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Optimal Design of PID Controller for an AVR System Using Flower Pollination Algorithm

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Abstract In this presented work, terminal voltage and reactive power control at the different conditions of load changes of synchronous generator in the AVR system is presented. To improve the step response of the alternator terminal voltage proportional integral derivative controller is carried out with optimization technique as Flower Pollination Algorithm (FPA) to optimally tuned the parameters of PID controller. The AVR system response with proposed FPA-PID controller is found to be better and compared that of with controllers in literature (42 in number). The performance is compared in terms of peak value, settling time and performance indices like ITAE, ISE and IAE. The robustness analysis of the proposed FPA based PID controller is considered for 156 plant conditions and varying time constants parameters as ±20% system conditions. The system stability with proposed FPA optimized PID controller also analysed in the form of eigenvalue, damping factor and frequency of oscillations.

Keywords: *AVR system modeling, PID controller, flower pollination algorithm*

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1. Introduction

To deliver the efficient, economically and reliably maintained electrical power supply to the load and consumers, the stability and performance of synchronous generator also improves in the power system network or power stations [1]. The synchronous generator has three main control systems such as exciter, governor and boiler. The objective of these control systems has to consistent a voltage and current by excitation system, steam pressure in the boiler by firing control and third one is control the torque speed of turbine by governor [2].

In this work, excitation system is considered which includes exciter and (AVR) Automatic Voltage Regulator. The aim of this control strategy is to deliver and economically maintain a generator terminal voltage at specific level. AVR is a device to control the variation of terminal voltage of synchronous generator at certain level under system uncertainties such as fault and load fluctuations. Due to this, steady-state error can take place in the uncontrolled AVR system [3]. To overcome this problem, PID controller is constructed because of it is robust and simple in structure.

Many optimization techniques have been developed such as classical methods, intelligent control techniques and soft-computing techniques. In the classical methods, Cohen-Coon (CC), TyreusLuyben (TL), Internal Model Control (IMC), Zeigler-Nicolas (ZN), Chien-Hrones-Rewich (CHR) method etc. are considered. Fuzzy Logic controller (FLC), Artificial Neural Network (ANN), Multilayer Perceptron Neural network (MLPNN), Neuro-Fuzzy controller etc. have considered in the Artificial intelligent techniques. In the categories of soft-computing techniques, different metaheuristic or nature inspired tuning techniques have been taken into account for example Hybrid Evolutionary Algorithm (HEA), Genetic Algorithm (GA), Particle Swam Optimization (PSO), Local Unimodal Sampling (LUS) algorithm etc.

Rao et al., 2014 [4] demonstrates a design of Internal Model Control (IMC) based PID controller cascade with lag-lead filter with modified IMC filter to provide load disturbance rejection for the first order process system. Mittal and Rai, 2016 [5] describes the performance of conventional controller for AVR system and presents the simulation results with IMC controller, PID controller and cascade controller. Bansal et al., 2012 [6] have explain a review on classical and intelligent computational techniques for tuning the PID controller such as ZN, CC, ACO, GA etc. are considered.

Artificial Neural Network (ANN) based MLPNN-AVR system and Feed Forward ANN (FFANN) based AVR system is presented by Memon [1] in respectively and improve the transient stability of synchronous machine. Shayeghi et al., 2015 [7] have described FLC based Fuzzy P + Fuzzy I + Fuzzy D (FP + FI + FD) controller and controlled the generator terminal voltage in the AVR system. For optimal tuning and robust performance Hybrid GAPSO optimization technique is used and comparisons are made with conventional PID and fuzzy PID controller.

Wong et al., 2009 [8] design a HEA which is a combination of GA and PSO technique to applied PID controlled AVR system and show that proposed new fitness function gives optimal and effective response. Mohanty et al., 2014 [3] presents the LUS algorithm to design PID controller for AVR system with modified objective functions and perform the simulation in terms of stability, settling time and peak overshoot.

In this research work, FPA based PID controller have designed to applied on AVR system and increase the effectiveness of the system response. The FPA is bioinspired and reproduction based optimization technique in which pollen is transferred from one flower to another flower through pollinators such as butterflies, bees and animals, known as pollination in the flower plants. Self-pollination and Cross-pollination are two types of pollination. The objective of this algorithm is the most fittest and optimal reproduction of flowering plants.

2. Description of AVR System Modeling

As Discussed previously, that AVR maintains the system voltage to its nominal value and measure this regulating voltage by sensor and again fed to the synchronous generator [9,10]. The AVR system consists for components defined by exciter, amplifier, generator and sensor. The general model of AVR system is shown in Figure 1.

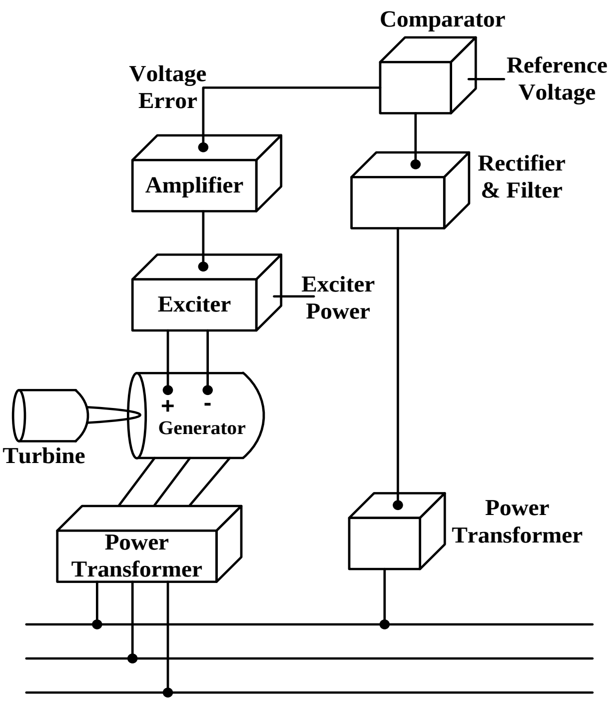

Figure 1. General model of AVR

2.1. Mathematical Modelling

The components of AVR represented by transfer function to demonstrate the dynamic performance of the system. The AVR system without and with PID controller are shown in Figure 2 and Figure 3, respectively. The used value of parameters of transfer function model such as gain and time constants are mentioned in Table 1. The mathematical modelling of AVR system is as follows:

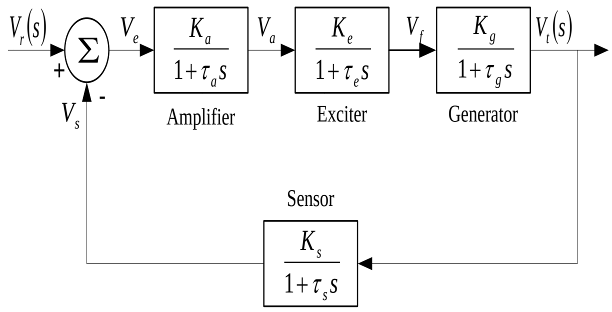

Figure 2. Model of AVR without controller

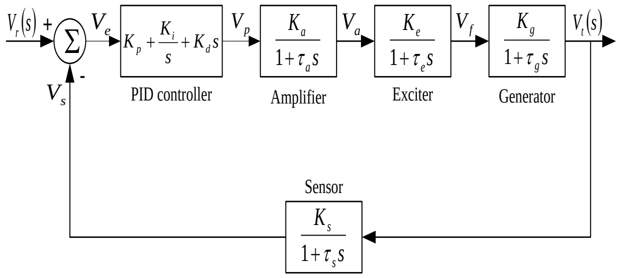

Figure 3. Model of AVR with controller

Table 1. Used value of AVR system parameters

Parameters Components	Transfer Function	Time Constants	Gain
Amplifier	$\frac{V_a(s)}{V_e(s)}=\frac{K_a}{1+\tau_a s}$	$\tau_a=0.1$	$K_a=10.0$
Exciter	$\frac{V_f(s)}{V_a(s)}=\frac{K_e}{1+\tau_e s}$	$\tau_e=0.4$	$K_e=1.0$
Generator	$\frac{V_t(s)}{V_f(s)}=\frac{K_g}{1+\tau_g s}$	$\tau_g=1.0$	$K_g=1.0$
Sensor	$\frac{V_s(s)}{V_t(s)}=\frac{K_s}{1+\tau_s s}$	$\tau_s=0.01$	$K_s=1.0$

2.1.1. Amplifier

The model of amplifier in terms of gain K_a and time constant τ_a are mathematically represented as in Eq. 1. The range of time constant and gain are considered as 10 to 400 and 0.02 to 0.1 seconds, respectively.

$$\frac{V_a(s)}{V_e(s)}=\frac{K_a}{1+\tau_a s} \tag{1}$$

2.1.2. Exciter

The transfer function model of exciter system shown in Eq. 2. The limits 1 to 400 is taken for exciter gain K_e and 0.25 to 1.0 second is assumed for time constants τ_e .

$$\frac{V_f(s)}{V_a(s)}=\frac{K_e}{1+\tau_e s}. \tag{2}$$

2.1.3. Generator

The Eq. 3 demonstrates the transfer function model in the form of gain and time constants. The range of time constants may vary between 1.0 to 2.0 seconds and gain may vary between 0.7 to 1.0.

$$\frac{V_f(s)}{V_f(s)} = \frac{K_g}{1+\tau_g s}. \tag{3}$$

2.1.4. Sensor

The mathematical equation of sensor model is denoted by Eq. 4. The set value of limits of time constants is 0.001 to 0.06 seconds and set value of limits of gain is 1.0 to 10.0.

$$\frac{V_s(s)}{V_t(s)} = \frac{K_s}{1+\tau_s s}. \tag{4}$$

2.2. PID Controller

The PID controller is a mechanism of control loop feedback and most commonly used controller to improve the quality of response of AVR system [11]. It has a short rise time i.e. fast speed of response and higher stability. It is a combination of three controller modes such as Proportional, Integral and derivative mode. In the first mode, if the value of K_p (proportional gain) changed in the increasing mode then steady-state error and rise time reduced. However, after certain limit the increasing value of K_p produced overshoot and system will be unstable [12,13].

Similarly, by enhance the value of integral gain K_i, rise time also decreased with eliminating steady-state error. Whereas, after specific limit increase overshoot with worse transient response by using raise value of integral gain. In the derivative mode, gain K_d may vary in the increasing manner then value of settling time and overshoot decreased with improved stability of the system [14].

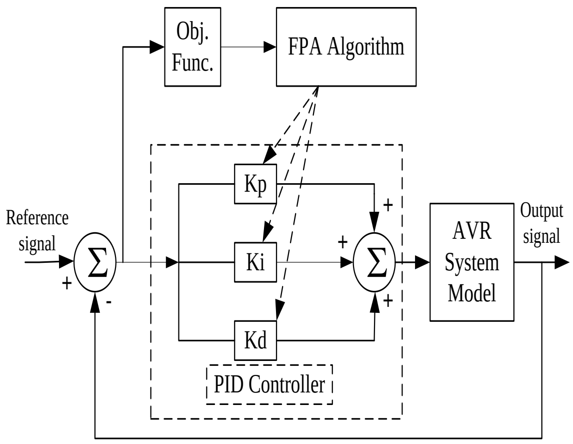

Figure 4. Block diagram of PID controller

The block diagram of PID controller with FPA optimization technique is presented in Figure 4. The s-domain transfer function represented by Eq. 5 and time domain output is denoted by Eq. 6 of PID controller.

$$TF_{PID} = K_p + \frac{K_i}{s} + K_d s \tag{5}$$

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(\tau)}{d(\tau)} \tag{6}$$

Where the error signal is denoted by e(t) and the control signal is shown by u(t). the tuning parameters K_p, K_i, K_d. are mostly required to design the PID controller.

2.3. Objective Function

In this research work, the design of PID controller is considered as problem of optimization. The objective function is evaluated as minimization of error signal as in Eq. 7 with parameters limits as in Eq. 8.

Minimize:

$$IAE = \int_{t=0}^{T_{sim}} \left| V_r(s) - V_s(s) \right| dt \tag{7}$$

Subjected:

$$\begin{aligned} K_p^{\min} &\le K_p \le K_p^{\max} \\ K_i^{\min} &\le K_i \le K_i^{\max} \\ K_d^{\min} &\le K_d \le K_d^{\max} \end{aligned} \tag{8}$$

3. Flower Pollination Algorithm

The nature inspired and biological system based optimization techniques are current trend to solve complex constraints and difficult problems in terms of optimal solution in engineering and industrial applications [15]. The FPA is a bio inspired algorithm which mimics the behaviour of pollination process of flower plants in the nature [16]. It is recently introduced by Xin-She Yang in 2012. The objective of flower plants is eventually reproduction through pollination.

3.1. Characteristics of bio-inspired FPA

The bio-inspired FPA is related with the process of pollination. In the process of pollination, pollen is transferred through pollinators such as butterflies, bees, insects and other animals [17]. In really, specific flower plants and insects have evolved together into a flower pollinator partnership. For example, some specific flowers are dependent on particular species of birds, insects, for actual process of pollination [18].

The pollination process in flowering plants is divided into two categories: Biotic and Abiotic. When pollen is transferred by insects, birds, butterflies, bees and animals, it is known as biotic pollination and about 90% in the nature [19]. If pollinators are not required to transform pollen then it is called as abiotic pollination and about 10% in the nature [19]. In such type of flowering plants, pollination can take place with the help of wind and diffusion. Grass is a good example of abiotic pollination. The types of pollination are represented in Figure 5.

Honeybees are the best pollinator in the nature because of they can develop flower constancy or pollinator constancy. That is, pollinator constancy is demonstrate as, the movement of particular pollinators to completely visit specific flower species though avoiding other species of flower plants [18]. Such pollinator constancy may have more beneficial as a consequence of this will increase the reproduction of same species of flower plant by transferring pollen to the nonspecific plant of flower [17].

The process of pollination can take place with the help of cross-pollination and self-pollination. Cross-pollination (allogamy) occur when pollen is transferred from one flower of a plant to another flower of different plant. However, self-pollination can take place when pollen transferred to the same flower or another flower of same branch, which frequently occur when reliable pollinator is not available [16]. Self and cross-pollination are represented in Figure 6.

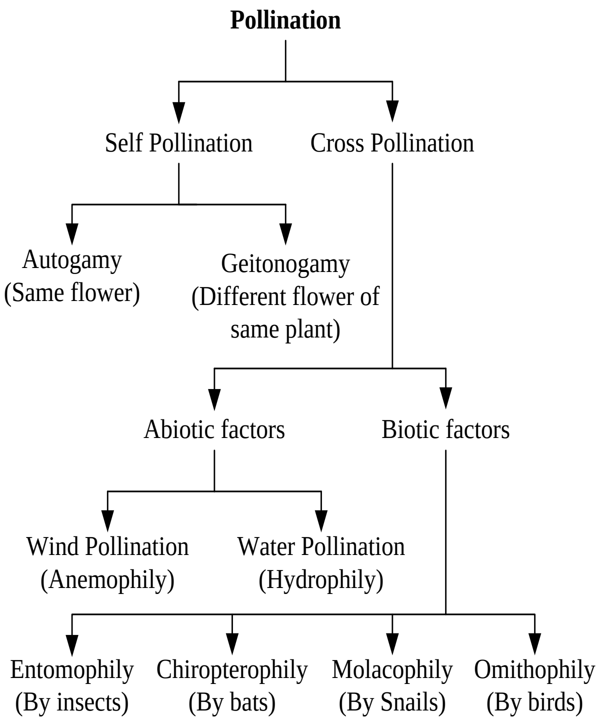

Figure 5. Types of pollination

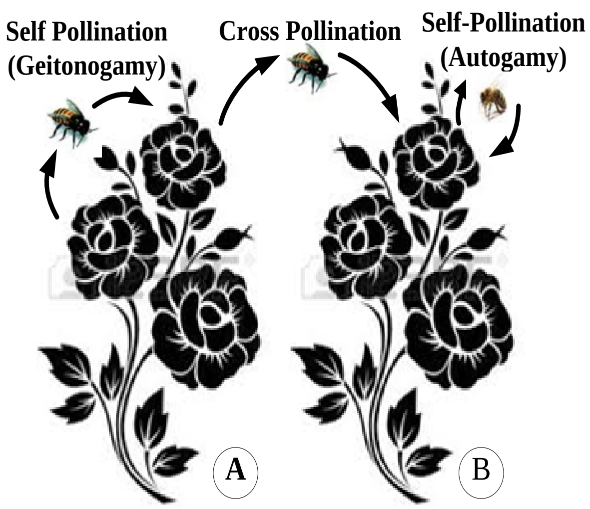

Figure 6. Self and cross pollination

Biotic, cross-pollination is considered as the global pollination, in which pollinators such as bees, butterflies and other flying insects transferred pollen from one flower to another at a long distance and these pollinators may behave as Lèvy flight with fly distance steps obey a Lèvy distribution [17]. Moreover, flower constancy can be used an increment steps using the similarity or difference of two flowers.

3.2. Mathematical Modelling of FPA

According to above characteristics of process of pollination following rules can be followed by the pollinators [20]:

When pollinators transferred pollen by performing Lèvy flight with process of global pollination then it is considered as biotic and cross-pollination.

Local pollination is coming into the categories of abiotic and self-pollination.

The same properties of two flowers are proportional to the probability of reproduction, it can be considered as pollinator constancy.

Switch probability $p \in [0,1]$ is used to control the process of local and global pollination. In the whole process of pollination because of physical proximity and other factor such as wind.

Based on the discussion of above characteristics of pollination process, The FPA optimization technique have developed, therefore, convert the above four rules in the form of mathematical modeling equations.

In the first step of global pollination, pollen gametes are transferred through pollinators such as flying insects can travel over a long distance. This process ensures that pollination and reproduction of the fittest solution define as f*. The rule 1 and flower constancy can be expressed as Eq. (9) [15].

$$y_i^{t+1} = y_i^t + P(y_i^t - f^*) \tag{9}$$

Where y_i^t define the pollen i or vector of solution y_i at generation t. The symbol f* presents the current optimal solution at current no. of iteration that is found among all the solution. Strength of the pollination represented by element P, which basically a step size.

The flying insects may travel over a long distance while transfer pollen so we can define this characteristics in terms of Lèvy flight. That is, $P > 0$ illustrated from a Lèvy distribution [15].

$$P \sim \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi}\frac{1}{s^{1+\lambda}}, (s >> s_0 > 0). \tag{10}$$

In Eq. (10) standard gamma function is represented by $\Gamma(\lambda)$ and this type of distribution is applicable for large steps $s > 0$. Considered value of λ is 1.5.

Equation (11) explain the local pollination and rule 2 plus flower constancy can be mathematically modelled as [15]:

$$y_i^{t+1} = y_i^t + \in\left(y_j^t - y_k^t\right) \tag{11}$$

Where pollen of different flowers of same plant shown by y_j^t and y_k^t. This basically mimics the flower constancy in a limited neighbourhood. If y_j^t and y_k^t belongs to the same species and same population, this become a local random walk if we describe $\in$ from a uniform distribution in the range [0,1] [15].

Mostly, at all scales, both global and local, activities of flower pollination can occur. In practices, adjacent flower patches are more likely to be pollinated by local flower pollens that those far away. Due to this, we can follow fourth rule (switch probability) p to switch between common global pollination to intensive local pollination. The pseudo code of the algorithm as following:

Pseudo code for Flower Pollination Algorithm

Initialize objective as minimization.
Define the population for n flowers.
Find current best solution f* in the initial population.
Describe the switch probability $p \in [0,1]$.
While (t <MaxIteration)
For i=1: n
If rand < p
Define step size P which follow Lèvy distribution.
Use Eq. (1) to perform global pollination.
else
Define $\in$ for uniform distribution [0,1].
Randomly select a j and k among all the solution.
Perform local pollination by Eq. (3).
end if
Calculate new solution.
If calculate solution is better, then update it in population.
end for
Get the optimal solution f*.
end while

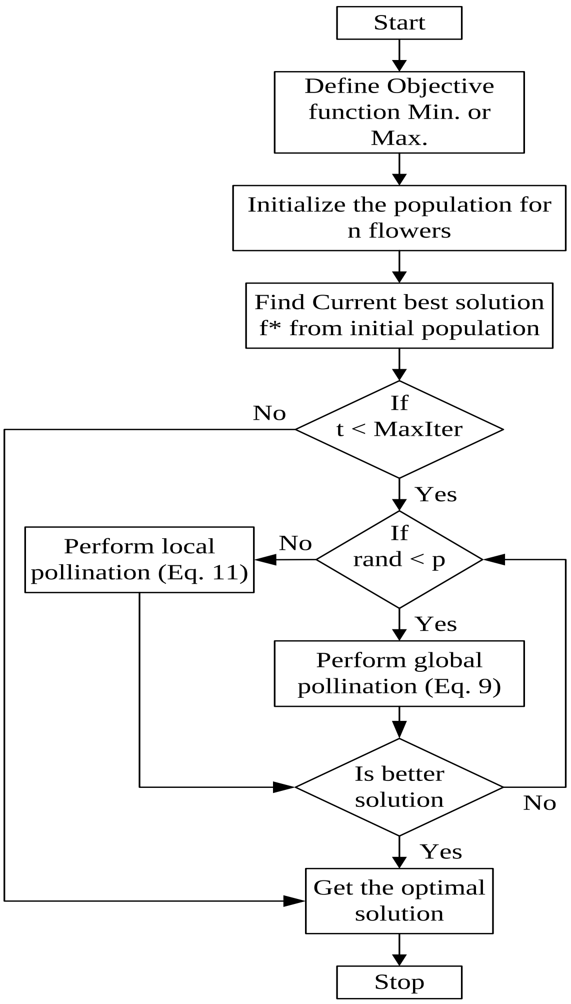

Figure 7. Flowchart of FPA

If we consider p=0.5 as initial value and find the most appropriate parameters range through parametric study. We can consider p=0.8 for better response for most of the applications. Algorithm for FPA shown below [13] and flow chart also presented in Figure 7.

4. Result and Discussions

4.1. Performance of FPA

The proposed PID controller tuning parameters are determined by application of optimization using FPA with sampling time 0.02 sec. The problem of optimization is considered as minimization of integral absolute error as defined in Eq. 7. The Simulink model of AVR system with global variables of PID controller as K_p, K_i and K_d is synthesized in MATLAB R2011b as shown in Figure 4. The IAE based objective function as in Eq. 7, with global variables is written in *.m file in MATLAB [21]. The upper and lower bound to the PID parameters are set as shown in Eq. 12. The Number of population size to FPA are considered as 10 and the dimension is set to 3. The switch probability is considered as p=0.8 and the maximum number of iteration count is set as 100 for considering the termination of optimization. The performance of optimization in terms of fitness function value and the variations of PID parameters with iteration count is set as 100 and sampling time set as 0.02 second during optimization is shown in Figure 8(a) – Figure 8(d).

$$\begin{aligned} 0.0 &\le K_p \le 1.5 \\ 0.0 &\le K_i \le 0.5 \\ 0.0 &\le K_d \le 0.5 \end{aligned} \tag{12}$$

4.2. PID Controller in Literature

In this section, the PID controllers using different techniques in literature are to be reviewed. The detail of the PID parameters with system parameters is enlisted in Table 2.

Afroomand, 2016 has considered the three variant of Vector Based Swarm Optimization (VBSO) based on mutation as well as selection of weighting coefficients and off-springs. The three variants of VBSO are represented by VBSO-1, VBSO-2 and VBSO-3 [19]. The VBSO variants perform well in terms of accuracy and speed of convergence; however, the VBSO-2 variant performs better with respect to other variants. Therefore, the data of best-performing variant, i.e. VBSO-2 is considered for comparison purposes and enlisted in Table 2.

Chatterjee, 2016, has presented the application of the Teaching Learning Based Optimization (TLBO) tuning of PID parameters in AVR system under generator parametric variation. It presented the dynamic behavior of generator and application of TLBO to control the system behavior through PID controller. The different PID controllers for different sets of K_g and τ_g are presented as enlisted in Table 2 [20].

The application of Gray Wolves Optimizer (GWO) for tuning the PID parameters is presented in [21]. In the

GWO, three levels of hierarchy are considered which is represented by α, β and δ. The last level of the hierarchy is ω. The parameters of PID controller tuning using (GWO) and conventional PID parameters are included in Table 1 [21].

The design and performance analysis of PID controller using multi objective non-dominated sorting genetic algorithm-II (NSGA-II) with application of AVR system is presented in [22]. The effect of cost function and PSO is considered for optimal design of PID parameters in [23]. The priority based objective function for minimization of ISE for tuning the PID parameters using Gravitational Search Algorithm (GSA) is shown in [24]. The CPSO is considered in [25]. The application of TLBO is as well considered in [26]. The Taguchi combined Genetic Algorithm (TCGA) based designed parametric values of PID controller for AVR system is presented in Table 2 [27].

The PID controller design using ZN, PSO, and Many Optimization Liaisons (MOL) are designed in [28]. The GA and PSO are considered for optimal tuning of PID parameters of an AVR system in [29]. The different values of the weighting factors are considered as 0.5 and 1.0 at different generations in [29] and included in Table 2. The PID controller tuned with ZN method is included in Table as presented in [30]. The application of Anarchic Society Optimization (ASO) for optimal design of PID control of an AVR system and comparing the results with VEPSO and CRPSO under varying conditions of and for five cases. These value are varied to analyze robustness of the proposed control strategy in [31]. The MOL is considered for optimal design of PID controller in [11,32].

The Pattern Search Algorithm (PSA) for tuning the PID parameters is presented in [33]. Mandal, 2011 has presented Memetic Algorithm (MA) to find optimal PID parameters for AVR system. It is explained by combining a competitive variant of differential evolution (DE) and a local search method. It presents a competitive variants of DE is used for global exploration and the classic soils Wet's algorithm (cDESW) is used as a local search process. PID parameters of this algorithm at different number of generations and different values of alpha are shown in Table 2 [34]. The application of PSO is revisited in [35] for designing the optimal values of PID parameters. Madinehi et al., 2011 have presented the application of Shuffled Frog Leaping (SFL) algorithm and PSO for determining the optimal PID parameters [36].

The application of chaotic ant swarm (CAS) algorithm based PID controller for AVR system is presented in [37]. The Lozi map based chaotic optimization approach is used in [12] for application of AVR system. The craziness based PSO (CRPSO) binary coded GA are the two props used to evaluate the optimal PID gains. Under nominal operating conditions, CRPSO proves to be more robust than GA in performing optimal transient performance. The PSO optimization approach for determining optimal PID parameters of an AVR system with two different set of are considered in [38].

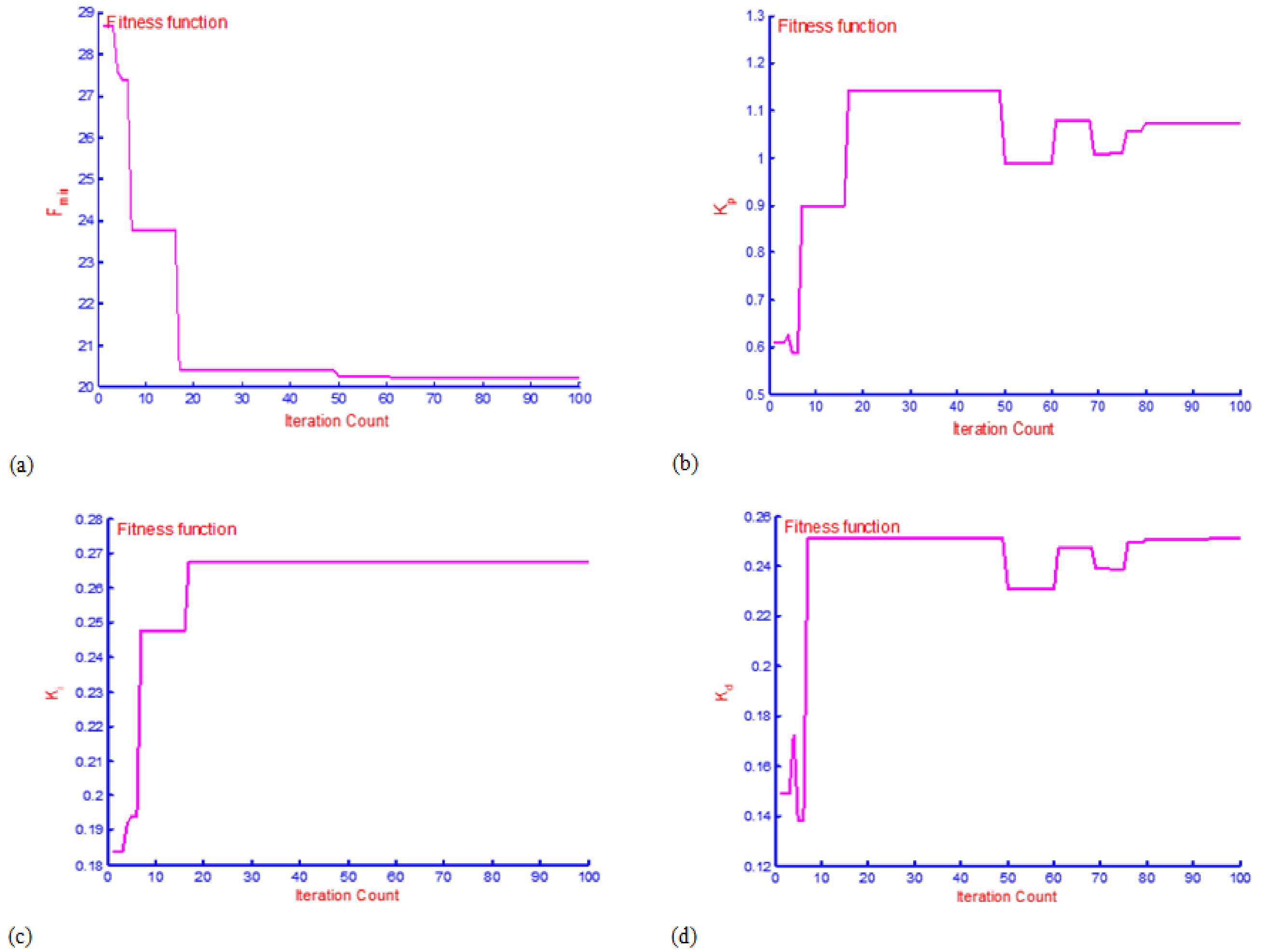

Figure 8. The behavior of FPA in terms of fitness function, PID parameters and iteration count

Table 2. The details of PID controllers in literature

Author/year	Amplifier $\left(\frac{K_a}{1+\tau_a s}\right)$	Exciter $\left(\frac{K_e}{1+\tau_e s}\right)$	Generator $\left(\frac{K_g}{1+\tau_g s}\right)$	Sensor $\left(\frac{K_s}{1+\tau_s s}\right)$	Algorithm	K_p	K_i	K_d
Proposed	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	FPA-PID	1.0753	0.2675	0.2512
Afroomand, 2016 [22]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=1$	VBSO-2	0.9977	0.6945	0.3110
Chatterjee, 2016 [23]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=0.7, \tau_g=1.2$	$K_s=1, \tau_s=0.01$	TLBO	0.5376	0.4001	0.1780
			$K_g=0.8, \tau_g=1$			0.5110	0.4015	0.1738
			$K_g=0.9, \tau_g=1$			0.5482	0.4020	0.1767
			$K_g=1, \tau_g=1$			0.5302	0.4001	0.1787
Verma, 2015 [24]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	-	0.601	1.160	0.0781
					GWO(α)	0.6459	0.4527	0.2128
					GWO(β)	0.6174	0.4327	0.2035
Yegireddy, 2015 [25]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	NSGA-II	0.7769	0.7984	0.3615
Aberbour, 2015 [26]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	PSO	0.6835	0.6322	0.2722
Kumar, 2015	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	GSA	0.60539	0.41477	0.20070
Gozde, 2014 [27]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	CPSO	1.3064	1.0454	1.2400
Priyambada, 2014 [28]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	TLBO	1.9522	0.4515	0.4753
Hasanien, 2013 [29]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	TCGA	0.6	0.5	0.2
						0.7	0.6	0.25
						0.8	0.7	0.3
Nirmal, 2013 [30]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	ZN	1.08	1.98	0.1469
					PSO	0.3452	0.4778	0.1017
					MOL	0.5523	0.4418	0.1572
Kumar, 2013 [31]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	PSO-PID $(\beta=1.0)$	0.6938	0.3780	0.3216
					GA-PID $(\beta=0.5)$	0.6233	0.3728	0.2820
Bayram, 2013 [32]	$K_a=10, \tau_a=0.05$	$K_e=10, \tau_e=0.5$	$K_g=0.8, \tau_g=1.5$	$K_s=1, \tau_s=0.05$	ZN-PID	0.71513	1.10020	0.11621
Shayeghi, 2012 [33]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=0.7, \tau_g=1$	$K_s=1, \tau_s=0.01$	ASO	0.9068	0.4626	0.3279
			$K_g=0.8, \tau_g=1.6$		VEPSO	0.8144	0.4215	0.2961
			$K_g=0.9, \tau_g=1.4$		CRPSO	0.6772	0.3334	0.2350
Sahu, 2012 [34]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	MOL	0.5473	0.3556	0.1668
Panda, 2012 [12]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	MOL (ITAE)	0.5857	0.4189	0.1772
Sahu, 2012 [35]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	PSA	1.2771	0.8471	0.4775
Mandal, 2011 [36]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	cDESW $(\alpha=1)$	0.6822	0.6297	0.2714
					cDESW $(\alpha=1.5)$	0.6287	0.4678	0.2212
Rahimian, 2011 [37]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	PSO	0.6770	0.5189	0.2287
Madinehi, 2011 [38]	$K_a=10, \tau_a=0.1$	$K_e=1, \tau_e=0.4$	$K_g=1, \tau_g=1$	$K_s=1, \tau_s=0.01$	SFL-PID	0.9761	0.2554	0.3602
					PSO-PID	0.9342	0.2492	0.2312
Zhu, 2009 [39]	$K_a=12, \tau_a=0.09$	$K_e=10, \tau_e=0.05$	$K_g=0.1, \tau_g=1.1$	$K_s=1, \tau_s=0.02$	CAS-PID	0.5613	0.3670	0.2326

Author/year	Amplifier $\left(\frac{K_a}{1+\tau_a s}\right)$	Exciter $\left(\frac{K_e}{1+\tau_e s}\right)$	Generator $\left(\frac{K_g}{1+\tau_g s}\right)$	Sensor $\left(\frac{K_s}{1+\tau_s s}\right)$	Algorithm	K_p	K_i	K_d
Dos, 2009 [14]	$K_a = 10, \tau_a = 0.1$	$K_e = 1, \tau_e = 0.4$	$K_g = 0.7, \tau_g = 1$	$K_s = 1, \tau_s = 0.01$	COLM	0.887	0.646	0.309
			$K_g = 0.7, \tau_g = 1.5$			1.174	0.647	0.456
			$K_g = 0.7, \tau_g = 2$			1.456	0.649	0.594
			$K_g = 1, \tau_g = 1$			0.622	0.453	0.218
			$K_g = 1, \tau_g = 1.5$			0.818	0.443	0.315
			$K_g = 1, \tau_g = 2$			1.021	0.456	0.418
Gaing, 2004 [40]	$K_a = 10, \tau_a = 0.1$	$K_e = 1, \tau_e = 0.4$	$K_g = 1, \tau_g = 1$	$K_s = 1, \tau_s = 0.01$	PSO-PID $(\beta = 1.0)$	0.6570	0.5389	0.2458
					PSO-PID $(\beta = 1.5)$	0.6254	0.4577	0.2187

4.3. Simulation Results

The transient response performance is compared and presented in Table 3. It represents the transient response comparison in terms of peak value and settling time with set value of sampling time is 0.02 seconds for the different PID controllers as demonstrate in the literature. The performance of Flower Pollination Algorithm based PID controller (FPA-PID) controller in terms of peak value and settling time is better as compared to other PID controllers in literature. The peak value and settling time of the system response with proposed FPA-PID is 0.9976 and 1.448 second, respectively and is mentioned in Table 3.

Afroomand, 2016 [19] generates the step response in terms of peak value and settling time with the help of VBSO-2 technique and values are 1.119 and 4.613 sec, respectively which is greater than the proposed FPA-PID controller. In Chatterjee, 2016 [20]; the TLBO technique is used to design the PID controller for varying generator parameters and presented the values of peak as 1.126, 1.137, 1.123, 1.129 and settling time as 4.690 sec, 4.575 sec, 4.747 sec, 4.804 sec, respectively as shown in Table 3. All the values of peak and settling time are also high in comparison to proposed FPA optimization technique.

Verma, 2015 [21] presents the Conventional PID, GWO and GWO technique for AVR system and evaluates the peak with values 1.648, 1.118, 1.117 and settling time with values 6.044, 4.727, 4.632, respectively. Yegireddy, 2015 [22] considered NSGA-II algorithm and evaluate the transient response in terms of peak value and settling time as 1.211 and 5.817, respectively. Aberbour, 2015 [23] represents the PSO-PID controller and calculate the peak value is 1.181 and settling time is 3.983 seconds.

The GSA, CPSO, and TLBO techniques are presented in [24,25,26], respectively with system response as peak value and settling time of generator terminal step response as shown in Table 3. Hasanien, 2013 [27] presents the three values of peak and settling time for three different values of PID parameters as 1.152, 1.161, 1.167 and 4.250, 4.117, 4.097, respectively, using TCGA method.

Nirmal, 2013 [28] represents the three methodologies throughout the article are ZN, PSO, and MOL and get the values of peak 1.642, 1.307, 1.144 and settling time with values 3.803, 4.651, 4.212, respectively. Kumar, 2013 [29] presents the use of PSO and GA technique at different values of $\beta = 1.0$ and $\beta = 0.5$, respectively. The step response comparison in terms of peak values and settling time are given by 1.100, 1.108 and 5.988 secs, 5.912 secs, respectively.

Bayram, 2013 [30] obtained peak value is 1.488 and settling time is 3.391 secs, which are designed using the ZN method. Shayeghi, 2012 [31] presents the controllers for AVR system using ASO, VEPSO, and CRPSO techniques with generator parametric variations. The response parameters using these controllers as peak values and settling time are 1.082, 1.082, 1.065 and 6.256, 6.275, 6.218, respectively.

Sahu, 2012 [32], Panda, 2012 [11] and Sahu, 2012 [33] gives the values of peak as 1.097, 1.118, 1.126 and settling time as 5.358, 4.938, 5.110 using optimization technique MOL, MOL(ITAE) and PSA, respectively. Mandal, 2011 [34] performs the cDESW technique at the value of weighting factor $\alpha = 1.0$ and $\alpha = 1.5$. The PID controller based on cDESW, gives response with peak value and settling time as 1.180 and 4.078 secs., respectively. However, the PID controller using cDESW, presents peak value as 1.131 and settling time as 4.728 secs [34].

Rahimian, 2011 [35] uses the application of PSO algorithm for designing the PID controller and the response presents peak with value 1.136 and settling time with value 4.594 sec. Madinehi, 2011 [36] obtain a values of peak and settling time by using SFL and PSO optimization techniques with values 1.019, 0.9863 and 6.008 sec, 1.519 sec, respectively as enlisted in Table 3. Zhu, 2009 [37] have presented the performance in peak value and settling time as 1.114 and 5.530 secs, respectively with the help of CAS-PID controller. In Dos, 2009 [12] perform the COLM technique for parametric variations of generator as shown in Table 3 and produces a peak with values 1.131, 1.103, 1.087, 1.127, 1.092, 1.078 and settling time with values 4.785 sec, 5.855 sec, 6.943 sec, 4.996 sec, 6.065 sec, 6.848 sec, respectively as mentioned in Table 3. Gaing, 2004 [38] consider PSO algorithm for different weighting factors and values and results with peak values and settling time as shown in Table 3.

Table 3. The comparison of the step response details in terms of settling time and peak

Author/year	Peak	Settling time (sec.)
Proposed	0.9976	1.448
Afroomand, 2016 [22]	1.119	4.613
Chatterjee, 2016 [23]	1.126	4.690
	1.137	4.575
	1.123	4.747
	1.129	4.804
Verma, 2015 [24]	1.648	6.044
	1.118	4.727
	1.117	4.632
Yegireddy, 2015 [25]	1.211	5.817
Aberbour, 2015 [26]	1.181	3.983
Kumar, 2015 [41]	1.112	4.995
Gozde, 2014 [27]	1.242	9.331
Priyambada, 2014 [28]	0.9430	6.332
Hasanien, 2013 [29]	1.152	4.250
	1.161	4.117
	1.167	4.097
Nirmal, 2013 [30]	1.642	3.803
	1.307	4.651
	1.144	4.212
Kumar, 2013 [31]	1.100	5.988
	1.108	5.912
Bayram, 2013 [32]	1.488	3.391
Shayeghi, 2012 [33]	1.082	6.256
	1.082	6.275
	1.065	6.218
Sahu, 2012 [34]	1.097	5.358
Panda, 2012 [12]	1.118	4.938
Sahu, 2012 [35]	1.126	5.110
Mandal, 2011 [36]	1.180	4.078
	1.131	4.728
Rahimian, 2011 [37]	1.136	4.594
Madinehi, 2011 [38]	1.019	6.008
	0.9863	1.519
Zhu, 2009 [39]	1.114	5.530
Dos, 2009 [14]	1.131	4.785
	1.103	5.855
	1.087	6.943
	1.127	4.996
	1.092	6.065
	1.078	6.848
Gaing, 2004 [40]	1.154	4.441
	1.128	4.861

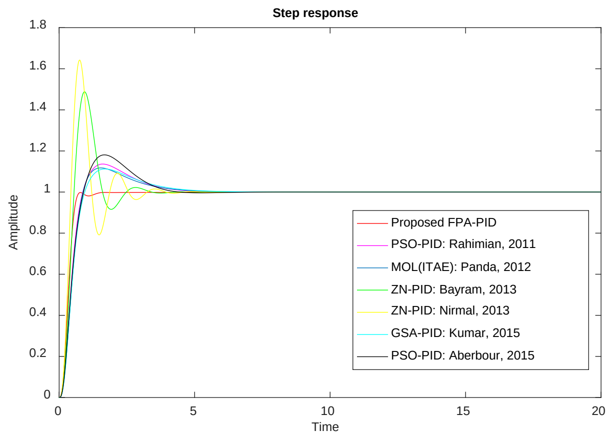

Figure 9. The sample response comparison of the AVR system with proposed PID controller (FPA-PID) and controllers in literature [11,23,24,28,30,35]

4.3.1. On Performance Indices

The step response of the AVR system is discussed in terms of performance indices like ISE, IAE and ITAE as well described below in Eq.13 – Eq. 15.

$$ISE = \int_{t=0}^{T_{sim}} \left|\Delta v(t)\right|^2 dt \tag{13}$$

$$IAE = \int_{t=0}^{T_{sim}} \left|\Delta v(t)\right| dt \tag{14}$$

$$ITAE = \int_{t=0}^{T_{sim}} t\left|\Delta v(t)\right| dt \tag{15}$$

4.3.2. Comparison of PIs

The analysis of the performance of PID controller design for the AVR system with different types of performance indices like Integral Square Error (ISE), Integral Absolute Error (IAE), and Integral Time Absolute Error (ITAE) as discussed in section 4.3.1 the minimum value of performance as compared to others. In Table 4, the evaluated performance indices as ISE, IAE and ITAE for proposed algorithm is 19.5332, 19.6362 and 199.8672, respectively. These values are lesser as compared to all other optimized controllers as presented in Table 4 and all these values are measured at simulation time 20 seconds and sampling time 0.02 seconds.

4.3.3. Based on ITAE

Madinehi, 2011 [36] gives better performance to other controllers in literature except proposed in terms of ITAE for PSO-PID controller with value as 199.8733. The ITAE value for ZN-PID controller in [28] is 200.1208. Verma, 2015 [21] presents the ITAE value as 200.1462 for conventional PID controller and higher in comparison to proposed resulting the poor performance. These controllers are poor in performance as compared to proposed but better to ZN-PID [30], PSO-PID [28] and SFL-PID [36] controllers with ITAE values 200.1764, 200.3359 and 200.3392, respectively.

On comparing ITAE in Table 4, the worst performing controllers are Gozde,2014 [25] for CPSO technique, Dos, 2009 [12] for COLM technique with generator parameters ($K_g = 0.7, \tau_g = 2.0$ and $K_g = 1.0, \tau_g = 2.0$), Kumar, 2013 [29] for different weighting factors using PSO and GA optimization technique with values as 201.2018, 200.7798, 200.7106, 200.6973, 200.6437, respectively.

4.3.4. Based on IAE

In this analysis, according to the best solution in Table 4, for IAE error function, only Madinehi, 2011 [36] for SFL-PID and PSO-PID controller obtained a best value as 19.6177 and 19.6087, respectively comparison to proposed FPA-PID controller with value as 19.6362 but all PID controllers in literature gives poor performance in comparison to proposed method.

According to the best solution, Shayeghi, 2012 [31] and Sahu, 2012 [32] appears to be fourth and fifth priority with IAE values 19.7100, 19.7287, using CRPSO and

MOL optimization technique respectively. Similarly, Zhu, 2009 [37] for CAS-PID controller with value of IAE as 19.8552.

The worst performing controllers are based on ZN-PID and conventional PID controllers in [21,28] with IAE values as 19.9594 and 19.9237, respectively. the other controllers in Bayram, 2013 [30], Gozde, 2014 [25], Sahu, 2012 [33], presents the IAE values as 19.9191, 19.9142, 19.8919, respectively.

4.3.5. Based on ISE

In this analysis, according to the best solution, PSO-PID controller in [36] obtains a best value as 19.4970 comparison to proposed method with ISE value as 19.5332. However, all remaining PID controllers in literature gives poor performance as compared to proposed FPA optimized PID controller.

Table 4. The performance indices of the response at simulation time 20 seconds

Particulars	ISE	IAE	ITAE
Proposed FPA	19.5332	19.6362	199.8672
Afroomand, 2016 [22]	20.0225	19.8660	200.4390
Chatterjee, 2016 [23]	19.8985	19.7600	200.4264
	19.9119	19.7609	200.4324
	19.8955	19.7612	200.4165
	19.9024	19.7600	200.4328
Verma, 2015 [24]	20.3968	19.9237	200.1462
	19.9276	19.7891	200.4418
	19.9136	19.7788	200.4384
Yegireddy, 2015 [25]	20.1439	19.8847	200.5055
Aberbour, 2015 [26]	20.0709	19.8578	200.4749
Kumar, 2015 [41]	19.8965	19.7689	200.4403
Gozde, 2014 [27]	20.3461	19.9142	201.2018
Priyambada, 2014 [28]	19.7814	19.7875	200.3595
Hasanien, 2013 [29]	19.9857	19.8099	200.4239
	20.0372	19.8433	200.4477
	20.0728	19.8671	200.4620
Nirmal, 2013 [30]	20.3210	19.9594	200.1208
	20.0947	19.8007	200.3359
	19.9344	19.7836	200.3656
Kumar, 2013 [31]	19.8664	19.7454	200.6973
	19.8703	19.7417	200.6437
Bayram, 2013[32]	20.2376	19.9191	200.1764
Shayeghi, 2012 [33]	19.8984	19.7938	200.5668
	19.8695	19.7727	200.5483
	19.7631	19.7100	200.4614
Sahu, 2012 [34]	19.8243	19.7287	200.3846
Panda, 2012 [12]	19.9006	19.7712	200.3950
Sahu, 2012 [35]	20.0667	19.8919	200.5511
Mandal, 2011 [36]	20.0697	19.8511	200.4751
	19.9525	19.7962	200.4647
Rahimian, 2011 [37]	19.9816	19.8172	200.4450
Madinehi, 2011 [38]	19.5415	19.6177	200.3392
	19.4970	19.6087	199.8733
Zhu, 2009 [39]	19.8662	19.7375	200.5569
Dos, 2009 [14]	20.0246	19.8552	200.4771
	20.0042	19.8554	200.6353
	19.9924	19.8559	200.7798
	19.9392	19.7892	200.4649
	19.8987	19.7842	200.5863
	19.8940	19.7906	200.7106
Gaing, 2004 [40]	20.0112	19.8244	200.4775
	19.9429	19.7915	200.4636

The SFL-PID controller [36], CRPSO-PID controller [31], TLBO-PID controller [26] with ISE values 19.5415, 19.7631, 19.7814, respectively, may be considered with third, fourth and fifth priority in selection of a controller as compared to controllers in literature and proposed one. However, the controller based on MOL optimization technique may be considered on sixth priority with ISE value as 19.8243 [32].

The worst performing controllers are verma, 2015 [21], Gozde, 2014 [25], Nirmal, 2013 [28] with ISE value as 20.3968, 20.3461, 20.3210, respectively. Similarly, Bayram, 2013 [30] and Yegireddy, 2015 [22] for ZN-PID controller and NSGA-II method presents the ISE values as 20.2376, 20.1439, respectively.

4.3.6. Eigenvalue Analysis

In this section, eigenvalue analysis is performed in terms of oscillatory modes, damping factor and frequency of oscillations for proposed FPA and PID controllers in literature with sampling time 0.02 seconds.

4.3.7. Based on Oscillatory Modes

In the analysis of oscillatory modes, proposed FPA optimized PID controller obtained better stability in comparison as compared to TCGA method [27], COLM technique [12] for generator parameters such as $\left(K_g = 1, \tau_g = 2\right)$, $\left(K_g = 0.7, \tau_g = 1\right)$ and, $\left(K_g = 0.7, \tau_g = 1.5\right)$ NSGA-II method [22], VBSO-2 method [19], ZN-PID controller [30], PSA-PID controller [33], Conventional PID controller [21] as presented in Table 5.

The worst performing controllers which are lies in the right half of s-plane and moves the system towards unstable region is ZN-PID controller [28] has first priority. Similarly, TLBO-PID controller [26], CPSO-PID controller [25] and COLM technique [12] have second, third, fourth priority, respectively as shown in Table 5.

4.3.8. Based on Damping Factor

The proposed FPA-PID controller calculate the value of damping factor is 0.0750 which is better because of oscillations damped out early in comparison to COLM technique [12] for varying generators parameters such as $\left(K_g = 0.7, \tau_g = 1\right)$, $\left(K_g = 1, \tau_g = 2\right)$, $\left(K_g = 0.7, \tau_g = 1.5\right)$ and $\left(K_g = 0.7, \tau_g = 2\right)$ presents the values of damping factor as 0.0722, 0.0691, 0.0309, -0.0025, respectively.

The NSGA-II method [22], VBSO-2 method [19], ZN-PID [30], Conventional PID [21], PSA-PID [33], CPSO-PID [25], TLBO-PID [26], ZN-PID [28] controllers obtained the values of damping factor as 0.0675, 0.0507, 0.0230, 0.0053, 0.0047, -0.0114, -0.0412, -0.0733, respectively as enlisted in Table 5.

4.3.9. Based on Frequency of Oscillations

In this analysis, proposed FPA optimized PID controller has frequency of oscillations with value 0.7588 which is better in comparison to Dos, 2009 [12] for generator parameters $\left(K_g = 0.7, \tau_g = 1.5\right)$ and $\left(K_g = 0.7, \tau_g = 2.0\right)$. The PSA-PID controller [33], CPSO-PID controller [25], TLBO-PID controller [26] also gives worst performance in comparison to proposed method with values of frequency of oscillations as shown in Table 5.

Table 5. The eigenvalue analysis and comparison with controllers in literature

Particulars	Mode of oscillations	Damping factor	Frequency (Hz)
Proposed FPA	-0.3576 ± 4.7529i	0.0750	0.7588
Afroomand, 2016 [22]	-0.2302 ± 4.5301i	0.0507	0.7210
Chatterjee, 2016 [23]	-0.6467 ± 3.4159i	0.1860	0.5437
	-0.6559 ± 3.3269i	0.1934	0.5295
	-0.6404 ± 3.4496i	0.1825	0.5490
	-0.6498 ± 3.3916i	0.1882	0.5398
Verma, 2015 [24]	-0.0190 ± 3.5671i	0.0053	0.5677
	-0.5526 ± 3.7309i	0.1465	0.5938
	-0.5821 ± 3.6537i	0.1573	0.5815
Yegireddy, 2015[25]	-0.2718 ± 4.0190i	0.0675	0.6396
Aberbour, 2015 [26]	-0.4088 ± 3.7994i	0.1070	0.6047
Kumar, 2015 [41]	-0.6020 ± 3.6229i	0.1639	0.5766
Gozde, 2014 [27]	0.0577 ± 5.0650i	-0.0114	0.8061
Priyambada, 2014 [28]	0.2490 ± 6.0409i	-0.0412	0.9614
Hasanien, 2013 [29]	-0.5369 ± 3.5856i	0.1481	0.5707
	-0.4250 ± 3.8495i	0.1097	0.6127
	-0.3222 ± 4.0883i	0.0786	0.6507
Nirmal, 2013 [30]	0.3402 ± 4.6263i	-0.0733	0.7363
	-0.5305 ± 2.6840i	0.1939	0.4272
	-0.6037 ± 3.4517i	0.1723	0.5494
Kumar, 2013 [31]	-0.5758 ± 3.8819i	0.1467	0.6178
	-0.6237 ± 3.6874i	0.1668	0.5869
Bayram, 2013 [32]	-0.0886 ± 3.8490i	0.0230	0.6126
Shayeghi, 2012 [33]	-0.3908 ± 4.3754i	0.0890	0.6964
	-0.4716 ± 4.1739i	0.1123	0.6643
	-0.6160 ± 3.8495i	0.1580	0.6127
Sahu, 2012 [34]	-0.6812 ± 3.4611i	0.1931	0.5509
Panda, 2012 [12]	-0.6086 ± 3.5624i	0.1684	0.5670
Sahu, 2012 [35]	-0.0236 ± 5.0343i	0.0047	0.8012
Mandal, 2011 [36]	-0.4110 ± 3.7963i	0.1076	0.6042
	-0.5499 ± 3.6779i	0.1479	0.5854
Rahimian, 2011 [37]	-0.4905 ± 3.8027i	0.1279	0.6052
Madinehi, 2011 [38]	-0.4358 ± 4.5620i	0.0951	0.7261
	-0.4702 ± 4.4774i	0.1044	0.7126
Zhu, 2009 [39]	-0.6639 ± 3.5019i	0.1863	0.5573
Dos, 2009 [14]	-0.3112 ± 4.2996i	0.0722	0.6843
	-0.1509 ± 4.8763i	0.0309	0.7761
	0.0134 ± 5.3453i	-0.0025	0.8507
	-0.5643 ± 3.6620i	0.1523	0.5828
	-0.4576 ± 4.1778i	0.1089	0.6649
	-0.3198 ± 4.6145i	0.0691	0.7344
Gaing, 2004 [40]	-0.4850 ± 3.7430i	0.1285	0.5957
	-0.5591 ± 3.6708i	0.1506	0.5842

4.4. Robustness Performance

Two conditions have analyzed to observe the stability and robust performance of the AVR system such as (a) The eigenvalue analysis with varying generator parameters (gain and time constants). (b) The time domain analysis with varying time constant parameters of AVR system for ± 20% conditions.

4.4.1. Eigenvalue Analysis for 156 Plants with FPA-PID Controller

In the literature, AVR system models represented based on changes in K_g and τ_g as shown in Table 2. The four plant conditions are considered in [20] from the range of $0.7 \le K_g \le 1.0$ and $1.0 \le \tau_g \le 1.2$. Dos 2009 [12] have analyzed six plant conditions of K_g and τ_g from the range of $0.7 \le K_g \le 1.0$ and $1.0 \le \tau_g \le 2.0$, respectively. In this paper, the generator parameters are subjected to change with step size of 0.10 within the range of parameters as shown in Eq. 16. The combined effect of these parameters obtained 156 plant conditions. The eigenvalue plot of the AVR system for different 156 plant conditions with proposed FPA-PID controller is shown in Figure 10.

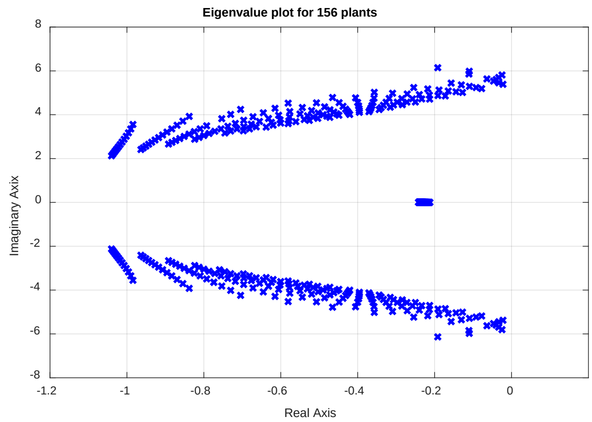

Figure 10. Eigenvalue plot for 156 plant conditions with proposed PID controller to AVR system

It can be seen that none of the eigenvalue is lying in right hand side of the s-plane. Therefore, the system is stable for these 156 plant conditions and providing to be robust in operation in terms of stability with proposed FPA optimize PID controller for such wide range of plant conditions.

$$0.4 \le K_g \le 1.5$$
$$0.8 \le \tau_g \le 2.0. \quad (16)$$

4.4.2. Performance with Varying AVR System

Robustness analysis of any power system is very necessary because of power system operating point varies with different values of load and also the system parameters are not constant [20]. In the presented work, to analyze the robustness of the AVR system with FPA optimized PID controller with sampling time set as 0.02 second, the uncertainties of the AVR system described in terms of varying time constants parameters of amplifier, exciter, generator and sensor between the range of -20% to +20% in steps of 5% for maintaining the actual response of the system in abnormal cases and observe the behavior of the AVR system.

The behavior of the AVR system with varying time constants along with the actual response is shown in Figure 12 to Figure 15. The robustness of the system performed by evaluating settling time, peak amplitude and PI's with ISE, IAE, ITAE as enlisted in Table 6. The open loop response of AVR system shown in Figure 11 produces the settling time and peak with values 8.542, 1.506, respectively. The values of ISE, IAE and ITAE with values 16.7520, 18.0661, 181.8482, respectively as shown in Table 6.

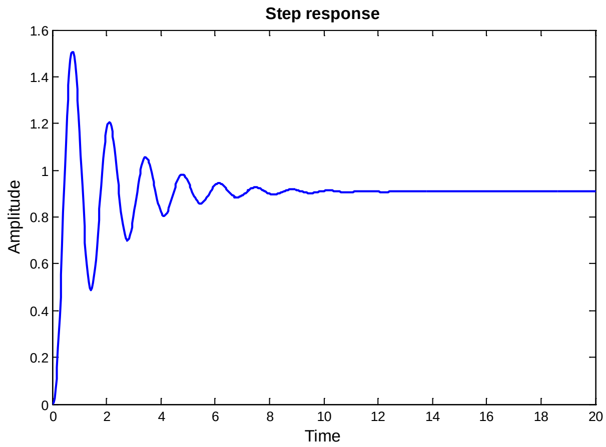

Figure 11. Response of AVR system without controller

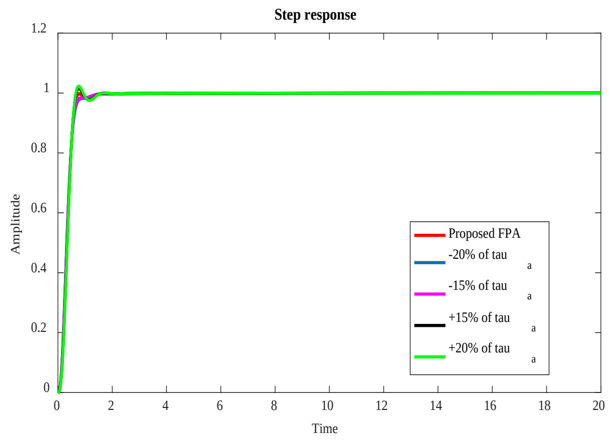

Figure 12. Robustness analysis of AVR system by changing time constant ranging from -20% to +20% for τ_a

Table 6. Robustness analysis of FPA-PID controller

S. No.	Controller	Time Cons-tant Para-meters	Rate of Change in %	Transient Response		Performance Indices		
				Settling Time	Peak	ISE	IAE	ITAE
1.	Without Controller	-	-	8.542	1.506	16.7520	18.0661	181.8482
2.	FPA-PID Controller	τ_a	-20%	1.385	-	19.5244	19.6362	199.8600
			-15%	1.404	0.9839	19.5270	19.6362	199.8618
			+15%	1.519	1.016	19.5396	19.6362	199.8726
			+20%	1.557	1.023	19.5418	19.6362	199.8744
3.		τ_e	-20%	1.385	-	19.5167	19.6363	199.8384
			-15%	1.461	0.9687	19.5209	19.6363	199.8456
			+15%	1.653	1.023	19.5453	19.6362	199.8888
			+20%	1.710	1.031	19.5492	19.6362	199.8960
4.		τ_g	-20%	1.385	0.9686	19.5132	19.6364	199.7958
			-15%	1.404	0.9768	19.5183	19.6363	199.8136
			+15%	1.576	1.014	19.5475	19.6361	199.9208
			+20%	1.633	1.019	19.5521	19.6361	199.9387
5.		τ_s	-20%	1.519	0.9959	19.5301	19.6342	199.8657
			-15%	1.519	0.9963	19.5309	19.6347	199.8661
			+15%	1.500	0.9991	19.5356	19.6377	199.8683
			+20%	1.538	0.9996	19.5364	19.6382	199.8687

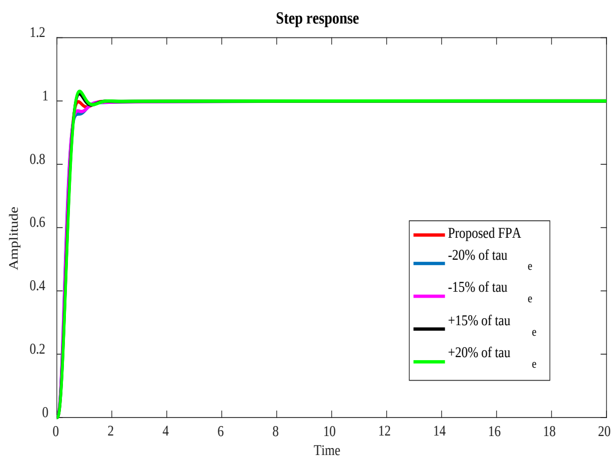

Figure 13. Robustness analysis of AVR system by changing time constant ranging from -20% to +20% for τ_e

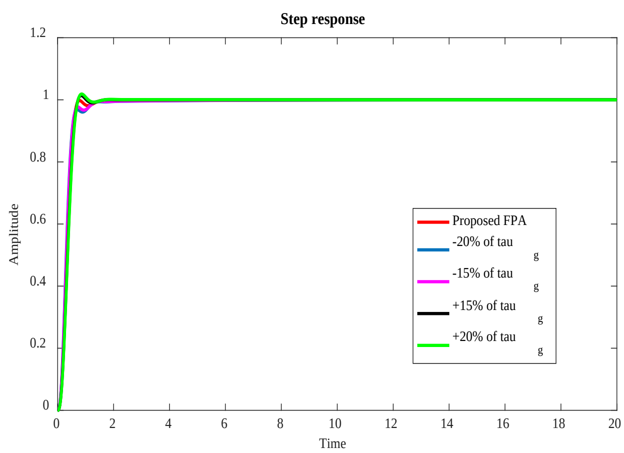

Figure 14. Robustness analysis of AVR system by changing time constant ranging from -20% to +20% for τ_g

In terms of transient response analysis, for rate of change of -20% of amplifier time constant (τ_a) peak is not produced and settling time with value as 1.385. The settling time as 1.404, 1.519, 1.557, and peak value as 0.9839, 1.016, 1.023, respectively from -15% to +20% for amplifier time constants. The settling time for the -20% of exciter time constants is 1.385 with no peak amplitude. For the time constant of exciter (τ_e) evaluates the settling time and peak values are 1.461, 1.653, 1.710 and 0.9687, 1.023, 1.031, respectively ranging from -15% to +20%.

For the generator time constant (τ_g) presents the settling time with values 1.385, 1.404, 1.576, 1.633 and peak with values 0.9686, 0.9768, 1.014, 1.019, respectively between the range of -20% to +20%. The time constants of sensor (τ_s) obtain the settling time as 1.519, 1.519, 1.500, 1.538 and peak value as 0.9959, 0.9963, 0.9991, 0.9996, respectively in the range of -20% to +20% as mentioned in Table 6.

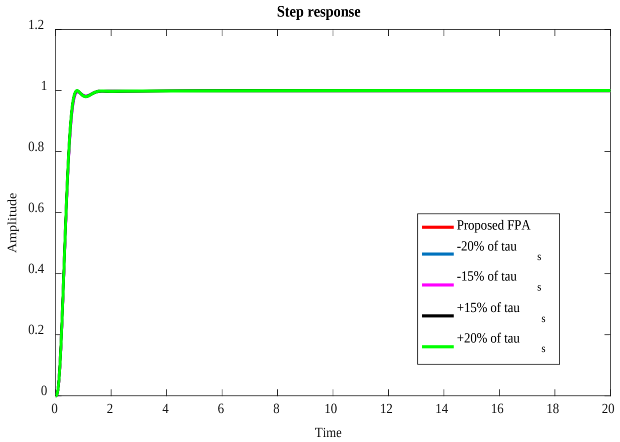

Figure 15. Robustness analysis of AVR system by changing time constant ranging from-20% to +20% for τ_s

In terms of performance indices, evaluates the error functions such as ISE, IAE and ITAE to check the robustness of the AVR system optimized with FPA-PID controller as presented in Table 6. The varying parameter τ_a from -20% to +20% obtained the ISE values as 19.5244, 19.5270, 19.5396, 19.5418, IAE values as 19.6362, 19.6362, 19.6362, 19.6362 and ITAE values as 199.8600, 199.8618, 199.8726, 199.8744, respectively. The exciter time constants τ_e represents the ISE with values 19.5167, 19.5209, 19.5453, 19.5492, IAE with values 19.6363, 19.6363, 19.6362, 19.6362 and ITAE with values 199.8384, 199.8456, 199.8888, 199.8960, respectively.

The time constant τ_g obtained the ISE values as 19.5132, 19.5183, 19.5475, 19.5521, IAE values as 19.6364, 19.6363, 19.6361, 19.6361 and ITAE values as 199.7958, 199.8136, 199.9208, 199.9387, respectively between the range -20% to +20% as shown in Table 6. The time constant τ_s produced the ISE with values 19.5301, 19.5309, 19.5356, 19.5364, IAE with values 19.6342, 19.6347, 19.6377, 19.6382 and ITAE with values 199.8657, 199.8661, 199.8683, 199.8687, respectively ranging from -20% to +20 % as enlisted in Table 6.

According to above analysis and simulation results, it is show that the FPA-PID controller is robust in nature.

5. Conclusion

In this work, the FPA optimization technique is considered to effective design of PID controller for AVR system. The optimally tuned FPA-PID controller is take into account using integral absolute error. The performance of proposed algorithm is measured for 100 number of iterations. The AVR system response with proposed FPA-PID controller is found to be better and compared that of with controllers in literature (42 in number). The performance is compared in terms of peak value, settling time and performance indices like ISE, IAE and ITAE. The robustness analysis of the proposed FPA based PID controller is considered for 156 plant conditions and varying time constants parameters as ±20% system conditions. The system stability with proposed FPA optimized PID controller also analyzed in the form of eigenvalues, damping factor and frequency of oscillations.

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