Tuning of Novel Fractional Order Fuzzy PID Controller for Automatic Voltage Regulator using Grasshopper Optimization Algorithm

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ABSTRACT:
One of the essential pieces of equipment in the power system is the Automatic Voltage Regulator (AVR) or synchronous generator excitation. The system's goal is to maintain the terminal voltage of the synchronous generator at the desired level. AVR is inherently uncertain. Hence, the proposed controller should be able to handle the problem. In this paper, Fractional Order Fuzzy PID (FOFPID) controller has been employed to control the system. To enhance the controller's performance, the Grasshopper Optimization Algorithm (GOA) is used to tune the controller's parameters. Unlike other methods, the FOFPID controller gains are not constant and alter in different operating conditions. The robustness of the controller has been investigated, and the comparative results show that the proposed controller has a better performance against other methods.

KEYWORDS: Automatic Voltage Regulator (AVR), Synchronous Generator Excitation, Fractional-order Fuzzy PID (FOFPID) Controller, Grasshopper Optimization Algorithm (GOA), Uncertainty.

1. INTRODUCTION

Reaching an acceptable and reliable voltage level in power systems is a challenging issue. Performance of the power systems will descend if the nominal voltage level deviates from the rated voltage (a particular voltage level of the power system's designed equipment). AVR has four major components as Amplifier, Exciter, Synchronous generator, and Sensor. The AVR is employed for checking the terminal voltage by adapting the voltage of the synchronous generator. Hence, it can handle the control problem of deviation between the nominal voltage and rated voltage to overcome the system failure.

The main problem in AVR is the high inductance of the alternator field windings and load variations. Stable and fast response to the regulator is critical to the system. Therefore, improvement of the AVR performance is significant for improving the voltage response of the AVR system. Various approaches have been developed in control theories, but PID is more popular because of its simplicity.

2. LITERATURE REVIEW

Zeng et al. [1] proposed a population-based iterated optimization algorithm with a multi-non-uniform mutation called RCEO-FOPID to design Fractional Order PID controllers (FOPID) in AVR systems. Gizi [2] designed a Fuzzy PID (FPID) controller by using Particle Swarm Optimization (PSO) and Sugeno Fuzzy Logic (SFL) to determine the optimal PID controller of generator parameters in the AVR system.

Teaching–Learning Based Optimization (TLBO) algorithm is developed [3] as an optimization technique to determine the optimum value of PID controller gains with first-order low pass filter installed in the AVR. Hasanien [4] developed an optimal design for the PID controller in the AVR system by using the Taguchi Combined Genetic Algorithm (TCGA) to reach the approximated values of design variables and minimize the maximum percentage overshoot, the rise time, the settling time, and the steady-state error of the terminal voltage of the synchronous generator to have an improved step response. Pradhan et al. [5] used the Ant

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Lion Optimization (ALO) to obtain the PID controlled AVR system's optimal tuning parameters. The proposed method has imperious value in transient and frequency domain analysis compared to other heuristic optimization algorithms. Authors in [6] introduced an authoritative optimization technique named Stochastic Fractal Search (SFS) that increases accuracy and reduces settling time. The presented algorithm has a better dynamic and static response profile of the concerned power system than the existing algorithms.

This paper introduces a FOFPID and FOPID controller to control the terminal voltage of the synchronous generator. In the proposed controllers, Fuzzy Inference System (FIS) determines the three gain of FOFPID controller and the gains and order of FOPID are achieved using GOA. Due to changing coefficients in versatile conditions, the FOFPID controller has better performance than the FOPID controller. The FIS has two inputs (error and derivative of error) and three outputs (gain of the controller). The location of Membership Functions (MFs), derivative and integral order of the controller have been achieved using GOA. Finally, the performance of the proposed controller has been examined with three different scenarios (based on uncertainty) and has been compared to the method of other articles (PID_GOA) [7]. This study is organized as follows: AVR modelling is expressed in Section 3. The equations and model of the Proposed FOPID and FOFPID controller are presented in Section 4. Section 5 demonstrates results and compares the proposed method with the other methods, and Section 6 represents the conclusions.

3. SYSTEM DESCRIPTION

AVR systems mainly consist of four main components including amplifier, exciter, generator, and sensor. As shown in Fig. 1, K_A, K_E, K_G, and K_R are the gains of amplifier, exciter, generator, and sensors, respectively. τ_A, τ_E, τ_G, and τ_R are inertia time constants of the amplifier, exciter, generator, and sensors, respectively.

The lower and upper bounds of the PID controller gains and other AVR system blocks can be taken from many various sources, but referring to the studies on the PID and AVR systems in [8], [9], and [10], the values are listed in Table I. The value of the transfer function of the closed-loop system can be obtained by replacing the parameters' chosen values. The values are chosen as K_A = 10.0, τ_A=0.1, K_E =1.0, τ_E =0.4, K_G = 1.0, τ_G =1.0, K_R =1.0, τ_R =0.01, and the transfer function is written in (1) as a ratio of incremental change in terminal voltage to the incremental change in the reference voltage change.

$$T(s) = \frac{\Delta v_t(s)}{\Delta v_{ref}(s)} = \frac{0.1s+10}{0.0004s^4+0.0454s^3+0.555s^2+1.514s+11} \quad (1)$$

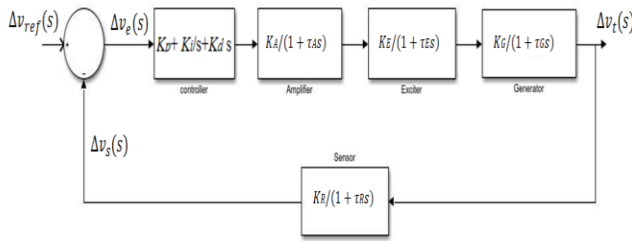

Fig. 1. Diagram of the described AVR system with PID controller.

Table 1. Components parameters Range.

Component	**Parameters Range**
PID controller	$0.2 \leq Kp, Ki, Kd \leq 2.0$
Amplifier	$10 \leq KA \leq 40$ $0.02 \leq \tau A \leq 0.1$
Exciter	$1 \leq Ke \leq 10$ $0.4 \leq \tau e \leq 1.0$
Generator	$0.7 \leq Kg \leq 1.0$ $1.0 \leq \tau g \leq 2.0$
Sensor	$0.001 \leq \tau R \leq 0.06$

4. CONTROLLER DESCRIPTION

4.1. FOPID Controller

Conventional PID controller, which has three gains, is one of the most used controllers designed in many linear systems. The way it works is that the error, derivative and integral of error are multiplied in three gains, hence the equation of control signal is expressed as follows.

$$U_{PID}(s) = (K_P e(s) + \frac{K_I}{S(e(s))} + K_D S(e(s))) \quad (2)$$

Where, $U_{PID}(t)$ is control signal and K_p, K_i, K_d are the proportional and integral and derivative gains, respectively. Fractional order systems are extensions of classical systems so that the order of derivative and integral are between zero and one. Caputo equation of fractional order derivative and integral is given in (3).

$$ {}_0I_t^{\alpha} y(t) = \frac{1}{\Gamma(\alpha)} \int_0^t y(\zeta)(t-\zeta)^{\alpha-1} d\zeta, t > 0 \quad (3\text{-}1)$$

$$ {}_0^C D_t^{\beta} y(t) = \frac{1}{\Gamma(m-\beta)} \int_0^t \frac{y^{(m)}(\zeta) d\zeta}{(t-\zeta)^{\beta+1-m}}; \quad m-1 < \beta \leq m \quad (3\text{-}2)$$

Where, $y(t)$ is a function, ${}_0I_t^{\alpha} y(t)$ and ${}_0^C D_t^{\beta} y(t)$ are the fractional order integral and derivative of $y(t)$, α, β are the orders of integral and derivative, $\Gamma()$ denotes the Gamma function. $\zeta \in R^+$ and $m \in N$. Laplace form of fractional order integral and derivative is presented in (4-1) and (4-2).

$$Y_1(s) = S^{\beta}\big(Y(s)\big) \quad (4\text{-}1)$$
$$Y_2(s) = S^{-\alpha}\big(Y(s)\big) \quad (4\text{-}2)$$

Where, $Y_1(s)$ and $Y_2(s)$ are the Laplace form fractional order derivative and integral. According to the calculations made in (3-4), output signal of FOPID controller is achieved in (5).

$$U_{FOPID}(s) = \left(K_P + \frac{K_I}{S^{\alpha}(e(s))} + K_D S^{\beta}(e(s))\right) \quad (5)$$

Where, $U_{FOPID}(s)$ is the control signal, $\frac{1}{S^{\alpha}}$ is the fractional-order integral and S^{β} is the fractional order derivative and its structure of FOPID is presented in Fig. 2.

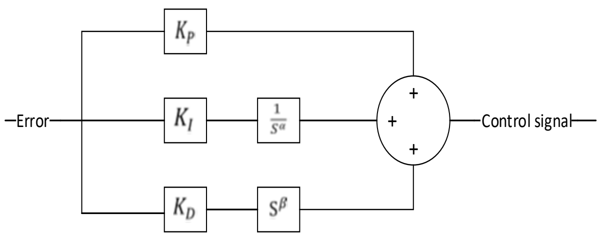

Fig. 2. Structure of FOPID controller.

4.2. Fuzzy Controller

Fuzzy Inference System (FIS) has the ability to control uncertain and nonlinear system and combine it as a smart controller with a classic controller such as PID to help the system performance [11]. Equation (6) expresses the general form of the fuzzy controller.

$$F(X) = \frac{\sum_{l=1}^{M} \theta^{l} w^{l}(X)}{\sum_{l=1}^{M} w^{l}(X)} \quad (6)$$

$F(X)$ is Fuzzy output, θ^{l} is the center of membership functions of consequent part, M is the number of fuzzy rules and $w^{l}(X)$ is the products of membership functions grades in antecedent part [12]. As mentioned above, the type of the fuzzy controller is Takagi-Sugeno (TSK). The fuzzy controller possesses two inputs (error and derivative of error) and three outputs (K_P, K_I, K_D). Equation (7) denotes each output of fuzzy controller.

$$F\left(X\middle|\theta_{K_P}\right) = \theta_{K_P}^{T}\zeta(X) \quad (7\text{-}1)$$
$$F\left(X\middle|\theta_{K_I}\right) = \theta_{K_I}^{T}\zeta(X) \quad (7\text{-}2)$$
$$F\left(X\middle|\theta_{K_D}\right) = \theta_{K_D}^{T}\zeta(X) \quad (7\text{-}3)$$

Where, $F\left(X\middle|\theta_{K_P}\right)$, $F\left(X\middle|\theta_{K_I}\right)$, $F\left(X\middle|\theta_{K_D}\right)$ are the outputs of fuzzy controller (the gains of FOFPID), respectively, $\theta_{K_P}^{T}$, $\theta_{K_I}^{T}$, $\theta_{K_D}^{T}$ are the consequent part of each outputs and $\zeta(X)$ is the normalized multiplication vector for grade in antecedent part. Thus, the gain of FOFPID has been varying during the simulation, and it can help the system to perform better than FOFPID controller [13]. The fuzzy controller possesses 3 Gaussian membership functions in the antecedent part and 9 Singleton membership functions in the consequent part. Fig. 3 shows the structure of FOFPID controller.

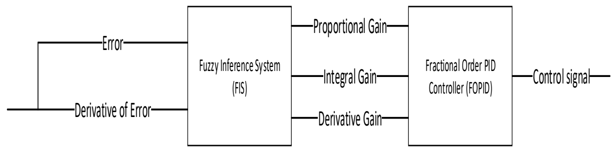

Fig. 3. Structure of FOFPID controller.

4.3. GOA

GOA is a population-based bio-inspired algorithm which models the behavior of grasshopper swarms to solve optimization problems [14]. The algorithm possesses two phases of repulsion (exploration) and attraction (exploitation) between grasshoppers. Like all population-based algorithms, it begins with the initial population (initial solutions), and in each iteration, they move toward the best position (best solution) [7]. The mathematical model of position updating using GOA is given as follows in (8).

$$X_i^d = r\left(\sum_{j=1}^{N} r\frac{ub_d - lb_d}{2} s\left(\left|x_j^d - x_i^d\right|\right)\frac{x_j - x_i}{d_{ij}}\right) + T_d \quad (8)$$

X shows the position of solution, d is the dimension of optimization problem, r is the coefficient (which is reduced after each iteration), ub_d and lb_d are the upper and lower bounds, respectively. s is the social forces between grasshoppers, d_{ij} is the distance between j-th grasshopper (x_j) and i-th grasshopper (x_i), and T_d is the target cost of the best solution [13]. s is calculated in (9).

$$s = fe^{\frac{-d}{l}} - e^{-d} \quad (9)$$

Where, f is the strength of attraction and l indicates the attraction coefficient.

The parameter r in (10) is proportional to the number of iterations and it balances between exploration and exploitation.

$$r = r_{\max} - t\,\frac{r_{\max} - r_{min}}{T} \quad (10)$$

$r_{\max}$ shows the maximum value (it is assumed to be 1), r_{min} is the minimum value (it is assumed to be 0.01), t is the current iteration and T indicates the number of iteration (which is assumed to be 50) [7]. The Pattern of grasshopper's swarm is shown in Fig. 4.

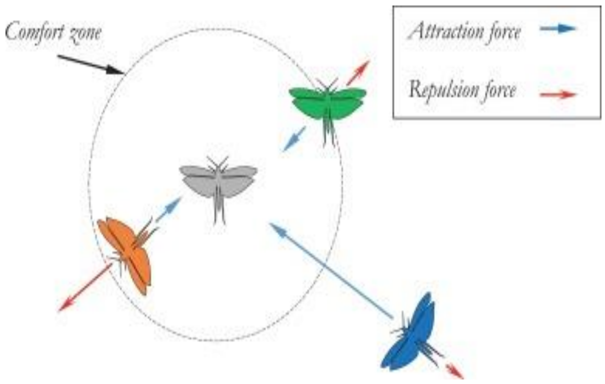

Fig. 4. grasshopper's swarm pattern.

In this study, parameters of FOPID and FOFPID controllers are optimized using GOA. Error is the difference between reference and output, so the employed objective function can be defined as Integral Absolute Error (IAE). Equation (11) demonstrates the equation of IEA.

$$IAE = \int_0^t |e(t)| \; dt \qquad (11)$$

Order of integral and derivative of FOPID and FOFPID controllers, three gains of FOPID controller, center and sigma of Gaussian membership function in the antecedent part and center of Singleton membership function consequent part of FOFPID are optimized via GOA.

5. RESULTS AND DISCUSSION

In this section, FOPID and FOFPID controllers are designed using GOA for control of AVR, and its results have been put into comparison with [7] (PID). In this manner, three scenarios (different nominal values) have been investigated to show the robustness of the proposed controller against uncertainty. The characteristics of the scenarios are described as follows:

$K_A = 10, K_e = 1, \; K_g = 1, \tau_A = 0.1, \tau_e = 0.4, \tau_g = 0.4, \tau_R = 0.01$

$K_A = 10, K_e = 1, \; K_g = 0.7, \tau_A = 0.02, \tau_e = 0.4, \tau_g = 0.7, \tau_R = 0.001$

$K_A = 15, K_e = 1, \; K_g = 1, \tau_A = 0.05, \tau_e = 0.5, \tau_g = 1.5, \tau_R = 0.06$

Fig. 5 shows the response of the three scenarios without controller and Fig. 6 illustrates the performance of the three controllers (FOPID, FOFPID and the one in [7]) in three scenarios.

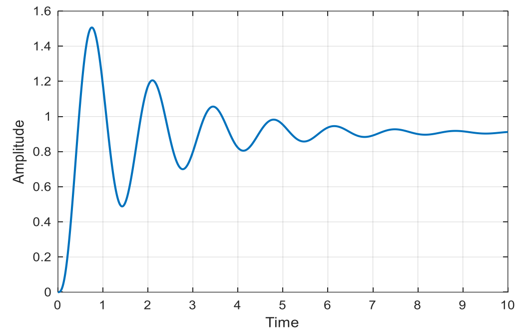

Fig. 5(a). Step response of AVR without controller in first scenario.

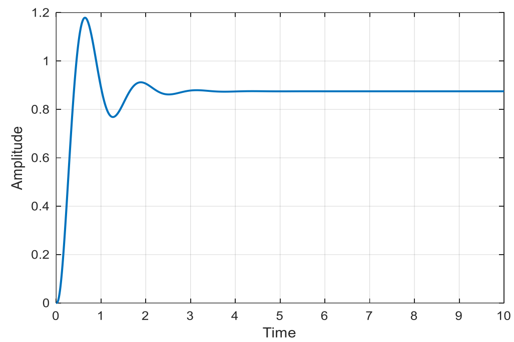

Fig. 5(b). Step response of AVR without controller in second scenario.

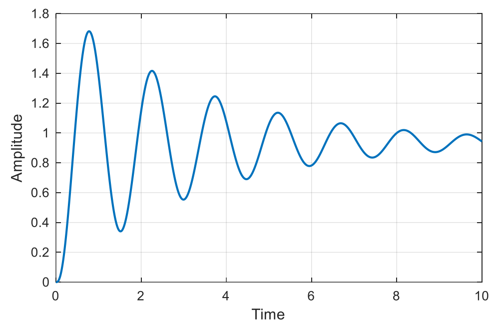

Fig. 5(c). Step response of AVR without controller in third scenario.

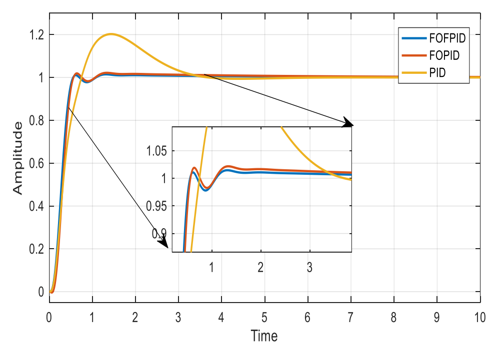

Fig. 6(a). Step response of AVR with PID [7], FOPID and FOFPID in first scenario.

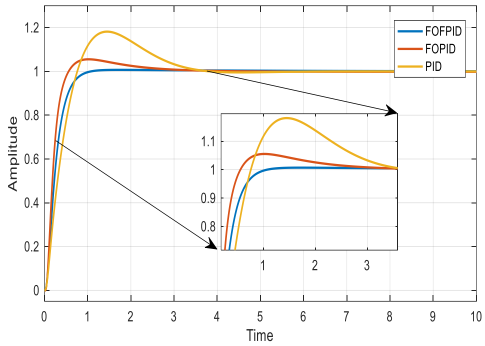

Fig. 6(b). Step response of AVR with PID [7], FOPID and FOFPID in second scenario.

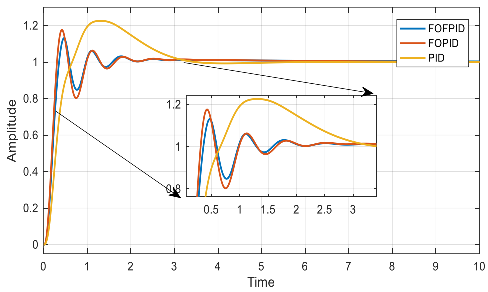

Fig. 6(c). Step response c.

As depicted in Fig. 6, FOFPID controller can perform better than other methods (less overshoot, undershoot and settling time) in controlling the AVR system. Some performance indices such as IAE and ITAE (Integral Time Absolute Error) have been used for better comparison, and its values are given in table II and III.

According to table II-VI, the performance of FOFPID controller is much better than FOPID and PID controllers. The gains of PID, FOPID and FOFPID are demonstrated in table VII and Fig. 7, respectively.

Table. 2. ITAE criteria for step response of AVR with PID [7], FOPID and FOFPID.

	$ITAE-1st$	$ITAE-2nd$	$ITAE-3th$
Open Loop	5.2323	6.3014	5.8584
PID [7]	0.6500	0.5961	0.6207
FOPID	0.1321	0.1667	0.4898
FOFPID	0.0740	0.1410	0.4008

Table. 3. IAE criteria for step response of AVR with PID [7], FOPID and FOFPID.

	$IAE-1st$	$IAE-2nd$	$IAE-3th$
Open Loop	1.6001	1.4744	2.0104
PID [7]	0.6630	0.6099	0.6863
FOPID	0.2980	0.3071	0.4338
FOFPID	0.2854	0.2836	0.3843

Table. 4. IAE criteria for step response of AVR with PID [7], FOPID and FOFPID in first scenario.

	Over Shoot	*rise time*	*settling time*
PID [7]	0.6630	0.4714	3.1823
FOPID	2.2544	0.2262	1.535
FOFPID	0.0011	0.2755	1.3596

Table. 5. IAE criteria for step response of AVR with PID [7], FOPID and FOFPID in the second scenario.

	Over Shoot	*rise time*	*settling time*
PID [7]	18.414	0.8412	3.1823
FOPID	7.4210	0.60	2.5178
FOFPID	0.1658	0.6524	1.2586

Table. 6. IAE criteria for step response of AVR with PID [7], FOPID and FOFPID in the third scenario/

	Over Shoot	*rise time*	*settling time*
PID [7]	22.5708	0.3733	3.0404
FOPID	17.5893	0.1882	1.9406
FOFPID	13.0406	0.2184	1.9206

Table. 7. Gains of PID [7] and FOPID.

	K_P	K_I	K_D	α	β
PID [7]	1.3825	1.4608	0.5462	1	1
FOPID	1.3544	0.4173	0.6111	0.9361	0.8324

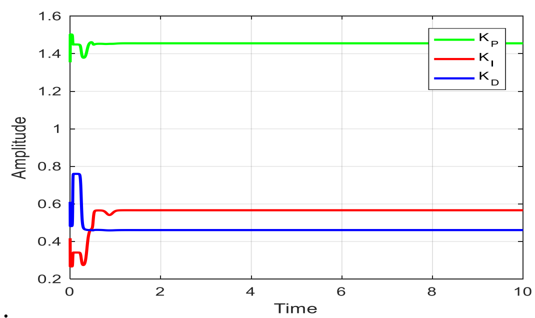

Fig. 7(a). Change gains of FOFPID in first scenario.

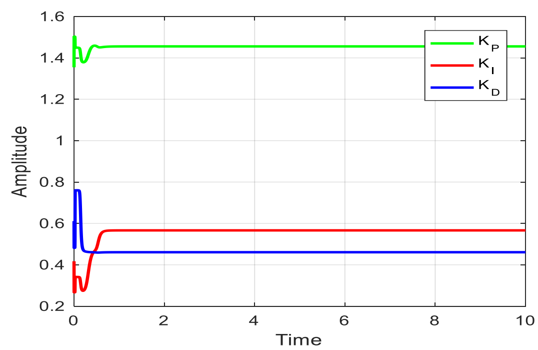

Fig. 7(b). Change gains of FOFPID in second scenario.

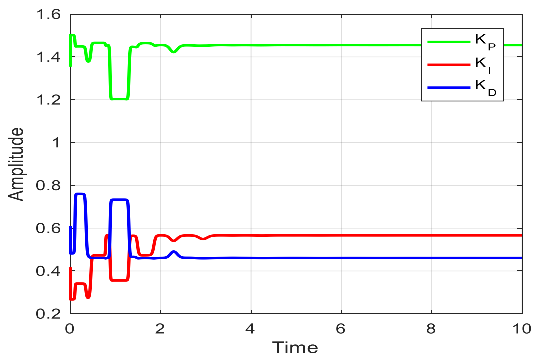

Fig. 7(c). Change gains of FOFPID in third scenario.

As shown in Fig. (7), the gains of FOFPID controller change over time due to the system's state and are not constant. Also, the gains of FOFPID are different for different system parameters, hence it can withstand against uncertainty and external noises. The process of changing the coefficient is listed as follows:

- In order to reduce the rise time, the system needs to be fast. Hence K_P and K_D must be big and K_I has small amount.
- In the transient state, in order to reduce overshoot and undershoot of the system, K_P and K_D have been decreased, and K_I has a normal value
- In steady state, the error must be zero. Therefore, K_I and K_P must be massive amounts and K_D has been decreased.

In practical design and implementation, the important point is that the gains changes in adaptive controllers such as the proposed controller should not be so fast and large that actuators cannot implement it. Fig. 8 shows the control signals of three controllers.

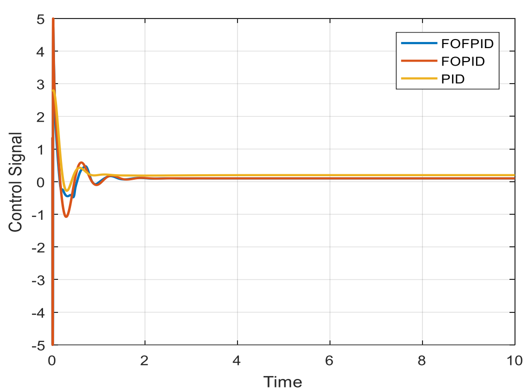

Fig. 8(a). Control signal of AVR with PID [7], FOPID and FOFPID in first scenario.

As shown in Fig. (8), the control signal, has a reasonable value and it is possible to implement the proposed controller.

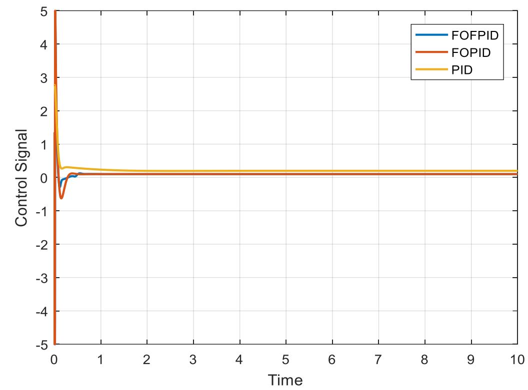

Fig. 8(b). Control signal of AVR with PID [7], FOPID and FOFPID in second scenario.

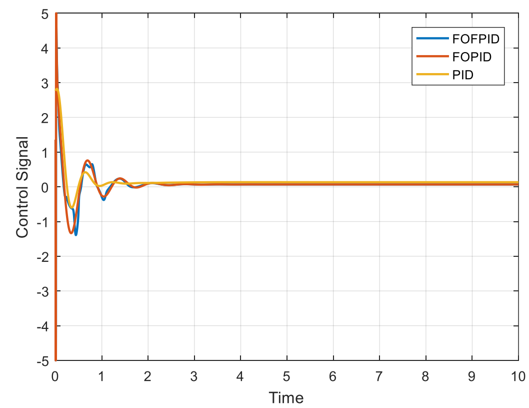

Fig. 8(c). Control signal of AVR with PID [7], FOPID and FOFPID in third scenario.

6. CONCLUSION

In this paper, the FOFPID controller and FOPID controller are developed to control the AVR. So as to optimize the parameters of both controllers, GOA is employed. By comparing the results, it can be concluded that both controllers can control the system in the presence of uncertainty. Additionally, simulation results endorse the superiority of FOFPID over FOPID and PID. In other words, the dynamic response of the AVR system with FOFPID has better characteristics (such as settling time) than FOPID and PID. Moreover, it proves that the FOFPID controller is a robust method in the presence of uncertainty. The FOFPID controller' gains have been changed caused by the different system parameters and different state of the system to improve the functionality of the system. For future works, some other algorithms such as whale optimization algorithm can optimize the controllers.

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