International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 /doi:10.14445/22315381/IJETT-V69I7P215

Volume 69 Issue 7, 101-108, July, 2021

A Comparative Study on PI – and PD – Type Fuzzy Logic Control Strategies

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Abstract *- Control strategies applying intelligent techniques e.g. fuzzy logic have been able to completely replace conventional regulators such as PI, PD and PID on designing an efficient control system. This paper investigates a comparative study of two fuzzy logic controllers (FLCs) which are representative of typical fuzzy logic – based control schemes. The working principle of such two FLCs are highly similar to the conventional PD and PI regulators, leading to the corresponding PD and PI-type names. The two FLCs proposed in this study are compared in terms of working principle as well as applicability for a specific control problem. A condition to evaluate the differences between such two FLCs is that they are employing the same input signals and fuzzy logic rule sets. Two scenarios of fuzzy rule sets are also provided for the comparison purpose. Numerical simulation results obtained by using MATLAB/Simulink environment demonstrates the feasibility of such two FLCs as well as asserts the dominance of the PI-type FLC together with a fully reasonable fuzzy rule set.*

Keywords — *PD-type FLC, PI-type FLC, input/output relationship, fuzzy rule set, control performance.*

I. INTRODUCTION

In the past decades, the conventional regulators such as PI (proportional integral), PD (proportional derivative) and PID (proportional – integral – derivative) were widely used for not only theoretical studies but also in practical control systems with acceptable performances. These regulators were characterized by simple structures and might be suitable for a number of control plants. However, the determination of gain factors represented for proportion, integration and derivation as well as the increasing complexity of the control systems in practice have made the application of conventional regulator highly challenging.

With a fast development of the technology and the increasing requirement for a control system in reality, the conventional regulators should be improved or even be eliminated to make a way for newly efficient controllers. Intelligent control strategies using artificial neural networks, fuzzy logic or bio-inspired optimization methods have also been used as dominant replacements. The artificial intelligence (AI) – based applications have been reported in various number of studies [1-5]. Among them, application in control field are highly dominant. Considered to be one of the worthy alternatives of traditional controllers, fuzzy logic controllers (FLCs) have shown their remarkable advantages. These controllers are highly suitable for nonlinear and/or uncertain systems which are not able to be mathematically modelled as differential equations. This is because the FLCs act depending only upon experiences and/or knowledge of experts through a set of fuzzy rules [6-10].

When designing an FLC model, it is necessary to consider not only the fuzzy rule base but also the membership functions corresponding to its input/output structure. Technically, the controllers applying fuzzy logic technique are plentiful for both theory and practice applications. Typically, based on the number of its inputs and outputs integrated with scaling factors, FLCs can be classified into two types PD-, PI- and PID-like FLCs. Among them, the first two ones have usually been applied as feasible candidates of conventional PD and PI regulators in dealing with control problems for both theoretical and practical applications [5, 11, 12].

This work focuses on creating a comprehensive comparison between two foresaid FLCs. Such two FLCs will be analyzed regarding their structure and working principle. Then, two fuzzy sets, namely full and simplified ones, will also be provided for the comparative purpose. A model of DC motors in speed control problem will be taken into account to verify the applicability of these two FLCs. Numerical simulations implemented in MATLAB package generating meaningful results are also to clarify the better controller between two FLCs. This should be able to make a possible reference for researchers or engineers to select the most suitable controller applying fuzzy logic technique for solving their control problems.

II. AN OVERVIEW OF CONVENTIONAL PID, PD AND PI CONTROLLERS

It should be obvious that PID regulators have been widely applied to design efficient control systems in industry. Technically, the PID – based control strategies are highly suitable for feedback control systems. The principle of such a conventional control system is delineated in Fig. 1.

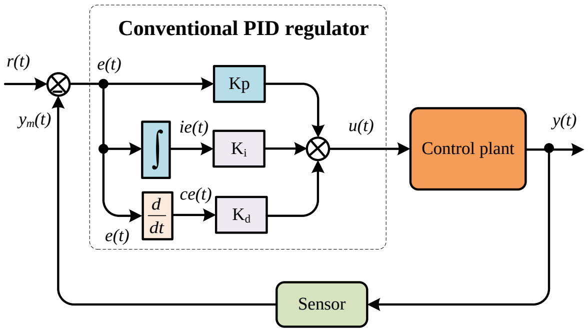

Fig. 1: A conventional PID-based control strategy

As can be seen from Fig. 1, a conventional PID regulator uses the input signal calculated as the error value $e(t)$ between the set-point or reference $r(t)$ and the measured value $y_m(t)$ of the output $y(t)$. The output signal of such a PID regulator considered to be the control signal $u(t)$ which is directly taken to the control plant. On the basis ground, the PID principle is presented by the following relationship between its input and output:

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

Where K_p, K_i and K_d are three factors of the PID controller. Such three coefficients are necessary to be determined by means of manual or adaptive/optimal techniques. Theoretically, the transfer function corresponding to the PID controller demonstrated in (1) is given below:

$$\begin{aligned} G_{PID}(s) &= \frac{U(s)}{E(s)} = K_p + K_i.\frac{1}{s} + K_d.s \\ &= \frac{K_d.s^2 + K_p.s + K_i}{s} \end{aligned} \tag{2}$$

In case of using the PD or PI controllers as sub-candidates of the PID regulators, two factors K_i and K_d presented in (1) or (2) should be treated as zero. In this perspective, the transfer functions corresponding to such two regulators are as follows:

$$G_{PD}(s) = K_p + K_d.s \tag{3}$$

$$G_{PI}(s) = \frac{K_p.s + K_i}{s} \tag{4}$$

The dynamic responses in accordance with the PD and PI regulators are depicted in Fig. 3. Technically, the PD regulators are considered to be suitable for control systems which require fast response as well as ability of future prediction. However, this type of regulators should be careful in use because of the derivative activity which is able to make the system unstable. In contrast, the PI regulators are able to eliminate the steady state error, ensuring the stability of the system. Nevertheless, such a PI-based control system may not be capable of predicting the future error as well as increasing dynamic response of the system.

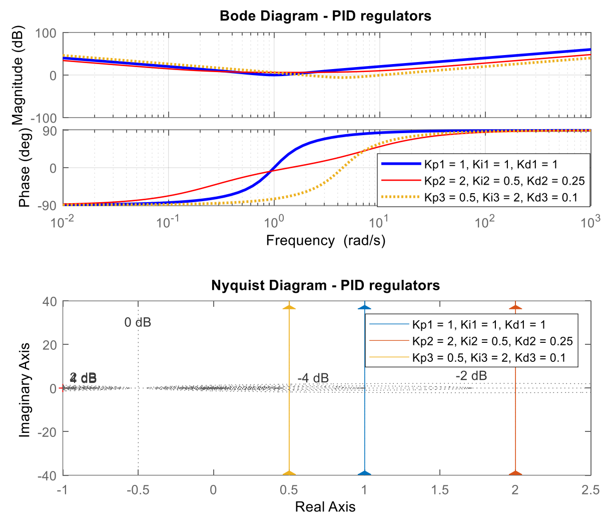

Fig. 2: An illustration of the dynamic responses regarding the PID regulators

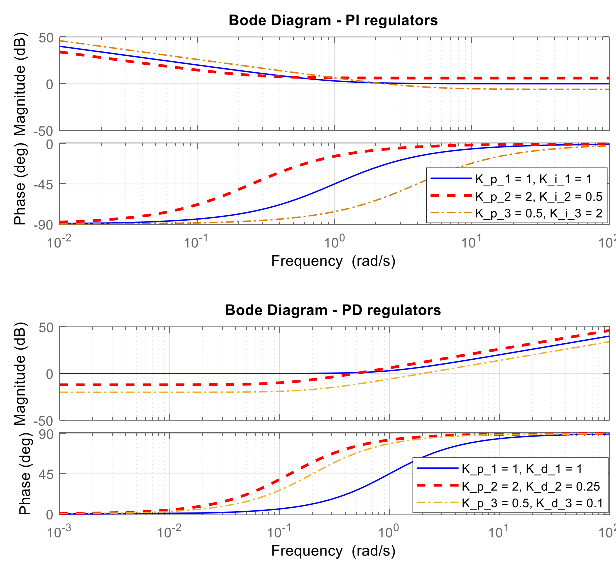

Fig. 3: The demonstration of the dynamic responses regarding the PD and PI regulators

III. PI – AND PD – TYPE FUZZY LOGIC CONTROLLERSPAGE STYLE

Fuzzy logic – based control strategies have been invented to initially replace with the PID controllers [13-14]. The disadvantages of the conventional PID regulators made the way for the appearance of the FLCs. Unlike the PID regulators, the FLCs act depending upon the expert's experiences, thus, they may not require a clarified model of control plant in which its parameters are clearly known, without nonlinearities and uncertainties. Instead, the control system applying FLCs is able to contain a number of unknown parameters as well as nonlinearities and/or uncertainties.

The initial idea to design a FLC was to replace the PID regulator, leading to two basic structures of the FLCs as illustrated in Fig. 4.

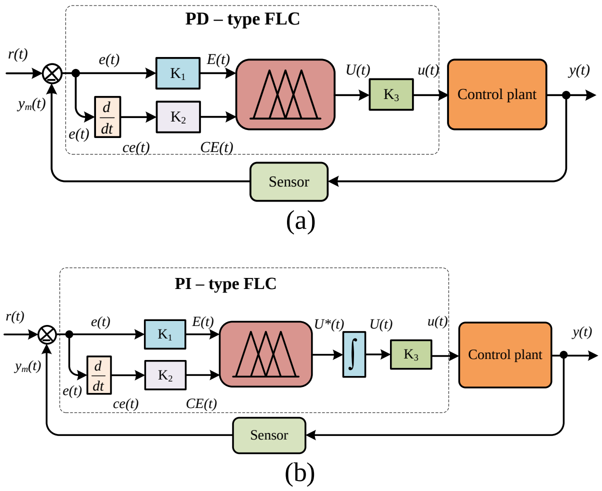

Fig. 4: Typical architectures of control strategies applying FLCs
(a) PD – type FLC
(b) PI – type FLC

Both FLC models delineated in Fig. 4 have two inputs: the error signal $e(t)$ between reference $r(t)$ and measured output $y_m(t)$, and the derivative of this error $ce(t)$. Obviously, the first one is identical to the PID regulators, however, the second one characterizes varying rate of the error signal which is highly meaningful in regulating the dynamics of the system. Similar to the conventional PID regulators, the output of such an FLC is sent to the control plant as shown in Fig. 4.

According to [5], a fuzzy logic model should be considered to be an approximate input/output relationship as given below for the PD-type FLC illustrated in Fig. 4(a):

$$U(t) = \alpha.E(t) + \beta.CE(t) \qquad (4)$$

Where α, β 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 K_1, K_2 and K_3 added by experts, the control signal u(t) is computed as:

$$\begin{cases} E(t) = K_1.e(t) \\ CE(t) = K_2.ce(t) \\ u(t) = K_3.U^*(t) \end{cases} \qquad (5)$$

Combine (3) and (4), the following expression can be derived:

$$\begin{aligned} u(t) &= K_3.\left(\alpha.K_1.e(t) + \beta.K_2.ce(t)\right) \\ &= K_{P\_FLC}.e(t) + K_{d\_FLC}\frac{de(t)}{dt} \end{aligned} \qquad (6)$$

Two factors K_{P_FLC} and K_{d_FLC} in the linear theory can be considered to be of similarity to the gain and derivative coefficients of a conventional regulator as mentioned in Section 2. That is why such an FLC architecture should be defined as PD-type FLC. Similar to such an FLC topology, the FLC model depicted in Fig. 4(b) has the output signal u(t) which can be calculated as follows:

$$\begin{aligned} u(t) &= K_3\int\left(\alpha.K_1.e(t) + \beta.K_2.ce(t)\right)dt. \\ &= K'_{P\_FLC}.e(t) + K'_{i\_FLC}\int e(t)dt \end{aligned} \qquad (7)$$

The expression (7) demonstrates the similarity of the foresaid FLC model and the conventional PI regulator. The two factors as given in (7) are considered to be a gain and integral factors of such a FLC model. As a result, a category of PI-like FLC architecture should be defined for this FLC model.

Theoretically, the PD-like FLC strategy is suitable for a system consisting of integral units or a system which requires stabilizing around an equilibrium. Meanwhile, the PI-like FLC – based control scheme may usually be employed for a system in which its steady-state error needs to be eliminated. However, such a FLC – based control system may affect response time as well as oscillating transient process. In this aspect, a comparison based on a number of simulations is necessary and it will be presented in the following section.

To design a FLC architecture following PI or PD structure, as mentioned earlier, especially for this study, it is necessary to determine three parts:

(i) Define two inputs ***E*** and ***CE*** with membership functions.

(ii) Define an output with membership functions.

(iii) Build the Mamdani fuzzy logic model with full 49-fuzzy rules or reduced 9-fuzzy rules.

TABLE I: Fuzzy rule table for the full FLC model [5]

	NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PS
ZE	NM	NM	NS	ZE	PS	PM	PM
PS	NS	NS	ZE	PS	PM	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PM	PB	PB	PB	PB

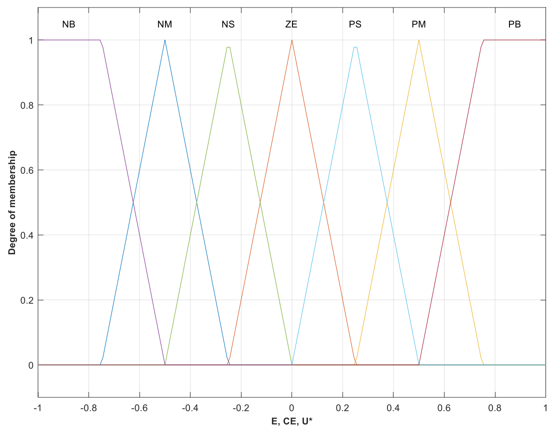

Fig. 5: An illustration of seven membership functions for full FLC topologies

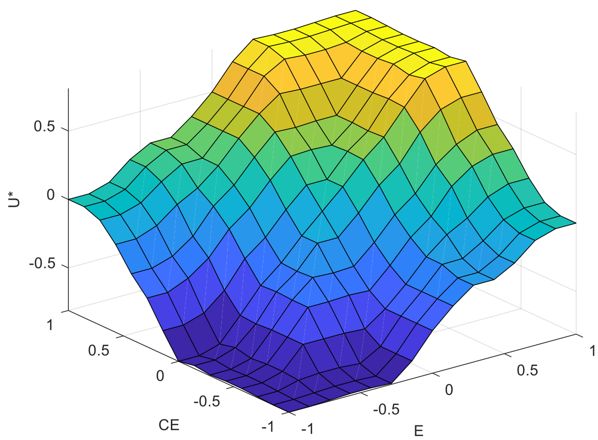

Fig. 6: A 3-D surface of the full FLC model

A table representing the full 49 fuzzy rule base for a conventional 2-input-1-output PD- or PI-like FLC model is delineated in Table I [5]. Noted that seven membership functions are employed for all two inputs and one output of both FLC models. These membership function together with a 3D-surface for such a full FLC model is illustrated in Fig. 5 and Fig. 6.

Besides, to accelerate the simulation process, the FLC models taken into account as mentioned above should be simplified. Here, all inputs and output use only three membership functions, namely N (Negative), Z (Zero) and P (Positive) with a much simple rule base presented below:

'1. If (E is N) and (CE is N) then (U* is N) (1)'
'2. If (E is N) and (CE is Z) then (U* is N) (1)'
'3. If (E is N) and (CE is P) then (U* is Z) (1)'
'4. If (E is Z) and (CE is N) then (U* is N) (1)'
'5. If (E is Z) and (CE is Z) then (U* is Z) (1)'
'6. If (E is Z) and (CE is P) then (U* is P) (1)'
'7. If (E is P) and (CE is N) then (U* is Z) (1)'
'8. If (E is P) and (CE is Z) then (U* is P) (1)'
'9. If (E is P) and (CE is P) then (U* is P) (1)'

The membership functions and a 3D surface of such a FLC model are also depicted as plotted in Fig. 7 and Fig. 8. It is obvious this model is more simple than the previous model. The efficiency of these two FLC models will be discussed in the next section in order to help us select a more suitable controller for a specific control problem.

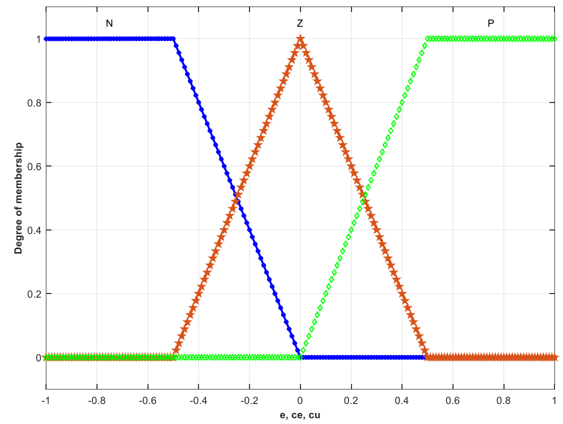

Fig. 7: Three membership functions for two inputs and one output of the simplified FLC structure

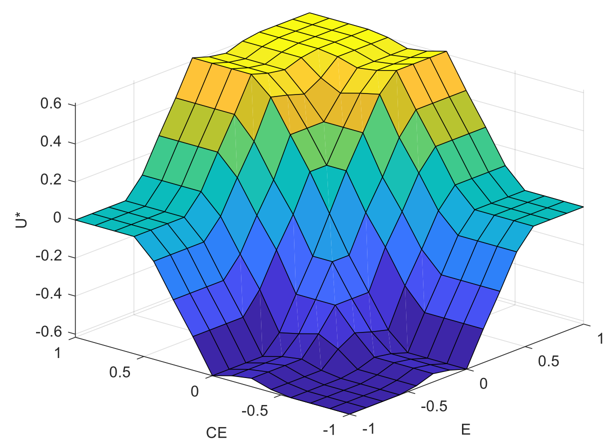

Fig. 8: A 3-D surface illustration of the simplified FLC model

IV. A CASE STUDY TO VERIFY THE PROPOSED CONTROL METHODOLOGY

A case study provided in this section is to consider a separately excited DC motor model for dealing with the speed regulation. The entire control strategy is depicted in Fig. 9 with regard to the selection of both PD- and PI-like FLCs. The DC motor has been considered here with parameters provided in Appendix of the current study and the mathematical model has been presented in [15].

It should be noted that two cases of load changes are used here as shown in Fig. 10. The first one is a step function with step time of one second. Meanwhile, the second one is a random torque which is assumed to have a unique sample time. With each case of load torque, two FLCs are applied in accordance with two rule sets as presented in the previous section.

With simulation parameters given in Appendix B, execute the first simulation case study, the results obtained are illustrated in Fig. 11 and Fig. 12. It is clear the PD-type FLC structure affecting on the control system a non-zero steady-state error. Even there is no overshoot for such a FL controller, the non-zero steady state makes this controller unperfected. By contrast, the PI-like FLC architecture is able to damp the steady-state error much better than the PD-type counterpart. Figures 11-12(b) continue describing this advantage. One thing needing to be considered here is that the full rule set applied for the FLC is also better than the simplified FLC does.

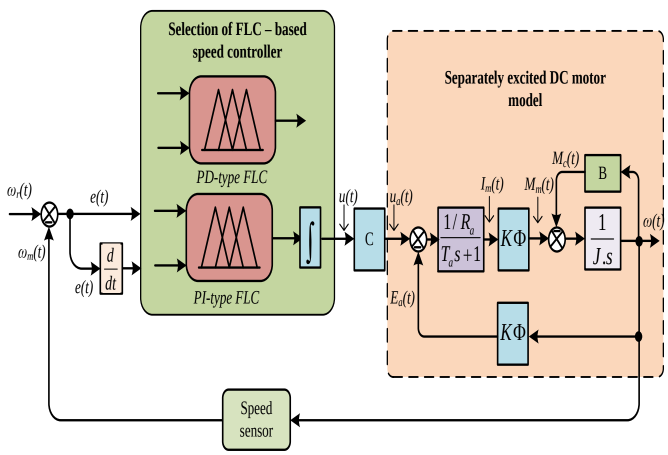

Fig. 9: A case study of applying two FLC models

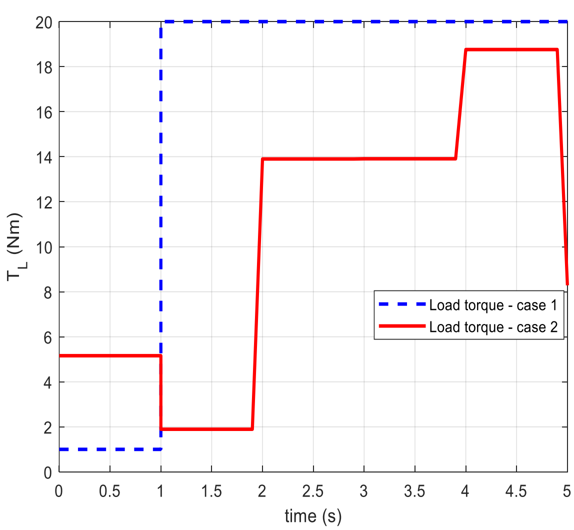

Fig. 10: Two cases of load torque T_L embedded in the control system illustrated in Figure 9

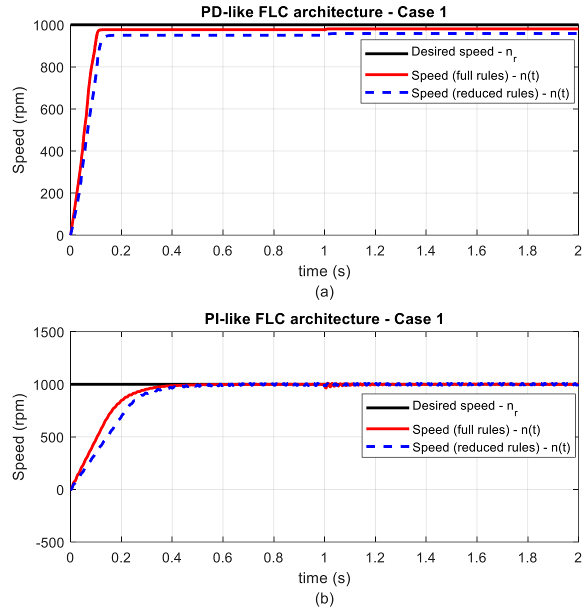

Fig. 11: Simulation results for the first case of T_L

The second simulation case brings a challenge to the control system applying two proposed FLC models. Illustrated in Figs. 13-14, the results are more similar to the reality where the load torque changes randomly over time. There is an important notice that the two simulation cases presented above are only to consider a rate speed set-point $n_r(t)$. The available evidence seems to suggest that the PI-like FLC is more suitable than the PD-like counterpart.

To demonstrate the applicability of the PI-type FLC structure, the third simulation case study should be provided. In this scenario, a random variation of motor speed has also been applied to the DC motor system. As can be seen clearly from Figs. 15-16, the dynamic response of the output speed $n(t)$ track well the reference signal. It is also apparent the full rules-based FLC has obtained the better control performances in comparison with the simplified one. However, the simulation time of such a simplified FLC is slightly faster than the full rule - based counterpart. Figure 17 then shows a whole comparison in accordance with three simulation cases. It should play attention to the following control criterion for the comparative goal:

$$ITAE = \int_0^{\tau} |n(t) - n_r| t dt \quad (8)$$

Where τ is the simulation time given as a candidate for the practical working time. Such a control performance is normally defined as integral time absolute error which is one of the most significant control indexes to evaluate performance of a control system. The illustration in Fig. 17 confirms the feasibility of the full rule-type PI – like FLC – based control strategy in dealing with the control problem proposed in this study.

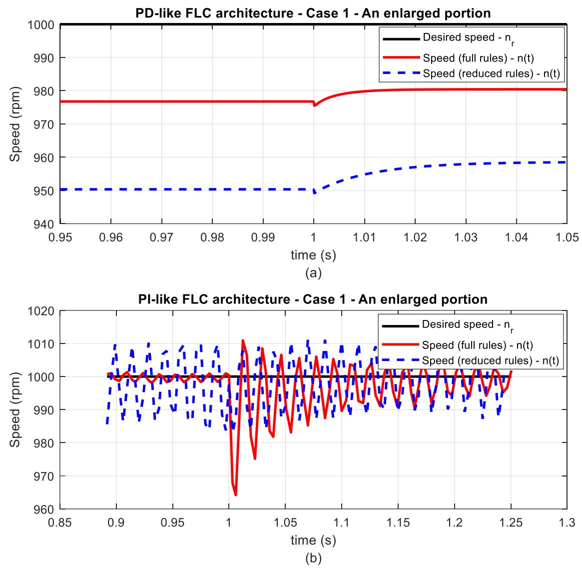

Fig. 12: Simulation results for the first case of T_L (continued)

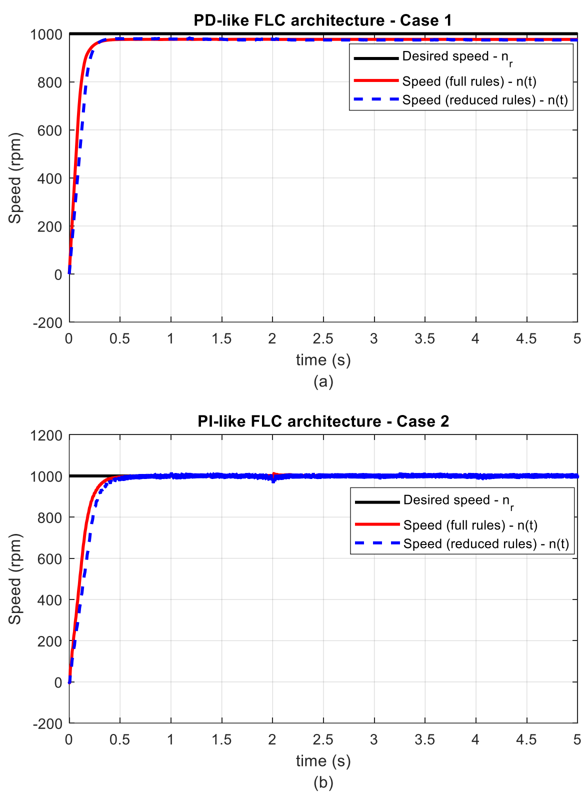

Fig. 13: Simulation results for the second case of T_L

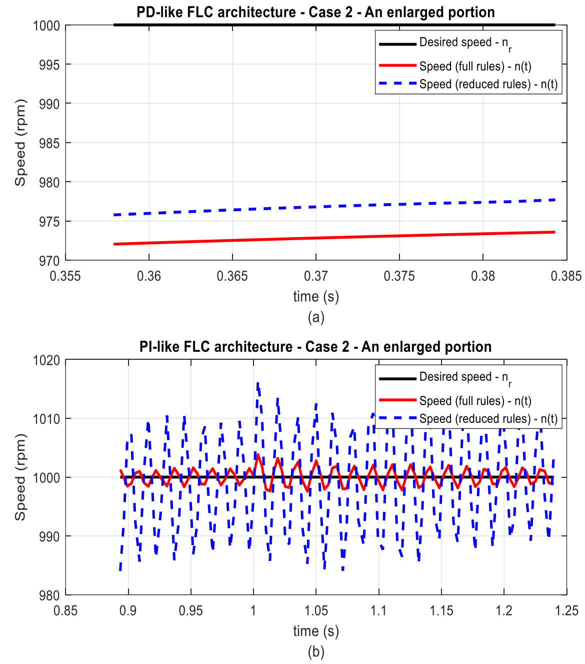

Fig. 14: Simulation results for the second case of T_L (continued)

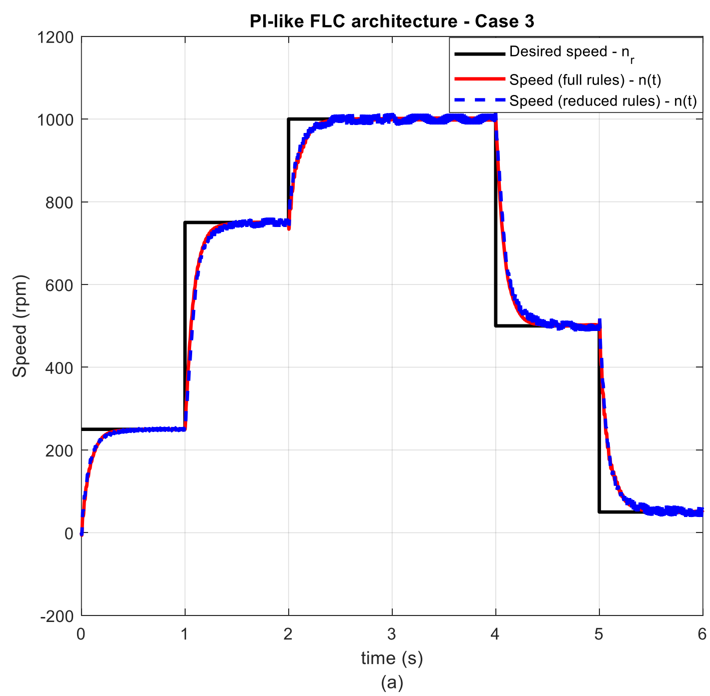

Fig. 15: Simulation results for the third case study

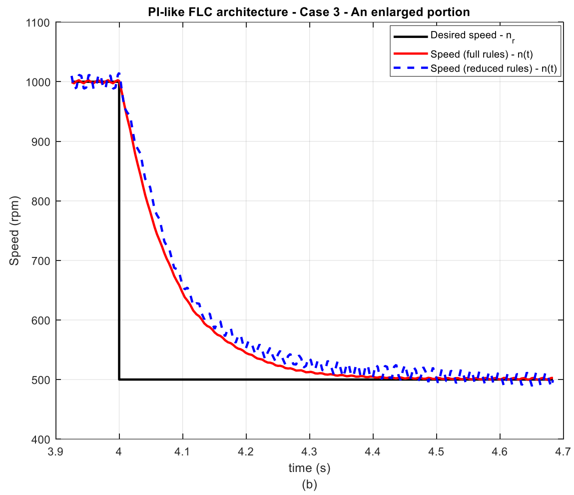

Fig. 16: Simulation results for the third case study (continued)

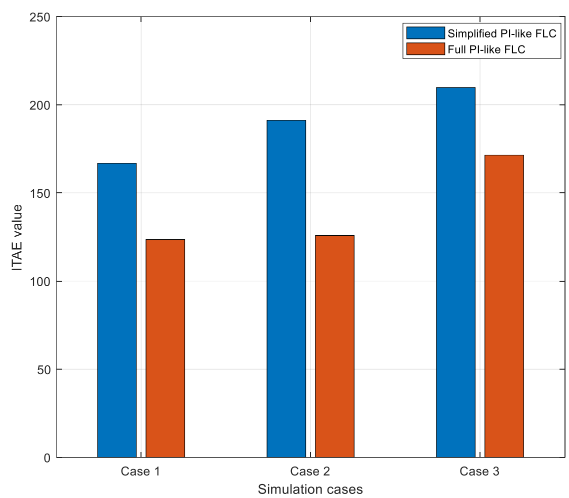

Fig. 17: A comparison between three simulation cases only consider the PI-like FLC models

V. CONCLUSIONS

This work has investigated a comprehensive comparison between two types of typical FLC models, namely PD- and PI-type fuzzy logic structures. In addition, two suitable fuzzy rule sets, namely simplified and full sets, have been provided. A number of numerical simulations applied for a case study of the DC motor's speed control has been used to demonstrate the feasibility of the two FLC models proposed in this study. It has also verified the superiority of the PI-type FL controller over the PD-like one in a specified control problem. Further evidence supporting this work may lie in the findings of a significant method to optimize elements of both FLC models provided in this paper. It seems to regard the optimization of membership functions, fuzzy rule set as well as scaling factors of these two FLC structures. In this perspective, optimization mechanisms can also be applied. The future work may concentrate on several well-known bio-inspired optimization methods, such as genetic algorithm and particle swarm optimization methodologies.

APPENDIX A
Nomenclature

No	Symbol	Description	Unit
1	La	Inductance of armature	H
2	Ra	Resistance of armature	Ω
3	Ta = La/Ra	Time constant of armature	second
4	Km	Gain factor of the motor	N/A
5	Φ	Flux of the excitation	Wb
6	J	Inertial torque of the motor	$Nm.s^2$
7	*B*	Rotational speed of generator	pu
8	$\omega(t)$	Rotational speed of the DC motor	rad/s
9	$\omega_r(t)$	Reference speed	rad/s
10	$n(t)$	Rotational speed of the DC motor	rpm
11	$n_r(t)$	Reference speed	rpm

APPENDIX B
DC motor parameters [15]

- La = 12 mH
- Ra = 140 mΩ
- J = 0.015 $Nm.s^2$
- B = 0.25 Nm.s
- KΦ = 0.85

ACKNOWLEDGMENT

The authors wish to thank Dr. Dao Thi Mai Phuong from Hanoi University of Industry for her discussion on the DC motor modelling. The authors would also like to thank reviewers for significant comments in order to improve this work.

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