# Design of Fuzzy-FOPID Controller Optimized by ICA for Control of AVR

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**ABSTRACT:**
In this paper Fuzzy-FOPID controller is used in order to control automatic voltage regulator (AVR) system. This controller has six parameters. In this paper optimization method is employed to determine the controller parameters. For this purpose, imperialist competitive algorithm (ICA) is used for its high accuracy and good performance. To illustrate performance of proposed controller, some simulations are carried out in MATALB and the results are compared with FOPID controller results. Good performance of proposed controller is validated by results of simulations.

**KEYWORDS:** Imperialist Competitive Algorithm, Optimization, Automatic Voltage Regulator (AVR), Fuzzy – FOPID, FOPID.

## 1. INTRODUCTION

Multiple generators in a power plant are connected to a common bus. Each generator has an automatic voltage regulator (AVR), which its objective is voltage control [1]. Due to system disturbances, electrical oscillations may long remain in the system and at last cause the system to become unstable. Therefore, control of the system is an important topic in the effective operation of the power system. To reduce these problems to some extent, the AVR is connected to the power generating plants. The AVR system keeps the terminal voltage of the alternator in the generating station and also helps in suitable distribution of the reactive power amongst the parallel connected generators [2].

Several control methods have been suggested in the literatures to control the AVR system. Conventional controller tuning methods like the minimum variance and pole placement techniques have been used in designing self-tuning regulators [3]. In some literatures optimization methods have been employed for controller design in power systems [4-7]. Particle swarm algorithm has been used for control of AVR system in [8]. In Ref. [9] Multi-objective optimization method has been employed for tuning a lead-lag compensator to control of AVR system. In [10] a kind of PSO has been used for tuning PID controller in an AVR system. A craziness based PSO has been employed in [11] to tune the PID parameters for a power system stabilizer (PSS) controlled AVR system.

Recently the fractional order PID (FOPID) controller has been employed in the design of AVR systems [12], [13]. In [12] FOPID controller with CAS algorithm has been proposed to control the AVR system. Also in Ref. [13] PSO based FOPID controller has been used to AVR optimization. Ref. [14] has developed a robust FOPID controller for AVR in power systems. In the proposed controller, optimum design parameters, such as, proportional, integral, derivative gains, integral and derivative constants, have been achieved by using cuckoo search (CS) algorithm.

Recently, fuzzy methods have been proposed for control of power systems in the literature [15-18]. In Ref. [15] an optimized fuzzy PID controller has been used for AVR system control. In Ref. [16] a fuzzy controller for load frequency control of a power system has been employed. The fuzzy controller based on PSO for automatic generation control of two area restructured power system has been used in [17]. In Ref. [18] a new design method for determining the optimal PID controller parameters of an AVR system, using a combined genetic algorithm (GA), radial basis function neural network (RBF-NN) and Sugeno fuzzy logic approaches, was proposed.

In this paper for controlling automatic voltage regulator (AVR) system, Fuzzy-FOPID controller has been employed. Imperialist competitive algorithm (ICA) has been used in order to tune the proposed controller parameters. For this purpose, optimizations have been done by four fitness functions. In order to evaluate the performance of Fuzzy-FOPID controller to control AVR systems, simulations have been carried out by FOPID controller too. Results illustrate good performance of proposed controller.

The rest of the paper is organized as below. In second section system under study is explained. The third section is devoted to describe basics of Fuzzy-PID and FOPID controllers. Fourth section briefly presents imperialist competitive algorithm. Simulation results are presented in fifth Section and finally in sixth section, conclusion is expressed.

## 2. UNDER STUDY SYSTEM

The AVR model used in this paper consists of five sections: the amplifier model, exciter model, generator model, excitation voltage limiter and the sensor model. The representative schematic diagram of the system is shown in Fig. 1. First order transfer function has been used for modeling amplifier, exciter, generator and sensor as follows [13 and 16]:

(A) Amplifier model:

$$\frac{V_R(s)}{V_C(s)}=\frac{K_A}{1+\tau_A s} \tag{1}$$

(B) Exciter model:

$$\frac{V_F(s)}{V_R(s)}=\frac{K_E}{1+\tau_E s} \tag{2}$$

(C) Generator model:

$$\frac{V_G(s)}{V_{F\lim}(s)}=\frac{K_G}{1+\tau_G s} \tag{3}$$

(D) Sensor model:

$$\frac{V_S(s)}{V_{out}(s)}=\frac{K_S}{1+\tau_S s} \tag{4}$$

Values of above parameters have been given in appendix.

## 3. THE BASICS OF CONTROLLERS

### 3.1. Fuzzy-FOPID

Fuzzy control design is composed of three important stages, namely, (I) knowledge base design, (II) Control tuning parameters and (III) membership functions [19]. These stages should be designed properly that Fuzzy controller performs its control objectives well. In this paper the Fuzzy-FOPID control introduced in [20] has been employed to control AVR system. As seen in Fig. 2 this controller has two inputs: (i) error and (ii) fractional derivation of error. Since description of membership functions with triangle shapes is more economical [21], triangle membership functions are widely used in the fuzzy controller's design. Fig. 2 shows employed controller in this paper. As seen in Fig. 2 this controller has two inputs: (i) error and (ii) fractional derivation of error. In this paper, triangle membership functions have been used in the Fuzzy-FOPID controller. Employed membership functions and fuzzy rules have been given in Fig. 3 and Table 1 respectively [20].

### 3.2. FOPID

Fractional Order PID is an appropriate structure which is used for control objectives. Firstly, this controller is introduced by Podlubny in 1999 [22]. This controller has five parameters of proportional gain (Kp), integral gain (Ki), derivative gain (Kd), integration order (λ) and derivation order (δ). Differential equation of FOPID is defined as below:

$$u(t)=k_P e(t)+k_t D_t^{-\lambda}e(t)+k_D D_t^{\delta} \tag{5}$$

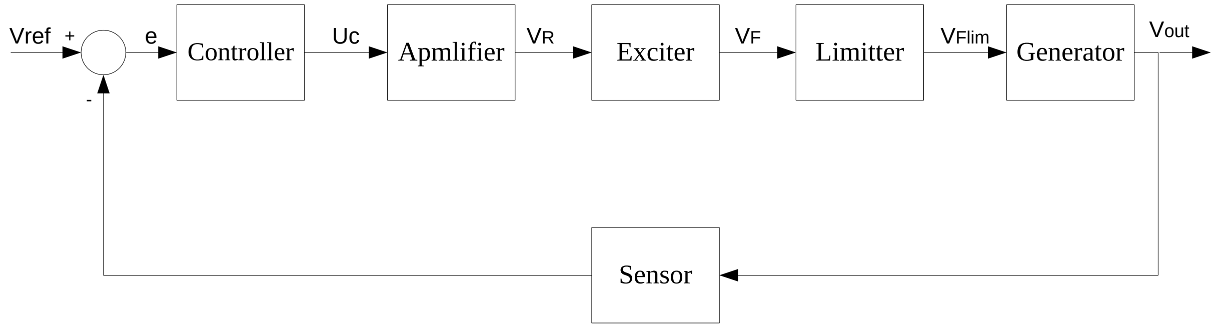


**Fig. 1**. Schematic representation of AVR system.

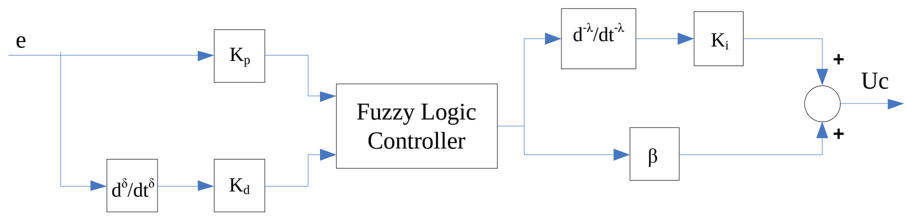


**Fig. 2.** The fuzzy-FOPID controller.

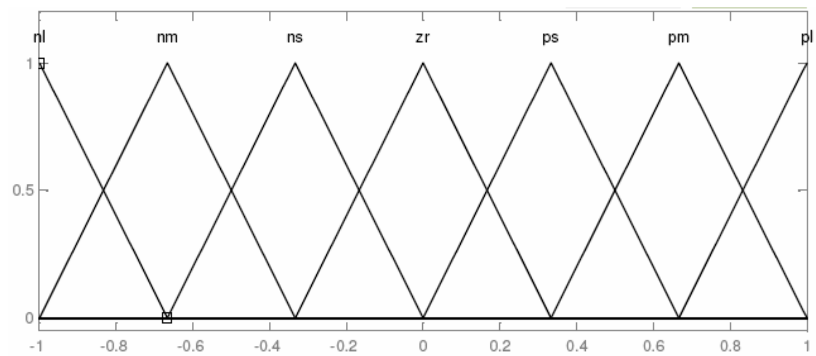


**Fig. 3.** The membership functions. [20]

**Table 1.** The fuzzy rules. [20]

| $e\text{–}de^{\delta}/dt^{\delta}$ | nl | nm | ns | zr | ps | pm | pl |
|---|---|---|---|---|---|---|---|
| pl | zr | ps | pm | pl | pl | pl | pl |
| pm | ns | zr | ps | pm | pl | pl | Pl |
| ps | nm | ns | zr | ps | pm | pl | pl |
| zr | nl | nm | ns | zr | ps | pm | pl |
| ns | nl | nl | nm | ns | zr | ps | pm |
| nm | nl | nl | nl | nm | ns | zr | ps |
| nl | nlnl | nl | nl | nl | nm | ns | zr |

Transfer function of FOPID is achieved by Laplace and it is as Eq.6:

$$G_c(s) = k_P + k_I s^{-\lambda} + k_D s^{\delta} \quad (6)$$

FOPID design procedure consists of determining the five parameters. Several design methodologies have been introduced to this type of controller, including: pole distribution [23], frequency domain strategies [24], state space design [25] and two-stage or hybrid strategy [26]. In this study imperialist competitive algorithm has been used for determining FOPID controller parameters. There are several approximation techniques to obtain discrete or continuous models of fractional order PID controller. One of these approximation methods is Oustaloup [27]. In this paper Oustaloup's 5th order rational approximation has been used. In frequency range of $[\omega_l ; \omega_h]$ H(s) =s$^r$ where $r \in R$ can be approximated as follow [27, 28]:

$$H(s) = K \prod_{k=-n}^{n} \frac{s+\omega'_k}{s+\omega_k} \quad (7)$$

Where

$$\omega_k = \omega_l \left(\frac{\omega_h}{\omega_l}\right)^{(k+n+0.5+0.5r)/(2n+1)} \quad (8)$$

$$\omega'_k = \omega_l \left(\frac{\omega_h}{\omega_l}\right)^{(k+n+0.5-0.5r)/(2n+1)} \quad (9)$$

$$K = \left(\frac{\omega_h}{\omega_l}\right)^{-\frac{r}{2}} \prod_{k=-n}^{n} \omega_k / \omega'_k \quad (10)$$

In above equations $\omega_h$ and $\omega_l$ are high and low transitional frequencies respectively.

## 4. IMPRTIALIST COMPETITIVE ALGORITHM

Recently using imperialist competitive algorithm is increased due to its good performance and high speed in obtaining optimization solutions [29-31]. Similar to other evolutionary algorithms, this algorithm begins with an initial population. Each individual of the population is named a country. Some of the best countries are selected to be the imperialist and the rest of population are considered as colonies. The colonies of initial countries are divided among the mentioned imperialists based on their power. The imperialists together with their colonies form some empires. The total power of an empire depends on both the power of the imperialist country and the power of its colonies. Fig. 4 shows the flowchart of the ICA. More information about ICA can be found in [32].

The values of system and imperialist competitive algorithm parameters are given in Table A in Appendix.

## 5. SIMULATION RESULTS

Simulation results are discussed in this section. ICA has been used in all cases for tuning the FOPID and Fuzzy-FOPID controllers. It should be noted that in this study, rise time is defined as time longs that output voltage reaches from 5% to 90% of its steady state value. In this paper to evaluate Fuzzy-FOPID controller two cases have been considered and simulations have been carried out in MATLAB environment.

### 5.1. Compare with FOPID

Firstly, in this case Fuzzy-FOPID controller parameters are optimized by following four fitness functions:

$$\text{ITAE+ISCO}=\int_0^T t\,|e|\,dt+\int_0^T u^2 dt \quad (11)$$

$$\text{ISTSE+ISCO}=\int_0^T t^2 e^2 dt+\int_0^T u^2 dt \quad (12)$$

$$\text{ISTES+ISCO}=\int_0^T (t^2 e)^2 dt+\int_0^T u^2 dt \quad (13)$$

$$\text{ITSE+ISCO}=\int_0^T te^2 dt+\int_0^T u^2 dt \quad (14)$$

In above equations, e is defined as difference between reference signal and output voltage. Since control signal value of controller should not saturate the controller, squared control signal value has been considered in mentioned fitness functions. Figs. 5-8 show the output voltages of AVR system according to defined fitness functions. As seen in these figures for all defined fitness functions, Fuzzy-FOPID controller has shorter rise and settling time and moreover smaller overshoot compared with other two controllers. Figs. 9-12 show control signals of above controllers according to defined fitness functions. As seen control signal values of Fuzzy –FOPID controllers are more less than FOPID controllers. A summary of simulation results is given in Table 2. With respect to Table 2 it can be found that by using proposed method overshoot is reduced by 83%, 70% and 82% with (Figs. 11-13) fitness functions respectively than FOPID controller. Moreover, rise time of $V_{out}$ is decreased by 24%, 8%, 2% and 5% with using of (Figs. 11-14) fitness functions respectively by using Fuzzy-FOPID controller than FOPID controller. It also can be understood that by employing Fuzzy-FOPID controller, settling time of $V_{out}$ is reduced with (11-13) fitness functions by 48%, 40% and 56% respectively than FOPID controller.

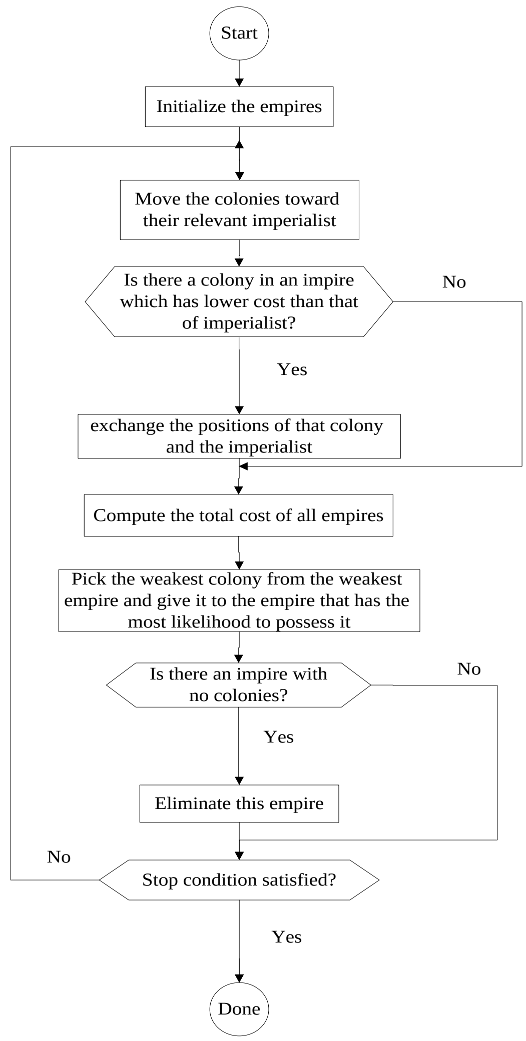


**Fig. 4.** Imperialist competitive algorithm flowchart.

### 5.2. Robustness to uncertainties

In this case performance of proposed controller is evaluated in presence of uncertainties in system parameters. Obtained parameters from ITAE+ISCO fitness function are used in this section for this purpose.

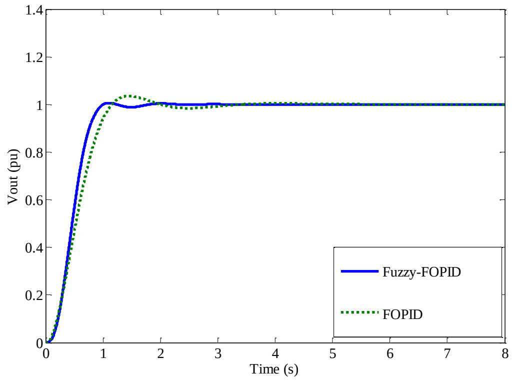


**Fig. 5.** Output voltage according to ITAE+ISCO fitness function.

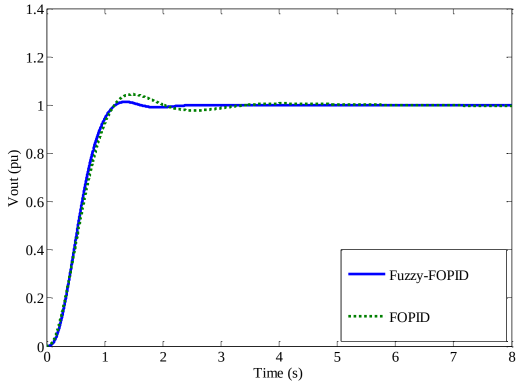


**Fig. 6.** Output voltage according to ISTSE+ISCO fitness function.

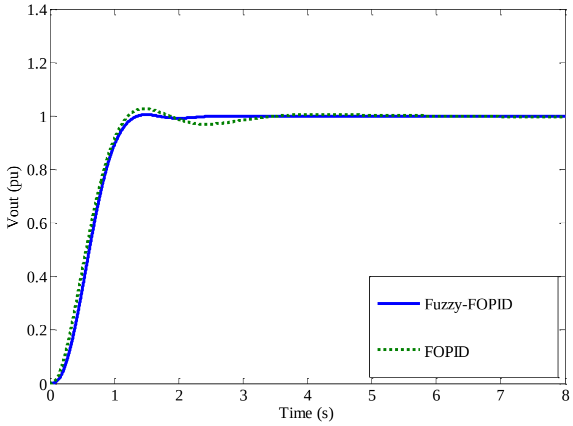


**Fig. 7.** Output voltage according to ISTES+ISCO fitness function.

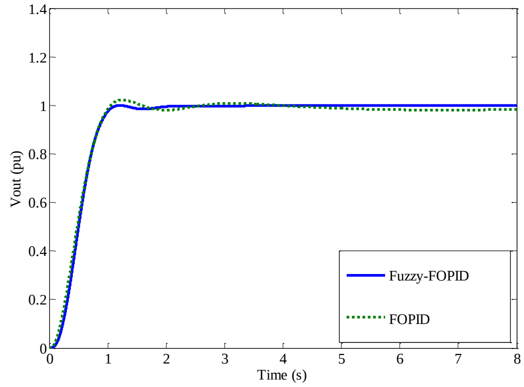


**Fig. 8.** Output voltage according to ITSE+ISCO fitness function.

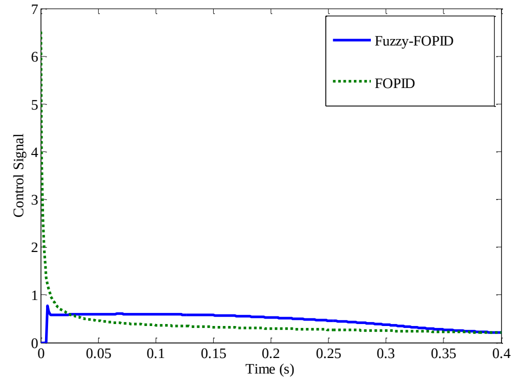


**Fig. 9.** Control signal according to ITAE+ISCO fitness function.

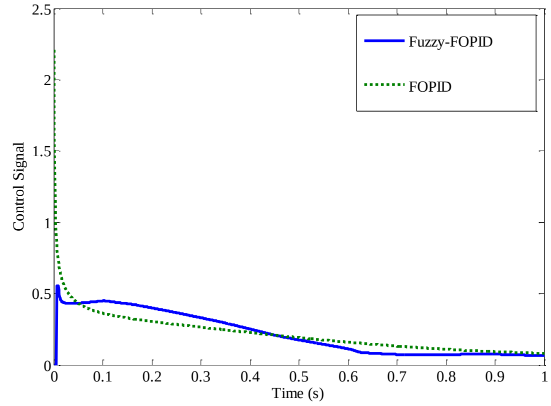


**Fig. 10.** Control signal according to ISTSE+ISCO fitness function.

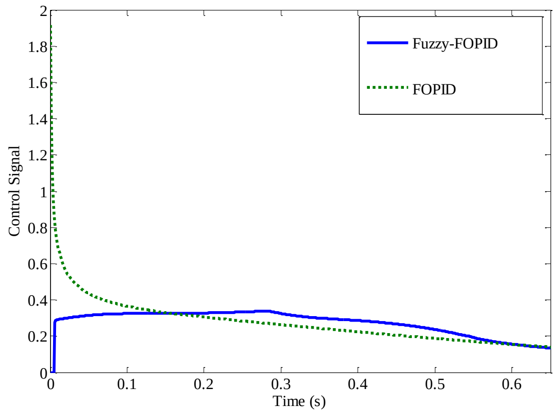


**Fig. 11.** Control signal according to ISTES+ISCO fitness function.

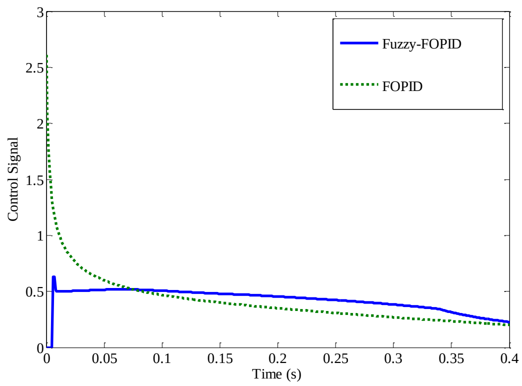


**Fig. 12.** Control signal according to ISTE+ISCO fitness function.

Firstly, it is assumed that exciter system parameters have 50 percent uncertainties. Results are shown in Figs. 13 to 14. As seen in these figures, proposed controller is more robust than other controllers. Figs. 15-16 exhibit performance of controllers in presence of 50 percent changes in generator parameters. It is seen in these figures that with change of parameters of generator by 50 percent, values of output voltage settling time and overshoot is highly increased when FOPID controllers is employed while amount of this increasing when Fuzzy – FOPID controller is used is much less. Figs. 17-18 show performance of two controllers when parameters of amplifier are changed by 50 percent. Total performance of Fuzzy-FOPID is better in this case too.

## 6. CONCLUSION

In this paper Fuzzy-FOPID controller for control of AVR system is proposed. For this purpose, ICA is used to optimize the Fuzzy-FOPID parameters. To evaluate the performance of Fuzzy-FOPID controller in control of AVR system, simulations are carried out with four

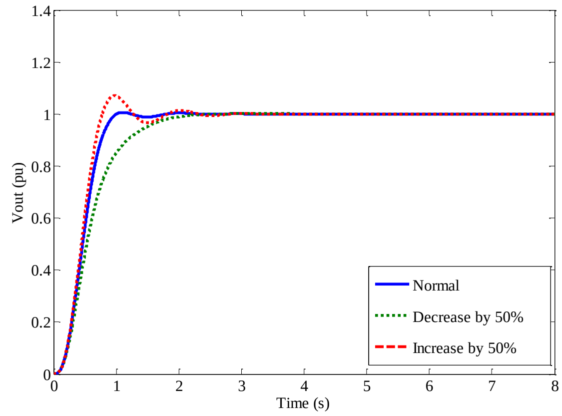


**Fig. 13.** Performance of Fuzzy-FOPID controller with 50% changes in exciter parameters.

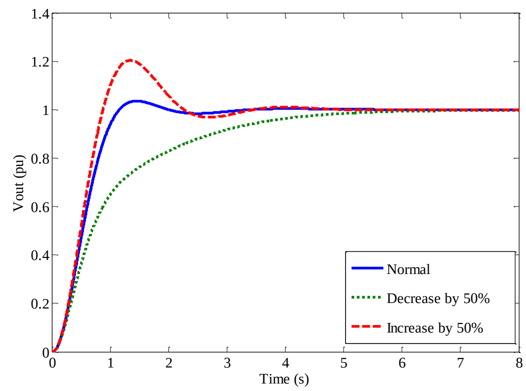


**Fig. 14.** Performance of FOPID controller with 50% changes in exciter parameters.

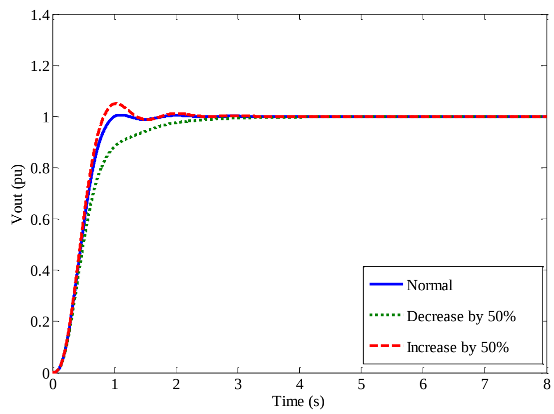


**Fig. 15.** Performance of Fuzzy-FOPID controller with 50% changes in generator parameters.

fitness function and results are compared with FOPID controller. Simulation results show that in all cases, the output voltage of system with Fuzzy-FOPID controller has shorter rise time and settling time and smaller overshoot rather than FOPID controller. Meanwhile

**Table 2.** The results of simulation.

| F.F.[v] | Controller | Kp | Kd | Ki | δ | λ | β | O.S.[iv] | R.T.[iii] | S.T.[ii] | F.F.V.[i] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *ITAE* | FOPID | 0.1789 | 0.0984 | 0.1829 | 0.6028 | -0.9682 | - | 3.54% | 0.7873 | 1.7753 | 0.50247 |
| | Fuzzy-FOPID | 0.6810 | 0.2562 | 0.9830 | 1 | -1 | 0.8613 | **0.62%** | **0.5960** | **0.9168** | **0.3476** |
| *ISTSE* | FOPID | 0.0928 | 0.1508 | 0.1867 | 0.3825 | -0.9446 | - | 4.47% | 0.7989 | 1.8585 | 0.20204 |
| | Fuzzy-FOPID | 0.6780 | 0.2558 | 0.5752 | 0.9891 | -1 | 0.6160 | **1.34%** | **0.7346** | **1.0988** | **0.1913** |
| *ISTES* | FOPID | 0.0471 | 0.1879 | 0.1863 | 0.3326 | -0.9296 | - | 2.77% | 0.8111 | 2.7960 | 0.2282 |
| | Fuzzy-FOPID | 1 | 0.5221 | 0.7092 | 1 | -1 | 0.3229 | **0.5%** | **0.8017** | **1.2292** | **0.1517** |
| *ITSE* | FOPID | -0.4756 | 0.6141 | 0.3641 | 0.2337 | -0.7175 | - | 2.21% | 0.6935 | - | 0.27586 |
| | Fuzzy-FOPID | -0.7959 | -0.2724 | -0.5777 | 0.9978 | -1 | -0.7154 | - | **0.6615** | **1.0220** | **0.2651** |

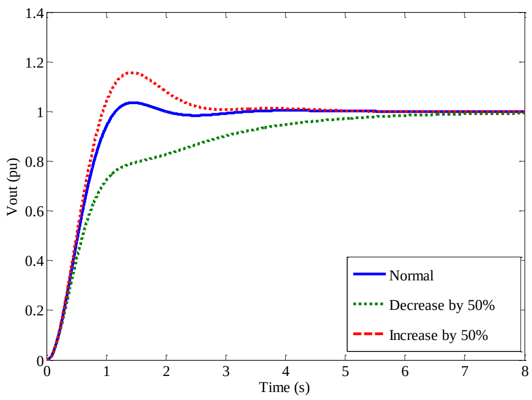


**Fig. 16.** Performance of FOPID controller with 50% changes in generator parameters.

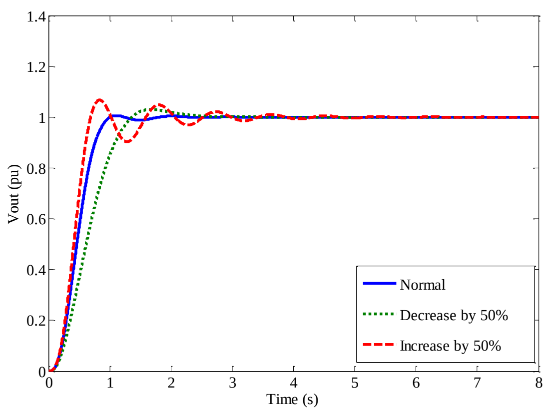


**Fig. 17.** Performance of Fuzzy-FOPID controller with 50% changes in amplifier parameters.

control signal peak value of Fuzzy-FOPID controller is much less than FOPID controllers. Also in this paper to evaluate the robustness of Fuzzy-FOPID controller in AVR system, three uncertainty cases are considered. Simulation results illustrate that in all cases, Fuzzy-FOPID controller has better performance in presence of uncertainties compared with FOPID controller.

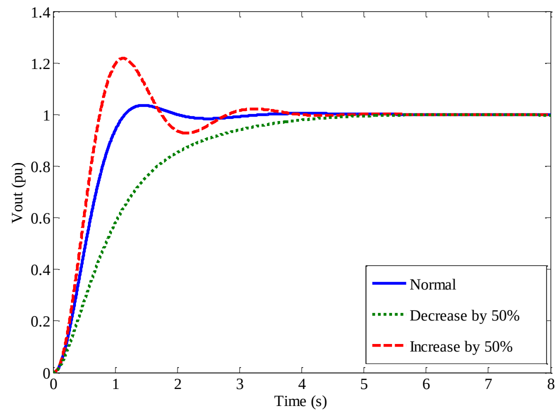


**Fig. 18.** Performance of FOPID controller with 50% changes in amplifier parameters.

## Appendix

**Table A.** The AVR system and ICA Parameters.

| AVR system | |
|---|---|
| $K_A$ | 10 |
| $\tau_A$ | 0.1 s |
| $K_E$ | 1 |
| $\tau_E$ | 0.5 s |
| $K_G$ | 1 |
| $\tau_G$ | 1 s |
| $K_S$ | 1 |
| $\tau_S$ | 0.06 s |
| ICA | |
| Number of population | 30 |
| Maximum of decades | 30 |
| β | 2 |
| Probability of Revolution | 0.1 |
| $\zeta$ | 0.1 |
| Number of empires | 2 |

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[i] Fitness Function Value

[ii] Settling Time

[iii] Rise Time

[iv] Over Shoot

[v] Fitness Function