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Research Article

BLDC Motor speed control with dynamic adjustment of PID coefficients: Comparison of fuzzy and classic PID

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ABSTRACT

Brushless DC (BLDC) motors, which have small volumes, are widely used in many areas from the aviation industry to industrial applications due to their high efficiency and torque. In parallel with the development of technology, the field of use continues to expand with the development of BLDC engine (BLDCM) control strategies and the decrease in control costs. In this thesis study, it is aimed to minimize the observed changes in rotor speed compared to the reference speed. To achieve this, PID parameters were tried to be changed simultaneously with fuzzy control techniques, taking the error value as a reference. The control system of the BLDC engine was designed in the MATLAB/Simulink environment. In the simulation, the operating stability of classical PID and PID with updated fuzzy-based parameters on two engines with the same features was compared at different speeds. As a result of the research, it was concluded that the correction of the speed observed in the rotor of the PID-controlled motor, whose fuzzy logic-based coefficients were updated, based on the reference speed was more stable and the percentage of exceedance for the reference value was lower, compared to the classical PID controlled motor.

1. Introduction

Electric motors have been one of the indispensable equipment of modern society from the 19th century to the present. Different practical applications made to date have led to various electric motor designs to meet the needs. Until the end of the 20th century, classical DC motors with high torque and efficiency were widely used in applications with variable speed and torque requirements. However, in these classical DC motors, where commutation is provided mechanically, some difficulties such as noise, wear, arc formation and maintenance requirements arising from the pressure of the brushes on the collector slices have negatively affected the use of classical DC motors. In applications where these drawbacks are not desired, classical DC motors have been replaced by different brushless motor designs [1].

The definition of the working principle of the brushless direct current (BLDC) motor, one of these designs, was introduced into the literature with the patent "Thyristor commutator circuit used to replace mechanical commutation" by Harrison and Rye in 1955 [2].

There is a permanent magnet in the rotor of the BLDC motor and coil groups in the stator. The coil groups located on the stator are energized with direct current according to the rotor position. Therefore, it is very important to know the rotor position of the BLDC motor. Rotor position can be determined with sensor control techniques as well as sensorless control techniques. Rotor position information is sent to the microcontroller. The microcontroller decides which of the stator winding groups should be energized and sends the relevant data to the driver circuit. This situation repeats throughout the operation of the BLDC motor. In this way, the BLDC motor continues to operate properly.

Brushless direct current motors (BLDCM) have continued to develop due to the impact of semiconductor

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technology in the electronics sector and new magnetic materials that have begun to be used. So much so that, thanks to the Hall sensors that began to be used in BLDC motors after the 1970s and the new permanent magnet materials discovered, numerous studies have been carried out on these motors. In addition, thanks to the developments in computer technology in the late 1990s, BLDC motor driver systems began to be used with computerized control techniques. Computer-controlled BLDC motor drive systems: It has enabled the development of different control strategies such as minimization of torque fluctuations, dynamic and constant speed response. Control techniques and theories in the literature continue to enrich with each new study conducted on computerized control techniques [3].

The fact that BLDC motors do not have a rotor winding reduces the diameter of the rotor, and thanks to the presence of the winding in the stator, the heat generated by the applied current is easily discharged to the external environment. The absence of collector sections also increases the operating speed range of the motor by eliminating dangerous voltage values that may occur between motor sections at high speeds. Mechanical losses due to the absence of brushes are reduced and arc formation is eliminated. BLDC motors have found use in many areas due to their smooth speed control.

Since there are no brushes in BLDC motors, commutation is carried out with an electronic driver card. For this reason, engine noise has decreased and the need for maintenance has been eliminated. BLDC motors have high torque and efficiency. Because they are long-lasting and precisely controlled; BLDC motors are used in many areas such as home appliances, the defense industry, robotic systems, aircraft, land and sea vehicles [4].

Fuzzy system: They are microcontroller-based artificial intelligence structures that reason in a way that simulates humanistic behaviors and the functioning of nature. Fuzzy control: They are systems used to solve problems in fuzzy structures and provide economic gains such as labor as well as time and energy in applications [5].

In the system simulated in the Matlab/Simulink environment, the use of sensorless control techniques is also preferred to eliminate the disadvantages caused by the cost and extra mechanisms caused by the position of the rotor sensors and components. When using sensorless control techniques, zero points detected by the Back EMF signal are generally used due to their practicality in applications.

In this article, PID with updated fuzzy-based parameters and classical PID system outputs were obtained in the MATLAB/Simulink environment. The outputs were compared with each other in 5 steps between 1000 rpm and 3000 rpm and the maximum overshoot percentage for variable speed regimes, considering settling time and steady-state errors.

2. Brushless DC Motors (BLDCM)

To ensure the operation of FDA motors, rotor commutation must be ensured properly. In sensor-based control techniques, rotor position information is obtained directly from sensors to ensure commutation, while in sensorless control techniques, the rotor must exceed a certain speed to ensure commutation. Because the stator back-EMF can be obtained accurately when the rotor reaches a certain speed. In FDA motors, where the rotor position is determined without using a sensor, commutation is carried out blindly for the first moment of development (until the minimum speed is reached) [6, 7].

2.1. BLDCM Principle of Operation

BLDCM stator phase windings are fed by sequentially switching the power electronic switching elements with the phase voltage appropriate to the rotor position. This process is called commutation. DC-DC converter circuits are used to supply the phase windings with appropriate phase voltages. BLDC engine's general control structure is shown in Figure 1.

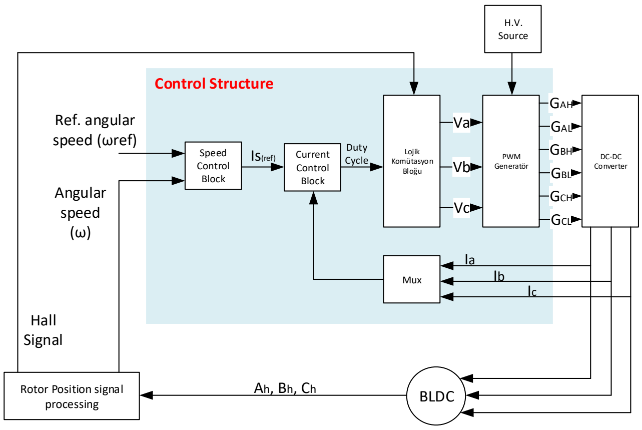

Figure 1. FDA engine general control structure

With rotor position sensor and sensorless control techniques, the rotor position signal is processed in the processing section and the rotor speed information is sent to the speed control block. At the same time, the Hall signal goes to the logic control block. The reference speed and current speed are compared by the speed block and the reference speed value is sent to the current control block. The current control block compares the current received from the converter with the reference current value and sends the duty cycle signal to the logic computation block. Appropriate voltage values for each phase are sent to the logic control block PWM generator. The BLDCM motor is driven by the converter block by sending the PWM generator high and low signal outputs for each phase.

The armature of the BLDC motor is a permanent magnet. Electronic commutation takes place in the armature. For this commutation (current direction change in a coil in the armature) to occur, shaft position information is needed. The position of the armature can be obtained with a sensor (Field Effect 'Hall Effect' or Optical

Sensor 'Encoder') or without a sensor (Back-Electromotor Force 'EMF'). Position data obtained with or without a sensor is compiled in the microcontroller. The microcontroller enables the motor to rotate by driving the switching elements used. Traditional brushless DC motors have 4 poles, but the torque of 8-pole BLDCMs produced in the same size is higher. The torque produced is increased by increasing the number of poles.

2.2. Dynamic Mathematical Model of BLDC Motor

The stator of the BLDC motor has three winding groups at 120^o angles relative to each other. There are permanent magnet groups in its rotor. Losses that may occur on the rotor, such as eddy losses, can be neglected due to the high resistance of magnet groups and stainless steel. Since BLDC motors are fed from a DC voltage source, the modeled equations of phase variables will be as follows [8].

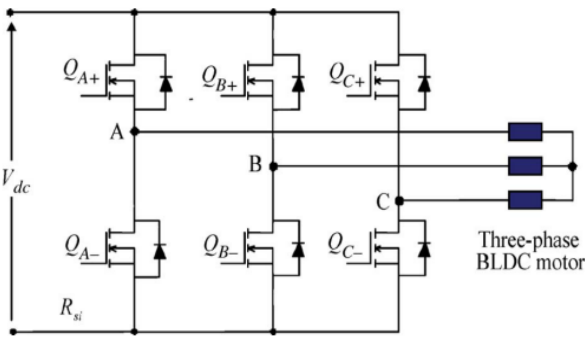

Figure 2. Typical inverter system for BLDCM [9]

Figure 2 shows the typical inverter circuit of a three-phase BLDC motor.

Other related equations to obtain the inverter system characteristic and mathematical model for a BLDC motor are taken from [8, 10].

The BLDC motor is connected to the output of the inverter as shown in figure 1. The inverter input cable connection end is connected to a constant voltage source. It is assumed that there is no power loss in the inverter and the motor winding is connected in star.

For a BLDC motor with three stator windings and a symmetrical and balanced supply system, the voltage equations of the modeled motor winding are expressed as follows [10];

$V_a, V_b\ ve\ V_c$ phase voltage of the motor,

$R_a, R_b\ ve\ R_c$ stator winding resistors,

$i_a, i_b\ ve\ i_c$ phase current of the motor,

$L_a, L_b\ ve\ L_c$ self-inductance of the motor winding,

$M_{ab}, M_{ac}, M_{ba}, M_{bc}, M_{ca}\ ve\ M_{cb}$ mutual inductances between stator windings,

$e_a, e_b\ ve\ e_c$ are back-EMF waveforms for each phase and are functions of the angular speed of the rotor shaft.

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + M_{ab}\frac{di_b}{dt} + M_{ac}\frac{di_c}{dt} + e_a \quad (1)$$

$$V_b = R_b i_b + L_b \frac{di_b}{dt} + M_{ba}\frac{di_a}{dt} + M_{bc}\frac{di_c}{dt} + e_b \quad (2)$$

$$V_c = R_c i_c + L_c \frac{di_c}{dt} + M_{ca}\frac{di_a}{dt} + M_{cb}\frac{di_b}{dt} + e_c \quad (3)$$

k_e, is the back-EMF constant.

$$e = k_e * \omega_m \quad (4)$$

Considering the above equation (1), (2) and (3), the mathematical model of BLDC motor in matrix form can be represented by the following equation,

$$\begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ba} & L_b & M_{bc} \\ M_{ca} & M_{cb} & L_c \end{bmatrix} \frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (5)$$

Generally, in today's BLDC motors, if it is assumed that the winding groups of the three-phase system are balanced, the resistance of each phase will be equal:

$$R_a = R_b = R_c = R$$

Since the BLDC motor has an external surface-mounted design and the stator self-inductances are independent of the rotor position, the stator self-inductances can be considered equal, therefore.

$$L_a = L_b = L_c = L$$

Since the stator self-inductances are considered equal, the mutual inductances can also be written equal.

$$M_{ab} = M_{ac} = M_{ba} = M_{bc} = M_{ca} = M_{cb} = M$$

Once the above assumptions are included, equation (5) can be rearranged.

$$\begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (6)$$

Electromechanical torque is expressed as:

J Moment of inertia of the motor,

B friction coefficient

ω_r angular speed

T_L load torque.

$$T_{em} = J\frac{d\omega_r}{dt} + B\omega_r + T_L \quad (7)$$

Electromagnetic torque of 3-phase BLDC motor; Since it depends on the current, speed and back-EMF waveforms, the instantaneous electromagnetic torque equation (7) can be modified and represented as:

$$T_{em} = \frac{1}{\omega_m}(e_a i_a + e_b i_b + e_c i_c) \quad (8)$$

3. Methods

BLDC motors are controlled by circuits created using basic power electronic components such as thyristors and MOSFETs. However, at this point, there are many control strategies studied in the literature to answer the question of which winding group will be energized and when. The purpose of the control strategies used is to control the engine to operate most efficiently in possible situations. The main purpose of such applications is to eliminate or minimize the error (difference between the reference value and the actual value) occurring in the closed-loop system. In the BLDCM engine, the operating cycle occurs in six steps:

1-Initial Status
2-Location determination
3-Clockwise rotation
4-Counterclockwise rotation

5-Speed control
6-Don't stop

3.1. Proportional Integral Derivative Control (PID)

Due to its structural simplicity, classical control methods are frequently used in BLDCM control. PI, PD and PID control systems used depending on the system needs are classical control methods. PID "Proportional Integral Derivative" control method is one of the most used classical control techniques in industrial applications due to its simple and fast response time. PID control consists of the combination of proportional-integral and derivative control methods [11-13].

There are parametric gain values that need to be adjusted for classical control systems to provide the expected performance from the BLDCM, which are listed as follows:

Kp: proportional gain
Ki: integral gain
Kd: derivative gain

Since these values used in classical control methods are obtained by trial and error, there are decreases in engine performance due to instantaneous changes in speed or load. [14, 15].

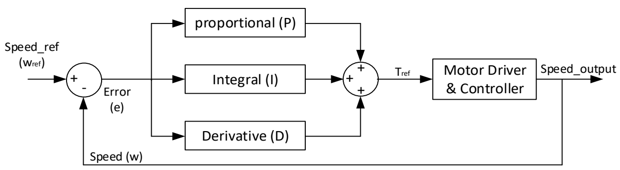

Figure 3. BLDCM PID Controller

Proportional Coefficient (Kp) increases the response speed required for the system and the reference-dependent regulation accuracy of the system. If the Kp value is taken large, the proportional coefficient may move the system above the expected reference value, causing the system to operate unstable. If the proportional coefficient is chosen too small, the expected response rate in case of error changes slows down and the regulation time (settlement time) is prolonged, reducing the regulation accuracy at the system output for the reference value taken. If the proportional coefficient decreases, the static and dynamic properties of the system deteriorate.

Integral Coefficient (Ki), Integral terms, ensures the elimination of constant distortions by reducing the steady-state error to zero in monitoring the targeted set point. By looking at the sum of error inputs, it regulates the output stability of the system in the long term. The proportional coefficient may not be able to correct regular errors that occur in the system. In this case, the steady state error is reduced by the Ki coefficient used. The Ki coefficient also reduces the instantaneous error values of the Kp coefficient, and the error values accumulated over time.

As a derivative term, it eliminates major errors that may be encountered in the future by estimating the possible error. The differential coefficient (Kd) is used to improve the dynamic properties of the system. It prevents the signal provided to the system from deviating in any direction by providing a response before the prediction error, which is the error value that may occur in the next process. A differential coefficient selected too high prolongs the relaxation process of the system output signal, prolongs the regulation time, and even reduces the system performance in preventing sudden increases in the output signal. The predictive advantage it brings increases the noise occurring at high frequencies.

The role of PID parameters in minimizing the stability of the system used, response speed, overshoot and steady-state errors is as follows.

PID is a control method performed by comparing data from sensors with reference data. The process steps can be listed as follows.

• The resulting error is multiplied by the proportional constant Kp.

• The error obtained is multiplied by the average of the errors obtained in the past period by the integral constant Ki.

• The rate of change of the error obtained is multiplied by the derivative constant Kd.

The multiplication results of Kp, Ki and Kd are collected and fed with "u".

$$Proportional\ constant = K_p e \qquad (1)$$

$$Integral\ constant = K_i \int_0^t e\, dt \qquad (2)$$

$$Derivative\ Constant = K_d \frac{d}{dt} e \qquad (3)$$

By summing the data obtained in (1), (2) and (3) above, the following equation (4) PID control equation is obtained.

$$u = K_p e + K_i \int_0^t e\, dt + K_d \frac{d}{dt} e \qquad (4)$$

Transfer function of PID control block.

$$\frac{T_{ref}}{e(t)} = K_p + \frac{K_i}{s} + K_d s$$

Table 1. General Effects of PID Gain Constants [16]

Earnings Type	Rising Time	Overshoot	Settling Time	SS Error
K_p	N	P	LP	N
Ki	LN	P	P	HP
K_d	LN	N	N	LP or LN

According to the data in the table, Kp; causes the rise and steady state error of the system to decrease (N), the overshoot time to increase (P), and the settling time to increase slightly (LP). Increasing Kp value; It causes a slight decrease in the rise time (LN), a high decrease in the steady-state error (HP), and an increase in the overshoot and settling times (P). Kd causes a gradual decrease in the rise time (LN), a decrease in the overshoot and settling times (N), and a small change in the steady-state error (LP or LN).

3.2. Fuzzy Tuned PID controller

Traditional methods are inadequate for applications requiring high precision. In this case, control techniques such as fuzzy logic, artificial neural networks, genetic algorithms and adaptive control are frequently used.

3.2.1. Fuzzy Logic Systems

It was suggested by Lotfi A. Zadeh in 1965 and started to be used on engines in 1974 when Ibrahim Mohammadan controlled the steam engine using fuzzy logic. Fuzzy logic systems are used in cases where it is difficult to create a mathematical model for classical control systems, where nonlinear systems are controlled based on human perception and experience. Today, BM-based applications are used in many areas from washing machines to elevator control [14].

Classical control methods are inadequate in cases where alternative output values are not clear depending on the system input value. Problems with positive results where intuition and experience are at the forefront, with answers that may vary from person to person due to the individual's experience and preferences, are essentially fuzzy problems. In such applications, decision theory is used to obtain system output.

Decision theory = Probability theory + Utiliy theory

The main differences between Classical and Fuzzy Logic theories are shown as follows: [17].

Table 2. Differences Between Classical and Fuzzy Logic [17]

Classical Lojic	Fuzzy Lojic
A or not A	A and not A
Definite	Partial
All or Nothing	to some extent
0 or 1	continuity between 0 and 1
Binary units	fuzzy units

3.2.2. Changing PID parameters with fuzzy

There are many techniques in the literature for Kp, Ki and Kd parameters used for PID. Ziegler-Nichols, Cohen-Coon, Chien-Hrones, Wang-Juang-Chan, Chien-Hrones-Reswick, Wang-Juang-Chan and ¼ decay rate optimization method are the main techniques used for PID parameters. It is preferred to use PI and PID controllers as controllers since it may create a steady state error for the system when only the P term is used. Although these techniques are guiding in obtaining appropriate setting values for PID, direct use of any of these methods can be harmful for some systems [18].

Although the proponents of the method above suggested optimization techniques for tuning PID coefficients, they could not guarantee that these methods were always effective. Therefore, the PID controller must change its current parameters autonomously to ensure stable operation of the system. There are studies in the literature that this need can be met by using an external controller or algorithm[19-24].

These generally used systems consist of real-time PID parameter regulation controllers and traditional PID. The PID regulation controller or algorithm selects the error (e) and the error rate of change (Δe) as system input parameters. It has been observed in the literature that the system input is assigned by using the ratio of these selected parameters (e) and (Δe) to the reference value [25].

Self-adjustment of the PID is provided with the Kp, Ki, and Kd values obtained as outputs of the system. The general figure used for PID change is given in Figure 4.

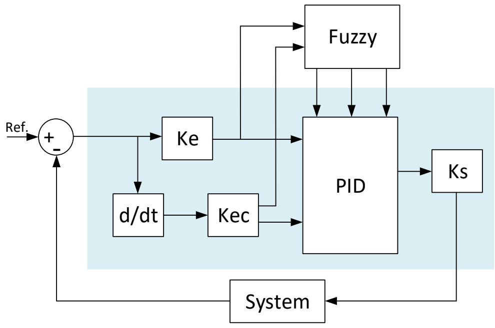

Figure 4. Changing PID parameters with fuzzy

4. Experimental Study

The BLDC motor was started using two different methods. Fuzzy speed data were compared with the classical PID controller and changing PID parameters under the same conditions for two motors with the same features.

4.1. BLDC Motor Speed Control with PID:

It is compared with the speed information entered as a reference and the angular speed information received from the motor in the PID block. The output signal is transferred to the logic commutation block. With the output received from the BLDCM hall sensor, the logic commutation block decides which switches will be triggered in the PWM generator block. The A-B-C phases of the BLDC motor are triggered appropriately with the voltage received from the PWM generator.

While the BLDC motor is controlled with PID, Ki = 2, Kp = 0.5 and Kd = 0.

4.2. BLDCM Speed Control with Fuzzy Tuning PID

The error difference is obtained from the speed information entered as a reference and the angular speed information received from the engine. Kp, Ki and Kd values were produced with Fuzzy algorithms using the obtained error value and the previous error value. PID was tuned with the Kp, Ki and Kd values found with these produced values. The input signal for PWM is generated with the PID output value. Thanks to the signal received from the PWM generator, the A-B-C phases of the BLDC motor were triggered appropriately with the switching elements used.

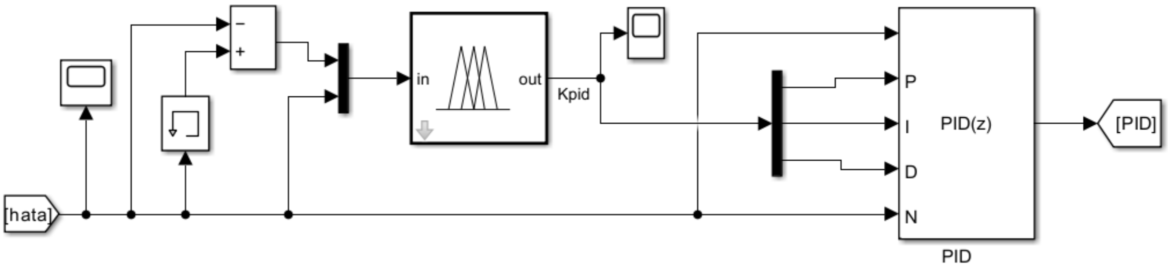

Figure 5. Changing PID parameters with fuzzy Simulink model

While creating Table 3, Table 4 and Table 5 fuzzy rule tables for Kp, Ki, Kd, the input values for fuzzy error (e) and change in error (Δe) were used.

Table 3. Fuzzy rule table created for Kp [26]

E/CE	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	PS	Z
NM	PB	PB	PM	PS	PS	Z	NS
NS	PB	PM	PM	PS	Z	NS	NS
Z	PM	PM	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NM	NM	NM	NB
PB	Z	NS	NS	NM	NM	NB	NB

Table 4. Fuzzy rule table created for Ki [26]

E/CE	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NM	NM	NS	Z	Z
NM	NB	NB	NM	NS	NS	Z	Z
NS	NB	NM	NS	NS	Z	PS	PS
Z	NM	NM	NS	Z	NS	PM	PM
PS	NM	NS	Z	PS	PS	PM	PB
PM	Z	Z	PS	PS	PM	PB	PB
PB	Z	Z	PS	PM	PM	PB	PB

Table 5. Fuzzy rule table created for Kd [26]

E/CE	NB	NM	NS	Z	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	Z
NS	Z	NS	NB	NM	NS	NS	Z
Z	Z	NS	NS	NS	NS	NS	Z
PS	Z	Z	Z	Z	Z	Z	Z
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

When creating Fuzzy, 2 input and 3 output values were assigned. While the first entry indicates the error value, the second entry indicates the amount of change in the error. The first of the output values gives the proportional constant Kp, the second gives the integral constant Ki, and the third gives the derivative constant Kd. The first input value is the error, which is the difference between the engine output speed and the reference speed value, and the second input value is taken as the amount of change (derivative) of the error.

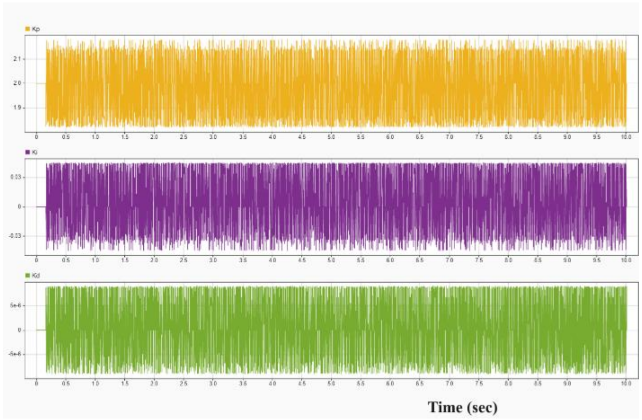

Figure 6. Changes of 3000 rpm Kp-Ki-Kd values over time

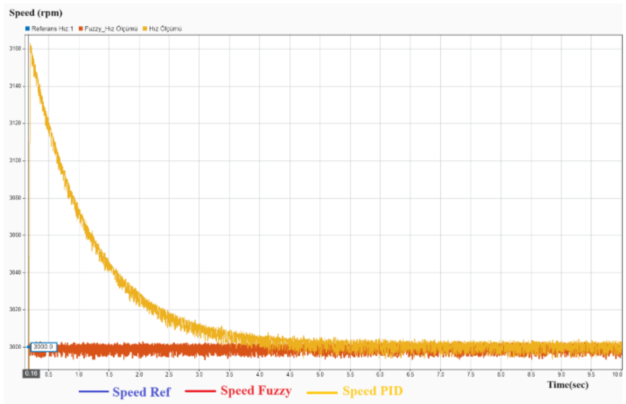

Figure 7. 3000 rpm PID and Fuzzy Controlled PID comparison

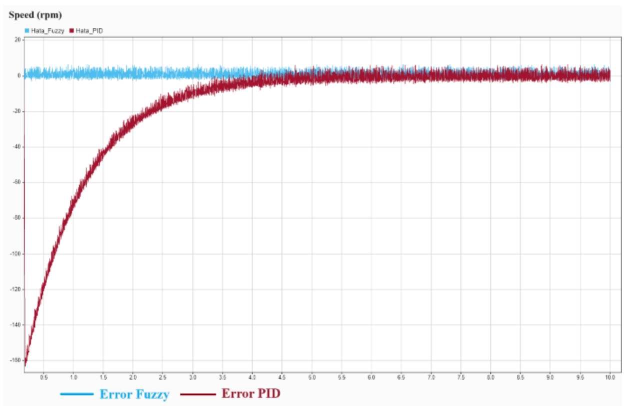

Figure 8. Comparing 3000 rpm PID and fuzzy control PID errors

Figure 7 shows the comparison of the data obtained from the PID controller and fuzzy tuning PID controller at 3000 rpm without load. According to the data obtained, it has been observed that the Fuzzy tuning PID controller settles faster than the PID controller and the overshoot rate is much lower. In Figure 8, the error amounts of the two controllers in rpm over time are compared. Accordingly, it is observed that the Fuzzy tuning PID controller makes faster adjustments than the PID controller and takes values close to the reference speed.

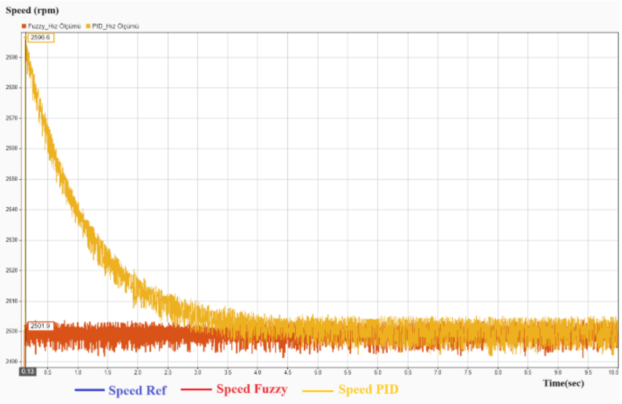

Figure 9. 2500 rpm PID and Fuzzy Controlled PID comparison

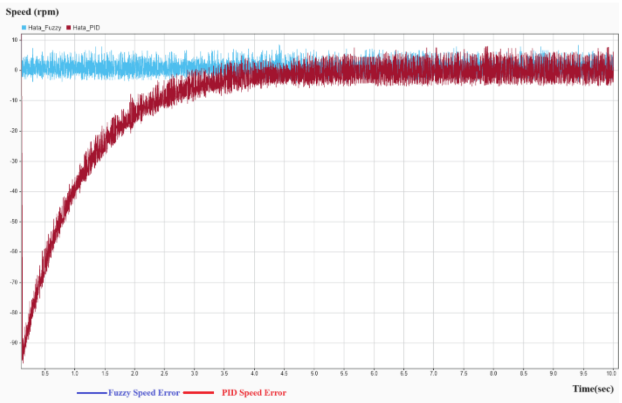

Figure 10. Comparing 2500 rpm PID and fuzzy control PID errors

Figure 9 shows the comparison of the data obtained from the PID controller and fuzzy tuning PID controller at 2500 rpm without load. According to the data obtained, it has been observed that the Fuzzy tuning PID controller settles faster than the PID controller and the overshoot rate is much lower. In Figure 10, the error amounts of the two controllers in rpm are compared over time. Accordingly, it is observed that the Fuzzy tuning PID controller makes faster adjustments than the PID controller and takes values close to the reference speed.

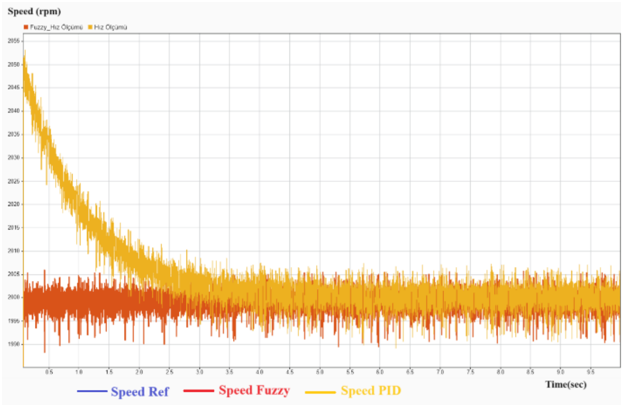

Figure 11. 2000 rpm PID and Fuzzy Controlled PID comparison

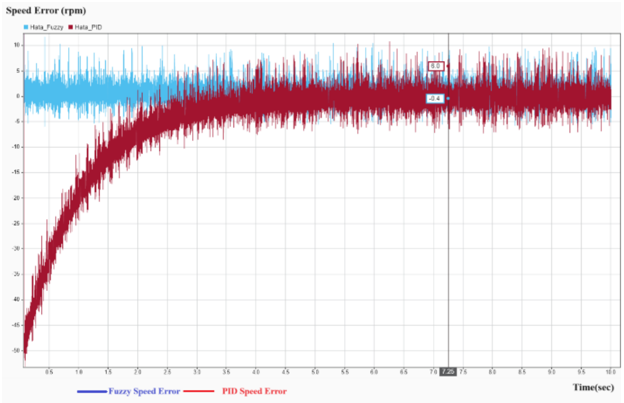

Figure 12. Comparing 2000 rpm PID and fuzzy control PID errors

Figure 11 shows the comparison of the data obtained from the PID controller and fuzzy tuning PID controller at 2000 rpm without load. According to the data obtained, it has been observed that the Fuzzy tuning PID controller settles faster than the PID controller and the overshoot rate is much lower. In Figure 12, the error amounts of the two controllers in rpm are compared over time. Accordingly, it is observed that the Fuzzy tuning PID controller makes faster adjustments than the PID controller and takes values close to the reference speed.

Figure 13. 1500 rpm PID and Fuzzy Controlled PID comparison

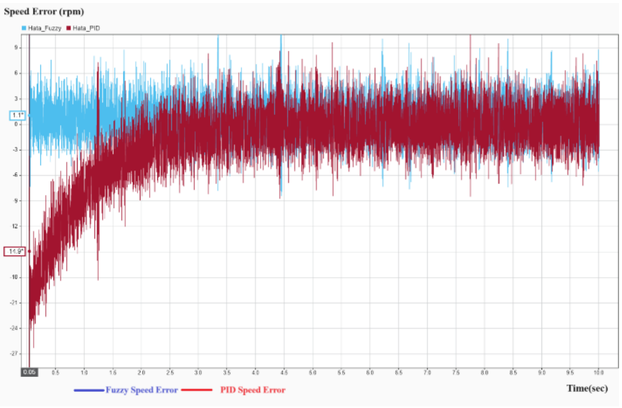

Figure 14. Comparing 1500 rpm PID and fuzzy control PID errors.

Figure 13 shows the comparison of the data obtained from the PID controller and fuzzy tuning PID controller at 1500 rpm without load. According to the data obtained, it has been observed that the Fuzzy tuning PID controller settles faster than the PID controller and the overshoot rate is much lower. In Figure 14, the error amounts of the two controllers in rpm are compared over time. Accordingly, it is observed that the Fuzzy tuning PID controller makes faster adjustments than the PID controller and takes values close to the reference speed.

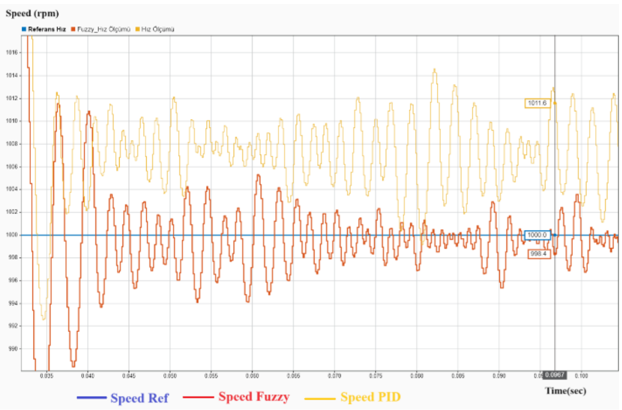

Figure 15. 1000 rpm PID and Fuzzy Controlled PID comparison

Figure 16. 1000 rpm PID and Fuzzy Controlled PID comparison

Figure 15 shows the comparison of the data obtained from the PID controller and fuzzy tuning PID controller at 1000 rpm without load. According to the data obtained, it has been observed that the Fuzzy tuning PID controller is more stable than the PID controller and the overshoot rate is lower. In Figure 16, the error amounts of the two controllers in rpm are compared over time. Accordingly, it is observed that the Fuzzy tuning PID controller makes more stable adjustments than the PID controller and takes values close to the reference speed.

Table 6. Comparison of Classic PID and Fuzzy self-tuning PID for Different Speeds

Speed (rpm)	Method	Rise Time (sn)	Settling Time (sn)	Maximum Overshoot (rpm)	Maximum Overshoot (%)	SS Error (rpm)
3000	Classic PID	0.167	1.22	163.3	5.4	11
	PID with fuzzy	0.167	0.167	2.9	0.096	8
2500	Classic PID	0.112	0,82	96.6	3.86	11.6
	PID with fuzzy	0.112	0.112	3.7	0.148	11
2000	Classic PID	0.071	0.4	18.2	0.91	14.2
	PID with fuzzy	0.071	0.071	5.3	0.265	14.0
1500	Classic PID	0.043	0.05	36.3	2.42	16.5
	PID with fuzzy	0.043	0.043	8.1	0.54	18.5
1000	Classic PID	0.0093	0.034	96.2	9.62	22.6
	PID with fuzzy	0.0093	0.034	96.2	9.62	23.6

In table 6, Fuzzy controlled PID and classical PID comparison results are given for different speeds without using criteria such as soft starting at startup and soft starting during development. According to the data obtained; No significant difference was obtained in reducing the rise time for both methods. Significant decreases in settling time were observed for each stage tested from 3000 rpm to 1000 rpm.

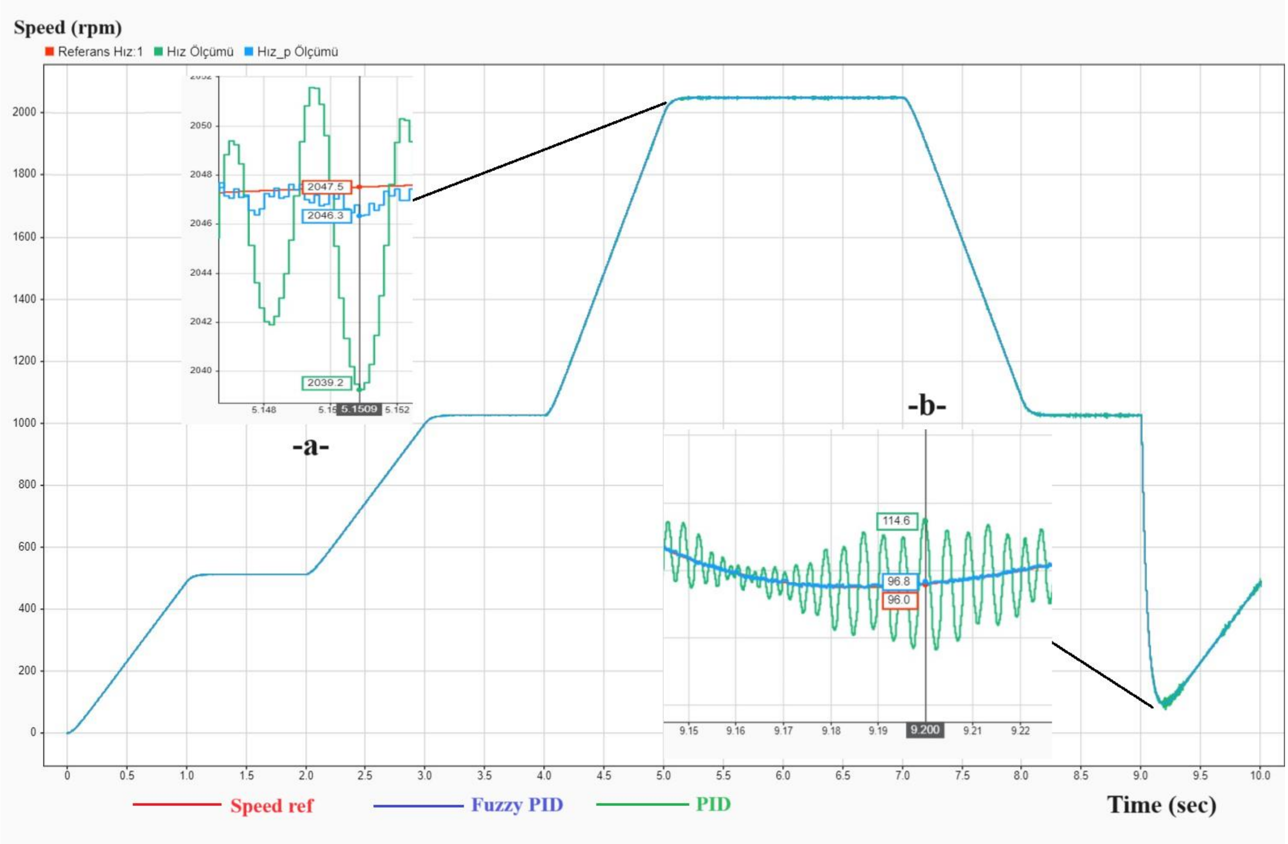

Figure 171. Comparison of PID and Fuzzy controlled PID under soft start and different speed conditions

When a soft start system is designed as in Figure 17, it has been concluded that the ability to adapt to the reference speed even at low speeds is much better than the classical PID for the motors in which the fuzzy adjustable PID controller is used under different speed conditions.

In Figure 17-a, although the reference speed value is 2047.5 rpm, it is observed that the speed value obtained with the classical PID is 2039.2 rpm and has an error of 8.3 rpm, while the speed obtained with the fuzzy tuned PID controller is 2046.3 rpm. and it appears to have an error of 1.2 rpm.

In Figure 17-b, although the reference speed value is 96.8 rpm, it is observed that the speed value obtained with the classical PID is 114.6 rpm and has an error of 17.8 rpm, while the speed obtained with the fuzzy tuned PID controller is 96 rpm and It appears to have an error of 0.8 rpm.

While the classical PID operates the system with a large percentage speed error of 17.39% at low speeds, the fuzzy tuned PID controller operates the system with a very low percentage speed error of 0.83%. While the classical PID operates the system with a large percentage speed error of 0.4% at high speeds, the fuzzy tuned PID controller operates the system with a very low percentage speed error of 0.059%.

5. Conclusions

Error (e) and the amount of change in error (Δe) are the input data for fuzzy. PID parameters Kp, Ki and Kd values are also fuzzy output data. With the fuzzy control system used, PID parameters were corrected simultaneously due to undesirable changes in speed. Classic PID comparison was made with changing PID parameters with fuzzy for different reference speed values of the created system BLDC motor.

As a result of the research.

- When comparing the fuzzy PID controller with the classical PID controller at 3000 rpm, the rise times were 0.167 seconds for both; The settling time gave better results with 1.22 seconds for the classical PID controller and 0.167 seconds for the fuzzy PID controller. When looking at the maximum exceedance as a percentage; While the classical PID controller was 5.4%, the fuzzy PID controller showed a more stable situation with 0.096%.
- When comparing the fuzzy PID controller with the classical PID controller at 2500 rpm, the rise times are 0.112 seconds for both; In settling time, the classical PID controller gave better results with 0.82 seconds, and the fuzzy PID controller gave better results with 0.112 seconds. When looking at the maximum exceedance as a percentage; While the classical PID controller was 3.86%, the fuzzy PID controller showed a more stable situation with 0.148%.

• When comparing the fuzzy PID controller with the classical PID controller at 2000 rpm, the rise times are 0.071 seconds for both; In settling time, the classical PID controller gave better results with 0.4 seconds and the fuzzy PID controller gave better results with 0.071 seconds. When looking at the maximum exceedance as a percentage; While the classical PID controller was 0.91%, the fuzzy PID controller showed a more stable situation with 0.265%.

• When comparing the fuzzy PID controller with the classical PID controller at 1500 rpm, the rise times are 0.043 seconds for both; In settling time, the classical PID controller gave better results with 0.05 seconds, and the fuzzy PID controller gave better results with 0.043 seconds. When looking at the maximum exceedance as a percentage; While the classical PID controller was 2.42%, the fuzzy PID controller showed a more stable situation with 0.54%.

• When comparing the fuzzy PID controller with the classical PID controller at 1000 rpm, the rise times are 0.0093 seconds for both; In the settling time, the classical PID controller gave the same result as 0.034 seconds, and the fuzzy PID controller gave the same result as 0.034 seconds. When looking at the maximum exceedance as a percentage; While the classical PID controller was 9.62%, the fuzzy PID controller showed the same stability as 9.62%.

On the other hand, when a soft start system is designed, it has been concluded that the ability of the fuzzy-based PID to adapt to the reference speed at all speeds is much better than the classical PID, even at low speeds. Consequently.

• Although the reference speed value is 2047.5 rpm, it is observed that the speed value obtained with the classical PID controller is 2039.2 rpm and has an error of 8.3 rpm, while the speed in the fuzzy PID controller is 2046.3 rpm and has an error of 1.2 rpm. It has been concluded that:

• Although the reference speed value is 96.8 rpm, it is observed that the speed value obtained with the classical PID controller is 114.6 rpm and has an error of 17.8 rpm, while the speed in the fuzzy PID controller is 96 rpm and has an error of 0.8 rpm. has been obtained.

It was concluded that the classical PID controller operates the system with a large percentage speed error of 17.39% at low speeds, while the fuzzy PID controller operates with a very low percentage speed error of 0.83%. It was concluded that the classical PID controller operates the system with a large percentage speed error of 0.4% at high speeds, while the fuzzy PID controller operates with a very low percentage speed error of 0.059%.

If the findings obtained from the simulations are to be generalized; It has been observed that the FDAM operated with the created fuzzy PID controller corrects the output speed signals more stable than the FDAM controlled with the classical PID controller. As a result of the comparisons, it was concluded that the fuzzy PID controller is faster in reference speed-dependent regulation than the classical PID controller. In addition, it was concluded that the amount of overshoot due to the reference speed was less and the engine speed settled to the reference speed value in a much shorter time.

When the rise times of fuzzy PID controller and classical PID controller data were compared, it was concluded that both reached the reference speed value at the same time. Although the rise time does not change, the overshoot percentage and settling times are significantly reduced thanks to systematically changing coefficients.

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