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Design of the Neutrosophic Membership Valued Fuzzy-PID Controller and Rotation Angle Control of a Permanent Magnet Direct Current Motor

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Abstract – In this paper, we propose a method based on the fuzzy logic controller (FLC) method, created by using neutrosophic membership values. This method is named as proportional integral derivative-neutrosophic valued fuzzy logic controller (PID-NFLC). We conducted a performance simulation test to compare the PID-NFLC with classical FLC for control of the rotation angle of a permanent magnet direct current (PMDC) motor. Rotation angle error and change of this error were used as the input variables of the FLC and NFLC units. In the suggested neutrosophic valued FLC (NFLC), placement of the input variables was evaluated on the universal set by using neutrosophic membership function approach. Error and error change were evaluated in two different NFLC unit separately from each other. Then, crisp outputs of the NFLC units are applied to PID controller. So, PID-NFLC was obtained. The proposed method and conventional FLC were tested in the SIMULINK. According to the test results, our suggested method is own lesser overshoot ratio and more fast rising time characteristics than the classical FLC. In addition, evaluation of error change, separately from the error in the proposed method is providing flexibility in the PMDC motor position control process.

Keywords - *PID, Fuzzy logic controller, neutrosophy, neutrosophic logic, PMDC motor, position control.*

1. Introduction

Proportional integral derivative (PID) controller is widely used in many control applications, especially in industrial process control. PID controller encompasses many important control characteristics such as easy design, zero-steady state error, low oscillation rate, and rapid response system [1, 2].

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Another popular type of controller is fuzzy logic controller (FLC). The fuzzy logic approach was first proposed by Zadeh in 1965 [3]. While a phenomenon is represented sharply as 0 or 1 in classical logic, it is represented by infinity values in [0,1] range in fuzzy logic. Thus, a phenomenon can be represented by indefinite values (vague, gray) in the fuzzy logic approach. It offers richer assessment for a phenomenon. For the [0,1] range, it is not an essentiality. However, usage of the [0,1] range provides amenities for the calculations, especially in engineering applications.

Neutrosophy and the neutrosophic set approach, which further extended the application of fuzzy logic and intuitionistic logic, were first proposed by Smarandache [4]. In this approach, unlike the case with fuzzy logic, a phenomenon is represented by three membership values named as true (T), indeterminacy (I), and false (F). For example, if A is a subset in an E universal set and x is an element of A, it can be represented as $x(0.7, 0.3, 0.4)$. This representation corresponds to $x(T,I,F)$. According to this representation, set A includes to x with 0.7 degrees, set A does not include to x with 0.4 degrees, and subsumption of x by A set with indeterminacy of 0.3 degrees. There is no necessity of $T+I+F=1$ [4]. T, I, F sets are not necessarily intervals. These sets may be discrete or continuous; single-element, finite, or infinite (countably or uncountably); or union or intersection of various subsets (real sub-unitary subsets) [5].

PID controllers, despite having an easy design possibility, cannot produce good results in an unstable and oscillating system [6]. In 1974, Mamdani presented an algorithm based on the fuzzy logic approach [7]. Today, FLCs are frequently used in different areas [8-12]. After Mamdani, some researchers have proposed the hybrid type (fuzzy-PID) controller, which is a combination of FLCs and PID controllers [13-15].

In the FLC design and fuzzy-PID design, membership function types of input variables and their placements on the universal set are important, and this situation has important implications on the control results [16,17]. In this study, in the fuzzification stage, T, I, and F membership functions are used for the each error and error change in the system to be controlled. These membership functions are grouped in certain regions on the universal set. Output rules based on the arrangement of the three membership functions were created in the rule table. Regional assessment can be improved via groupings of input variables as T, I, and F membership functions. In addition, the evaluation of error change separately from the error provides control flexibility of the overshoot ratio in the PMDC motor position control process. The proposed method and classical FLC methods were tested on the rotation angle of the shaft of a PMDC motor and the results were compared.

2. Preliminaries

2.2. Basics of Neutrosophic Set and Neutrosophic Logic

Basic operations of neutrosophic set/logic are as follows.

Definition 1 [18] X is a universal set. x is a element in X. A is a neutrosophic subset in X. For A subset,
$T_A(x)$: Truth membership function.
$I_A(x)$: Indeterminacy membership function.
$F_A(x)$: Falsity membership function.
$T_A(x)$, $I_A(x)$ and $F_A(x)$ functions are real standard or non-standard subsets of $]0^-, 1^+[$.

$T_A(x)$: $X \rightarrow]0^-, 1^+[$
$I_A(x)$: $X \rightarrow]0^-, 1^+[$
$F_A(x)$: $X \rightarrow]0^-, 1^+[$
There is no restriction on the sum of $T_A(x)$, $I_A(x)$ ve $F_A(x)$, and so;
$0^- \leq sup\ T_A(x) + sup\ I_A(x) + sup\ F_A(x) \leq 3^+$. (1)
Definition 2 [18] A is a single valued neutrosophic set (SVNS) in X.
$A = \{\langle x, T_A(x), I_A(x), F_A(x)\rangle : x \in X\}$.
$T_A(x)$: $X \rightarrow [0,1]$
$I_A(x)$: $X \rightarrow [0,1]$
$F_A(x)$: $X \rightarrow [0,1]$
$0 \leq T_A(x) + I_A(x) + F_A(x) \leq 3$ for all $x \in X$. (2)
Definition 3 [18] A is a SVNS. Complement of A is denoted by A^c and for all $x \in X$;
$T_{A^c}(x) = F_A(x)$
$I_{A^c}(x) = 1 - I_A(x)$
$F_{A^c}(x) = T_A(x)$
$A^c = \{\langle x, F_A(x), 1 - I_A(x), T_A(x)\rangle : x \in X\}$
Definition 4 [18] A and B are SVNS, can be written as $A = B$, if and only if $A \subseteq B$ and $B \subseteq A$.
Definition 5 [19] A, B, and C are neutrosophic sets and for all $x \in X$.
Intersection:
$T_C(x) = min\ (T_A(x), T_B(x))$
$I_C(x) = min\ (I_A(x), I_B(x))$
$F_C(x) = max\ (F_A(x), F_B(x))$
Union:
$T_C(x) = max(T_A(x), T_B(x))$
$I_C(x) = max\ (I_A(x), I_B(x))$
$F_C(x) = min\ (F_A(x), F_B(x))$
Complement:
$T_{\bar{A}}(x) = F_A(x)$
$I_{\bar{A}}(x) = 1 - I_A(x)$
$F_{\bar{A}}(x) = T_A(x)$

2.3. PID Controller and FLC

Three basic parameters, named as K_p, K_i, and K_d, play a leading role in achieving the desired system performance of PID controller. In the PID control technique, the error is multiplied by the K_p coefficient, integral of the error is multiplied by the K_i coefficient, and derivative of the error is multiplied by the K_d coefficient; finally, these multiplications are collected. Thus, the control signal is obtained. The time-domain representation of the control signal for a PID controller is shown in the Equation 3, as shown below.

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t) \quad (3)$$

$$e(t) = r(t) - y(t) \quad (4)$$

In Equations 3 and Equation 4 mentioned above, $r(t)$, $e(t)$, $u(t)$, and $y(t)$ refer to the reference signal, error signal, control signal, and output signal, respectively.

FLC is another commonly used type of controller. FLC consists of four main units. These are fuzzification, rule base, fuzzy inference mechanism, and defuzzification units. In general, errors and error change are used as input variables in classical FLC. A classical FLC block diagram is shown in Figure 1.

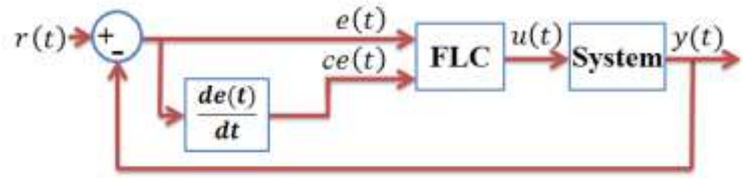


Figure 1: Classical FLC block diagram.

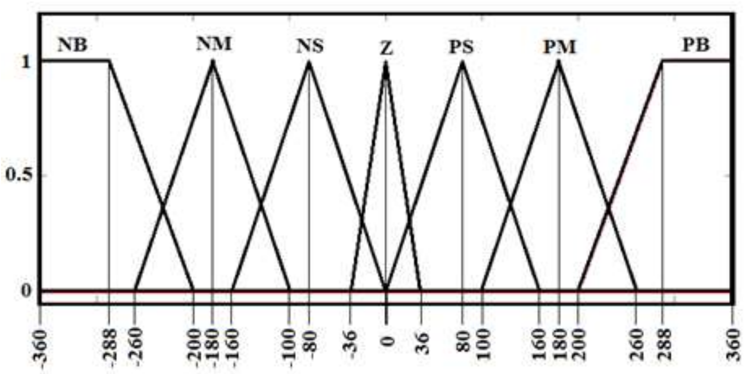
In the fuzzification stage, the input variables are passed from the membership functions (triangular, Gaussian curve, bell curve, trapezoidal, Cauchy functions). In this manner, subsets of the input variables on the universal set and membership values of the input variables are obtained. The rule base includes rules of control related to the system to be controlled. In the fuzzy inference stage, fuzzy control answer is obtained by using fuzzy operators and rule base. In the defuzzification stage, the fuzzy control answer transforms to the applicable crisp control signal to the system to be controlled.

3. Method

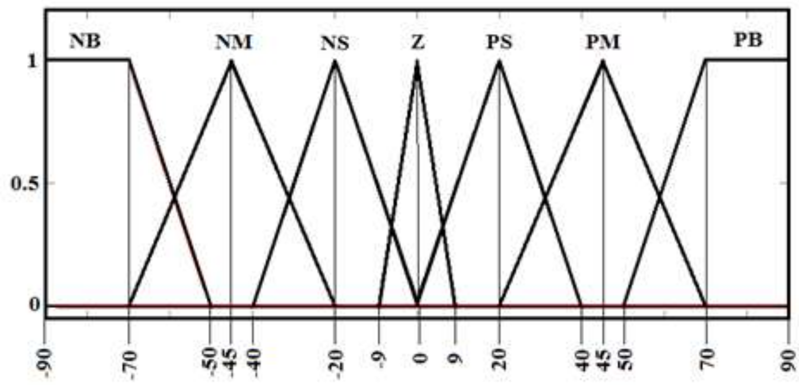
In this study, the usage of neutrosophic membership values for the classical FLC is suggested. Further, performance comparison of NFLC and classical FLC for control of the rotation angle of a PMDC motor was undertaken. Error and error change were used as the input variables for all FLC units.

The abbreviations NB, NM, NS, Z, PS, PM, and PB in the figures and tables refer to the linguistic expressions “Negative Big,” “Negative Medium,” “Negative Small,” “Zero,” “Positive Small,” “Positive Medium,” and “Positive Big,” respectively. The abbreviations VD, D, LD, Z, LI, I and VD indicate the linguistic expressions “Very Decrease", "Decrease", “Little Decrease,” “Zero,” “Increase,” and “Very Increase,” respectively. e_T, e_I, and e_F represent the truth, indeterminacy, and falsity membership values.

The applied membership functions and rules in the classical FLC unit are shown in Figure 2 and Table 1, respectively.



(a)



(b)

Figure 2: The input MFs used in the FLC unit. (a) For error. (b) For error change.

Table 1: The rules applied in the classical FLC unit.

1. If (e is NB) and (ce is NB) then (output1 is NB)	26. If (e is Z) and (ce is PS) then (output1 is PS)
2. If (e is NB) and (ce is NM) then (output1 is NB)	27. If (e is Z) and (ce is PM) then (output1 is PM)
3. If (e is NB) and (ce is NS) then (output1 is NB)	28. If (e is Z) and (ce is PB) then (output1 is PB)
4. If (e is NB) and (ce is Z) then (output1 is NM)	29. If (e is PS) and (ce is NB) then (output1 is NM)
5. If (e is NB) and (ce is PS) then (output1 is NS)	30. If (e is PS) and (ce is NM) then (output1 is NS)
6. If (e is NB) and (ce is PM) then (output1 is NS)	31. If (e is PS) and (ce is NS) then (output1 is Z)
7. If (e is NB) and (ce is PB) then (output1 is Z)	32. If (e is PS) and (ce is Z) then (output1 is PS)
8. If (e is NM) and (ce is NB) then (output1 is NB)	33. If (e is PS) and (ce is PS) then (output1 is PS)
9. If (e is NM) and (ce is NM) then (output1 is NM)	34. If (e is PS) and (ce is PM) then (output1 is PM)
10. If (e is NM) and (ce is NS) then (output1 is NM)	35. If (e is PS) and (ce is PB) then (output1 is PB)
11. If (e is NM) and (ce is Z) then (output1 is NM)	36. If (e is PM) and (ce is NB) then (output1 is NS)
12. If (e is NM) and (ce is PS) then (output1 is NS)	37. If (e is PM) and (ce is NM) then (output1 is Z)
13. If (e is NM) and (ce is PM) then (output1 is Z)	38. If (e is PM) and (ce is NS) then (output1 is PS)
14. If (e is NM) and (ce is PB) then (output1 is PS)	39. If (e is PM) and (ce is Z) then (output1 is PM)
15. If (e is NS) and (ce is NB) then (output1 is NB)	40. If (e is PM) and (ce is PS) then (output1 is PM)
16. If (e is NS) and (ce is NM) then (output1 is NM)	41. If (e is PM) and (ce is PM) then (output1 is PM)
17. If (e is NS) and (ce is NS) then (output1 is NS)	42. If (e is PM) and (ce is PB) then (output1 is PB)
18. If (e is NS) and (ce is Z) then (output1 is NS)	43. If (e is PB) and (ce is NB) then (output1 is Z)
19. If (e is NS) and (ce is PS) then (output1 is Z)	44. If (e is PB) and (ce is NM) then (output1 is PS)
20. If (e is NS) and (ce is PM) then (output1 is PS)	45. If (e is PB) and (ce is NS) then (output1 is PS)
21. If (e is NS) and (ce is PB) then (output1 is PM)	46. If (e is PB) and (ce is Z) then (output1 is PM)
22. If (e is Z) and (ce is NB) then (output1 is NB)	47. If (e is PB) and (ce is PS) then (output1 is PB)
23. If (e is Z) and (ce is NM) then (output1 is NM)	48. If (e is PB) and (ce is PM) then (output1 is PB)
24. If (e is Z) and (ce is NS) then (output1 is NS)	49. If (e is PB) and (ce is PB) then (output1 is PB)
25. If (e is Z) and (ce is Z) then (output1 is Z)	

In the "*fuzzy"* interface of the MATLAB, the applied features of the classical FLC unit are given in Table 2.

Table 2: Features of the fuzzy interface for classical FLC.

FIS type	"mamdani"
Rule connections	"and"
For "and" method	"min"
For defuzzification	"centroid"

The application of the SIMULINK block for the classical FLC method in the study is depicted in Figure 3.

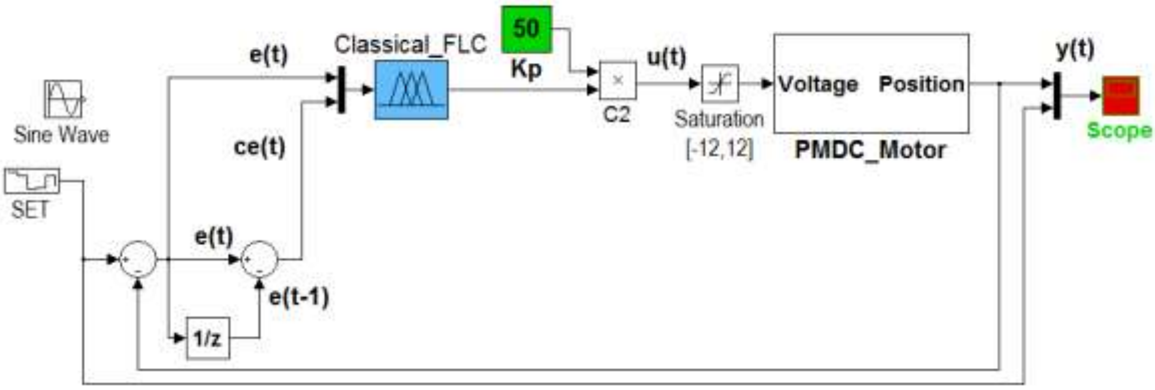
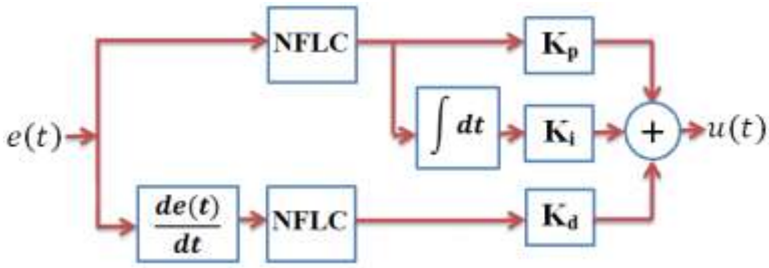
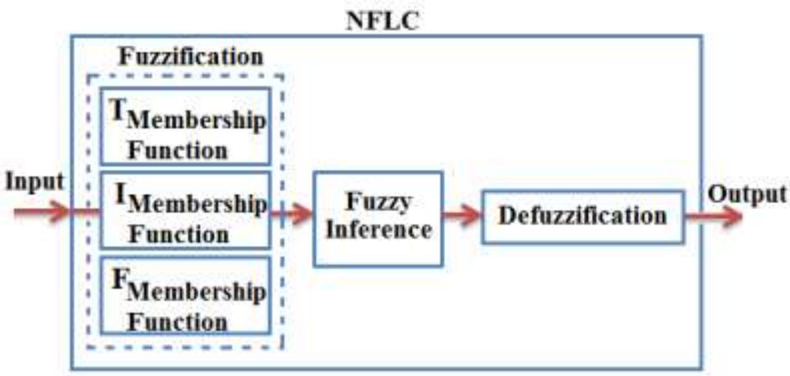


Figure 3: Application of the SIMULINK block for the classical FLC method in the study.

In the proposed method, error and error changes were considered in two separate fuzzy inference units. The controller block diagram of the proposed method is shown in Figure 4.



(a)



(b)

Figure 4: a: Block diagram of the suggested method (NFLC) b: Representation of internal sutructure of the NFLC [20]

The block diagram shown in Figure 4 is a general representation of the proposed method. According to the type of application, any of the K_p, K_i, and K_d (i.e., gains) values can be taken as zero. Application of the SIMULINK block for the suggested NFLC method in the study is shown in Figure 5. As clearly seen from Figure 5, K_i value is equal to zero (or no) for this application.

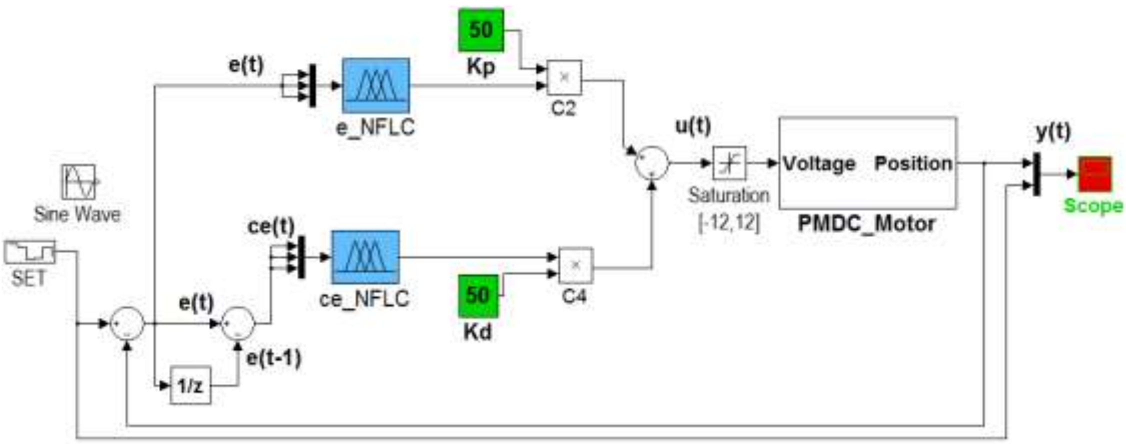


Figure 5: Applicaiton of the SIMULINK block for the suggested (NFLC) method in the study.

T, *I*, and *F* membership functions used for error and error change in each NFLC units are grouped on the universal set in the same manner. The only difference between the membership functions of error and membership functions of error change is the scales of universal sets. For the fuzzification, triangular and trapezoid membership functions are used. Membership functions of the error and membership functions of the error change are shown in Figures 6 and 7, respectively. Further, the applied rules in the NFLC units are provided in Table 3.

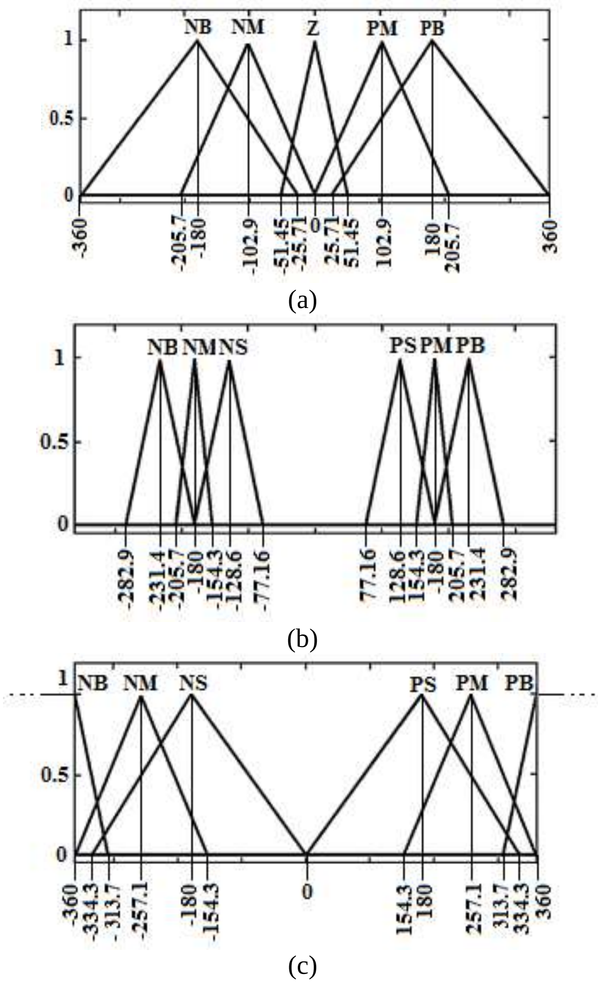


Figure 6: Used MFs in NFLC units for error (a) *T* MF. (b) *I* MF. (c) *F* MF [20].

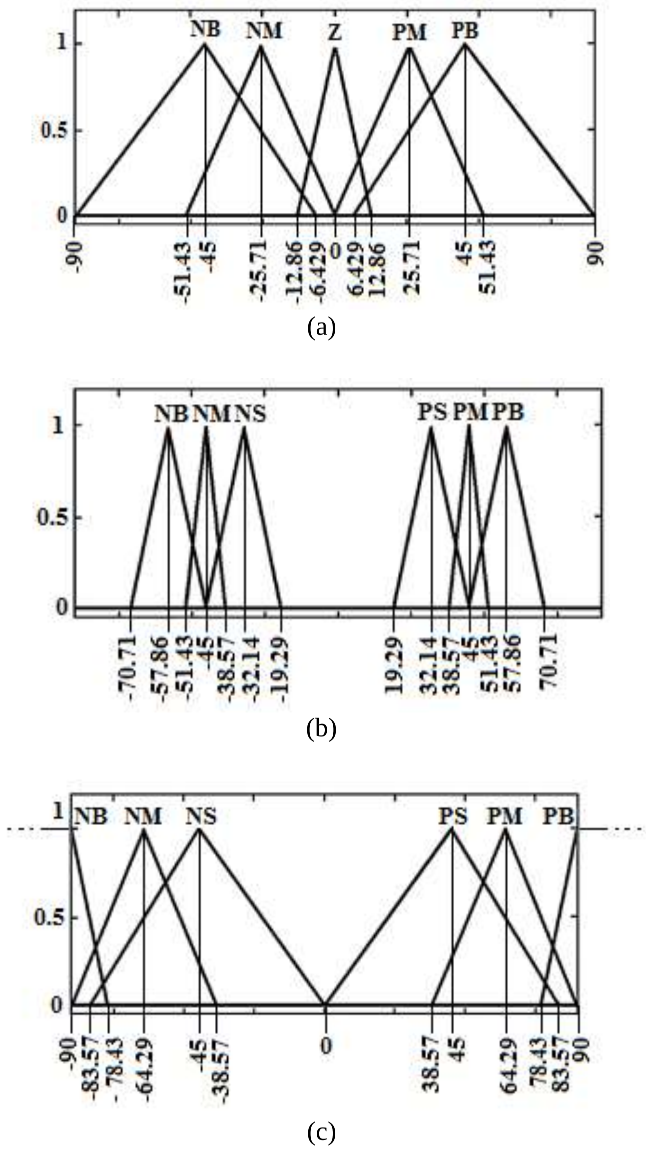


Figure 7: Used MFs in NFLC units for error change (a) *T* MF. (b) *I* MF. (c) *F* MF [20].

Table 3: Used rules in NFLC units [20].

1. If (e_T is Z) or (e_F is PS) then (output1 is Z)	11. If (e_T is PB) or (e_I is PB) or (e_F is PM) then (output1 is I)
2. If (e_T is Z) or (e_F is NS) then (output1 is Z)	12. If (e_T is NB) or (e_I is NB) or (e_F is NM) then (output1 is D)
3. If (e_T is PM) or (e_F is PS) then (output1 is LI)	13. If (e_T is PB) or (e_I is PB) or (e_F is PM) then (output1 is I)
4. If (e_T is NM) or (e_F is NS) then (output1 is LD)	14. If (e_T is NB) or (e_I is NB) or (e_F is NM) then (output1 is D)
5. If (e_T is PM) or (e_I is PS) or (e_F is PS) then (output1 is LI)	15. If (e_T is PB) or (e_F is PM) then (output1 is VI)
6. If (e_T is NM) or (e_I is NS) or (e_F is NS) then (output1 is LD)	16. If (e_T is NB) or (e_F is NM) then (output1 is VD)
7. If (e_T is PB) or (e_I is PS) or (e_F is PS) then (output1 is LI)	17. If (e_T is PB) or (e_F is PB) then (output1 is VI)

8. If (e_T is NB) or (e_I is NS) or (e_F is NS) then (output1 is LD)	18. If (e_T is NB) or (e_F is NB) then (output1 is VD)
9. If (e_T is PB) or (e_I is PM) or (e_F is PS) then (output1 is I)	19. If (e_F is PB) then (output1 is VI)
10. If (e_T is NB) or (e_I is NM) or (e_F is NS) then (output1 is D)	20. If (e_F is NB) then (output1 is VD)

In the "*fuzzy"* interface of the MATLAB, same features are used in both NFLC units. These features are given in Table 4.

Table 4: Features of the fuzzy interface for NFLC.

FIS type	"mamdani"
Rule connections	"or"
For "or" method	"max"
For defuzzification	"centroid"

The same output membership functions are used in all FLC and NFLC units. Output membership function used for crisp output value (in the FLC and NFLC units) is shown in Figure 8.

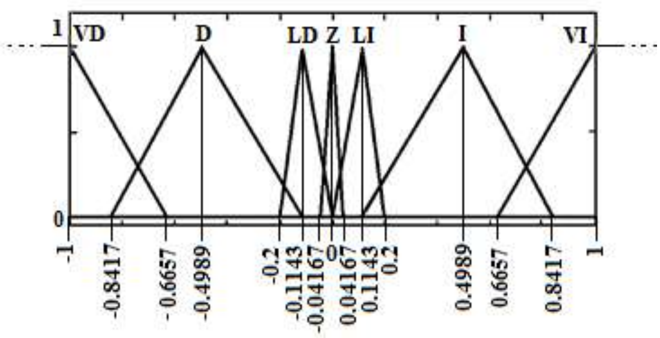


Figure 8: Used output MFs in FLC and NFLC units [20].

4. Applications

In this section, the proposed method and classical FLC method were tested on a PMDC motor model. Applications were performed with the two-test format. In the first test, different K_p, K_i, and K_d values are used for different step reference signals. In the second test, a sinusoidal reference signal isgiven and the tracking ability of the shaft of the PMDC motor to the reference signal is tested. The used transfer function of the PMDC motor model in applications is given in Equation 3 below.

$$TF_{motor} = \frac{\theta(s)}{V(s)} = \frac{K}{s\left((Js+B)(Ls+R)+K^2\right)} \tag{3}$$

K, J, R, L and *B* parameters of the PMDC motor are as follows;

$K = 0.007384$; $R = 1.2284$; $L = 0.000230081$; $J = 0.0009$; $B = 0.00724$

In the Equation 3, θ indicates the rotary angle of the shaft of the motor, and V refers to the voltage applied to the motor. The study was performed with different K_p, $K_{i,}$ and K_d (i.e

Gains) values. In the first application, performances of the classical FLC and proposed method are tested by giving different reference signals. Reference signals and system responses for different gain values are given in Figure 9.

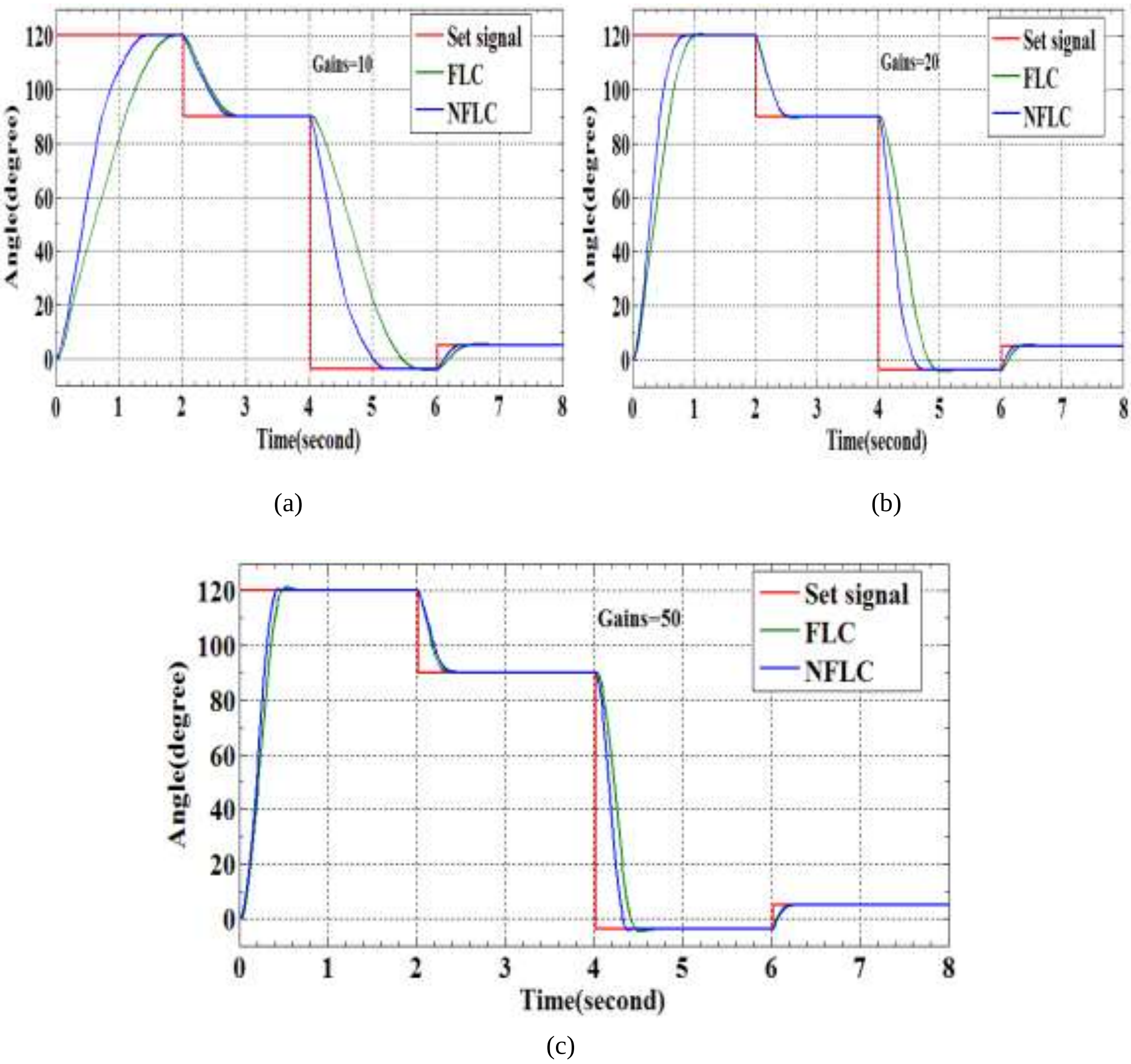
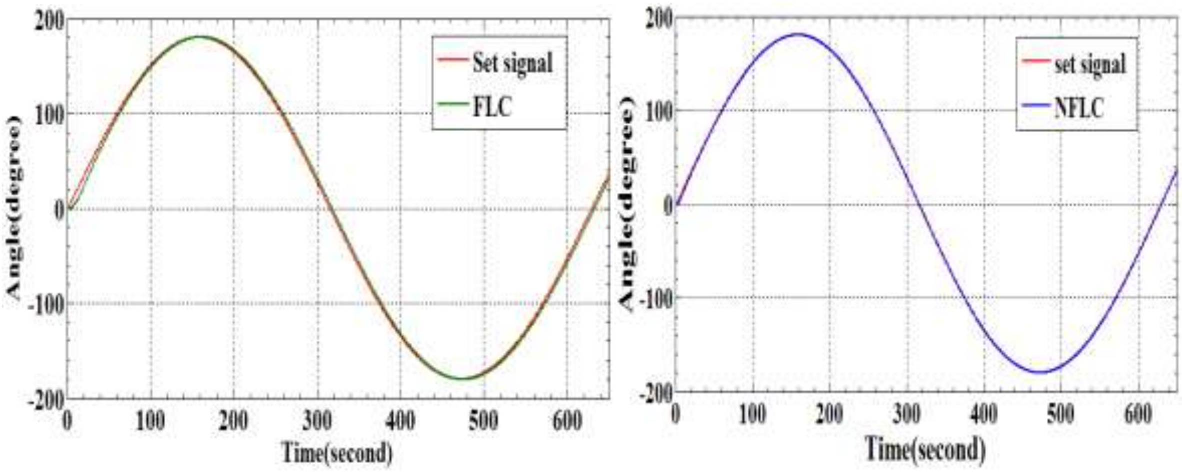


Figure 9: Different reference values and received response curves from the system. Reference values: 120, 90, -4, 5, 90, and 20 degrees. (a) Gain values=10. (b) Gain values=20. (c) Gain values=50.

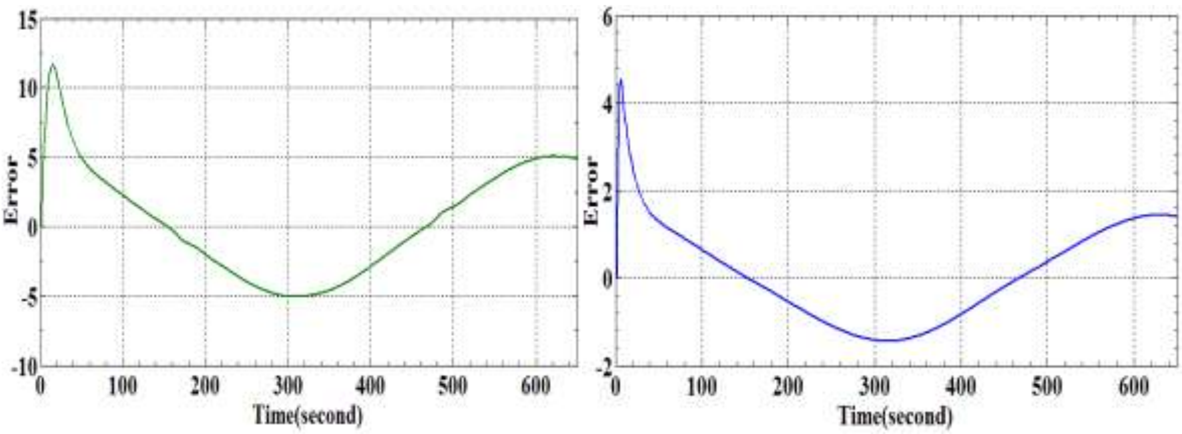
Obtaining low overshoot rates and low oscillation rates are important for position control applications. As can be seen from Figure 9, the results obtained with the proposed method in big gain values have less overshoot rates than those yielded by the classical FLC. Further, the rising time obtained with the proposed method is shorter than the classical FLC. Neither the classic FLC nor the proposed method show oscillation and steady state error.

In the second application example, the tracking ability of the system was tested for a reference sine curve of amplitude 180 unit amplitude and frequency of 1 radian/sec generated by a reference signal. In this example, the gain values are taken as 50 because the best results are obtained with gain values equal to 50 for controllers. Sinusoidal reference and response of the system for this reference are shown in Figure 10.



(a) (b)

Figure 10: Sinusoidal refence signal and system output. (a) Classical FLC method. (b) Suggested method.



(a) (b)

Figure 11: Change graph of the error for the Sinus referance signal. Gain values=50. (a) Classical FLC method. (b) Suggested method.

Figure 11 shows the error between the sinusoidal reference applied to the system and responses of the system. As can be seen easily from Figures 10 and 11, the path tracking error with the proposed method is lesser than with the classical FLC.

5. Conclusion

In this paper, we propose a FLC method based on neutrosophic membership function. Furthermore, the suggested method was compared with conventional FLC approach. The proposed method and conventional fuzzy logic methods were tested for control of rotation angle of a PMDC motor shaft. The obtained results showed that the proposed method has lower overshoot rate and a shorter rising time than the classical FLC method. This implies that the proposed method can be used in the PMDC motor position control applications.

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