DESIGN OF PID - LIKE SUGENO - BASED FUZZY LOGIC CONTROLLERS TO GENERATOR SPEED CONTROL OF A HYDROPOWER PLANT

THIẾT KẾ CÁC BỘ ĐIỀU KHIỂN LOGIC MỜ SUGENO KIỂU PID ĐỂ ĐIỀU KHIỂN TỐC ĐỘ MÁY PHÁT ĐIỆN TRONG NHÀ MÁY THỦY ĐIỆN

Nguyen Ngoc Khoat[1], Nguyen Duy Trung[1,*]

ABSTRACT

Fuzzy logic - based control strategies have been considered to be a feasible replacement of conventional PID regulators due to their dominant advantages. One of the most outstanding characteristics of a fuzzy logic - based control scheme is that the system might not require full parameters as well as an exact model; instead, it depends only upon experts' understanding about the control plant. This paper proposes the design of a novel PID - like Sugeno - based fuzzy logic controller. With a significant set of fuzzy rules and four scaling factors tuned by a proper optimization method, such a Sugeno - based inference model is completely able to solve a lot of complicated control problems. A typical control issue concerning the speed stability of generators in hydropower plants applying the studied fuzzy logic controllers will also be taken into consideration. Promising simulation results obtained demonstrate effectiveness and applicability of the control methodology proposed in this study.

Keywords: *PID, Sugeno-based inference, FLC, Scaling factors, Generator speed control.*

TÓM TẮT

Các chiến lược điều khiển áp dụng kỹ thuật logic mờ đã dần được xem là giải pháp thay thế khả thi cho các bộ điều khiển PID truyền thống do những lợi thế nổi bật của chúng. Một trong những đặc điểm nổi bật nhất của bộ điều khiển logic mờ mang lại là hệ thống không yêu cầu đầy đủ thông tin cũng như một mô hình toán học chính xác; thay vào đó, nó chỉ phụ thuộc vào kinh nghiệm của chuyên gia về hệ thống. Bài báo này đề xuất việc thiết kế của một bộ điều khiển logic mờ loại Sugeno kiểu PID mới. Với một tập mờ hợp lý và bốn hệ số chỉnh định được xác định bởi một thuật toán tối ưu hóa đủ tốt, một bộ điều khiển mờ kiểu Sugeno như vậy hoàn toàn có thể giải quyết được nhiều bài toán điều khiển phức tạp. Một bài toán điều khiển điển hình liên quan đến sự ổn định tốc độ của máy phát trong các nhà máy thủy điện áp dụng các bộ điều khiển logic mờ đang xét cũng sẽ được trình bày trong bài báo này. Các kết quả mô phỏng đạt được đầy hứa hẹn minh chứng cho hiệu quả và tính ứng dụng của thuật toán điều khiển đã đề xuất trong nghiên cứu này.

Từ khóa: *PID, Suy luận mờ kiểu Sugeno, FLC, các hệ số chỉnh định, điều khiển tốc độ máy phát.*

[1]Faculty of Control and Automation Engineering, Electric Power University
[*]Email: trungnd@epu.edu.vn
Received: 15/4/2022
Revised: 25/5/2022
Accepted: 29/8/2022

1. INTRODUCTION

PID (Proportional - Integral - Derivative) regulators have been widely used in both academic and industrial domains due to their simple structure [1-3]. However, when the control systems have been being developed in terms of size, complexity as well as special characteristics e.g. uncertainties and nonlinearities, these conventional controllers might not be suitable candidates anymore. In this perspective, the development of intelligent control strategies using fuzzy logic and artificial neural network has created appropriate controllers as promising replacements of the conventional counterparts [4-8]. Dominant advantages of the smart controllers such as fuzzy logic technology – based ones are those the systems might not rely on the exact mathematical model as well as full parameters of the object under control. It also means that the proper operation of the controller from this point of view depends only on experiences of experts or engineers. This leads to the concept "intelligence" which can be embedded in this type of controllers [5].

Studying on the fuzzy logic controllers, it should be obvious there are several issues need to be considered. First, it is hard to select a suitable structure of the fuzzy logic controller (FLC). Technically, a PI - or PI - like structure can be employed. This work, as intended to create a comparison between a conventional PID and FLC, focuses on designing PID-based FLCs. Such a FLC model seems to be dependent on the PID operation, characterized by a set of scaling factors. The other problems when applying the FLCs include the selection of membership functions, fuzzy rules as well as type of inference. Consider the inference methods, it was found that two mechanisms, namely Mamdani and Sugeno, have been usually employed in both academic and industrial fields. This work chose the Sugeno inference is a studying model due to its outstanding advantages. They include good computational efficiency, working well with linear techniques in replacements of PID control, high suitability with optimization and adaptive techniques, guaranty of continuity of the output surface and suitableness of mathematical analysis [8].

The rest of this study is arranged as follows. The next section will present the overview of traditional PID regulators together with the design of Sugeno inference - based FLC under consideration. Section 3 focuses on a case study applying this type of FLCs in control problem of generators in a hydropower plant. Eventually, section 4 also provides conclusion and future work raised from this study.

2. CONTROL STRATEGIES APPLYING PID - LIKE SUGENO - BASED FUZZY LOGIC CONTROLLERS

2.1. Conventional PID controllers in control systems

The term "PID" standing for a technical phrase of proportional plus integral and plus derivative has been extremely popular in academic and practical domains. It can be said that the PID regulators have been widely applied in huge number of control systems. A typical form of conventional PID regulators is shown in Figure 1. A conventional PID regulator relying upon tracking control operation has one input e(t) which can be denoted as error between reference and real signal of the control plant. Its output u(t) meaning control signal is taken to the control plant to handle it as requested. The major goal of a PID controller is to manipulate the real output y(t) following a desired trajectory by means of damping the error e(t) to be satisfied an acceptable tolerance. The control signal resulting from a conventional PID can be expressed below:

$$u(t) = K_p.e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (1)$$

Three factors in (1), namely K_p, K_i and K_d, denote gain, integral and derivative coefficients, respectively. In the frequency domain, the transfer function of a PID controller can be deduced as:

$$G_{PID}(s) = \frac{K_d.s^2 + K_p.s + K_i}{s} = K.\left(1 + \frac{1}{T_i.s} + T_d.s\right) \quad (2)$$

Where K, T_i and T_d denote gain, integral time constant and derivative time factor, respectively. It is clear the operation of a PID depends upon the selection of these factors. This process is defined as a tuning process.

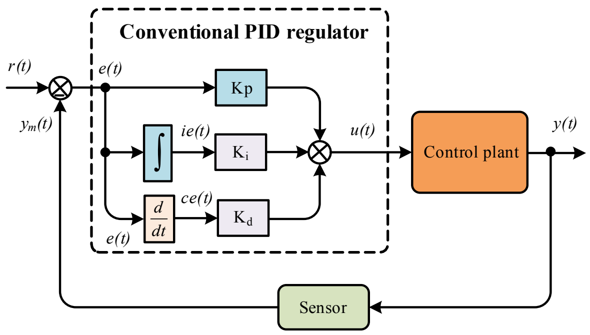
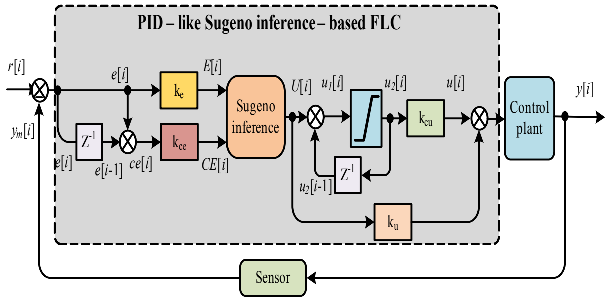


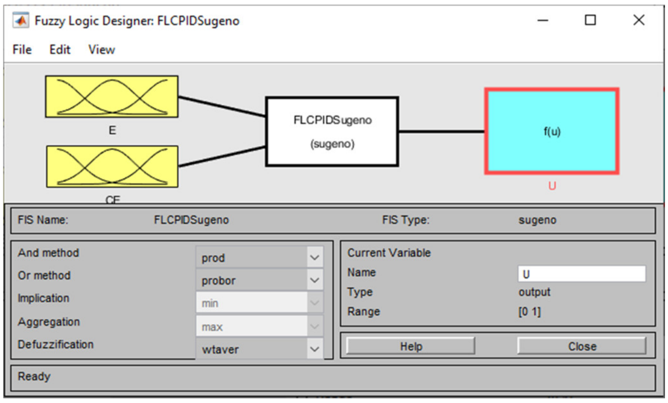
Figure 1. A typical control strategy applying a conventional PID controller

2.2. Design of PID - like Sugeno - based fuzzy logic controllers

Based on the PID principle, a Sugeno inference model is designed as shown in Figure 2(a). The interface of implementing the PID controller in MATLAB software is illustrated in Figure 2(b). Remember that there are four factors need to be determined, ensuring control quality of the system. Two input scaling coefficients, k_e and k_{ce}, are added to modify two input signals of the FLC: e[i] and ce[i]. Meanwhile, the other two factors, k_u and k_{cu}, are embedded to tune two outputs of the FLC.



(a)



(b)

Figure 2. Structure of a PID-like Sugeno-based FLC

(a) Theoretical principle (b) Matlab model

As seen in Figure 2(a), a typical rule of the Sugeno inference can be described below:

"If input 1 is **A** and/or input 2 is **B**, then the output is Z = **A***input 1 + **B***input 2 + C" (3)

It means that in a Sugeno inference, the relationship of input/output can be considered as a linearity interconnection. Consider the PID-type Sugeno fuzzy logic model in descrete form as shown in Figure 2, the output signal is as follows:

$$u[i] = k_{cu} \,.\, u_2[i] + k_u \,.\, U[i] \quad (4)$$

$$u_2[i] = \begin{cases} u_{max} & \text{for} \quad u_1(t) \ge u_{max} \\ u_1[i] & \\ u_{min} & \text{for} \quad u_1(t) \le u_{min} \end{cases} \quad (5)$$

Where u_{max} and u_{min} denote saturation levels of the PI-like Sugeno inference (see Fig. 3). Meanwhile, u_1(i) can be computed from u_2[i-1] and u*[i] which is derived from the implication based on Sugeno fuzzy rule as mentioned previously. The relationship presented in (4) and (5) makes the Sugeno model more obvious with regards to mathematical analysis and applications.

3. CASE STUDIES AND DISCUSSIONS

The control methodology applying proposed PID - like Sugeno - based FLC will be testified in this section. Consider generator's speed control of a hydropower plant as shown in Figure 3. It should be clear this is one of the most crucial control problems of the electric hydropower plant in order to ensure the stability and efficiency of the system [9-11]. A typical diagram representing a hydropower plant is depicted in Figure 3. Major units such as speed governor, hydraulic turbine and penstock, generator and load are highly significant in the speed control problem. The mathematical models for these vital units as well as simulated parameters are represented in [9]. The main control objective of this control strategy is to maintain the speed of generator at a nominal value. This is meaningful to keep the frequency of the system oscillated around a desired value e.g. 50 or 60 Hz under an acceptable tolerance, making the control system stable and reliable.

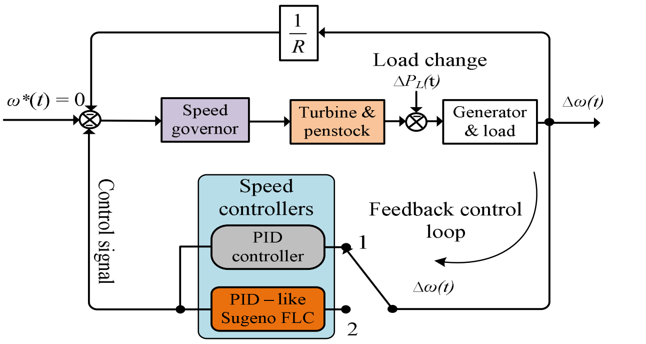


Figure 3. Speed control methodology of a hydro power plant applying different controllers

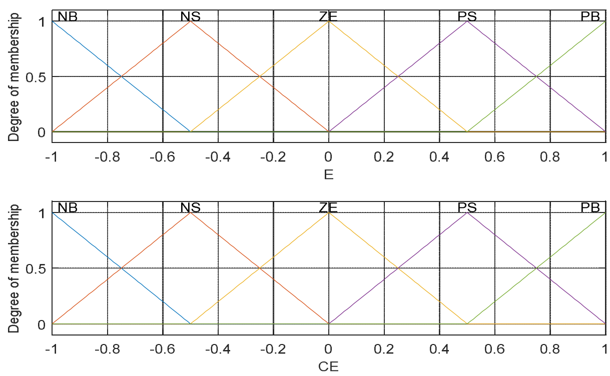


Figure 4. Illustration of input membership functions for the proposed FLC

To deal with the speed control mentioned above, we use the PID - Sugeno FLC controller as presented in the previous section with the designed parameters indicated in Table 1 and Figure 4 and Figure 5. To demonstrate the effectiveness of the proposed FLC, let's consider the following two cases of load changes $\Delta P_L(t)$, which cause fluctuations in the generator's speed.

(1) $\Delta P_L(t)$ is assumed to randomly change between a small range [-10%; 10%] as shown in Figure 7. The simulation results for this scenario are plotted in Figures 7-9.

(2) $\Delta P_L(t)$ is supposed to randomly vary belonging to a big limit [-50%; 50%] as presented in Figure 10. Also, Figures 10-13 show simulation results for this perspective.

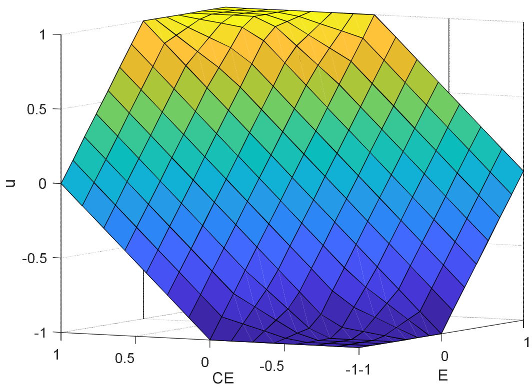


Figure 5. A 3D representation of the fuzzy logic rules corresponding to Table 1

It should be obviously the two simulation scenarios mentioned above are highly significant, matching the real conditions. Using the PSO (particle swarm optimization) method to determine four scaling factors of the Sugeno - based FLC. The procedure of the PSO is presented in Figure 6. It is noted that the terminated criteria are normally maximum number of iterations The simulation parameters used in this section is shown in the Appendices of this paper.

```
Initialize a population of particles
    (Noted that No. of variables: npar = 4 for 4 variables (k_e, k_ce, k_u and k_cu))
do
    for each particle p with position x_p do
    calculate fitness value f(x_p)
    if f(x_p) < f(p_best_p) then
    x_p → p_best_p
    endif
    endfor
Define g_best as global optimization point
    for each particle p do
    compute velocity (x_p, p_best_p, g_best_p) → v_p
    update position (x_p, v_p) → v_p → x_p
    endfor
while (Terminated criteria are not satisfied)
```

Figure 6. Pseudo code of the PSO algorithm

To verify the outstanding effectiveness of the proposed Sugeno FLC, in this section, beside the conventional PID regulators, a feasible Mamdani PI - like FLC presented in [12] will also be taken into consideration, especially in the second simulation scenario. From Figures 7-13, it was found that the PID - like Sugeno FLC - based inference model is completely able to solve the generator speed control,

P-ISSN 1859-3585 | E-ISSN 2615-9619

outperforming the conventional PID regulators. The control systems resulting from the proposed intelligent controllers are obtaining much better control performances. Not only the generator speed fluctuations but also other parameters of the system applying the proposed FLC are capable of satisfying promising control criteria. Consider the IAE (integral absolute error) of the generator speed deviations obtained from the traditional PID regulator, PI-FLC [12] and the proposed Sugeno - FLC represented by:

$$IAE = \int_0^\tau |\Delta\omega(t)|\,dt \qquad (6)$$

Two Figures (8 and 13) illustrate this criterion with respect to time domain. It is obvious the Sugeno PID - like FLC achieves much better control index in comparison with that of the conventional PID as well as the Mamdani PI-like FLC ones. It also verifies the applicability of the proposed control methodology.

Table 1. A set of fuzzy logic rules for the proposed Sugeno FLC

		E				
		NB	NS	Z	PS	PB
CE	NB	NB	NB	NB	NS	Z
	NS	NB	NB	NS	Z	PS
	Z	NS	NS	Z	PB	PB
	PS	NS	Z	PS	PB	PB
	PB	Z	PB	PS	PB	PS

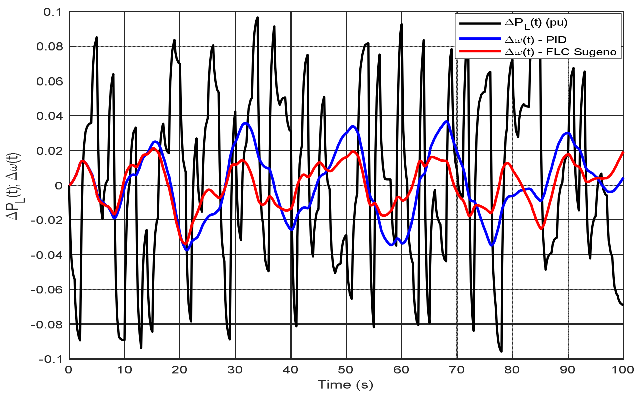


Figure 7. Simulation results for the first case

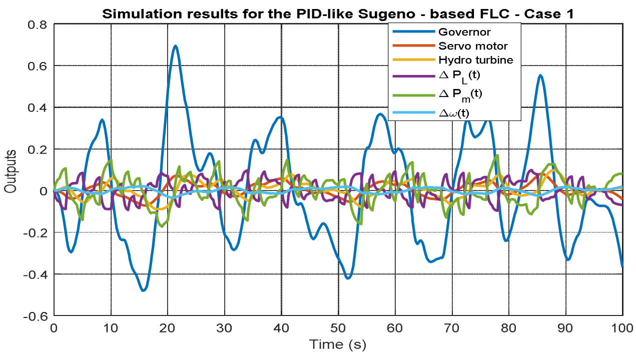


Figure 8. Simulation results applying the proposed PID-like Sugeno FLC for the first case

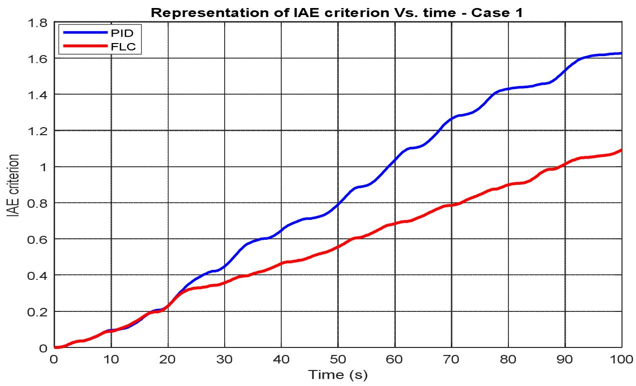


Figure 9. Comparison of the PID and proposed FLC using the IAE criterion

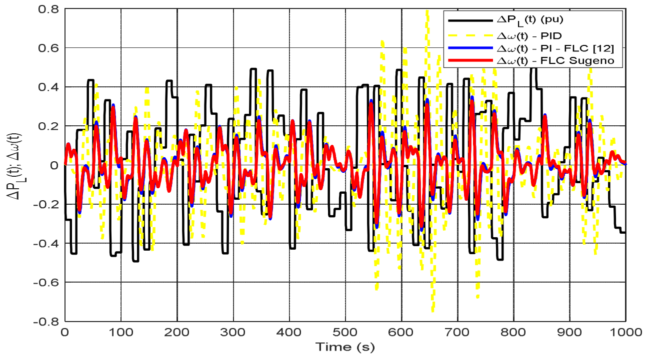


Figure 10. Comparative simulation results for the second case

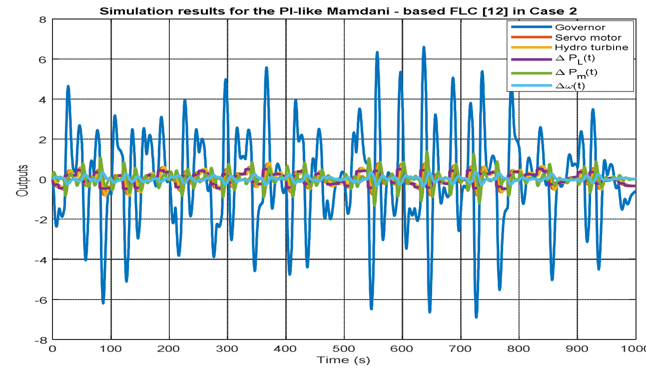


Figure 11. Simulation results for the first case using the PI - like FLC proposed in [12]

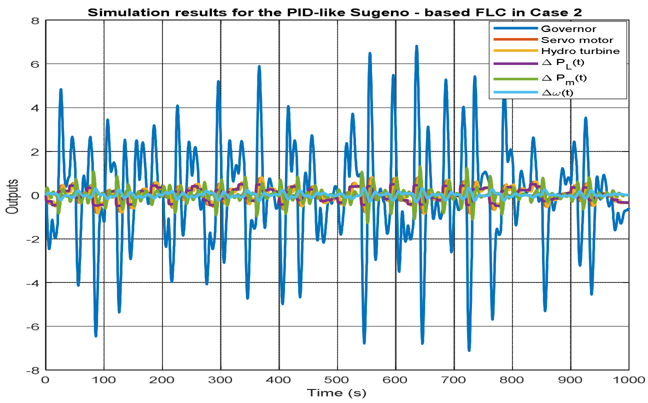


Figure 12. Simulation results for the first case using the proposed Sugeno FLC - major outputs

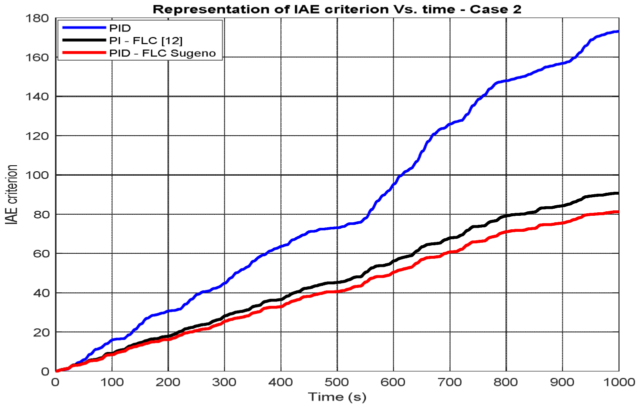


Figure 13. IAE criterion for the second case resulting from the PID, PI-like FLC and the proposed Sugeno FLC

4. CONCLUSION

This work has concentrated on designing and applying a PID-like Sugeno inference -based FLC in dealing with complicated control problems. The conclusions are deduced as follows:

(i) The conventional PID regulators may not be suitable for the modern and complex control systems now.

(ii) The Sugeno – based FLCs are totally able to be a feasible candidate for solving the above control issues.

(iii) If four factors of the smart FLCs as mentioned above are optimized by a proper optimization method, the Sugeno inference model can be successfully applied in a numerous number of complicated control systems.

(iv) A typical generator speed control using the FLC under this study for a hydropower plant verifies the feasibility of the proposed controller.

Future work will focus on designing and comparing the proposed Sugeno inference model with the Mamdani one with regards to the same problem to answer the question "What is the efficient intelligent fuzzy logic controller which can be used for a large layer of complicated control problem?".

APPENDICES

Power plant's parameters [9]

Tg = 0.5 (s); Tw = 2; M = 10; D = 1; Rp = 0.05; RT = (2.3 - (Tw-1.0)*0.15)*Tw/M;

TR = (5.0 - (Tw - 1.0)*0.5)*Tw;

TH = (RT/Rp)*TR;

PSO parameters:

Size of the swarm: N = 8; Dimension of the problem: npar = 4; Maximum number of iterations: Nmax = 20; constraint: Lb = $[0\ 0\ 0\ 0]^T$; Ub = $[2\ 2\ 2\ 2]^T$.

REFERENCES

[1]. Bose B.K., 2001. *Modern Power Electronics and AC Drives*. Prentice Hall.

[2]. Sravan Bharadwaj C., Sudhakar Babu T., Rajasekar N., 2018. *Tuning PID controller for inverted pendulum using genetic algorithm.* In: Konkani A., Bera R., Paul S. (eds) Advances in Systems, Control and Automation. Lecture Notes in Electrical Engineering, vol 442. Springer, Singapore.

[3]. Karl JA., Richard M.M., 2020. *Feedback Systems*. Princeton University Press, Version V3.1.5.

[4]. Silva Sergio, Fernandes Lopes Felipe, Valderrama Carlos, Fernandes Marcelo, 2020. *Proposal of Takagi-Sugeno Fuzzy-PI Controller Hardware*. Sensors, 1-28.

[5]. Thrishantha N., Ferat S., Mo M.J., 2009. *Intelligent Control Systems with an Introduction to System of Systems Engineering*. CRC Press, 1st Edition.

[6]. Mohamed El.A., 2021. *Fuzzy TOPSIS*. CRC Press.

[7]. Mehdi RA., 2021. *Applications of Fuzzy Logic in Planning and Operation of Smart Grids*. Springer.

[8]. Dadios Elmer (editor), 2012. *Fuzzy Logic - Controls, Concepts, Theories and Applications*. IntechOpen.

[9]. Kundur P., 1994. *Power system stability and control*. New York, USA: McGraw-Hill.

[10]. Ngoc Khoat N., 2020. *Study on a novel speed control strategy of hydraulic turbines applying artificial neural network and metaheuristic optimization technique*. International Journal of Electrical Engineering and Technology (IJEET), vol. 11(10), pp. 311-321.

[11]. Gezer Dogan, et al., 2018. *Speed Control of Hydraulic Turbines for Grid Synchronization Using Simple Adaptive Add-Ons*. Measurement and Control, vol. 51, no. 7–8, pp. 276–284.

[12]. Ngoc-Khoat Nguyen, Duy-Trung Nguyen, 2021. *A Comparative Study on PI - and PD - Type Fuzzy Logic Control Strategies*. International Journal of Engineering Trends and Technology, 69(7),101-108.

THÔNG TIN TÁC GIẢ

Nguyễn Ngọc Khoát, Nguyễn Duy Trung

Khoa Điều khiển và tự động hóa, Trường Đại học Điện lực