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Evaluation and Comparative Analysis of Speed Performance of Brushless DC Motor using Digital Controllers

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Abstract: This paper presents modeling, performance evaluation, and comparative analysis of speed performance of brushless DC motor (BLDCM) by using digital controllers. Speed performance analysis is carried out by using time response specifications which are useful for determining the effectiveness of the digital controllers. The wide spread of BLDCM in many areas due to the advantages of BLDCM over the conventional widely used motors such as induction motor and brushed DC motor. Advantages of BLDCM include higher efficiency, lower maintenance, longer life, reduced losses, single excitation, etc. Controllers are used to improve the transient and steady state speed response of the BLDCM. In many applications conventional PID controller is widely used to control the speed of the BLDCM but the main issue with the conventional PID controller is that it requires manual tuning of the parameters such as proportional, integral, and derivative gain constant. Even though the auto-tuning methods are available with the PID controller it is not adaptive itself to handle the conditions such as variations in parameters, disturbances in load, etc. In this Paper the Fuzzy-PID controller is used to control the speed of the BLDCM and Transient and steady state speed performance analysis is carried out using conventional PID controller and Fuzzy-PID to showcase the comparative analysis between two controllers. MATLAB/SIMULINK environment is used for modeling of the BLDCM and its drive/control system.

Keywords: Brushless DC Motor (BLDCM), Fuzzy Logic Controller (FLC), Modeling of BLDC drive/control system, of PID controller, Transient and steady state analysis

I. INTRODUCTION

Brushless DC motor in short BLDCM also known as the permanent magnet DC motors. Permanent magnet motors are the motors which are the motors uses permanent magnet to create the main magnetic field in order to replace the field winding. Most of the conventional motors have stationary field winding and rotating armature winding but in case of the permanent magnet motors the field winding replaced with the permanent magnets and it is rotating part. While the armature winding is the stationary part. An electronic commutation is used for commutation of the BLDCM, Electronic commutation is carried out by means of the three-phase inverter with trapezoidal waveforms. There is no presence of mechanical commutation part as that of the brushed DC motor hence there is absence of commutator bars and brush gears. The BLDCMs are extensively used as efficient industrial drives for machine tools, computer hard disk drives and control applications.

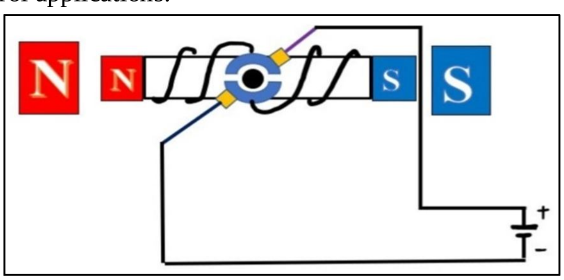

Fig. 1 Schematic of Brushed DC Motor

Fig. 1 shows the schematic of brushed DC motor where commutation is of mechanical type and as there is presence of the commutator bars and brushes gears hence it has lower efficiency due to the power loss in this mechanical commutation. One key difference between the brushed DC motor and the BLDCM is that in brushed DC motor, electromagnet is the rotating part while the permanent magnets are the stationary part but in BLDCM electromagnet is a stationary part while the permanent magnets are the rotating part as shown in Fig. 2.

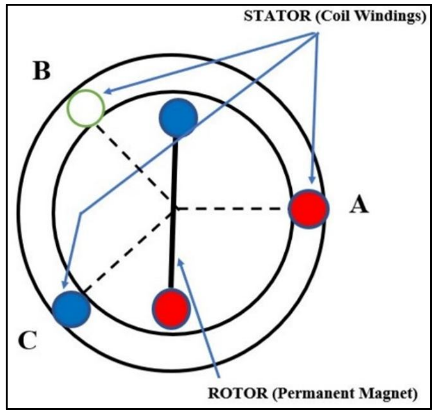

Fig. 2 Schematic of BLDCM

From the comparison between the two schematic it can be concluded that the BLDCM can be treated as the flipped version of permanent magnet brushed DC motor. From few decades PID controller is widely used in industrial control application as it provides advantages of proportional, integral, and derivative action of the controlling parameters. In actual scenario and for efficient control action, the exact mathematical modeling of the system required but the exact mathematical model of the system is mostly complex and nonlinear in nature which is the main concern of the conventional controllers. Due to this approximation the system may produce the better transient and steady state response but not the optimum one. In actual scenario the motor parameters are always subjected to the change due to the change in physical, electrical, mechanical, and environmental parameters of the system. Electrical conditions involve change in winding resistance, terminal resistance, change in ON state resistance of the power electronic switches used for controlling purposes. Mechanical parameters involve changes in inertia, friction, inertia elements in coupling and decoupling, etc. Environmental parameters include change in temperature, moisture, humidity, etc. These changes in parameters not properly addressed by the conventional PID controller hence the Fuzzy- PID is used because of the advantage of adaptiveness in control action.

The information referred from various literatures for carrying out this study is as follows. Closed loop speed control system along with comparison between conventional PID controller and fuzzy logic controller is discussed in [1]. Comparative analysis between speed performance of BLDCM using PI controller, FLC and Fuzzy-PI is presented in [2]. Comparative analysis between speed performance of conventional PI controller, anti-windup PI controller, and fuzzy logic controller is described in [3]. Bidirectional control scheme of the PID controller for speed control of the BLDCM presented in [4]. Speed of the BLDCM using PI and fuzzy controller is described in [5]. Adaptive PID controller is used to control the speed of the BLDCM in [6]. Design and comparison between Fuzzy-PID controller and adaptive Fuzzy-PID controller are presented in [7]. PI and fuzzy controller is used to control speed of the BLDC motor in [8].

This paper is organized into five sections. Section II deals with the mathematical modeling of the BLDC motor. Section III deals with the details regarding the working of the BLDCM. Section IV presents modeling of the proposed speed control system for BLDCM. Section V deals with the result and discussion on speed performance of the BLDC motor. Paper ends with the conclusion presented in section VI.

II. MATHEMATICAL MODELING OF BLDCM

The equivalent electrical circuit of the three phase BLDC motor is shown in Fig. 3. From equivalent circuit of BLDC motor, phase voltage Va, Vb, and Vc equation in the form of the matrix is given in Eq. (1).

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} + \begin{bmatrix} (L-M) & 0 & 0 \\ 0 & (L-M) & 0 \\ 0 & 0 & (L-M) \end{bmatrix} \frac{d}{dt} \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} + \begin{bmatrix} Ea \\ Eb \\ Ec \end{bmatrix} \tag{1}$$

Where,

R: Per phase resistance, Ia: Per phase current of phase a, Ib: Per phase current of phase b, Ic: Per phase current of phase c, L: Per phase self-inductance of the coil, M: Per phase mutual inductance of the coil, Ea: Back EMF per phase of phase a, Eb: Back EMF per phase of phase b, and Ec: Back EMF per phase of phase c.

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As input to the BLDC motor is from the inverter to excite the motor. Line voltage equation is preferable because at any one instant two windings are excited to create two poles. Line voltages Vab, Vbc, and Vca in matrix form is given in Eq. (2).

$$\begin{bmatrix} Vab \\ Vbc \\ Vca \end{bmatrix} = \begin{bmatrix} R & -R & 0 \\ 0 & R & -R \\ -R & 0 & R \end{bmatrix} \begin{bmatrix} L-M & M-L & 0 \\ 0 & L-M & M-L \\ M-L & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} + \begin{bmatrix} Ea-Eb \\ Eb-Ec \\ Ec-Ea \end{bmatrix} \quad (2)$$

Torque equation for BLDC motor is given as

$$\mathrm{Te} - \mathrm{Tl} = J\frac{d\omega}{dt} + B\omega \quad (3)$$

Where, T_e: Electromagnetic Torque, T_l: Load Torque, B: Viscous Friction Coefficient, J: Moment of Inertia, and W: Angular Velocity of Rotation

$$T_e = K_t \times I \quad (4)$$

Where, K_t: Torque Coefficient

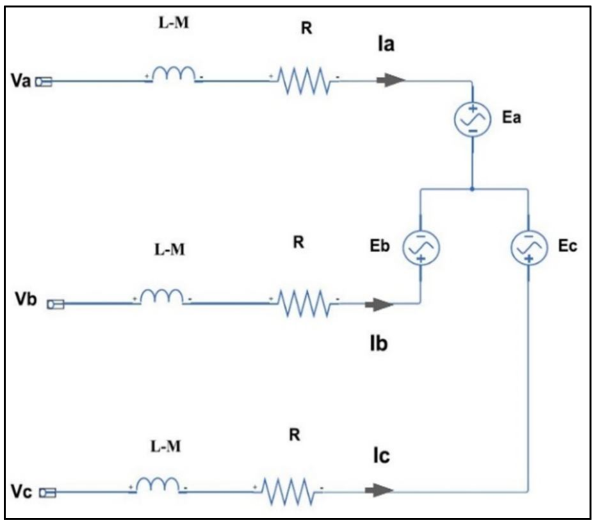

Fig. 3 Equivalent Electrical Circuit of BLDCM

Commutation is required to rotate the motor and commutation is provided by a three-phase voltage source inverter. Even though a three-phase supply is provided by an inverter but at any instant, only two phases are excited to energize any two winding at a time. Let for an instant phase a and b are energized then relation between Ia and Ib is given in Eq. (5).

$$Ia = -Ib \quad (5)$$

Ignoring back EMF transient, Ea and Eb are equal in magnitude and reverse in polarity, relation between Ea and Eb is given in Eq. (6).

$$\mathrm{Ea} = -\mathrm{Eb} \quad (6)$$

By using Eq. (6) in Eq. (2) and assuming Vab=Vd i.e., line voltage, Vab between phase a and b is given in Eq. (7).

$$\mathrm{Vd} = 2\mathrm{RI} + 2(\mathrm{L}-\mathrm{M})\frac{dI}{dt} + 2\,\mathrm{Ea} = \mathrm{Ra} * \mathrm{I} + \mathrm{La} * \frac{dI}{dt} + \mathrm{Ke}\,\omega \quad (7)$$

At no load (T_l = 0), Eq. (3) is given as

$$\mathrm{Te} = J\frac{d\omega}{dt} + B\omega \quad (8)$$

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Volume 9 Issue X Oct 2021- Available at www.ijraset.com

By using Eq. (4) in Eq. (8), resultant equation is given as

$$Kt * I = J\frac{d\omega}{dt} + B\omega \tag{9}$$

$$I = \frac{J\frac{d\omega}{dt} + B\omega}{Kt} \tag{10}$$

$$I = \frac{J}{Kt} * \frac{d\omega}{dt} + \frac{B}{Kt} * \omega \tag{11}$$

By using Eqn. (11) in Eqn. (7), result of Vd is given as

$$Vd = Ra * (\frac{J}{Kt} * \frac{d\omega}{dt} + \frac{B}{Kt} * \omega) + La * \frac{d(\frac{J}{Kt} * \frac{d\omega}{dt} + \frac{B}{Kt} * \omega)}{dt} + Ke\,\omega \tag{12}$$

$$Vd = (\frac{J * La}{Kt})\frac{d\hat{}(2)\omega}{dt\hat{}(2)} + (\frac{J * Ra + La * B}{Kt})\frac{d\omega}{dt} + (\frac{B * Ra + Kt * Ke}{Kt}) * \omega \tag{13}$$

From eq. (13), the output of the BLDC motor is dependent on the input line voltage and it implies that BLDC motor speed control can be easily achieved by controlling the input line voltage. eq. (13) is the second-order differential equation and it can be easily solved and the transfer function is obtained by using Laplace transform. Laplace transform on eq. (13) is given in eq. (14)

$$Vd(s) = (\frac{J * La}{Kt})S2\omega(s) + (\frac{J * Ra + La * B}{Kt})S\omega(s) + (\frac{B * Ra + Kt * Ke}{Kt})\omega(s) \tag{14}$$

For BLDC motor, output is the rotation of the shaft i.e., ω(s) and input is voltage Vd(s), so transfer function T_v(s) is given in Eq. (15).

$$Tv(s) = \frac{\omega(s)}{Vd(s)} = \frac{Kt}{(J * La)(S^2) + (J * Ra + La * B)(s) + (B * Ra + Kt * Ke)} \tag{15}$$

From the Eq. (15), block diagram of the BLDCM at no load is shown in Fig. 4.

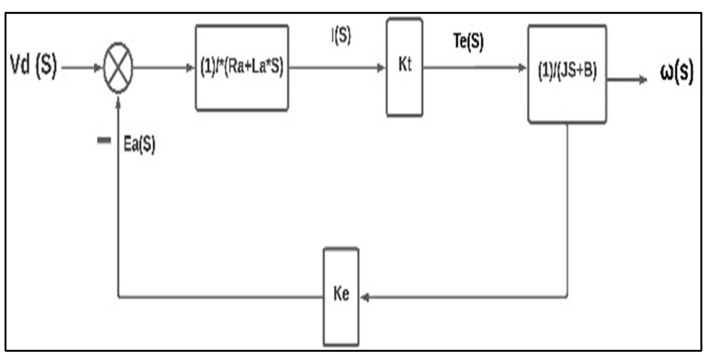

Fig. 4 Block diagram of BLDCM at no load

Transfer function when output is rotation of shaft ω(s) and input is load torque i.e., T_l (s) then transfer function (T_l(s)) is given in Eq. (16).

$$Tl\,(s) = \frac{\omega(s)}{Tl\,(s)} = \frac{(Ra + La * S)}{(J * La)(S^2) + (J * Ra + La * B)(s) + (B * Ra + Kt * Ke)} \tag{16}$$

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From the Eq. (14), block diagram of the BLDCM at any load T_l is shown in Fig. 5.

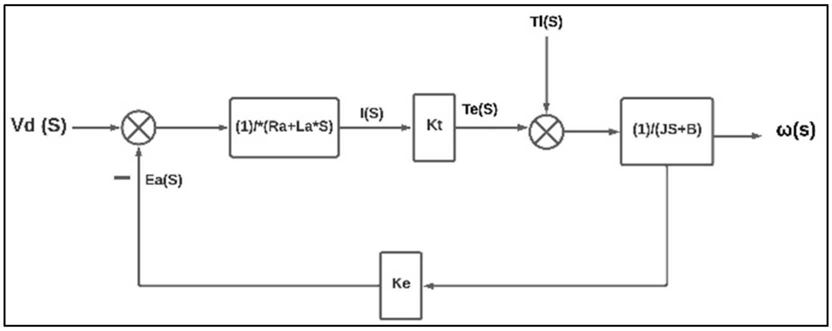

Fig. 5 Block diagram of BLDCM with load torque

From Eq. (16) and Eq. (17), it is concluded that BLDCM speed depends on input voltage and load torque and hence the speed control of the BLDC motor can be controlled by using input voltage as well as load torque. BLDC motor speed ω(s) in terms of V_d and T_l is given in Eq. (18).

$$\omega(s) = \frac{Kt * Vd(s)}{(J * La)(S^2) + (J * Ra + La * B)(s) + (B * Ra + Kt * Ke)} + \frac{(Ra + La * S) * Tl(s)}{(J * La)(S^2) + (J * Ra + La * B)(s) + (B * Ra + Kt * Ke)} \quad (18)$$

III. WORKING OF BLDCM

BLDCM is considered as single pole pair for understanding purpose. Single pole pair means there is a north and south pole on rotor which is created by using permanent magnet while the pole on stator also having one north and south pole. Stator windings are placed at the 120 degrees apart from each other and there are three windings as indicated by ‘A’, ‘B’, and ‘C’. Rotation of the BLDCM solely depends on the excitation of stator winding in a such way that two coils out of three are excited at a time to give resultant pole as shown by dotted line in the Fig. 6. This dotted line is the pole pair created on the stator and attract rotor permanent magnet to align itself in this way BLDCM starts rotating.

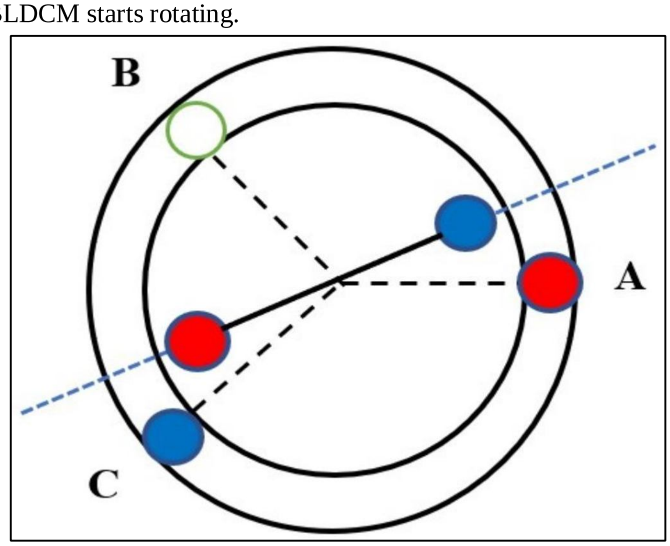

Fig. 6 Alignment of Rotor with Stator Magnetic Field

As BLDCM is a electronically commuted motor. Three phase inverter is used for the electronic commutation. Commutation process is the way so that rotor of the motor keeps on rotating. So, the Three phase inverter excite stator winding in a such way that rotor keep on rotating as shown in Fig. 7. Inverter converts DC applied to it into AC with the trapezoidal waveform and excite the any two-coil winding by turning on the one switch from high side and one switch from low side.

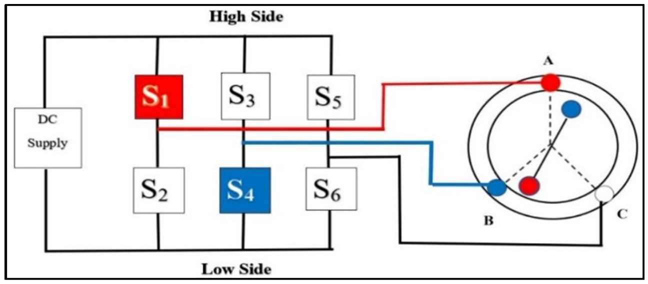

Fig. 7 BLDCM with three phase VSI

Block diagram for speed control of BLDCM is shown in Fig. 8. Main components for controlling the speed of BLDCM include Hall effect sensor, commutation logic, three phase inverter, PWM generator, controller, etc. Closed loop system is a negative feedback closed loop system helps in reducing the error between desired and measured speed. Hall effect sensor is used to sense the rotor position and indicate the current sector of the rotor. The sector information is the forwarded as a signal to the commutation logic. This commutation logic decides the next switching pattern for three phase inverter so that to excite stator winding in a such way that new stator pole pair is created in next sector. PWM generator is a combination of PWM frequency generator and DC to DC converter to make input voltage variable. Controller and negative feedback is used to track desired speed with improved time response specifications.

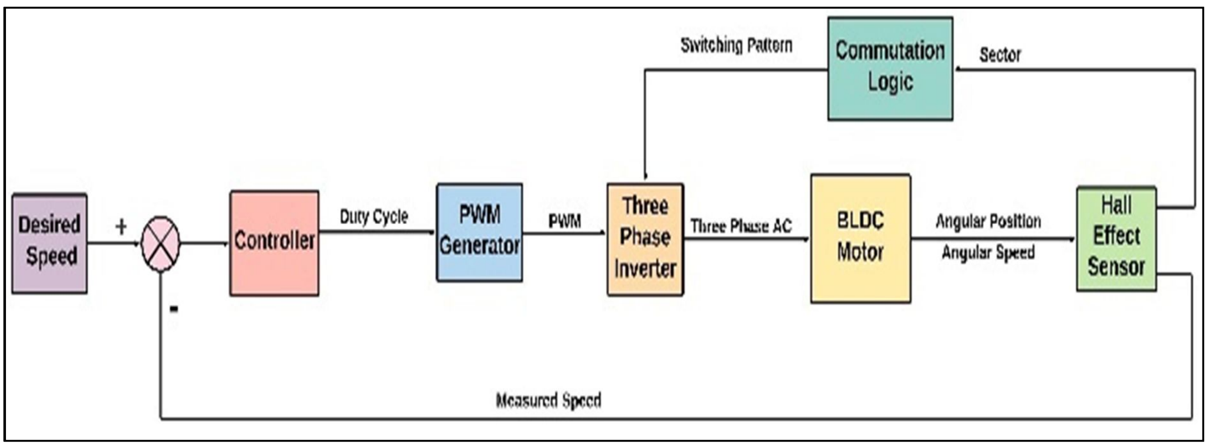

Fig. 7 block diagram for speed control of BLDCM

Rotor position and sector information for single pole BLDCM is shown in Table I. For two pole pair BLDCM the angle will be divided in multiple of the 30 degree instead of 60 degrees and stator will have 6 coils instead of 3. Sector nothing but the area that is covered by the permanent magnet rotor when it tries to align with the pole pair created by the stator winding.

TABLE I
Rotor Position Versus Sector

ϴ (Degree)	Sector
$0 < \Theta \leq 60$	1
$60 < \Theta \leq 120$	2
$120 < \Theta \leq 180$	3
$180 < \Theta \leq 240$	4
$240 < \Theta \leq 300$	5
$300 < \Theta \leq 360$	6

Commutation logic is the logic of turning on the stator winding in order to continue rotation and guide the inverter for switching according to the sector information. Table II shows commutation logic table for single pole pair BLDCM. ‘H’ indicates high side switch whereas ‘L’ indicates low side switch of the inverter. ‘A’, ‘B’, and ‘C’ are the phases of three phase inverter. ‘0’ and ‘1’ indicates the OFF and ON status of the switches.

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Volume 9 Issue X Oct 2021- Available at www.ijraset.com

TABLE III
Commutation Logic

A_H	A_L	B_H	B_L	C_H	C_L
1	0	0	0	0	1
0	0	1	0	0	1
0	1	1	0	0	0
0	1	0	0	1	0
0	0	0	1	1	0
1	0	0	1	0	0

Pulse width modulation is the way of generating variable DC voltage form the input DC supply. Fig. 9 shows the modulation of 100 Volts DC voltage to get 50 Volts by using PWM. The output of PWM depends upon the duty cycle (Δ) and it is the ratio of time for which signal is given to the PWM generator (T_{on}) and the total period (T) of the PWM signal.

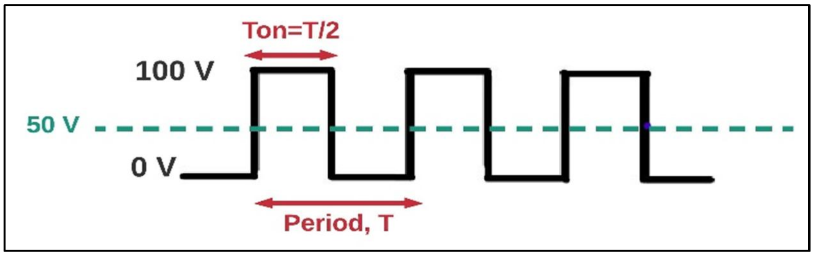

Fig. 8 Pulse Width Modulation (PWM)

Mathematically duty cycle (Δ) and percent duty cycle (%Δ) are given in Eqn. (19) and Eqn. (20), respectively.

$$\Delta = \frac{Ton}{T} \tag{19}$$

$$\%\,\Delta = \frac{Ton}{T} * 100 \tag{20}$$

Higher the ON period (T_{on}) of switches, the higher the output voltage of the buck converter. For 50 Volts at the output ON period should be kept for half period means duty cycle is 0.5 and percent duty cycle is 50 %. The PWM has averaging effect to get the desired level of variable output voltage hence by changing the duty cycle output voltage can be made variable depending upon the input duty cycle to the PWM generator.

IV. MODELING OF PROPOSED SPEED CONTROL SYSTEM FOR BLDCM

Speed control model of BLDC motor includes blocks or subsystem of components used to drive the BLDCM. Blocks/subsystem for various components to drive BLDCM are discussed in this section. MATLAB/SIMULINK environment is used to model subsystem and overall control system for Speed control of the BLDCM.

A. BLDCM Block

Fig. 10 shows the block of BLDCM. Ports on left side are for electrical connection whereas on the right side are for mechanical connection.

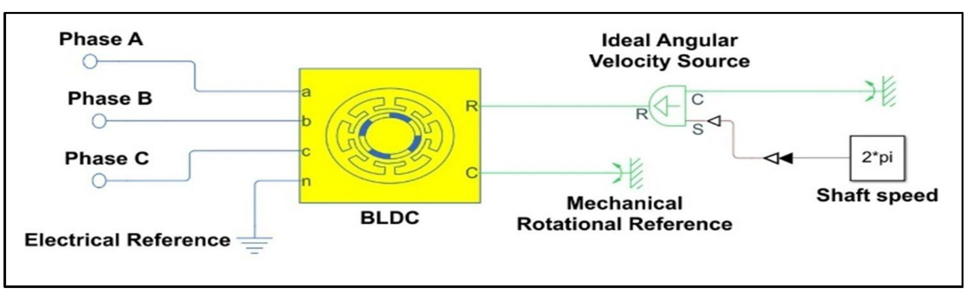

Fig. 9 BLDCM block

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Volume 9 Issue X Oct 2021- Available at www.ijraset.com

B. Three Phase Inverter subsystem

Fig. 11 shows the subsystem for the three-phase inverter where MOSFET switches are used for modeling purposes. Current and voltage sensors are used to sense the current and voltage that is acts as the input to the BLDCM.

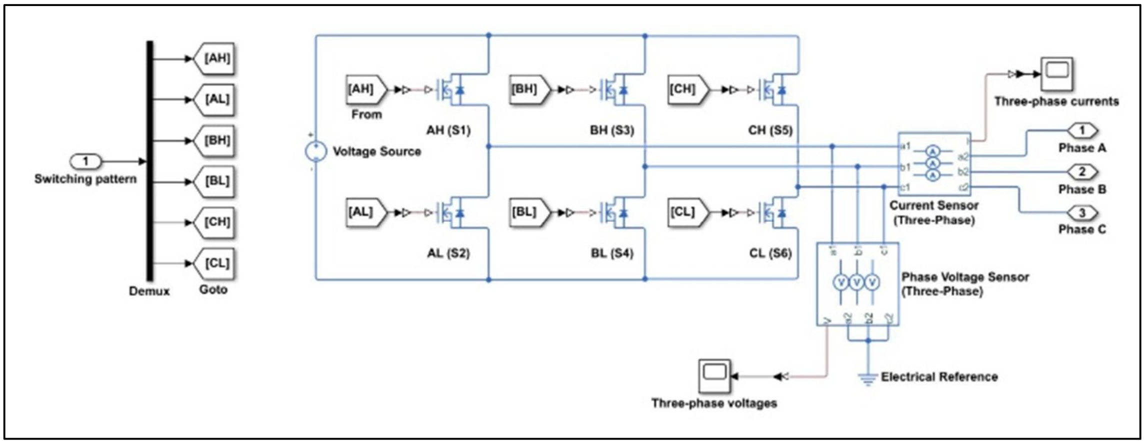

Fig. 10 Three Phase Inverter Model

C. Hall Effect Sensor Subsystem

Fig. 12 shows the subsystem for Hall effect sensor which is based on the Table I discussed in section III.

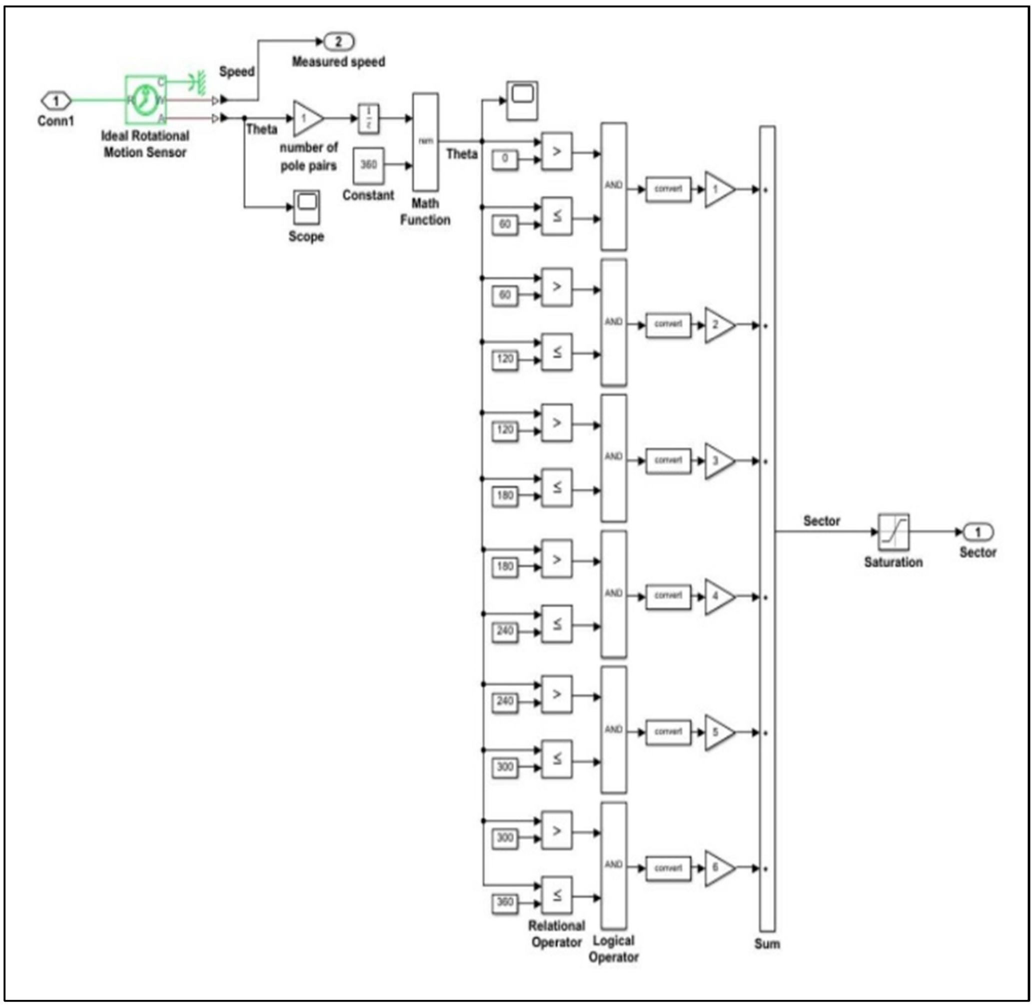

Fig. 11 Hall effect sensor subsystem

D. Commutation Logic Subsystem

Commutation logic subsystem is shown in Fig. 13. This subsystem based on the Table II discussed in the section III.

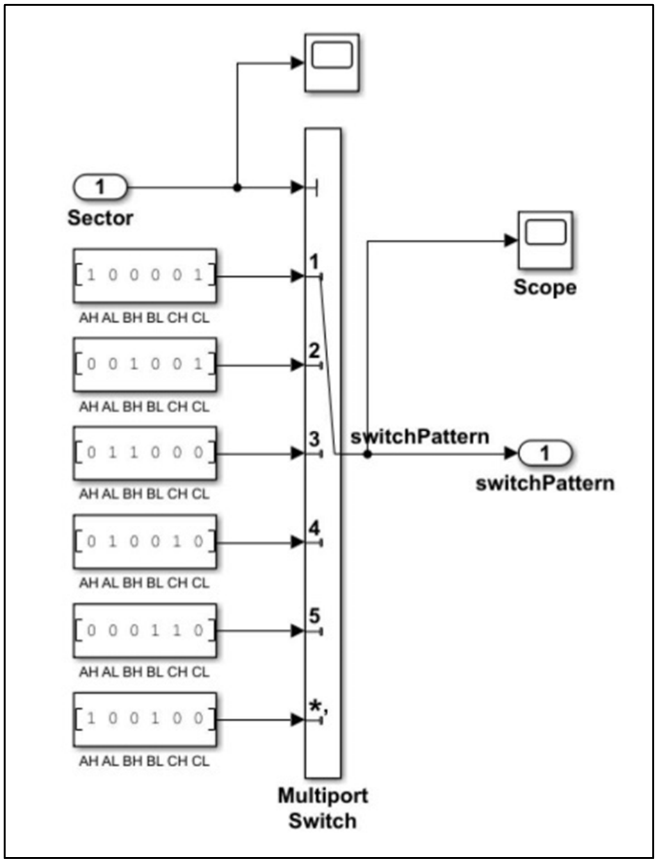

Fig. 12 Commutation Logic Model

E. Pulse Width Modulator Subsystem

Subsystem for PWM generator along with buck converter is shown in Fig. 14. It is necessary to obtain variable DC to the three phase inverter so as get variable speed as well as to track desired speed more efficiently.

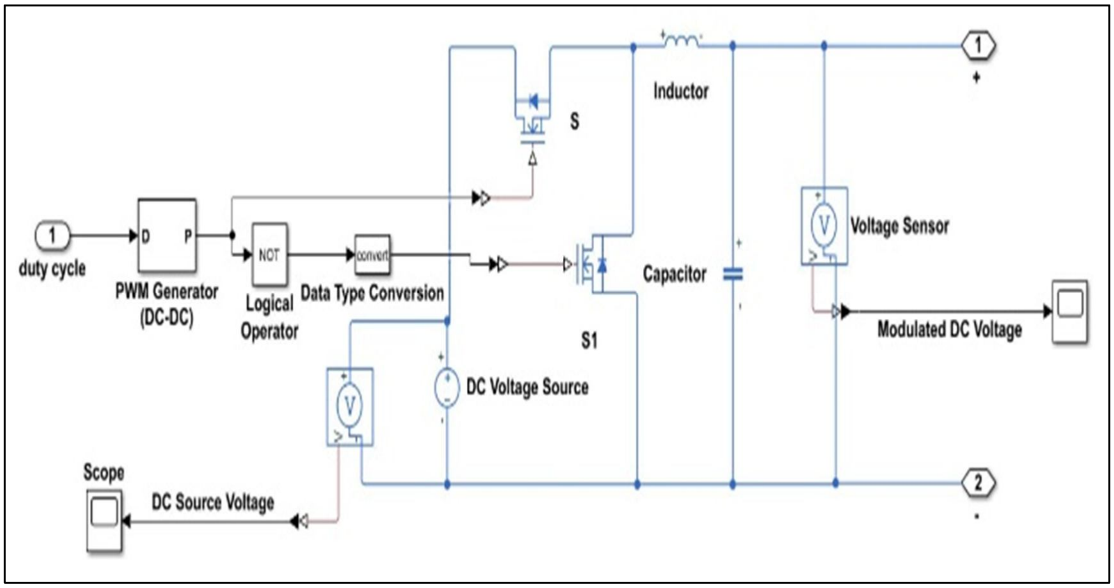

Fig. 13 PWM Generator (Buck Converter) subsystem

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F. Controllers Modeling

Controllers modeling involve modeling of the following controllers:

1) PID Controller
2) Fuzzy- PID Controller

a) Conventional Controller: The controller has input as an error between desired and measured speed and output as the duty cycle to the PWM generator. Fig. 15 shows the model for the PID controller. This controller model is converted into a subsystem and named "Controller" and can be used directly while modeling the overall speed control system.

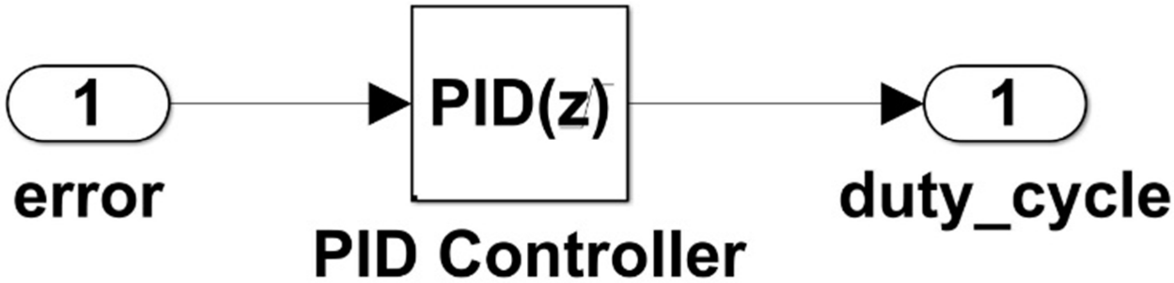

Fig. 14 PID Controller block

Selection of controller and tuning of parameters for the conventional controller can be done by Clicking on block parameters as shown in Fig. 16.

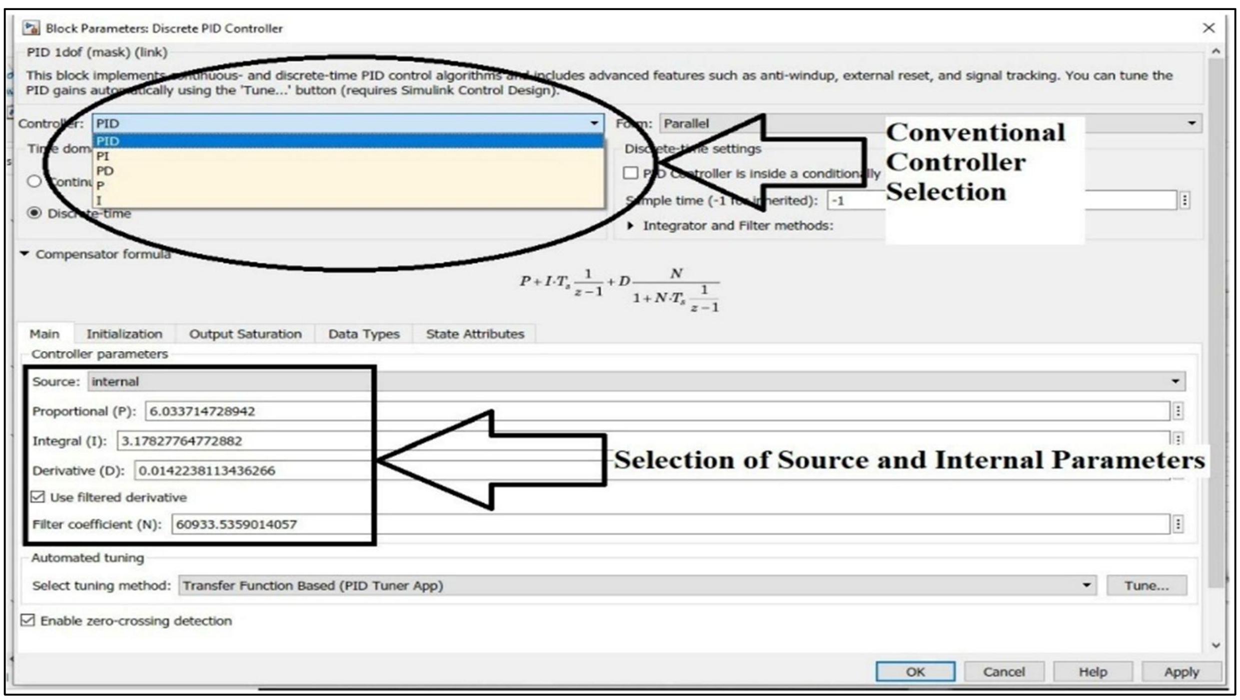

Fig. 15 Selection of Controller & its Parameters

From the controller drop down menu, controllers such as P, I, PD, PI, and PID can be selected. After selecting the controller parameters can be tuned manually but before tuning the source for parameters need to be chosen. There are two sources available for parameter one is internal and another is external. Internal source is chosen when only conventional controller is used for controlling the speed of the BLDCM but in case of the Fuzzy-PID External source is chosen. Another difference between internal and external parameters is that when internal parameters are chosen then the input of the controller is one but in case of external parameters input ports are more than one.

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Volume 9 Issue X Oct 2021- Available at www.ijraset.com

b) Fuzzy-PID Controller: MATLAB block to implement fuzzy logic controller is shown in Fig. 17. It is a block which can be used in fuzzy-PID controller. The input to this block is crisp value of error and output is the duty cycle for PWM.

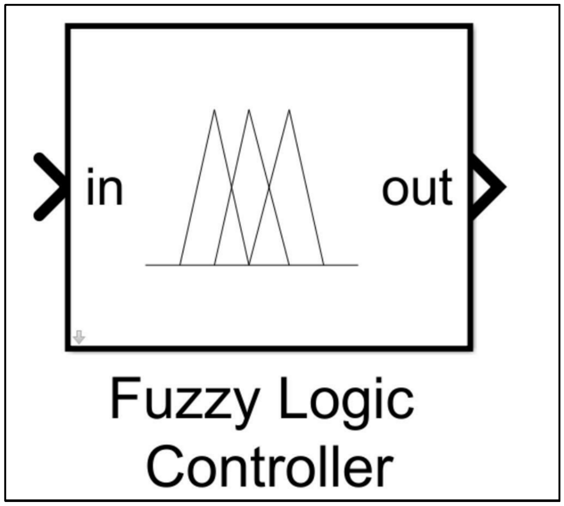

Fig. 16 Fuzzy Logic Controller block

Working of fuzzy logic controller is based upon the fuzzy inference system (FIS) file which need to be design separately in fuzzy logic designer. After designing the FIS, it is saved as ".fis" file. This file can be either saved in workspace or in the folder. This file name with ".fis" extension is mentioned in block parameter of the fuzzy logic controller as in this case it is mentioned in block parameter as 'FIS_Rule_Base.fis'. Fig. 18 shows block parameters window for fuzzy logic controller.

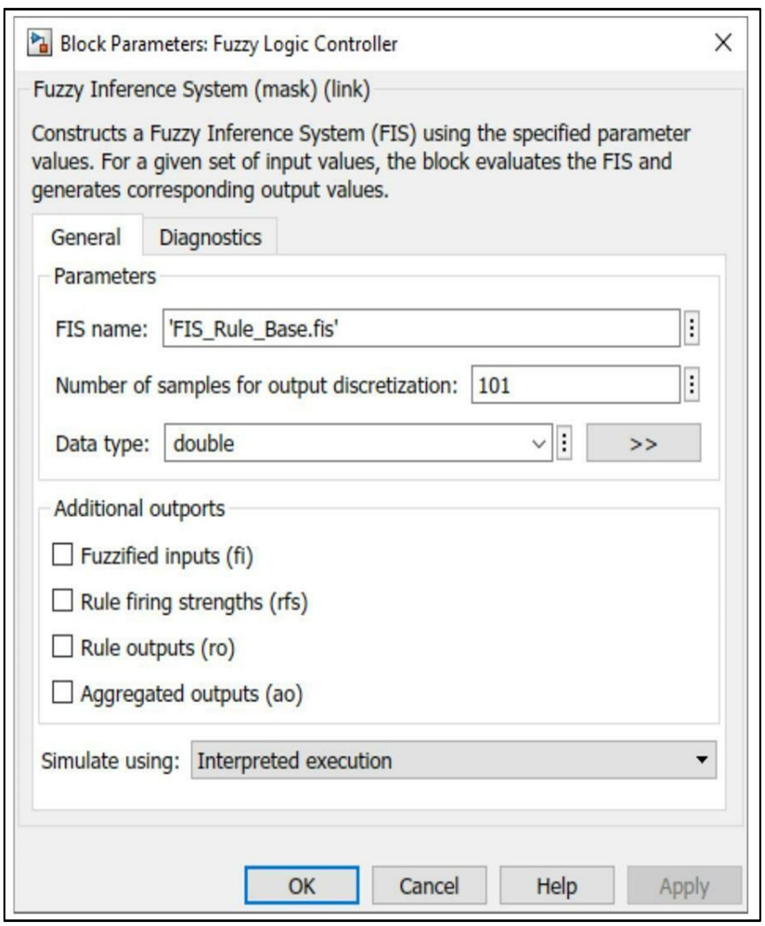

Fig. 17 Block Parameter for Fuzzy Logic Controller

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Volume 9 Issue X Oct 2021- Available at www.ijraset.com

Fuzzy logic designer is fuzzy inference system (FIS) designer containing the Input, output, and rule base for fuzzy logic controller. Fuzzy logic designer window is shown in Fig. 19. As there are two inputs are provided to the fuzzy logic controller one is 'Error I' and another is 'change in Error (CE)' hence two input are there are two input in FIS. One output is there named as 'Duty_Cycle_D' which is the crisp output value from FIS. Rule base is stored in FIS indicated by the middle block.

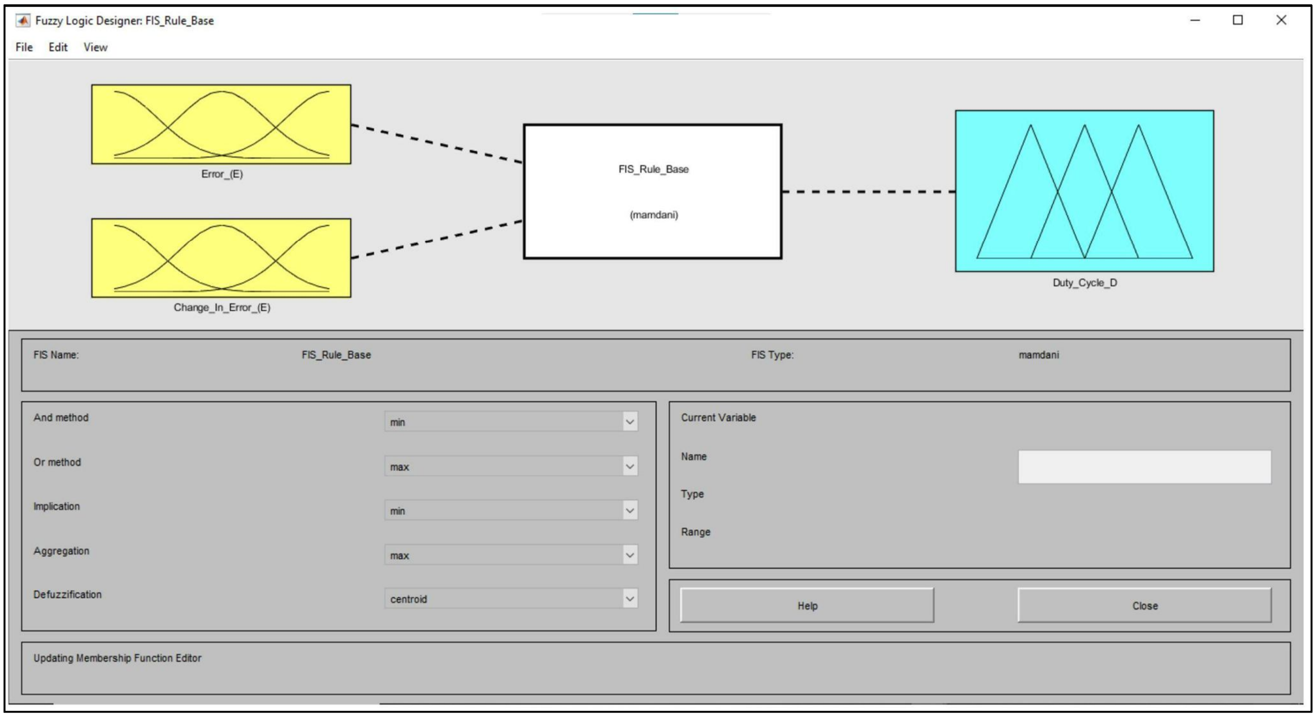

Fig. 18 Fuzzy Logic Designer

One FIS variable is error and it is indicated by 'Error_(E)'. Membership function editor is used to convert crisp input variable value into linguistic variable. Membership function editor is shown in Fig. 20 where crisp input variable 'Error_(E)' is converted into three linguistic variables using triangular membership function (trmf) indicated by 'NE', 'ZE', and 'PE'. Range for the universe of discourse can be set in the range section.

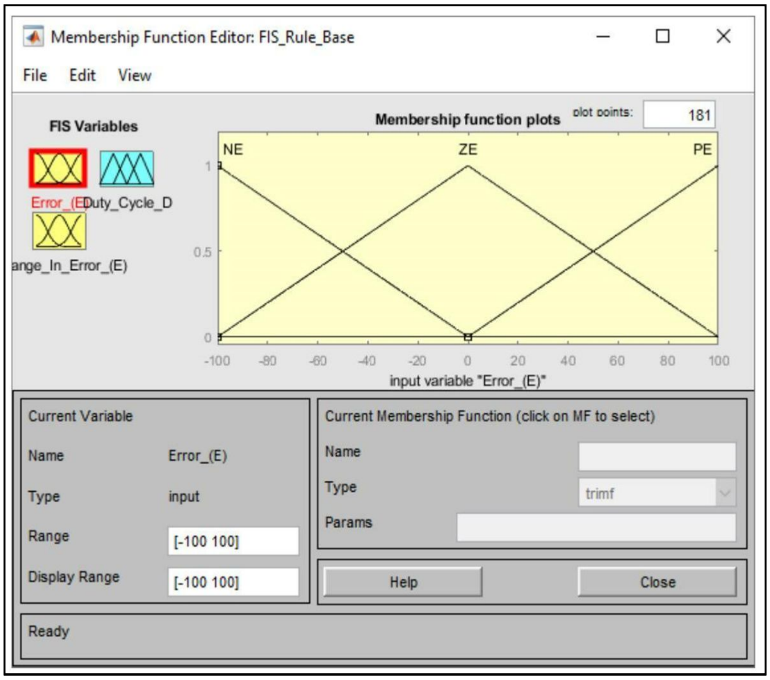

Fig. 19 Membership Functions for Error

Membership function editor for set up the membership function for the crisp input variable ‘Change_In_Error_(CE)’ is shown in Fig. 21. The triangular membership functions ‘NCE’, ‘ZCE’, and ‘PCE’ are used for conversion from crisp input to linguistic variables.

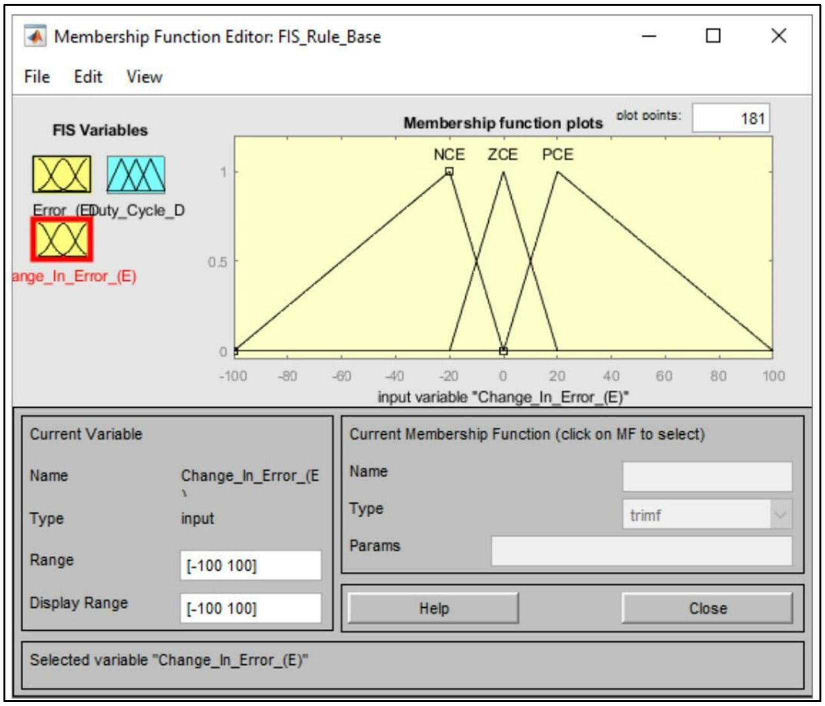

Fig. 20 Membership Function for Change in Error

Membership editor for editing the output variable of the FIS i.e. duty cycle of the PWM is shown in Fig. 22. Three triangular membership functions which are ‘DC’, ‘NC’, and ‘IC’ are used.

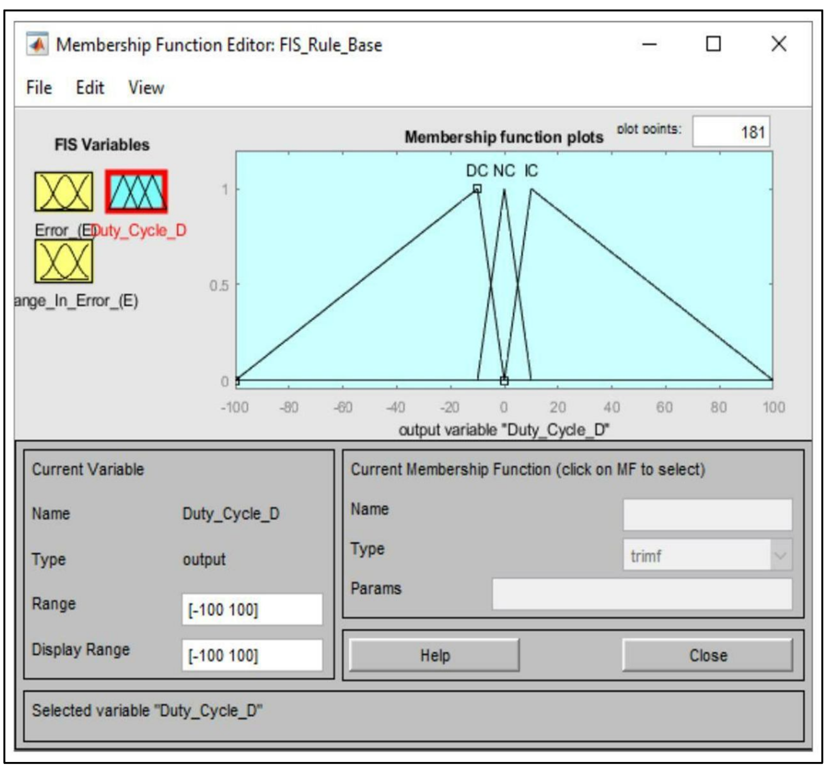

Fig. 21 Membership Function for Duty Cycle

The next step after design and editing the input and output variables is to set up rules. Rules or rule base establishes the relationship between the input and output variables. Rule editor is used to edit the rule as shown in Fig. 23.

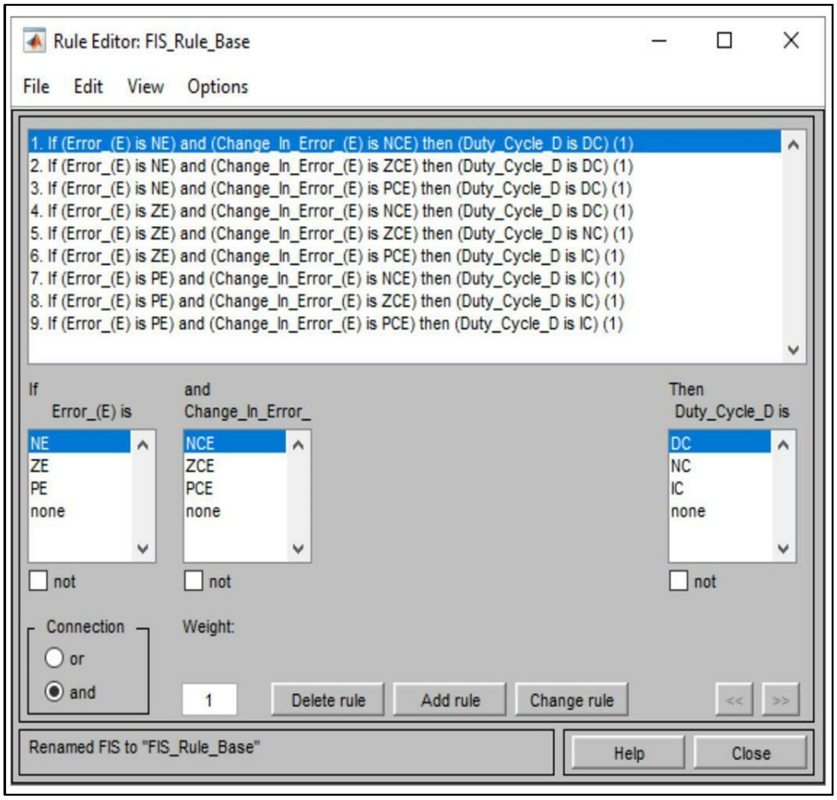

Fig. 22 Rule Base

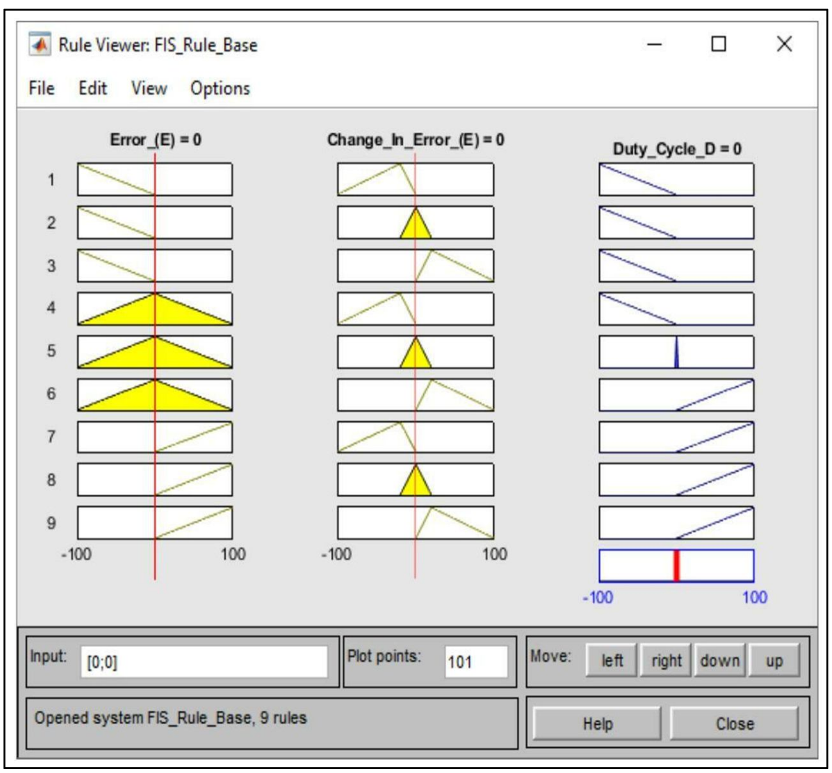

Fig. 23 Rule Viewer

Rule viewer help for view the relation between the input and output variable as shown in Fig. 24. When error is zero and change in error also zero in that case duty cycle must have no change means zero. By this way relation between in input and output variables can be seen in rule viewer which help in final implementation of the FIS into the complete system model.

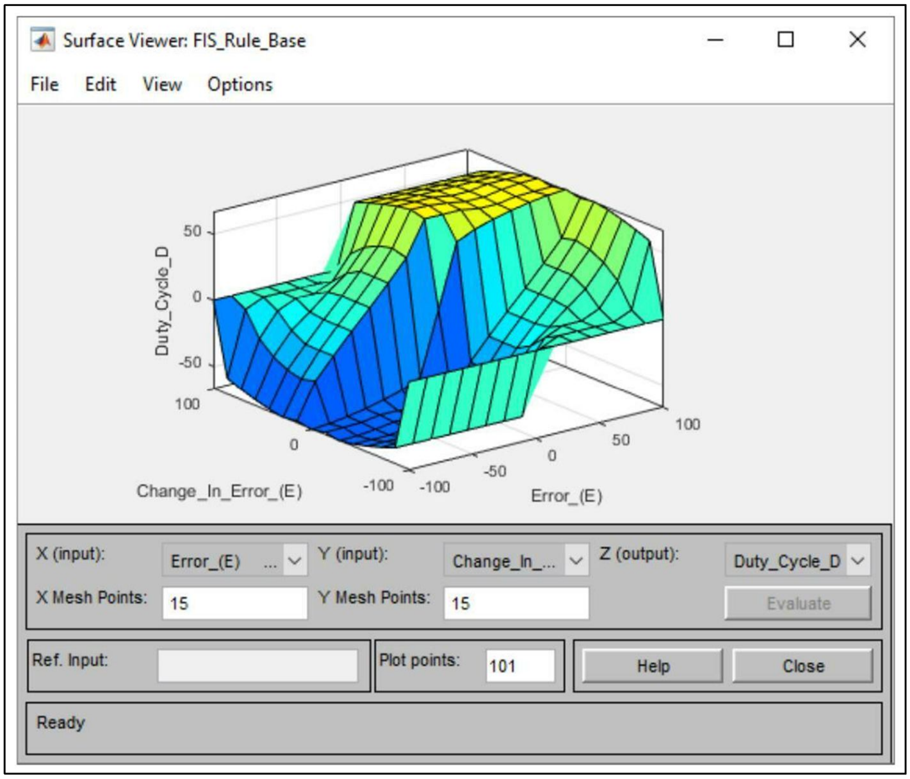

Fig. 24 Surface Viewer

Surface viewer is the graphical way of representing the rule base which indicates the relation between input and output variable in 3D form. Surface viewer for the rule base for FLC for controlling the BLDC motor is shown in Fig. 25.

Fuzzy-PID controller is the combination of the conventional PID controller and the FLC. Any conventional controller can be combined with the FLC by selecting the conventional controller from P, I, PD, PI, and PID in block parameter section of the PID controller as shown in Fig. 26. Parameters such as K_p, K_i, K_d, and N are taken as input from the FLC and hence the source for parameters is selected as external.

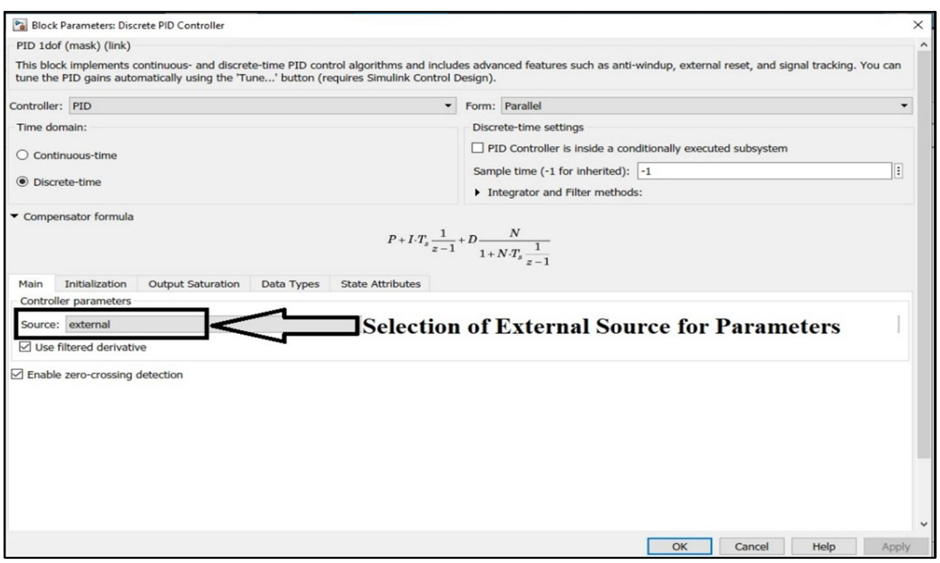

Fig. 25 Selection of external source in PID controller

As the external source for parameters is chosen the PID controller shows the five input ports as shown in Fig. 27. these ports named as P, I, D, N and one unnamed port. This unnamed pot is the actual input port of the PID controller and remaining port i.e., P, I, D, and N used for collecting values for K_p ,K_i ,K_d ,and N form FLC using Demux block, respectively.

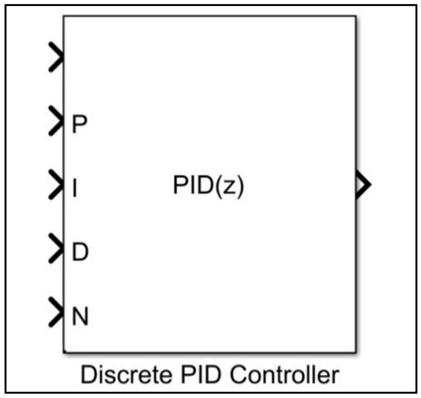

Fig. 26 Conventional Controller for Fuzzy-PID controller

Figure 28 shows the MATLAB model for the Fuzzy PID controller. Filter coefficient is considered as 100. Mux block is used to multiplex two inputs i.e., Error and Change in Error and through mux it is given to the FLC. De-mux is used to de-multiplex the single output from the FLC into proportional and integral parameters. All parameters such as K_p, K_i, and K_d for PID ontroller are taken as output from the de-mux block.

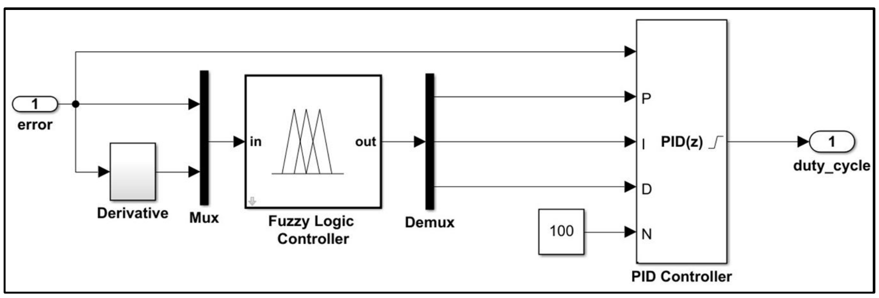

Fig. 27 Controller Subsystem for Fuzzy-PID Controller

G. Model for Speed Control System of BLDCM

Speed control model of BLDCM is shown in Fig. 29. The blocks/subsystem discussed previously in this section are used for modeling purpose.

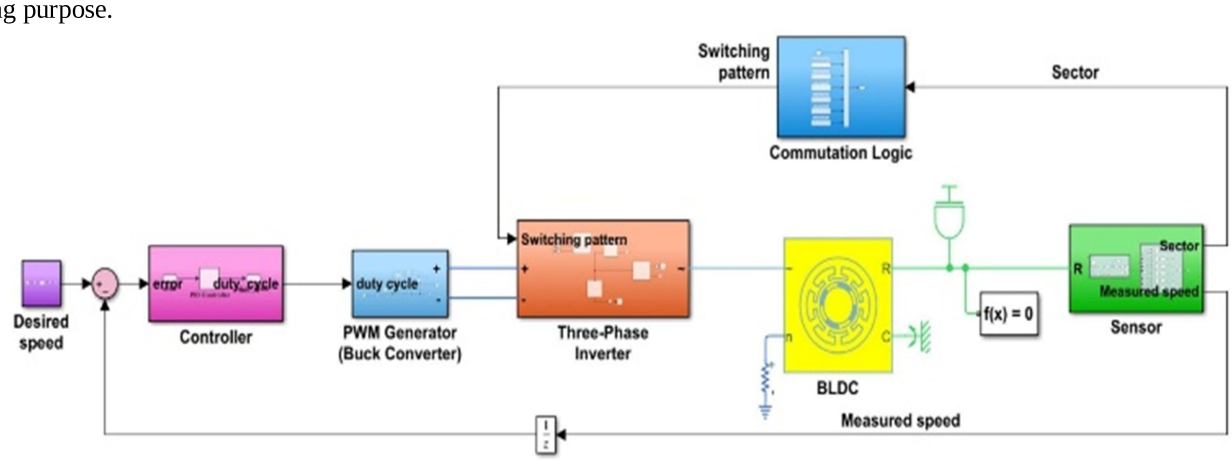

Fig. 28 Overall speed control model for BLDCM

Actuating the signal from the controller is the duty cycle of the buck converter. Based on the duty cycle from the controller and frequency provided to the PWM generator, the constant DC voltage is modulated at the output of the buck converter. This modulated voltage is given to the three-phase inverter so that the BLDC motor tracks the desired speed.

V. RESULT AND DISCUSSION

In this paper, MATLAB/SIMULINK environment is used for modeling and simulation and it is used to investigate the speed control of BLDC motor using PID controller and Fuzzy–PID controller. Table III presents the BLDCM parameters used for the simulation purpose.

TABLE IIIII
BLDCM PARAMETERS

Sr. No.	Parameter	Symbol	Value	Unit
1	Stator per phase resistance	R	1.43	Ω
2	Stator per phase inductance	L	9.4	mH
3	Inertia constant	J	5.5×10^{-3}	Kg-m^2
4	Friction coefficient	B	2×10^{-3}	
5	Rotor flux	Ø	0.2158	Wb
6	Desired speed	N	100	rpm

Fig. 30 shows the speed response of the BLDCM using conventional PID controller. The value of proportional constant, derivative constant and the integral constant taken as 1, 1, and 1.5 respectively. The value of delay time and rise time obtained from graph are 0.257 milli-sec and 0.394 milli-sec, respectively. Peak overshoot time is 0.743 milli-sec and having peak overshoot 89.72 %. Settling time and steady state error are 1.64 sec and 1.4 rpm, respectively.

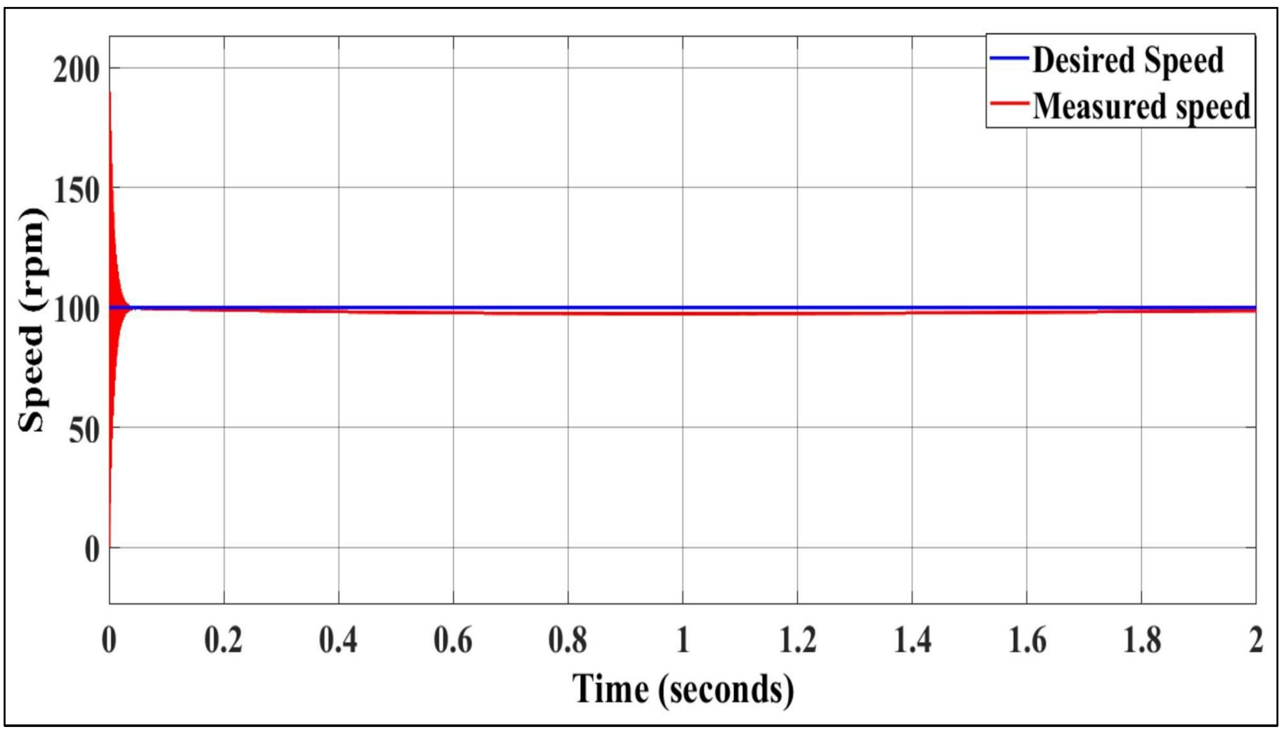

Fig. 30 Speed response of BLDCM using PID controller

The speed response of the BLDC motor and time using Fuzzy-PID is shown in Figure 31. The value of delay time and rise time obtained from graph are 0.185 milli-sec and 0.369 milli-sec, respectively. Delay time and rise time are best as compared with all controllers discussed till this point. Peak overshoot time is 0.5 milli-sec and having peak overshoot 40.44 %. Which indicates improved peak overshoot time as compared to the PID controller discussed before. Settling time and steady state error are 2.07 milli-sec and 1.4 rpm, respectively. Steady state error is between 2 % band. So, Fuzzy-PID is seems to be best controller as compared to the PID controller. Comparative analysis between time response specifications of speed response of BLDCM using PID controller and Fuzzy-PID controller is given in Table IV.

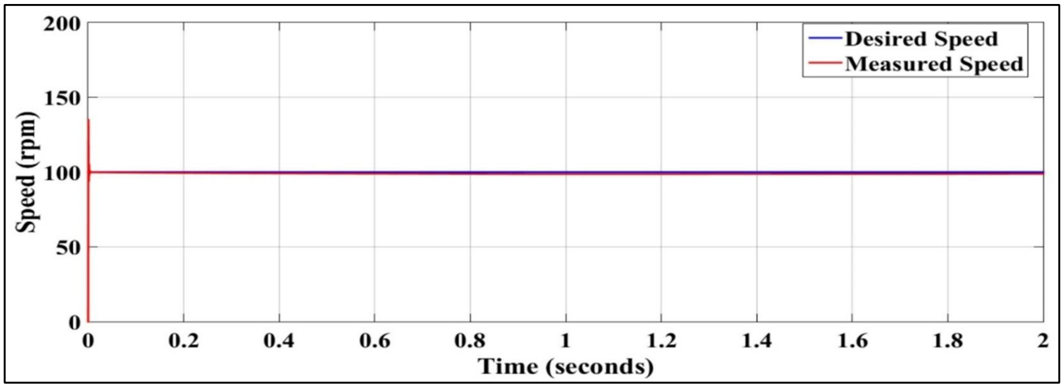

Fig. 31 Speed response of BLDCM using Fuzzy-PID controller

From the table, Delay time, rise time, peak time, and settling time for Fuzzy-PID controller is less as compared to PID controller. Settling time is reduced in a such extent that it is getting in millisecond while with PID controllers is having settling time for speed response in second. Due to decrease in settling time BLDCM tracks desired speed in a best way than PID controller. If steady state error is taken into consideration, then it is within 2 % band.

TABLE IVV
COMPARATIVE ANALYSIS

Time Response Specifications	Conventional PID Controller	Fuzzy-PID Controller
Delay Time, t_d	0.257 milli-sec	0.185 milli-sec
Rise Time, t_r	0.394 milli-sec	0.369 milli-sec
Peak Time, t_p	0.743 milli-sec	0.5 milli-sec
Percent Peak Overshoot, $\%M_p$	89.72 %	40.44 %
Settling Time, t_s	1.64 sec	2.07 milli-sec
Steady State Error, E_{ss}	1.4 rpm	1.4 rpm

VI. CONCLUSIONS

Speed performance of BLDCM using conventional PID controller as well as Fuzzy-PID controller is performed and comparative analysis between their speed performances shows that the delay time, rise time, peak time, settling time all these parameters are improved hence it is concluded that Fuzzy-PID controller is helping BLDCM to track desired speed faster than the conventional PID controller as well as the peak overshoot is also reduced to its half value without increase in the steady state error hence overall speed performance is improved by using the Fuzzy-PID controller shows that the Fuzzy-PID is more effective than that of the conventional controller.

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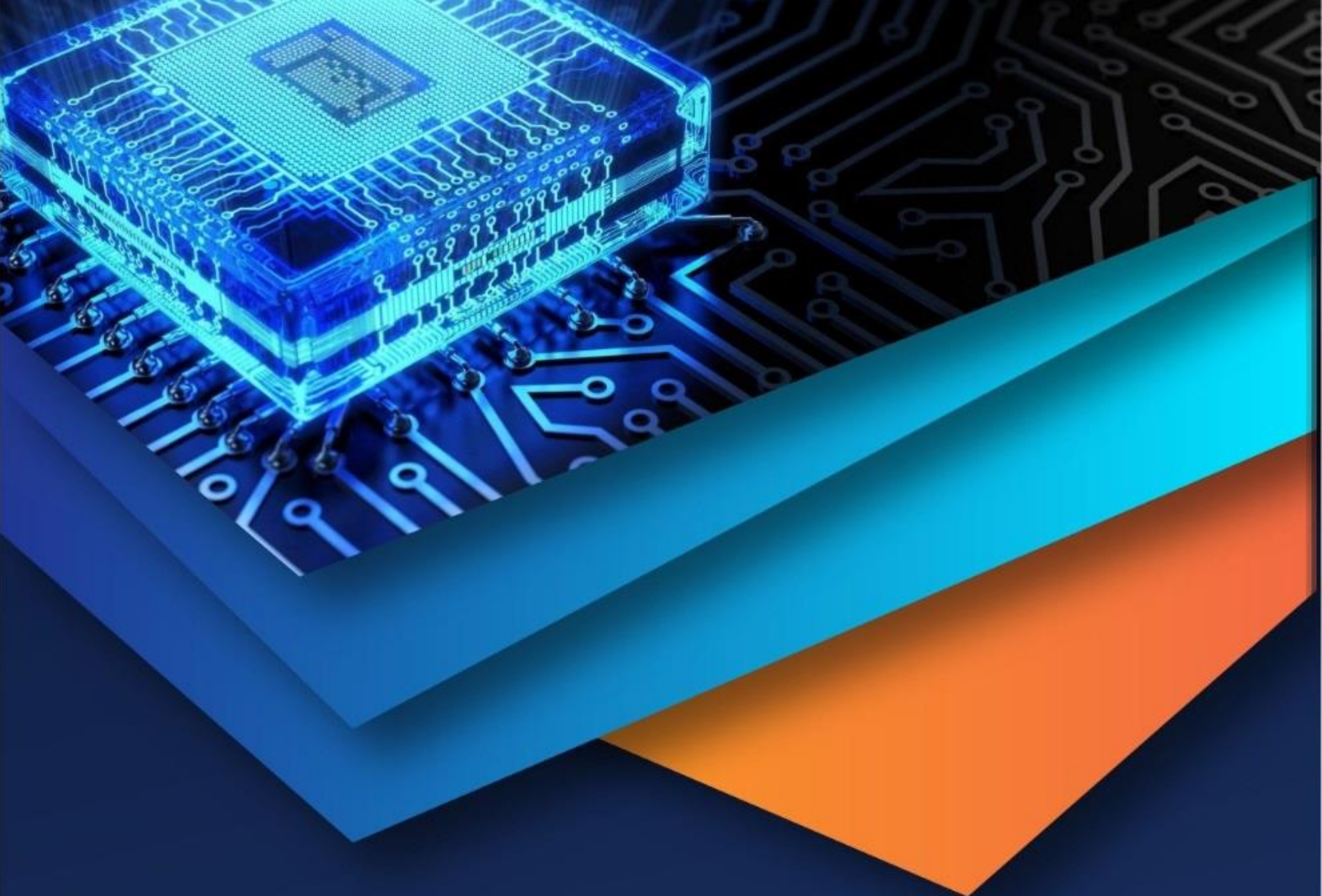

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