Enhancing the Transient Performances and Stability of AVR System with BFOA Tuned PID Controller

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Abstract: This paper proposes an optimal tuning of Proportional Integral Derivative (PID) controller using Bacterial Foraging Optimization Algorithm (BFOA), to enhance the control performances and stability of Automatic Voltage Regulator (AVR) system. A new objective function designed with necessary time domain specifications is considered in this research work for tuning the gain parameters of PID controller. The effectiveness of the proposed BFOA tuned PID controller is extensively absorbed by analyzing the output performance, stability and robustness of the system. The superiority of the proposed approach is distinctly demonstrated by comparing their results with recently documented results of Swarm Intelligence (SI) techniques such as Differential Evolution (DE), Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC) algorithms and Many Optimizing Liaisons (MOL) algorithm.

Keywords: Automatic Voltage Regulator, Bacterial Foraging Optimization Algorithm, PID Controller.

1. INTRODUCTION

Nowadays, voltage and frequency control has gained more importance with the growth of interconnected power systems. In power systems the real power is sensitive to frequency variations and it is regulated with LFC loop and the reactive power is sensitive to the voltage variations and it is regulated with AVR loop (Hadi Saadat, 1999). During the last decades the researchers have more attention to LFC over AVR although the main objective of the control strategy in an interconnected power system is to generate both voltage and frequency within the permissible limits. Recently, lots of research works are focused on investigating the coupling effects between LFC and AVR (Ahamad et al., 2013; Abediniya et al., 2011; Elyas Rakshani et al., 2009) which are undoubtedly prove the necessity of voltage control on minimizing the real power losses.

In general, the reactive power deviations affect the terminal voltage of the system and the role of AVR is to hold the voltage magnitude of synchronous generator at a specified level and also to enhance the system stability. The primary means of generator reactive power control in AVR loop is done with the excitation control and the supplementary control action is provided with conventional controllers like Proportional (P), Integral (I), Proportional Integral (PI) and PID controller or with an intelligent controllers. The essential selection criteria of these controllers are evaluated by its proper control performances, fast response and its robustness towards the non linearity, time varying dynamics, disturbances and other factors. The PID controller has been recommended as a reputed controller in this accord and can be used as a supplementary controller for AVR system. Normally, the gain parameters PID controllers are computed through trial and error or conventional Ziegler–Nichols methods (Katsuhiko Ogata, 2008).

So many optimization techniques are developed nowadays for optimal tuning of these gain parameters (Indranil Pan and Saptarshi Das, 2013; Seyed Abbas Taher, 2014). Among them the Swarm Intelligent (SI) techniques are very popular only because of, providing good quality of solutions within a short duration of time for mixed integer nonlinear optimization problems (Anil Kumar and Rajeev Gupta, 2013). Although, these techniques have been used in almost all fields of engineering (Noureddine Bouarroudj et al., 2015), the effectiveness is dreadfully confirmed in control and stability domain. The SI techniques generally consist of a population of natural or artificial swarms, interacting locally with one another and also with their environment. This phenomenon aids to find an optimal solution in any field of optimization problems.

The earlier research work proves that both the transient performances and the stability of an AVR system can be improved with ABC tuned PID controller compared to Differential Evolution (DE) and Particle Swarm Optimization (PSO) algorithm (Haluk and Cengiz, 2011). For the same system configurations, an alternate optimization algorithm named MOL was proposed (Panda et al., 2012) and compared with the results of ABC algorithm (Haluk and Cengiz, 2011). The MOL algorithm proves its effectiveness over ABC by focusing only two of the transient measuring parameters called maximum peak and settling time. However, the rise time of the system, which is one of the main transient measures to be considered for analyzing the transient performances, is higher in MOL based tuning. When, the system is having high rise time characteristics, the settling time of the system also increased drastically in most of the cases. This can be clearly demonstrated when the system is subjected to any kind of uncertainties/ disturbances. Correspondingly, in MOL based tuning (Panda et al., 2012), the system exhibits rapid variations in settling time and peak time during the robustness performance analysis with parameter variations. In MOL based tuning, the phase margin of the system is negative and also the bandwidth of the system is very poor comparing to other optimization methods which may surely affects the stability of the system. The above analyses clearly reveal that the stability and robustness of the AVR cannot be fully improved with the MOL tuned PID controller.

To overcome the difficulties discussed above, the BFOA, an interesting SI algorithm that has been widely accepted as a global optimization algorithm of current interest is used in this research work for tuning the optimal gain parameter of supplementary PID controller in AVR system related to the dynamics in input. BFOA mimics the group foraging strategy of Escherichia Coli (E.Coli) bacteria in multi- optimal function optimization and is proposed by K. M. Passino (Passino, 2010). The BFOA has already been applied to many of the electrical power system studies like optimal power flow, distributed generation, and Load Frequency Control (LFC) (Belwin et al., 2013; Devi and Geethanjali, 2014; Ali and Abd-Elazim, 2011) in addition to the real world problems (Bharat and Madhusudan, 2011; Qin and Jianmin, 2012) and proved its effectiveness over ultimate algorithms like Genetic Algorithm (GA) and PSO.

The objective function plays a major role in optimization problems. Normally, minimization of integrated absolute error (IAE), or integrated time absolute error (ITAE), or the integral of squared-error (ISE), or the integrated of time-weighted-squared-error (ITSE) are used as an objective function for optimal tuning of PID controller. In contrast to others a new objective function with fundamental time domain specifications such as maximum peak, rise time, settling time, and steady-state error is used in this paper to enhance the transient performances of the AVR system.

The results of the proposed approach are analyzed in three different ways such as transient analysis, stability analysis and robustness analysis to prove its superiority over other algorithms. At first, the output response of the system with proposed approach is analyzed with the essential transient measuring parameters like Maximum Peak, Settling time, Rise Time and Peak Time. Further, the stability of the system is demonstrated with necessary stability margins such as peak gain, phase margin, gain margin and delay margin.

When an engineer designs a control system, the design is usually based on some mathematical model for the system to be controlled. However, the system model is only an approximation. In reality the system may behave differently than the model indicates, or the system parameters may vary with time. In order to obtain satisfactory control design, it is mandatory that the control system performs well, not only on the adopted nominal model, but also on the actual physical process. This leads directly to the requirement of control design robustness, which demands that satisfactory performance is achieved for the uncertain model and the class of possible perturbations. In this way this manuscript did the various types of robustness analysis to ensure the proper design of the controller which is well established section 4.3-4.5.

In this paper the robustness is analysed in three methods. In first method, the robustness is analyzed by absorbing the maximum deviations of the system performances under parameter variations. In second method, the robustness is analysed by applying variable load to the system instead of fixed step change in load. And in third method, the robustness is analysed by applying band limited white noise to the input reference voltage of the system. All these analyses confirms that the proposed BFOA tuned PID controller is superior over others in way of enhancing the transient performances, control performances, stability and robustness of AVR system. Hence in practice, the system will work quite well.

2. DESCRIPTION OF LINEARISED AVR MODEL

AVR is an essential area of power system operation and control that determines the stability and quality of power supply. The main objective of AVR is to maintain the magnitude of terminal voltage of a synchronous generator at its nominal value. A linearised model of simple AVR system is shown in Fig. 1 and the corresponding parameter ranges are listed out in Table 1 (Haluk and Cengiz, 2011). The system comprises of four main components, namely sensor, amplifier, exciter and generator. The variation in terminal voltage of synchronous generator is continuously measured with a potential transformer, commonly known as a voltage sensor. This measured voltage is rectified, smoothed and compared with a reference signal in a comparator.

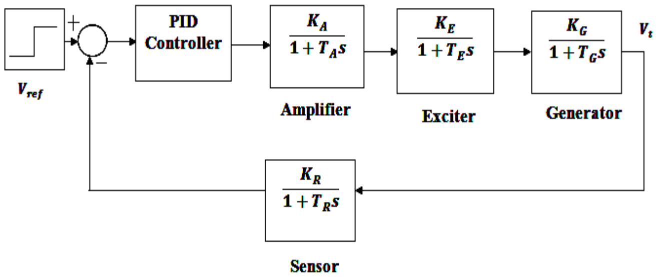

Fig. 1. Linearised model of Automatic Voltage Regulator.

Table 1. Parameter limits in AVR system

Model Name	Parameter limits	Used Parameter values
PID controller	$0.2 \le K_p \le 2$ $0.2 \le K_i \le 2$ $0.2 \le K_d \le 2$	Optimum values
Amplifier	$10 \le K_a \le 40$ $0.02 \le T_a \le 0.1$	$K_a = 10$ $T_a = 0.1$
Exciter	$1 \le K_e \le 10$ $0.4 \le T_e \le 1$	$K_e = 1$ $T_e = 0.4$
Generator	K_g depends on load (0.7-1) $1 \le T_g \le 2$	$K_g = 1$ $T_g = 1$
Sensor	$0.001 \le T_s \le 0.06$	$K_s = 1$ $K_g = 0.01$

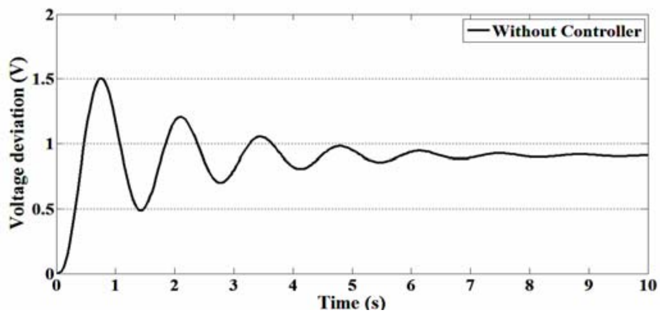

Fig. 2. Output response of AVR without controller.

The output error voltage of the comparator is 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 AVR system without any controller is depicted in Fig. 2. It is clear from the figure that the output response of the system without any controller has more number of oscillations and also has high value of final steady state error.

A supplementary controller such as P, I, PI, and PID controller is installed in this uncontrolled AVR system to reduce the steady state error and also to improve the dynamic performances. Compared to the performances of other controller the PID controller is very popular in control process owing to its main contribution for the enhancement of control and stability of system as follows (Qing-Guo et al., 2008):

• The steady state error is zeroed with an integral part of the PID controller by adding pole to the origin and by increasing the system type by one.

• The derivative part of the PID controller leads to increase the stability of the system and reducing the overshoot.

• The transient performances of the system are also enhanced with the derivative action by adding a finite zero to the open loop transfer function of the system.

• The PID controller also convinces the essential selection criteria of controllers such as proper control performance, maximum speed and its robustness towards the non linearity, dynamics and disturbances.

To improve transient response characteristics and to minimize steady- state error the gain parameters of PID controller in AVR system should be suitably tuned relative to the variation in parameter/ load which leads to the development of optimization algorithms. In this research article the optimal tuning of PID controller for AVR system is done with BFOA based tuning methodology.

3. BACTERIAL FORAGING OPTIMIZATION ALGORITHM (BFOA)

The BFOA, mimics the foraging (locating, handling, ingesting food) of E.Coli bacteria in a nutrient search space. On this accord, initially random set of solutions are generated in a search space, in which each solution represent a bacteria. Further the fitness values of these individuals are evaluated. The excellent individuals are then located with the usage of objective function and retain other individuals according to the fitness value with certain operations. Finally, with these procedure effective set of solutions are yield for next iterations. The repetition of these algorithmic steps will be continued until achieving an optimal solution (Swagatam et al., 2009).

The E.Coli bacteria undergo four stages during this foraging strategy. They are chemotaxis, swarming, reproduction and elimination- dispersal correspondingly. The detailed descriptions of these stages are in the next sub clauses.

3.1 Chemotaxis

In Chemotaxis, the locomotion of E. coli via a set of relatively rigid flagella is simulated with two types of alternate movement named run and tumble, which enables the bacterium to search for nutrients. Let, *S* is the total population of bacterium in search space, *i* represent the iteration, index of chemotactic step is denoted as *j*, reproduction is indicated by *k* and *l* represents the elimination- dispersal.

Initially, random populations of particles are generated and the value of objective function/ fitness function (1) for each particle can be computed using (10).

$$J(i,j,k,l) = \text{Function}\ (P(i,j,k,l)) \quad (1)$$

The better fitness value at each chemotactic movement are then predicted using (2) and store at local memory (3).Then, each particle makes a chemotactic movement by tumbling and swimming action (4).

$$J_{last} = J(i,j,k,l) \quad (2)$$

$$J_{local}(i,j) = J_{last} \quad (3)$$

$$\theta^{'}(j+1,k,l) = \theta^{'}(j,k,l) + C(i)\varphi(j) \quad (4)$$

Where, *C(i)* (for *i=1, 2…S*) is the size of step taken in random direction *φ(j)*. Where *φ(j)* can be represented as depicted in (5)

$$\varphi(j) = \frac{\Delta(i)}{\sqrt{\Delta^{T}(i).\Delta(i)}} \quad (5)$$

Where, Δ indicates a vector in random direction whose elements are in the range of [-1, 1]. After the chemotactic movements the particles reach a new position in search space and the value of objective function for this new position can be evaluated through (6) and the best fitness value is again stored (7).

$$J(i,j+1,k,l) = \text{Function}\ (P(i,j+1,k,l)) \quad (6)$$

$$J_{local}(i,j+1) = J(i,j+1,k,l) \quad (7)$$

When, the fitness value *J* evaluated for the current chemotactic movement *J (j+1, k, l)* is less than the previous one *J (j, k, l)* for minimization problems then another step will be taken in same direction. Otherwise the bacterium will tumble in random direction.

3.2 Swarming

Swarming is an interesting grouping behaviour of the motile species. In this mechanism the E. coli cells are arranged themselves in a travelling ring and moving towards the nutrients with a cell to cell signalling. The cells when stimulated by a high level of succinate will release an attractant known as aspartate which helps them to align in a group. In optimization problem this phenomenon is used to move the particles towards a global optimal solution. The mathematical representation of this swarming can be termed as specified in (8):

$$\begin{aligned} J_{cc}(\theta, P(j,k,l)) &= \sum_{i=1}^{S} J_{cc}^{i}(\theta, \theta^{i}(j,k,l)) \\ &= \sum_{i=1}^{S}\left[-d_{attract}\exp\left[-w_{attract}\sum_{m=1}^{p}\left(\theta_m-\theta_m^i\right)^2\right]\right] \\ &+ \sum_{i=1}^{S}\left[-h_{repel}\exp\left[-w_{repel}\sum_{m=1}^{p}\left(\theta_m-\theta_m^i\right)^2\right]\right] \end{aligned} \tag{8}$$

Where, $d_{attract}$ and $w_{attract}$ are the depth and width of attractant respectively, h_{repel} and w_{repel} are the height and width of repellent respectively and p is the dimension of optimization problem.

3.3 Reproduction

Reproduction phenomenon is one of the major driving forces of BFOA. The health of each particle is computed with its fitness value (9) and the least healthy bacteria can be identified by sorting the fitness value in ascending/ descending order. During reproduction, the least healthy bacteria which means, the solution with worst fitness value (Maximum fitness value in minimization problems) are eventually die and the other healthier bacteria each split into two, which then starts exploring the search place from the same location. This maintains the population size as constant.

$$J_{health}^{i} = \sum_{j=1}^{N_C+1} J(i,j,k,l) \tag{9}$$

3.4 Elimination- Dispersal

Elimination- Dispersal is happened due to the occurrence of sudden environmental changes or attack. Each bacterium in the population is subjected to elimination-dispersal with the small assigned probability. The frequency of chemotactic steps is greater than the frequency of reproduction steps, which in turn greater in frequency than elimination-dispersal event. This process helps in reducing the behaviour of stagnation often seen in parallel search algorithms. Bacteria parameters chosen for this case study are:

Number of bacteria =10; Number of chemotactic steps =10; Number of reproduction steps = 2; Probability of Elimination- Dispersal = 0.25; No. of elimination- dispersal events = 2.

4. RESULTS AND DISCUSSIONS

4.1 Transient Performance Analysis with BFOA Tuned PID controller

The Fig. 3 shows the optimal tuning of PID controller for AVR system with BFOA approach. In ABC tuned PID controller for AVR system ITSE is considered as an objective function (Haluk and Cengiz, 2011) and in MOL based tuning ITAE is considered as an objective function (Panda et al., 2012). A new objective function (J) is designed in this paper with the time domain specifications which includes maximum peak, rise time, settling time, and steady-state error (10). This objective function can yield optimal control parameters that can provide good characteristics performances in both frequency and time domain analysis.

$$J = (1-\Delta v^{-\beta})(P_m + E_{ss}) + \Delta v^{-\beta}(T_{st} - T_r) \tag{10}$$

Where, Δv is the deviation in voltage, β is constant and its value here is taken as 0.5, t_{sim} in the maximum simulation time and it is taken as 10s in this paper, P_m is the maximum peak of the output wave form, E_{ss} is the steady state error and T_{st} , T_r are settling time and rise time respectively.

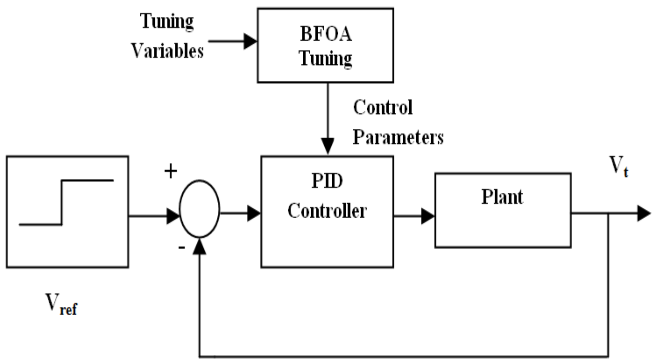

Fig. 3. BFOA tuned PID controller for AVR system.

The optimized gain parameters of PID controller for various approaches are represented in Table 2. The related output responses of AVR system obtained with proposed BFOA tuned PID controller is compared with other recently reported heuristic algorithms (Haluk and Cengiz, 2011; Panda et al., 2012) as shown in Fig. 4. In the same way, the measuring parameters of transient responses such as Maximum peak, Settling Time with 5% bant, Rise Time and Peak Time corresponding to Fig. 4 are tabulated in Table 3.

Table 2. Tuned optimal gain parameters of PID controller for different algorithms

Gain	BFOA	MOL	ABC	PSO	DE
K_p	1.087	0.5857	1.6524	1.7774	1.9499
K_i	0.83064	0.4189	0.4083	0.3827	0.4430
K_d	0.4077	0.1772	0.3654	0.3184	0.3427

The excellence of ABC algorithm has already proved when comparing with DE and PSO algorithms (Haluk and Cengiz, 2011) and hence in this research work ABC and MOL algorithms are preferred for further comparison. The Table 3 clearly demonstrates that, in the proposed method the maximum peak is reduced to 93.88%, the settling time is reduced to 82.59%, the rise time is reduced to 99.04% and the peak time is reduced to 93.14% with respect to the results obtained with ABC algorithm. Likewise, the rise time and peak time attained with the proposed BFOA are reduced to 44.89% and 47.65% respectively when compared to MOL algorithm.

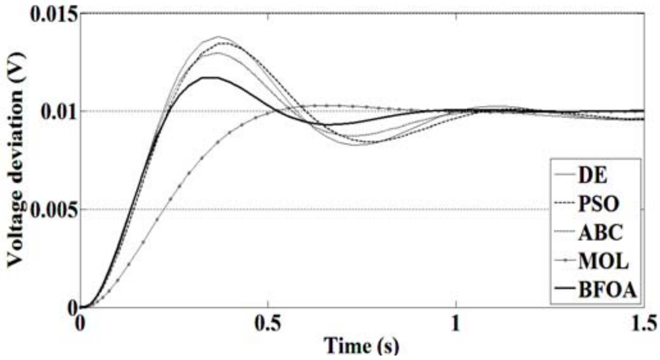

Fig. 4. Comparison of output transient response of AVR system.

Table 3. Results of transient response analysis of AVR

Algorithm types	Maximum Peak (V)	Settling Time (s)	Rise Time (s)	Peak Time (s)
DE	1.330	0.952	0.152	0.360
PSO	1.300	1.000	0.161	0.380
ABC	1.250	0.920	0.156	0.360
MOL	1.019	0.516	0.343	0.703
BFOA	1.174	0.759	0.154	0.335

The MOL algorithm describes its effectiveness only with the minimum overshoot and settling time of the AVR system correlate with ABC algorithm. However, the rise time and the peak time of the system with MOL tuned PID controller are increased extremely to 219.87% is 204.95% compared to ABC algorithm. This enormous value of rise time occurring with MOL algorithm also affects the settling time of the system when the system experiences any kind of disturbances or uncertainties and this will be clearly demonstrated in section 4.3. However, in the proposed BFOA approach all the transient measuring parameters are significantly reduced. Hence, the above discussions confirm that better transient performances can be obtained through the optimal tuning of PID controller using BFOA than other optimization algorithms.

4.2 Stability Analysis with Bode plot and Root locus Methods

The stability of any system is examined with two of the familiar approaches in control system domain named bode plot and root locus (Gopal, 2006). Generally, bode analysis gives information about frequency response of the system. The bode plot of AVR system with the proposed BFOA approach is shown in Fig. 5 and substantial stability measures computed with bode plot for different approaches are specified in Table 4.

Large value of peak gain corresponds to small amount of damping in the system that causes large overshoot and oscillations in the step response of the system. In contrast to other approaches, peak gain is considerably reduced with the BFOA and hence the transient stability of the system is improved.

The stability of the MOL tuned AVR system is indecisive because of negative phase margin. In the proposed approach the gain margin of the system is evaluated as infinite and the phase margin also considerably increased. Another good measure of stability margin is the delay margin which is the smallest time delay required to make the system unstable.

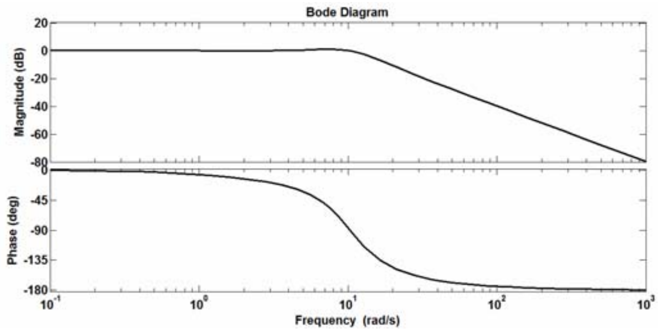

Fig. 5. Bode plot analysis of the AVR system.

Table 4. Comparative stability measures of AVR system for different algorithms

Stability measures	BFOA	MOL	ABC	PSO	DE
Peak Gains (dB)	0.965	0.0	2.87	3.75	4.20
Phase Margin (deg.)	91.45	-180	69.4	62.2	58.4
Delay Margin (s)	0.156	Inf	0.111	0.103	0.092
BW (HZ)	13.04	6.3373	12.88	12.18	12.80

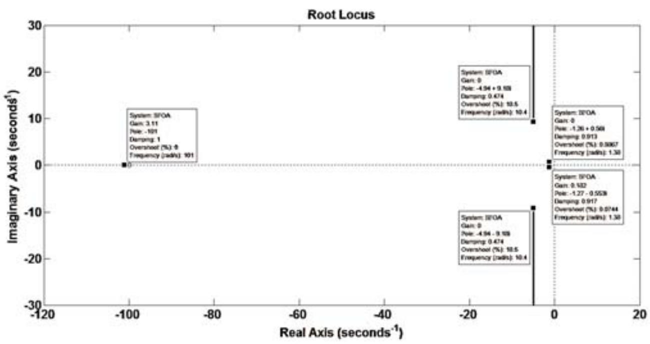

Fig. 6. Root locus analysis of the AVR system.

The delay margin of the system is also increased with the BFOA approach. The increased gain margin, phase margin and delay margin certainly ensures the stability of the system with the proposed BFOA. The increase in bandwidth causes low distortion on the output performances of the system. In MOL based approach the bandwidth of the system is very low. Hence the amount of distortion in output performances of the AVR system obtained with this MOL tuned PID controller might be comparatively higher than other approaches.

The bandwidth of the AVR system with BFOA is increased by 1.24% compared to ABC tuned system and 106% compared to MOL tuned system. All the above reviews persuade that the stability of the AVR system is much improved with the proposed BFOA tuned PID controller compared to other optimization algorithms.

The root locus analysis of the AVR system with essential specifications of poles is clearly illustrated in Fig. 6. The Eigen values and corresponding Damping Ratios (DR), evaluated by this root locus analysis are enumerated in Table 5. The table clearly illustrates that all the poles are located in left half of the *S* plane. These negative poles again ensure that the system is stable. Damping is the inherent ability of the system to oppose the oscillatory nature of the system's transient response. The damping ratio is one of the fundamental stability measures in root locus analysis. More damping has the effect of less percent overshoot and also produces transient responses with lesser oscillatory nature. It is clear from Table 5 that, the damping ratios of dominant complex poles in the BFOA approach are considerably increased. Damping ratio of AVR system tuned by BFOA algorithm is 128.28 % more than ABC tuned system and 26.63% higher than MOL tuned system. Hence the root locus approach assures that, the stability and transient responses of the AVR system are enhanced with BFOA tuned PID controller over other algorithmic approaches.

Table 5. Comparative root locus analysis of AVR system with different algorithms

BFOA		MOL		ABC	
Eigen values	DR	Eigen values	DR	Eigen values	DR
-1.26+0.56*i*	0.91	-100	1	-100.98	1
-1.26-0.56*i*	0.91	-2.11	1	-3.75+8.40*i*	0.4
-4.94+9.18*i*	0.47	-1.06	1	-3.75-8.40*i*	0.4
-4.94-9.18*i*	0.47	-4.92+4.72*i*	0.72	-4.74	1
-101.12	1	-4.92-4.72*i*	0.72	-0.25	1

4.3 Robustness analysis with parameter variations

The better way 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. 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. The Fig. 7-10 exhibits the output responses of the AVR system under parameter variations in specified ranges. The optimized gain parameters of PID controller with proposed BFOA technique related to these parameter variations are scheduled in Table 6. The transient evaluating parameters such as maximum peak, settling time, rise time and peak time are evaluated with these gain parameters and the values are depicted in Table 7.

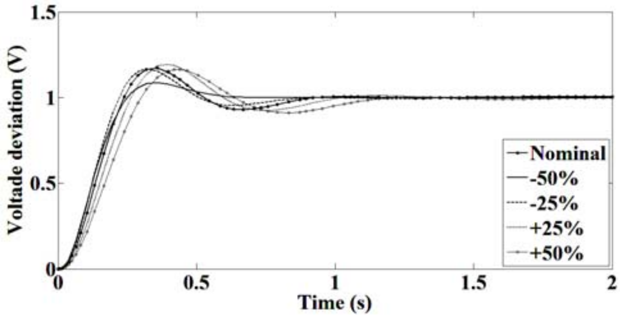

Fig. 7. Output response of AVR for percentage change in T_a.

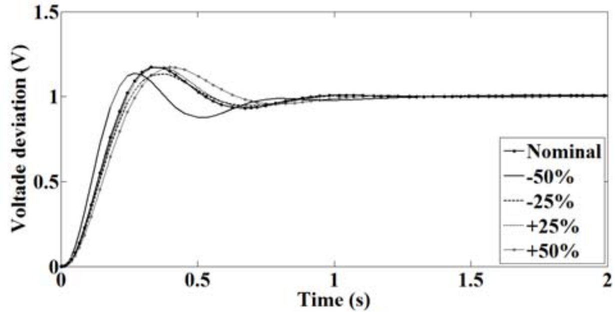

Fig. 8. Output response of AVR for percentage change in T_e.

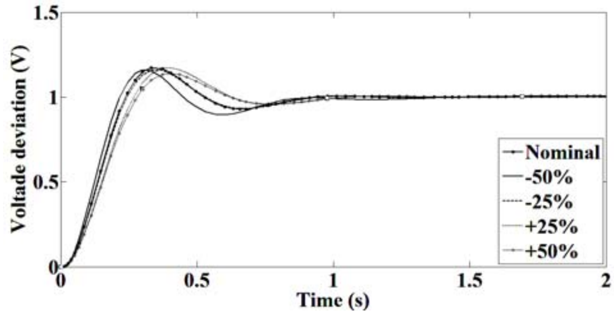

Fig. 9. Output response of AVR for percentage change in T_g.

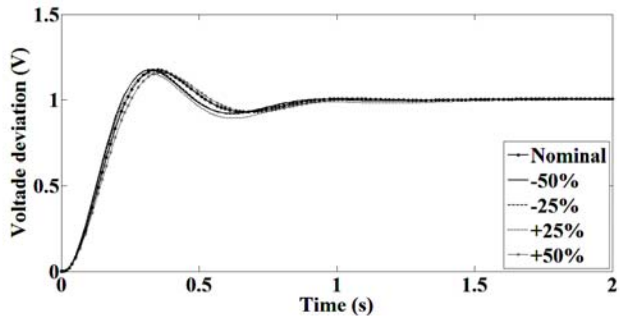

Fig. 10. Output response of AVR for percentage change in T_s.

Table 7 clearly depicts that, the deviations of all the transient measures are in small ranges referred to its nominal values. For detailed analysis the Range of Deviation (ROD) and the percentage of Maximum Deviation (%MD) are also evaluated with the proposed approach and compared with the documented results of ABC (Haluk and Cengiz, 2011) and MOL (Panda et.al., 2012) algorithms as scheduled in Table 8. As discussed in section 4.1, the Table 8 clearly demonstrates that, even the MOL algorithm depicts minimum value of settling time at nominal system conditions, the %MD of settling time and peak time are enormously increased when the system is subjected to parameter variations.

Table 6. Tuned gain parameters of PID controller for parameter variations

Parameter deviation	K_p	K_i	K_d
Variation of T_a between (-50% to +50%)			
-50%	1.1749	0.8328	0.3024
-25%	1.2797	0.8444	0.3845
+25%	1.0308	0.7687	0.3893
+50%	0.8715	0.5876	0.3718
Variation of T_e between (-50% to +50%)			
-50%	0.9145	0.7367	0.3057
-25%	0.9345	0.7531	0.2845
+25%	1.1456	0.8242	0.4844
+50%	1.2108	0.7289	0.4823
Variation of T_g between (-50% to +50%)			
-50%	0.7215	0.7369	0.2419
-25%	0.8793	0.7793	0.2986
+25%	1.2675	0.7542	0.4135
+50%	1.2973	0.7431	0.4877
Variation of T_s between (-50% to +50%)			
-50%	1.1700	0.8623	0.4633
-25%	1.1333	0.8574	0.4545
+25%	0.9451	0.6724	0.4442
+50%	0.9713	0.7351	0.3723

Table 7. Robustness analysis of the AVR system with parameter variations

Parameter Deviation	Maximum Peak (V)	Settling Time(s)	Rise Time(s)	Peak Time(s)
Variation of T_a between (-50% to +50%)				
-50%	1.0842	0.4648	0.1616	0.3297
-25%	1.1643	0.4584	0.1438	0.3024
+25%	1.1936	0.8674	0.1725	0.3824
+50%	1.1627	0.9945	0.1961	0.4155
Variation of T_e between (-50% to +50%)				
-50%	1.1624	0.7368	0.1416	0.3152
-25%	1.1603	0.7643	0.1581	0.3400
+25%	1.1691	0.5644	0.1759	0.3725
+50%	1.1386	0.5509	0.1831	0.4163
Variation of T_g between (-50% to +50%)				
-50%	1.1624	0.7368	0.1416	0.3152
-25%	1.1603	0.7643	0.1581	0.3400
+25%	1.1691	0.5644	0.1759	0.3725
+50%	1.1386	0.5509	0.1831	0.4163
Variation of T_s between (-50% to +50%)				
-50%	1.1739	0.7295	0.1440	0.3174
-25%	1.1785	0.7385	0.1448	0.3267
+25%	1.1528	0.7893	0.1494	0.3191
+50%	1.1578	0.8014	0.1657	0.3467

For AVR with the proposed BFOA approach, the average value of % MD of the maximum overshoot, settling time, rise time and peak time under parameter variations are computed from Table 7 as 0.675%, 9.81%, 17.18% and 19.17% respectively. The earlier documented results (Haluk and Cengiz, 2011) illustrate that, in ABC algorithm these deviations are depicted as 5.6%, 27.5%, 27.5%, and 24.7% and in MOL algorithm these deviations can be evaluated as 4.07%, 189.44%, 14.53% and 168.8%. Hence, the above discussions clearly reveals that, the average deviations of transient measuring parameters, evaluated from the output response of AVR with proposed BFOA tuned PID controller under parameter variations are very minimum comparing to ABC and MOL algorithms. Thereby it is confirmed that, the robustness of the AVR can be effectively improved with the proposed BFOA tuned PID controller.

Table 8. Range of Deviation and percentage of Maximum deviation due to parameter variations

Parameters	ROD	% MD [BFOA]	% MD [MOL]	% MD [ABC]
Parameters for variation of T_a				
Maximum Peak (V)	0.1094	1.71	5.90	11.20
Settling Time (s)	0.5297	30.87	105.43	54.40
Rise Time (s)	0.0522	26.91	14.40	23.10
Peak Time (s)	0.1131	23.92	170.00	22.20
Parameters for variation of T_e				
Maximum Peak (V)	0.0394	0.20	6.30	0.80
Settling Time (s)	0.2011	2.34	223.51	32.70
Rise Time (s)	0.0507	16.02	22.60	33.90
Peak Time (s)	0.1483	25.23	435.20	32.20
Parameters for variation of T_g				
Maximum Peak (V)	0.0305	0.37	3.50	7.20
Settling Time (s)	0.2134	0.57	377.03	22.80
Rise Time (s)	0.0415	18.53	13.30	37.10
Peak Time (s)	0.1011	24.17	68.10	37.70
Parameters for variation of T_s				

Maximum Peak (V)	0.0257	0.42	0.60	3.20
Settling Time (s)	0.0719	5.46	51.77	0.20
Rise Time (s)	0.0217	7.27	7.80	16.00
Peak Time (s)	0.0293	3.39	1.90	6.90

4.4 Robustness analysis with variable load perturbations

In this paper, the robustness of the system is analyzed in another way by applying the time varying load perturbations to AVR ranges between (0-100s) instead of, fixed step change in load as indicated in Fig. 11a. As per the discussions made in the previous sections, it is confirmed that the MOL tuned PID controller in AVR has miserable transient performances, stability and robustness. Hence, in this section the robustness of AVR under load dynamics is analyzed only between the ABC tuned PID controller and the proposed BFOA tuned PID controller. The comparative output voltage deviation of AVR corresponding to the variable load is shown in Fig. 11b. Furthermore, for clear perceptibility some random portions indicated as A and B in the time range of (10-20s) and (50-70s) of Fig. 11b are enlarged and exhibited in Fig. 11c and Fig. 11d. All these figures indubitably illustrate that, the transient performances of AVR such as maximum overshoot, settling time, rise time and peak time of AVR characteristics under the dynamics in load is much improved with the proposed BFOA tuned PID controller comparing to ABC approach. Hence, it is again confirmed that the robustness of AVR system is enhanced with the proposed approach.

4.5 Robustness analysis with band limited noise

To analyze the practical implementation of this BFOA optimized PID controller for AVR system, and to examine the robustness, the tuning is performed by applying band limited white noise with different magnitudes to the input reference voltage of the system (Mohammad Kiani et al., 2013) as shown in Fig. 12.

The noise in practical AVR system is mainly created from the generator, amplifier, sensor and also by the thermal variations of the system. Theoretically, continuous white noise has a correlation time of zero, a flat Power Spectral Density (PSD), and a total energy of infinity. The white noise is a useful theoretical approximation when the noise disturbance has a correlation time that is very small relative to the natural bandwidth of the system. Hence, in National Grid Electricity Transmission (NGET), the performance of the real time system under this noise criterion is analyzed in frequency domain by injecting random band limited white noise to the AVR reference (National grid, 2012).

In the view of above, the effect of band limited-white noise is simulated using Matlab Simulink software, by a random sequence with a correlation time much smaller than the shortest time constant of the system and injected to the reference voltage of the linearised AVR model of this research work.

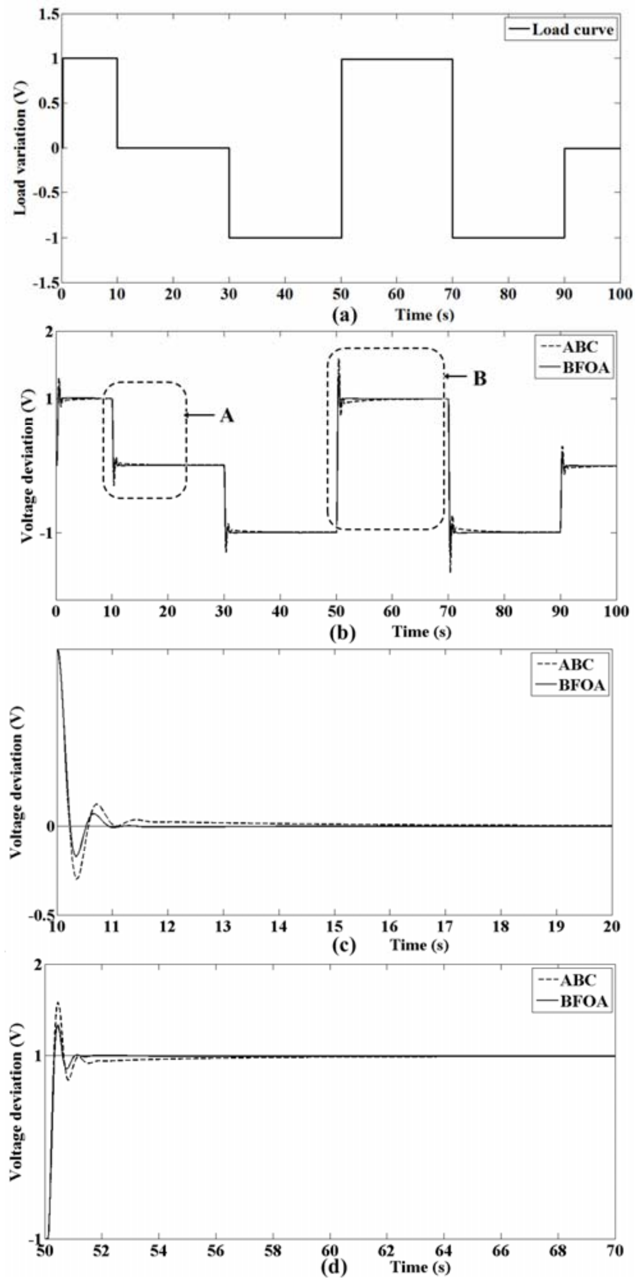

Fig. 11. Robustness analysis of AVR with variable load.

The magnitude of noise signal is attuned by changing the Signal-to-Noise Ratio (SNR) to specified values (11) such as, SNR = 40dB, SNR=30dB and SNR=20dB respectively.

$$SNR(db) = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \tag{11}$$

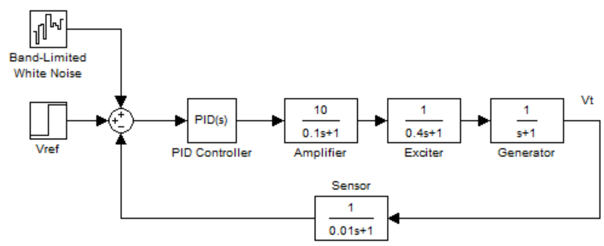

Fig. 12. Robustness analysis of AVR with band limited noise.

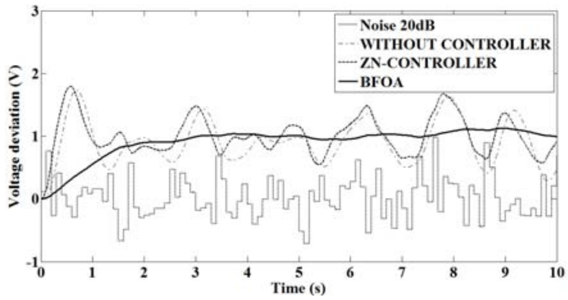

Fig. 13. Output of AVR system with noise value SNR=20 dB

The Fig. 13, Fig. 14 and Fig. 15, shows the comparative output response analysis of the AVR system in presence of band limited white noise with different magnitudes. It can be seen from these figures that, the output response with BFOA tuned PID controller has minimum oscillations compared to ZN tuned PID controller and also to a non controller system for all magnitudes of noise signal. Hence, it is evidently proved that, the input noise rejection capability of the proposed BFOA optimized controller may enhance the reliability, robustness of the system and also make it more suitable for the practical implementation in realistic power system.

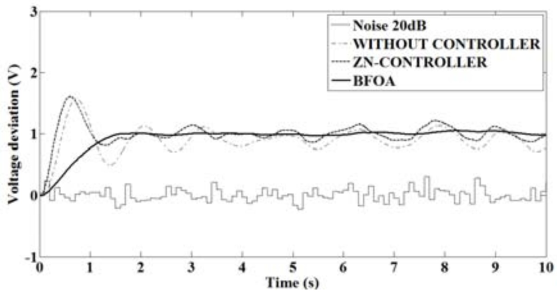

Fig. 14. Output of AVR system with noise value SNR=30 dB.

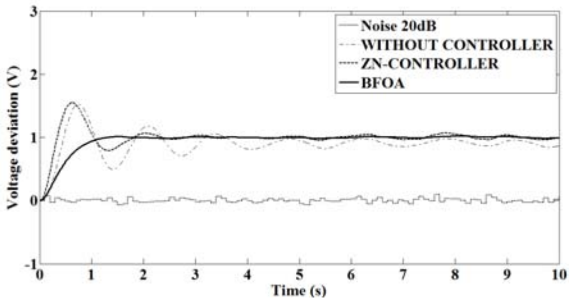

Fig. 15. Output of AVR system with noise value SNR=40 dB.

4.6 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 (Noureddine Bouarroudj et al., 2015). Moreover, the convergence can also be visualized through the positional values (control parameters) corresponding to each iterations.

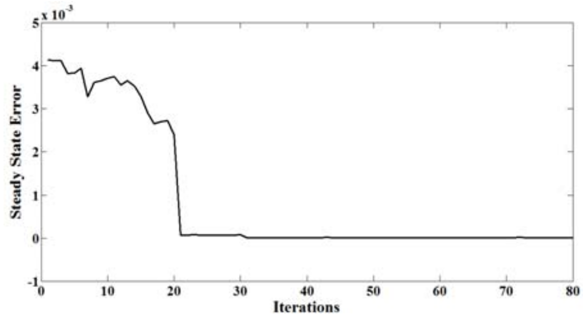

Fig. 16. Convergence analysis of BFOA for AVR system.

The Fig. 16 shows the final steady state error value of AVR evaluated with BFOA over consecutive iterations and the control parameters equivalent to these iterations are shown in Fig. 17. It is clear from these figures that the solution by proposed BFOA is converged to high quality solutions at the early iterations (about 20 iterations). This feasible convergence characteristic can enhance the suitability of proposed approach to real-time power systems.

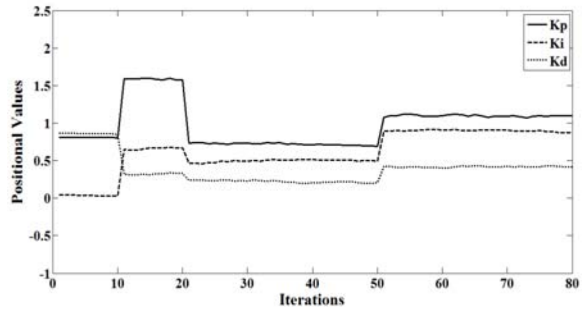

Fig. 17. Positional values of BFOA for consecutive iterations.

5. CONCLUSION

The amenity of using BFOA to enhance the control and stability of AVR system is discussed in this paper. In AVR, the stable and fast response of the regulator is difficult to achieve due to the high inductance of the generator field windings and load variation. Hence, various control structures have been proposed for the AVR system, however, among these controllers the proportional plus integral plus derivative (PID) is suggested as the most preferable controller in this paper. The gain parameters of PID controller in AVR system are, effectively tuned with proposed BFOA approach and the improvement in closed loop performances are clearly demonstrated in detail in this paper. Minimization of voltage deviations in output response is considered as a main objective of AVR and a new fitness function with all the essential time domain specifications is introduced in this paper to satisfy this objective. The potency of the proposed algorithm is confirmed by comparing the output responses, stability and robustness of the system with the recently reported modern heuristic algorithms such as MOL, ABC, PSO and DE algorithms.

The transient response analysis assures that, the maximum peak, settling time, rise time and peak time of the system is considerably reduced with the proposed approach. Increased stability margins of the AVR system accomplished through a bode analysis and improved damping ratios along with negative poles accomplished through a root locus analysis undoubtedly approved the stability of AVR system with proposed BFOA compared to other optimization methods.

To validate the practical applicability of the proposed approach, the simulation model of the AVR test system is demonstrated with different methods of robustness analysis. Initially, the output response of the system under the practical constraints such as, disturbances and uncertainties is examined by applying load and parameter variations to the test system. Further, the noise rejection capability of the proposed approach is tested by applying band limited white noise to the input reference voltage of the system model. All these analyses clearly reveal that, the deviations in output response of the system are very much reduced with the proposed approach, and the system is more stable under any practical constraints of the power system. In addition, the convergence analysis of the proposed BFOA tuned PID controller in AVR system is examined in this paper. The result of convergence analysis evidently proves that, global optimal solutions with faster convergence characteristics can be obtained with the proposed approach and this can make the system more feasible for practical implementation. All these analysis certainly assures that effective tuning of controllers, better control performances, enhancement in system stability and robustness can be obtained through the proposed BFOA tuned PID controller.

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