Research on a Sugeno Fuzzy Logic Controller Compared to a Mamdani-Based PI-Type Fuzzy Logic Inference Model

Nguyen Tri*, Nguyen Ngoc Khoat

Abstract—Fuzzy logic – based control schemes have been selected as a perfect replacement for traditional regulators e.g. PI and PID due to their undeniable advantages such as no need of exact models and only depending upon expert's experiences. It should be prominent in using these fuzzy logic structures the PI-like Mamdani and Sugeno – based inference models have been widely used in academic studies. This paper focuses on creating a theoretical analysis and comparison for both of them. A typical case study regarding the speed control of a hydropower plant against various load changes is taken into consideration in order to demonstrate the applicability of the proposed control strategy. This is considered to be one of the most crucial control strategies for operation and stability of a hydropower plant. It was found that a lot of promising simulation results obtained by using Matlab/Simulink software when applying the PI-like Sugeno fuzzy logic controller are superior to those of the existing counterparts such as conventional PID and Mamdani – based one in dealing with the generator's speed control problem presented in this study.

Index Terms—PI – like fuzzy logic controller; Mamdani; Sugeno; speed control; control criteria.

1. Introduction

It is clear era control systems are considered to be more complicated with increasingly high criteria. Control systems are being fast increased in terms of size, complexity and computation, making the design of efficient control strategies highly challenging. In this aspect, the traditional regulators using PID (Proportional – Integral – Derivative), PI (Proportional – Integral) or PD (Proportional – Derivative) have been gradually becoming obsolete and they might not be suitable for high quality control systems.

Fuzzy logic controllers have been evaluated as a perfect replacement for the conventional regulators [1-3]. There is a rapidly growing literature on application of the fuzzy logic – based control strategy, which indicates that this type of controller is completely able to deal with a huge number of complex control problems. Such an intelligent controller depending upon fuzzy logic inference may not require an exact mathematical model of a control plant [3-4]. In contrast, it seems to rely only on knowledge of experts concerning the control system under the designing. It means that the fuzzy logic control schemes are fully suitable to systems which are being characterized by nonlinearities as well as uncertainties.

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Consider typical fuzzy logic control approaches, two types of controllers are usually employed, namely PI-like Mamdani and Sugeno – based ones [5-6]. The term "PI – like" means that the working principle of these two fuzzy logic controllers is seemingly depending upon the conventional PI regulator. Meanwhile, Mamdani and Sugeno – based inferences are actually well – known in designing a fuzzy logic architecture. However, to select the better one for a specific control problem might make not only academicians but also engineers somewhat confusing.

This paper investigates to create a significant comparison between them and put forward the claim that the Sugeno – based inference model is properly more suitable and effective than the Mamdani counterpart. The available evidence with regards to a typical control problem of a hydropower plant against load changes demonstrates this statement. Simulation results obtained by using Matlab/Simulink package in various scenarios of load disturbances validate the effectiveness and superiority of the Sugeno – based inference model in comparison with those of the Mamdani and conventional PID ones.

2. Control strategies applying Sugeno and Mamdani - based fuzzy logic controllers

2.1. Conventional PID controllers in control systems

It was clearly found that PID controllers have been widely employed not only in theoretical studies but also in real industry. A typical form of conventional PID regulators is shown in Fig. 1. It is noted that a conventional PID regulator relying upon tracking control operation has one input $e(t)$ which can be denoted as error between reference $r(t)$ and real signal $y(t)$ of the control plant. Meanwhile, 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.

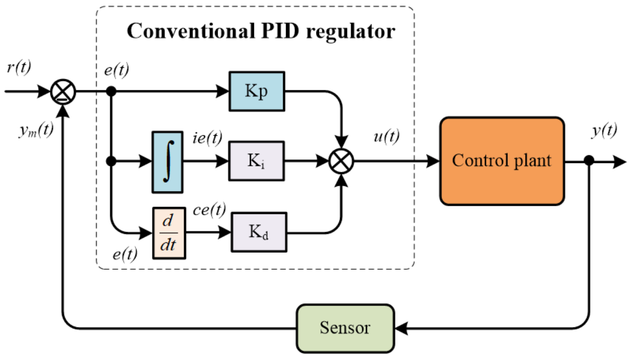


Fig. 1: A typical control strategy applying a conventional PID controller

In the continuous-time domain, the principle of a conventional PID is [2-3]:

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

where K_p, K_i and K_d denote factors of the PID controller, namely gain, integral and derivative coefficients. Such three coefficients are necessary to be determined by means of manual or adaptive/optimal techniques. In case of using a family member of the PID controllers, i.e. PI or PD regulator, the remaining unit is omitted. For instance, the PI controller when cancelling the derivative part Kd has the following structure:

$$u(t) = K_p \cdot e(t) + K_i \int e(t)dt \quad (2)$$

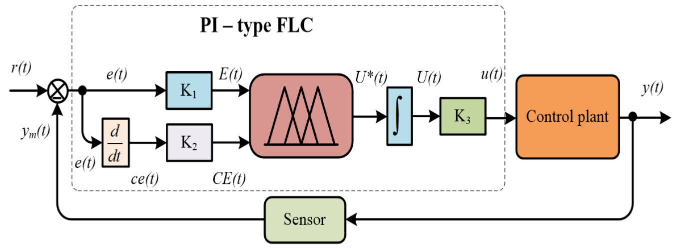
It is noted that the PI controller can usually be used to avoid large disturbances and noise occurrence during the operation process, whereas the PID counterpart may be suitable for dealing with higher order capacitive processes. In many control systems, the PI controllers have been usually employed as a replacement of the PID regulators due to these reasons as well as its simpler structure. This characteristic has led to a large number of intelligent control architectures imitating PI's operation principle, such as fuzzy logic – based ones.

2.2. PI – like fuzzy logic controllers

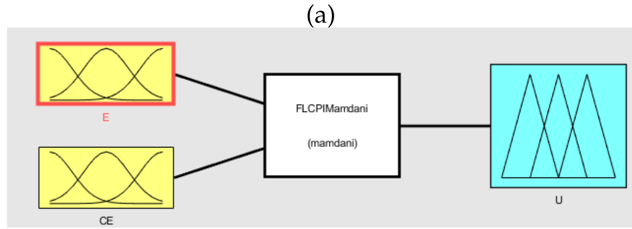
Theoretically, the PI-like fuzzy logic controller depends on the operation principle of a PI regulator presented in the previous section. In this section, two types of these fuzzy logic controllers are taken into account: Mamdani and Sugeno inference-based architectures.

2.2.1. Mamdani model – based PI-like fuzzy logic controller

A typical model using Mamdani inference is depicted in Fig. 3. There are two inputs, error $e(t)$ and its derivative $ce(t)$ together with one output $u(t)$ creating a PI-type fuzzy logic model.



(a)



(a)

Fig. 2: The typical control strategy applying PI-like Mamdani-based FLC (a) Theoretical principle (b) Matlab/Simulink model

According to [2-3], a Mamdani fuzzy logic model with a proper set of fuzzy rules should be considered to be an approximate input/output relationship as given below for the PI-type FLC illustrated in Fig. 2:

$$\begin{aligned} U(t) &= \int U^*(t)dt \\ &= \int [\alpha \cdot E(t) + \beta \cdot CE(t)]dt \end{aligned} \quad (3)$$

Where α, λ are two internal gain factors which are approximately calculated depending upon the fuzzy logic rule base. It can be seen from Figure 4(a), with three scaling factors K1, K2 and K3 added by experts, the control signal u(t) is computed as:

$$\begin{cases} E(t) = K_1 \cdot e(t) \\ CE(t) = K_2 \cdot ce(t) \\ u(t) = K_3 \cdot U(t) \end{cases} \quad (4)$$

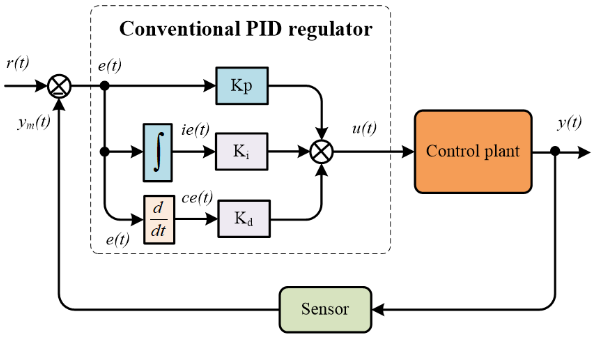
From (3) and (4), one can be obtained below:

$$U(t) = k_3 \int \left[\alpha \cdot k_1 \cdot e(t) + \beta \cdot k_2 ce(t)\right] dt \quad (5)$$

After a simple operation, the final relationship can be deduced:

$$U(t) = k_{P\_FL} \cdot e(t) + k_{I\_FL} \int e(t)dt \quad (6)$$

Where two factors, $k_{P\_FL} = \beta.k2.k3$ and $k_{I\_FL} = \alpha.k_1.k_2$ seem to be similar to two coefficients, gain and integral factors of the conventional PI regulator as mentioned earlier.



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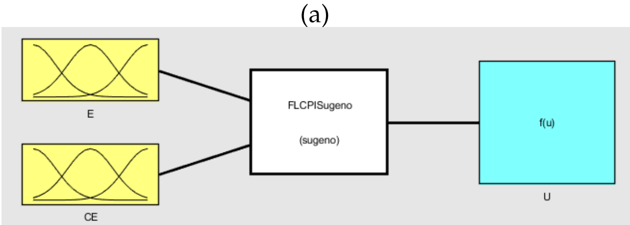

(b)

Fig. 3: The typical architecture of control strategy applying PI-like Sugeno-based FLC (a) Theoretical principle (b) Matlab/Simulink model

2.2.2. Sugeno model – based PI-like fuzzy logic controller

Sugeno inference method has been applied to design a PI-like fuzzy logic controller. Figure 3 illustrates a typical structure of such a type of fuzzy logic architecture.

It means that in a Sugeno inference, the relationship of input/output can be considered as a linearity interconnection. Consider the PI-type Sugeno fuzzy logic model in descrete form as shown in Fig. 3, according to [6], the output signal can be expressed below:

$$u[i] = K_3.u_2[i] \quad (7)$$

$$u_2[i] = \begin{cases} u_{\max} & \text{for} \quad u_1(t) \geq u_{\max} \\ u_1[i] & \text{for} \quad u_{\min} \leq u_1(t) \leq u_{\max} \\ u_{\min} & \text{for} \quad u_1(t) \leq u_{\min} \end{cases} \quad (8)$$

Where umax and umin 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 (7) and (8) makes the Sugeno model more obvious with regards to mathematical analysis and applications.

2.2.3. Comparison of Mamdani and Sugeno methods applied to fuzzy logic controllers

It should be obviously found that Mamdani inference and Sugeno counterpart are completely different in terms of their principle and applications. The Mamdani models are highly suitable for controlling plants, which seem to be difficult to mathematically establish their models. Whereas, the Sugeno method has been evaluated to be successfully applied in control objects with only inexact models. Especially, the Sugeno inference model is highly suitable for nonlinear systems, which can be linearized in finding control solutions. It can be said from theory and applications that advantages of Sugeno inference method include 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. In contrast, the Mamdani architecture is highly intuitive, having widespread acceptance and being proper to human inputs. Eventually, to evaluate and/or compare comprehensively a Sugeno model and a Mamdani counterpart might be a difficult task. It seems to be a feasible evaluation if such two control solutions are applied to only one control plant with the same scenarios of constraints.

3. Case studies and discussions

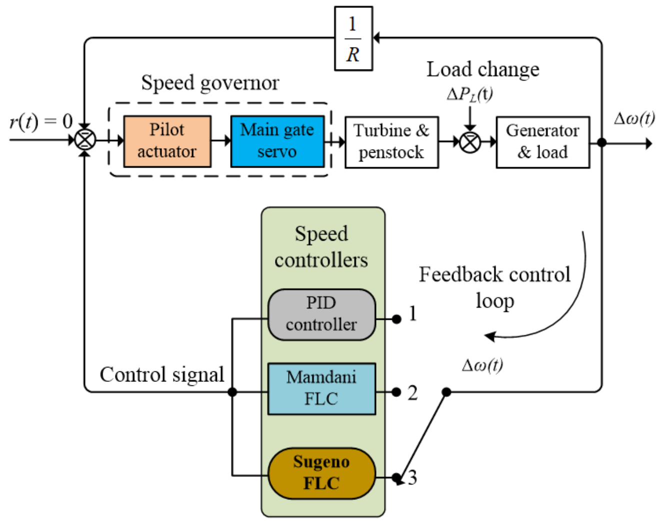

Fig. 4: Speed control of a hydro power plant applying different controllers

In this section, a case study will be considered in order to verify feasibility of the FLCs applying both Mamdani and Sugeno inferences presented earlier. The control problem chosen in this study is the speed control of a hydropower plant. In general, small hydropower plants are still highly popular in Vietnam, and the speed control of generators plays a vital role in control and operation of the power station [7-12]. It was found that a hydropower plant includes a number of major components, such as speed governor, hydraulic turbine and generator as shown in Fig. 4 [7]. The speed governor technically consists of a pilot actuator and a main gate servo motor. The electric generator, when modelled for the speed control problem, usually integrates with load models. The transfer functions of these units are given in Table 1 [7]. The control problem focuses on designing an efficient solution to maintain speed of the electric generator against load changes. Obviously, if the generator's speed which is proportional to the system frequency varies, it will strongly affect a lot of equipment in power networks. As a result, it must be controlled to be maintained in an acceptable range.

It means that the error between the actual speed and desired ones of a generator must be damped to satisfy significant tolerance.

TABLE 1: Transfer functions of major components of the hydropower plant

	Components	
	Pilot actuator	**Servo motor**
Transfer function	$W_p(S) = \frac{1}{T_p.s+1}$	$W_g(S) = \frac{1}{T_g.s+1}$
	Hydraulic turbine	**Generator - load**
Transfer function	$W_T(S) = \frac{1-T_w s}{1+0.5T_w.s}$	$W_{gen-load}(S) = \frac{1}{M.s+D}$

TABLE 2: Fuzzy logic rules for the PI-like fuzzy inference system

U		E				
		NB	**NS**	**ZE**	**PS**	**PB**
CE	**NB**	NB	NB	NB	NS	ZE
	NB	NB	NB	NS	ZE	PS
	ZE	NS	NA	SE	PB	PB
	PS	NS	ZE	PS	PB	PB
	PB	ZE	PB	PS	PB	PS

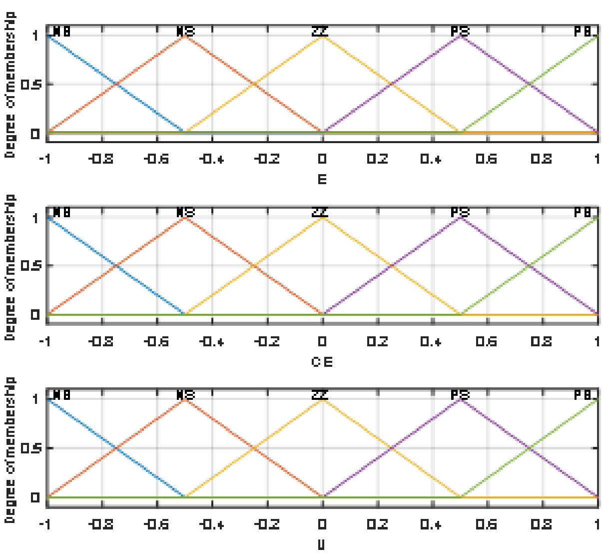

Fig. 5: Membership functions two inputs and one output of the Mamdani inference

To solve this control problem, a numerous number of controllers have been taken into consideration. This paper concentrates on designing three typical types of them as shown in Fig. 4 including traditional PID regulator, intelligent Mamdani and Sugeno – based models. To create a significant comparison between the two fuzzy logic controllers, let us consider the same set of fuzzy rules as indicated in Table 2. The membership functions for two inputs and one output of the Mamdani – based inference models are expressed in Fig. 5. The Sugeno inference has the similar inputs to the Mamdani one, but the output membership functions are different as shown in Fig. 6.

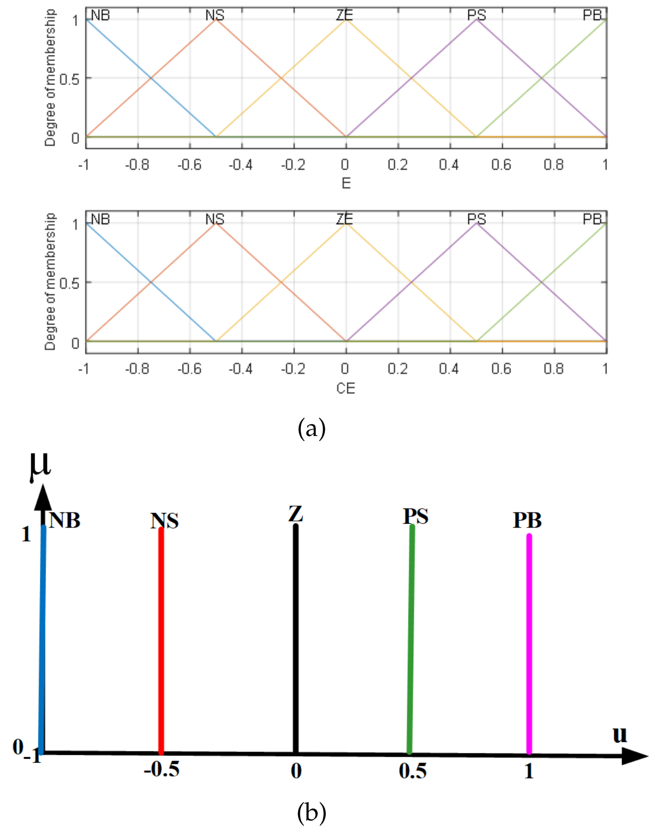

Fig. 6: Membership functions of (a) two inputs and (b) output for the Sugeno inference

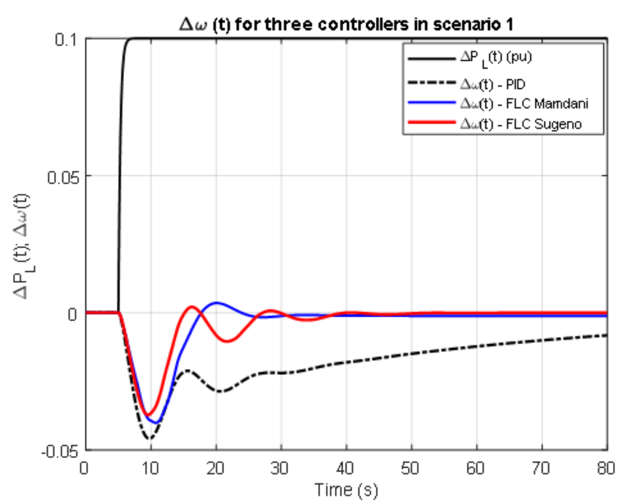

Fig. 7: Speed deviations for the first scenario using different controllers

In order to compare three aforementioned controllers, two simulation scenarios regarding the load change $\Delta P_L(t)$ are taken into consideration as follows: (i) Scenario 1 (shown in Figs. 7-8): $\Delta P_L(t)$ appears as a step unit with the magnitude of ten in percentage. (ii) Scenario 2 (illustrated in Figs. 9-10): $\Delta P_L(t)$ is embedded in the power system as a random function with respect to time domain. This is actually considered as a practical perspective of the power network with randomly continuous load changes.

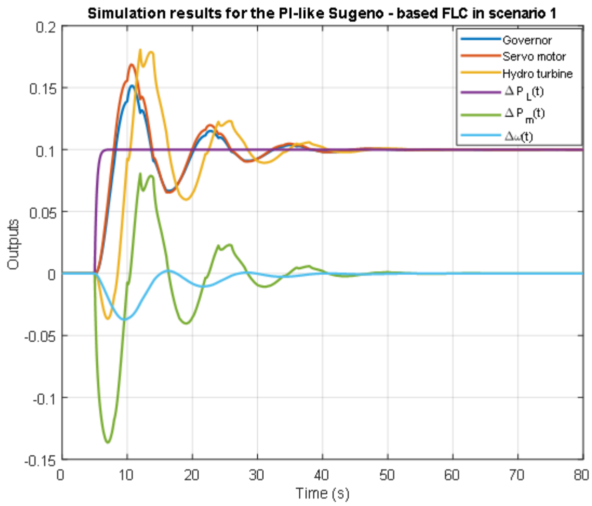

Fig. 8: Outputs for the first scenario using Sugeno – based PI-like fuzzy logic controller

To execute simulation process, a set of necessary parameters should be employed as mentioned in Appendix of the paper. It is also noted that scaling factors of two fuzzy logic controllers as well as the traditional PID regulator are determined by an appropriate optimization mechanism. In this study, the ABC (artificial bee colony) technology is applied for this mission. Fig. 7 describes a comparison of generator's speed deviations resulting from two fuzzy logic controllers as mentioned earlier together with the conventional PID regulator. It was clearly found that the fluctuations of speed variation of the two fuzzy logic controllers have been damped more quickly than that of the PID regulator. Major control criteria i.e., undershoots and settling times of the two intelligent controllers are much better than those of the conventional one. Consider two fuzzy logic controllers it can be seen that the control criteria of the Sugeno model are also better than those of the Mamdani one. Obviously, main control criteria resulting from the Sugeno inference – based controller, especially undershoot, rise time, settling time and settling error are the best in this scenario. Figure 8 only shows simulation results for the Sugeno model. Both deviations of the generator's speed and mechanical power taken to the generator are forced to satisfy acceptable tolerances. Meanwhile, output signals of the speed governor, servo motor and hydro turbine are tracking the load change to be settle at the same time with that of the speed fluctuation.

Similarly, in the second scenario, when a random load change is assumed to embed in the system, the simulation results are illustrated in Figs. 9-10. This is a more significant case suitable for the reality. It is apparent results from the Sugeno – based PI – like fuzzy logic controller are much better than those of the Mamdani one as well as the conventional PID regulator. In this scenario, the Sugeno model is completely able to eliminate the generator's speed fluctuation with promising control performances, demonstrating the feasibility of this fuzzy logic controller.

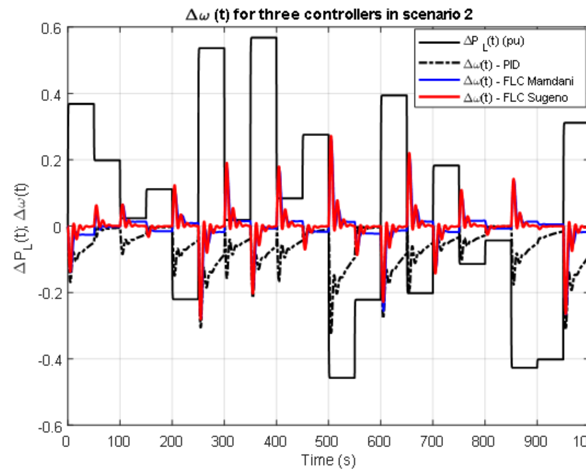

Fig. 9: Speed deviations for the second scenario using different controllers

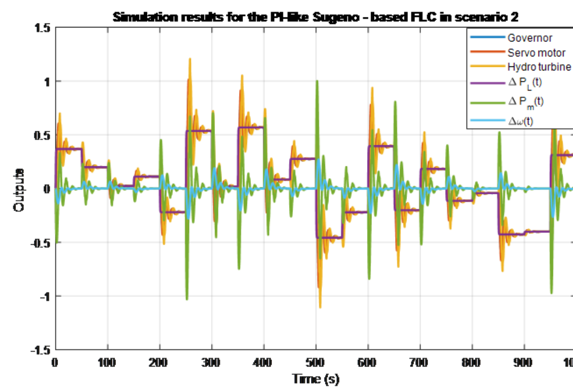

Fig. 10: Outputs for the second scenario using Sugeno – based PI-like FLC

4. Conclusion and future work

This study has investigated a comparison between Mamdani and Sugeno – based PI – like fuzzy logic controllers. Some of the main contributions can be deduced as follows:

(i) A theoretical analysis regarding the operation principle of the Mamdani and Sugeno inferences has been provided.

(ii) The Mamdani and Sugeno models were applied to design a typical controller e.g. PI-like fuzzy logic control methodology. This is an effective control structure which can be used in a huge number of complex control systems.

(iii) A case study applying the two fuzzy logic controllers mentioned above concerning a hydropower grid in dealing with the generator's speed control against load changes has been taken into consideration.

Simulation results from the case study with various scenarios of load changes were analyzed and compared to verify the feasibility of the two fuzzy logic controllers. It should be clear the Sugeno model in this case study provided better control performances in comparison with the Mamdani counterpart. Future work inspired from this study will concentrate on investigating more complicated control systems, which can apply the Sugeno-based PI – like fuzzy logic controller to testify its applicability and effectiveness. In addition, practical applications of the proposed fuzzy logic controller should be taken into consideration in order to further enhance this study.

Appendix

TABLE 3: Simulation parameters [7]

Components	**Pilot actuator**	**Servo motor**	**Hydraulic turbine**	**Generator load**
Parameters	Tp = 0.5(s)	Tg = 0.5(s)	Tw = 2(s)	M = 10(pu) D = 1(pu)

References

[1] G. Chen, T. T. Pham, and N. Boustany, "Introduction to Fuzzy Sets, Fuzzy Logic, and Fuzzy Control Systems", *Applied Mechanics Reviews*, vol. 54, no. 6, pp. B102–B103, Nov. 2001, doi: 10.1115/1.1421114.

[2] B. K. Bose, "Modern power electronics and AC drives" *Upper Saddle River, NJ: Prentice Hall*, 2002.

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

[4] M. G. Simões, "Artificial intelligence for smarter power systems: fuzzy logic and neural networks" *London: Institution of Engineering and Technology*, 2021.

[5] Minh, Vu & Tamre, Mart & Moezzi, Reza & Oliver, Mets & Jurise, Martin & Ahti, Polder & Leo, Teder & Juurma, Märt "Performances of PID and Different Fuzzy Methods for Controlling a Ball on Beam" *Open Engineering*, 16, 145 – 151, 2016.

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

[7] P. Kundur, N. J. Balu, and M. G. Lauby, "Power system stability and control" *New York: McGraw-Hil*l, 1994.

[8] Nand Kishor, R.P. Saini, S.P. Singh, "A review on hydropower plant models and control", *Renewable and Sustainable Energy Reviews*, 11(5), 776-796, 2007.

[9] P. S. R. Murty, "Operation and control in power systems", 2. ed. *Hyderabad: BSP, BS Publications*, 2011.

[10] H. Bevrani and T. Hiyama, "Intelligent Automatic Generation Control". 2017. *Accessed*: Apr. 20, 2022. [Online].

[11] H. Bevrani and T. Hiyama, "Intelligent Automatic Generation Control", *CRC Press*, 2016.

[12] Naghizadeh, Ramezan Ali & Jazebi, Saeed & Vahidi, Behrooz "Modeling Hydro Power Plants and Tuning Hydro Governors as an Educational Guideline", *International Review on Modelling and Simulations*, 5(4), 1780 – 1790, 2012.

[13] G. A. Munoz-Hernandez, S. P. Mansoor, and D. I. Jones, "Modelling and Controlling Hydropower Plants" *London: Springer London*, 2013. doi: 10.1007/978-1-4471-2291-3.

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