



## Neutrosophic valued PID controller for closed loop V/f speed control of permanent magnet synchronous motor

### Sabit mıknatıslı senkron motorun kapalı çevrim V/f hız kontrolü için nütrosifik değerli PID denetleyicisi

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#### Abstract

In this article, a neutrosophic logic-based closed loop V/f control system has been established by creating a fuzzy inference system and a neutrosophic fuzzy logic controller (NFLC) in Matlab. Although NFLC can control by taking uncertainty and imprecise data into account, it can sometimes fall short in applications that require fast and accurate responses. Therefore, the NFLC-PID block diagram has been established to test in a Simulink environment with permanent magnet synchronous motor (PMSM). The NFLC-PID takes into account the imprecise data provided by the NFLC and provides a more accurate feedback. Thus, the control performance of the system is further improved. The simulation results demonstrate that the NFLC-PID managed the PMSM efficiently and successfully.

**Keywords:** Permanent magnet synchronous motor, Fuzzy logic controller, Neutrosophic fuzzy logic controller

#### 1 Introduction

In conventional set theory, the inclusion or exclusion of an element in a set is indicated by the numbers 0 (not included) and 1 (included). But we also employ intermediate (fuzzy) values when calculating value. Fuzzy logic was first suggested by Zadeh [1]. A degree of membership serves to represent an event, usually with a value in the range [0,1]. The level of affiliation is determined using membership functions (MF). By determining MF's in fuzzy set theory, the relationship between cognitive and stimulating expressions can be modeled. The problem is solved by the computed MF, and the procedure can be seen as a transition from object behavior to function.

Fuzzy set theory is widely employed in many industries, including robotics, finance, health, and signal processing [2, 3, 4]. It is also widely used in the field of automatic control [5]. A controller derived from the design procedure of a fuzzy logic-based controller is called a fuzzy controller (FC) or fuzzy logic controller (FLC). FLC is especially used in uncertainty and nonlinear systems [6]. The type of MFs used in an FLC design must be carefully considered.

#### Öz

Bu makalede, Matlab'da bir bulanık çıkarım sistemi ve bir nütrosifik bulanık mantık denetleyici (NFLC) oluşturularak nütrosifik mantık tabanlı kapalı döngü V/f kontrol sistemi kurulmuştur. NFLC, belirsizlik ve kesin olmayan verileri hesaba katarak kontrol yapabilmesine rağmen, bazen hızlı ve doğru yanıtlar gerektiren uygulamalarda yetersiz kalabilir. Bu nedenle sabit mıknatıslı senkron motor (PMSM) ile bir Simulink ortamında test etmek için NFLC-PID blok diyagramı oluşturulmuştur. NFLC-PID, NFLC'nin sağladığı kesin olmayan verileri de dikkate alarak daha doğru bir geri bildirim yapar. Böylece, sistemin kontrol performansı daha da geliştirilmiştir. Simülasyon sonuçları, NFLC-PID'in PMSM'yi verimli ve başarılı bir şekilde yönettiğini göstermektedir.

**Anahtar kelimeler:** Sabit mıknatıslı senkron motor, Bulanık mantık denetleyicisi, Nütrosifik bulanık mantık denetleyicisi

Numerous studies have found that the kind of membership and different locations have an effect on the results of the control process [7, 8]. In particular, in [9], an FLC-based PI controller has been proposed and successfully applied to the speed control of a PMSM.

Neutrosophy has been suggested by Smarandache [10]. It is an advanced use of fuzzy logic. In addition to being a fuzzy logic declaration of membership, it describes the ambiguity and falsity of information obtained by various observers, either by insufficient information or accumulation errors, or by a lack of borders. In order to portray an event in neutrosophy, three MFs are used: truth ( $\tau$ ), uncertainty ( $\beta$ ), and falsehood ( $\varphi$ ). According to neutrosophic set theory, if an element  $x$  from the set  $A$  is given, this is expressed by the formula  $A(x) = \langle \tau, \beta, \varphi \rangle$ . There are no restrictions on  $\tau, \beta$ , or  $\varphi$ . When data are combined from several sensors in multiple applications, the neutrosophic cluster is essential for usability and consistency. For a better classification process, an innovative classification process is proposed by creating an optimal rule in the neutrosophic cluster in [11]. A study was conducted on parking airplanes without human intervention

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by taking the membership values of the FLC as a neutrophic number in [12]. Studies have been conducted in the literature on the use of neutrophic logic in control applications [13,14].

PID controllers, or variations of such acronyms (P, PI, and PD), are frequently used in automatic controls and industrial uses because they provide advantages including simple construction and durability [15]. The error  $K_p$  (proportional), the total system error  $K_i$  (integral), and the  $K_d$  (differential) coefficients are multiplied by the variance of the error per unit of time. As a result, the PID controller's control signal is obtained. Despite having a very straightforward design process, the typical PID controller does not produce the greatest results when it comes to regulating unstable systems and resonant structural vibration systems [16]. The PID controller's integral time constant and continuous proportional gain make them sensitive to changes in parameters, load disturbances, and speed. In the literature, researchers have combined traditional PID and fuzzy set theory (fuzzy-PID) to achieve greater efficiency in control results [17].

A permanent magnet provides the field excitation in permanent magnet synchronous motors (PMSM), an AC synchronous motor. Due to their advantages including high efficiency, high power factor, high power density, and maintenance-free operation, PMSM are favoured in a number of applications. The power density is greater than that of induction motors with the same values because there is no stator power used to generate the magnetic field. A digitally controlled inverter is necessary for operation of a PMSM with permanent magnets in order to generate torque at zero speed. High-performance motor control is indicated by a motor that spins smoothly over its whole speed range, has full torque control at zero speed, and accelerates and decelerates quickly. The motor controller ensures that the motor characteristics match the characteristics of the load. The vector based PID control design is widely used in AC electric motor drives and is easy to implement. This conventional PID controller is generally preferred for PMSM control [18].

PMSM systems are constantly subject to various degradation in industrial applications. These distortions may be PMSM's parameter uncertainties and other non-linear factors, as well as external charge decays [19]. As long as the conditions don't change, the PI controller system can achieve good speed performance [20]. However, linear control methods, such as the PID control method, are unable to provide the PMSM control system with sufficiently high performance due to the nonlinearity of the PMSM's dynamic characteristics, parameter uncertainties, and load distortions [21]. Speed monitoring performance can be dangerous in the use of PID controllers as parameter variations and load distortions are common in PMSM drives. Therefore, more complex control methods are required since PMSM has nonlinear mathematical dynamics and the parameters change over time, as well as systems with distortions such as unmeasurable load torque. A sensorless speed-controlled PV system powered PMSM driver system based on fuzzy logic controller is reported in

one of the studies on topic [22]. In another study [23], a speed control system of brushless direct current motor (BLDC) based on neutrosophic logic is carried out. Vector based control called as field-oriented control (FOC) is used to control speed of BLDC in this study [23]. V/f control, vector control, and direct torque control are the most often employed control strategies for PMSMs. The V/f control method proposed in this study does not require vector control or direct torque control, which both include complicated algorithms that require more work to compute and have worse accuracy for PMSM. This is a crucial practical benefit of the suggested plan. In comparison to vector control with nearly identical steady-state performance, V/f control is incredibly straightforward and offers a number of significant advantages.

In this research, closed loop V/f speed control of surface-mounted permanent magnet synchronous motor (PMSM) based on neutrosophic valued PID controller is carried out. Hence, an innovative design has been obtained by adding neutrophic MFs to the traditional PID system for speed control of PMSM. The neutrophic MFs  $\tau, \beta, \varphi$  are utilized for fuzzy inference systems (FIS), which we take at specific intervals for blurring reasons. This is different from the standard fuzzy logic design. Therefore,  $\tau, \beta, \varphi$  MFs are situated at various positions (by grouping). A more thorough investigation of the issue is provided by the examination of  $e$  and  $ce$  in two FISs utilizing neutrosophic MFs. Because grouping the antecedent factors using  $\tau, \beta, \varphi$  MFs and evaluating "e" and "ce" individually results in a more effective regional control. In this design, the two FIS outputs are summed after multiplying with the  $K_p, K_i$  and  $K_d$  coefficients and the NFLC structure is obtained.

When it comes to stability and robustness, NFLC outperforms classical PID control. Due to this, two comparisons between NFLC and traditional PID control were made in this work. Also, when combined with the NFLC, the PID controller provides a more accurate feedback, taking into account the imprecise data provided by the NFLC. Thus, the control performance of the system is further improved. When NFLC and PID controller are combined, they have advantages such as providing more precise control by taking into account imprecise data, managing range values and variable speeds, easily controlling multiple inputs and outputs, increasing product quality and reducing costs by providing faster and more accurate control. Since it does not require expertise in a specific field, it can be used in many different application areas. In addition, it also has disadvantages such as being a complex control system and responding slower than other control systems.

There are six sections in this article. General explanations have been made in the first part of the study to make it easier to understand. A brief introduction to neutrosophic clusters and neutrosophic logic is given in the second chapter. In the third chapter, a mathematical model of PMSM is given. NFLC is introduced in the fourth chapter. In the fifth chapter, two applications have been carried out in Matlab / Simulink for speed control of PMSM and the projected NFLC and PID have been contrasted.

Finally, a discussion of the simulation's findings is presented.

## 2 Neutrosophic logic and neutrosophic set

Neutrosophy offers a new concept called representing uncertainty and it can resolve a few issues that fuzzy logic cannot [24]. For instance, two referees receive an article to review and both of them determine the acceptance of the article as 90%. The two referees can, however, come from different backgrounds. Let one of them be an authority in this field, and the other a novice. Although they have the same acceptance rate, the effects of the two reviewers on the final decision of the article must be different. Similar issues that fuzzy logic struggles with include forecasting weather under ambiguous conditions, predicting stock prices, and making political decisions.

In comparison to other theories, neutrosophy is closer to the human mind because it captures the ambiguity of the information or linguistic error it receives from many observers. Uncertainty may result from inaccurate data collection, randomness, or inadequate information [25]. Here are a few characteristics of neutrosophic sets.

- A universal set is  $X$  and a component of  $X$  is  $x$ . A neutrosophic subset of  $X$  is  $A$ . The functions for subset  $A$  are listed here:  $\varphi_A(x)$ ,  $\beta_A(x)$  and  $\tau_A(x)$  are falsity, indeterminacy, and truth membership function, respectively.  $\tau_A(x)$ ,  $\beta_A(x)$  and  $\varphi_A(x)$  functions are subsets of  $]0^-, 1^+[$  [26]. There is no restriction on the sum of  $\tau_A(x)$ ,  $\beta_A(x)$  and  $\varphi_A(x)$ , and  $0^- \leq \sup \tau_A(x) + \sup \beta_A(x) + \sup \varphi_A(x) \leq 3^+$ .

- One-valued neutrosophic set (SVNS) in  $X$  is  $A$  ( $A = \{ \langle x, \tau_A(x), \beta_A(x), \varphi_A(x) \rangle : x \in X \}$ ) [26].

$$\tau_A(x), \beta_A(x), \varphi_A(x): X \rightarrow [0,1], \text{ and} \\ 0 \leq \tau_A(x) + \beta_A(x) + \varphi_A(x) \leq 3 \text{ for all } x \in X.$$

- $A$  and  $B$  are SVNS and can be written as  $A = B$ , if and only if  $A \subseteq B$  and  $B \subseteq A$  [25].

- $A, B$ , and  $C$  are neutrosophic sets and for all  $x \in X$  [27]. The equations for these sets are as follows.

$$\begin{aligned} \tau_A(x) \cap \tau_B(x) &= \tau_C(x) = \min(\tau_A(x), \tau_B(x)), \\ \beta_A(x) \cap \beta_B(x) &= \beta_C(x) = \min(\beta_A(x), \beta_B(x)), \\ \nu_A(x) \cap \nu_B(x) &= \nu_C(x) = \max(\tau_A(x), \tau_B(x)), \\ \tau_A(x) \cup \tau_B(x) &= \tau_C(x) = \max(\tau_A(x), \tau_B(x)), \\ \beta_A(x) \cup \beta_B(x) &= \beta_C(x) = \max(\beta_A(x), \beta_B(x)), \\ \nu_A(x) \cup \nu_B(x) &= \nu_C(x) = \min(\tau_A(x), \tau_B(x)). \end{aligned}$$

## 3 Mathematical modelling of PMSM motor

To analyze and control a PMSM, it is first necessary to know its mathematical model. The stator structures of the PMSM and conventional wound rotor synchronous motor (SM) are comparable. The opposing electromotive force (EMF) generated by permanent magnets (PM) and the opposite EMF generated by an excited coil are identical. As

a result, the PMSM's mathematical model is comparable to that of the traditional rotor-wound SM.

The electrical and mechanical equivalent circuit of an 8-pole, 3-phase PMSM is shown in Figure 1. An equivalent electrical circuit is shown on the left and a mechanical section connected to a load on the right. Permanent magnets are placed in the rotor of the PMSM. In synchronous motors, the energy conversion process is performed by generating an electromagnetic torque by the interaction of a magnetic field generated in the motor air gap and changing over time with the permanent magnetic field generated by permanent magnets placed on the rotor [28].

To achieve a desired operating speed, the 3-phase stator voltages must vary as a function of the rotor position ( $\theta_r$ ). The synchronous motor's angular velocity ( $\omega_r$ ) is frequency-dependent and depends on the voltage provided to the stator windings [28]. In the traditional PMSM, the motor operates at synchronous speed by changing the working speed dynamics with the frequency control of the 3-phase source voltage.

In order to be able to compare the experimental results with the simulation method and to determine the points obtained in the simulation, a simulation study was performed for the system used in the application. The magnetic synchronous motor mathematical model was developed with this objective in mind. The following equations, which form the mathematical model in the  $a, b, c$  phase system of a magnetic synchronous motor, can be obtained.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} \lambda_{ma} \\ \lambda_{mb} \\ \lambda_{mc} \end{bmatrix} \quad (1)$$

where  $V_a, V_b, V_c$  are phase-neutral voltages,  $\lambda_{ma}, \lambda_{mb}, \lambda_{mc}$  are the permanent magnet fluxes linking the stator windings,  $R_s$  is stator winding resistance.

$$T_e = p \left\{ \frac{1}{2} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}^T \begin{bmatrix} \frac{\partial L_{aa}}{\partial \theta_r} & \frac{\partial L_{ab}}{\partial \theta_r} & \frac{\partial L_{ac}}{\partial \theta_r} \\ \frac{\partial L_{ba}}{\partial \theta_r} & \frac{\partial L_{bb}}{\partial \theta_r} & \frac{\partial L_{bc}}{\partial \theta_r} \\ \frac{\partial L_{ca}}{\partial \theta_r} & \frac{\partial L_{cb}}{\partial \theta_r} & \frac{\partial L_{cc}}{\partial \theta_r} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}^T \begin{bmatrix} \frac{\partial \lambda_{ma}}{\partial \theta_r} \\ \frac{\partial \lambda_{mb}}{\partial \theta_r} \\ \frac{\partial \lambda_{mc}}{\partial \theta_r} \end{bmatrix} \right\} \quad (2)$$

can be represented as in mechanical equations that contain the machine's mechanical magnitudes. The rotor speed can be obtained from the mechanical equation as follows:

$$T_e - T_y = \frac{d\omega_r}{dt} \frac{J}{p} \quad (3)$$

where  $\omega_r$  is rotor angular velocity (rad/s),  $J$  is reduced moment of inertia to the shaft of the machine,  $p$  is the quantity of pole pairs,  $T_y$  is load torque. In this manner, the aforementioned equations yield the machine's model.

In this manner, the aforementioned equations produce the machine's model.

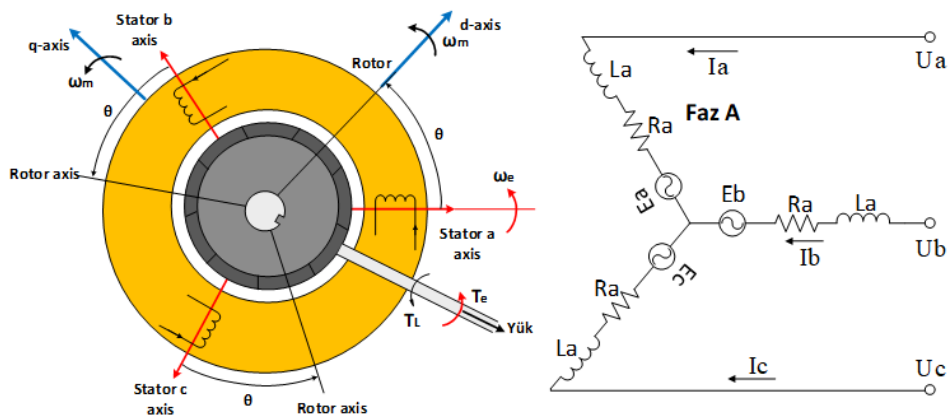


Figure 1. Electrical and mechanical equivalent circuit of PMSM

#### 4 PID controller and fuzzy logic controller

All control systems work to achieve the intended state by keeping an eye on the system's variables. If the system output value deviates from the desired value, the controller's job is to take remedial action. The system's reference value and measured output value are both determined by the controller input data. The controller processes the input data and gives the system the desired output. The benefits of proportional, integral, and derivative control are all combined in a single controller known as PID control. An key issue is how to set the PID controller's parameters in the control area. The parts that makeup PID controllers are managed with a parameter. These parameters ( $K_p, K_i, K_d$ ) take different values for each system. The internal structure of the PID controller is depicted in a block diagram in Figure 2. The PID controller's construction can be seen as a combination of proportional gain, integrator, and derivative circuits in the block diagram.

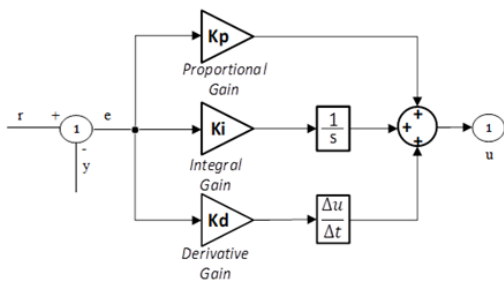


Figure 2. Structure of PID

Here is a time-domain representation of the control signal for a PID controller, as given by Equation (4).

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{d}{dt} e(t) \quad (4)$$

Equation (4) and (5) each specify the reference signal, error signal, control signal, and output signal, using the symbols  $r(t), e(t), u(t)$  and  $y(t)$ , respectively.

$$e(t) = r(t) - y(t) \quad (5)$$

PID control; It is an audit that combines the advantages of three basic control effects into a single unit. Proportional control ( $K_p$ ) increases overshoot but lowers steady-state error and rising time. Integral control ( $K_i$ ) corrects the system's steady-state error but worsens the transient response. In other words, Integral control increases overrun and settling time but decrease rise time. Differential control ( $K_d$ ) reduces the system settling time and system overshoot.

Another common form of control is FLC. Four units make up FLC. As seen in the Basic FLC in Figure 3, these include defuzzification, fuzzy inference, rule basis, and fuzzification. The task of the fuzzification is to convert the exact input values received from the input into fuzzy values. In this fuzzification; Measuring input variables in real-time, scaling with operations such as multiplying or dividing input variables by a fixed number, converting the selected linguistic space to discrete, converting each of the real input variables measured into linguistic variables according to the discourse space of that variable and finding their membership values such transactions are carried out [29]. The control rules pertaining to the system to be controlled are contained in the rule base. In FLC, as "if 'status' then 'result'" a rule base is created. This established rule base contains fuzzy expressions rather than definitive statements. If input is "Yes" then output "No" is a classical approach. However, rules in the fuzzy approach; It is laid out "if input is 'low' then output is 'medium'; if input is 'medium' then output is 'less'; if entry is 'too' then output is 'too low' ..." in the form. Thus, using imprecise linguistic information such as "less", "much", "medium" ... enables the control system to think like a human [30]. In fuzzy logic, curves are called membership functions to show the membership degrees in the set to which an element belongs. Each component of the fuzzy set has a defined degree of membership. There are many shapes used as membership functions such as triangle, trapezoid, gaussian, bell curve, s, z, pi, sigmoid, cauchy, trapeze. Among them, triangle, trapezoid, and gaussian are the three most commonly used membership functions [31]. Typically, FLC input variables include errors and error modification. Figure 3 displays a traditional FLC block diagram.



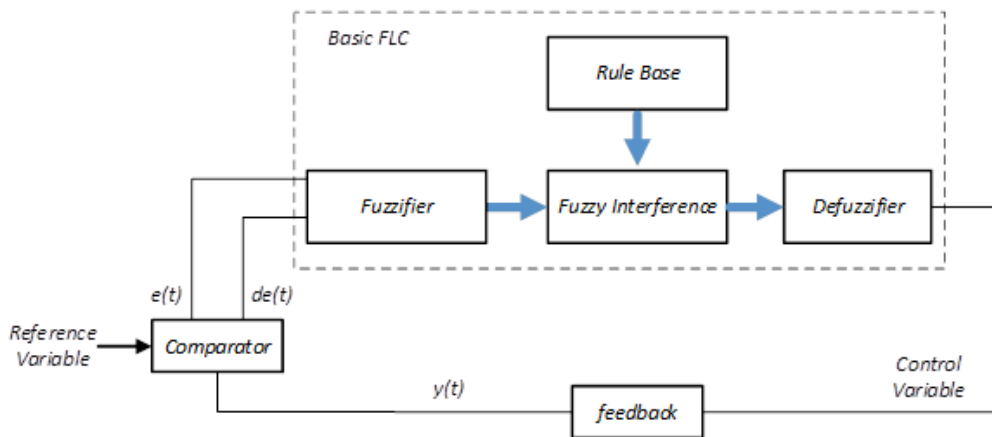


Figure 3. Classical FLC block diagram

Using fuzzy operators and the rule base, the FLC response is obtained during the fuzzy inference stage. The FLC response transforms into a control signal that is applicable to the system to be controlled during the blur phase.

The decision-making unit is the unit that processes the fuzzy data applied from the entrance and passing through the fuzzing unit using the rule base and database in the knowledge base and presents the obtained fuzzy data to the defuzzification unit. In the process, first of all, the data received with the help of the database are determined to which clusters they belong. Then, the relevant rules are selected from the rule base and inferences are made. Then, again with the help of the database, the results obtained as a result of the rules are determined to what extent they belong to which clusters, and fuzzy data are obtained and presented to the defuzzification unit. Various methods are used for this functioning in the decision-making unit. Mamdani, Larsen,

and Takagi Sugeno-Kang (TSK) can be given as examples of these methods. In this study, the Mamdani method was preferred. The final stage of the fuzzy logic controller, the defuzzification unit, is used in methods such as Mamdani and Larsen methods, where the result values are obtained as a fuzzy set.

### 5 Fuzzy logic controller with neurosophic valuation

Although fuzzy logic contains ambiguity, it does not explicitly convey uncertainty. The classic fuzzy set theory does not provide the level of detail that the neurosophic set method does. The approach we provide was developed through evaluation using a neurosophic cluster approach and fuzzy-PID control. Neurosophic MFs are employed to provide a more thorough error assessment by analyzing 'e' and 'ce' in two separate FISs.

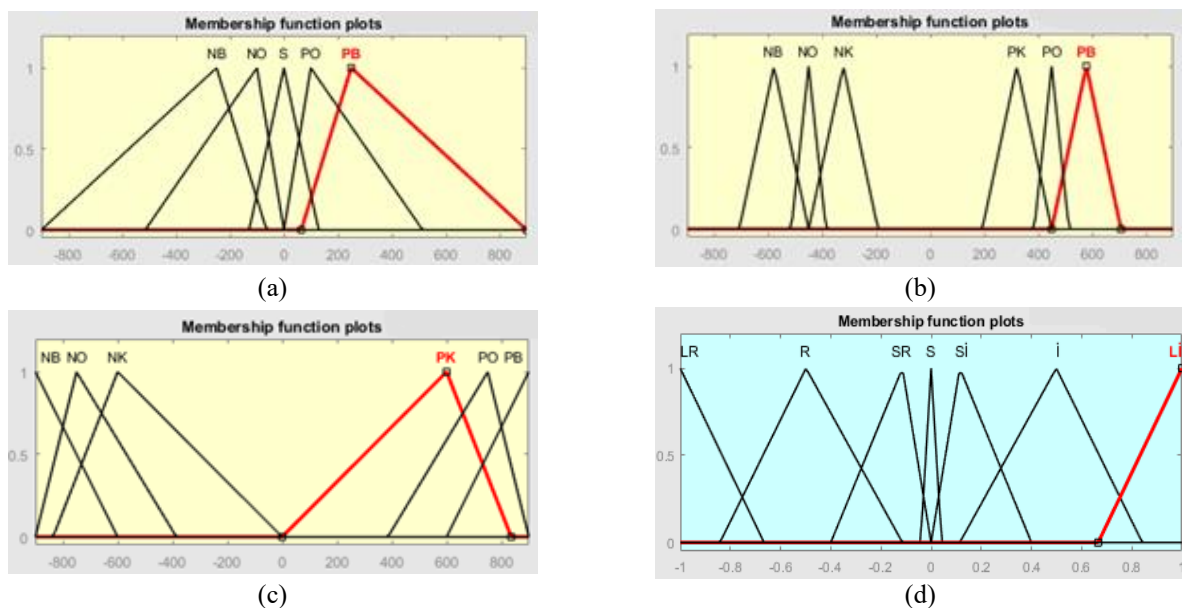
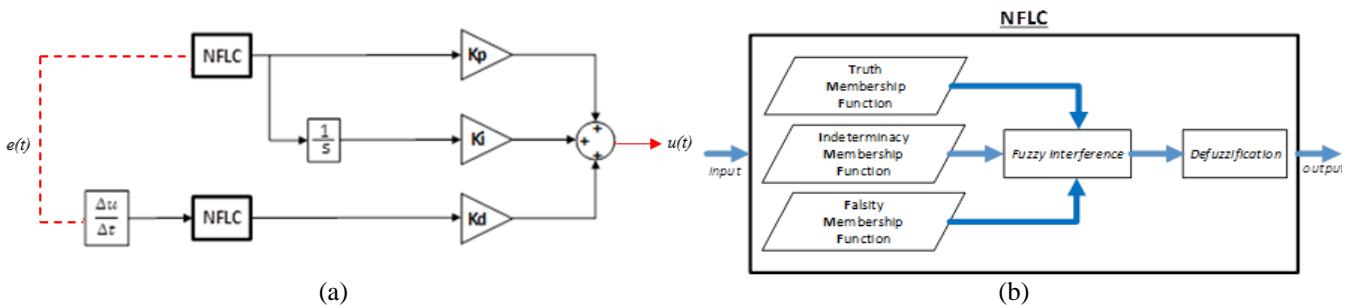


Figure 4. The input and output MFs used in the NFLC units for 'e' and 'ce'. (a)  $\tau$  MF, (b)  $\beta$  MF, (c)  $\varphi$  MF, (d) output MFs

**Table 1.** Used rules in NFLC units

1. If ( $e_\tau$ is Z) or ( $e_\varphi$ is PS) then ( $u$ is Z)	11. If ( $e_\tau$ is PB) or ( $e_\beta$ is PB) or ( $e_\varphi$ is PM) then ( $u$ is PM)
2. If ( $e_\tau$ is Z) or ( $e_\varphi$ is NS) then ( $u$ is Z)	12. If ( $e_\tau$ is NB) or ( $e_\beta$ is NB) or ( $e_\varphi$ is NM) then ( $u$ is NM)
3. If ( $e_\tau$ is PM) or ( $e_\varphi$ is PS) then ( $u$ is PS)	13. If ( $e_\tau$ is PB) or ( $e_\beta$ is PB) or ( $e_\varphi$ is PM) then ( $u$ is PM)
4. If ( $e_\tau$ is NM) or ( $e_\varphi$ is NS) then ( $u$ is NS)	14. If ( $e_\tau$ is NB) or ( $e_\beta$ is NB) or ( $e_\varphi$ is NM) then ( $u$ is NM)
5. If ( $e_\tau$ is PM) or ( $e_\beta$ is PS) or ( $e_\varphi$ is PS) then ( $u$ is PS)	15. If ( $e_\tau$ is PB) or ( $e_\varphi$ is PM) then ( $u$ is PB)
6. If ( $e_\tau e_\mu$ is PM) or ( $e_\beta$ is NS) or ( $e_\varphi$ is NS) then ( $u$ is NS)	16. If ( $e_\tau$ is NB) or ( $e_\varphi$ is NM) then ( $u$ is NB)
7. If ( $e_\tau$ is PB) or ( $e_\beta$ is PS) or ( $e_\varphi$ is PS) then ( $u$ is PS)	17. If ( $e_\tau$ is PB) or ( $e_\varphi$ is PB) then ( $u$ is PB)
8. If ( $e_\tau$ is NB) or ( $e_\beta$ is NS) or ( $e_\varphi$ is NS) then ( $u$ is NS)	18. If ( $e_\tau$ is NB) or ( $e_\varphi$ is NB) then ( $u$ is NB)
9. If ( $e_\tau$ is PB) or ( $e_\beta$ is PM) or ( $e_\varphi$ is PS) then ( $u$ is PM)	19. If ( $e_\varphi$ is PB) then ( $u$ is PB)
10. If ( $e_\tau$ is NB) or ( $e_\beta$ is NM) or ( $e_\varphi$ is NS) then ( $u$ is NM)	20. If ( $e_\varphi$ is NB) then ( $u$ is NB)



**Figure 5.** Block diagram of the NFLC (a) and representation of the NFLC's internal structure (b)

In Figure 4, the positioning and variation in density of  $\tau, \beta, \varphi$  MFs is depicted. Also, in Figure 4 the expressions NB, NM, NS, Z, PS, PM and PB, respectively, are “negative large”, “negative medium”, “negative small”, “zero”, “positive small”, “positive medium”, and “positive big”. Also, the terms LR, R, SR, S, Sİ, İ, Lİ represent the linguistic expressions “reduce a lot”, “reduce”, “reduce a little”, “zero”, “increase a little”, “increase” and “increase a lot”, respectively, in Figure 4d. Table 1 displays the rule base used in the FLC unit. Here  $e_\varphi, e_\beta$  and  $e_\tau$  represent values of false, uncertainty, and accuracy membership, respectively.

Error and alterations error were taken into account in two different fuzzy inference units in the NFLC technique. Figure 5 displays the suggested method's controller block diagram.

Figure 5's block diagram serves as a general representation of the NFLC technique. Figure 6 shows how the Simulink block was used by the NFLC approach in the study. The parameters of the PMSM used are presented in Table 2.

System responses showing the performance of the NFLC are given below. Figure 7 displays the electromagnetic torque and speed response for the NFLC

model created in Matlab for PMSM. The speeds reach the desired value of 1500 rpm in 5ms.

**Table 2.** Parameters of the motor used

Engine parameters	Values
Resistance ( $R_s$ )	0.7 $\Omega$
Inductance ( $L$ )	2.72e-3 H
Back EMF flat area	120 degrees
Torque constant	0.84 Nm/A <sub>peak</sub>
Voltage constant	87.9646 (V <sub>peak</sub> L-L/krpm)
Flux linkage	0.105 Vs
Inertia ( $J$ )	0.8e-3 kgm <sup>2</sup>
Number of poles ( $p$ )	4
Viscous damping	1e-3 Nms

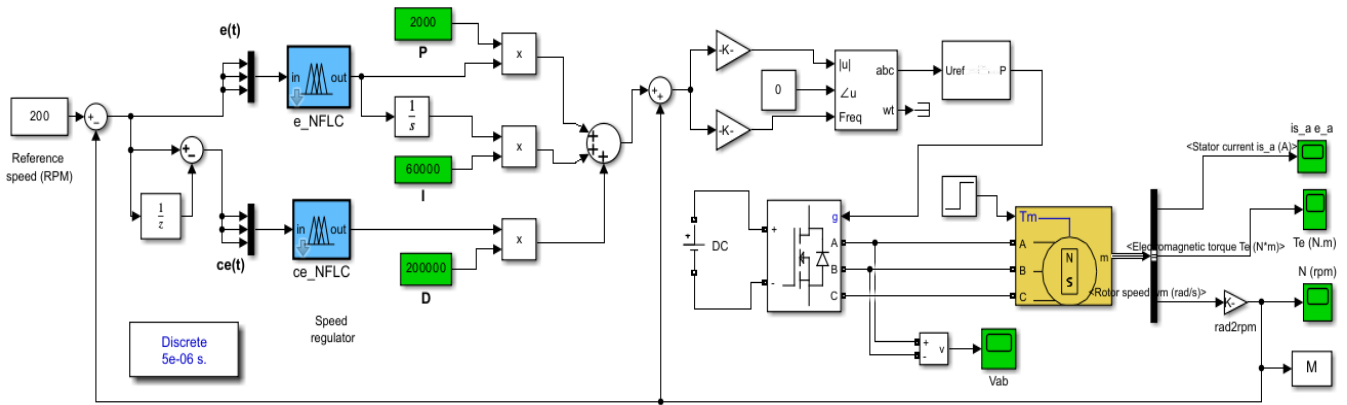
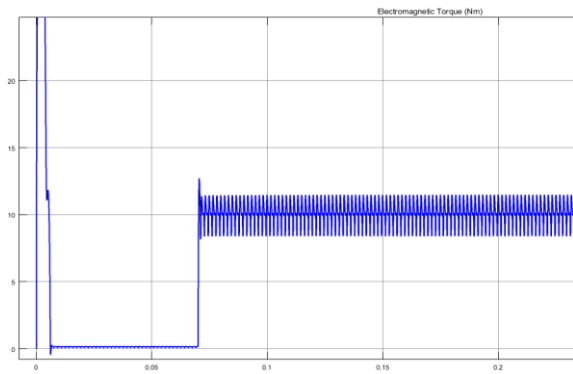
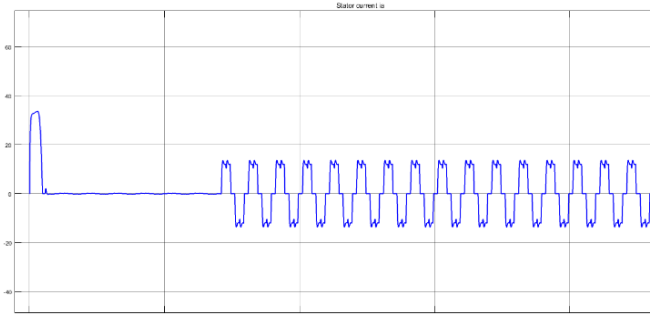


Figure 6. Application of the NFLC approach in the Simulink block study

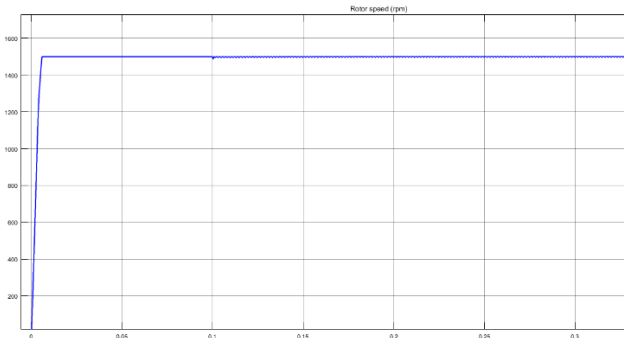


(a)

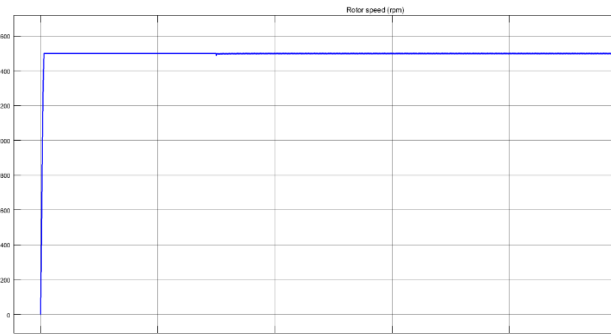


(b)

Figure 7. (a) Elektromagnetic torque, (b) stator current  $i_a$



(a)



(b)

Figure 8. Speeds response for NFLC on load change a) at 0.1 seconds, b) at 0.3 seconds

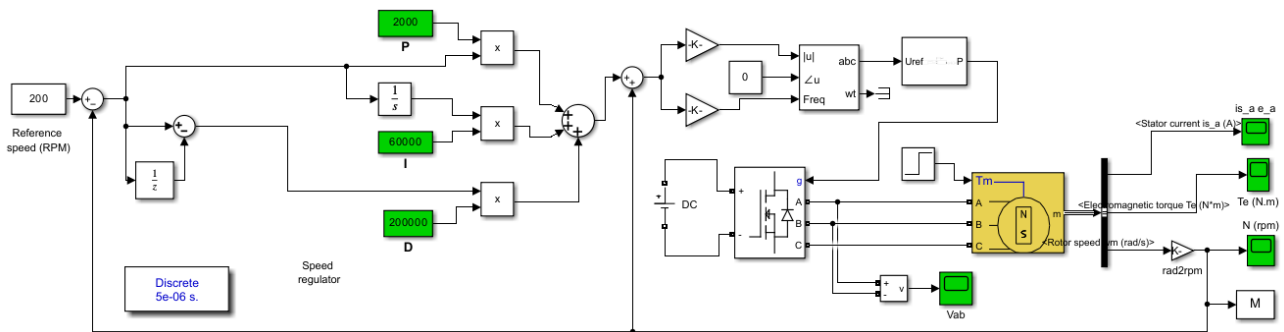
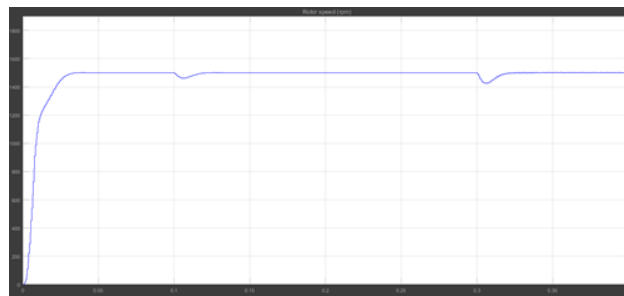
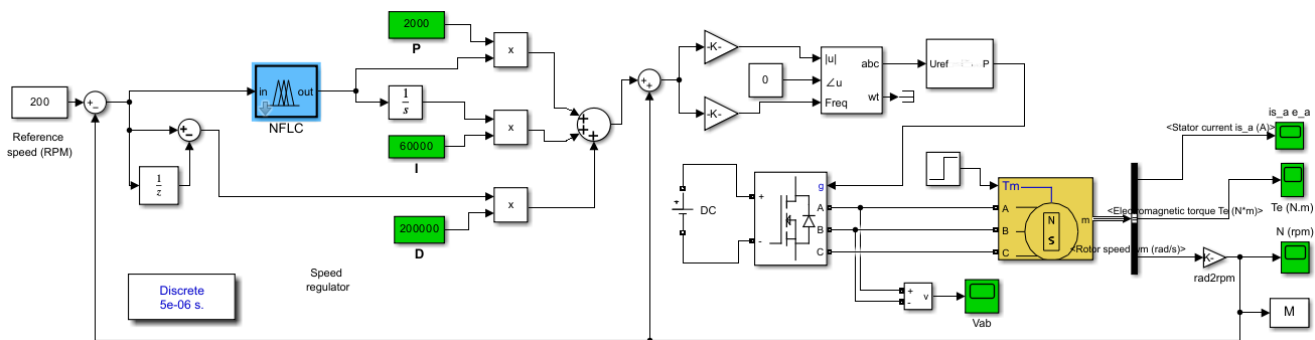


Figure 9. Simulink block used in the PID technique application



**Figure 10.** Speeds response for conventional PID on load change at 0,1 and 0,3 seconds



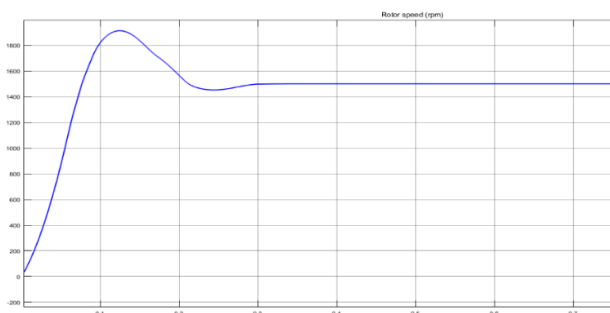
**Figure 11.** Simulink block used in the FLC technique application

Figure 8 demonstrates the speed response for NFLC on load change at 0.1 and 0.3 seconds that PMSM manages to set back to 1500 rpm successfully when the load torque changes occur either load increase and decrease.

For PID applied to PMSM, the Simulink block is given in Figure 9. Also, Figure 10 shows the speed response of the PMSM for the PID at load change at 0.1 and 0.3 seconds, rather than setting the speed to 1500 rpm when the load increase or decrease in load torque changes occur.

Comparing Figures 8 and 10, it can be shown that NFLC performs better than conventional PID control, notably in terms of stability and robustness.

The Simulink block for FLC applied to PMSM is given in Figure 9. Also, it is seen that at 0.1 load condition, the NFLC system reaches the reference speed with less oscillation than the fuzzy logic control system (Fig. 12).



**Figure 12.** Speeds response for FLC on load change at 0.1

## 6 Results

The FLC method we suggest in this study is based on the neutrosophic membership function. Neutrosophic valued fuzzy logic control (NFLC) method was tested for control of the speed of a PMSM. The simulation findings demonstrate that neutrosophic fuzzy logic has effectively and successfully controlled PMSM, indicating that the proposed method may be applied to applications involving PMSM speed control. When NFLC and PID, which are both utilized in V/f control and the FOC method, are put side by side, NFLC performs better in the V/f control method.

### Conflicts of Interest

No conflict of interest was declared by the authors.

**Similarity rate (iThenticate):** % 18

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