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Investigation of 2DOF FOPI controller for synchronous generator voltage stability

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Abstract

Voltage instability is one of the basic problems in power systems that have always been considered. This instability occurs when a disturbance, increased usage, or change in system condition causes a progressive and uncontrollable drop in voltage. In order to achieve voltage stability, tools such as s In the generator, one of the reliable methods is to use the automatic voltage regulator (AVR) system. In fact, each AVR needs to maintain the reactive power of the synchronous generator at the demand level, stable voltage and frequency of the power sources. hunt capacitors and power electronic equipment, etc., were introduced. In this research, the effectiveness of the control scheme based on proportional-integral fractional order (FOPI) controller for automatic voltage regulation (AVR) system is presented. In this study, a 2DOF FOPI controller is proposed that deviates from the standard integer order to show the superiority of the additional degrees of freedom in the network and controller structure. To improve the performance of AVR, an particle swarm optimization algorithm (PSO) is proposed to adjust the parameters. This method achieves significant robustness to system parameter perturbations and perturbation discontinuities. In the staircase response analysis, it is observed that the settling time and overshoot of the system can be reduced compared to the recently published designs. Various analyzes have shown that the proposed controller is superior to the PI controller in terms of robustness.

Keywords: stability, voltage regulation, synchronous generator, fractional order controller
2020 MSC: 68T07

1 Introduction

Voltage stability is the ability of a power system to maintain constant acceptable voltages on all system buses under normal operating conditions and after exposure to a disturbance. A system enters a voltage instability state when a disturbance, an increase in load demand, or a change in the system state causes a progressive and uncontrollable drop in voltage. The main cause of instability is the inability of the power system to respond to reactive power demand. The root of the problem is usually the voltage drop that occurs when active power and reactive power flow through the inductive reactance's associated with the transmission network. The progressive drop of the bus voltage can also be associated with the departure of the rotor angles. For example, the gradual loss of synchronism of the machines as the rotor angles between two groups of machines approach or exceed 180° results in very low voltages at the intermediate points of the network. Voltage instability is basically a local phenomenon. However, the consequences may be far-reaching. More complex voltage collapse than instability is usually the result of a sequence of events associated with

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voltage instability that results in a low voltage profile over a significant portion of the power system. Severe voltage fluctuations lead to equipment shutdown, system islanding and transmission line interruption. Therefore, a voltage regulator is essential to achieve satisfactory performance of a power system.

Reactive power, because of its high value, through several tools including stabilizers, shunt capacitors, power electronic devices such as flexible alternating current transmission system (FACTS), shunt and series reactors, static VAR compensator (SVC) and AVR has reached equilibrium. Currently, two main methods of voltage regulation are used [12], with the AVR system proving to be the optimal method to achieve this balance. The AVR system works by controlling the DC excitation voltage in the synchronous generator in a closed-loop manner, which in turn balances the reactive power. AVR is used as the heart of the system in controlling the excitation of generators. The main purpose of AVR is to control the terminal voltage by adjusting the generator excitation voltage. The AVR must track the generator terminal voltage at all times under all load conditions to maintain the voltage within predetermined limits [13].

Nowadays, the use of suitable control technique for AVR system is more important for voltage stability, more reliability and research in this field. The PID controller has been the most commonly used control technique due to its simple structure and implementation. However, PID tuning is critical and not always optimally robust. Since the last decade, a fractional order PID (FOPID) controller has gained much attention. Some research has been done on the robustness with fractional order derivative and integral for uncertainty problems [13]. In recent years, the emergence of meta-heuristic optimization algorithms for the purposes of optimal setting of system parameters has increased. Since these methods are problem-independent, they can be applied to a wide range of applications. Although this optimization was developed in the 1950s, in the last decade, a number of nature-inspired optimizations have been adopted for AVR controllers. The comparative study with different PID structures, the methodology of setting the system parameters has always been discussed [2, 6, 9, 15, 17, 18].

This research intends to investigate the performance of the AVR system by using the PI controller due to its simpler adjustment than the PID controller and giving it a higher degree of freedom under the title of fractional order integral proportional controller. To adjust the parameters of this controller, the particle swarm optimization algorithm has been used, which has proven to lead to acceptable results. At the end, the robustness of the proposed control system is checked by applying a step voltage and changing the system parameters.

2 AVR system and its parameters

AVR is one of the main power system control mechanisms that work locally in a synchronous generator. In other words, AVR is a locally controlled closed loop system that keeps the SG terminal voltage constant. Therefore, it provides the reactive power balance of the entire power system and contributes to its voltage stability and reliability. The main parts of an AVR system generally include amplifier, exciter, generator, voltage sensor and comparator elements as shown in Figure 1 [7]. In this system, the terminal voltage of the synchronous generator is continuously sensed by a voltage sensor. It is then rectified and smoothed for comparison with the DC reference signal in the comparator to produce an error signal. After that, this signal is amplified and sent to the input of the controller. Finally, the controller controls the generator field windings on the exciter circuit [7]. Synchronous generator excitation control includes manual and automatic operating modes. In these modes, the automatic mode is called AVR system.

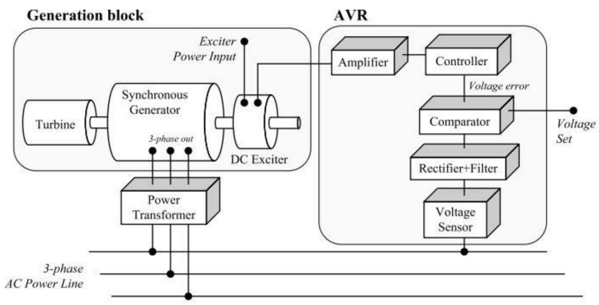

Figure 1: A controlled AVR system for SG

is used to model the components of AVR system depicted in Fig. 1, for both analogue and digital AVRs, the linearized general closed loop model and its parameters – apart from the controller parameters – are obtained as in Fig. 2 and Table 1,respectively [8].

Table 1: The parameters of AVR model [5]

	Transfer function	**Parameter limits**	**Used parameter values**
Amplifier	$K_a/(T_a s + 1)$	$10 \leq K_a \leq 40,\ 0.02 \leq T_a \leq 0.1$	$K_a = 10,\ T_a = 0.1$
DC Exciter	$K_e/(T_e s + 1)$	$1 \leq K_e \leq 10,\ 0.4 \leq T_e \leq 1.0$	$K_e = 1,\ T_e = 0.4$
Generator	$K_g/(T_g s + 1)$	$0.7 \leq K_g \leq 1.0,\ 1.0 \leq T_g \leq 2.0$	$K_g = 1,\ T_g = 1$
Sensor	$K_s/(T_s s + 1)$	$0.001 \leq T_s \leq 0.06$	$K_s = 1,\ T_s = 0.001$

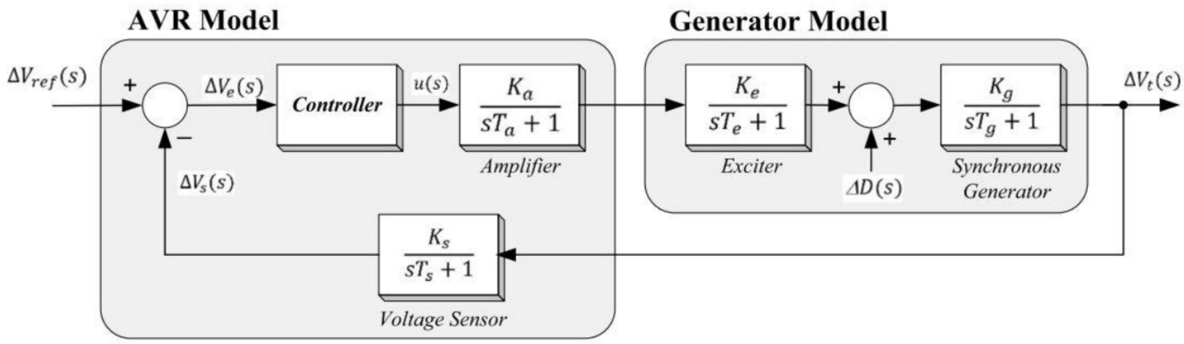

Figure 2: Linear model of AVR system.

What makes the AVR system work correctly is a suitable and good control method for the control part of this system. In past studies in this field of research, many of its statements are the use of PI and PID controllers [1] and [10]. By now, it is well known that the PID controller is the most common control technique used in industry, education, and science due to its simple control structure. But accurate and adaptive tuning of a PID controller is an important challenge for control engineers when system and environment parameters change [3]. To deal with this challenge, the self-tuning PID controller is often preferred over the current more complex control methods [4]. In fact, it can be said that the acceleration in the popularity of self-tuning PID control for AVR using heuristic algorithms started in the early 2000s, and so far many applications have been proposed in this field. On the other hand, since the classical 1DOF-PID controller is only sensitive to lateral load perturbations, a 2DOF-PID controller was proposed to obtain good tuning and tracking capabilities in 1984 [1]. Rajinkans et al applied this type of controller in AVR in order to achieve a reasonable system for both load disturbance and setpoint change in 2015 for the first time [17]. In addition, Gozde proposed a 2DOF-PI controller with PSO algorithm for AVR in 2020, and he proved the superiority of the method using time and frequency domain stability analysis and two different robustness analyzes for instantaneous and continuous disturbances [10].

While the field of research was conducted to obtain the best tuned parameters, the use of fractional calculus (FC) has been emerging at a remarkable pace since the last decade for the best tuned parameters. Based on this theory, FOPID has been developed and has achieved significant results in the field of control engineering [2, 18]. FC theory has been used not only in PID, but also in the field of fuzzy logic [9]. This is due to the additional degree of freedom that provides load-side control. Since the fractional derivative in FOPID is very sensitive to noise, it is difficult to estimate the equivalent transfer function [19]. When dealing with high-frequency noise at high sampling rates, the complexity can increase steeply. In addition, we need to achieve several objectives of the designed controller without adding complexity to the solution. With this motivation, FOPI is adopted for the simple structure. In fact, 2DOF FOPI helps the response speed by using the appropriate performance index. Therefore, in this work, a fractional-order PI, i.e., 2DOF FOPI, controller that has a new shape with a change in system feedback is designed. The new controller is derived for the AVR system.

This paper shows promising results compared to recent works on 2DOF PI for the same system.

3 Fractional order proportional integral controller

3.1 FOPI controller

The FOPI linear model can be shown in Figure 2, where C(s) is the controlling parameter and is defined as follows:

$$C(s) = K_p + \frac{K_i}{S^\lambda} \tag{3.1}$$

where, K_p and K_i are proportional and integral parameters. Here, the new parameter λ is a fractional positive real value between 0 and 1. The value of λ cannot be negative because it reverses the polarity to zero. To have a more accurate optimal value of λ, the upper bound and lower bound for adjustment are set to 0 and 1, respectively.

3.2 2DOF-FOPI controller

The use of fractional order PI controller with two degrees of freedom (2DOF FOPI) helps the response speed by using the appropriate performance index.

The linear model of this system can be shown in Figure 3. In this system, $C_r(s)$ is called the transfer function of the set point controller and $C_y(s)$ is called the feedback transfer function of the controller, which is defined as follows [14]:

$$C_r(s) = K_c\left(\beta + \frac{1}{T_i s^\lambda}\right) \tag{3.2}$$

$$C_y(s) = K_c\left(1 + \frac{1}{T_i s^\lambda}\right) \tag{3.3}$$

where K_c is the controller gain, T_i is the integral time constant, which must be positive and has units of time. As T_i gets smaller, the integral value increases as T_i is in the denominator and β is the setpoint weighting factor, having range from 0 to 1 complying to small gain theory. This is because, the value of β becomes 1 $C_r(s)$ and $C_y(s)$ will be equal. Thus defeating the whole purpose of 2DOF structure and reducing it to classical 1DOF PI controller. Furthermore, if β is more than 1, this increases the value of K_c which leads to instability.

$$u(s) = C_r(s)\Delta V_{ref}(s) - C_y(s)\Delta V_s(s) \tag{3.4}$$

where ΔV_{ref} or V_{ref} is the generated voltage which is used to compare to the terminal voltage, ΔV_t or V_t to achieve a determined control. ΔV_s or V_s is the sensor voltage in the form of feedback to ascertain suitable load side voltage drop tracking.

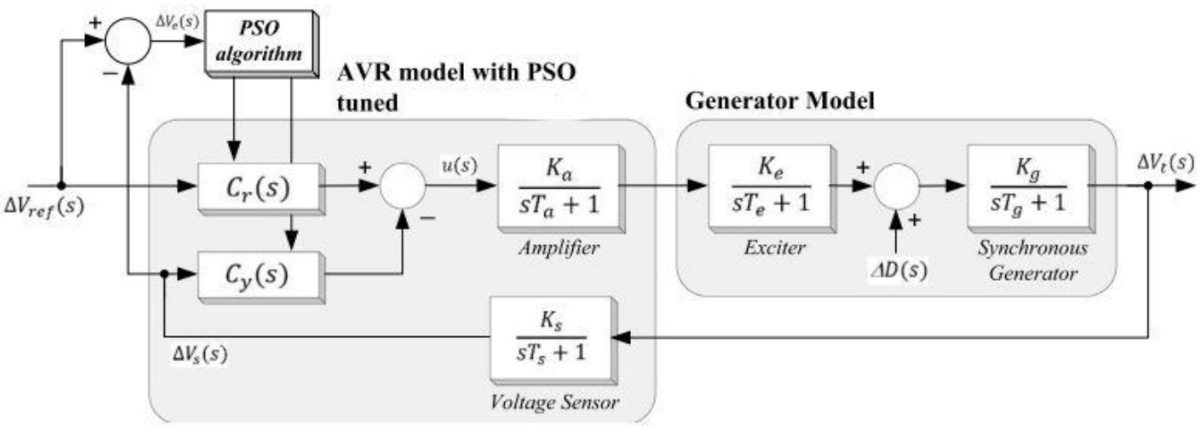

Figure 3: Linear model of AVR system.

3.3 PSO algorithm

PSO is a heuristic global optimization technique which belongs to the category of evolutionary search algorithms [11]. It solves optimization problems based on the behavior of existing virtual social groups in nature (flocks of birds, swarms, etc.) as reported by [16]. Furthermore, the method has shown improvements in minimizing cost functions,

Table 2: The pseudo code of PSO algorithm

Initialization
Repeat
Evaluate the fitness values of particles
Compare the fitness values to determine the local and global better particles
Update the velocities and positions of the particles
Until (requirements are met)

Table 3: The computed controller parameters

	K_p	K_i	K_c	T_i	λ	β
1DOF PI	0.035	0.021	–	–	–	–
2DOF PI	–	–	0.494	0.871	–	0.332
FOPI	0.2114	0.1429	–	–	0.979	–
2DOF FOPI	–	–	0.1085	0.8364	0.961	0.0212

particularly when they have non-linear characteristics, multiple optimal values, and high dimensionality [20]. The pseudo code of the algorithm is presented in Table 2.

In this step, using the PSO algorithm, we obtain the controller parameters, which are described in Table 3.

In Table 2, the information about 2DOF PI is also entered from [10] so that the effects of the additional degree on the controller are more tangible.

4 Step response analysis

The step responses obtained from the examined control systems are presented in Fig. 4. The results of step response analysis are given in Table 4. The results show that using an additional degree for the PI controller provides a much better response. The 2DOF FOPI controller has reached the acceptable voltage range with the shortest time. Also, in 1DOF FOPI mode, the system shows a more optimal response.

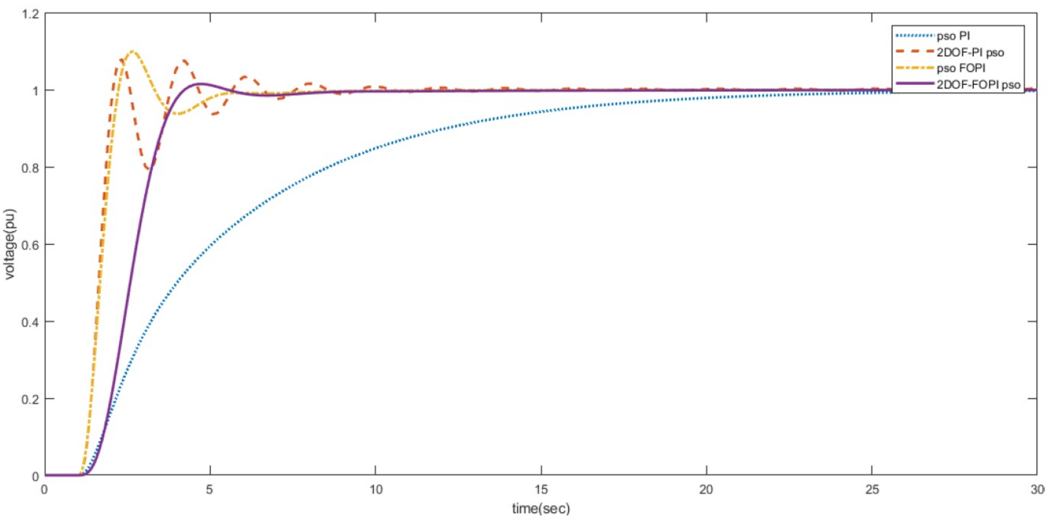

Figure 4: Step responses of the control systems.

2DOF FOPI has brought the generator output to the desired voltage with the shortest settling time and the least overshoot, which shows its superiority over 2DOF PI.

Table 4: The voltage deviations in disturbance analyses

	Maximum Overshoot(%)	Peak Value(v)	Peak time(sec)	Settling time (%2band) (s)
1DOF PI	0.000	1.000	30.000	20.132
2DOF PI-PSO	8.152	1.080	2.279	7.318
FOPI-PSO	10.520	1.099	0.607	5.072
2DOF FOPI-PSO	1.560	1.018	4.741	3.992

5 Robustness analysis

After determining the parameters of the controller, we must examine the system's resistance to failures or load changes. For this purpose, we use two methods of disturbing and changing the parameters of the AVR system.

5.1 Disturbing actions

In normal conditions for all designed AVR systems, the reference step input voltages are applied as 1 pu at the first second of the analysis time interval. $\Delta D(s)$ is also applied as a voltage increase of 1 pu at the 15th second of the analysis time interval. Obtained results of the analysis is represented in Figs. 5. Also, the values of voltage deviations are summarized in Table 5.

The analysis shows that the voltage deviation of 1DOF PI is more than the permissible limit. Also, in the case of using FOPI, it is clear that we have the lowest voltage deviation compared to classical PI. These results prove the superiority of using more degrees of freedom in the PI controller.

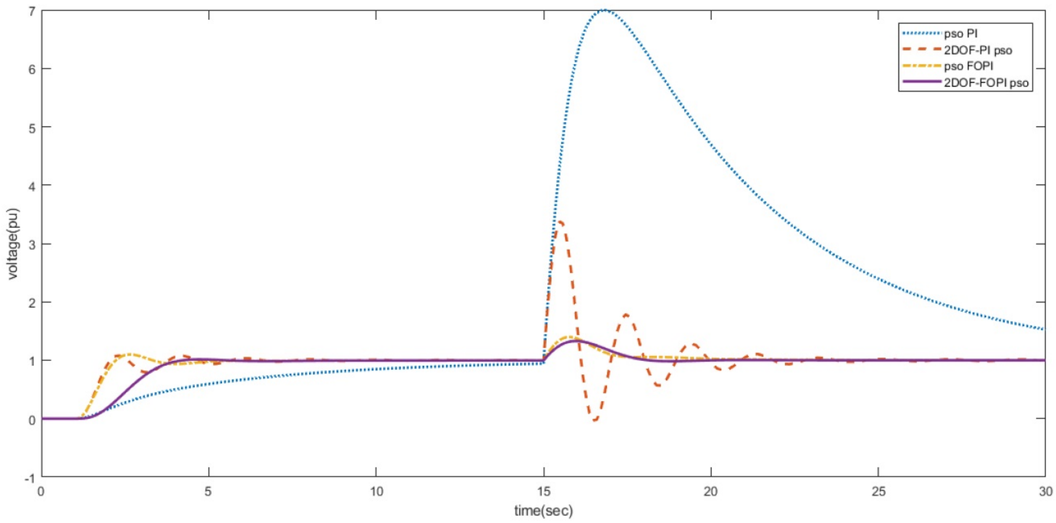

Figure 5: The results of disturbance analysis.

Table 5: The voltage deviations in disturbance analyses.

	Minimum voltage (pu)	Maximum voltage (pu)
1DOF PI	1.000	7.468
2DOF PI	0.451	3.048
FOPI	1.000	1.398
2DOF FOPI	0.980	1.327

5.2 Change AVR system parameters

Since the parameters of the power system are not constant, the operating point of the system changes as the load changes. To analyze the robustness of the control system, the time constants of the AVR system components are checked separately from -50% to +50% in steps of 25%. Figures 6 to 9 show the responses of AVR systems for four changing time constants in the 2DOF FOPI control system.

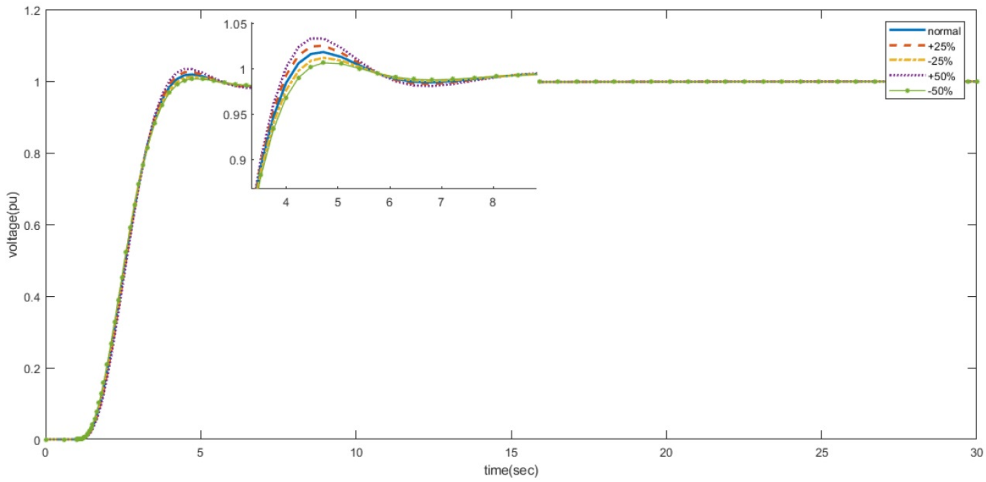

Figure 6: The effect of T_a changes on the control system.

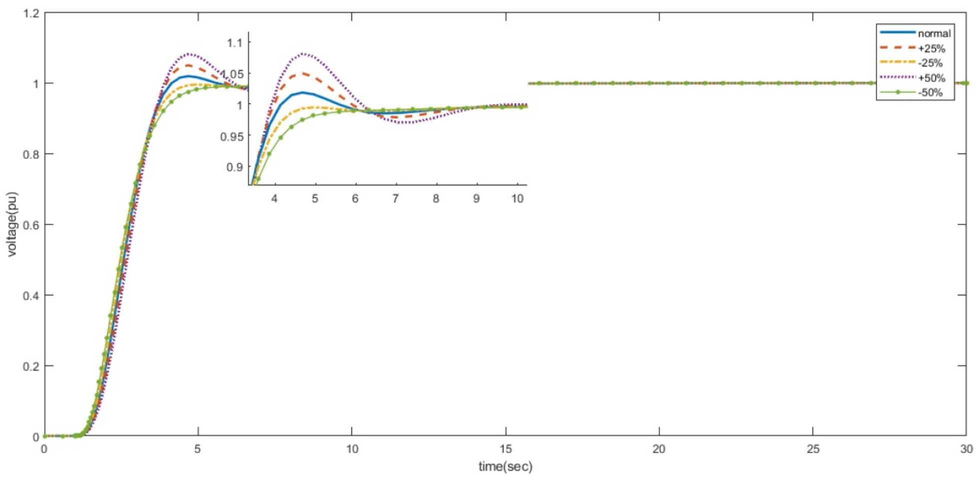

Figure 7: The effect of T_e changes on the control system.

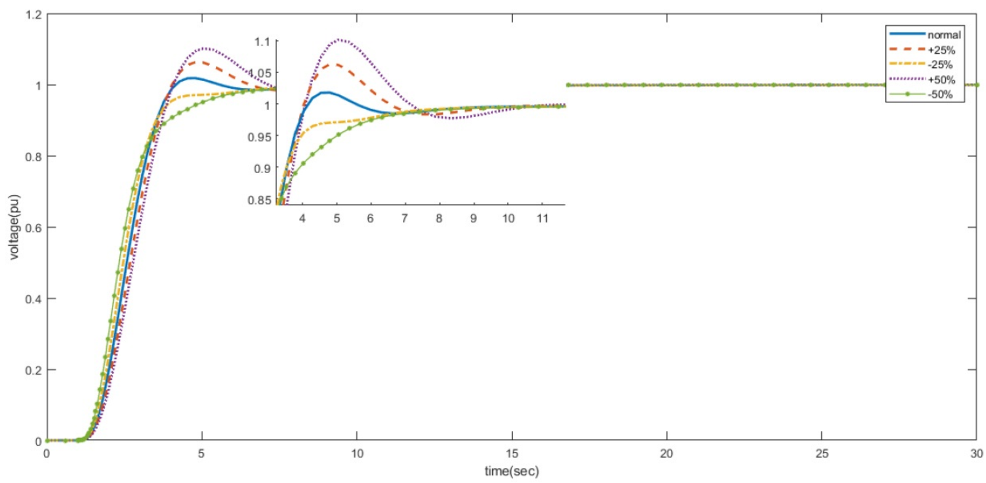

Figure 8: The effect of T_g changes on the control system.

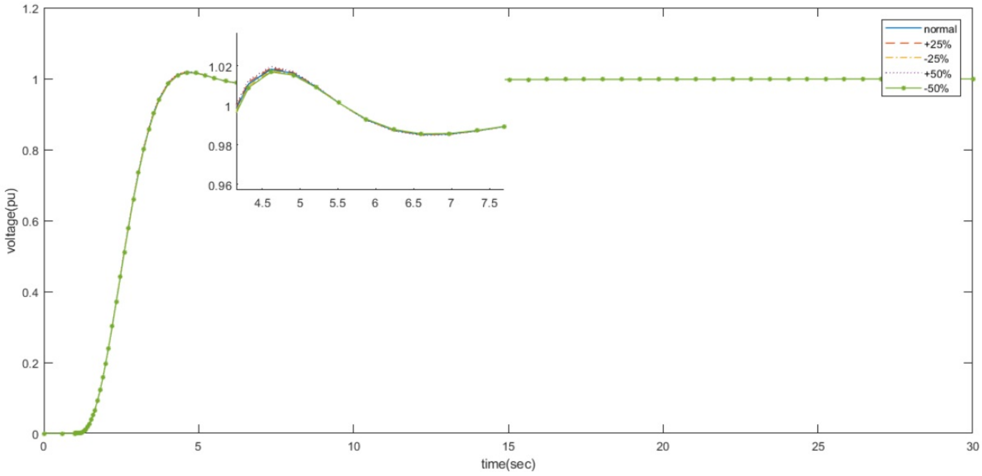

Figure 9: The effect of T_s changes on the control system.

From the results of changing the parameters of the AVR system, it is clear that the 2DOF FOPI controller can maintain its stability in the changes of the system and does not go out of the allowed voltage range.

6 Conclusions

In this research, a fractional order structure for the PI controller with two degrees of freedom, i.e. 2DOF FOPI was designed for the AVR system. From the obtained results, it was observed that the new 2DOF FOPI had a good performance significantly against load disturbances and parameter changes, which is in the control strength part was discussed. With the help of the fractional arithmetic theory, additional degree of freedom was applied in the controller transfer function and it was shown that the use of fractional order for the PI controller can lead to the desired responses. The PSO algorithm was used to adjust the controller parameters, which showed acceptable responses. After obtaining the parameters, a step voltage of 1pu was used to analyze and measure the proposed controller against the disturbance to which the presented system reacted with the desired speed. It was also shown that the introduced controller can respond well to changing the parameters of the AVR system. In future studies, this approach can be applied to multi-zone hybrid power systems where advanced fractional control schemes can be useful.

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