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INTELLIGENT TUNING OF PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER USING HYBRID BACTERIAL FORAGING PARTICLE SWARM OPTIMIZATION FOR AUTOMATIC VOLTAGE REGULATOR SYSTEM

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Key words: Automatic generation control, Automatic voltage regulator, Bacterial foraging particle swarm optimization algorithm, Proportional integral derivative (PID) tuning.

In this paper, an advanced optimization algorithm named hybrid bacterial foraging particle swarm optimization (BFPSO) algorithm is proposed, for optimal tuning of proportional integral derivative (PID) controller of an automatic voltage regulator (AVR) system. An objective function, designed with fundamental time domain specifications is also considered in this research work. The effectiveness of the proposed approach is examined by the transient performances, stability and robustness of the system and also by the convergence characteristics of the proposed algorithm. The reliability of the proposed approach is investigated in this paper, by including the physical constraints such as parameter changes and nonlinearity such as band limited noise to the AVR system model. In this paper, a comparative study is also made with the earlier documented results of modern heuristic approaches namely, bacterial foraging optimization algorithm (BFOA), artificial bee colony (ABC) algorithm, and also with the conventional Ziegler Nichols (ZN) method to validate the superiority of the proposed approach. All the simulation results clearly prove that the proposed BFPSO tuned PID controller has better control performances compared to other optimization approaches.

1. INTRODUCTION

Generally, the excitation system of generator manipulates the voltage and controls the reactive power flow. The reactive power is sensitive to the voltage variations and it is regulated with automatic voltage regulator (AVR) loop. However, AVR is an essential control loop, which can control both voltage and reactive power and thereby, it can also regulate the real power of the system [1]. Recently, lots of research works proves the contribution of AVR to govern both real and reactive power in power system [2–4]. Hence, this research article is mainly intended to enhance the performance of AVR with an optimal control mechanism.

Generally, the reactive power deviations affect the terminal voltage of the system. The role of AVR is to hold the voltage magnitude of synchronous generator at a specified level and also to enhance the system stability. In an AVR loop the primary means control is done with the excitation control, and the supplementary control is provided with the conventional controllers like proportional (P), integral (I), proportional integral (PI) and PID controller. Among these controllers, the PID controller is mostly preferred because of its proper control performances, fast response and its robustness towards the non linearity, time varying dynamics, disturbances and other factors. Further, the derivative part of this controller adds a finite zero to the transfer function of the system and thereby improving the transient performances and stability of the systems.

However, tuning the gain parameters of the PID controllers is always a challenging task. These gain parameters are generally computed through trial and error or conventional ZN methods [5]. The trial and error is time consuming and it provides suboptimal results in most of the cases. The gain parameters calculated by ZN method is not pliable for the nonlinearities and disturbances introduced in the system, which may obligate the system towards instability. To overcome these draw backs, abundant swarm intelligent (SI) optimization techniques such as bee algorithm (BA) [6], particle swarm optimization (PSO) [7], chaotic ant swarm (CAS) [8–10], artificial bee colony (ABC) algorithm [11], differential evolution (DE) [11] are now being developed for the optimal tuning of PID parameters in AVR system.

In our previous research paper, one of such prominent optimization approach named BFOA was proposed for optimal tuning of PID controller in AVR system [12]. However, the earlier researches clearly reveal that the BFOA approach has certain drawbacks. In BFOA, if the particles find out an optimal fitness value in the search space, the swim length is adapted to be a smaller one. Otherwise larger swim length will be adapted and makes the particles to enter in to an exploration state. This inconsistency may also affect the convergence characteristics of BFOA. Also the conventional BFOA depends on random search directions which may lead to delay in reaching global solution [13].

To overcome these difficulties, the BFOA is commonly combined with PSO or genetic algorithm. The superiority of these hybrid algorithms compared to individual optimization algorithms are confirmed in various fields of research [14–17]. In view of the above, an attempt also has been made in this paper for optimal design of BFPSO based PID controller for AVR loop in power system.

In AVR system, the modified multi-objective function that has proven its superiority over conventional single-objective functions in earlier documented research articles [6, 12] , are precisely chosen in this research article for optimal tuning of PID controller with BFPSO approach.

A detailed analysis is made in this research article by examining the transient performances and robustness of the AVR system with BFPSO approach. The convergence characteristics of the proposed BFPSO algorithm is also analysed with the output steady state error over consecutive iterations. All these analyses, under both linear and

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nonlinear conditions of the power system undoubtedly reveal that, the proposed BFPSO tuned PID controller in AVR system proves its dominance over some other established approaches such as ABC and BFOA in the references [11, 12].

2. DESCRIPTION OF AVR MODEL

AVR is one of the important areas of power system operation and control. It determines the stability and quality of power supply. The main function of AVR is to control the terminal voltage and reactive power of an alternator, and also to share the reactive power to all the generators connected in parallel. Figure 1 shows the linearised model of simple AVR system with BFPSO tuned PID controller. For effective comparison of system performances, the identical system configurations as stated in references [11, 12] are used in this article.

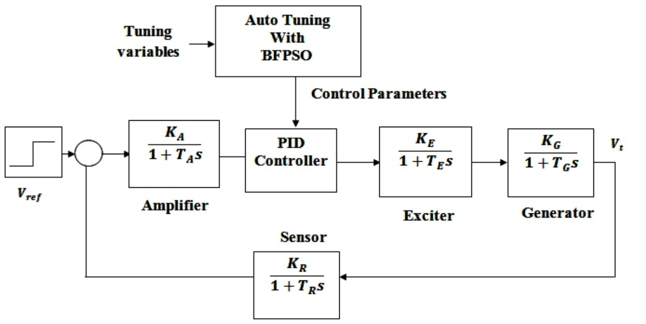

Fig. 1 – Linearised model of BFPSO tuned PID controller for AVR.

In AVR, the voltage control is performed with four main components, namely sensor, amplifier, exciter and generator. The potential transformer, commonly known as voltage sensor is used to measure the variation in terminal voltage of synchronous generator. This measured voltage is rectified, smoothed and compared with a reference signal in a comparator. The error output voltage from the comparator is then amplified with an amplifier, for increasing the sensitivity of the system and is used to control the field windings of the generator by means of an exciter.

The output response of the AVR system without any controller was demonstrated in detail in the earlier literature [12]. To enhance the output performance of a non controller AVR system, one of the promising conventional tuning methodologies named Ziegler-Nichols continuous cycling approach is initially used in this research paper to evaluate the control parameters of PID controller in AVR system [18]. In addition, a combined optimization algorithm named hybrid BFPSO algorithm which was not prominently used for AVR system in earlier researches is also proposed in this manuscript, for effective tuning the controller.

The main objective of AVR is to minimize the voltage deviation in output response for the step change in reference voltage. Hence, an objective function/ fitness function is formulated [6] as minimization of output voltage deviation, including essential time domain specifications such as maximum peak, rise time, settling time, and steady-state error (1, 2) to improve the system response

$$\text{Objective function} = \text{Min}\,(\text{J}) \tag{1}$$

$$J = \left(1 - \Delta\nu^{-\beta}\right)\left(P_m + E_{ss}\right) + \Delta\nu^{-\beta}\left(T_s + T_r\right) \tag{2}$$

where J is the fitness value of each particle, $\Delta\nu$ is the deviation in voltage, P_m is the maximum peak of the output wave form, E_{ss} is the steady state error and T_s , T_r are the settling time and rise time respectively. Normally, the value of weighting factor β is chosen in the range of (0.5÷1.5) depends on the designer requirements. The value of β is chosen above 0.7 to reduce overshoot, and its value is chosen below 0.7 to reduce the rise time and settling time [6]. Using trial and error approach different values of β between the desirable ranges were tried and its value is finally chosen as 0.5 in this research work.

3. BACTERIAL FORAGING PARTICLE SWARM OPTIMIZATION (BFPSO)

The two main steps named reproduction and elimination -dispersal in BFOA approach prevents the solution being trapped into local optima and makes BFOA to produce global optimal solutions along with reliable system performances. However, the unit length movement of tumbling process in BFOA is randomly generated. This may delay the process of convergence. The ability of exchanging social information with personal best and global best solutions in PSO algorithm seems to be better comparing to BFOA.

The BFPSO combines the advantages of both BFOA and PSO techniques, which makes use of the global search mechanism of PSO to BFOA. Accordingly, in BFPSO during the tumbling action the search direction of each swarm is oriented by its individual best and global best positions [15].

The procedural steps of BFPSO algorithm is as follows:

Step 1: The essential parameters of both BFOA and PSO algorithms algorithm are initialized at first [19, 20].

Step 2: The initial chemotactic movement of particles can be computed using BFOA approach as follows [12]:

Let, the index of S is represented as i , N_c denoted as j , N_{re} indicated by k and N_{ed} represented as l and the iterations are framed with these indexes. Initially, S number of random solutions K_p, K_i, K_d as a set of positional values P within a specified range (3) and are generated in a search space. For each iterations, the fitness value J of every particle is computed with their positional values P using the objective function (2). Hence, here in (4) & (8) "Function" mean the objective function provided in (2).

$$0 \le K_p, K_i, K_d \le 2 \tag{3}$$

$$J\left(i, j, k, l\right) = \text{function}\ \left(P\left(i, j, k, l\right)\right). \tag{4}$$

The excellent solution is then located with the minimum fitness value (2). In computational programming it is just done by sorting all the fitness values in descending order and selecting the last one (5). Then, each particle makes a chemotactic movement (6) in random direction

$$J_{last} = J\left(i, j, k, l\right) \tag{5}$$

$$P(i, j+1, k, l) = P(i, j, k, l) + C(i)\,\varphi(j) \tag{6}$$

where $C(i)$ $(for\ i = 1, 2, \ldots. S)$ is the size of step taken in random direction $\varphi(j)$. The value of $\varphi(j)$ can be calculated with a random vector (7).

$$\varphi(j) = \frac{\Delta(i)}{\sqrt{\Delta^{T}(i).\Delta(i)}} \tag{7}$$

where Δ indicates a vector in random direction whose elements are in the range of [–1, 1]. After the chemotactic movement the particles reach a new position $P(i, j+1, k, l)$ in search space. The fitness value (J) for this new position can be evaluated (8) using the objective function (2) and the best fitness value is again computed and stored as J_{last} (5).

$$J(i, j+1, k, l) = \text{function}\left(P(i, j+1, k, l)\right) \tag{8}$$

when the fitness value J evaluated for the current chemotactic step $J(i, j+1, k, l)$ is less than the previous one $J(i, j, k, l)$, another step will be taken by every particle in the same direction. Otherwise, the bacterium will tumble in random direction. This consecutive movement lead the particles to move towards the direction of decreasing the fitness function and finally to reach the best fitness value.

Step 3: For each particle i, at each chemotactic movement j, compute the best fitness value as local best with the index of J_{local} (9) and the corresponding positions with a set of control parameters K_p, K_i, K_d are predicted as local best positions P_{local} (10).

$$J_{local}(j) = J(i, j+1, k, l) \tag{9}$$

$$P_{local}(j) = P(i, j+1, k, l). \tag{10}$$

Step 4: At the end of each chemotactic movement, best fitness among J_{local} is evaluated and stored as J_{global} and the corresponding position of the particle is stored as P_{global}.

Step 5: During the next iteration, the position of each particle will be changed with the velocity equations (11, 12) designed using PSO algorithm [21].

$$\begin{aligned} \mathrm{v}(\mathrm{j}+1) = \mathrm{w} * \mathrm{v}(\mathrm{j}+1) + \mathrm{c}_1 * \mathrm{r}_1 \left(\mathrm{P}_{\mathrm{local}}(\mathrm{j}) - \mathrm{P}(\mathrm{j}+1)\right) \\ + \mathrm{c}_2 * \mathrm{r}_2 \left(\mathrm{P}_{\mathrm{global}}(\mathrm{j}) - \mathrm{P}(\mathrm{j}+1)\right) \end{aligned} \tag{11}$$

$$\varphi(j+1) = v(j+1). \tag{12}$$

Step 6: substitute this new velocity (12) in (6) and repeat the algorithmic steps 2 – 6 over the specified number of chemotactic movements.

Step 7: Continue the algorithm with the significant reproduction operation and elimination-dispersal event as of BFOA approach [12, 22]. The flowchart representation of BFPSO algorithm is also depicted in Fig. 2.

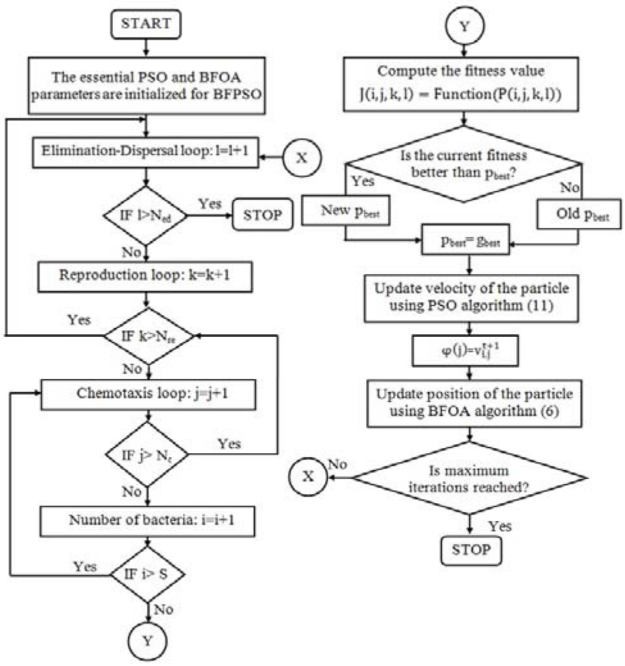

Fig. 2 – Flowchart representation of BFPSO algorithm.

4. RESULTS AND DISCUSSIONS

4.1. TRANSIENT PERFORMANCE ANALYSIS

The optimal gain parameters of PID controller evaluated through proposed BFPSO algorithm, conventional ZN method, BFOA and ABC algorithms [11, 12] are listed in Table 1. The comparative output responses of the AVR system with the tuned PID control parameters of all the approaches are shown in Fig. 3. To analyze the transient performances of the system, the essential transient measuring parameters such as maximum peak, settling time, rise time and peak time of the proposed approaches are measured from Fig. 3 and compared with the conventional ZN and other documented results [11, 12] as illustrated in Table 2.

Table 1

Optimal gain parameters of PID controller

Gain	Proposed BFPSO	ZN method	BFOA [12]	ABC [11]
K_p	1.0247	1.02101	1.087	1.6524
K_i	0.77658	1.87429	0.83064	0.4083
K_d	0.39618	0.13904	0.4077	0.3654

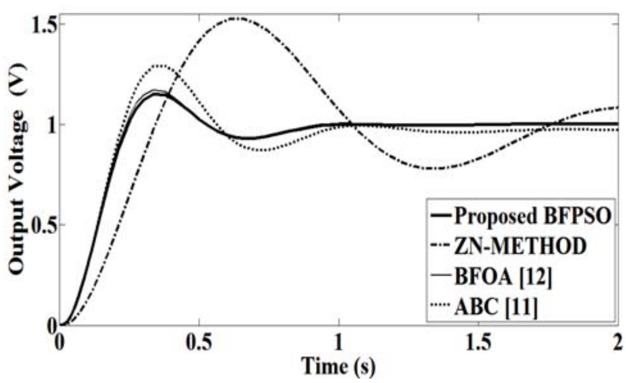

Fig. 3 – Comparison of output transient responses.

It can be seen from Fig. 3 and Table 2 that compared to ZN tuned controller, all the transient measuring parameters like maximum peak, settling time, rise time and peak time in step response of AVR is extremely reduced in proposed BFPSO tuned PID controller. When compared to ABC tuned PID controller, in BFPSO the most important parameters such as maximum peak is reduced by 7.84 %, the settling time is reduced by 16.09 % and the peak time is reduced by 7.5 %. Likewise, compared to BFOA, the maximum peak is reduced by 1.87 % and the peak time is reduced by 0.6 % in BFPSO approach. However, in this transient analysis the settling time and the rise time seems to be better in BFOA approach the superiority of the proposed BFPSO algorithm is evidently proved in subsequent analysis carried out in this paper. Hence, it is confirmed that transient performances of AVR can be significantly improved with BFPSO tuned PID controller compared to other optimization methodologies.

Table 2

Results of transient response analysis of AVR system

Transient parameters	Proposed BFPSO	ZN-method	BFOA [12]	ABC [11]
Maximum peak (V)	1.152	1.530	1.174	1.250
Settling time (s)	0.772	2.278	0.759	0.920
Rise time (s)	0.160	0.228	0.154	0.156
Peak time (s)	0.333	0.626	0.335	0.360

4.2. STABILITY ANALYSIS WITH BODE PLOT AND ROOT LOCUS

The stability of the system is examined with two of the familiar approaches namely, bode plot and root locus [11, 12] as illustrated in Figs. 4 and 5. In this paper, the significant stability measures such as peak gain, phase margin, delay margin and bandwidth measured from bode plot of the system are considered for scrutinizing the stability of the system. These stability measures are computed from the transfer function of the AVR system, with optimally tuned PID controllers and listed in Table 3.

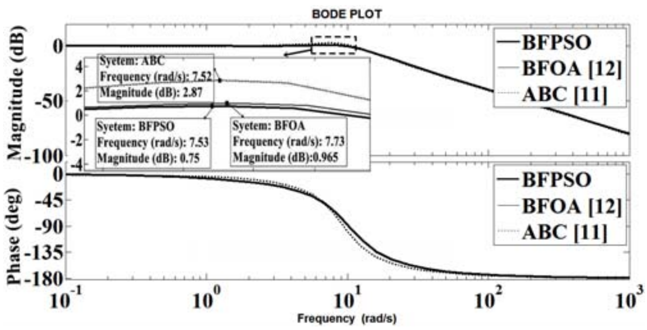

Fig. 4 – Comparison of bode plot for AVR system.

Table 3

Bode analysis of AVR system with stability measuring parameters

Stability measurements	Proposed BFPSO	BFOA [12]	ABC [11]
Peak gains (dB)	0.75	0.965	2.87
Phase margin (deg.)	95.653	91.45	69.4
Delay margin (s)	0.171	0.156	0.111
Bandwidth (Hz)	13	13	13

Large value of peak gain corresponds to a small amount of damping in the system that causes large overshoot and oscillations in the step response of the system. For clear visibility, the peak gain of bode plot is enlarged further as shown in Fig. 4. The figure shows that the peak gain is considerably reduced with the BFPSO compared to BFOA and ABC algorithms. Hence, it is confirmed that the transient stability of the system is much improved with the proposed BFPSO approach.

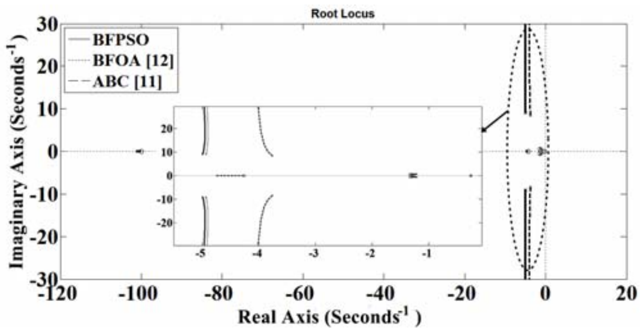

Fig. 5 – Comparison of root locus for AVR system.

The significant stability measuring parameters namely, phase margin and gain margin are higher in proposed BFPSO approach. Another good measure of stability is the delay margin, which is the smallest time delay required to make the system unstable, is also considerably increased with the proposed BFPSO approach. Thus, the increased gain margin, phase margin and delay margin again ensures the improvement in system stability with the proposed BFPSO approach. All these discussions illustrate that, the stability of the AVR system is much improved with the proposed BFPSO tuned PID controller compared to other optimization algorithms.

Further, the investigation of time domain and stabilization behaviors of the system is done with root locus analysis. The eigen values and the damping ratios of the system computed from root locus analysis for different control methodologies are described in Table 4.

Table 4

Eigen values and damping ratios evaluated from root locus analysis

Proposed BFPSO		BFOA [12]		ABC [11]	
Eigen values	*Damping ratio*	*Eigen values*	*Damping ratio*	*Eigen values*	*Damping ratio*
–1.21+0.578i	0.9	–1.26+0.56i	0.9	–100.98	1.0
–1.21–0.578i	0.9	–1.26–0.56i	0.9	–3.75+8.40i	0.4
–5.00+9.03i	0.5	–4.94+9.18i	0.5	–3.75–8.40i	0.4
–5.00–9.03i	0.5	–4.94–9.18i	0.5	–4.74	1.0
–101.09	1.0	–101.12	1	–0.25	1.0

It is observed from Table 4 and Fig. 5 that all the poles are located in left half of the S plane in the proposed BFPSO, which ensures the stability of the system. More damping has the effect of less percent overshoot and also produces transient responses with lesser oscillatory nature. It is also clear from Table 4 that, both BFOA and BFPSO, the damping ratios of dominant complex poles are higher and 125 % more than ABC algorithm. This can reduce the oscillations and overshoot of the system.

4.3. ROBUSTNESS ANALYSIS OF AVR SYSTEM

4.3.1. Robustness analysis under parameter variations

One of the right ways to analyze the robustness of the system is, to vary the linear time-varying parameters of the system with respect to nonlinearities and/ or uncertainties.

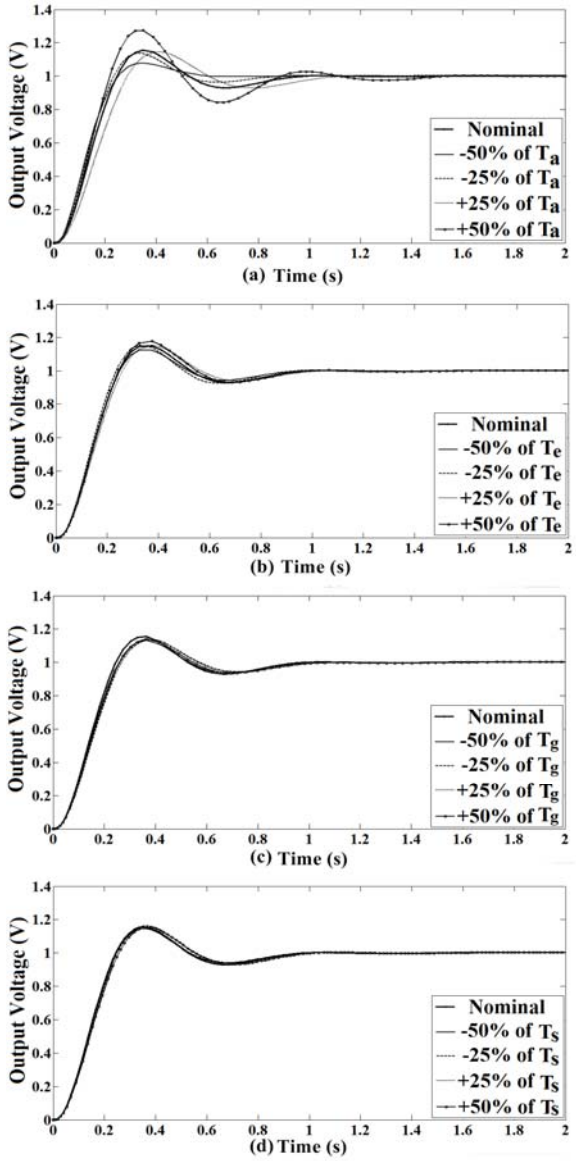

Fig. 6 – Output response of AVR under parameter (T_a, T_e, T_g, T_s) variations.

Table 5

Output measurements of AVR under parameter variations

Parameter variations	Maximum peak (V)	Settling time (s)	Rise time (s)	Peak time (s)
Variation of T_a between (–50% to +50%)				
–50%	1.0776	0.4425	0.1612	0.3285
–25%	1.1392	0.4591	0.1518	0.3370
+25%	1.1469	0.8971	0.1878	0.4117
+50%	1.2733	0.8176	0.1415	0.3528
Variation of T_e between (–50% to +50%)				
–50%	1.1306	0.7084	0.1618	0.3528
–25%	1.1575	0.7423	0.1524	0.3458
+25%	1.1548	0.7834	0.1695	0.3797
+50%	1.1765	0.7876	0.1593	0.3803
Variation of T_g between (–50% to +50%)				
–50%	1.1310	0.7667	0.1674	0.3505
–25%	1.1379	0.7839	0.1761	0.3812
+25%	1.1443	0.7763	0.1719	0.3755
+50%	1.1381	0.7944	0.1704	0.3689
Variation of T_s between (–50% to +50%)				
–50%	1.1310	0.7667	0.1674	0.3505
–25%	1.1379	0.7839	0.1761	0.3812
+25%	1.1443	0.7763	0.1719	0.3755
+50%	1.1381	0.7944	0.1704	0.3689

Accordingly, the time constants of the amplifier T_a, exciter T_e, generator T_g and the sensor T_s of the AVR system are varied in the adequate range of –50 % to +50 % in steps of 25 % to examine the robustness. Figures 6 a–d exhibits the output voltage responses of the AVR system under parameter variations in specified ranges. It is well understood from Fig. 6 that, in the proposed BFPSO approach all the deviations in output response under the parameter variations are in small ranges, referred to the nominal system response.

4.3.2. Robustness analysis with band limited noise

In this article, the robustness of the system is also examined by applying band limited white noise to the input reference voltage of the system. In this phenomenon, the tuning is performed in presence of noise signal with different magnitudes [23]. The magnitude of noise signal is attuned by changing the signal-to-noise ratio (SNR) to specified values (13) such as, SNR = 40 dB, SNR = 30 dB and SNR = 20 dB respectively.

$$\mathrm{SNR}(\mathrm{db}) = 10\log_{10}\left(\frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}}\right). \tag{13}$$

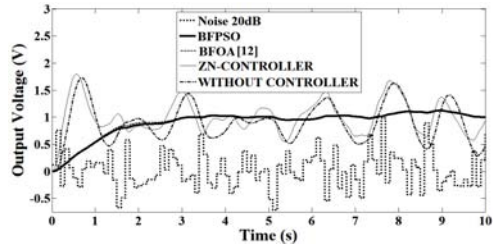

Fig. 7 – Output response of AVR system at SNR = 20 dB.

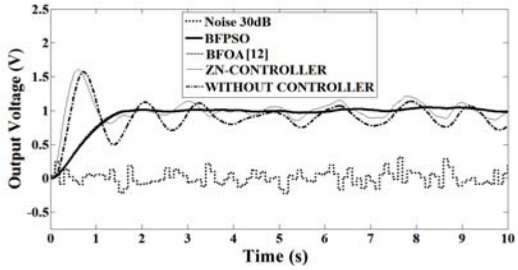

Fig. 8 – Output response of AVR system at SNR = 30 dB.

Figures 7, 8 and 9 show the comparative output response analysis of the AVR system in presence of noise with different magnitudes. These figures evidently proves that, the proposed BFPSO tuned controller is robust and also can perform adequately under the noise constraint compared to BFOA, conventional ZN tuned PID controller and also to a non-controller system.

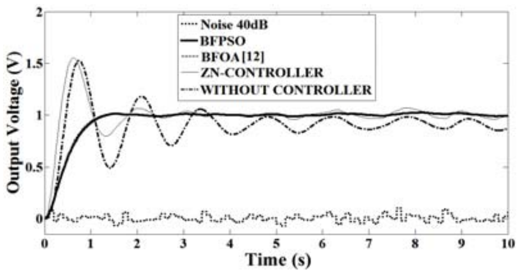

Fig. 9 – Output response of AVR system at SNR = 40 dB.

4.4. CONVERGENCE ANALYSIS

All the optimization problems are targeted to have a minimum convergence time. The evolutionary tendency of these algorithms is investigated with the convergence of output, and is measured through the final steady state error of system response over consecutive iterations. Figures 10a and 10b show the final steady state error value of AVR evaluated with BFPSO and BFOA respectively over consecutive iterations. For clear visibility and ease of comparison, the y axis of Fig. 10a is enlarged to the same range of Fig. 10b. These figures confirm that the BFPSO algorithm has prominent convergence characteristics. It is also proved from these figures that the global optimal solution can be obtained earlier with BFPSO algorithm compared to BFOA approach, because the latter has more fluctuations in convergence characteristics and has more instability in their positional values over successive iterations.

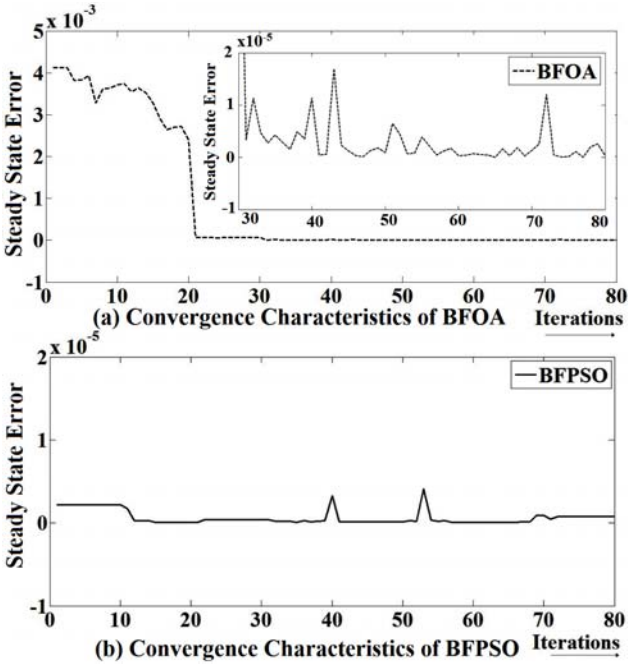

Fig. 10 – Convergence characteristics of BFOA and BF-PSO.

5. CONCLUSION

In this research paper, tuning of PID controller in an AVR system is formulated as an optimization problem and investigating a suitable algorithm to search for optimal control parameters are discussed. One of the recent, successive hybrid optimization algorithms named BFPSO is proposed in this research work and the potential benefits of this algorithm are compared to the earlier documented results of BFOA, ABC and also to the conventional ZN method of tuning. Minimization of error in output response of AVR system is considered as a main objective of the problem. An objective function that includes the essential time domain specifications is considered in this paper. The results obtained from the transient response analysis reveal that, the step response of AVR with BFPSO tuned PID controller has minimum peak, settling time, rise time and peak time compared to other approaches. However, it is well observed from stability analysis that the AVR system with BFPSO tuned PID controller is more stable over BFOA and other optimization algorithms. Additionally, the robustness analyses carried out in this paper assures that, the proposed BFPSO tuned PID controller is affected very less for the changes in system parameters, variations and also for a noise phenomenon. Finally, the convergence analysis over BFOA and BFPSO algorithm confirms that the BFPSO algorithm takes minimum convergence time and the convergence characteristics have fewer fluctuations compared to BFOA. It is confirmed from all the analysis that, the BFPSO algorithm is designated as a suitable one for effective tuning of PID controller in AVR system and it can control the system optimally and robustly.

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