Further, the simulation results obtained with the proposed BA based FOPID-PSS are compared with those obtained with FireFly algorithm (FFA) based FOPID-PSS. Simulation results show the effectiveness of BA for FOPID-PSS design, and superior robust performance for enhancement power system stability compared to other with different cases.

1. Introduction

Under environmental and economic pressures, power system quite becomes more heavily loaded and poorly damping [1]. Therefore, power system stability may be mostly defined as the property of a power system that allows it to remain in a condition of operating stability under normal operating conditions and to regain an adequate state of equilibrium after disturbance [2].

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Power system stabilizers (PSSs) must be able to supply suitable stabilization signals over a wide range of operating conditions and perturbations. With the increase in electric power demand and need to command the system at a faster and great flexible way in the competitive situation, current power systems can reach stressed conditions less difficult than the last years. The sudden disturbance causes the unstable system or weakly damped oscillations that have been noticed more often in electrical power systems around the world.

In recent years, due to the rapid development of computer technology, the use of optimization tools becomes feasible to help in the implementation of power system stabilization control. Several advanced control designs based on artificial intelligence have been introduced to design lag-lead PSS structures [3–13]. These methods can design a robust PSS by including parameter uncertainty and non-linearity of the electrical power system and provide the best stabilization for a wide range of operating conditions. The authors in [14] intend to suggest a stable fuzzy wavelet neural-based adaptive PSS (SFW-NAPSS) for improving the power system stability. A self-recurrent Wavelet Neural Network (SRWNN) is used in the proposed approach with the purpose of constructing a self-recurrent consequent part of a Takagi–Sugeno–Kang (TSK) fuzzy model for each fuzzy rule.

On the other hand, several novel metaheuristic algorithms have been proposed in the literature for PSS robust setting. Such algorithms can augment the computational effectiveness, such as Genetic algorithm (GA) [15,16], Particle Swarm Optimization (PSO) [17,18] and Bat algorithm (BA) [19,20]. In [21], a new Sparse Recursive Least Square (SPARLS) algorithm is proposed to adjust the PSS parameters to meet the operating conditions. Additionally, the proposed work has been performed on SMIB different perturbations.

During these years, the control processes have given better advances in the industry [22]. Fractional-order proportional-integral-derivative (FOPID) controllers have received a great attention in the previous years, from both an industrial and an academic point of view [23–25]. However, simple tuning rules and no effectiveness still exist for these controllers like those specified for the integer PID controllers [26,27]. The PID controller, for the reason of its functional simplicity is mostly used in industrial applications. Conversely, their parameters are often adjusted using test or experiences and error methods. Unluckily, it is absolutely hard to properly adjust gains' PID, because many industrial systems are often burdened with problems such as structural complexity, uncertainties and nonlinearities.

In [28], a robust PID-based PSS is suggested to appropriately function over a wide range of operating conditions. Doubts in plant parameters, due to deviation in load patterns and generation, are expressed in the form of a polytopic structure. The problem of PID control is initially decreased to a generalized static output feedback synthesis. In [29], the authors suggested a simple analytical method for computing the set of three terms of robust stabilizing PSSs. Therefore, stabilization of the proposed interval plant by a PID controller and a phase lead compensator based PSS is dealt with using generalized Kharitonov's theorem. Furthermore, necessary and sufficient constraints for characterizing the robust stabilizing three term controllers are derived by applying the Routh–Hurwitz criterion to a set of segment/vertex plants.

Therefore, PSO algorithm is one of the robust optimization methodologies in the procedure of solving the best PID controller parameters problem. As in [30], an optimal PSO based PID PSS is proposed, which utilizes the speed deviation as the input. In [31], a design method for the stability improvement of a SMIB power system using PID-PSS has been developed, in which its parameters are optimized by Hybrid Particle Swarm-Bacteria Forging Optimization (PSBFO) technique. A real coded GA based PID is produced in [32] to enhance power system dynamic, in which the proposed stabilizer's parameters are adjusted by using real coded GA.

The power generation control devices have become important in the real-time control and operation of power systems and management in broadly changing power system control environments. In [33], it has been suggested a dynamic simulator is utilized to simulate a synchronous power plant in real time. To examine the control devices in virtual environments using Real Time Interface, the SMIB model is executed in Digital Signal Processor of dSPACE hardware, a platform for real time simulation.

Yang developed a new capable metaheuristic BA. Preliminary studies suggest that the BA can have superior performance over PSO and GA [34]. A robust design stabilizer based on the combination of PSS and fractional order PID is investigated in this work. The combination has been done by multiplying the output of PSS to the FOPID output with optimal parameters of this later. The main purpose of FOPID-PSS is to produce an appropriate torque on the mechanical part of the generator and to supply the better damping of power system. Moreover, the authors suggest the employment of Bat algorithm to ensure the best coordination between PSS and FOPID and avoid the bad overlap of the signals as well as to obtain optimal parameters. The FOPID-PSS design has formulated an optimization problem based on various performance indices. To prove the applicability of this design, it has been validated on a SMIB power system under different cases. The advantage of this process work is that the system excitation will be powerful to insert effective signal whatever nature of the disturbance.

This article is organized as follows. Section 2 presents the description of a (SMIB) power system. Three diverse proposed stabilizers are described in Section 3. We addressed in Section 4 the different objective functions, which are the performance indices based tuning. Section 5 presents a review on the proposed algorithms. In Section 6, the effectiveness of the proposed stabilizer FOPID-PSS based BA is tested on a SMIB under different objective functions and compared with PID-PSS and PSS based BA. Also, comparison extended between FOPID-PSS based BA and FOPID-PSS based FFA, to prove the effectiveness of this new algorithm.

2. Power system

In this paper, the power system under study composes of the single machine connected to an infinite bus (SMIB) through a transmission line as shown in Fig. 1, whereas, Fig. 2 shows the well-known Phillips–Heffron block diagram of the linearized model of the SMIB power system. Here, a fourth order model has modeled the synchronous machine. A power system can be formulated as follows:

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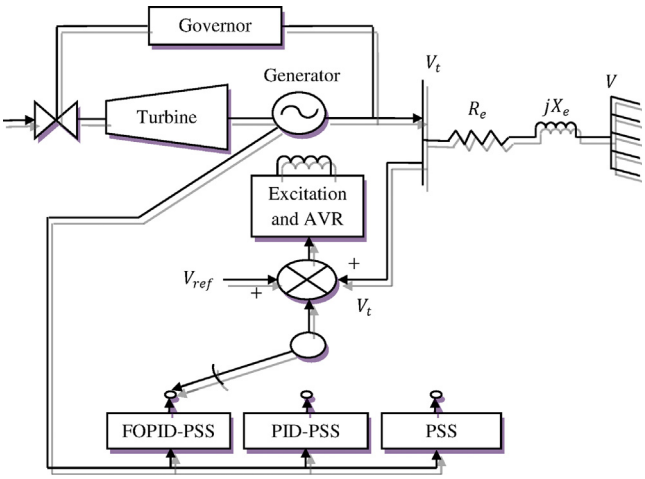

Figure 1 Schematic line diagram of single-machine-infinite-bus power system.

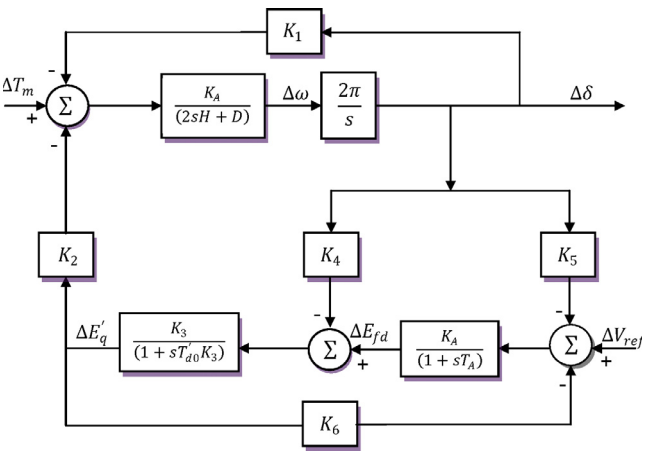

Figure 2 Heffron–Phillips block diagram for SMIB power system.

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

where X is the vector of the state variables and U is the vector of input variable. The state vector of the generator is given as $[\omega, \delta, E_q', E_{fd}]^T$ and U is the PSS output signal. This model is commonly used for the analysis of parameter values tuning of PSS [35].

$$\begin{cases} \omega = \dfrac{(P_m - P_e - D\omega)}{M} \\ \delta = \omega_0(\omega - 1) \\ E_q' = \dfrac{(-E_q + E_{fd})}{T_{do}'} \\ E_{fd} = \dfrac{-E_{fd} + K_a(V_{ref} - V_t)}{T_a} \end{cases} \tag{2}$$

The state equations of power system can be written as follows:

$$\dot{X} = AX + BU \tag{3}$$

where A is a 4×4 matrix and is given by $\partial f/\partial X$, while B is the input matrix with order 4×1 and is given by $\partial f/\partial U$. The A and B are calculated with each operating point. The state vector X is a 4×1 and the input vector U is a 1×1.

3. Proposed stabilizers

3.1. Power system stabilizer

The conventional structure of the PSS is used in this study as shown in Fig. 3(a), and its transfer function is given by the relationship (4) [2]. It comprises of a block of K_{PSS} gain followed by a high-pass filter of time constant T_W and lead-lag structured phase compensation blocks with time constants T_1, T_2, T_3 and T_4. It is important to mention that the suggested stabilizers are designed to reduce the power system oscillations after a wide perturbation so as to enhance the power system stability. The output stabilizer V_{PSS} is a voltage signal that adds to the input voltage signal of the exciter system. The input signal of such a structure is usually the deviation of the synchronous speed $\Delta\omega$.

$$U(s) = K_{PSS}\left(\frac{sT_w}{1+sT_w}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)\Delta\omega(s) \tag{4}$$

3.2. PID based PSS

The operating function of a PID based PSS is to create a proper torque on the rotor of the generator involved in such a manner that the phase lag between the machine electrical torque and the exciter input is compensated, as given in Fig. 3(b). The additional stabilizing signal is the one proportional to speed. A broadly speed input signal is considered during all the study as in [36]. The transfer function of the PID-PSS is given by

$$U(s) = \left[K_{PSS}\left(\frac{sT_w}{1+sT_w}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)\right][K_p + K_i/s + K_d s]\Delta\omega(s) \tag{5}$$

3.3. FOPID based PSS

To improve the robustness and performance of PID control systems, Podlubny has proposed an extension to the PID controllers, which can be called $PI^{\lambda}D^{\mu}$ (FOPID) controller because of involving a differentiator of order μ and integrator of order λ. This controller is described in more detail in [23]. The Riemann–Liouville (RL) definition is a commonly used concept of the fractional differintegral. The RL expression for the fractional-order derivative has the following form:

$$\alpha D_t^{\alpha} F(t) = \frac{1}{\Gamma(n-\alpha)}\left(\frac{d}{dt}\right)^n \int_{\alpha}^{t} \frac{f(\tau)}{(t-\tau)^{1-(n-\alpha)}} d\tau \tag{6}$$

$\Gamma(\cdot)$ is Euler's Gamma function that specifies the factorial, and allocates operator, to get non-integer values. A substitute description, based on the notion of fractional differentiation, which is the Grunwald–Letnikov definition is displayed by

$$\alpha D_t^{\alpha} F(t) = \lim_{g\to 0} \frac{1}{\Gamma(\alpha) g^{\alpha}} \sum_{d=0}^{(t-\alpha)/g} \frac{\Gamma(\alpha+d)}{\Gamma(g+1)} f(t-dg) \tag{7}$$

By introducing the concept of fractional order operator $\alpha D_t^{\alpha} F(t)$, one can note that the integrator can be unified.

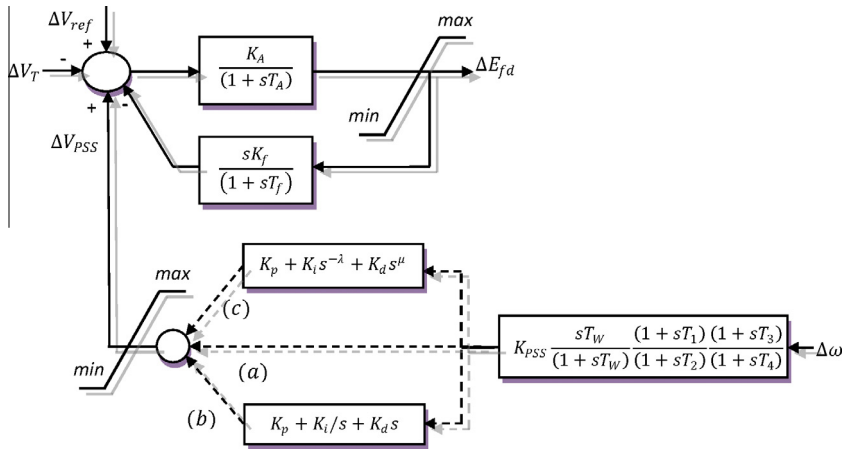

Figure 3 Various of proposed stabilizers with an excitation system.

The transfer function of FOPID is obtained through Laplace transform and is written as follows:

$$G_c(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu} \tag{8}$$

The differential equation of a FOPID controller can be given as

$$u(t) = K_p e(t) + K_i D_t^{-\lambda} e(t) + K_d D_t^{\mu} e(t) \tag{9}$$

Design of FOPID controller involves the design of following parameters: K_i, K_d, K_p, and μ, λ, which are the integral, differential, proportional constants, fractional order derivative and integral elements respectively. $PI^{\lambda}D^{\mu}$ controller is great flexible and gives the possibility of tuning more carefully the dynamical proprieties of a robust control system (see Fig. 4).

In this work, a novel robust hybrid stabilizer based on the combination of a conventional PSS and $PI^{\lambda}D^{\mu}$ controller is considered to design the optimal PSS (FOPID-PSS), by providing greater damping of power system. The transfer function of the FOPID-PSS to modulate the excitation voltage is given by Eq. (10) and is displayed in Fig. 3(c).

$$U(s) = \left[K_{\mathrm{PSS}}\left(\frac{sT_w}{1+sT_w}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)\right][K_p + K_i s^{-\lambda} + K_d s^{\mu}]\Delta\omega(s) \tag{10}$$

4. Objective function

In this article, we used performance indices including Integral Absolute Error (IAE), Integral Squared Error (ISE), Integral of the Time-Weighted Absolute Error (ITAE), Integral of Time multiplied by the Squared Error (ITSE), to minimize the error signal; in other terms minimize the overshoots and settling time in power system oscillations, and compare them to find the best suitable one, where, BA has been applied to minimize the values provided by the objective functions of the system that is given by

$$\mathrm{ISE} = \int_0^{\mathrm{tsim}} e(t)^2 dt \tag{11}$$

$$\mathrm{IAE} = \int_0^{\mathrm{tsim}} |e(t)| dt \tag{12}$$

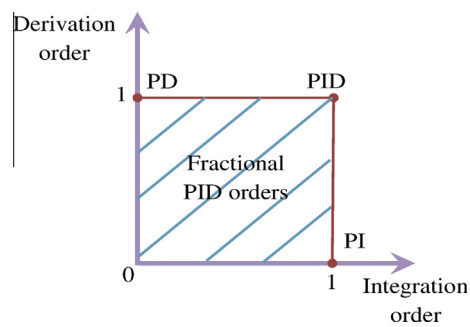

Figure 4 Fractional order PID form.

$$\mathrm{ITAE} = \int_0^{\mathrm{tsim}} t|e(t)| dt \tag{13}$$

$$\mathrm{ITSE} = \int_0^{\mathrm{tsim}} t(e(t))^2 dt \tag{14}$$

where tsim is total simulation time. Typical ranges of the optimized parameters are shown in Table 1. In this study, the time constant T_w is considered as 10.0 s.

5. Proposed algorithms

5.1. Bat algorithm

The bat-inspired metaheuristic algorithm, called the Bat algorithm (BA), was newly implemented by Yang [34], inspired by the echolocation of microbats [37]. In the nature, echolocation can have just a few thousandths of a second (up to about 8–10 ms) with a changing frequency in the area of 25–150 kHz, matching to the wavelengths of 2–14 mm in the air [38].

Microbats usually utilize echolocation for searching for prey. During roaming, microbats produce short pulses, but, their emitted pulse rates augment and the frequency is tuned up, when a potential prey is nearby. The augment of the frequency, called frequency-tuning, together with the acceleration of pulse emission will shorten the wavelength of echolocations and therefore augment precision of the detection [38]. The echolocation characteristics of microbats can be idealized as the following rules:

Table 1 Typical ranges of the optimized parameters.

	K	T_1	T_2	T_3	T_4	K_P	K_i	K_d	μ	λ
Min	0.1	0.01	0.01	0.01	0.01	0.001	0.001	0.001	0.1	0.1
Max	5	2	2	2	2	1.2	1.2	1.2	1	1

(a) All bats utilize echolocation to sense distance, as well as they also recognize the difference between prey/food and background barriers in a few magical manner;
(b) Bats fly randomly with velocity v_j at position x_j with an unchanging frequency f_{min}, varying loudness A_0 and wavelength λ to look for prey. They can routinely tune the rate of pulse emission $r \in [0, 1]$ and adjust the wavelength (or frequency) of their emitted pulses, depending on the proximity of their aim; and
(c) While the loudness can change in many manners, we suppose that the loudness varies from a great (positive) A_0 to a least constant value A_{min}.

One must identify for every bat (j), its velocity v_j and position x_j in a d-dimensional search space, the novel solutions velocities v_j^t and x_j^t at time step t can be written as follows:

$$f_j = f_{min} + (f_{max} - f_{min})\alpha \tag{15}$$

$$v_j^t = v_j^{t-1} + (x_j^{t-1} - x^*)f_j \tag{16}$$

$$x_j^t = x_j^{t-1} + v_j^t \tag{17}$$

where α in the range of $[0, 1]$ is a random vector drawn from a uniform distribution and is the current global best location, after comparing all the solutions among all the n bats at the current iteration x^* is located. As the product $\lambda_j \cdot f_j$ is the velocity increment, one can utilize either f_j (or λ_j) while fixing the other factor, to tune the velocity change. For implementation, every bat is randomly assigned a frequency which is drawn uniformly from (f_{min}, f_{max}). The local search is principally a random walk around the current best solutions, and a novel solution for every bat can be generated locally by

$$x_{new} = x_{old} + \varepsilon A^t \tag{18}$$

where $\varepsilon \in [0, 1]$ is a random number, while $A^t = \langle A_j^t \rangle$ is the average loudness of all the bats at this time step. As the loudness generally reduces once a bat has found its prey, the rate of pulse emission augments, as any value of convenience; the loudness can be selected. The loudness is typically chosen from $[A^0, A_{min}] = [1, 0]$. Supposing $A_{min} = 0$ means that a bath has just found the prey for the moment stop emitting any noise. The rate of pulse emission and the loudness is given by

$$r_j^{t+1} = r_j^0[1 - \exp(-\gamma t)], \quad A_j^{t+1} = \beta A_j^t \tag{19}$$

where β and γ are constants. In the simulated annealing, β is like to the cooling factor of a cooling schedule. For any $\gamma > 0$ and $0 < \beta < 1$

$$A_j^t \to 0, \ r_j^t \to r_j^0, \ \text{as } t \to \infty \tag{20}$$

In the easiest case, we can select $\beta = \gamma$. In the standard BA, we can choose $\beta = \gamma$ 0.9–0.975 in most cases.

Pseudo code of Bat algorithm based FOPID-PSS is given as follows:

Identify Objective function $f(x)$, $x = (x_1, x_2, \ldots, x_{10})^T$,
where $x(1) = K, x(2) = T_1, x(3) = T_2, x(4) = T_3, x(5) = T_4$,
$x(6) = K_P, x(7) = K_i, x(8) = K_d, x(9) = \mu, x(10) = \lambda$;
– *Initialize the bat population:*
$x_j (j = 1, 2, \ldots, 10)$ and $v_i (npop = 20)$
– *Define pulse frequency:*
f_j at x_j, which $(f_{min} = 0, f_{max} = 1)$
– *Initialize pulse rates and the loudness:*
$(r = 0.5, A = 0.5)$
– *Define the boundaries of the parameter:*
$(L_b; U_b)$; see Table 1
while $(t < (t_{max} = 50))$; t_{max}: *Max number of iterations*
Tuning frequency generate novel solutions,
and updating velocities and locations/solutions (Eqs. (16)–(18)),
if $(rand > r)$
Choose a solution between the best solutions.
Generate a local solution around the selected best solution,
(Eqs. (19) and (20)),
end if
Generate a new solution by flying randomly,
if $(rand < A \ \& \ f(x_j) < f(x^*))$
Admit the new solutions,
Augment r_j *and decrease* A_j,
end if
Class the bats and searching the current best x^*,
end while
Display result of final iteration (minimum function value) and best (optimized parameter value)

5.2. FireFly algorithm

The FireFly Algorithm (FFA) is a new metaheuristic given in [39], nature inspired, which is based on the social flashing behavior of fireflies. Hence, Fireflies flash in order to allure a mating partner as well as for protection against predators.

There are three specific idealized laws in the FFA, which are based on several of the major flashing characteristics of real fireflies:

– all fireflies are unisex,
– their attractiveness is commensurate to their brightness, and
– the brightness of a firefly is changed or resolved by the landscape of the objective function.

The shape of attractiveness function of a firefly in the FFA is calculated by the following equation:

$$\beta(r) = \beta_0 \exp(-\gamma r^k), \ \text{with } k \geqslant 1, \tag{21}$$

Table 2 Optimal BA based proposed stabilizer parameters for case II.

Bat algorithm	FireFly algorithm
Number of iteration = 50	Number of iteration = 50
Number of population = 20	Number of population = 20
Loudness = 0.5	Variation of attractiveness = 0.5
Pulse rate = 0.5	Randomization = 0.8
Pulse frequency ($f_{\min} = 0$, $f_{\max} = 1$)	Absorption coefficient = 1

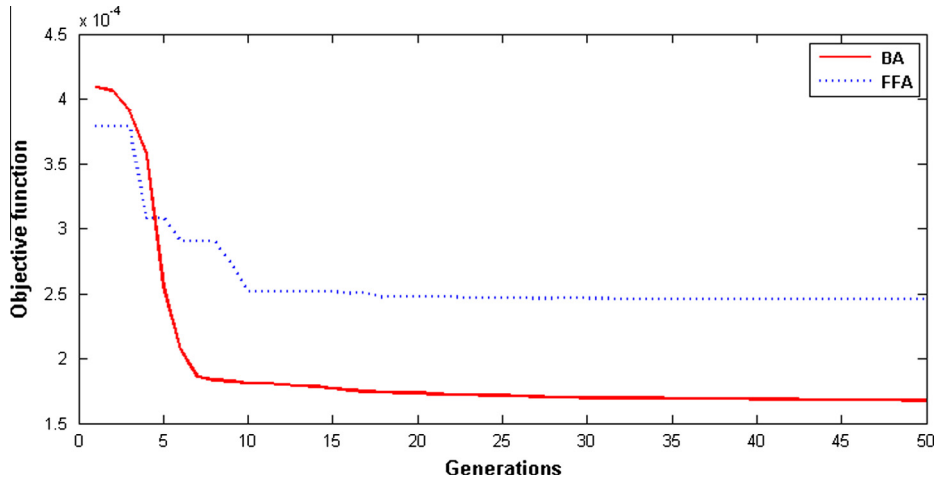

Figure 5 Evolution of objective function of FOPID-PSS with different algorithms for ITAE based tuning under case II.

Table 3 Optimal BA based proposed stabilizer parameters for case II.

Stabilizer type	(PI)	Stabilizer parameters									
		K	T_1	T_2	T_3	T_4	K_P	K_i	K_d	μ	λ
FOPID-PSS	IAE	4.9989	1.9983	1.9984	1.9981	0.0660	1.1976	1.1998	1.1977	0.1001	0.9994
PID-PSS	IAE	5.0000	1.9233	0.0100	0.1005	0.4098	1.2000	0.0113	1.1624	–	–
PSS	IAE	2.0377	1.8181	1.9978	0.2245	0.1595	–	–	–	–	–
FOPID-PSS	ISE	5.0000	1.9999	2.0000	0.0311	1.9148	1.1992	1.2000	1.2000	0.3399	0.1001
PID-PSS	ISE	5.0000	0.0100	2.0000	0.1122	0.1806	1.2000	0.0238	1.2000	–	–
PSS	ISE	4.9933	1.7666	0.8307	0.1518	0.0866	–	–	–	–	–
FOPID-PSS	ITAE	4.9884	1.9652	1.9660	1.9997	0.0679	1.1764	1.1946	1.1480	0.1000	0.5649
PID-PSS	ITAE	5.0000	2.0000	2.0000	1.0076	1.0086	1.2000	1.1555	1.1851	–	–
PSS	ITAE	5.0000	0.0100	2.0000	0.0245	0.0246	–	–	–	–	–
FOPID-PSS	ITSE	4.9987	1.9997	1.9985	0.9048	0.0125	1.1996	0.6380	1.1976	0.1003	1.0000
PID-PSS	ITSE	5.0000	2.0000	2.0000	0.6048	0.5845	1.2000	1.2000	1.2000	–	–
PSS	ITSE	4.9995	2.0000	2.0000	0.0610	0.3766	–	–	–	–	–

where β_0 at $r = 0$ is the initial attractiveness, r is the distance between two fireflies and γ is a fixed light absorption coefficient which controls the reduction of the light intensity.

The distance r_{ij} between any two fireflies at position x_i and x_j is defined as Cartesian distance:

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2}, \tag{22}$$

where $x_{i,k}$ is the kth element of the spatial coordinate position x_i of ith firefly while d denotes the number of dimensions.

In the movement of a firefly, each firefly i moves to another more attractive firefly j as follows:

$$x_i = x_i + \beta_0 * \exp(-\gamma r_{ij}^2) * (x_j - x_i) + b * \left(rand - \frac{1}{2}\right) \tag{23}$$

where b means a step size scaling factor. Eq. (23) has three terms. The first term represents the position of the ith firefly while the second term offers a social element of moving the firefly i toward the more attractive firefly j, and the last term is utilized for the random movement of the ith firefly within the search space.

6. Results and discussions

In this section, we have used BA as an effective algorithm, to tune the proposed FOPID-PSS parameters and improve the performance of the power system, by supplying the excellent damping under disturbances. A SMIB has been chosen in this work. To confirm the effectiveness of the proposed FOPID-

Table 4 Optimal FFA based FOPID-PSS parameters for case II.

Stabilizer	(PI)	Stabilizer parameters									
		K	T_1	T_2	T_3	T_4	K_P	K_i	K_d	μ	λ
FOPID-PSS	IAE	3.4971	1.6710	1.6153	0.0935	0.9538	1.1499	0.7232	0.7590	0.3285	0.3967
	ISE	4.9945	1.7068	1.2429	0.1151	0.4971	0.8346	0.5260	0.8809	0.4839	0.4608
	ITAE	3.7037	1.9563	1.8030	0.4602	0.7015	0.7865	0.2939	0.8634	0.7045	0.7629
	ITSE	4.9690	1.8401	1.7832	0.3957	0.2180	0.5018	0.7321	1.0859	0.3991	0.9869

Table 5 Optimal objective function values of various stabilizers using BA.

Stabilizer type	Performance indices (PI) values			
	IAE	ISE	ITAE	ITSE
Case I				
FOPID-PSS	$\mathbf{6.5613 \times 10^{-5}}$	$\mathbf{1.4671 \times 10^{-8}}$	$\mathbf{9.7740 \times 10^{-5}}$	$\mathbf{7.5030 \times 10^{-5}}$
PID-PSS	1.0972×10^{-4}	2.0528×10^{-8}	1.8174×10^{-4}	1.0221×10^{-4}
PSS	1.5035×10^{-4}	2.3072×10^{-8}	2.3366×10^{-4}	1.6511×10^{-4}
Case II				
FOPID-PSS	$\mathbf{1.3170 \times 10^{-4}}$	$\mathbf{5.8500 \times 10^{-8}}$	$\mathbf{1.6767 \times 10^{-4}}$	$\mathbf{2.4689 \times 10^{-4}}$
PID-PSS	1.6495×10^{-4}	8.6302×10^{-8}	2.6629×10^{-4}	3.1627×10^{-4}
PSS	2.0786×10^{-4}	1.0761×10^{-7}	4.6732×10^{-4}	3.8927×10^{-4}
Case III				
FOPID-PSS	$\mathbf{1.4422 \times 10^{-4}}$	$\mathbf{6.7548 \times 10^{-8}}$	$\mathbf{1.8910 \times 10^{-4}}$	$\mathbf{2.8766 \times 10^{-4}}$
PID-PSS	1.7307×10^{-4}	9.7079×10^{-8}	2.7745×10^{-4}	3.5770×10^{-4}
PSS	2.1545×10^{-4}	1.2019×10^{-7}	4.9212×10^{-4}	4.4175×10^{-4}

Table 6 Comparison of objective function values between BA and FFA based FOPID-PSS.

Stabilizer type	Performance indices (PI) values			
	IAE	ISE	ITAE	ITSE
Case I				
BA based FOPID-PSS	$\mathbf{6.5613 \times 10^{-5}}$	$\mathbf{1.4671 \times 10^{-8}}$	$\mathbf{9.7740 \times 10^{-5}}$	$\mathbf{7.5030 \times 10^{-5}}$
FFA based FOPID-PSS	8.5074e−005	1.7755e−008	1.0727e−004	1.0252e−004
Case II				
BA based FOPID-PSS	$\mathbf{1.3170 \times 10^{-4}}$	$\mathbf{5.8500 \times 10^{-8}}$	$\mathbf{1.6767 \times 10^{-4}}$	$\mathbf{2.4689 \times 10^{-4}}$
FFA based FOPID-PSS	1.5090×10^{-4}	6.9023×10^{-8}	2.4580×10^{-4}	3.0836×10^{-4}
Case III				
BA based FOPID-PSS	$\mathbf{1.4422 \times 10^{-4}}$	$\mathbf{6.7548 \times 10^{-8}}$	$\mathbf{1.8910 \times 10^{-4}}$	$\mathbf{2.8766 \times 10^{-4}}$
FFA based FOPID-PSS	1.5953e−004	7.8875e−008	2.5382e−004	3.5353e−004

PSS, a classical lead-lag structure PSS and PID-PSS are considered for comparison purposes.

We also performed same simulation by implementing BA and FFA algorithms. Before carrying out the optimization process, some parameters must be set in the BA and FFA, to acquire good performance. The specification of each algorithm is shown in Table 2.

In order to demonstrate the robustness performance of the proposed method, we used performance indices (PI) including IAE, ISE, ITAE and ITSE. The performance indices values are calculated with three cases, which are considered as follows:

- Case I: 5% step change in the reference mechanical torque.
- Case II: 10% step change in the reference mechanical torque.
- Case III: 10% step change in the reference mechanical torque, the active power of the generator is decreased by 15% and the reactive power is increased by 15%.

The evolution of the objective function ITAE with FOPID-PSS depending on the number of generations for case II is given in Fig. 5, and shows that the final value of the objective function is 1.6767×10^{-4} for BA and 2.4580×10^{-4} for FFA.

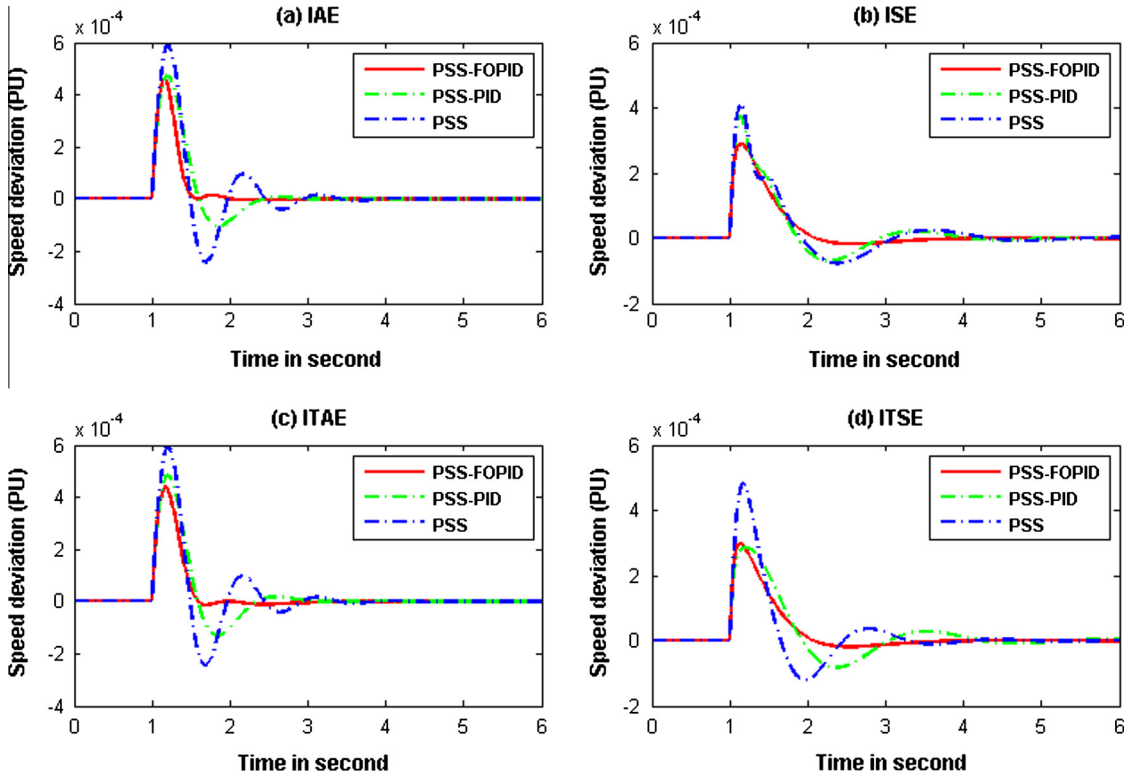

Figure 6 Speed deviation of BA based proposed stabilizers for case I with (a) IAE, (b) ISE, (c) ITAE and (d) ITSE based tuning.

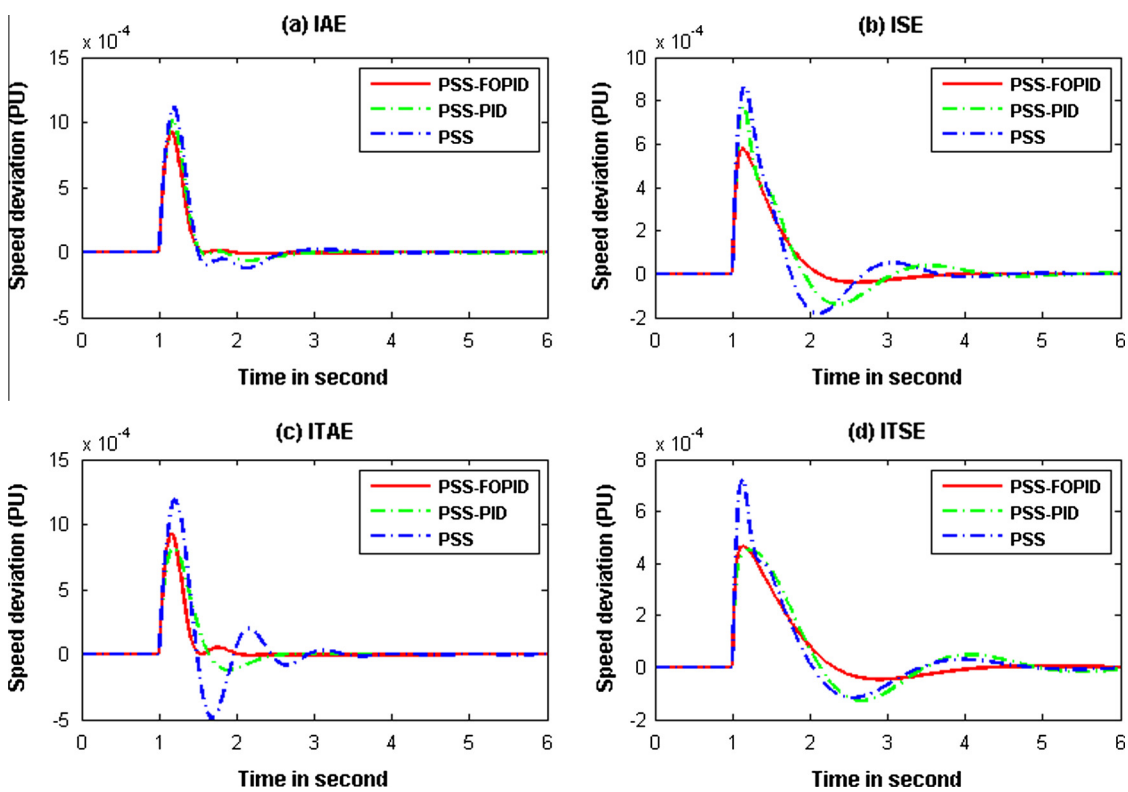

Figure 7 Speed deviation of BA based proposed stabilizers for case II with (a) IAE, (b) ISE, (c) ITAE and (d) ITSE based tuning.

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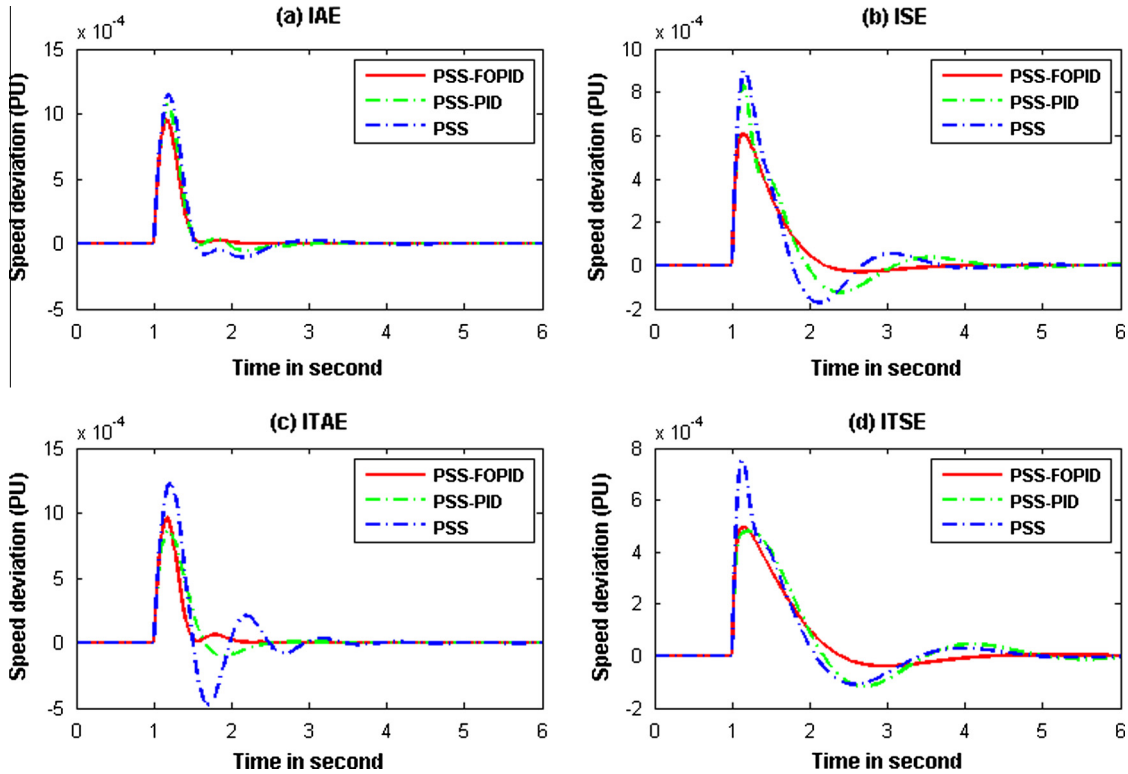

Figure 8 Speed deviation of BA based proposed stabilizers for case III with (a) IAE, (b) ISE, (c) ITAE and (d) ITSE based tuning.

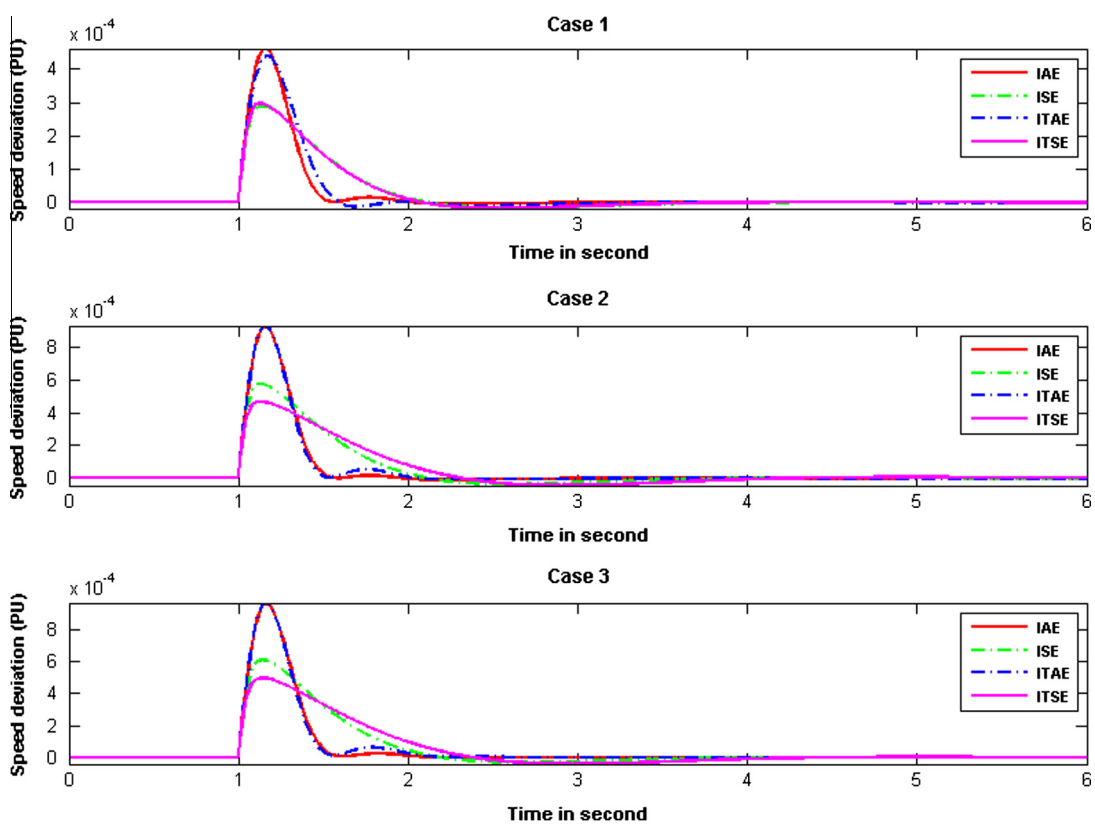

Figure 9 Speed deviation of BA based FOPID-PSS with different PI based tuning for case I, case II and case III.

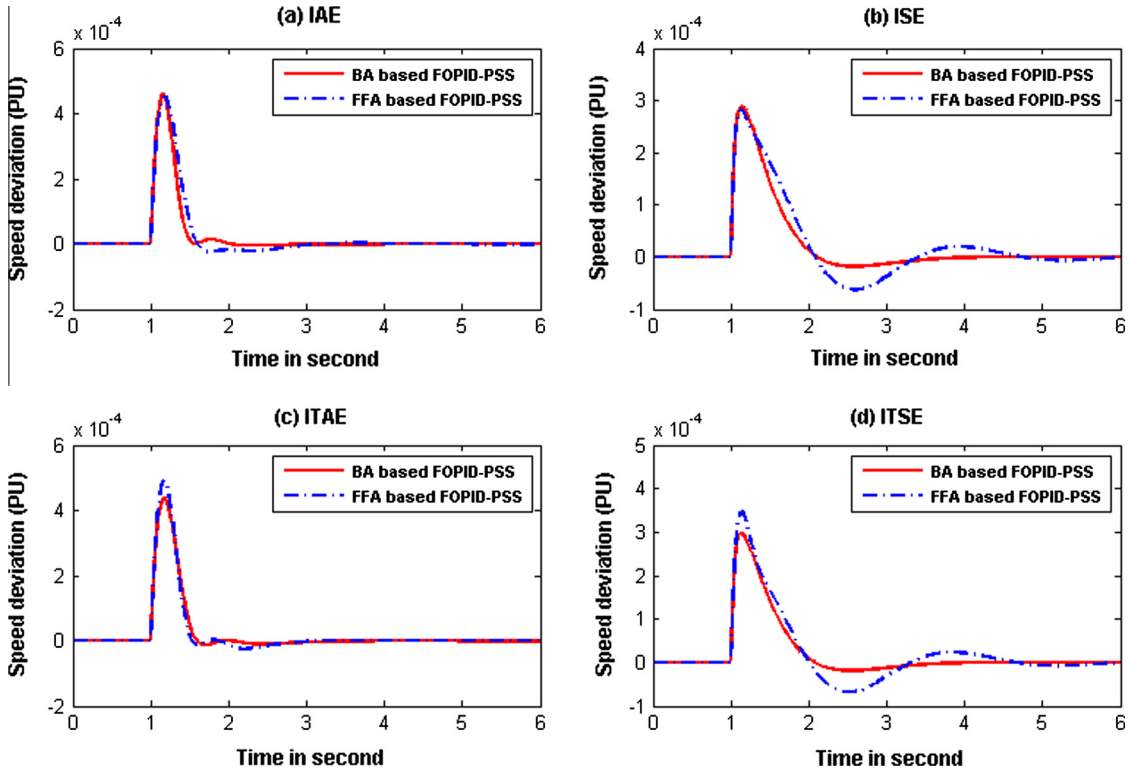

Figure 10 Speed deviation of BA and FFA based FOPID-PSS for case I with (a) IAE, (b) ISE, (c) ITAE and (d) ITSE based tuning.

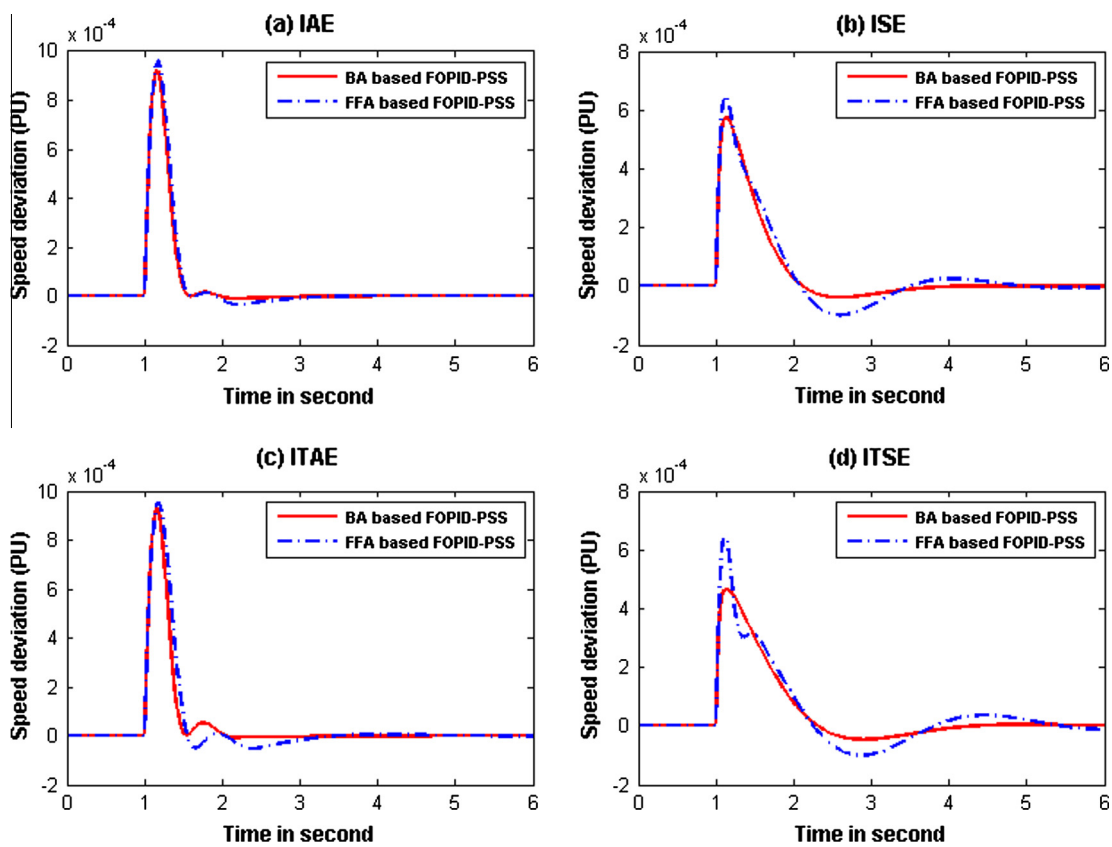

Figure 11 Speed deviation of BA and FFA based FOPID-PSS for case II with (a) IAE, (b) ISE, (c) ITAE and (d) ITSE based tuning.

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The convergence rate of BA is clearly the best, compared to the FFA.

Tables 3 and 4 show the ending values of the optimized parameters using BA for each stabilizer and FFA for FOPID-PSS respectively under case II. It should be noted that the proposed algorithms BA and FFA are run several times and the best parameters of different stabilizers are selected.

Optimal objective function values of BA based FOPID-PSS, PID-PSS and PSS stabilizers for all cases are shown in Table 5. It can be observed that the performance indices value obtained with the proposed BA based FOPID-PSS stabilizer is less than PID-PSS and PSS stabilizers for all operating conditions. In addition, the optimal set of values of fractional integral order (λ) and fractional derivative order (μ) for FOPID-PSS provides superior result for each objective function, which proves that FOPID-PSS is much better than two other stabilizers in minimizing error criteria with different operating conditions.

Table 6 presents a comparison of the objective function values between BA and FFA based FOPID-PSS for three cases. The simulation results obtained clearly indicate that the proposed BA based FOPID-PSS supplies much better values. Thus, all four objectives (IAE, ISE, ITAE and ITSE) have the minimum value with BA based FOPID-PSS due to the robustness of BA. Also, these results validate the performance of the proposed BA based FOPID-PSS comparatively with FFA based FOPID-PSS stabilizer, which confirm the optimal selection of the parameter settings of the proposed BA under all operating conditions.

The comparison of speed responses of BA based FOPID-PSS, PID-PSS and PSS stabilizers for each objective function with different cases is recorded in Figs. 6–8, and obviously demonstrates that the proposed BA based FOPID-PSS has a better response than the others. Moreover, all four figures above confidently confirm that BA gives the minimum values of all performance indices analyzed for proposed FOPID-PSS stabilizer. On the other hand, the proposed stabilizer shows that the stability of the system is improved; the system reaches to the steady state with FOPID-PSS stabilizer faster than others for each objective function and the oscillation is quickly damped. It is also observed that the BA based FOPID-PSS can successfully decrease the settling time and overshoot compared to the other stabilizers with different operating conditions, which demonstrate the superiority of the proposed FOPID-PSS using BA.

Fig. 9 shows a comparison of speed response for BA based FOPID-PSS with all objective functions under different disturbances. This figure greatly illustrates that the proposed FOPID-PSS with ITSE and ISE tuning has more oscillations, but it has smaller overshoot compared to that obtained with IAE and ITAE based tuning, whereas, the system overshoot with IAE and ITAE based tuning is bigger than the ITSE and ISE based tuning. However, settling time is improved in case of FOPID-PSS with ITSE and ISE tuning. Thus, these

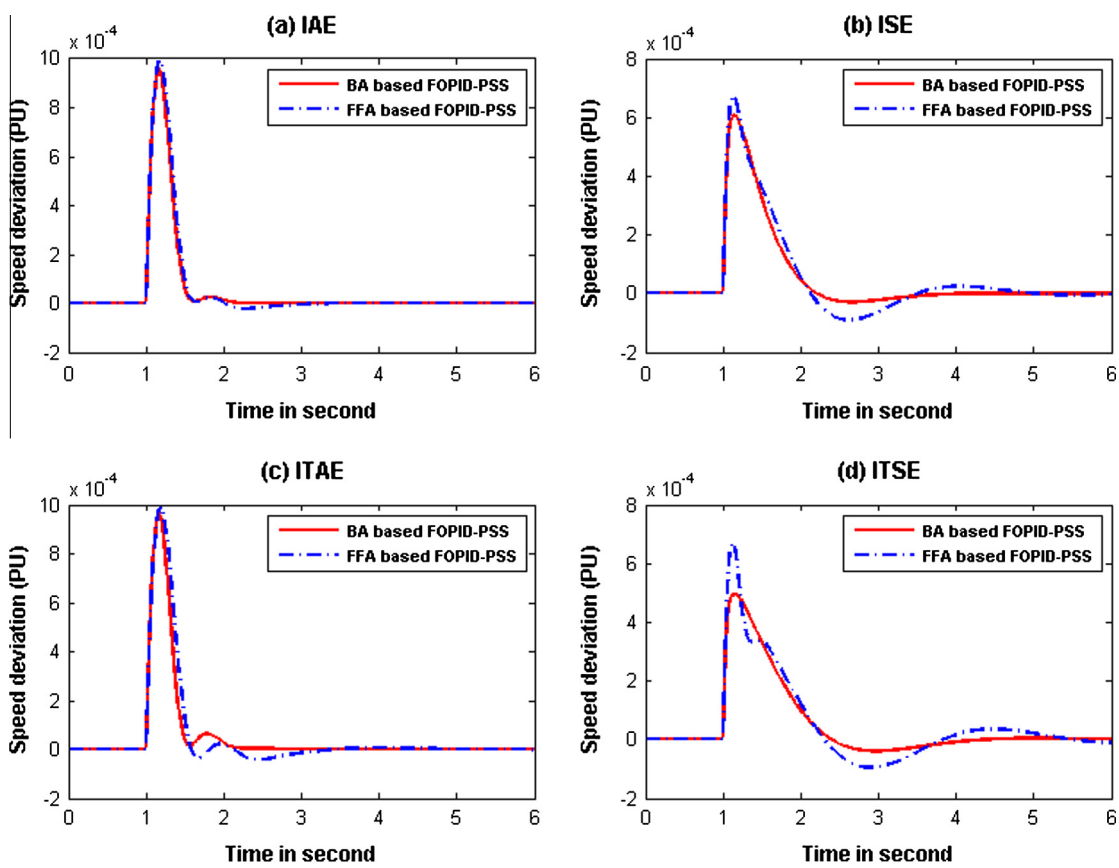

Figure 12 Speed deviation of BA and FFA based FOPID-PSS for case III with (a) IAE, (b) ISE, (c) ITAE and (d) ITSE based tuning.

Table 7 Settling time (T_S) for speed response with BA based proposed stabilizers and FFA based FOPID.

Stabilizer type	Settling time (T_S) for performance indices (PI)			
	IAE	ISE	ITAE	ITSE
Case I				
BA based PSS	3.2502	4.1091	3.2314	3.7068
BA based PID-PSS	2.3299	3.8569	2.8410	4.9980
BA based FOPID-PSS	**1.8875**	**3.4226**	**2.6298**	**3.3585**
FFA based FOPID-PSS	2.7546	5.4372	2.6343	5.3328
Case II				
BA based PSS	2.5173	3.4824	3.2298	4.4883
BA based PID-PSS	2.6693	4.0212	2.4240	5.9593
BA based FOPID-PSS	**1.5126**	**3.4453**	**1.9395**	**3.9485**
FFA based FOPID-PSS	2.6117	4.5602	2.9649	5.1603
Case III				
BA based PSS	3.1378	3.4974	3.3001	4.4880
BA based PID-PSS	2.5297	4.0261	2.3549	5.8907
BA based FOPID-PSS	**1.9413**	**3.3343**	**2.0410**	**3.9337**
FFA based FOPID-PSS	2.3673	4.5592	2.8708	5.1773

results indicate the advantage and disadvantage of each objective function in terms of settling time and overshoot of the power system.

The speed response of BA and FFA based FOPID-PSS with IAE, ISE, ITAE and ITSE based tuning for three cases is given in Figs. 10–12. From the results, the designed FOPID-PSS stabilizer using BA shows superior performance over stabilizers, in terms of settling time and the system overshoot. Hence we can conclude that the system with the proposed stabilizer achieves excellent robust performance of system stability and provides better damping in comparison with the other algorithms. Also, this result confirms the superiority of the proposed BA in tuning FOPID-PSS compared with FFA for all cases.

In order to show a better comparison and evaluate the performance of each proposed stabilizer design, the settling time (T_S) characteristic of the output of the system is used and shown in Table 7 for each stabilizer.

The simulation results in Table 7 show that the proposed FOPID-PSS stabilizer using the BA achieves minimum settling time for each objective function and with different cases, when compared to other stabilizers due to a higher penalty on both error and time in the minimization criterion, which proved the effectiveness of proposed stabilizer. Also, these results obviously confirm that BA outperforms FFA in stabilizing the power system under these severe disturbances.

7. Conclusion

In this article, we have applied a recent metaheuristic optimization BA, to determine a novel robust hybrid stabilizer FOPID-PSS parameters based on performance indices (PI) including IAE, ISE, ITAE and ITSE for the first time. The simulation result illustrates that the proposed FOPID-PSS design can provide better results as compared to PID-PSS and PSS, and it has better control performance. Also, we have shown that BA based FOPID-PSS is a suitable way for robust power system stabilizer to improve power system under disturbances compared to FFA-FOPID for three cases. The proposed Bat algorithm has been proved as an efficient method for the optimal design of a fractional order PID-PSS stabilizer and provided a fast time domain response and well damped oscillation, which demonstrated the advantage of the proposed BA to obtain the best parameters of PSS under different disturbances.

Hence, we review our work to propose a new PSS based on a novel Fractional Order Fuzzy Proportional Integral Derivative (FOFPID) controller, using Bat algorithm based on multi-objective function (MOBA), where, MOBA will be suggested to search the best novel PSS parameters.

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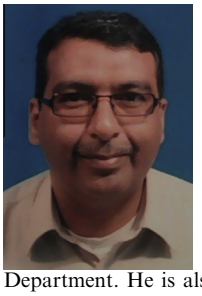

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