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Voltage Stability Improvement of Synchronous Generator by Using AVR Self-Turning Based on the Adaptive Fuzzy-PID Controller

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Abstract: The primary goal of this paper is to develop and apply an adaptive fuzzy (AF) based on the proportional integral derivative (PID) controller for the automatic voltage regular (AVR) system in the synchronous generator (SG) to improve output voltage stability. This proposed AF-PID is applied to ameliorate the shortcomings of the traditional PID controller by determining the optimal coefficients for the controller. Firstly, the initial coefficients of the traditional PID controller are calculated by using the Ziegler-Nichols method. After that, it develops the AF algorithm based on the fuzzification, rules of the fuzzy controller, and defuzzification of the voltage signals for self-tuning the coefficients to add the traditional PID controller. The transient response of the system is simulated and analyzed by considering the different step changes in reference voltage. The efficacy of the proposed AF-PID controller for the AVR system in the SG is illustrated by comparing it with traditional PID and without the controller based on the obtained results from the case studies. It can be concluded that when applying the proposed method, the transient response characteristics of the system from the perspective of simulating via the time domain under any sudden load changes in system operation, such as the rise time, steady-state error, max peak overshoot, and settling time are greatly improved. The simulation has been performed using the MATLAB/Simulink program.

Keywords: Automatic voltage regular (AVR), Synchronous generator (SG), Adaptive fuzzy (AF), Voltage stability.

1. Introduction

Nowadays, electrical energy can be generated from two other types that are the generation source from solar photovoltaic and rotating machines. The electricity generator based on the rotating machines is the synchronous machine. Unlink the induction machine that is widely used as an electric motor. Meanwhile, the synchronous machine is predominantly used as an electric generator. The synchronous generator (SG) is commonly applied for variable speed turbines. The SG operates at a variable speed and will generate the variable voltage and frequency. In addition, The SG's output voltage is instability while changing the electrical load.

Voltage stability in the power network under varying conditions is one of the important control concerns of power systems. This is closely related to power quality, grid security, and dependability since the equipment used in the electrical power system is chosen based on the normal voltage level. When the grid's voltage level varies, it causes major changes in the dynamics of the system, which may lower the performance and shorten the lifetime of the linked devices.

In the power system, voltage stability is closely tied to changes in reactive power. As a result, systems without reactive power significantly impact voltage instability, and the power system's control devices suffer damage. Additionally, injecting reactive power flow is another aspect of local bus voltage stabilization. The generator excitation system, also known as the automatic voltage regulator (AVR) system or the reactive power compensation device, also known as the flexible alternating current transmission system (FACTS device), is installed in the electrical power system in order to achieve the aforementioned objectives.

The output voltage stability at the power plant employing the SG is a key factor and must be considered highly. Therefore, while designing and operating the generator system, it is vital to pay attention to the stability of the output voltage, which may assist the power system in maintaining stability. The AVR system is placed on the SG to control and maintain the output voltage at a generally constant amount [1]. In addition, the AVR is responsible for dividing the reactive power amongst the SGs working in parallel situations [2]. This AVR system is a closed-loop control system employing multiple controllers to provide higher dynamic performance and miniaturize the steady-state error. Among these, the proportional integral derivative (PID) controller consists of the proportional, integral, and derivative coefficients. Because of the simple design, straightforward implementation, and strong performance in a broad variety of operating situations, this controller has been extensively utilized. Finding the values of these three coefficient values that give the optimal system control performance, however, is problematic [3].

There are ways to determine the three coefficients of the PID controller. The conventional tuning procedures, such as the Ziegler-Nichols (ZN) created in 1942 [4] and Cohen-Coon (CC) presented in 1953 [5] have been the most common until the last two decades [6]. These approaches can not deliver the greatest performance in the case of the control utilized in the closed loop. However, in order to acquire the greatest performance, it relies on the expertise of the designer [7].

Some algorithms based on the heuristic optimization technique have been developed to tackle the disadvantages of the ZN and the CC approaches. For example, the genetic algorithm (GA) was developed to find the PID-AVR controller coefficients [8]. The advantage of this approach is tweaking the optimum coefficients depending on the complexity of the considered performance index. It is only to specify a suitable target function and create a finite limit on the optimal coefficients [1]. The particle swarm optimization (PSO) was developed to optimize the PID-AVR coefficients [9]. When using this method, the SG system is increased the stability margin and is improved the operating performance. An extensive study on the chaotic PSO (CPSO) was developed in 2014 [10]. Comparing the PSO, the AVR system's performance based on the CPSO is enhanced in the case of the peak overshoot and setting time. Ant colony optimization (ACO) is a metaheuristic algorithm developed to find solutions to difficult combinatorial optimization problems [11]. In that number, the ACO is proposed to tune the PID-AVR coefficients [12]. However, this method has its main disadvantage, such as slow convergence and easily falling into local optimum because of having too many coefficients. The bacteria-foraging optimization (BFO) algorithm was developed in 2022 [13] and employed to modify the settings of the PID controller of AVR [14]. The BFO has remarkable tunability of the coefficients of PID by establishing a good balance between time domain indices that may assist the system in attaining stability. However, this method's slow convergence is a disadvantage [15]. In addition, the obtained coefficients related to research experience are based on the choice of a metaheuristic tuner [16].

Some additional studies suggested employing different artificial intelligence (AI) approaches to optimize the PID coefficients in the AVR system, such as fuzzy logic [17], neural network [18], artificial neural network (ANN) [19], and neural-fuzzy logic (NFL) [20]. Compared to the above-mentioned heuristic approaches, these methods have several shortcomings, such as the convergence time, training procedure and modifying the membership function [21]. To overcome the mentioned drawback, many researchers tried to combine these methods with other ones or modify them to enhance their efficiency and convergence time and to procure the minimum step response characteristics. For example, the authors of [22] combined the GA and PSO. This method can tune the PID coefficients faster and better than PSO and GA. Another method using the GA to combine the BFO is developed in 2011 [23]. The obtained results using this method achieve the best AVR step response. Another method using the combination between the PSO and the BFO was proposed in 2019 [24]. As result, the AVR step response is better in comparison to the conventional PSO and PFO methods.

Although there have been numerous studies on the use of various optimization techniques for determining the PID controller's coefficients for the AVR system of the SG, it is not known which of the developed algorithms performs the best in terms of quick convergence and the determination of the PID coefficients for the AVR step response. According to the analysis of the related literature in Section 1.2, the fuzzy logic method is widely used and has stepped up as a powerful controller. Recently, it has been applied in many power systems and electric drive applications. This work targets the improvement of the output voltage of the SG by finding the PID controller coefficients for the AVR system. For this reason, the adaptive fuzzy PID (AF-PID) controller proposes for investigation. The produced AF is not the controller, but it uses to determine the additional coefficients in the PID controller. This AF is implemented as a controller connected in series with

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a nominal PID controller. The nominal PID controller settings will be adjusted by adding the constants based on the mandani type fuzzy logic rule when a disturbance happens. These optimal PID controller coefficients are determined utilizing the hybrid control system between the nominal PID controller and the AF algorithm. The control coefficients of the nominal PID controller are the optimally selected constant values. The modified coefficients are calculated using the AF algorithm based on the fuzzification, fuzzy controller rules, and voltage signals defuzzification. The robustness analysis of the suggested technique has been evaluated using the simulated case studies and compared with the nominal PID controller. The simulation results using MATLAB/Simulink confirmed that the proposed AF-PID controller improves the voltage reference tracking in the AVR-SG system. Therefore, the primary contributions of this work are explicitly described as follows:

(*i*) The control quality for the AVR is improved by determining the PID control coefficients;

(*ii*) The SG's output voltage quality is ensured when the grid voltage oscillation (including the grid fault and load change);

(*iii*) it develops the AF algorithm base on the fuzzification, rules of the fuzzy controller, and defuzzification of the input and output voltage signals. The transient response characteristics including the peak overshot, rising time, and steady-state error improved.

The structure of this research is as follows: Following the Introduction section, Section 2 provides the theoretical development of the AVR system and its model under investigation. The AVR system's control strategy is developed in Section 3. The results of verifying the recommended control approach are discussed in Section 4, and Section 5 concludes with recommendations.

2. Theory development

The AVR is one of the necessary automated equipment in generator sets. It is utilized to keep the terminal voltage magnitude of the SG at a predetermined level. If the AVR fails, the SG will lose excitation. This lack of excitation will cause the voltage to decrease rapidly, leading the SG to shut down on an under-voltage fault. If the SG does not have an under-voltage protection set, it may continue to run, which could cause severe damage to the power generation system.

Fig. 1 illustrates the connection of the AVR unit to the SG set linked to a turbine. The objective is the quality and stability enhancement of SG. The AVR unit includes basic models such as a sensor, comparator, amplifier, and exciter. The plant includes of fundamental components such as a turbine, generator, and power grid. In reality, the SG is working at the frequency of 50 Hz with the set output voltage, and it will revolve at a constant speed. However, its speed is influenced by altering the load. As known, the speed will decrease as the load rises, and vice versa. This has been an issue for AVR in retaining voltage stability. Hence, if we expect the SG

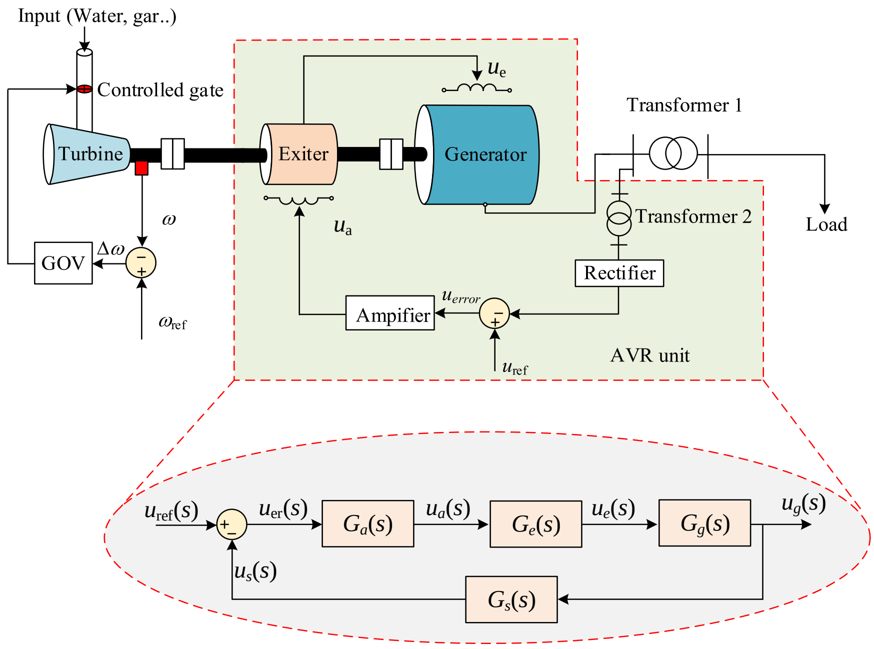

Figure. 1 The AVR-connected synchorous generator system

to be operated at a constant speed while the load fluctuates, the AVR system's stability is crucial, and its control mechanism is required to create.

There are two approaches to simulate the AVR, namely the transfer function and the state variable method. For simplicity and convenience of application, the transfer function approach is utilized to emulate the AVR system. The linearized model of the AVR system without a controller consists of four sub-models and may be expressed under the closed-loop form as indicated in the zoom-in of Fig. 1. All sub-models are provided by a basic first-order transfer function that comprises a gain of k and a time constant of τ specified in second. The subscript "*a*" signifies the amplifier, "*e*" denotes the exciter, "*g*" refers the generator, and "*s*" denotes the sensor. These transfer functions are developed as follows:

Sensor model **($G_s(s)$):** This type comprises the transformer and bridge rectifier. The transformer receives the terminal voltage of the SG $u_g(s)$. It travels via the bridge rectifier to produce a feedback voltage $u_s(s)$. Its transfer function is described as follows:

$$G_s(s) = \frac{u_s(s)}{u_g(s)} = \frac{k_s}{1+s\tau_s}$$
$$\text{with } \begin{cases} 0.9 \le k_s \le 1.1 \\ 0.001 \ sec \le \tau_s \le 0.06 \ sec \end{cases} \quad (1)$$

where k_s and τ_s are the gain and the time constant of the sensor model, respectively and $u_s(s)$ is the output voltage.

Amplifier model **($G_a(s)$):** The output voltage of the sensor model is compared with the input reference voltage to generate the voltage error $u_{\text{er}}(s)$. Then this voltage error is enlarged by the amplifier model to generate the voltage signal $u_a(s)$. Its transfer function is described as follows:

$$G_a(s) = \frac{u_a(s)}{u_{\text{er}}(s)} = \frac{k_a}{1+s\tau_a}$$
$$\text{with } \begin{cases} 10 \le k_a \le 40 \\ 0.02 \ sec \le \tau_a \le 0.1 \ sec \end{cases} \quad (2)$$

where k_a and τ_a are the gain and the time constant of the amplifier model, respectively.

Exciter model **($G_e(s)$):** This model is the main component of the AVR. Its base function is to deliver the direct current to the field winding. In addition, it also has other functions, such as controlling and protecting the system based on the control of field current. The exciter voltage signal $u_e(s)$ is generated from the voltage signal $u_a(s)$ through this model. Its transfer function is represented as follows:

$$G_e(s) = \frac{u_e(s)}{u_a(s)} = \frac{k_e}{1+s\tau_e}$$
$$\text{with } \begin{cases} 1 \le k_e \le 40 \\ 0.4 \ sec \le \tau_e \le 1 \ sec \end{cases} \quad (3)$$

where k_e and τ_e are the gain and the time constant of the exciter model, respectively.

Generator model **($G_g(s)$):** The terminal voltage of the SG is dependent on the load level, excitation voltage, and rotation. Its transfer function is modelled as follows:

$$G_g(s) = \frac{u_s(s)}{u_e(s)} = \frac{k_g}{1+s\tau_g}$$
$$\text{with } \begin{cases} 0.7 \le k_g \le 1.0 \\ 1 \text{ sec} \le \tau_g \le 2 \text{ sec} \end{cases} \quad (4)$$

where k_g and t_g are the gain and time constants of the generator model, respectively.

Herein, the generator model is similar to different models in conditions of its transfer function. However, k_g and τ_g are dependent on the connected-load conditions.

Therefore, the whole transfer function considering the generator terminal voltage $u_g(s)$ and the reference voltage $u_{\text{ref}}(s)$ utilizes Mason's gain rule is shown in the zoom-out part of Fig. 1 and it can be represented under the closed-loop form as follows:

$$G_{\text{AVR}}(s) = \frac{u_g(s)}{u_{\text{ref}}(s)}$$
$$= \frac{k_g k_a k_e (1+s\tau_s)}{(1+s\tau_g)(1+s\tau_a)(1+s\tau_e)(1+s\tau_s)+k_g k_a k_e k_s} \quad (5)$$

Fig. 2 shows the simulation results of the step response of two AVR1 and AVR2 systems corresponding to the coefficients in Table 1. From these results, we see that the terminal voltage of the SG has a large overshoot and oscillation, high steady-state error, and slow response time in the case of the AVR1, and a similar issue happens with the AVR2.

As we have in the simulation results in Fig. 2, even for generator gain of k_g = 1, the AVR step response is not sufficient. This value is larger than the system leading to an unlimited response, a high steady-state error, and loss of the stability system. An example of the load condition having the value of k_g is 1.07, and the system instability is severe, as can be seen in the sky-blue line in Fig. 2.

To solve this problem, we need to design a controller for the AVR system. This controller

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Table 1. Coefficients of the studied two AVR systems without a controller

Gains	Values		Time constants	Values	
	AVR1	AVR2		AVR1	AVR2
k_s	1	1	t_s	0.01 sec	0.01 sec
k_a	10	10	t_a	0.1 sec	0.1 sec
k_e	1	1	t_e	1 sec	0.4 sec
k_g	1	1	t_g	0.4 sec	0.4 sec

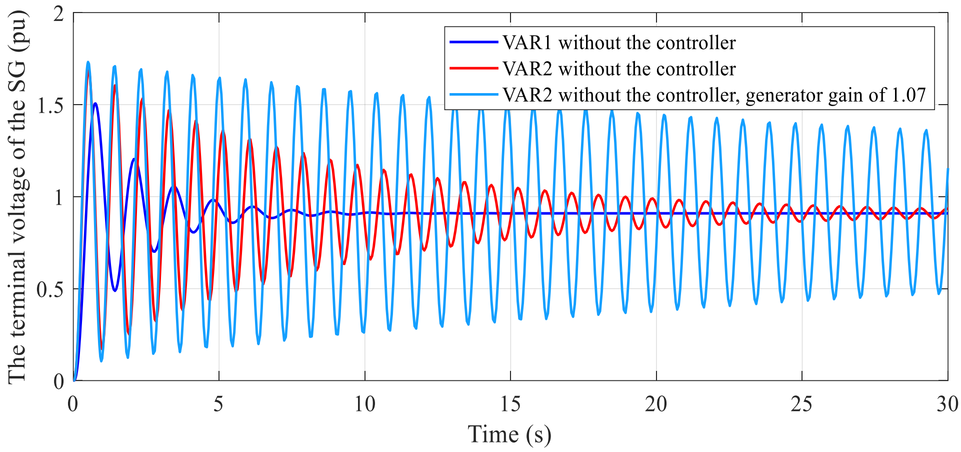

Figure. 2 The output voltage response of two AVR systems without the controller

requires improving the transient response characteristics of the system under any sudden load changes in operation.

3. Control solutions for the AVR system

3.1 Problem description

As analysed above, the design of the AVR controller system in the SG needs to be reminded of the following remarks:

Remark 1: when the generator works in the condition of variable output load, AVR system structure coefficients in Eq. (5) will be variable and uncertain.

Remark 2: Connecting and shedding loads or faults in the power grid will result in an unexpected voltage drop or surge. This problem makes the terminal voltage of the generator not maintain a stable level.

3.2 The traditional controller

In any system, the controller plays a crucial role, and the remedial control action hep its realization. The most dominant function of the controller is to keep the output at the desired level and eliminate the difference between the measured output value and the reference value. The PID controller is the most widely used type of controller in industrial control systems due to its simplicity and ease of implementation.

In order to improve the transient response and decrease the steady-state error of the AVR system in Eq. (5), the PID controller is chosen as a solution. Fig. 3 shows the transfer function model of the AVR system connecting the PID controller. In this study, the continuous s-domain is used to simulate the PID controller system and it can see zoom-out this figure. The transfer function of the PID controller model is represented as follows:

$$G_{PID}(s) = \frac{u_c(s)}{u_{\mathrm{er}}(s)} = k_p + \frac{k_s}{s} + k_d s \quad (6)$$

The transfer function of the AVR system uses Mason's gain rule and it can be given in Eq. (7).

$$G_{\mathrm{AVR}}(s) = \frac{u_g(s)}{u_{\mathrm{ref}}(s)} = \frac{(s^2 k_d + s k_p + k_i)(1+s\tau_s)k_g k_a k_e}{s(1+s\tau_g)(1+s\tau_a)(1+s\tau_e)(1+s\tau_s) + (s^2 k_d + s k_p + k_i)k_g k_a k_e k_s} \quad (7)$$

Table 2. The parameter value of the PID controller

Parameter	k_p	k_i	k_d
Value	$0.60k_u$	$\frac{2k_p}{p_u}$	$\frac{k_p p_u}{8}$

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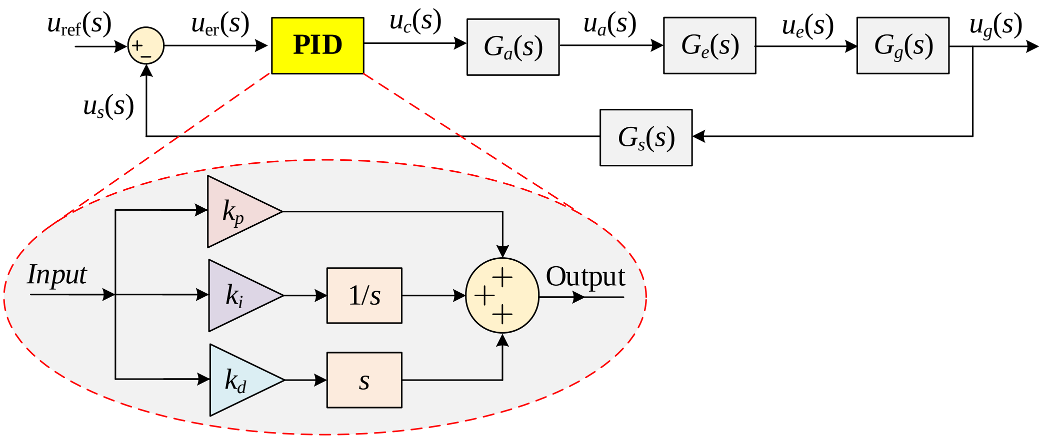

Figure. 3 The AVR system with a PID controller under the transfer function model

where k_p is the proportional gain, it helps to generate a signal that is proportional to the input error according to the sampling time; k_i is the integral time constant, it helps to create the adjustment signal so that the error is decreased to zero; k_d is the derivative time constant, it helps to produce an adjustment signal so that it is proportional to the rate of change of the input error.

There are many methods to determine the PID controller coefficients, such as software, Cohen-Coon, and Ziegler-Nichols. Among them, the Ziegler-Nichols method, including two ways, namely the step response and ultimate frequency, is widely used today. In this paper, the ultimate frequency is re-applied to calculate the coefficients of the PID controller. Firstly, we drive the system into the condition of instability by increasing the proportional gain k_p when it is reached sustained oscillations meaning that it is reached the critical value of gain k_u. Secondly, we measure the period of oscillation from the step response method, which is the critical time constant p_u. Once these k_u and p_u values are obtained, the coefficients of the PID controller can be calculated as listed in Table 2. Applying this method, with k_u = *0.3* and p_u = *3*, the PID controller coefficients corresponding to the AVR1 system are given by the following equation.

$$G_{PID}(s) = 0.18 + \frac{0.12}{s} + 0.0675s \tag{8}$$

The terminal voltage step response when using this method is also shown in Fig. 4. Observing this figure, the AVR1 system response when using the PID controller. The result shows that the steady-state error, settling time and percent overshoot is still high since in a conventional PID controller, the coefficients k_p, k_i, and k_d are fixed based on the system's output response. These control coefficients ensure a good and fast response in the limited input range. Considering the actual conditions, the grid-connected voltage of the generator must maintain stability; the AVR system with the conventional PID controller is not appropriate. Therefore, a controller that automatically adjusts these coefficients is needed for the system. In order to achieve the goal, this study provides an optimal solution and will present in Sub-section 3.3.

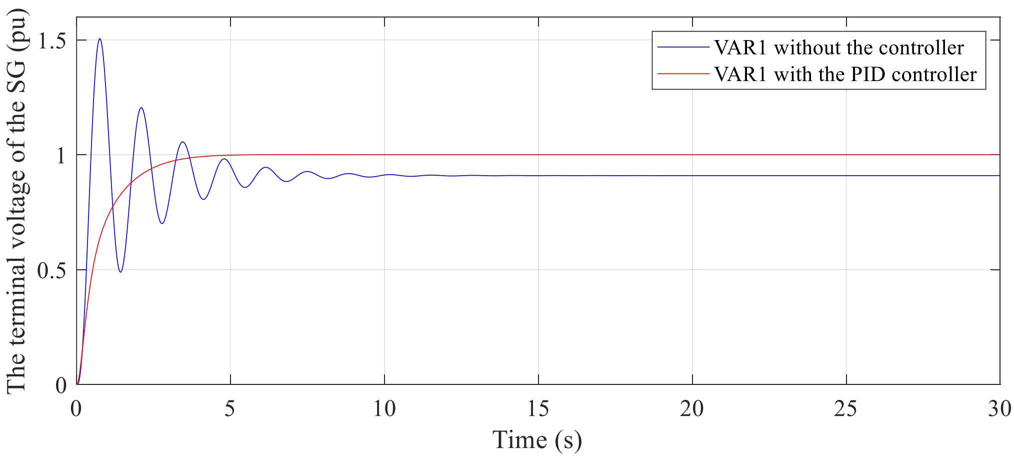

Figure. 4 The terminal voltage response of AVR1 system without and with the PID controller

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3.3 The proposed controller

As mentioned in Subsection 3.1, using the PID controller to control the generator voltage will not bring about high efficiency since the control signal is fixed and not optimal. In order to overcome this problem, the fuzzy-based optimization method is proposed to tune the coefficients in the PID controller. The structure of the proposed controller of the AVR system is shown in Fig. 5. This control is one of the configurations in a hybrid control system between the PID controller and fuzzy algorithm. The control signal received from the proposed AF-PID strategy from Eq. (6) can be rewritten under the self-turning based on the fuzzy solution as follows:

$$u_f(s) = u_{fp}(s) + u_{fi}(s) + u_{fd}(s) \tag{9}$$

where u_{fp}, u_{fi}, and u_{fd} are the AF-PID control coefficients, and it can be determined as follows:

$$\begin{cases} u_{fp}(s) = k_{p0}u_{\mathrm{er}}(s) + k_{pf} \\ u_{fi}(s) = k_{i0}\int_0^s u_{\mathrm{er}}(s)\,ds + k_{if} \\ u_{fd}(s) = k_{d0}\frac{du_{\mathrm{er}}(s)}{ds} + k_{df} \end{cases} \tag{10}$$

in which k_{p0}, k_{i0}, and k_{d0} are the original coefficients of PID controller. The k_{pf}, k_{if}, and k_{df} are the coefficients generated by the fuzzy to add the PID coefficients.

The used adaptive fuzzy is designed to generate k_{pf}, k_{if}, and k_{df} from two input signals (the error u_{er} and its change $u_{\mathrm{er}}c$ based on the fuzzification, rules, and defuzzification modules. The output of the fuzzy system can be expressed as follows:

$$u_f = \frac{\sum_{i=1}^{h} B^i\left[\prod_{j=1}^{n}\mu_{A_j^i}\left((u_{er})_j\right)\right]}{\sum_{i=1}^{h}\left[\prod_{j=1}^{n}\mu_{A_j^i}\left((u_{er})_j\right)\right]} \tag{11}$$

where $\mu_{A_j^i}\left((u_{er})_j\right)$ represents the membership function value fuzzy variable $(u_{er})_j$, h is the number of IF-THEN rules, and $.A_1^i, A_2^i, \ldots, A_n^i.$, and B^i are the input and fuzzy output variables. The simple IF-THEN rules with a condition and conclusion as expressed in Eq. (12)

$$\text{IF} \quad (u_{er})_1 \text{ is } A_1^i \ \ldots \text{ and } (u_{er})_n \text{ is } A_n^i \quad \text{THEN } u_f = B^i \tag{12}$$

The proposed fuzzy inference system is seen in Fig. 6(a). This structure has two input signals, including the error u_{er} and its change $u_{er}c$ and three output signals, including the k_{pf}, k_{if}, and k_{df} are the additional PID coefficients. The procedure of the proposed AF-PID method is realized based on the three steps below:

***Step 1: Fuzzification*:** The fuzzification module is used to transform the error u_{er} and its change $u_{er}c$ into the semantic value and the fuzzy range of u_{er} and $u_{er}c$ are a uniform fuzzy range [- 45 45] and [- 1×10^5 1×10^5], respectively. The fuzzy sub-sets of u_{er} and $u_{er}c$ are [NE NSS NS ZE PS PSS PO] and [NS ZE PS], respectively, where NE is negative; NSS is negative small small; NS is negative small; ZE is zero; PS is positive small; PSS is positive small small; PO is positive.

***Step 2: Fuzzy controller rules*:** This step establishes the fuzzy inference rules between the input-output variables based on input-output data. The fuzzy sub-sets of k_{pf}, k_{if}, and k_{df} are [NEE NE NSS NS ZE PS PSS PO POO], [NEe Ne NSs Ns Ze Ps PSs Po POo], [nee ne nss ns ze ps pss po poo], where NEE is Negative Negative and POO is Positive Positive. The fuzzy set of k_{pf}, k_{if}, and k_{df} is presented with the range of values 0 to 1. As mentioned in Eq. (12), communion is realized based on the simple IF-THEN rules with a condition and conclusion: "IF the error u_{er} is A_i and $u_{er}c$ is B_j, THEN k_{pf}, k_{if}, and k_{df} are C_{ij}, D_{ij}, and E_{ij}" respectively, where A_i, B_j, C_{ij}, D_{ij}, and E_{ij} are corresponding to the fuzzy subsets of u_{er}, $u_{er}c$, k_{pf}, k_{if}, and k_{df} , respectively. An example of the ith rule is "IF u_{er} is NS and $u_{er}c$ is PS THEN k_{pf}, k_{if}, and k_{df} are ZE, Ze, and ze", respectively. The fuzzy inference rules are generated and summarized in Table 3, and the rule bases view is shown in Fig. 6(b). There are 21 rules for each k_{pf}, k_{if}, and k_{df} . The surface viewer of the proposed AF-PID controller is described in Fig. 6 (c). Observing this figure, the input variables u_{er} and $u_{er}c$ are distributed in the range of [-45 45] and [-1×10^5 1×10^5], respectively, and the output of k_{pf} is distributed in the range of [-0.15 0. 5].

Step 3: Defuzzification: The defuzzification applies to convert the fuzzy value into numeric values. After the defuzzification, the three control coefficients u_{fp}, u_{fi}, and u_{fd} can be obtained from Eq. (10). Therefore, the control signal received from the proposed AF-PID strategy is shown in Eq. (9).

The terminal voltage step response of the AVR1 system is as shown in Fig. 7, when applying the proposed method and coefficients in Table 4. As can

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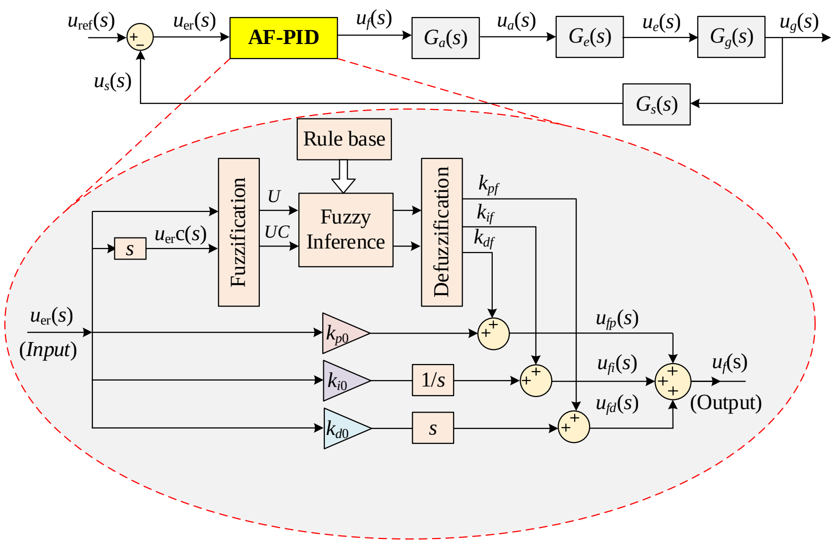

Figure. 5 The proposed self-tuning fuzzy-PID controller for The AVR system

Table 3. Rules of input and output coefficients

	u_{erC}	u_{er}						
		NE	NSS	NS	ZE	PS	PSS	PO
k_{pf}	NS	NEE	NE	NSS	NS	ZE	PS	PSS
	ZE	NE	NSS	NS	ZE	PS	PSS	PO
	PS	NSS	NS	ZE	PS	PSS	PO	POO
k_{if}	NS	NEe	Ne	NSs	Ns	Ze	Ps	PSs
	ZE	Ne	Nss	Ns	Ze	Ps	PSs	Po
	PS	Nss	Ns	Ze	Ps	PSs	Po	POo
k_{df}	NS	nee	ne	nss	ns	ze	ps	pss
	ZE	ne	nss	ns	ze	ps	pss	po
	PS	nss	ns	ze	ps	pss	po	poo

Table 4. The parameter of the AF-PID controller

Parameter	k_{p0}	k_{i0}	k_{d0}	k_{pf}	k_{if}	k_{df}
Value	0.18	0.12	0.0675	[-0.15 0.15]	[-0.005 0.005]	[-0.003 0.003]

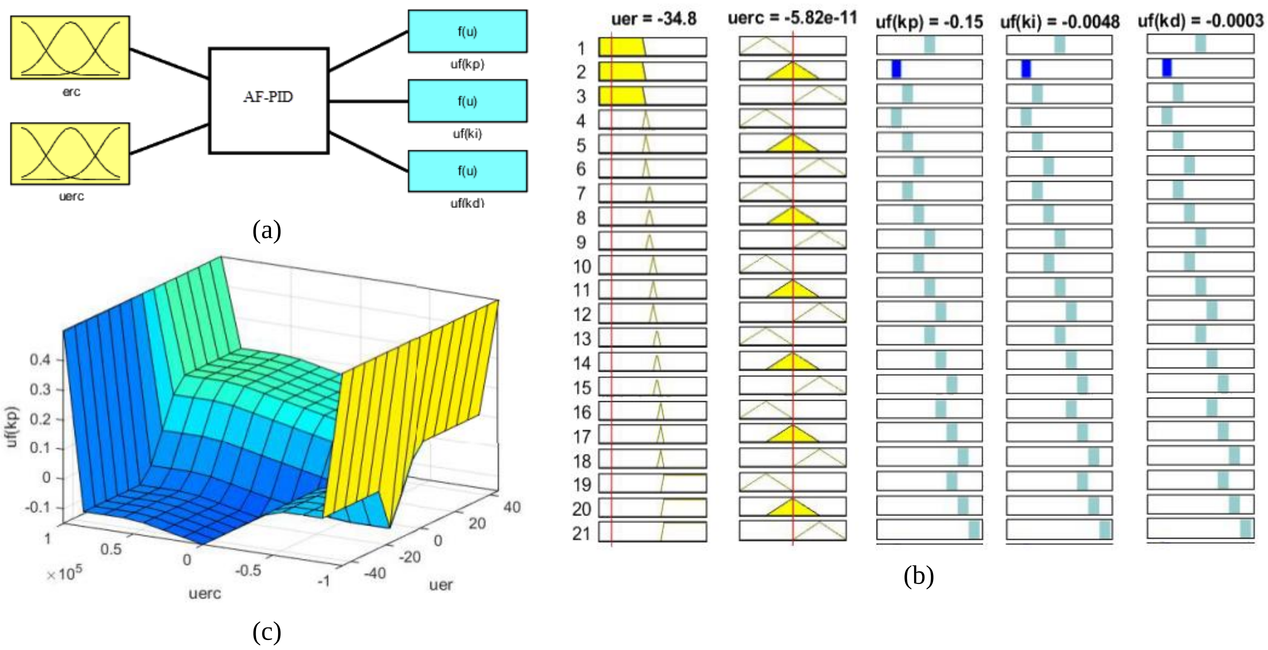

Figure. 6 The fuzzy processing procedure: (a) Fuzzy inference block, (b) Rule base view of input and output signals, and (c) Control surface viewer

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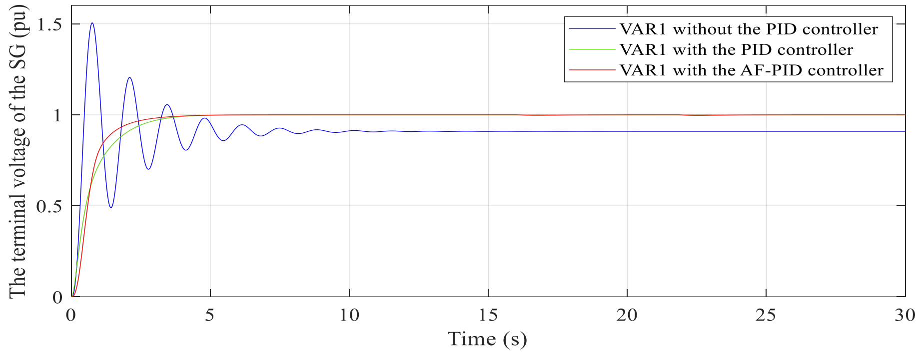

Figure. 7 The terminal voltage response of the AVR1 system with and without the controllers

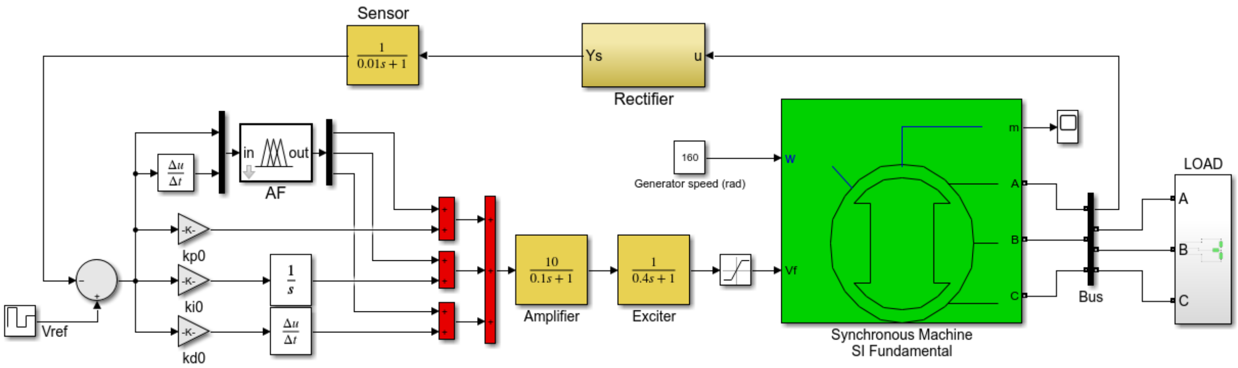

Figure. 8 The tested AVR-SG-connected system

Table 5. The parameter of synchronous generator

Parameter	Value	Parameter	Value
The three-phase nominal power P_n (VA)	8100	Stator resistance per phase R_s (Ω)	1.62
The nominal line-to-line voltage U_n (Vrms)	400	Stator leakage inductance L_l (H)	0.004527
The nominal frequency f_n (Hz)	50	The load active power P_{Load} (W)	3000

see in this figure, the overshoot, settling time, and rise time of the system were reduced to minimal. This tends to smooth out operations and improve overall efficiency.

4. Test the SG system with AVR controller

The AVR-SG-connected system with the structure of a single machine infinite bus is considered for testing the proposed method as shown in Fig. 8. All parameters are shown in Table 4, Table 5, and Fig. 8. The system is simulated under the conditions of changing the terminal voltage and rotating at the synchronous speed of SG. The change of the terminal voltage is considered as the different loading conditions. It is focused on simulation and materialized using the MATLAB/Simulink simulation program in the following three cases.

4.1 Unchanging terminal voltage

The simulation for this case is made by considering three unchanging reference voltage values. Fig. 9(a), (b), and (c) show the response of the system in conditions of reference voltages of 170 V, 190 V, and 220 V, respectively. Observing Fig. 9 shows that the peak overshoot and rise time of the generator's terminal voltage for using both PID and AF-PID controllers is the same. However, the system reaches the steady state in a shorter time using the AF-PID controller than PID one. Observing the zoom-out of Fig. 9, the system reached the steady state and took 4 seconds when using the proposed controller. Meanwhile, that took 7 seconds when using the traditional PID controller.

4.2 Sudden decrease of the terminal voltage

The second case is performed to determine the robustness of the proposed controller in the condition that the voltage sudden reduced from 220 V to 190 V, 170 V, and 150 V at 10 sec. These changes in the terminal voltage are considered as the different loading conditions. Observing the obtained result in Fig. 10 (a), when reducing the voltage at the value of 190 V, the steady-state error reduces, the rise time is improved, but the system is lost stability when applying the conventional PID. If the voltage

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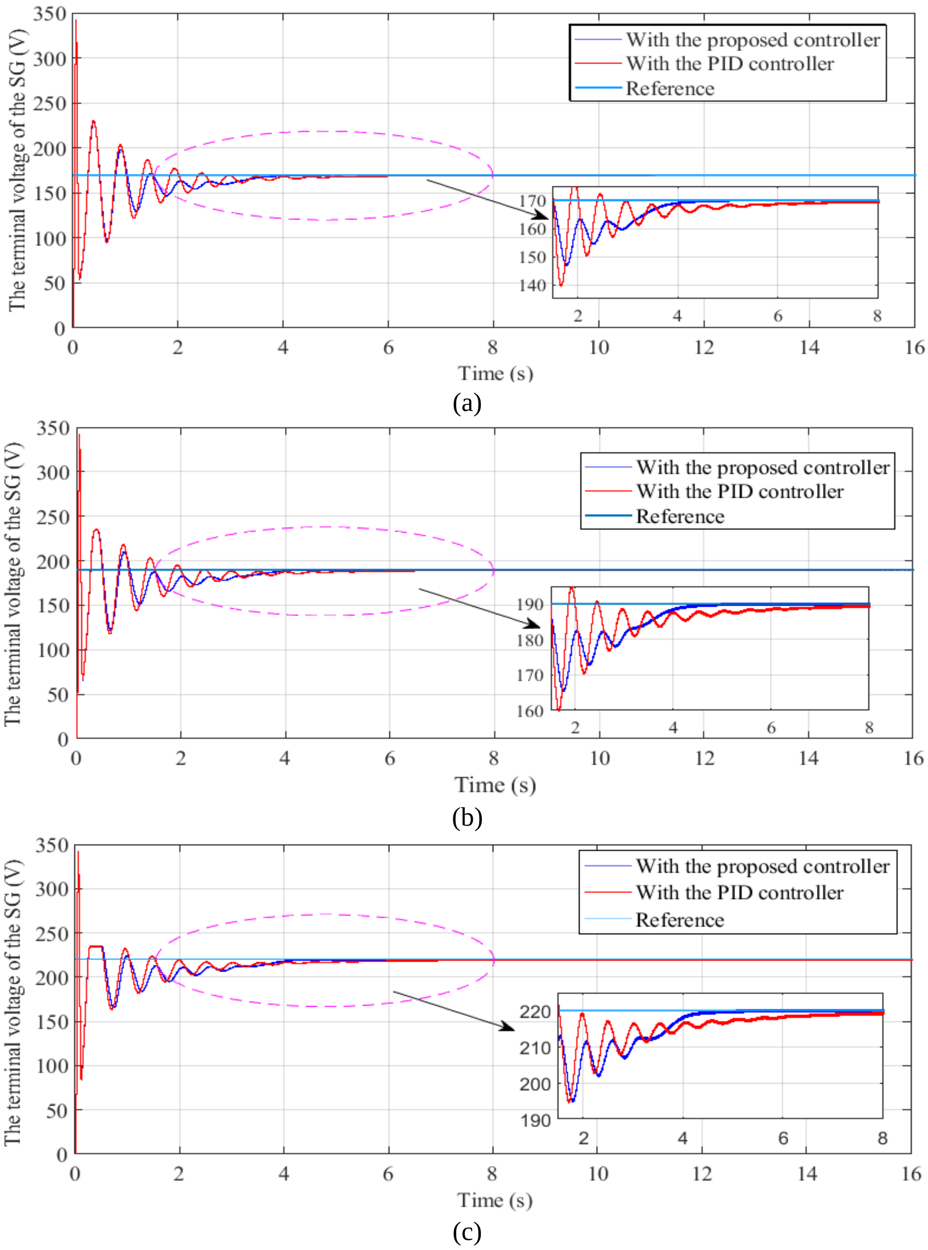

Figure. 9 The system's terminal voltage response with three unchanging reference voltage values: (a) the reference voltage of 170 V, (b) the reference voltage of 190 V, and (c) the reference voltage of 220 V

continues reducing to 170 V and even 150 V, as shown in Fig. 10 (b) and (c), the peak overshot time is higher, but the rise time does not change. However, compared to the conventional PID controller, the overshoot, settling time, and damping ratio are improved for applying the proposed controller. This result can see in three tested cases from the zoom-out in Fig. 10.

4.3 Sudden increase and decrease of the terminal voltage

As known, the voltage on the power system changes all the time continuously under various influences, especially affected due to load switching. The third test is simulated to confirm the feasible controller when given several load-changing conditions. Fig. 11 (a) shows the system's response in the condition that the voltage suddenly reduced from 220 V to the 190V at 7 sec and continued reducing to 150 V at 14 sec from the previous value. As can be seen in this figure, the best results are related to the proposed controller under the overshoot and settling time.

Fig. 11 (b) shows the system's response in the condition that the voltage suddenly reduced from 220 V to 150 V at 7 sec and continued increasing to 150 V at 14 sec from the previous value. As seen in this figure, the best results are related to the proposed

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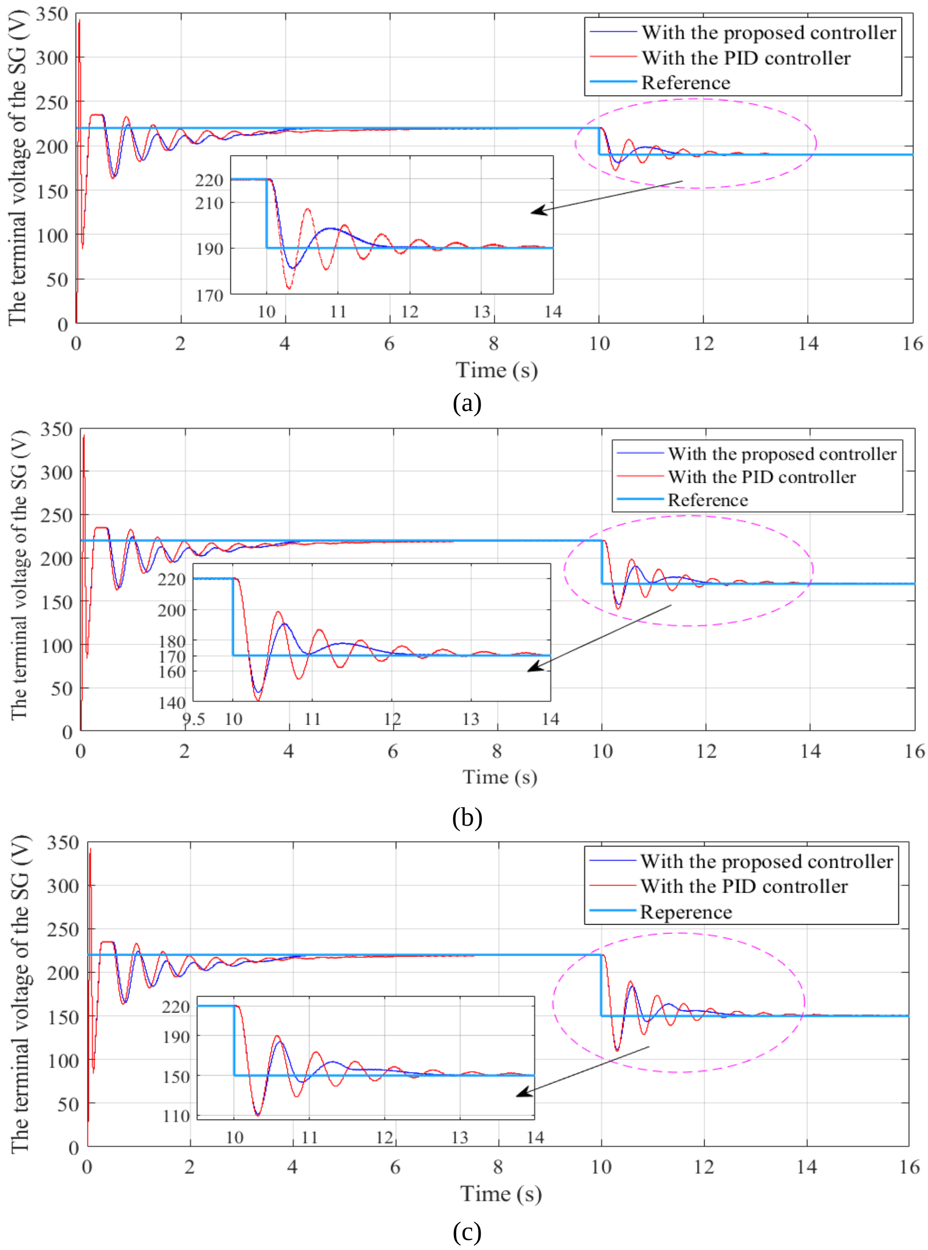

Figure. 10 The system's terminal voltage response with the sudden decrease voltage: (a) From 220 V to 190 V, (b) From 220 V to 170 V, and (c) From 220 V to 150 V

controller under the overshoot and the settling time for the case that the voltage suddenly increases from 150 V to 190 V at 14 sec.

Fig. 11 (c) shows the system's response in the condition that the voltage suddenly increased from 190 V to 220 V at 7 sec and then continued reducing to 150 V at 14 sec from the previous value. As seen in this figure, the best results are related to the proposed controller under the overshoot and the settling time for the case that the voltage suddenly increases from 190 V to 220 V at 7 sec.

5. Conclusions

This paper proposed the AVR system's controller to improve the SG's output voltage stability. To solve this problem, the PID control technique was selected since the response provided by the AVR may create a DC source that fulfills the excitation needs of the generator. The hybrid control system between the nominal PID controller and the AF algorithm is proposed to adjust the optimum coefficients of the PID controller. The AF method is developed based on the fuzzification, rules of the fuzzy control, and defuzzification of the voltage signals to determine the optimal coefficients to change the traditional PID controller coefficients.

MATLAB/Simulink program used to simulate the transient response of the AVR-SG system considering several different case studies in the reference voltage step changes (different load

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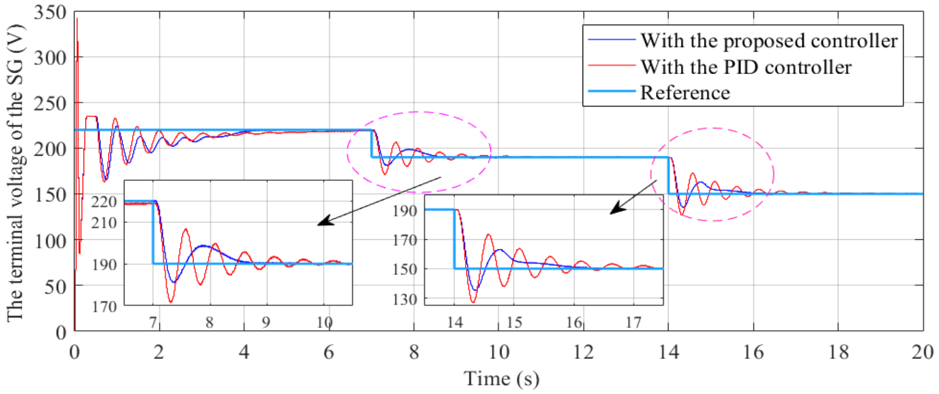
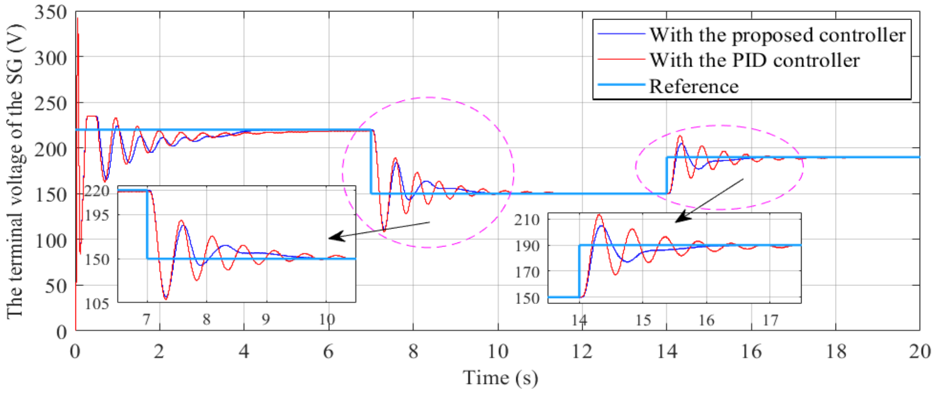
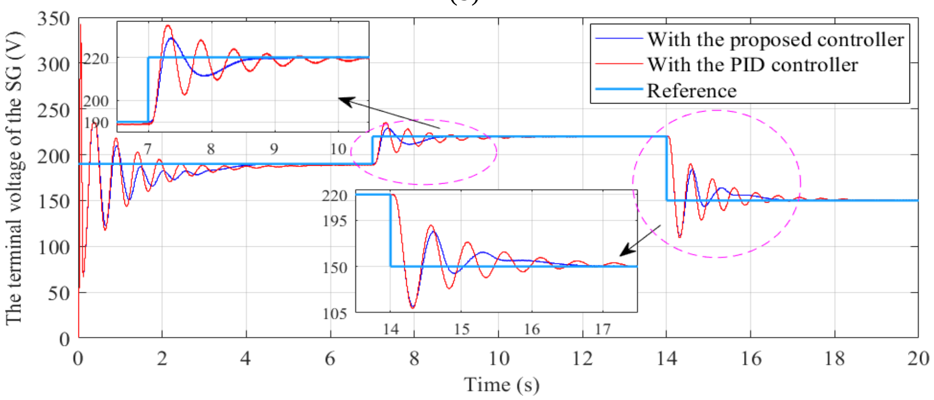


(a)



(b)



(c)

Figure. 11 The system's terminal voltage response with the sudden increase and decrease voltage: (a) Decrease from 220 V to 190 V and then to 150V, (b) Decrease from 220 V to 150 V and then increase to 190 V, and (c) Increase from 190 V to 220 V and the decrease to 150 V

conditions). Based on the simulation results, it can be concluded that the AVR-SG system using the proposed controller can improve the characteristics of transient step response of the output voltage better than the Ziegler-Nichols method-based PID controller, such as the rise time, the steady-state error, peak overshoot along with fast convergence time are substantially improved.

Further in this work is the development of a test hardware system to evaluate the results obtained from the simulation.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, L.V.D.; methodology, N.D.H.; software N.D.H. and L.V.D.; validation, L.V.D. and L.C.Q.; formal analysis, N.D.H.; investigation, L.C.Q.; resources, L.V.D.; data curation, N.D.H.; writing-original draft preparation, N.D.H.; writing-review and editing, L.V.D.;

visualization, L.C.Q.; supervision, L.V.D. All authors have read and agreed to the published version of the manuscript.

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