Performance of BLDC motor with PI, PID and Fuzzy controller and its Comparative Analysis

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***Abstract*— This paper compares the speed control of brushless DC motor (BLDC) using Proportional Integral controller (PI), Proportional Derivative controller (PID), and Fuzzy controller. Conventional PI controllers are mostly used controllers in industries till now. The conventional PID controllers are also used in industries because of their simplicity and ease of retuning on-line. . But both PI and PID gives a poor performance in various operating condition. Hence it is compared with the fuzzy logic controller which gives an effective speed response. BLDC motor is widely used in industries because of their high reliability, high efficiency, and high starting torque and low electrical noise. When compared with conventional controllers, the fuzzy controller gives a better speed response. The fuzzy controller improves the performance of the motor and other operating conditions such as rise time, settling time, overshoot percentage. The overall methodology is simulated using Matlab/Simulink.**

***Keywords* — BLDC motor, PI controller, PID controller, Fuzzy controller**

I. INTRODUCTION

There are two types of DC motors used in the industry. One is a conventional DC motor and another one is a brushless DC motor. In conventional DC motor flux is produced by the current through the field coil of stationary pole structure. They are known for excellent characteristics but there are some advantages like regular maintenance of commutators, regular replacement of brushes, and high initial cost. It cannot be used in a clean or explosive environment. The second type is the BLDC motor. The permanent magnet in brushless DC motor provides necessary air gap flux instead of wire wound field poles. BLDC motors are electronically commutated and its stator is stacked with steel laminations and windings are distributed. The rotor is made up of permanent magnets and has alternate north and south poles. The speed of the BLDC motor control is controlled by PI, PID, and fuzzy controllers. The PI controllers are been used in industries for a long time. It fails to operate in dynamic conditions. The PID is also widely used in industries because of the ease of retuning on-line. But at the same time tuning the PID controller parameter is difficult because of poor robustness, good dynamic response. Hence the optimal state is difficult to achieve. The fuzzy logic controller is proven good for complex, non-linear, and unknown model systems. Hence the control is simple and effective. The proposed method shows the block diagram of the general system.

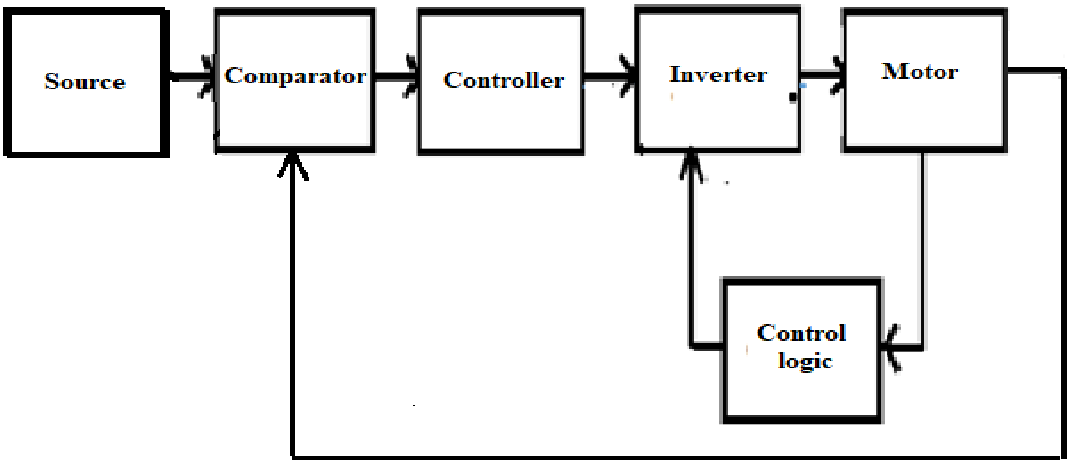

Fig. 1. Block diagram of the general model

II. BLDC MOTOR

A BLDC motor provides a large amount of torque over a vast speed range. Hence this motor is considered a high-performance motor. The torque and speed performance curve characteristics are the same as the DC motor, the brushed DC motor as BLDC motor is derivatives of these motors. The major difference between the Brushed DC motor and the Brushless DC motor is an arrangement of brushes. BLDC motors are electronically commutated and do not have brushes and hence it is called a BLDC motor. The is sinusoidal in the case of PMSM, however in BLDC this back-emf is modified to trapezoidal, and due to this modification BLDC motor is said to be a modified form of Permanent magnet synchronous motor (PMSM). The “commutation region” of the back–emf of the BLDC motor is very small. But it should not be very narrow as to make it very difficult to commutate a phase of the motor when driven by the current source inverter. For a smooth torque production, the flat constant portion of emf should be 120 degrees as shown in figure 7.

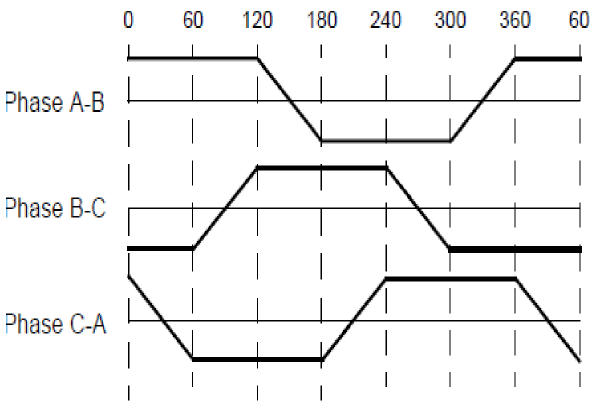

Fig. 2. **Back emf of BLDC motor – Trapezoidal waveform**

A. BLDC motor hall sensors

To rotate the BLDC motor, the stator winding of the BLDC motor must be powered in a sequence. The position of the rotor must be known to determine which winding will be enabled following the energizing sequence. The Hall Effect sensors mounted on the stator can sense the rotor positions. The rotor magnetic poles give a low or high signal whenever it passes near the hall sensors indicating that the north or south beam passes near the sensors. The combination of these three hall sensors signals determines the exact sequence of commutation. This motor is equipped with three hall sensors to determine the rotor position. These hall sensors are placed at every 120 °. Six different calculations are possible with these hall sensors as shown in figure 8. The commutation of the phase depends on the values of the Hall sensor. The hall sensor values change as the power supply to the coils changes. The torque remains high and constant with right synchronized commutations.

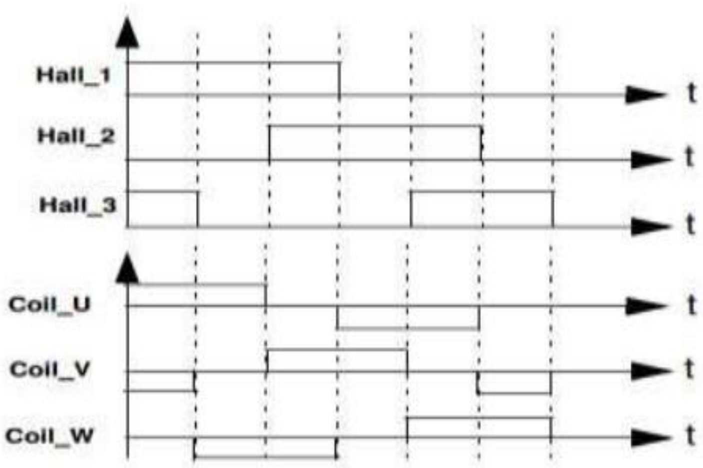

Fig. 3. **Energizing of the coil based on the hall sensor signal**

B. Phase commutation

A typical three coil BLDC motor is considered. The phase commutation depends on the hall sensor values. When the coils of the motor are rightly supplied, the magnetic field is created and the rotor rotates. The most simple commutation method used to drive the BLDC motor is the on and off a scheme that is either motor is conducting or not conducting. Only two windings are energized at one time and the third one is floating. Connecting the coils to the power supply and the neutral bus causes the current to flow. This is called a trapezoidal commutation. A power stage with three half-bridge with six switches is used to command brushless DC motors. Hall sensor values indicate which switches should be turned off. Figure 9 shows the schematic of a six-step inverter.

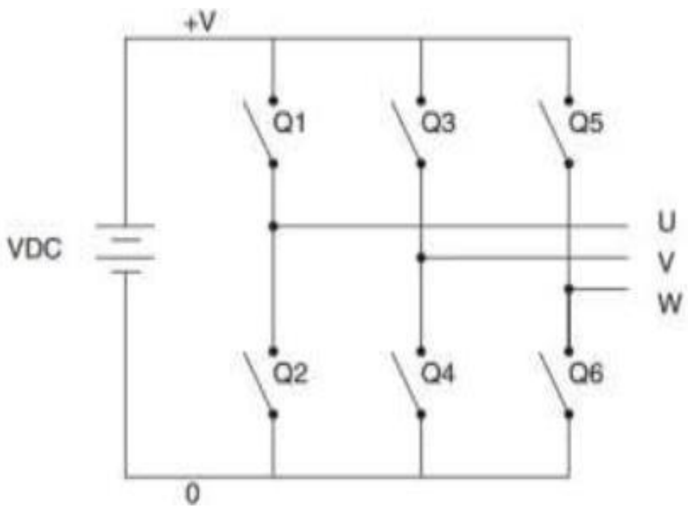

Fig. 4. **Schematic diagram of six step inverter**

C. Operation of Brushless DC Motor

Each commutation sequence is energized as follows: the first winding is energized with positive power where current enters into the winding; the second winding is energized with negative power where current exits the winding and the third is in a non-energized condition. The magnetic field generated by the stator coils interacts with permanent magnets of the rotor to produce torque. The magnetic field produced by the windings should shift position as the rotor rotates to align with the stator to keep the motor running. The sequence of energizing the windings is called a "Six-Step Commutation". Only two windings out of the three BLDC Motor windings are used at a time. Each Step is equivalent to 60 electrical degrees, so six steps make a full, 360-degree rotation. The current is controlled by one full 360, due to which there is only one current path. A Six-step commutation is typically useful in applications that require high speed and commutation frequencies. A six-step Brushless DC Motor has lower torque efficiency than a PMSM because it is trapezoidal commutated.

III. CONTROL SYSTEM OF BLDC MOTOR

As shown in figure 1 the speed control system of the BLDC motor consists of two control loops. The inner loop is to control the inverter gates with electromotive force. The outer loop is to control the speed of the motor with the help of a controller.

A. Current control loop

The inverter gate signals are produced by decoding the Hall Effect signals of the motor. The three-phase outputs of the inverter are applied to BLDC stator windings. The switching sequence of the IGBT determines the rotor position and is detected by hall sensors mounted on the stator. The hall effect sensors sense the current or flux and generate 3 digit signals (+1, -1, 0) for every 60 degrees till the completion of one full cycle i.e 360 degrees. The induced emf signals are decoded by logic gates and six gate signals are generated for every 60 degrees. The inverter voltage applied to the motor winding is controlled by these gate signals. The following table 1 shows gate logic signals.

Hall A	Hall B	Hall C	EMF A	EMF B	EMF C	Q1	Q2	Q3	Q4	Q5	Q6
0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	-1	1	0	0	0	1	1	0
0	1	0	-1	1	0	0	1	1	0	0	0
0	1	1	-1	0	1	0	1	0	0	1	0
1	0	0	1	0	-1	1	0	0	0	0	1
1	0	1	1	-1	0	1	0	0	1	0	0
1	1	0	0	1	-1	0	0	1	0	0	1
1	1	1	0	0	0	0	0	0	0	0	0

Table 1. Gate logic signals

In an IGBT inverter, each switch conducts for 120 degrees and only two switches conduct for every 60 degrees. This is used to control BLDC control due to its trapezoidal waveform and it has 6 modes of operation. Hence current and motor torque are controlled.

Cycle (in degrees)	Switching Sequence
0 - 60	5,6
60 - 120	6,1
120 – 180	1,2
180 – 240	2,3

240 – 300	3,4
300 - 360	4,5

Table 2. Switching signals

B. Speed control loop

The inverter gate signals are produced by decoding the Hall Effect signals of the motor. The three-phase outputs of the inverter are applied to BLDC stator windings. The switching sequence of the IGBT determines the rotor position and is detected by hall sensors.

a) PI Controller

PI controller is used to eliminating the steady-state error. It is the output sum of two terms, proportional and integral. The P controller utilizes the gain Kp and produces the output which is proportional to the current error value. The system becomes unstable when the proportional gain is high. To make the system stable, integral action comes into the action. It does not have the ability to predict the future errors of the system as it cannot decrease rise time and eliminate the oscillations. The output of the PI controller in the time domain is as shown as follows:

$$\text{Output} = K_p e(t) + K_i \int_0^t e(t)dt \quad (1)$$

Where K_p is the proportional gain, K_i is an integral gain. Figure 5 shows the block diagram of the PI controller.

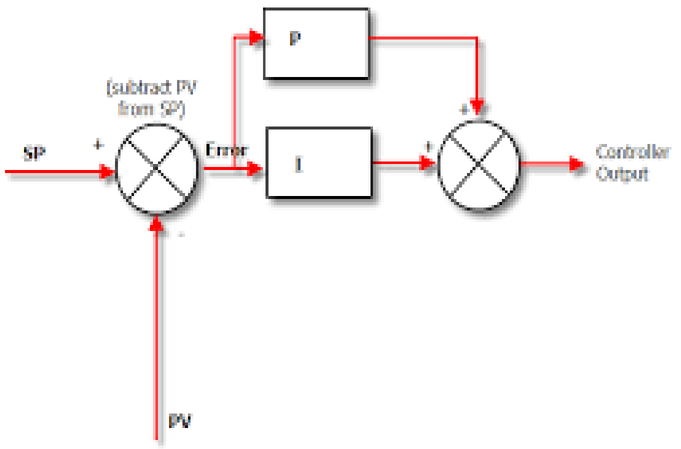

Fig. 5. Block diagram of PI controller

b) PID Controller

In the PID controller, the derivative gain component is added in addition to the PI controller to eliminate the overshoot and the oscillations occurring in the output response of the system. It is the output sum of three terms, proportional, integral, and derivative term. The controller gives zero steady error, fast response, no oscillations, and high stability. The output of the PID controller in the time domain is as shown as follows:

$$\text{Output} = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de}{dt} \quad (2)$$

Where K_p is the proportional gain, K_i is integral gain, K_d is derivative gain. The figure 6 shows the block diagram of PI controller.

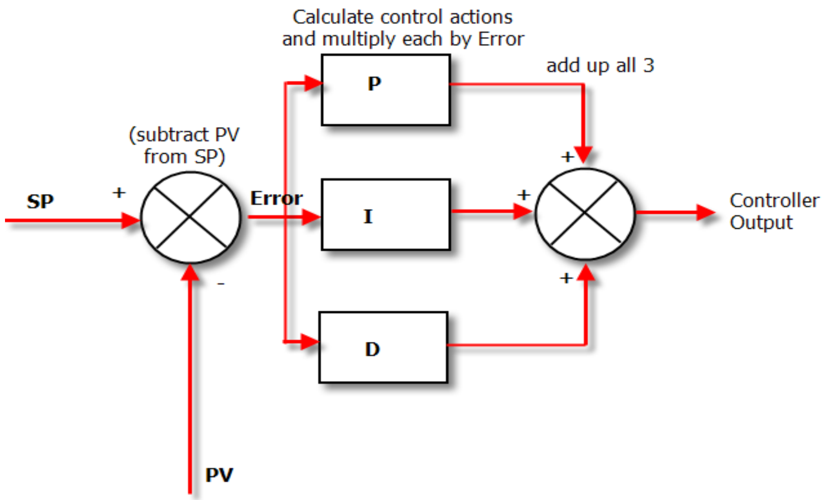

Fig. 6. **Block diagram of PID controller**

c) Fuzzy Controller

A fuzzy logic controller is used to design MATLAB Fuzzy logic toolbox. There are four basic components: - fuzzification, a knowledge base, an inference engine, and a defuzzification interface. Fuzzification is a process in which fuzziness is added to the data in fuzzy logic. Fuzzy linguistic variables are a formal representation of a system made through IF-THEN rules. The encoded knowledge about a system in statements of the form - IF (a set of conditions) is satisfied THEN (a set of consequents) can be inferred. Defuzzification is a process of converting a fuzzy set to a single crisp value. Figure 7 shows the block diagram of the Fuzzy controller.

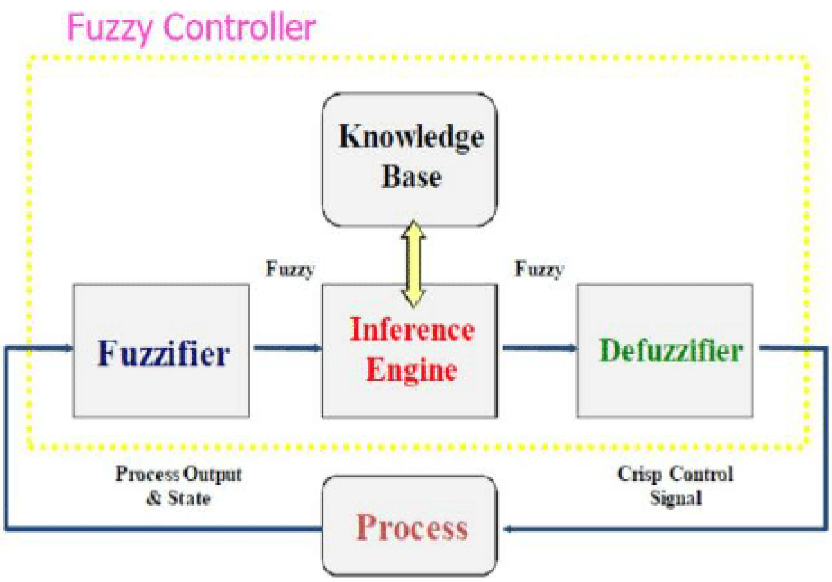

Fig. 7. **Block diagram of Fuzzy logic controller**

IV. RESULTS AND DISCUSSION

The BLDC motor rated 1kW, 500V, and 3000 rpm is driven by a six-step inverter and is simulated in MATLAB using different controllers like PI, PID, and Fuzzy. The performance of rotor and other operating conditions such as rise time, settling time, percentage of overshoot, and stability phenomenon. The speed from the output response is compared with the reference speed and the error signal is given to the respective controller. The output of the controller is given to the six-step inverter whose gate signal is produced by decoding the Hall Effect signals. Table 3 shows the specification of the BLDC motor rating. Hence the process is continued till the desired speed is obtained. Figure 8 shows the Matlab Simulink model of Speed control of BLDC motor with PI controller.

BLDC Motor rating	
Supply voltage	96
No. of poles	5
Rated speed	3000 rpm
Motor rating	1KW

Table 3. Specification of BLDC motor rating

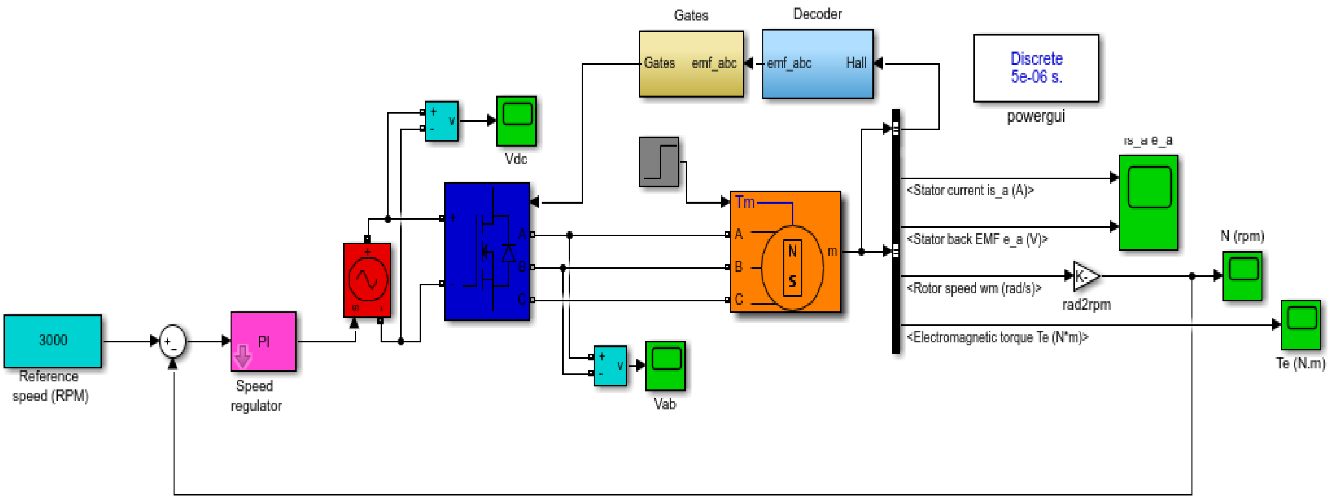

Fig. 8. Simulink model of speed control of BLDC motor with PI controller

Figure 9 shows the Matlab Simulink model of Speed control of BLDC motor with a PID controller. The speed of the BLDC motor is controlled using PI, PID. These controllers can regulate the duty cycle and hence control the voltage applied to the BLDC motor. The speed of the BLDC motor is directly proportional to the applied voltage. Reference speed is set to the speed of the BLDC motor. Any change in speed will be given as an error signal to the PI and PID controller. It takes the signal and accordingly increases as well as decreases the duty cycle of the applied gate signal.

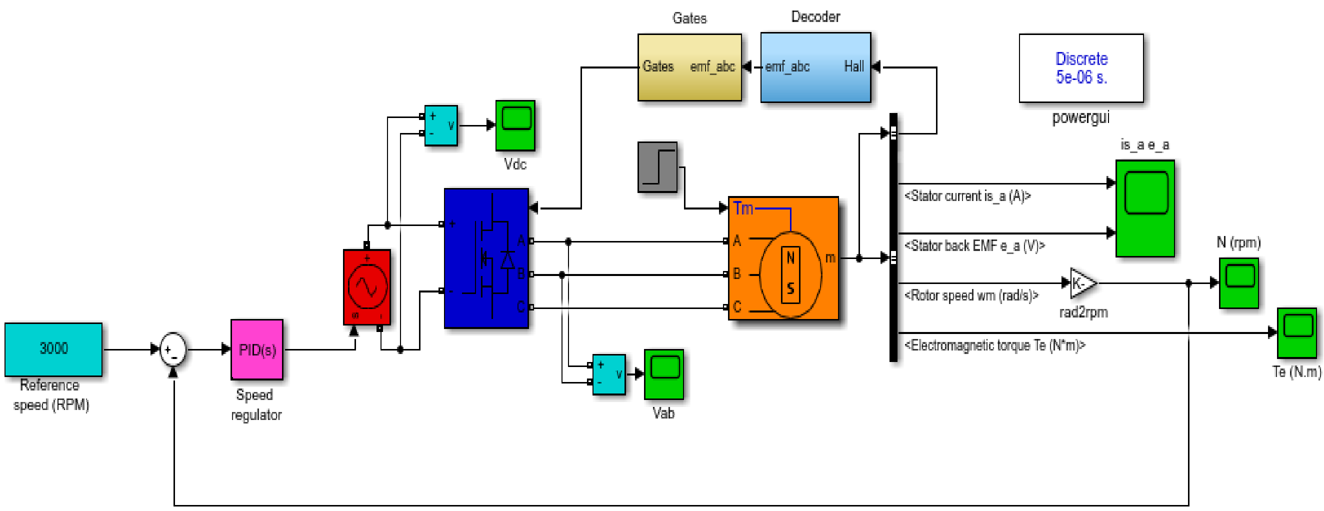

Fig. 9. **Simulink model of speed control of BLDC motor with PID controller**

Figure 10 shows the Matlab Simulink model of Speed control of BLDC motor with Fuzzy controller. Here Mamdani based fuzzy system is used. The fuzzy system consists of two input variables which are error in speed and rate of change in speed and one output variable as shown in figure 11. The triangular membership function has been used for its simplicity and great performance. Each universe of discourse is divided into seven fuzzy sets such as Negative big (NB), Negative medium (NM), Negative small (NS), Zero (Z), Positive small (PS), Positive medium (PM), Positive big (PB). A rule base consisting of forty-nine rules has been developed on the pre-defined membership functions of two inputs (e is the error and ce change in error). The rule matrix is shown in Table 4.

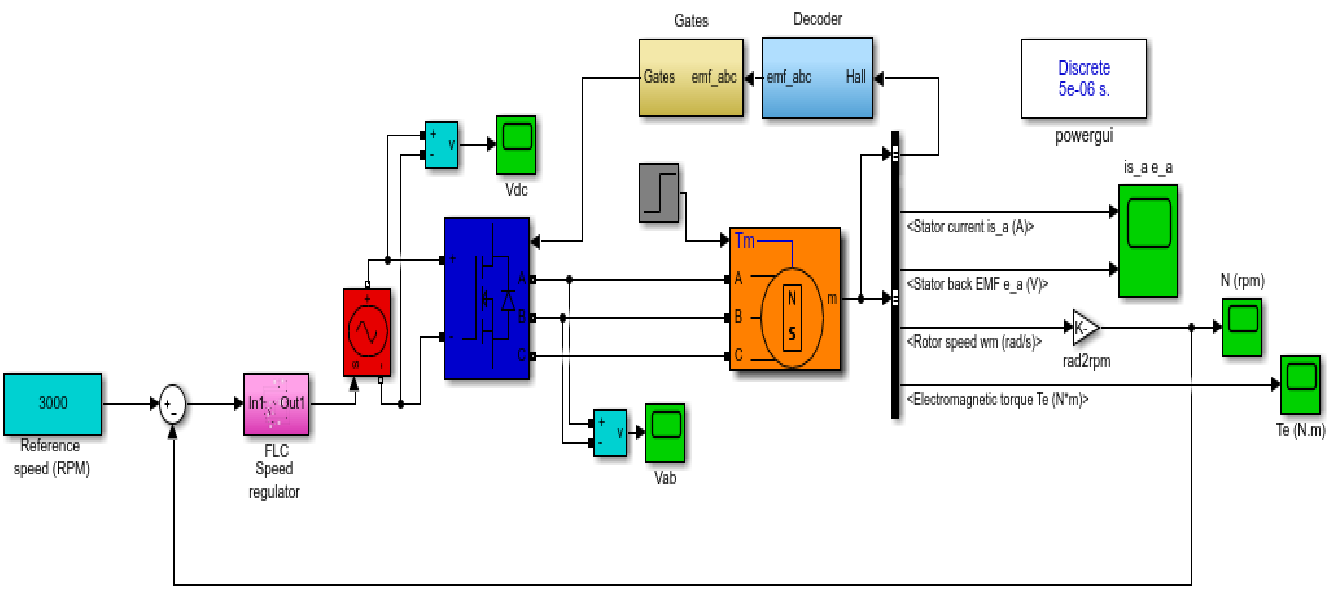

Fig. 10. **Simulink model of speed control of BLDC motor with Fuzzy controller**

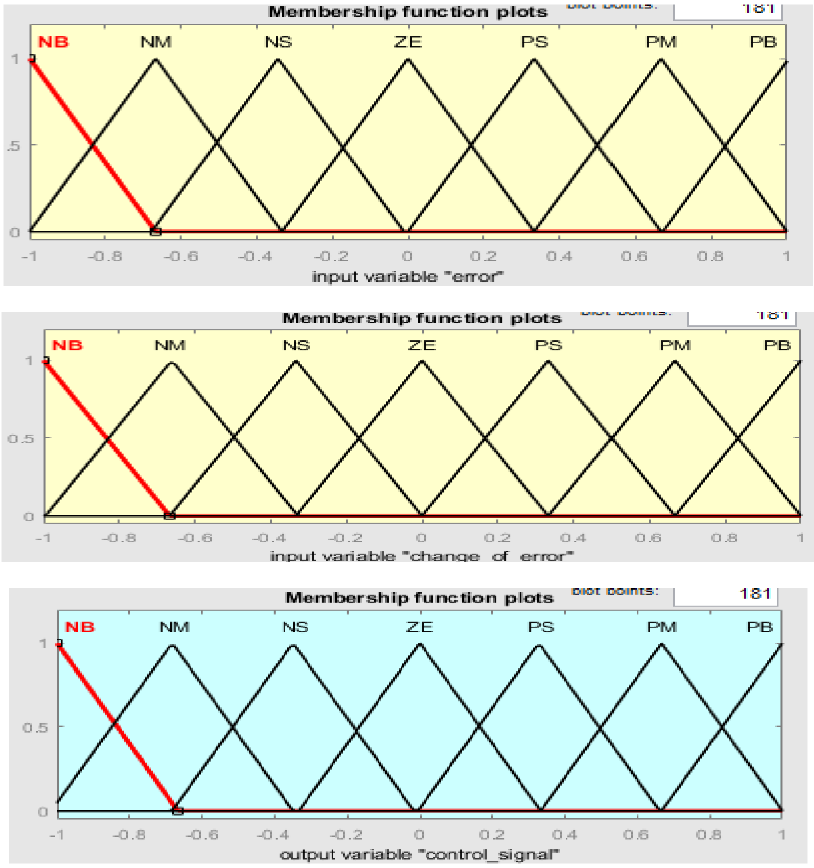

Fig. 11. **Membership function of error, change of error and control signal**

e/ce	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NB	NM	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Table 4. Membership function of error, change of error, and control signal

Figure 12 shows DC voltage fed to the inverter with various controllers.

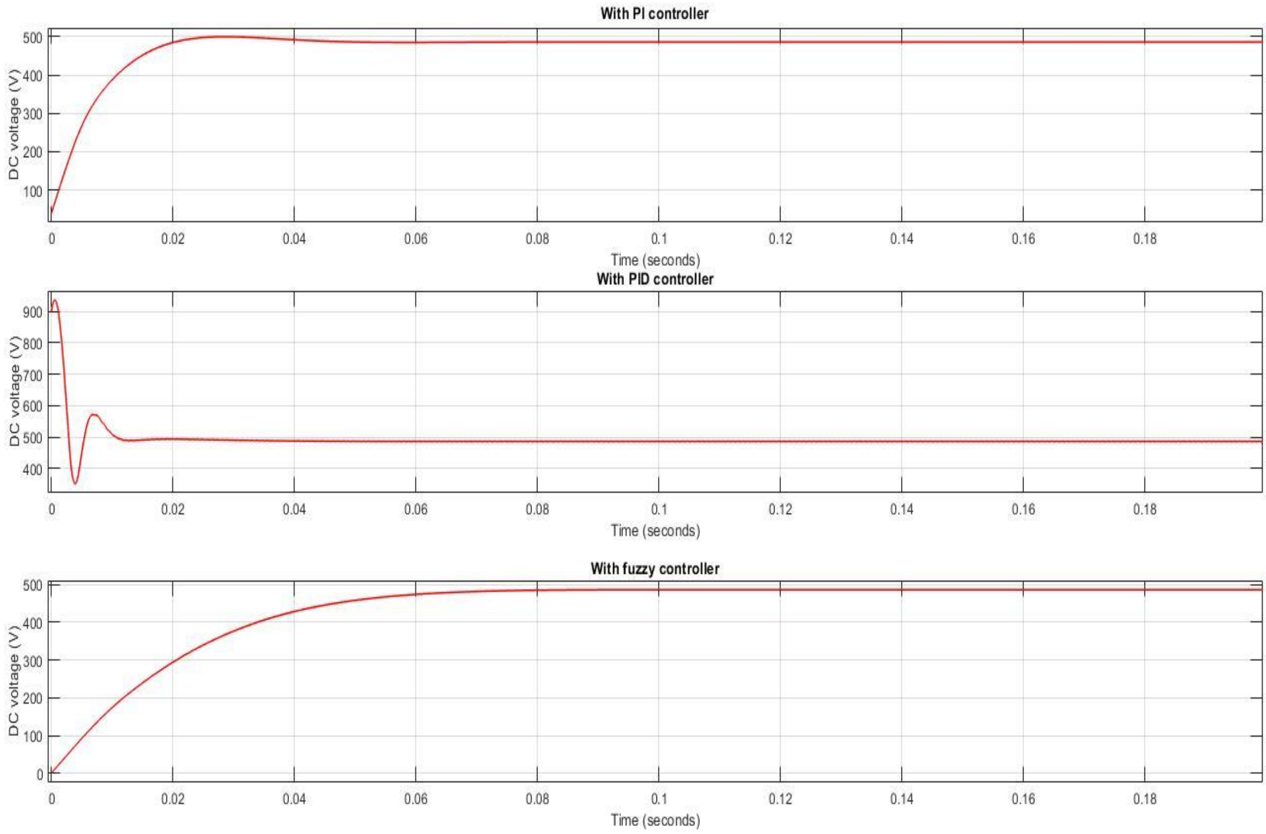

Fig. 12. Source voltage

The figure 13 shows ac voltages of the six step inverter for various controllers. The inverter converts DC to AC. The output voltage from the inverter is applied to the BLDC motors stator windings.

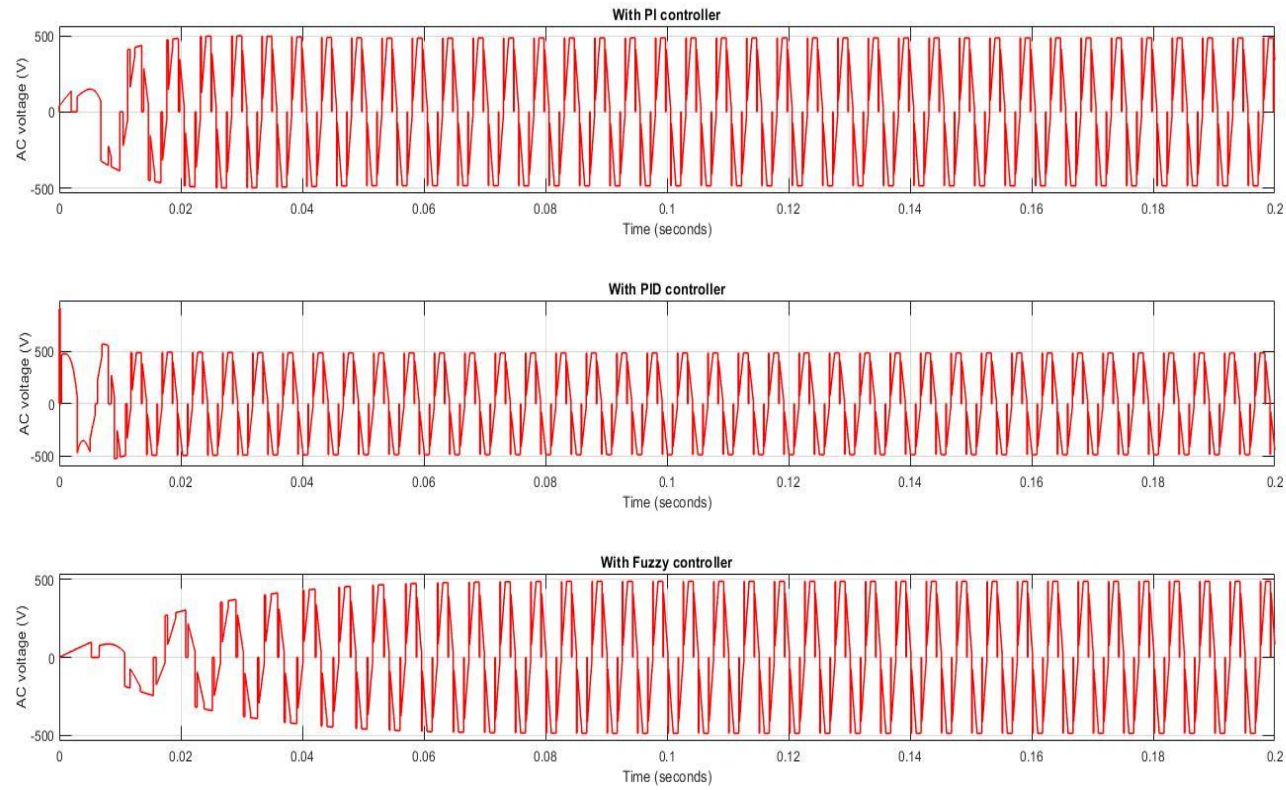

Fig. 13. Six step Inverter voltage

The figure 14 shows the back emf of stator windings of the motor for various controllers. It is seen from the figure that phasor voltages are displaced by 120 deg. It is observed that the stator currents are quasi sinusoidal in shape and displaced by 120 deg. The stator current waveforms are shown in figure 15.

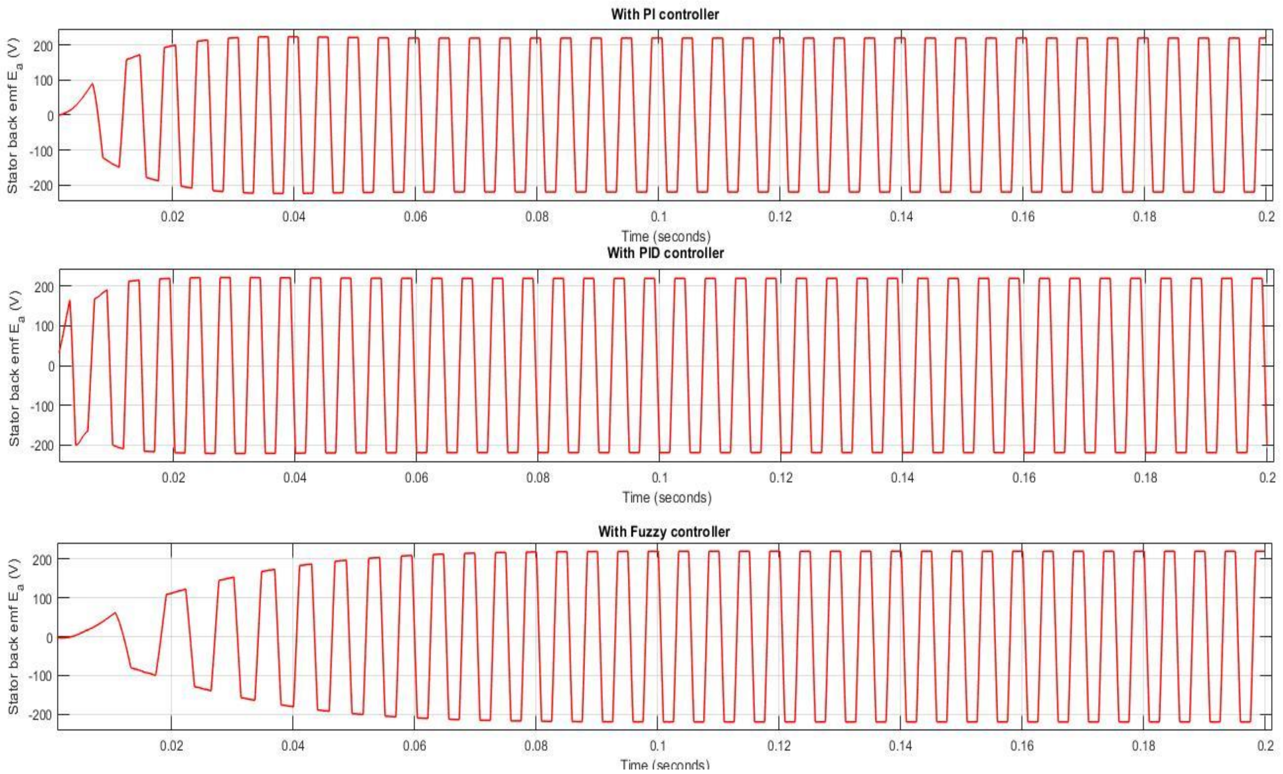

Fig. 14. **Stator back emf of BLDC motor**

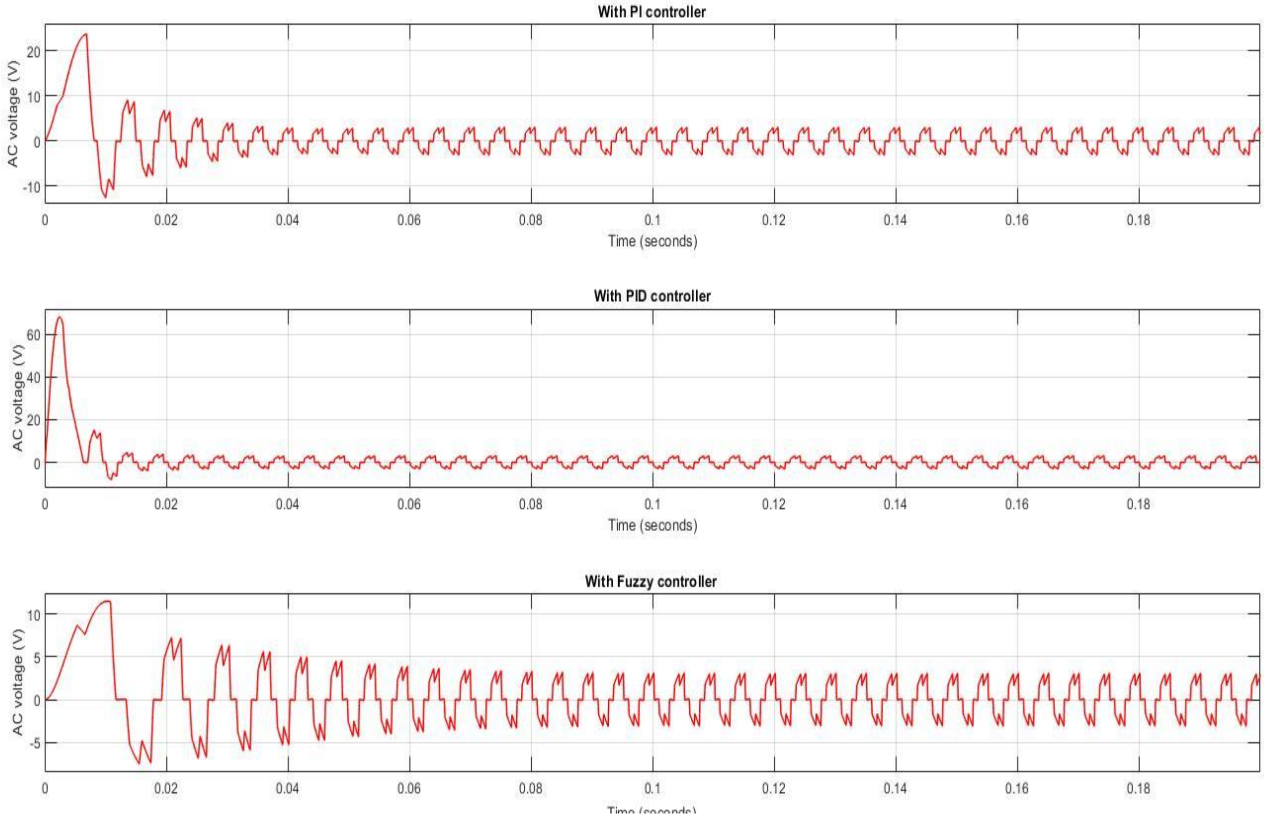

Fig. 15. **Stator currents of BLDC motor**

Figure 16 shows the sawtooth waveform of the electromagnetic torque signal Te for various controllers. Figure 17 shows the rotor speed of the BLDC motor using various controllers. It is observed that the motor achieves the speed of 3000 rpm in all cases but with different rise time, settling time, and stability. Figure 18 shows the comparison of speed for various controllers.

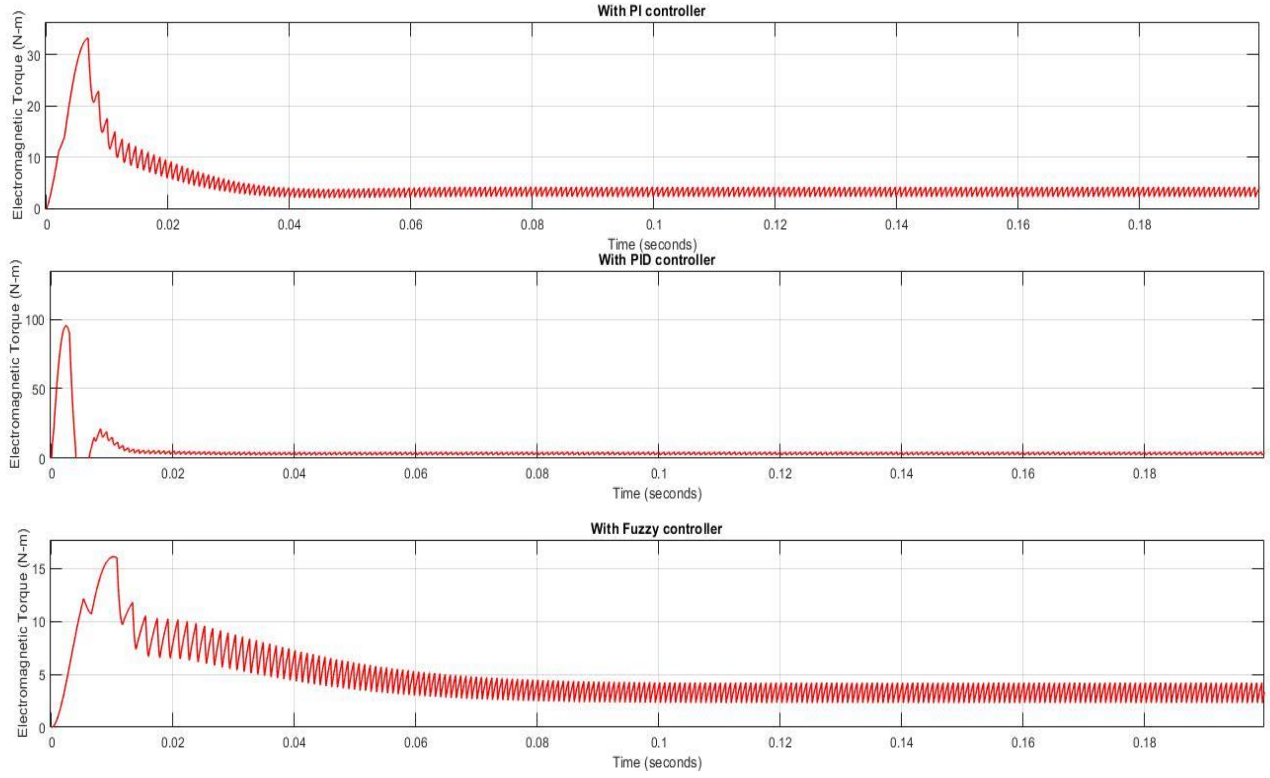

Fig. 16. Electromagnetic torque of BLDC motor

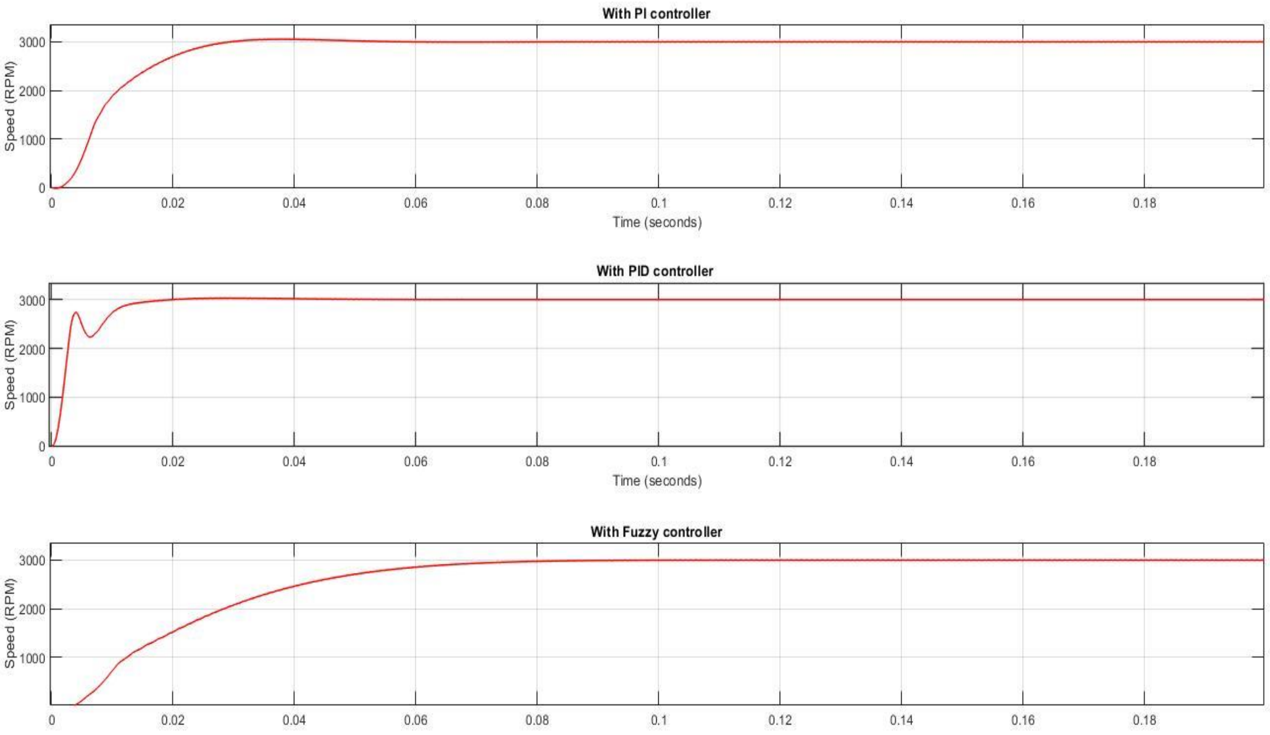

Fig. 17. **The rotor speed of the BLDC motor**

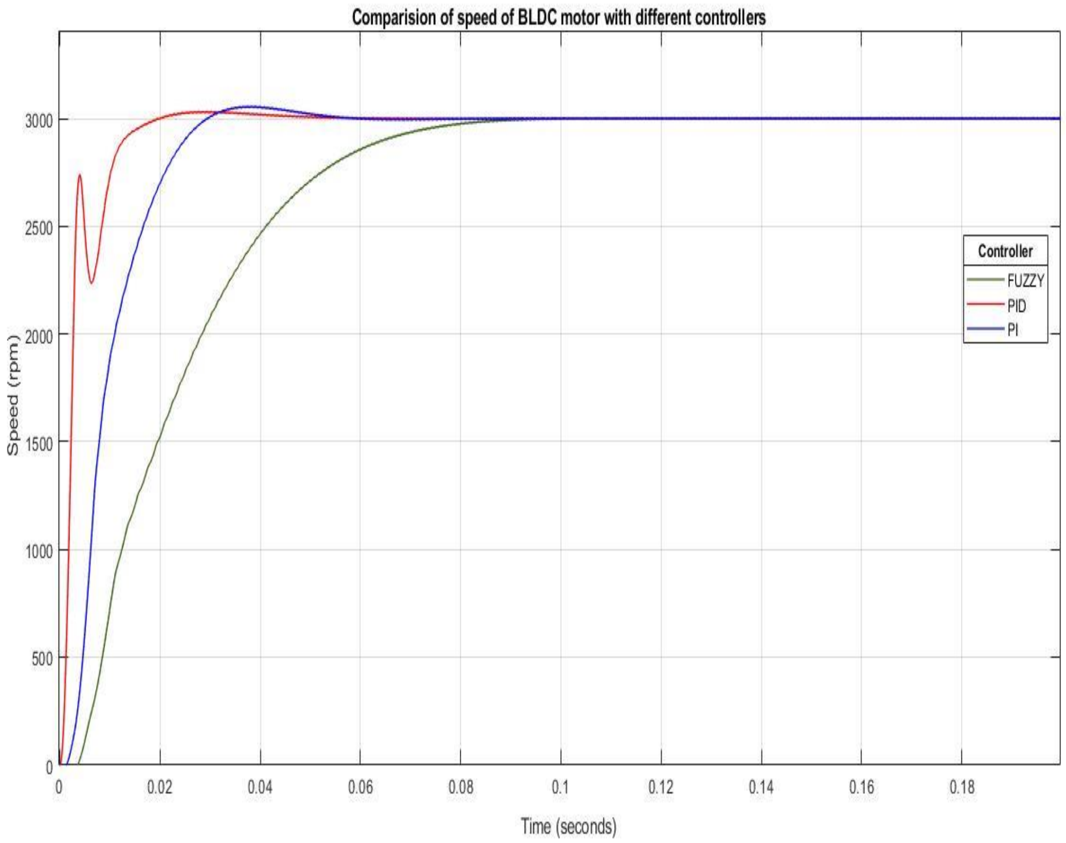

Fig. 18. Comparison of the speed of BLDC with different controllers

Table 5 shows the comparison of various operating conditions such as rise time, settling time, and overshoot percentage.

Controller	Rise time T_R (sec)	Settling time T_S (sec)	Overshoot Percentage (%)
PI controller	0.03	0.06	1.7
PID controller	0.01	0.06	0.9
FUZZY controller	0.08	0.11	0

Table 5. Characteristics of speed response

The rise time of the PID controller is less than the PI and fuzzy controller. The settling time of PI and PID is the same and lesser than the fuzzy controller. The overshoot percentage of PI is 1.7% more than the fuzzy controller and the overshoot percentage of PID is 0.9% more than the fuzzy controller.

CONCLUSION

A six switch, three half-bridge inverter is powered by a controlled voltage source which drives the three-phase BLDC motor rated 1 kW, 500 Vdc, 3000 rpm. The model is simulated using Matlab/Simulink and its performance is analyzed with different controllers

The gate signals to the inverter are produced by decoding the hall effect signals of the motor. The three-phase output of the inverter is applied to the BLDC stator windings. The motor current has a quasi sinusoidal waveform. and the emf has a sawtooth waveform. The speed of the BLDC motor is controlled by a PI, PID, and fuzzy controller. The stator emf, stator current, rotor speed, and electromagnetic torque are analyzed. The operating conditions such as rise time, settling time, and overshoot percentage is calculated. It is seen that even though the fuzzy controller has slightly more rise time and settling time, the percentage overshoot is zero. The PID controller proves to be a better controller than the PI and Fuzzy controller in terms of rising time and settling time and Fuzzy controller proves to better controller than PI and PID in terms of overshoot. Hence for future work, a Fuzzy –PID controller can be designed to overcome these conditions.

REFERENCES

[1] K.Sushita, N. Shanmugasundaram "Performance Analysis of Solar operated BLDC motor" International Journal of Advanced Science and Technology, Vol. 29, No. 7, (2020), pp. 1517-1527.

[2] Shanmugasundaram.N &Thangavel.S (2017) "Modeling And Simulation Analysis of Power Cable A Three Level Inverter Fed Induction Motor Drive" Journal of Computational and Theoretical Nano Science ISSN NO 15461955, Vol. 14, 972–978, 2017 AMER SCIENTIFIC PUBLISHERS

[3] N.Shanmugasundaram, R.Vajubunnisa Begum "Implementation of Tracking System Using IOT for Smart City" International Journal of Management, Technology And Engineering Volume V, Issue XII, December/ 2018, ISSN NO : 2249-7455 PP NO 5347-5353

[4] N. Shanmugasundaram, K. Sushita, S. Pradeep Kumar and E.N. Ganesh "Genetic algorithm-based road network design for optimising the vehicle travel distance" *Int. J. Vehicle Information and Communication System, Vol. 4, No. 4, 2019*

[5] Akash Varshneya, Deeksha Guptab, Bharti Dwivedi, "Speed Response of Brushless DC Motor using Fuzzy PID Controller under Varying Load Condition" , Journal of Electrical Systems and Information Technology 00 (2017) 000–000

[6] S.Priya, Althaf Patan, " Speed Control of Brushless Dc Motor Using Fuzzy Logic Controller," IOSR Journal of Electrical and Electronics Engineering, Volume 10, Issue 6 Ver. I (Nov – Dec. 2015), PP 65-73

[7] Pranoti K. Khanke, Sangeeta D. Jain, "Comparative Analysis of Speed Control of BLDC Motor Using PI, Simple FLC and Fuzzy – PI Controller" , 2015 International Conference on Energy Systems and Applications (ICESA 2015)

[8] C. Sheeba Joice, P. Nivedhitha, "Simulaton of speed control of brushless DC motor, with Fuzzy Logic Controller", International Journal of Electrical, Electroics and Data communication, volume-2, Issue -4, April– 2014.

[9] Shivanand Pandey, Bhagirath Pandey, "DC motor torque control using Fuzzy Proportional Derivative controllers", International Journal of Engineering and Advance Technology, volume 3, Issue 6, Aug 2014.

[10] Manoj Kushwah, Prof. Ashis Patra, "Tuning PID controller for speed control of DC motor using soft computing technique – A Review", Advnce in Electronic and Electric Engineering, Volume 4, Issue 02, Aug 2014.