Enhancing the Control Performance of Automatic Voltage Regulator for Marine Synchronous Generator by Using Interactive Adaptive Fuzzy Algorithm

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Abstract. Currently, Adaptive Fuzzy Control is considered the most effective tool in the nonlinear control system. In this paper, we studied an automatic voltage regulator (AVR) system based on the Interactive Adaptive Fuzzy Algorithm (IAFA) to change the field excitation of the synchronous generator maintaining constant terminal voltage under the effect of unknown disturbances. The Fuzzy function calibrates the AVR controller to adapt to the varying output voltage of the generator, and its performance was compared with that of the recently used tuning methods for the same system configuration and operating conditions to validate the effectiveness of the proposed method. The results show that the proposed AVR-based IAFA method outperformed its conventional counterparts in terms of stability voltage response brings us high performance in simulation and experiment.

Keywords: Adaptive fuzzy control · Automatic voltage regulator · Interactive adaptive · Synchronous generator · Varying output voltage

1 Introduction

The certainty that electricity is now crucial to the work of all marine equipment. The Ship Power System (SPS) is a kind of ‘nervous system’ because it is covering not only energy but also the automation of modes that allow it to control systems composed of numerous elements that exceed the perceptual abilities of the sailor [1]. Moreover, the technical requirements currently being deployed for the management system, energy, water, or economic operation of the ship have significantly increased requirements for class and dependability of power source. The Automatic Voltage Regulator (AVR) is a key component of the power system owing to the purpose of improving power system stability, power quality, and power system economics [2].

N.-S. Vo et al. (Eds.): INISCOM 2021, LNICST 379, pp. 379–392, 2021.
https://doi.org/10.1007/978-3-030-77424-0_31

In general, there are two important control systems on board that are steering system and electric power system. Many researchers are devoted to developing enhanced technology and artificial intelligence in the autopilot on the steering system for its outstanding advantages [3–8]. Numerous proposed advanced control solutions, including Fuzzy [3], Hybrid Fuzzy [4] and Fuzzy Adaptive [5, 6], Neural Network [7], and Recurrent Cerebellar Model Articulation [8], have demonstrated the effectiveness and stability of these algorithms. Meanwhile, many classic controllers such as PID and LQR are applied for the electric power system yet. Moreover, there are not too many studies on modern control theory applied to increase the quality of the electrical system on board, especially voltage stabilizers for generators.

Related to Synchronous Generator to ensure the quality of the electrical system, the adaptive control strategy is proposed in [9] for Virtual Synchronous Generator, and the optimal damping ratio of the controller is maintained to suppress the oscillation of power and frequency of the generator. The authors clarified the performance of the system enhanced since the response time and overshoots are optimized. In order to enhance the adaptability and robustness of induction generator, the adaptive nonlinear controller built by adding the estimated uncertainty value is designed [10] to improve the regulation performance of the system in case of grid faults and parameter uncertainty.

In recent years, Adaptive Fuzzy Control (AFC) has got a great extension and lots of novel results to deal with problems of uncertainty and disturbance of nonlinear system in works of literature [5, 6], and [11–15]. The research results all have the same conclusion that is AFC strategy can guarantee that all the signals in the closed-loop system which are bounded under a class of switching signals with average dead-time. Moreover, adaptive reliability guaranteed the control performance of uncertain nonlinear systems. This is the reason that motivates us to use the novel AFC strategy for Marine Synchronous Generator because it always has to work in the harsh conditions of the environment and working mode.

In this paper, we aimed to enhance the control performance of AVR for Marine Synchronous Generator by using Interactive Adaptive Fuzzy Algorithm (IAFA). We carefully designed the IAFA controller for reducing the effect of uncertain parameters and disturbances. The main contributions of this paper are given as follow:

(i) We first built the Automatic Voltage Regulator Model and then given some Remark and Assumption.
(ii) By simulation, we determined that the Fuzzy PID controller design for AVR is not highly feasible under impacts of the drop voltage or time-delay caused by the nonlinear characteristics. However, our suggested solution, one kind of Hybrid Fuzzy Interactive algorithm, is Interactive Adaptive Fuzzy Algorithm.
(iii) Interactive Adaptive Fuzzy Algorithm is designed. By using the error between the output signal of the AVR ideal model and the AVR actual model, the compensation controller is added to the model.
(iv) Finally, the hardware is designed for the experiments.

The rest of the paper is organized as follows. Section 2 shows the design of automatic voltage regulator model and Sect. 3 describes the structure of the proposed IAFA.

Section 4 presents the simulation, experimental results, and discussions. Finally, the concluding remarks are given in Sect. 5.

2 Automatic Voltage Regulator Model

An automatic voltage regulator (AVR) maintains a constant voltage across the synchronous generator output at different load levels. This scheme is solved by adjusting the output voltage of the synchronous generator based on regulating the excitation voltage [16]. The AVR model consists of four main components: the amplifier, the exciter, the generator, and the sensor. A schematic diagram of the AVR total principle [17] is illustrated in Fig. 1.

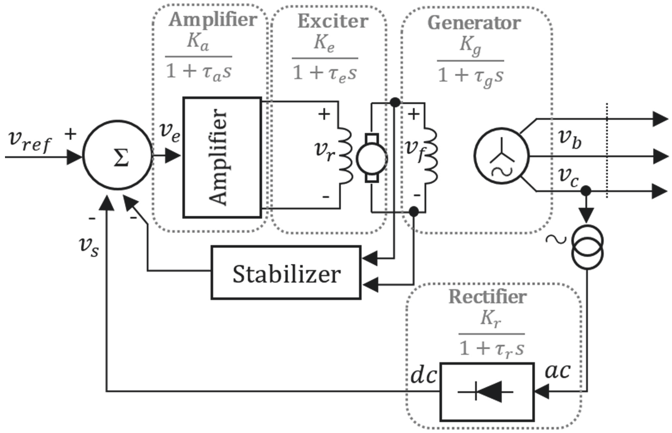


Fig. 1. The schematic diagram of the AVR total principle.

The Amplifier Model. v_e is the error voltage between the output voltage of the generator and the setpoint. Then the error $v_e = v_{ref} - v_s$ is amplified. The transfer function of the amplifier model is given by

$$G_a(s) = \frac{v_{ref}(s)}{v_e(s)} = \frac{K_a}{1 + \tau_a s} \tag{1}$$

Since the time constant τ_a of the stationary exciter is small, then the equivalent transfer function becomes the gain connected between the synchronous generator and the AVR controller [18]. Besides, K_a is the gain of the stationary exciter, used to adjust control signal.

The Exciter Model. The exciter model supplies the DC voltage to the excitation coil, which has a time constant τ_e and amplification coefficient K_e [19]. The excitation voltage v_r is performed to the excitation coil independent of the generator voltage. The v_f voltage is proportional to the output voltage of the synchronous generator. The transfer function of the exciter model is described below:

$$G_e(s) = \frac{v_f(s)}{v_r(s)} = \frac{K_e}{1 + \tau_e s} \tag{2}$$

The Generator Model. The output voltage of the synchronous generator depends on the excitation voltage v_f, the rotation speed of the traction motor, the load level, and the load characteristics [20]. The generator model consists of the time constants and gain constants of τ_g and K_g, respectively. The transfer function of the generator model is expressed as follows:

$$G_g(s) = \frac{v_t(s)}{v_f(s)} = \frac{K_g}{1 + \tau_g s} \tag{3}$$

The Rectifier Model. In the rectifier model, the transformer converts the AC voltage of the generator to a suitable AC voltage. Then, the rectifier transforms this voltage to DC voltage as the feedback signal (v_s) for the AVR system [21]. The transfer function of the rectifier model is described as

$$G_r(s) = \frac{v_s(s)}{v_t(s)} = \frac{K_r}{1 + \tau_r s} \tag{4}$$

Therefore, the transfer function of the AVR system is related to the generator output voltage $v_t(s)$ to the reference voltage $v_{ref}(s)$ defined as follows:

$$G(s) = \frac{v_t(s)}{v_{ref}(s)} = \frac{K_a K_e K_g K_r (1 + \tau_r s)}{(1 + \tau_a s)(1 + \tau_e s)\left(1 + \tau_g s\right)(1 + \tau_r s) + K_a K_e K_g K_r} \tag{5}$$

The open-loop transfer function of the AVR system can be rewritten as

$$K_g(s)H(s) = \frac{K_a K_e K_g K_r}{(1 + \tau_a s)(1 + \tau_e s)\left(1 + \tau_g s\right)(1 + \tau_r s)} \tag{6}$$

Remark: If the generator operates in the actual conditions under the characteristics of load-varying, the generator parameters will exhibit high nonlinearity.

Assumption: The excitation voltage usually remains in the fixed status. If the voltage drop occurs due to the load-varying characteristics, the output voltage is not stable. As such, the assumptions are more reasonable.

In this paper, the authors aim to suggest an Interactive Adaptive Fuzzy Algorithm for the AVR system under the condition of Assumptions. The goal is to keep the output voltage of the generator at precision level and stability, while the fuzzy function calibrates the AVR controller to adapt to the varying output voltage of the generator.

3 Interactive Adaptive Fuzzy Algorithm

3.1 Fuzzy PID Controller

Proportional-Integral-Derivative (PID) controllers are widely used in industrial applications, especially the AVR control systems [22–24]. This solution had the advantage of simple structural and stable output. However, these cover bounded activities without considering the voltage drop in the generator output. In this study, the authors propose a PID controller as the main controller whose transfer function is described as [23]

$$u_{PID}(s) = K_p + \frac{K_i}{s} + K_d s \tag{7}$$

To enhance the control quality of the AVR system, we propose the Fuzzy controller has a double-input $e(t)$, $de/d(t)$, and a triple-output, K_p, K_i and K_d [25]. The outputs of the fuzzy controller calibrate the coefficient K_p, K_i and K_d suitably, respectively. In this paper, the symbols {*NB, NBB, NS, NSS, ZE, PSS, PS, PBB, PB*} are the MFs notations, whose values correspond to big negative, near big negative, small negative, near small negative, zero, near small positive, small positive, near big positive and big positive. Thence, these fuzzy sets of the fuzzy controller are established as follows:

$$\begin{aligned} e &= \{NB\ NBB\ NS\ NSS\ ZE\ PSS\ PS\ PBB\ PB\} \\ de/dt &= \{NB\ NS\ ZE\ PS\ PB\} \\ K_p &= \{ZE\ PSS\ PS\ PBB\ PB\} \\ K_i &= \{ZE\ PSS\ PS\ PBB\ PB\} \\ K_d &= \{ZE\ PSS\ PS\ PBB\ PB\} \end{aligned}$$

The rule designation form B^i is a binary variable which makes out the rule consequence and B^i is expressed as

$$R_i : \text{If } \hat{e}_1 \text{ is } A_1^i \ \ldots \text{and } \hat{e}_n \text{ is } A_n^i \text{ then } u \text{ is } B^i \tag{8}$$

where $A_1^i, A_2^i, \ldots A_n^i$ and B^i express the fuzzy sets. By applying the center average defuzzifier, the fuzzy response can be computed as

$$u_f = \frac{\sum_{i=1}^{h} B^i [\prod_{j=1}^{n} \mu_{A_j^i}(\hat{e}_j)]}{\sum_{i=1}^{h} [\prod_{j=1}^{n} \mu_{A_j^i}(\hat{e}_j)]} \tag{9}$$

for $\mu_{A_{kj}^i}(\hat{e}_j)$ is the membership functions, h is the number of If-Then rules [26, 27]. The fuzzy output can calibrate the K_p, K_i and K_d coefficients according to the error $e(t)$. The PID coefficients are calibrated by

$$\begin{cases} K_p(s) = K_p(s-1) + u_f(kp)\Delta K_p \\ K_i(s) = K_i(s-1) + u_f(ki)\Delta K_i \\ K_d(s) = K_d(s-1) + u_f(kd)\Delta K_d \end{cases} \tag{10}$$

Substituting Eq. 10 into Eq. 7, the Fuzzy PID (F-PID) controller [28] can be written as

$$u_{fPID}(s) = K_p(s)e(s) + K_i(s)\int_0^s e(s)ds + K_d(s)\frac{de(k)}{dk} \tag{11}$$

However, in case of the system is controlled by the F-PID controller under the impacts of the voltage drop out or time-delay, the system is obtained result is not highly feasible. Thus, we propose the Interactive Adaptive Fuzzy Algorithm to calibrate the AVRs response to adapt to the ideal model. Then, the operation mechanism of the IAFA solution begins in the continuation section and the adaptive fuzzy controller for the AVR model will be introduced in Fig. 2.

3.2 Interactive Adaptive Fuzzy Algorithm Solution

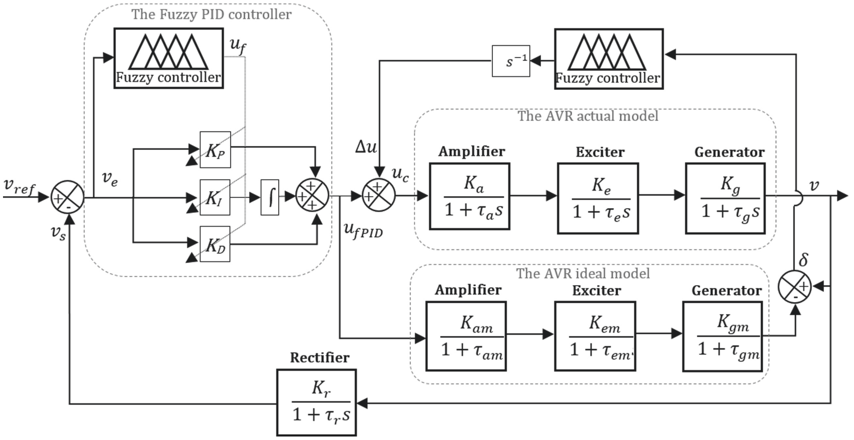


Fig. 2. The adaptive fuzzy controller for AVR model.

The weakness of the F-PID solution is only to carry out on the small range of input error. The control signal of the actual AVR model is adjusted by the adaptive coefficient Δu which is established by the fuzzy function [25]. The ideal model is given by

$$G_m(s) = \frac{K_{am}K_{em}K_{gm}}{(1+\tau_{am}s)(1+\tau_{em}s)\left(1+\tau_{gm}s\right)} \tag{12}$$

The adjustment performs corresponding to the error δ, i.e., the error between the output signal of the AVR ideal model and the AVR actual model. The error δ is computed as follows:

$$\delta = \left(\frac{K_aK_eK_g}{(1+\tau_a s)(1+\tau_e s)\left(1+\tau_g s\right)}\right)u_c - \left(\frac{K_{am}K_{em}K_{gm}}{(1+\tau_{am}s)(1+\tau_{em}s)\left(1+\tau_{gm}s\right)}\right)u_{fPID} \tag{13}$$

Table 1. The rules for Δu adaptive adjustment

Δu		$d\delta/d(t)$		
		Ns	Ze	Ps
$\delta(t)$	Ne	$Ne_{\Delta u}$	$Nss_{\Delta u}$	$Ns_{\Delta u}$
	Ns	$Nss_{\Delta u}$	$Ns_{\Delta u}$	$Ze_{\Delta u}$
	Ze	$Ns_{\Delta u}$	$Ze_{\Delta u}$	$Ps_{\Delta u}$
	Ps	$Ze_{\Delta u}$	$Ps_{\Delta u}$	$Pss_{\Delta u}$
	Po	$Ps_{\Delta u}$	$Pss_{\Delta u}$	$Po_{\Delta u}$

The control signal of the actual model is defined as

$$u_c = u_{fPID} + \Delta u \tag{14}$$

Coefficient Δu defines the adaptive adjustment force. It is well calibrated to remove the error of the actual model. In this paper, we apply the fuzzy control consisting of double-input: the error $\delta(s)$, and the velocity error $d\delta/ds$ for defining the Δu adaptive force. The fuzzy rules with 15 rules for Δu adaptive adjustment is given in Table 1.

The IAFA proposed aims to remove the error value δ. The control signal of the AVR actual model corrects Δu to adapt to the AVR ideal model. That is, $\delta \rightarrow 0$ when $t \rightarrow \infty$, respectively.

$$\left(\frac{K_a K_e K_g}{(1+\tau_a s)(1+\tau_e s)\left(1+\tau_g s\right)}\right)u_c = \left(\frac{K_{am} K_{em} K_{gm}}{(1+\tau_{am} s)(1+\tau_{em} s)\left(1+\tau_{gm} s\right)}\right)u_{fPID} \tag{15}$$

4 Simulations and Experiments

4.1 Configuration Parameter

In this paper, we accomplish the simulation of the designed model in the same parameters and conditions of AVRs in two cases, employed by using Matlab 2019a software. The simulation result shows the comparisons between the IAFA and the others strengthening

Table 2. The structure parameters for AVR model

Components	Range of coefficient	Selection value
Amplifier	$10 < K_a < 400; 0.02 < \tau_a < 0.1s$	$K_a = 10; \tau_a = 0.1$
Exciter	$1 < K_e < 400; 0.4 < \tau_e < 1s$	$K_e = 1; \tau_e = 0.4$
Generator	$0.7 < K_g < 1; 1 < \tau_g < 2s$	$K_g = 1; \tau_g = 0.4$
Rectifier	$0.001 < \tau_r < 0.06s$	$K_r = 1; \tau_r = 0.01$

the performance of the novel method. The IAFA solution (express in Sect. 3) with the adaptive goal (define at Eq. 15) performs on the AVR model, whose operation parameters are supplied by Table 2 [22] as

In case 1, the IAFA and others control, both methods are achieved the output voltage of the ship generator to the expected value (380 voltage) in around 100 s. This case performs the simulations under both non-disturbance and disturbance conditions. In case 2, we apply these solutions to adjust the output voltage down to 350 voltage from the current level is 380 voltage in the time range of the 50s to 100s. The simulation results are outlined in Figs. 3, 4, and Fig. 5 show that the IAFA (red line), F-PID (blue line), and PID (black line) can maintain the stability of the output voltage of the ship generator to the desired voltage. The disturbance vectors [29] take into account as $d(t) = J^T(\psi)b$ with the first-order Markov process that expresses the disturbances. In which, b shows the disturbance impacts with $b(0) = [0KN.m]^T$, and $T\epsilon R^{3\times 3}$ expresses the diagonal matrix of time constant, $\omega\epsilon R^3$ is a zero-mean Gaussian white noise vector, and $\psi = 3\times 10^2$ is the diagonal magnitude matrix ofω.

$$\dot{b} = -T^{-1}b + \psi\omega \tag{16}$$

4.2 Simulation Results

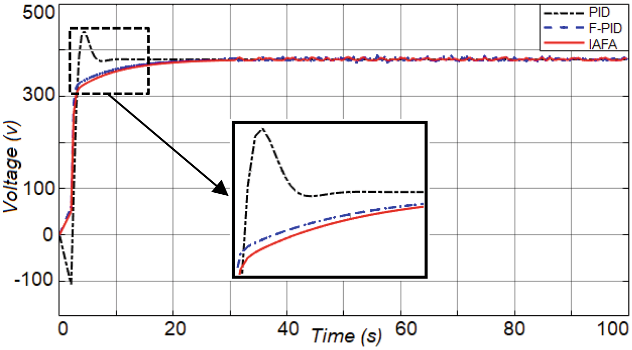


Fig. 3. The AVR response of simulation cases 1 without disturbance. (Color figure online)

The results comparisons of the AVR controllers demonstrate that the IAFA solution guarantees a stable response in every simulation case under disturbance impacts. After doing so, the proposed IAFA meets the questions according to Assumption and Remark. In the case of using a PID controller, the overshoot value is larger than the others. The classical solution cannot see the engineering requirements under disturbances operations. Besides this, the F-PID solution supplies a good performance within the limited range of disturbance. However, the F-PID results are not satisfactory in the case of the drop voltage impact. By using the IAFA solution, the output voltage does not fluctuate according to the disturbance impact. The erroneous is inside of the limited range. In the drop voltage, the response fluctuates in lower case and follow-up the desired value. The proposed

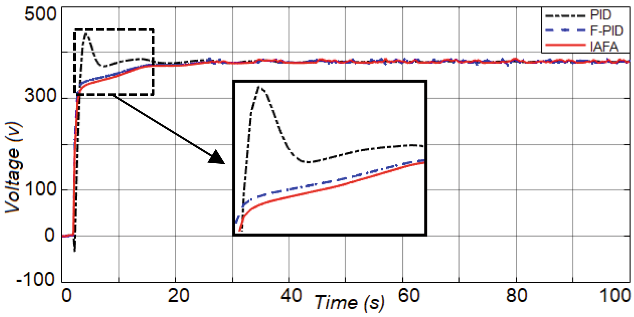


Fig. 4. The AVR response of simulation cases 1 with disturbance. (Color figure online)

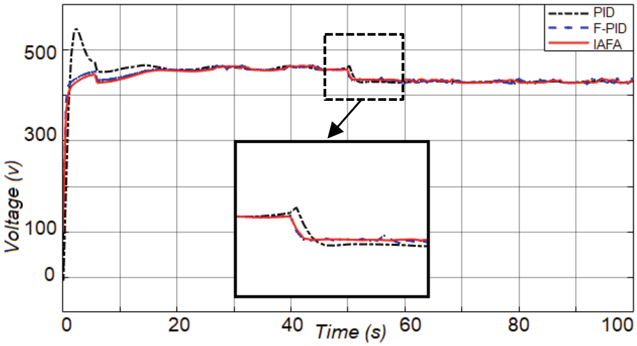


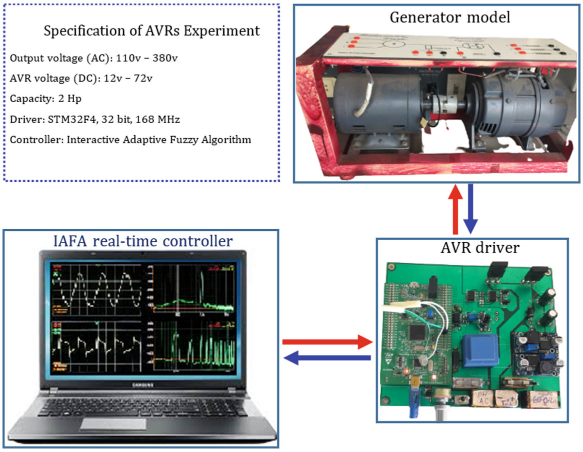
Fig. 5. The AVR responses of simulation cases 2.

IAFA has significantly enhanced the performance quality deal with the fluctuation level and erroneous.

4.3 AVR Experimental Model

We build the embedding IAFA controller on the AVR experimental model [30], which's structure and specification present in Fig. 6. The control program has been applied in full by Matlab software. This real-time controller realizes the control program directly into the STM32F4 Kit by the C+ software compiled. The STM32F4 Kit receives the setpoint value from the computer. Then the center processing compares it with the actual value to find the established error. Based on the established error, the IAFA real-time controller computes the control command for the AVR operation to keep the output voltage stable. The control signal converts into a corresponding voltage that acts as an IGBT firing angle. The amplitude of the IGBT firing angle will change the excitation voltage (0–72 VDC).

We experiment with the proposed solution in two cases. In case 1, the IAFA and F-PID solutions control the output voltage to reach a 180 VAC level around 100s. These experimental results are given the expression in detail by Figs. 7 and 8. Also, we apply these controllers to regulate the AC voltage of the ship generator down to the 150 VAC



Specification of AVRs Experiment

Output voltage (AC): 110v – 380v

AVR voltage (DC): 12v – 72v

Capacity: 2 Hp

Driver: STM32F4, 32 bit, 168 MHz

Controller: Interactive Adaptive Fuzzy Algorithm

Fig. 6. The AVR experimental model

level at the 50th second. Figure 9 and 10 reveal that the proposed IAFA can correct the output voltage to achieve the desired level.

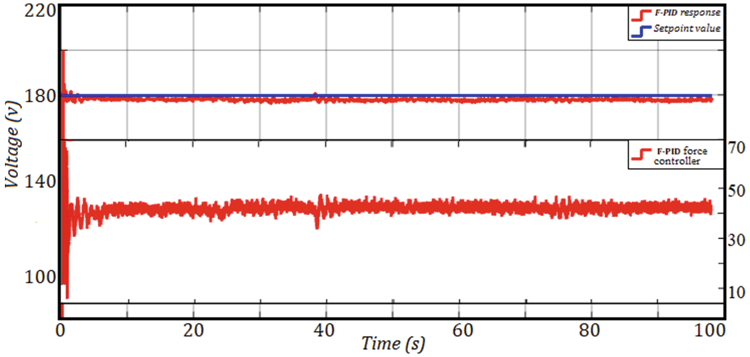


Fig. 7. The F-PID responses for the experiment cases 1

The output voltage is not feasible if the AVR applies the F-PID solution (described in Fig. 7). However, the proposed IAFA (expressed in Fig. 8) showing the result is less overshoot and more stable. In case 2, it is worth noting that the fluctuation of the IAFA is less than the F-PID at the switching time. The satisfactory results confirm that the IAFA can adapt to the disturbance impacts in the actual condition.

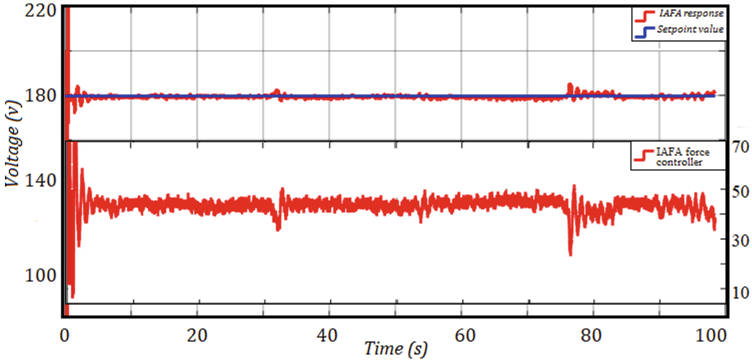


Fig. 8. The IAFA responses for the experiment cases 1

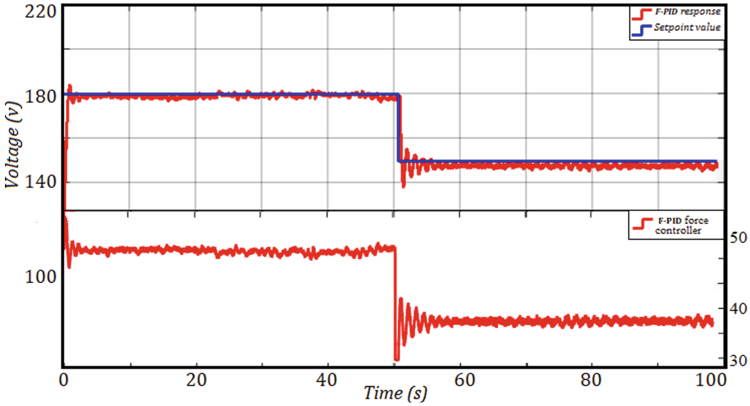


Fig. 9. The F-PID responses for the experiment cases 2

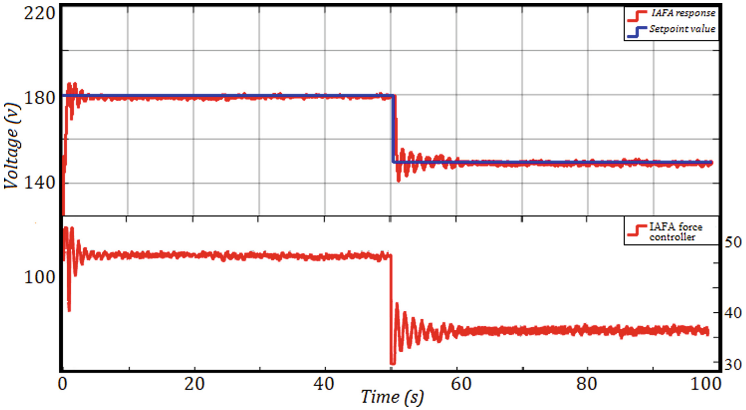


Fig. 10. The IAFA responses for the experiment cases 2

5 Conclusions

In this paper, we proposed the novel automatic voltage regulator model by combining the F-PID controller and Fuzzy controller to create the interactive adapt to adjust the field excitation of the ship's generator maintained the stable of voltage under the effect of disturbances. In case the amount of load-varying or voltage drops occur in the running process, the simulation and experiment demonstrated that the system attained the lowest fluctuation, and the IAFA can keep the voltage stable for a long time. The satisfactory results indicate that the IAFA is a promising study direction for maritime generator control in the actual operation.

Acknowledgements. This study was supported by the Applied Basic Research Program of Ministry of Transport of Vietnam DT203039 (2020).

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