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Speed control of PM brushless DC motor using sensorless hybrid controller

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ABSTRACT

In most industrial processes, rising productivity necessitates increased demand on electrical motors in order to minimize costs and improve drive system efficiency. The sensorless technique is preferred. Brushless DC (BLDC) motors compete with a wide range of different motor types in the motion control industry. The nonlinearity of BLDC motor characteristics is challenging to manage with a traditional proportional integral derivative (PID) controller. The PID controller's fuzzy logic allowed it to tune itself while operating online. Hybrid approaches outperform stand-alone algorithms because they can overcome their weaknesses without losing their advantage. The purpose of this study is to present a fuzzy PI+D controller that is simulated over a wide range of reference speeds, loads, and parameter variations. This paper presents a model of a sensorless BLDC motor with a speed controller. The responses of the rotor speed, electromagnetic torque, stator back electromotive force (EMF), and stator currents are effectively monitored. The findings from the simulation indicate that the hybrid controller presented in this study exhibits resilience to rapid load torque and parameter fluctuation. Furthermore, it demonstrates superior dynamic performance and exhibits notable enhancements in speed tracking and system stability. The performance of the system is enhanced through the utilization of the proposed hybrid intelligent controller.

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1. INTRODUCTION

The requirement for better productivity in most industrial processes, including electrical, mechanical, construction, petroleum, iron and steel, power, paper, and beverage industries, is putting additional demands on mechanisms coupled to electrical motors. These electric motors have been around for over a century and play an important role in the advancement of modern technologies. A better understanding of energy conversion principles, together with the development of new and improved materials, has led to more advanced machine design. This causes a variety of operational issues due to the quick dynamics and instability. That is why the system requires control to achieve stability and function at the required level [1]. Brushless DC (BLDC) motors are widely employed in a variety of industrial applications due to their high efficiency, torque, and compact size. The BLDC motor is typically defined as a permanent magnet synchronous motor with a trapezoidal back electromotive force waveform [2].

In a brushless motor, the magnets are located in the rotor, while the windings are in the stator. As the name implies, brushes are absent, hence commutation is handled electronically via switches to vary the current in the windings depending on rotor position feedback [3]. As a result, BLDC motors frequently employ either internal or external position sensors to detect the real rotor. The permanent magnet brushless DC (PMBLDC) motor's rotor position commutation method has two aspects: sensor control and sensorless control. The latter sensorless techniques provide advantages such as cost savings, improved performance, and the elimination of the difficulty in maintaining the sensor. The motor is controlled using a variety of sensorless control techniques and algorithms, including direct back electromotive force (EMF) zero crossing, terminal voltage sensing, and a field-oriented controller (FOC). This study describes a sensorless method for driving a three-phase BLDC motor with a FOC system using a hysteresis comparator. FOC is the process of managing the stator currents using vector control to simplify the analysis and control of the permanent magnet BLDC drive system and improve dynamic response [4].

The best speed-tracking BLDC motor drives can be achieved by designing an appropriate speed controller. Several current control strategies have recently been proposed for BLDC motor speed control design [5]. The typical proportional integral derivative (PID) controller algorithm, on the other hand, is simple, stable, adaptable, and very reliable. The controller tries to reduce the error by changing the tuning parameters [6], [7]. The PID controller can add a fuzzy logic controller (FLC) to their control system for optimization without changing much of the system topology or replacing the standard controller [8], [9].

Based on the traditional technique, a speed PID controller was successfully constructed for closed-loop operation of the BLDC motor, so that the motor operates around the reference speed. The simulated BLDC motor system stabilizes in 0.05 seconds, with just a slight overshoot [10]. We created a new model of a BLDC motor with a real back EMF waveform [11]. The real back EMF in the traditional BLDC motor simulation model is slightly different from the ideal trapezoidal back EMF. This approach minimized the error in the usual simulation, resulting in a virtually true back EMF waveform acquired by simulation. The modeled three-phase BLDC motors demonstrated functioning and derived the BLDC state space model by applying FLC to stabilize the derived rotor speed. The simulated BLDC motor speed response settling time is 0.014 seconds with no overshoot and a steady-state inaccuracy of 0.0225% [12].

The performance of a three-phase permanent magnet BLDC motor based on a filtered mechanism will be evaluated using FLC [13]. These sensors may necessitate more investment and regular maintenance; they may also be harmed by adverse conditions. Speed control is possible when the BLDC control system is nonlinear or when there is a sudden load disturbance or parametric fluctuation. To address these issues, an intelligent control technique like fuzzy logic is used. The simulated sensor BLDC motor speed response was 0.01 second settling time with no overshoot. It is also proposed to use hybrid fuzzy PID control to evaluate the performance of the Hall effect sensor-based BLDC motor [14]. It is straightforward and efficient to manage speed just with FLC. However, combining fuzzy and PID controllers will offer combined benefits such as improved performance, reduced speed error, and the elimination of manual interference in control. This BLDC motor speed response yielded a settling time of 0.2 seconds and a quick rising time of 0.002 seconds.

In recent years, there has been a significant increase in the demand for the utilization of permanent magnet motor drives in a variety of industrial applications. Among the intrinsic benefits of these machines are high power density, low inertia, great efficiency, and high-speed capabilities [15], [16]. This is one of the reasons why this is the case. The BLDC motor is a nonlinear construction that requires a sophisticated nonlinear design, despite the fact that the advantages described above are present. As their name suggests, traditional direct current (DC) motors are subject to physical constraints regarding speed and lifetime due to brush wear, which necessitates routine maintenance. Control systems that do not require the use of physical sensors are gradually replacing BLDC motors that have sensors. This particular position sensor has a number of drawbacks, including the fact that it raises additional expenses and decreases the reliability of the system. For the purpose of managing the speed, this study does away with the mechanical position sensor and instead provides an electrical state as an alternative. A BLDC motor has a trapezoidal back EMF waveform, and although it should theoretically provide a constant torque, there is a torque ripple within the motor because of the inaccuracy of the EMF waveform. As a result, our sensorless vector-controlled BLDC motor drive offers improved dynamic speed response and a reduced amount of torque ripples. Given that the BLDC motor drive system must adhere to specific standards in order to accommodate the dynamic response to speed and torque.

In this study is designed a solution that blends standard controllers and fuzzy logic controllers to achieve the best of both worlds. This allows us to avoid classic controller concerns like oscillation, overshoot, and steady-state inaccuracy. Fuzzy logic control does not require the drive system's mathematical model. The challenges listed above are overcome by incorporating a fuzzy controller into conventional control, which changes the controller's control settings for real-time data. Fuzzy controllers will respond to feedback values and can automatically control PID gains. In this work, a fuzzy logic-based PI+D controller is investigated for superior real-time performance, stability, and other attributes compared to classic PID control. This controller is expected to track the reference speed and electromagnetic torque with the highest dynamic response. The purpose of this study is to illustrate the dynamic response of speed with the hybrid fuzzy PID controller to control the motor speed and maintain the BLDC motor performance behavior constant when the sudden load and parameters change. As a result, the fuzzy logic controller may modify PID gains online. Overall, the permanent magnet sensorless BLDC motor responded better to the hybrid fuzzy PI+D control system than to the standard PID controller. The suggested method contains a fuzzy logic controller for online PI+D gain adjustment, as well as a sensorless vector control algorithm for detecting optimal rotor position.

2. RESEARCH METHOD

This study's approach includes the following tasks for each specified target. The first task is to conduct a literature review, which entails gathering all theoretical information about the BLDC motor drive and comparing it to previous similar research. This includes reading books, articles, research, simulation tools, and other resources about the speed control of a sensorless PM motor using an intelligent controller. This is followed by a study of the dynamic modeling of BLDC motor drive theory, as well as the working concept of the BLDC drive system, which employs sensorless vector control to identify proper rotor position using the hysteresis comparator. Next, develop an efficient control algorithm hybrid fuzzy PI+D speed controller to track the nonlinear BLDC motor's reference response. A performance comparison of PI, PI+D, auto tuning, and fuzzy PI+D speed controllers is also carried out. Later in this study, the speed controller's ability to track the reference response of the permanent magnet BLDC motor is demonstrated; each block is modeled independently and integrated using MATLAB/Simulink.

Figure 1 shows how the fundamental block diagram of PM brushless DC motor control is connected. This motor control system consists of four major components: a pulse width modulation (PWM) inverter, a BLDC motor, a sensorless algorithm, and a speed controller. Each block is modeled independently before being combined. Speed regulation is a critical feature of brushless DC motor drives for accurate speed and position control applications. In this case, a fuzzy PI+D speed controller constructs an outer closed loop to control the rotor speed utilizing sensorless techniques, resulting in a correct commutation sequence using a hysteresis current controller. The current error is supplied into a comparator equipped with a hysteresis band.

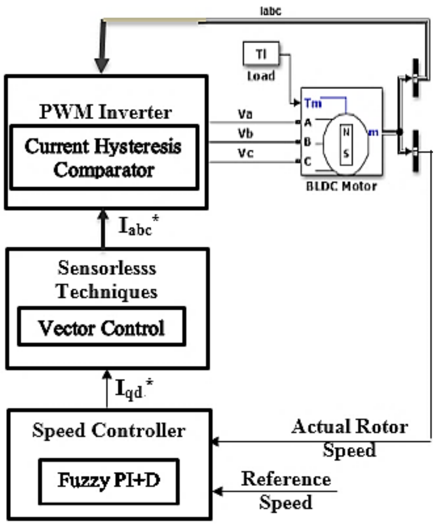


Figure 1. Architecture of sensorless BLDC motor

Every winding in the stator has the same resistance, and both the self and mutual inductances remain unchanged throughout the whole winding. During this time, the back EMF waveforms of each phase are identical to one another. In order to determine the dynamic equations of the BLDC motor using the assumption, it is possible to use electrical and mechanical equations [17]. These equations are generated based on the equivalent circuit of the BLDC motor system. Each winding of a BLDC motor generates a voltage that is known as the back EMF when the motor is rotating. This voltage is in opposition to the main voltage that is delivered to the windings. In the three-phase BLDC motor, the back electromagnetic field (EMF) is connected to a function of the rotor position, and the phase angle difference between the back EMF of each phase is two hundred and twenty degrees. In order to both start the motor and provide the appropriate commutation sequence in order to turn on the power devices, the rotor position of the motor must be determined. The period is 3600, and the phase shift that occurs between each phase current and the back electromagnetic field is 120 degrees of electrical rotation. As the rotor travels, the magnetic field that is produced by the windings should shift position in order to catch up with the stator field. This action is necessary in order to keep the motor operating. A process that is referred to as "Six Step Commutation" is what defines the sequence of energizing the windings. The trapezoidal back electromagnetic field waveforms are described in this model as a function of the rotor position, and the rotor position is determined by a physical sensor [18].

$$e_{\mathrm{a}} = K_{\mathrm{e}}\omega_{\mathrm{r}} f(\theta_{\mathrm{r}}) \tag{1}$$

$$e_{\mathrm{b}} = K_{\mathrm{e}}\omega_{\mathrm{r}} f(\theta_{\mathrm{r}} - 2\pi/3) \tag{2}$$

$$e_{\mathrm{c}} = K_{\mathrm{e}}\omega_{\mathrm{r}} f(\theta_{\mathrm{r}} - 4\pi/3) \tag{3}$$

In the context of rotor position, the functions $f_{\mathrm{a}}(\theta_{\mathrm{r}})$, $f_{\mathrm{b}}(\theta_{\mathrm{r}})$, and $f_{\mathrm{c}}(\theta_{\mathrm{r}})$ are defined as follows:

$$fa(\theta_r) = \begin{cases} 1 & 0 \le \theta_r < \frac{\pi}{3} \\ \left(\frac{3}{\pi}\right)\theta_r & \frac{\pi}{3} \le \theta_r < \frac{2\pi}{3} \\ -1 & \frac{2\pi}{3} \le \theta_r < \frac{4\pi}{3} \\ -\left(\frac{3}{\pi}\right)\theta_r + 3 & \frac{4\pi}{3} \le \theta_r < \frac{5\pi}{3} \\ 1 & \frac{5\pi}{3} \le \theta_r < 2\pi \end{cases} \tag{4}$$

fb (θ_{r}) and fc (θ_{r}) are 120 electrical degree and 240 electrical degree phase shifted with respect to $f_{\mathrm{a}}(\theta_{\mathrm{r}})$. The phase current and the phase back EMF are in phase.

Two of the three electrical windings are activated at the same time in the commutation system, which is based on the position of the motor as determined by feedback sensorless. Figure 2 depicts the back EMF correlating to the rotor position. However, in practice, it was difficult to produce pure trapezoidal back EMF due to the non-uniformity of magnetic materials and the design trade-off [19]. The stator currents take the form of a quasi-square wave in phase with the corresponding back EMF, resulting in constant unidirectional torque. The electromagnetic torque is created by the interplay of magnetic fields produced by stator coils and PMs. The magnitude of the three-phase reference current I* is calculated using the reference torque provided in (5).

$$I^* = \frac{T^*}{K_T} \tag{5}$$

In a balanced condition, three-phase currents always meet the following conditions:

$$I_{\mathrm{a}} + I_{\mathrm{b}} + I_{\mathrm{c}} = 0 \tag{6}$$

There are three-phase reference currents (I_a^*, I_b^* and I_c^*) that are generated by the reference current generator block. These currents are generated by taking the value of the reference current I^*, which is presented in Table 1. Every time the hysteresis current controller rotates through sixty degrees, it undergoes a change in state, and the entire cycle is completed by taking six steps. Because of the straightforward and relatively inexpensive feedback and drive devices, six-step commutations are a cost-effective method of electronic commutation than other methods. During each commutation sequence, one of the windings is energized to positive power (current enters the winding), the second winding is negative (current departs the winding), and the third winding is in a position where it is not activated whatsoever [20]. In order to force the motor current to follow the reference, the hysteresis current controller performs a comparison between the source current and the reference current. Using three distinct current controllers, one for each phase, is the goal of current hysteresis control. This is the goal of the control. The three references Because of the requested speed and the actual position of the rotor, instantaneous current values for the a, b, and c phases are created, as shown in Figure 3.

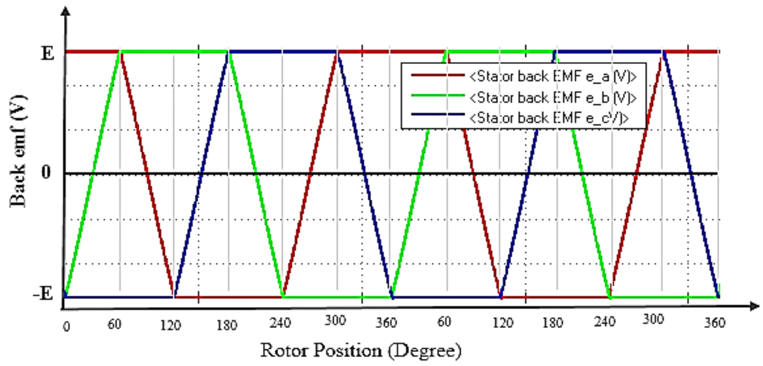


Figure 2. An ideal trapezoidal back EMF waveform for a BLDC motor

Table 1. Switching sequence of rotation of magnetic field for BLDC motor

Sequence number	Switching interval degree	Phase current		
		I_a^*	I_b^*	I_c^*
1	0-60	I^*	$-I^*$	0
2	60-120	I^*	0	I^*
3	120-180	0	I^*	$-I^*$
4	180-240	$-I^*$	I^*	0
5	240-300	$-I^*$	0	I^*
6	300-360	0	$-I^*$	I^*

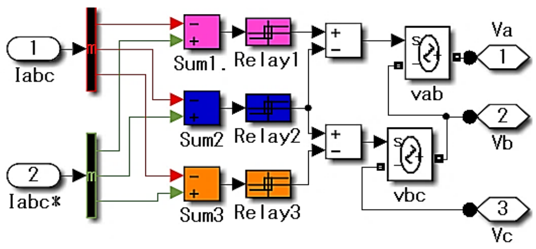


Figure 3. Block diagram of PWM inverters

The utilization of sensorless control in the BLDC motor offers numerous benefits compared to the utilization of physical sensors, such as reduced expenses, compactness, and noise. A sensorless drive refers to a PM brushless drive that operates solely on electrical measurements, without the need for position sensors. The measurement process does not require any physical components, but rather solely relies on electrical dimensions. The avoidance of investment in sensors results in a reduction in the overall cost of the system. The sensor's maintenance issue is also resolved [21].

In the context of AC motors, it is necessary to regulate both the phase angle and the magnitude of the stator current, thereby ensuring control over the current vector. Hence, the designation "vector control" is employed in reference to AC motors. The concept of vector control, also known as FOC, in electrical drives involves regulating both the magnitude and phase of the stator current in each phase. In order to enhance computational efficiency and streamline processes, it is common practice to convert machine models into rotating reference frames. The stationary reference frame is characterized by the fixation of the d and q axes on the stator. In this configuration, either the d or q axis aligns with a phase axis of the stator. The rotating frame allows for the possibility of either securing the rotating d-q axis to the rotor or enabling them to move at a synchronous speed. The selection of the rotor reference frame is based on the fact that the position of the rotor has an independent influence on the stator voltages and currents, induced electromotive forces (EMFs), and torque [22]. The process of decomposing the a-phase, b-phase, and c-phase currents, followed by their summation, yields:

$$i_q = k_q(i_a \cos\theta + i_b \cos(\theta - 120°) + i_c \cos(\theta + 120°)) \quad (7)$$

$$i_d = k_d(i_a \sin\theta + i_b \sin(\theta - 120°) + i_c \sin(\theta + 120°)) \quad (8)$$

The zero-sequence current will be utilized as a third current.

$$i_0 = k_0(i_a + i_b + i_c) \tag{9}$$

In order to simplify the numerical coefficients in the generalized KVL equations, the constants k_0, k_q, and k_d are selected. The constants k_q, k_d and k_0 are commonly selected as 1/3, 2/3, and 2/3, respectively. This selection results in the d-q quantities having an equivalent magnitude to that of the three-phase quantities.

$$\begin{bmatrix} i_q \\ i_d \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos\ \theta & cos\ (\theta-120) & cos\ (\theta+120) \\ sin\ \theta & sin\ (\theta-120) & sin\ (\theta+120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{10}$$

The a-b-c variables are obtained from the d-q variable through the inverse of the Park transformation [23] is given as (11).

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} cos\ \theta & sin\ \theta & 1 \\ cos\ (\theta-120) & sin\ (\theta-120) & 1 \\ cos\ (\theta+120) & sin\ (\theta+120) & 1 \end{bmatrix}\begin{bmatrix} i_q \\ i_d \\ i_0 \end{bmatrix} \tag{11}$$

In a state of equilibrium, the value of io is zero, resulting in the absence of any flux generation. Given these circumstances, the d-q transformation can be expressed as (12).

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} cos\ \theta & sin\ \theta \\ cos\ (\theta-120) & sin\ (\theta-120) \\ cos\ (\theta+120) & sin\ (\theta-240) \end{bmatrix}\begin{bmatrix} i_q \\ i_d \end{bmatrix} \tag{12}$$

The accuracy of the rotor position θ_r is crucial for the coordinate transformations from the rotating reference frame to the stationary reference frame, as evident from the equation. The current controllers convert the output from the one-dimensional time-invariant system d-q coordinates to a three-dimensional system a-b-c coordinates, which are dependent on both time and speed. Ideally, it is desirable for the direct axis component to have a value of zero. Therefore, the required value of I_d has been established as a constant of 0, while I_q represents the necessary torque component. The block diagram depicted in Figure 4 illustrates the FOC technique employed for the conversion of I_{qd} to I_{abc} in a three-phase balanced BLDC motor derive system [24].

Speed controllers are of utmost importance in determining the operational efficiency of drive systems. The controller employs rotor speed feedback in comparison to a commanded speed to regulate the speed of the BLDC motor, as depicted in Figure 5. The speed controller's output is utilized by the FOC system to control the quadrature winding current, which is directly correlated with the electromagnetic torque of the motor. The rotor flux linkage in a BLDC motor is determined by the permanent magnets, resulting in a constant commanded direct winding current of zero.

PID controllers are control loop feedback mechanisms that are widely used in industrial control systems [25]. PID control is a very useful method used in feedback control systems to determine the best values for the desired response. There are various tuning methods available, including manual tuning and auto tuning. Tuning the PID controller by trial and error can waste time in both SISO and MIMO systems. Intelligent control techniques, such as fuzzy control and hybrid fuzzy PID control, have been developed and applied to motor drives to improve operating performance [26]. Fuzzy control embeds ambiguous human logic into computer programs. BLDC motors are nonlinear and can be easily influenced by parameter changes and load disturbances. The primary advantage of FLC over conventional controllers is that no mathematical model is required for controller design [27].

The FLC can be used to modify PI+D parameters online. The hybrid fuzzy PI+D controller used in this study is based on two input errors and the rate of change in error, which are fed into the PI+D controllers. In general, designing a hybrid fuzzy PI+D controller entails three phases. First, the rule base is created by translating a skilled human operator's experience controlling a PMBLDC motor into linguistic terms. Second, appropriate membership functions are selected. Finally, the controller's scaling gains are determined. The trail-hit method is used to improve performance by adjusting the rule base, membership function parameters, and scaling gains. Figure 6 depicts the overall structure of the used hybrid fuzzy PI+D controller, which consists of the traditional PI+D controller and the fuzzy logic controller used to control the permanent magnet BLDC motor.

In a fuzzy structure, error and change of error are scaled by two quantitative coefficients, K_e and K_{ce}, to match the range of the membership functions. The K_P and K_I will convert the control quantity to a basic domain that the BLDC motor can handle. Speed error is calculated by comparing the reference speed ω_r. The fuzzy rules are developed based on a simulation of the BLDC motor drive system. The fuzzy inference operation is carried out using the 25 rules. Figure 7 shows the method used to achieve the desired speed value.

At stage A, the error is positive, indicating the desired speed is the actual speed. Additionally, the change error is negative, indicating that the response is moving in the correct direction. Therefore, the FLC will proceed in this direction, as shown in Table 2. When the controlled BLDC motor is initiated, it is necessary to promptly eliminate the input error in order to achieve system stability. This can be achieved by enhancing the system's response speed, which can be achieved by selecting a larger K_P. Additionally, it is important to avoid excessive overshoot, so a smaller K_I should be chosen. When applying the identical criteria at Stage B, it is observed that the error is negative and the change error is significantly negative. Consequently, the response is indicating an incorrect direction, prompting FLC to alter its trajectory and proceed towards Stage C until it attains the desired velocity. However, this outcome provides a precise calculation for fuzzy control. This precise calculation should be transformed into a linguistic format by utilizing the If (condition), Then (results) statement. The formulation of rules is based on the understanding of the behavior of PMBLDC motors and the expertise of control engineers. In this context, the centroid defuzzification algorithm is employed to calculate the crisp value [28], [29] as the center of gravity for the membership function of Δi_q. This method is commonly utilized in hybrid fuzzy PI+D control systems.

$$\Delta i_{\mathrm{q}}(K_{\mathrm{P}}, K_{\mathrm{I}}) = \frac{\sum_{k=1}^{n} \Delta i_{\mathrm{q}} \mu(\Delta i_{\mathrm{q}})}{\sum_{k=1}^{n} \mu(\Delta i_{\mathrm{q}})} \tag{13}$$

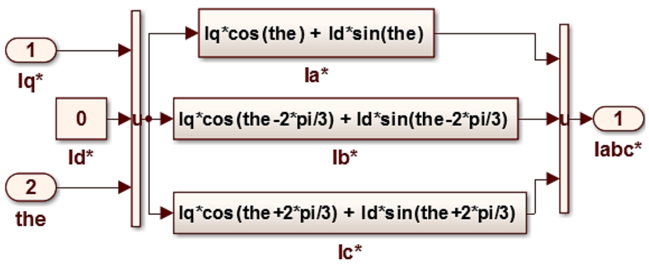


Figure 4. Modified Park transformation of the BLDC motor

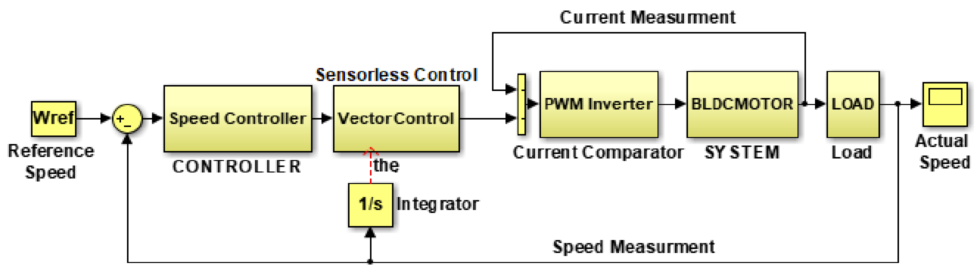


Figure 5. Block diagram of speed control BLDC motor system

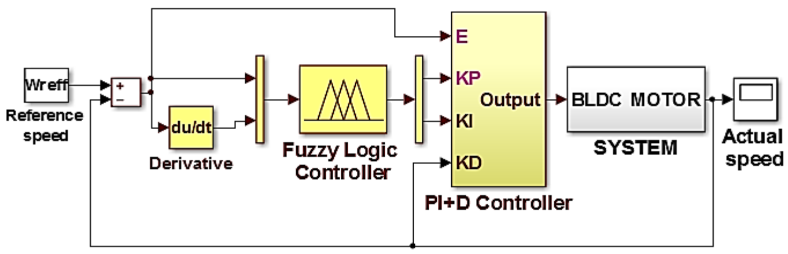
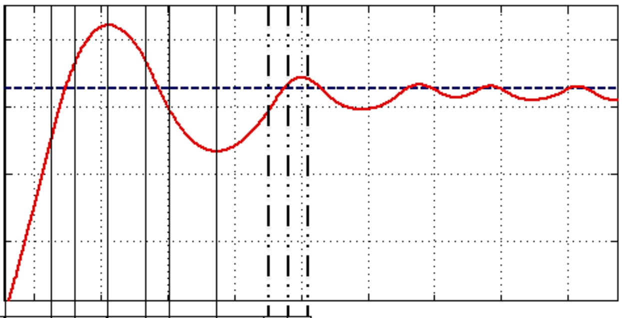


Figure 6. The structure of fuzzy PI+D controller of BLDC motor



Region	A	Z	B	C	Z	D	A	Z	B
E	+	0	-	-	0	+	+	0	-
CE	-	-	-	+	+	+	-	-	-
U	+	0	-	+	0	-	+	0	-

Figure 7. Error and change error approach in FLC dynamic analysis

Table 2. Base of rules for five membership functions

		Change error				
	K_p/K_I	NB	NS	Z	PS	PB
Error	NB	PB/NB	PB/NB	PB/NB	PS/NS	Z/Z
	NS	PB/NB	PB/NB	PS/NS	Z/Z	NS/PS
	Z	PB/NB	PS/NS	Z/Z	NS/PS	NB/PB
	PS	PS/NS	Z/Z	NS/PS	NB/PB	NB/PB
	PB	Z/Z	NS/PS	NB/PB	NB/PB	NB/PB

3. RESULTS AND ANALYSIS

3.1. Simulation of the system

In this study, the software package MATLAB/Simulink® 2013a was used to simulate the operation of a permanent magnet BLDC motor under dynamic conditions. Simulink® is a toolbox extension for the MATLAB program. The paper presents the simulation results of the permanent magnet brushless DC (PMBLDC) motor using the proposed speed controller for sensorless vector control, which is based on the current hysteresis comparator in terms of tracking capability, rotor speed behavior, sensitivity of motor parameters, and torque response quickness. This study aims to compare the performance of BLDC motor speed control using a hybrid fuzzy PI+D approach to a conventional PID controller by extensive simulation for various operating conditions. Simulations have been performed on the BLDC motor that has the ratings as shown in Table 3.

Table 3. The numerical values for BLDC motor specifications of model [14]

No	Simulation parameters	Symbol	Value
1	Rated Speed	ω	3000 rpm
2	Rated Voltage DC	V_{DC}	310 volts
3	Rated Power	P_{rated}	3.1 kW
4	Number of phases	--	3
5	Load Torque	T_L	10 Nm

3.2. Simulink model

Each block in the MATLAB/Simulink model of a permanent magnet BLDC motor is implemented individually and then combined, as depicted in Figure 8. It encompasses all the necessary elements of the drive system within the simulation model. The BLDC motor speed control simulation is conducted using a hybrid fuzzy PI+D controller in MATLAB/Simulink 2013a. The speed controller's output is transmitted to a sensorless vector control. Ultimately, the regulated voltage derived from the pulse width modulation (PWM) inverter is supplied to the motor in order to achieve accurate rotor positioning through the utilization of the current hysteresis comparator. The hybrid fuzzy PI+D controller is responsible for driving the dynamic response of the BLDC. The simulation result is studied by modeling all the components of the actual drive system. The system is discretized in the simulation using a powergui block, with a sampling period of 50 μs. Additionally, various scopes provide the anticipated outcomes for evaluating the outcomes.

The objective of the hybrid fuzzy PI+D controller proposed in this study is to effectively preserve the set point while also enabling automatic adaptation to new set point values. The utilization of a fuzzy PI+D control system offers enhanced robustness and improved tracking capabilities for speed control in situations where there is a need for parameter variation or a sudden change in rotational speed. To compare the effects of all of the control strategies, by using the hit and trial method we get the values as follows: K_P=915, K_I=0.01, K_D=301 this proposed hybrid controller according to triangular membership function with 25 rules.

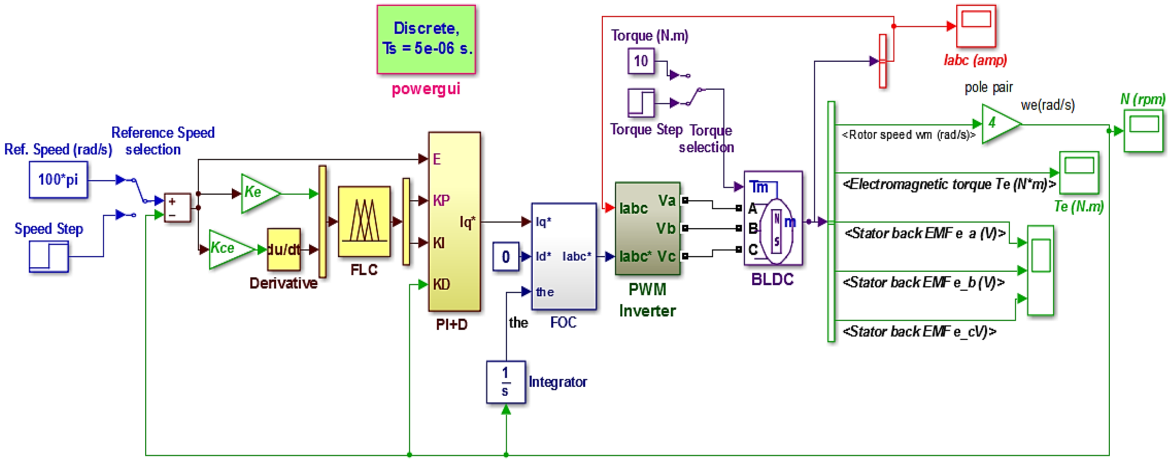


Figure 8. Overall Simulink model of the BLDC motor control

3.3. Simulation results

The BLDC motor drive's overall MATLAB/Simulink model allows you to simulate how the machine operates in various modes using a sensorless hybrid fuzzy PI+D algorithm. The simulation results are used to forecast the performance of the actual BLDC motor drive. The simulation lasted 0.1 second. Simulation studies were conducted to assess the performance of both censored and sensorless technique-based BLDC motor speed control at the same rate and conditions. The rotational speed begins at zero and rises to the no-load speed.

To provide a proper commutation sequence using sensorless vector control in addition to minimizing system cost and good performance like settling time and steady-state error, but introduce oscillation due to the hysteresis comparator. According to the data presented in Figure 9, when employing the sensor-based scheme, the BLDC motor's output speed response reaches a stable state within a time frame of 15 milliseconds. This is accompanied by an overshoot of 3604 rpm and a steady-state error of 485 rpm. In contrast, when employing the sensorless scheme, the actual rotor speed response of the brushless DC (BLDC) motor reaches a stable value of 5.0 milliseconds, accompanied by an overshoot of 3296 revolutions per minute (rpm) and a speed ripple of 100 rpm.

The simulation results for the system without any load for the BLDC motor are assumed to be without any load. However, in reality, this scenario is seldom encountered due to the presence of friction in the motor system, which acts as a load and necessitates the motor to generate torque in order to overcome it. The application of load torque to the brushless DC (BLDC) motor results in a reduction in its rotational speed. The reduction in velocity is deemed unsatisfactory in industrial contexts with regards to the operational efficiency of any motor. A speed controller is implemented as a solution to address this issue.

According to Figure 10, an increase in the load on the BLDC motor leads to a decrease in speed. The speed response without any load overshoots around 3470 rpm, and the speed response with loads TL=10 Nm overshoots around 3300 rpm, but the speed response with loads TL=20 Nm overshoots around 3134 rpm with a large steady-state error compared to other loads, and all oscillates slightly. The sensorless scheme is used to simulate the impact of parameter variation, such as a moment of inertia or friction coefficient, on the speed response. Figure 11 demonstrates that the BLDC exhibits a high dynamic speed response as a result of its permanent magnet and low inertia rotor. If the inertia rotor is $0.8*10^{-3}$ kgm^2, the output speed response of the BLDC motor rises at 2.75 milliseconds with ripple 100 rpm. On the other hand, if the inertia rotor is $1.6*10^{-3}$ kgm^2, the response time of the BLDC motor's output speed is increased by 4.25 milliseconds and ripples 62 rpm with a small overshoot.

Figure 12 depicts the developed electromagnetic torque for various load conditions. The system operates properly regardless of whether there is no load or full load. Initially, it climbs to 40 Nm, 45 Nm, and 55 Nm with ripple 16 Nm, 12 Nm, and 10 Nm for command torque load T_L=0, T_L=10, and T_L=20 respectively, and decreases rapidly to its reference value to the steady speed of 3000 rpm. Figure 13 illustrates that the initial current is elevated and subsequently diminishes as the acceleration reaches the nominal speed. This simulation observes that the stator currents are quite "noisy," and has no quasi-square wave.

The rotor position generates three-phase symmetric stator back electromotive force (EMF) waveforms. The relationship between EMF and speed is well-established. The trapezoidal back electromotive force (EMF) waveforms acquired at a reference speed of 3000 rpm in the absence of the controller are depicted in Figure 14. The trapezoidal stator back electromotive force (EMF) exhibits an initial magnitude of approximately 126 V, which subsequently decreases to 110 V with a slight oscillation of 3 V.

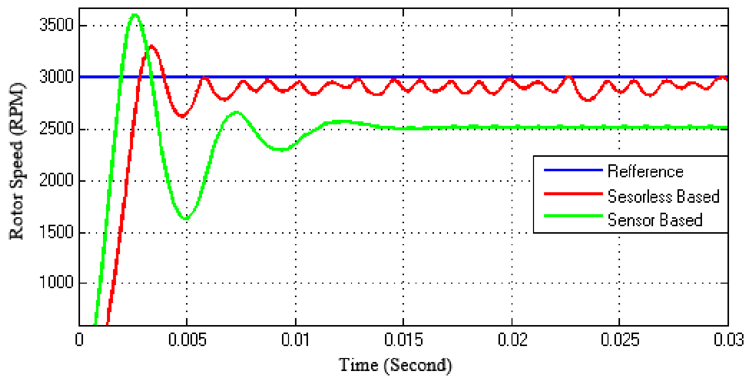


Figure 9. Speed response for sensored and sensorless based derive

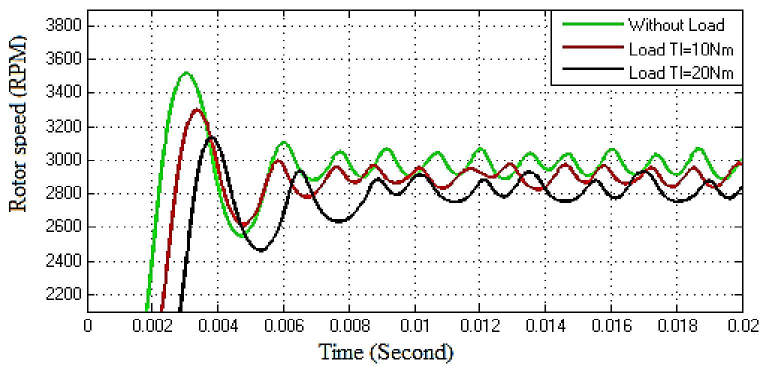


Figure 10. Speed response of the BLDC motor with variable load torque

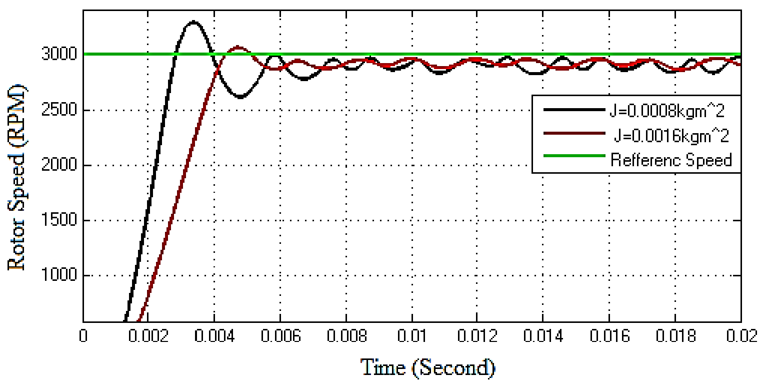


Figure 11. Speed response with variation of moment inertia

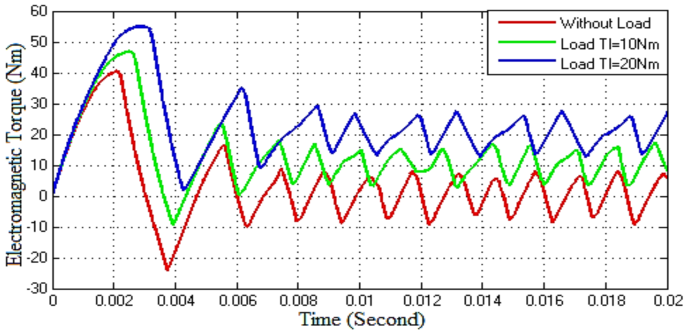


Figure 12. Developed electromagnetic torque with load variation

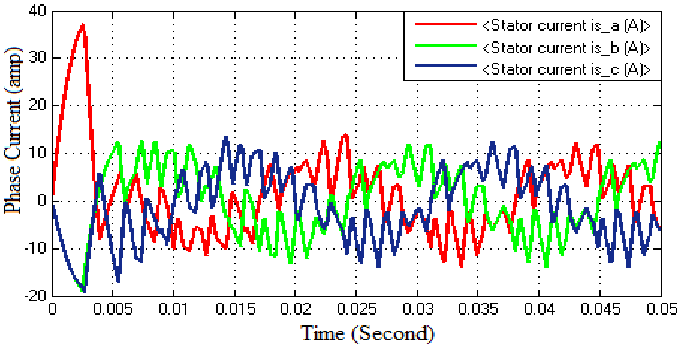


Figure 13. Stator phase currents of BLDC motor

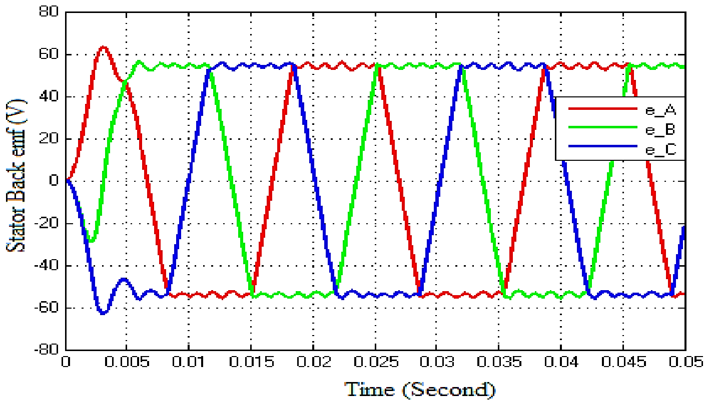


Figure 14. Back EMF waveform of sensorless BLDC motor

The traditional method for addressing these problems involves manually adjusting the proportional, integral, and derivative gains by observing the system's response. To obtain a favorable speed tracking performance manual speed PI controller with K_P=10 and K_I=25. Nevertheless, the proportional-integral (PI) controller exhibits certain drawbacks, including elevated initial overshoot, susceptibility to controller gains, and sluggish response which may be either sudden load disturbance or parameter variation. PI+D controller has less oscillation and better settling time compared to other manual PID controllers. As shown in Figure 15 using these speed controllers the actual rotor speed response reached the reference speed after 5.0 milliseconds for the optimal PID control loop. Rotor speed response stabilizes in 5 milliseconds for manual PI+D controller. The system with these conventional speed controllers also gives an undesired starting overshoot value as shown in Figure 16. In order to enhance performance, it is imperative to concurrently enhance both transient behavior and steady behavior. This proposition suggests the utilization of hybrid fuzzy PID control. The speed controller in question possesses the ability to autonomously calculate the parameters of a controller that is linked to a brushless DC (BLDC) motor, potentially without the need for any user intervention.

Using a hybrid fuzzy PI+D controller with triangular fuzzification, the speed response of the BLDC motor can follow the reference rotor speed with a settling time of 3 milliseconds without overshooting. As shown in Figure 17 without any controller, the adjusted time was long. However, the utilization of a fuzzy auto-adjust PI+D controller resulted in minimal oscillation and overshoot, with an adjusted time of merely 3.0 milliseconds for rated electromagnetic torque T_L=10 Nm and 4.4 milliseconds for electromagnetic torque T_L=20 Nm and it may take delay time and lacks rapid response due to abrupt fluctuations in load torque. If the control system necessary for operating the motor with parameter variation does not impact the speed, then it is advisable to employ an intelligent controller rather than a conventional PID controller in this scenario. The hybrid fuzzy PI+D controller demonstrates autonomy from parameter fluctuations in the BLDC motor, leading to enhanced performance in terms of rotor speed response.

Figure 18 displays the response of the rotor speed output of a BLDC motor as the parameters vary, using both conventional PI+D and fuzzy PI+D controllers. The proposed fuzzy PI+D controller has been found to achieve motor speed stabilization within 3.0 milliseconds for a moment inertia of 0.8*10-3 kgm^2 and 4.4 milliseconds for a moment inertia of 1.6*10-3 kgm^2, without any initial overshoot. The BLDC motor, when equipped with a hybrid fuzzy PI+D controller, exhibits a reduced presence of ripples in its electromagnetic torque waveform. Additionally, the load torque returns to its reference value within a brief period, in contrast to the conventional PID controller.

The simulation results, depicted in Figure 19, indicate that the stability time for the conventional PI+D control system is 4.5 milliseconds. However, when employing a fuzzy PI+D control system, the electromagnetic torque remains unaffected and remains constant within 3.0 milliseconds. The drive's torque response, when using this hybrid fuzzy PI+D controller, exhibits a smooth curve in comparison to conventional PI+D controllers. To initiate the operation of the BLDC motor and activate the power devices in the inverter, it is necessary to employ a fuzzy PI+D controller that enables vector control of the rotor position and ensures a suitable commutation sequence. The stator currents exhibit a quasi-square waveform that is in phase with the corresponding back electromotive force (EMF), as determined by a hysteresis comparator.

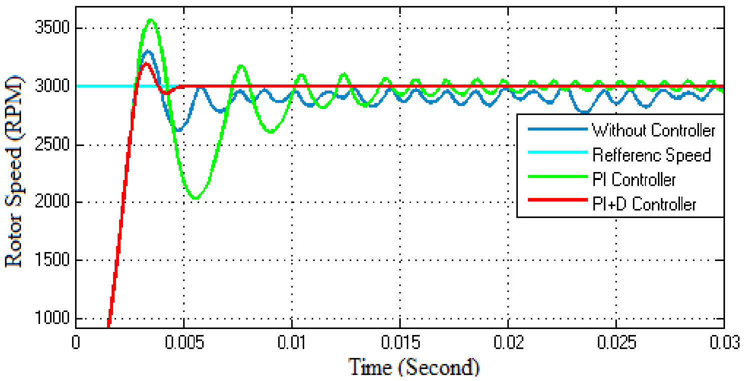


Figure 15. BLDC drive speed response using manual PID controller

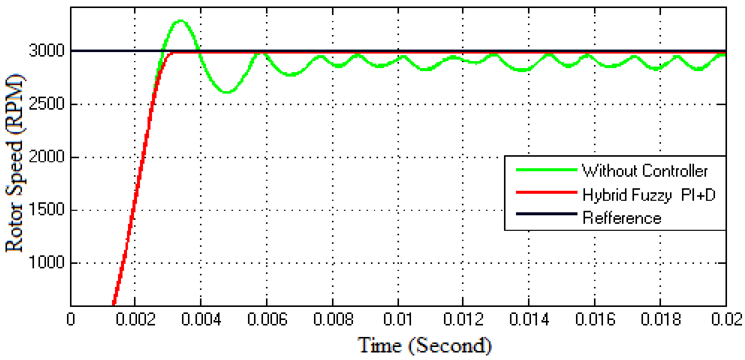


Figure 16. Speed response of BLDC using hybrid fuzzy PI+D

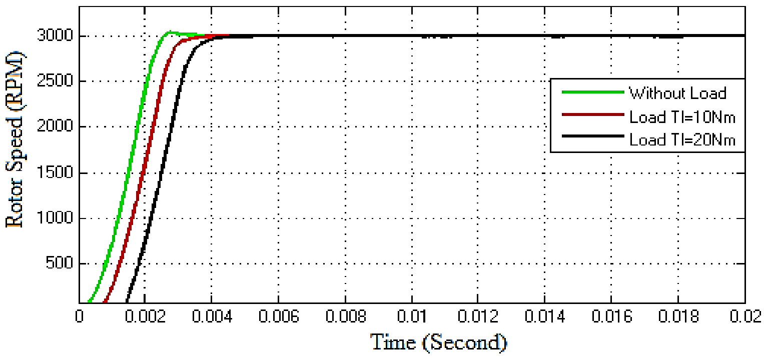


Figure 17. Speed response for different load with controller

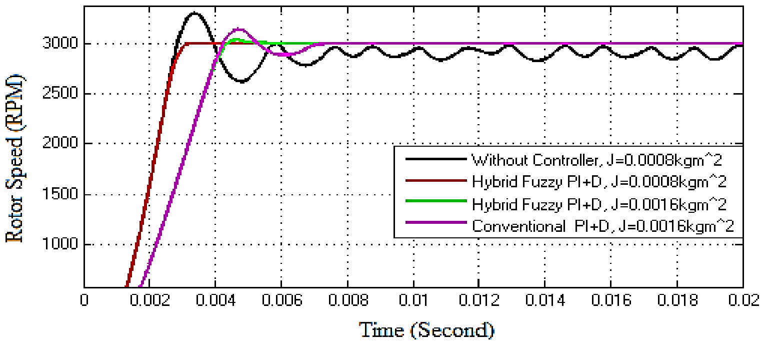


Figure 18. Speed response parameter variation for BLDC

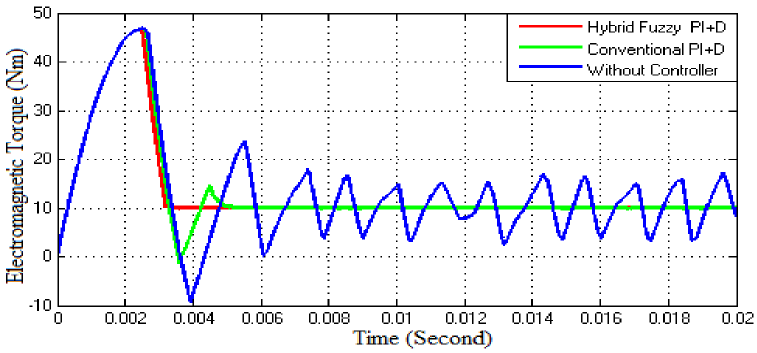


Figure 19. Electromagnetic torque with PI+D and hybrid fuzzy PI+D controller

According to Figure 20, the initial current exhibits overshooting as a result of the elevated starting torque, but subsequently returns to a uniform quasi-square pattern. The BLDC motor achieves a steady state current of 7.143 amp at 3.0 milliseconds, while it attains a predetermined speed of 3000 rpm through the utilization of a hybrid fuzzy PI+D controller. A current comparator is employed by the drive to produce a quasi-square waveform from the trapezoidal back electromotive force (EMF). The stator currents in three phases are regulated in a quasi-square configuration to align with the trapezoidal back electromotive force (EMF) and produce a consistent value based on the position of the rotor.

According to the data presented in Figure 21, the phase currents exhibit quasi-square behavior when employing the proposed fuzzy PI+D controller. This behavior is akin to the characteristics observed in the stator phase currents of BLDC motors. Specifically, in each commutation sequence, only two out of the three stator windings are energized, resulting in a 120-degree phase difference between them. The findings from the modeling of the trapezoidal back electromotive force (EMF) response, employing a hybrid fuzzy PI+D control system, demonstrate exceptional performance and effective real-time control. This enables the rapid stabilization of the brushless DC (BLDC) motor. The data acquired, as depicted in Figure 22, demonstrate that the actual stator back electromotive force (EMF) is uniformly trapezoidal, with the only variation observed in the starting time. Back electromotive force (EMF) is directly proportional to the speed. Given a steady speed of 3000 rpm, the back electromotive force (EMF) remains constant at 110 V without any oscillation.

The electronic switches in the BLDC motor controlled the rotor position to ensure accurate commutation and rotation of the motor. The back EMF is displaced by 120 electrical degrees from one phase to another for a three-phase motor. In every 60 electrical degrees of rotation, the PWM changed its combination of hysteresis comparator states to represent the rotor position. It is identical to the ideal waveforms of the BLDC motor as shown in Figure 23.

The objective of this study is to provide a concise overview of the analysis conducted on sensorless vector control of a permanent magnet brushless DC (BLDC) motor. Additionally, the study intends to assess the effectiveness of sensorless mechanisms, specifically conventional PID controllers and intelligent fuzzy controllers, in controlling motor drives. The comparative findings are presented in Table 4. This study examines the performance of the brushless DC (BLDC) motor when controlled by standard PID and fuzzy PID controllers. The study revealed that the control approach using a hybrid fuzzy PID controller had superior performance across all dimensions. The fuzzy controller offers several benefits, including automatic rule determination, reduced computational time, faster learning, and lower error rates compared to alternative approaches. The simulation results presented in Table 4 indicate that the hybrid fuzzy PI+D controller achieves favorable dynamic characteristics of the BLDC motor without the need for physical sensors. It accurately tracks the rotor speed with minimal settling time, minimizes overshoot and steady-state error, eliminates oscillation, and outperforms conventional PID controllers.

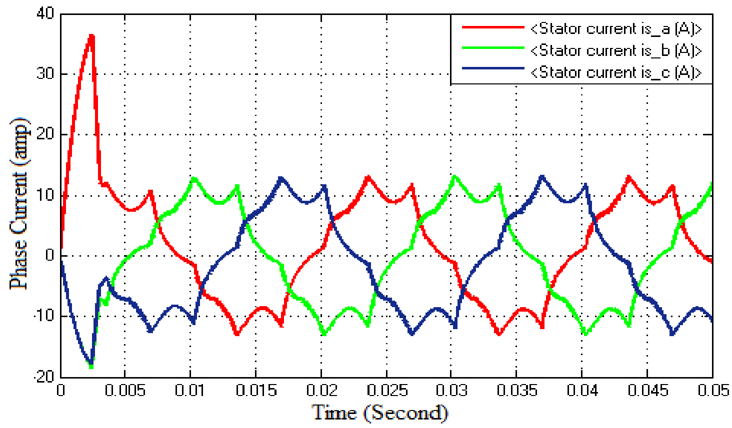


Figure 20. Stator currents using hybrid fuzzy PI+D controller

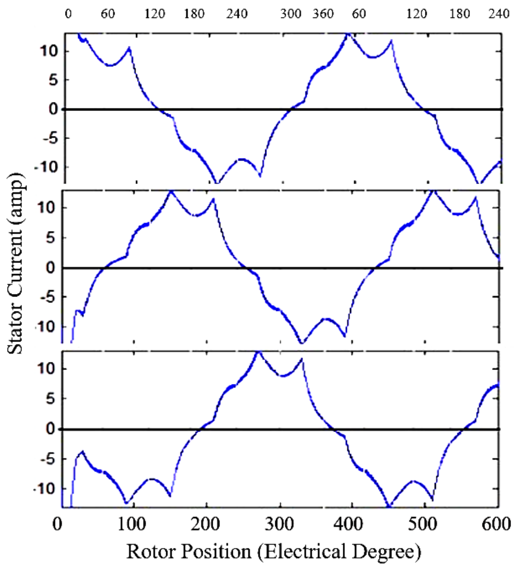


Figure 21. Stator current vs rotor position of BLDC motor

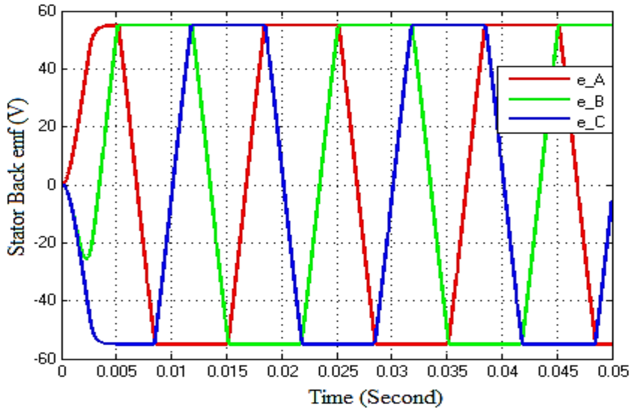


Figure 22. Trapezoidal back EMF using hybrid fuzzy PI+D controller

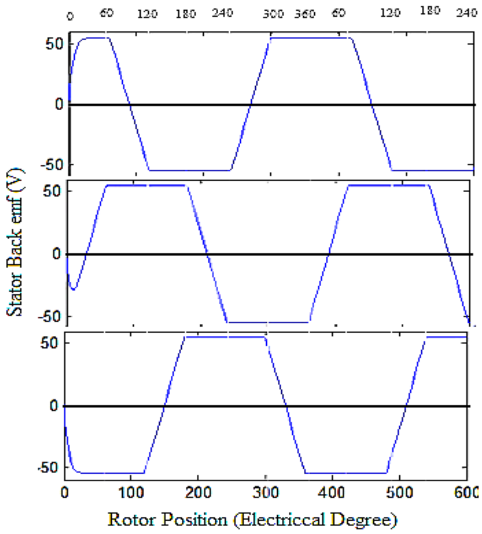


Figure 23. Stator back EMF vs rotor position of BLDC motor

Table 4. Performance metrics of different speed controllers

Controller	Conventional PID			Intelligent fuzzy
Parameters	PI	PI+D	PI+D_tuning	Fuzzy PI+D
Rise Time (millisecond)	2.5	2.8	1.2	3
Settling Time (millisecond)	10	5	7.5	3
Overshoot (%)	Large	6.7	9.566667	0
Peak amplitude	3550	3200	3287	2999.5
Final value	--	2999	2999.997	2999.5
Steady state error (%)	--	0.033	0.0001	0.016
Speed ripples (%)	2	0.033334	0.3466	0.029338
Torque ripples (%)	150	6.75	--	5
Stability	Less	Moderate	Better	Best

4. CONCLUSION

This paper assesses the performance of a three-phase permanent magnet motor powered by a three-balanced power supply and used as a sensorless BLDC motor. Several measurements are made to control the speed of the BLDC motor without the requirement for an external sensor for appropriate commutation, using a hysteresis comparator. The primary advantage of using this vector control system to manage the speed of a BLDC motor is that it improves dynamic performance and provides strong stabilization. The entire system's cost is reduced because only a current sensor is required. Conventional PID controllers have an initial overshoot, which is undesirable, but using a fuzzy logic-based PID controller can improve the performance analysis of the BLDC motor even more. This controller is found to operate better, successfully eliminating overshoot and sluggish reaction time without the need for any system mathematical calculations.

The results show that a fuzzy logic-based PI+D controller outperforms a normal PI+D controller when operating conditions change, such as a rapid load or parameter changes. This strategy improves system performance, such as startup overshoots and response time. A hybrid fuzzy PI+D controller can achieve the desired real speed and torque values in a short amount of time. The conclusion is that a hybrid fuzzy logic PI+D controller for BLDC motors is more robust, stable, and insensitive to parameter fluctuations than traditional PI+D controllers because desired speed and torque values may be obtained in a short period of time. In the future, the suggested work can be integrated with a neuro-fuzzy PID controller and other optimization techniques to obtain more dependable output, resulting in improved performance in the BLDC motor sensorless control sector. This method will be less expensive and provide better dynamic response.

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