CHAPTER-1
INTRODUCTION

1.1. Background

Brushless dc (BLDC) motors are preferred as small horsepower control motors due to their high efficiency, silent operation, compact form, reliability, and low maintenance. However, the problems are encountered in these motor for variable speed operation over last decades continuing technology development in power semiconductors, microprocessors, adjustable speed drivers control schemes and permanent-magnet brushless electric motor production have been combined to enable reliable, cost-effective solution for a broad range of adjustable speed applications.

Household appliances are expected to be one of fastest-growing end-product market for electronic motor drivers over the next five years [3]. The major appliances include clothes washer's room air conditioners, refrigerators, vacuum cleaners, freezers, etc. Household appliance have traditionally relied on historical classic electric motor technologies such as single phase AC induction, including split phase, capacitor-start, capacitor–run types, and universal motor.

These classic motors typically are operated at constant-speed directly from main AC power without regarding the efficiency. Consumers now demand for lower energy costs, better performance, reduced acoustic noise, and more convenience features. Those traditional technologies cannot provide the solutions.

1.2. Typical BLDC motor applications

BLDC motors find applications in every segment of the market. Such as, appliances, industrial control, automation, aviation and so on. We can categorize the BLDC motor control into three major types such as [9]-

- Constant load
- Varying loads
- Positioning applications

1.2.1. Applications with Constant Loads

These are the types of applications where a variable speed is more important than keeping the accuracy of the speed at a set speed. In these types of applications, the load is directly coupled to the motor shaft. For example, fans, pumps and blowers come under these types of applications. These applications demand low-cost controllers, mostly Operating in open-loop.

1.2.2. Applications with Varying Loads

These are the types of applications where the load on the motor varies over a speed range. These applications may demand high-speed control accuracy and good dynamic responses. In home appliances, washers, dryers and compressors are good examples.

In Automotive, fuel pump control, electronic steering control, engine control and electric vehicle control are good examples of these. In aerospace, there are a number of applications, like centrifuges, pumps, robotic arm controls, gyroscope controls and so on. These applications may use speed feedback devices and may run in semi-closed loop or in total closed loop. These applications use advanced control algorithms, thus complicating the controller. Also, this increases the price of the complete system.

1.2.3. Positioning Applications

Most of the industrial and automation types of application come under this category. The applications in this category have some kind of power transmission, which could be mechanical gears or timer belts, or a simple belt driven system. In these applications, the dynamic response of speed and torque are important. Also, these applications may have frequent reversal of rotation direction.

A typical cycle will have an accelerating phase, a constant speed phase and a deceleration and positioning phase. The load on the motor may vary during all of these phases, causing the controller to be complex. These systems mostly operate in closed loop.

There could be three control loops functioning simultaneously: Torque Control Loop, Speed Control Loop and Position Control Loop. Optical encoder or synchronous resolves are used for measuring the actual speed of the motor. In some cases, the same sensors are used to get relative position information. Otherwise, separate position sensors may be used to get absolute positions.

Computer Numeric Controlled (CNC) machines are a good example of this.

1.3. A comparison of BLDC with conventional DC motors

In a conventional (brushed) DC-motor, the brushes make mechanical contact with a set of electrical contacts on the rotor (called the commutator), forming an electrical circuit between the DC electrical source and the armature coil-windings. As the armature rotates on axis, the stationary brushes come into contact with different sections of the rotating commutator. The commutator and brush-system form a set of electrical switches, each firing in sequence, such that electrical-power always flows through the armature-coil closest to the stationary stator (permanent magnet).

In a BLDC motor, the electromagnets do not move instead, the permanent magnets rotate and the armature remains static. This gets around the problem of how to transfer current to a moving armature. In order to do this, the commutator assembly is replaced by an intelligent electronic controller. The controller performs the same power-distribution found in Review on brushless dc motor modelling.

BLDC motors have many advantages over DC motors. A few of these are [36]:

- High dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

1.4. Review on brushless dc motor modeling

Recent research [1] [2] has indicated that the permanent magnet motor drives, which include the permanent magnet synchronous motor (PMSM) and the brushless dc motor (BLDC) could become serious competitors to the induction motor for servo applications.

The PMSM has a sinusoidal back emf and requires sinusoidal stator currents to produce constant torque while the BLDC has a trapezoidal back emf and requires rectangular stator currents to produce constant torque. Some confusion exists, both in the industry and in the university research environment, as to the correct models that should be used in each case.

The PMSM is very similar to the standard wound rotor synchronous machine except that the PMSM has no damper windings and excitation is provided by a permanent magnet instead of a field winding. Hence the d, q model of the PMSM can be derived from the well-known [3] model of the synchronous machine with the equations of the damper windings and field current dynamics removed.

As is well known, the transformation of the synchronous machine equations from the abc phase variables to the d, q variables forces all sinusoidal varying inductances in the abc frame to become constant in the d, q frame. In the BLDC motor, since the back emf is no sinusoidal, the inductances do not vary sinusoidaly in the abc frame and it does not seem advantageous to transform the equations to the d, q frame since the inductances will not be constant after transformation. Hence it is proposed to use the abc phase variables model for the BLDC. In addition, this approach in the modeling of the BLDC allows a detailed examination of the machine's torque behaviour that would not be possible if any simplifying assumptions were made.

The d, q model of the PMSM has been used to examine the transient behaviour of a high performance vector controlled PMSM servo drive [8]. In addition, the abc phase variable model has been used to examine the behaviour of a BLDC speed servo drive [5].

Application characteristics of both machines have been presented in [6].

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1.5. A brief on control of BLDC motor

The ac servo has established itself as a serious competitor to the brush-type dc servo for industrial applications. In the fractional-to-30-hp range, the available ac servos include the induction, permanent-magnet synchronous, and brushless dc motors (BLDC) [4]. The BLDC has a trapezoidal back EMF, and rectangular stator currents are needed to produce a constant electric torque. Typically, hysteresis or pulse width-modulated (PWM) current controllers are used to maintain the actual currents flowing into the motor as close as possible to the rectangular reference value [1].

It is shown that, because of the trapezoidal back EMF and the consequent no sinusoidal variation of the motor inductances with rotor angle, a transformation of the machine equations to the well-known d, q model is not necessarily the best approach for modelling and simulation. Instead, the natural or phase variable approach offers many advantages.

Because the controller must direct the rotor rotation, the controller needs some means of determining the rotor's orientation/position (relative to the stator coils.) Some designs use Hall effect sensors or a rotary encoder to directly measure the rotor's position. The controller contains 3 bi-directional drivers to drive high-current DC power, which are controlled by a logic circuit. Simple controllers employ comparators to determine when the output phase should be advanced, while more advanced controllers employ a microcontroller to manage acceleration, control speed and fine-tune efficiency. Controllers that sense rotor position based on back-EMF have extra challenges in initiating motion because no back-EMF is produced when the rotor is stationary.

The design of the BLDC servo system usually requires time consuming trial and error process, and fail to optimize the performance. In practice, the design of the BLDC motor drive involves a complex process such as model, devise of control Scheme, simulation and parameters tuning. In a PI controller has been proposed for BLDC motor. The PI controller can be suitable for the linear motor control. However, in practice, many non- linear factors are imposed by the driver and load, the PI controller cannot be suitable for non-linear system.

1.6. Problem statement

To achieve desired level of performance the motor requires suitable speed controllers. In case of permanent magnet motors, usually speed control is achieved by using proportional integral

Although conventional PI controllers are widely used in the industry due to their simple control structure and ease of implementation, these controllers pose difficulties where there are some control complexity such as nonlinearity, load disturbances and parametric variations. Moreover PI controllers require precise linear mathematical models. As the permanent magnet BLDC machine has nonlinear model, the linear PI may no longer be suitable.

The Fuzzy Logic (FL) approach applied to speed control leads to an improved dynamic behaviour of the motor drive system and an immune to load perturbations and parameter variations. Fuzzy logic control offers an improvement in the quality of the speed response. Most of these controllers use mathematical models and are sensitive to parametric variations. These controllers are inherently robust to load disturbances. Besides, fuzzy logic controllers can be easily implemented.

1.7. Thesis organization

This thesis contains six chapters describing the modeling and control approach of a permanent magnet brushless dc motor organized as follows Chapter 2 discussed principal brushless dc motor, brushless dc motor operation with inverter with 120 degree angle operation , mathematical modelling of machine in state space form.

Chapter 3. describes PI speed controller of brushless dc motor and modeling of PI control of brushless dc motor drive, back emf function modeling and Hall effect sensor switching and gate function algorithm.

Chapter 4 describes the fuzzy logic control structure and modeling of fuzzy speed control of brushless dc motor with triangular membership function.

Chapter 5 describes the hybrid fuzzy PI controller operation and its modeling with analysis.

Chapter 6 describes the conclusion of the speed control strategies of the brushless dc motor and further work to be carried out.

CHAPTER-2

BLDC MOTOR DRIVE AND ITS OPERATION

2.1. Brushless DC motor background

BLDC motor drives, systems in which a permanent magnet excited synchronous motor is fed with a variable frequency inverter controlled by a shaft position sensor. There appears a lack of commercial simulation packages for the design of controller for such BLDC motor drives.

One main reason has been that the high software development cost incurred is not justified for their typical low cost fractional/integral kW application areas such as CNC machine tools and robot drives, even it could imply the possibility of demagnetizing the rotor magnets during commissioning or tuning stages. Nevertheless, recursive prototyping of both the motor and inverter may be involved in novel drive configurations for advance and specialized applications, resulting in high developmental cost of the drive system. Improved magnet material with high (B.H), product also helps push the BLDC motors market to tens of kW application areas where commissioning errors become prohibitively costly. Modelling is therefore essential and may offer potential cost savings.

A brushless dc motor is a dc motor turned inside out, so that the field is on the rotor and the armature is on the stator. The brushless dc motor is actually a permanent magnet ac motor whose torque-current characteristics mimic the dc motor. Instead of commutating the armature current using brushes, electronic commutation is used. This eliminates the problems associated with the brush and the commutator arrangement, for example, sparking and wearing out of the commutator-brush arrangement, thereby, making a BLDC more rugged as compared to a dc motor. Having the armature on the stator makes it easy to conduct heat away from the windings, and if desired, having cooling arrangement for the armature windings is much easier as compared to a dc motor [10].

In effect, a BLDC is a modified PMSM motor with the modification being that the back-emf is trapezoidal instead of being sinusoidal as in the case of PMSM. The "commutation region" of the back-emf of a BLDC motor should be as small as possible, while at the same time it should not be so narrow as to make it difficult to commutate a phase of that motor when driven by a Current Source Inverter. The flat constant portion of the back emf should be 120° for a smooth torque production.

The position of the rotor can be sensed by using an optical position sensors and its associated logic. Optical position sensors consist of phototransistors (sensitive to light), revolving shutters, and a light source. The output of an optical position sensor is usually a Logical signal.

2.2. Permanent-Magnet BLDC motor structure

Fig.2.1. illustrates the transverse section structure of a brushless DC motor. The stator windings of BLDC are similar to those in a polyphase AC motor, and the rotor is composed of one or more permanent magnets. Brushless DC motors (BLDC) contain a powerful permanent magnet rotor and fixed stator windings. The stationary stator windings are usually three phases, which means that three separate voltages are supplied to the three different sets of windings [15]. Brushless DC motors are different from AC synchronous motors in that the former incorporates some means to detect the rotor position (or magnetic poles) to produce signals to control the electronic switches as shown

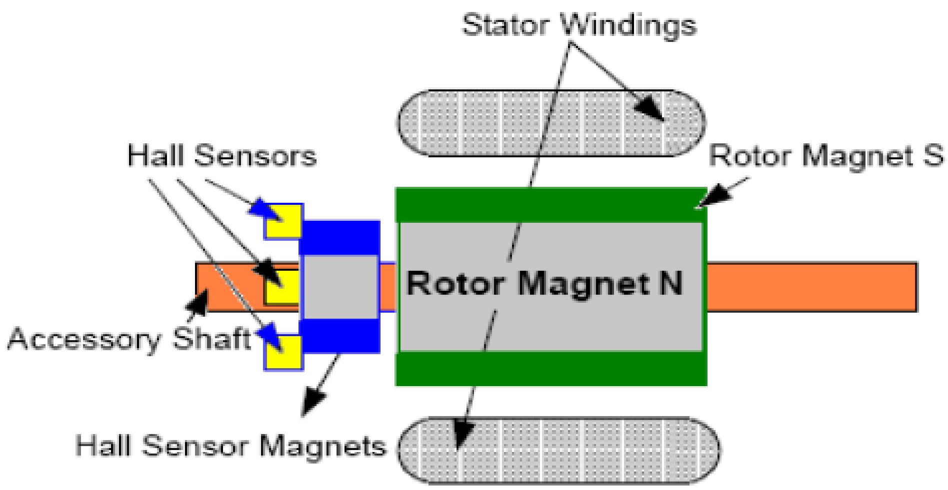


Fig.2.1. Transverse section structure of a brushless dc motor

2.3. Principle of operation of BLDC Motor

A brush less dc motor is defined as a permanent synchronous machine with rotor position feedback. The brushless motors are generally controlled using a three phase power semiconductor bridge. The motor requires a rotor position sensor for starting and for providing proper commutation sequence to turn on the power devices in the inverter bridge.

Based on the rotor position, the power devices are commutated sequentially every 60 degrees. Instead of commutating the armature current using brushes, electronic commutation is used for this reason it is an electronic motor. This eliminates the problems associated with the brush and the commutator arrangement, for example, sparking and wearing out of the commutator brush arrangement, thereby, making a BLDC more rugged as compared to a dc motor.

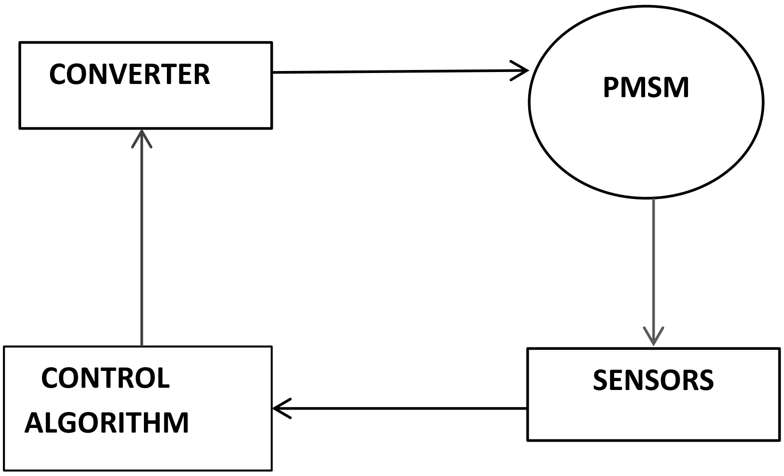


Fig.2.2. Block Diagram of BLDC motor

The basic block diagram of brushless dc motor is shown in fig.2.2. The brush less dc motor consist of four main parts power converter, permanent magnet-synchronous machine (PMSM) sensors, and control algorithm. The power converter transforms power from the source to the PMSM which in turn converts electrical energy to mechanical energy. One of the salient features of the brush less dc motor is the rotor position sensors ,based on the rotor position and command signals which may be a torque command ,voltage command ,speed command and so on the control algorithms determine the gate signal to each semiconductor in the power electronic converter.

The structure of the control algorithms determines the type of the brush less dc motor of which there are two main classes voltage source based drives and current source based drives. Both voltage source and current source based drive used with permanent magnet synchronous machine with either sinusoidal or non-sinusoidal back emf waveforms.

Machine with sinusoidal back emf may be controlled so as to achieve nearly constant torque. However, machine with a non- sinusoidal back emf) offer reduces inverter sizes and reduces losses for the same power level [11].

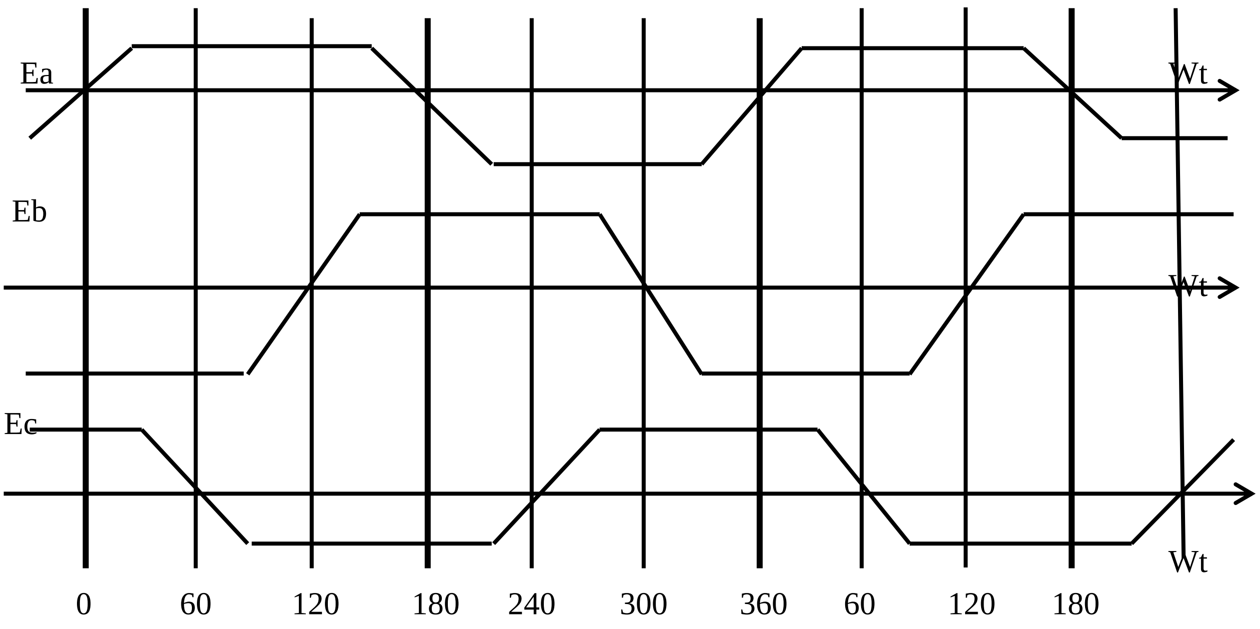


Fig.2.3. Trapezoidal back EMF of three phase BLDC motor

2.4. BLDC motor operation with Inverter

There are two types of voltage-source inverters which are generally used to drive the permanent-magnet synchronous machine; the 120' and the 180'. The 120' inverter system offers advantages for certain applications due to the inherently larger timing tolerances which prevent inverter malfunction due to "shoot through." Also, with the 120' inverter it is possible to program the switching of the inverter using the back emf of the machine as reference [14].

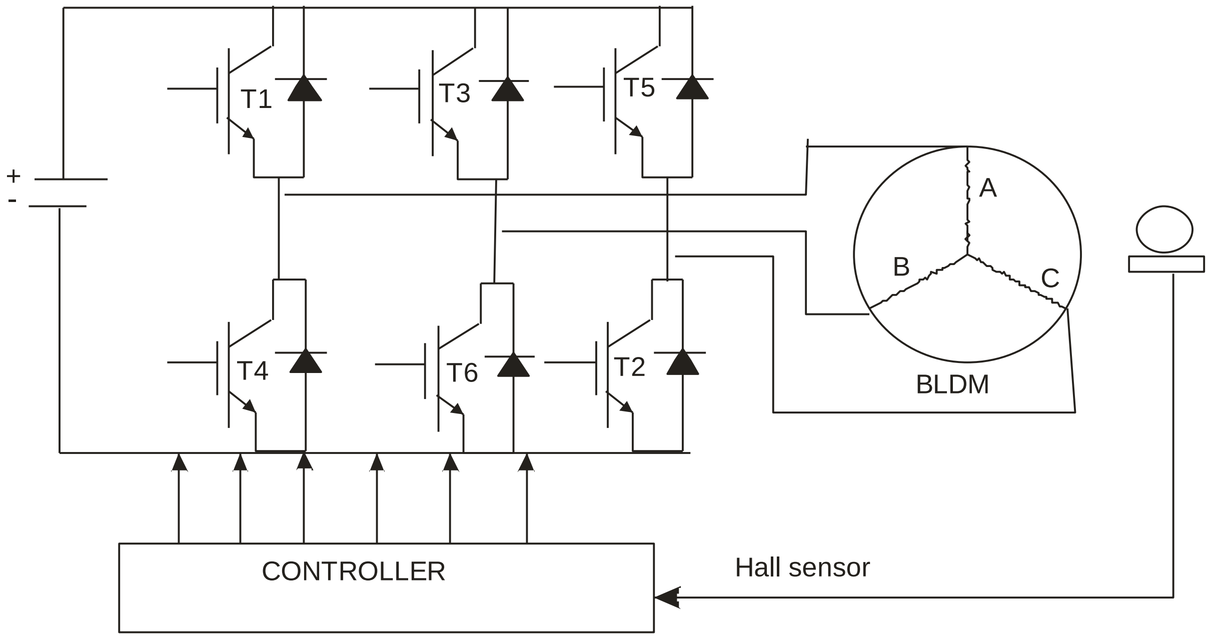


Fig.2.4. Three phase bridge inverter using IGBT

2.5. Three phase 120^o mode VSI operation

The power circuit shown in fig. 2.4. for 120^o mode VSI, each thyristor conducts for 120^o of a cycle. The table below listed shows that T1 conducts for 120^o and for the next 60^o, neither T4 conducts nor T2 conducts [14].

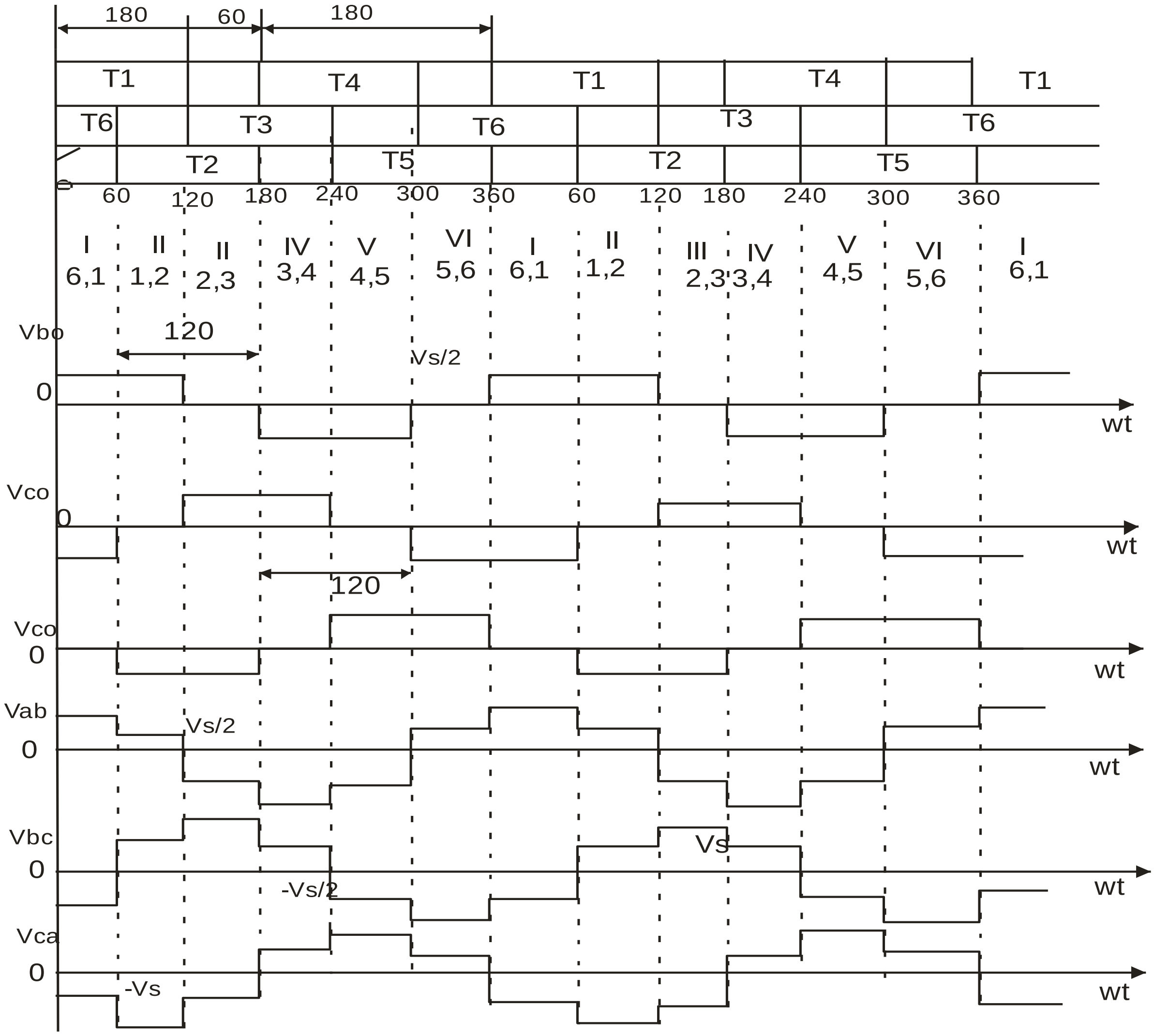


Fig.2.5.- Voltage waveform for 120° mode six step three phase VSI

Now T4 conducts so T4 is turned on at $\omega t = 180^o$ and it further conducts for the 120^o, i.e. from wt= 180^o, series connected IGBTs T1, T4 do not conduct. At wt = 300^o , T4 is turned off , then 60^o elapses before T1 is turned on again at wt = 360^o . in the second row, T3 is turned on at wt = 120^o. Now T3 conducts for 120^o, then 60^o interval elapses during which neither T3 nor T6 conducts after which T6 conducts again. The third row is also completed similar way. This table shows that T6, T1 should be gated for step I ; T1, T2 for step II; T2, T3 for step III and so on. During each step only two thyristors conducts- one from the upper group and one from the lower group as shown in figure below.

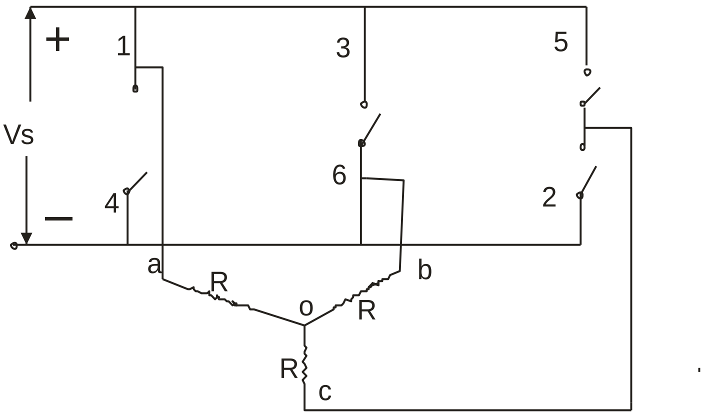
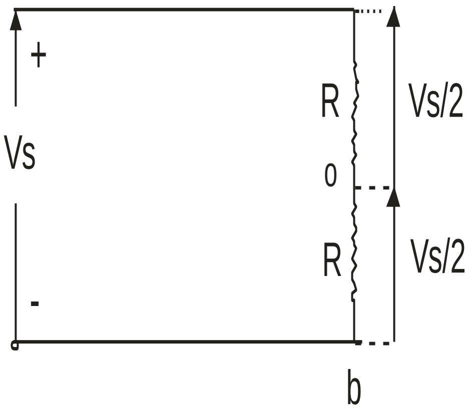


Fig.2.6(a). when T1 and T6 on (0-60°)



$v_{ao} = \frac{V_s}{2}$, $v_{bo} = -\frac{V_s}{2}$ and $v_{co} = 0$

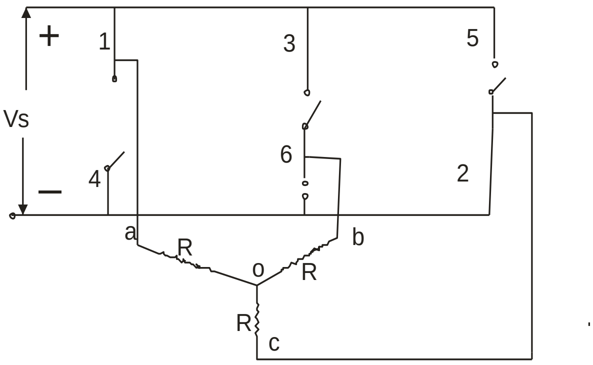
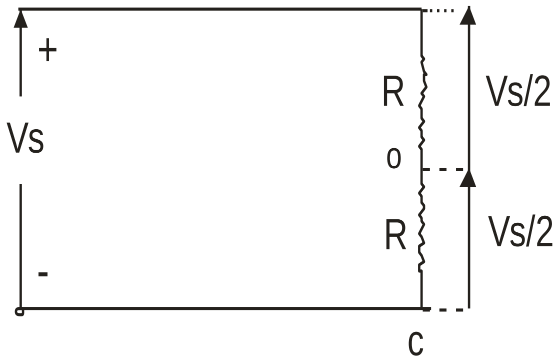


Fig.2.6 (b). when T1 and T2 on (60-120°)



$$v_{ao} = V_{\frac{s}{2}} ,$$

$$v_{co} = -\frac{V_s}{2} \; and \; v_{bo} = 0$$

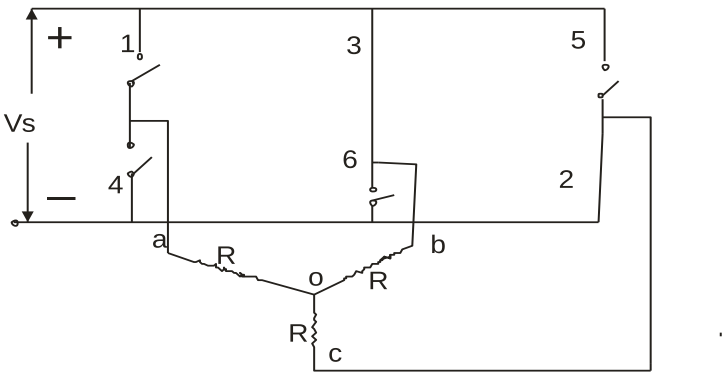
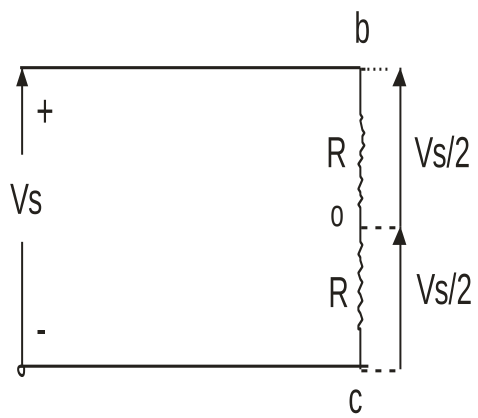


Fig.2.6 (c). when T3 and T2 on (120-180°)



$$v_{bo} = V_{\frac{s}{2}} , v_{ob} = \frac{V_s}{2} \; v_{co} = -\frac{V_s}{2} \; and \; v_{ao} = 0$$

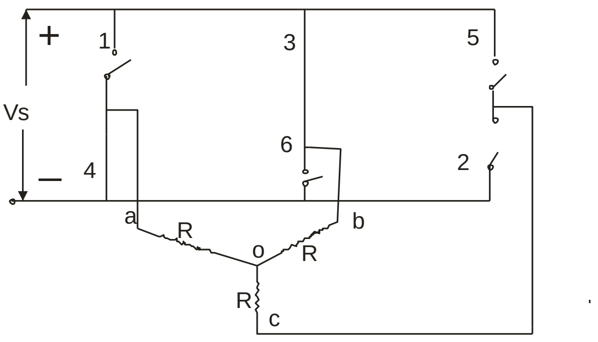
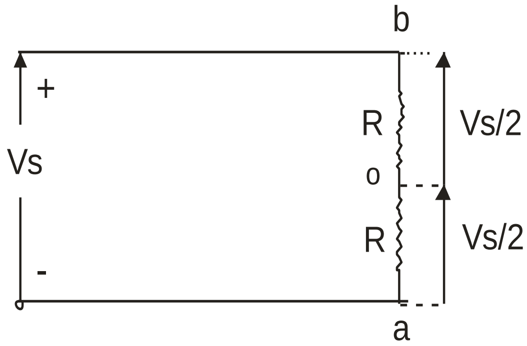


Fig. 2.6(d). when T4 and T3 on (180-240^o)



$$v_{bo} = V_{\frac{S}{2}}, \qquad v_{ao} = -\frac{V_s}{2} \; and \; v_{co} = 0$$

The circuit models for steps I-IV are shown in the fig. where load is assumed to be resistive and star connected. During step I, thyristor 6, 1 are conducting and as such load terminal a is connected to the positive bus of dc sources whereas terminal b is connected to negative bus of dc source. Load terminal c is not connected to dc bus. The line to neutral voltage –

$$v_{ao} = V_{\frac{S}{2}}, v_{ob} = \frac{V_S}{2} \; or \; v_{bo} = -\frac{V_S}{2} \; and \; v_{co} = 0 \qquad (2.1)$$

These voltages are shown in fig. during step I of 0-60^o. for step II, thyristors 1,2 conduct and load voltages are $v_{ao} = V_{\frac{S}{2}}, v_{bo} = -\frac{V_S}{2} \; and \; v_{co} = 0$. these voltages are plotted in fig.2.5.

the line voltages-

$$v_{ab} = v_{ao} - v_{bo}$$

$$v_{bc} = v_{bo} - v_{co}$$

And $$v_{ca} = v_{co} - v_{ao} \qquad (2.2)$$

It has been shown that phase has one positive pulse and one negative pulse (each of 120^o duration) for one cycle of output alternating voltage. The line voltage however, has a six steps per cycle of output alternating voltage.

2.6. Mathematical analysis of Inverter (six step mode of operation)-

Basically it is an electronic motor and requires a three-phase inverter in the front end as shown in In self- control mode the inverter acts like an electronic commutator that receives the switching logical pulse from the absolute position sensors. The drive is also known as an electronic commutated motor.

Three – phase bridge inverters are widely used for ac motor drives and general purpose ac supplies. The circuit consists of three half bridges, which are mutually phase shifted by $\frac{2\pi}{3}$ angle to generate the three phase voltage waves. The input dc supply is usually obtained from a single phase or three phase utility power supply through a diode bridge rectifier and LC or C filter [12].

The square – wave phase voltage with respect to the fictitious dc centre tap can be expressed by Fourier series as [12].

$$\mathrm{v_{ao}} = \frac{2\mathrm{V_s}}{\pi}\left[\cos \omega t - \frac{1}{3\cos 3\omega t} + \frac{1}{5\cos 5\omega t} - \cdots \ldots\right] \qquad (2.3)$$

$$\mathrm{v_{bo}} = \frac{2\mathrm{V_s}}{\pi}\left[\cos\left(\omega t - \frac{2\pi}{3}\right) - 1/3\cos\left(\omega t - \frac{2\pi}{3}\right) + 1/5\cos\left(\omega t - \frac{2\pi}{3}\right) - \cdots\right] \qquad (2.4)$$

$$v_{co} = \frac{2V_s}{\pi}\left[\cos\left(\omega t + \frac{2\pi}{3}\right) - \frac{1}{3}\cos\left(\omega t + \frac{2\pi}{3}\right) + \frac{1}{5}\cos\left(\omega t + \frac{2\pi}{3}\right) - \cdots.\right] \qquad (2.5)$$

Where Vs = dc supply voltage.

The line voltage can therefore be constructed from above equations (2.3-2.5). as-

$$v_{ab} = v_{ao} - v_{bo} \tag{2.6}$$

$$= \frac{2\sqrt{3}V_s}{\pi}[\cos(\omega t + \frac{\pi}{6}) + 0 - \frac{1}{5}\cos 5\left(\omega t + \frac{\pi}{6}\right) - \frac{1}{7}\cos 7\left(\omega t + \frac{\pi}{6}\right) + \cdots]$$

$$v_{bc} = v_{bo} - v_{co} \tag{2.7}$$

$$= \frac{2\sqrt{3}V_s}{\pi}[\cos\left(\omega t - \frac{\pi}{2}\right) + 0 - \frac{1}{5}\cos 5\left(\omega t - \frac{\pi}{2}\right) - \frac{1}{7}\cos 7(\omega t - \frac{\pi}{2}) + \cdots]$$

$$v_{ca} = v_{co} - v_{a0} \tag{2.8}$$

$$= \frac{2\sqrt{3}V_s}{\pi}[\cos(\omega t + \frac{5\pi}{6}) + 0 - \frac{1}{5}\cos 5\left(\omega t + \frac{5\pi}{6}\right) - \frac{1}{7}\cos 7\left(\omega t + \frac{5\pi}{6}\right) + \cdots]$$

Note that the line fundamental voltage amplitude is

Basically the inverter can operate in the following two modes $\sqrt{3}$ times that of the phase voltage, and there is a leading phase shift angle of $\frac{\pi}{6}$ .The line voltage waves have the characteristic six stepped wave shape, and are analogous to line current waves in a phase controlled bridge rectifier. The characteristic harmonics in the waveform are 6n +_1, where n = integer. The phase fundamental as well as the harmonic components are balanced with the mutual phase - shift angle of $2\pi/3$. Because of the characteristic wave shape, this type of inverter called a square wave or six stepped inverter [12].

2.7. Machine dynamic model

The BLDC motor has three stator windings and a permanent magnet rotor on the rotor. Rotor induced currents can be neglected due to the high resistivity of both magnets and stainless steel. No damper winding are modelled the circuit equation of the three windings in phase variables are obtained [15].

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} Rs & 0 & 0 \\ 0 & Rs & 0 \\ 0 & 0 & Rs \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2.9)$$

Where V_{as} , V_{bs} and, V_{cs} are the stator phase voltages; Rs is the stator resistance per phase; i_a , i_b and i_c are the stator phase currents; L_{aa} , L_{bb} and L_{cc} are the self-inductance of phases a, b and c;L_{ab} , L_{ba} ,and L_{ca} are the mutual inductances between phases a, b and c; e_a , e_b and e_c are the phase back electromotive forces .It has been assumed that resistance of all the winding are equal. It also has been assumed that if there in no change in the rotor reluctance with angle because of a no salient rotor and then.

$$L_{aa} = L_{bb} = L_{cc} = \mathrm{L} \quad (2.10)$$

$$L_{ab} = L_{ba} = L_{ca} = L_{ac} = L_{cb} = L_{ac} = \mathrm{M} \quad (2.11)$$

on substituting the equations (2.3) and (2.2) in (2.1) we obtained BLDC motor model as

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} Rs & 0 & 0 \\ 0 & Rs & 0 \\ 0 & 0 & Rs \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2.12)$$

where V_{as}, V_{bs} and V_{cs} are phase voltages and may be designed as

$$V_{as} = V_{ao} - V_{no}, \quad V_{bs} = V_{bo} - V_{no} \text{ and } V_{cs} = V_{co} - V_{no} \quad (2.13)$$

Where V_{ao} , V_{bo} , V_{co} and V_{no} are three phase and neutral voltages referred to the zero reference potential at the mid- point of dc link .

The stator phase currents are constrained to be balanced i.e.

$$i_a + i_b + i_c = 0 \tag{2.14}$$

This leads to the simplifications of the inductances matrix in the models as then

$$Mi_b + Mi_c = -Mi_a \tag{2.15}$$

Therefore in state space from-

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} Rs & 0 & 0 \\ 0 & Rs & 0 \\ 0 & 0 & Rs \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L-M & M & M \\ M & L-M & M \\ M & M & L-M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{2.16}$$

It has been assumed that back EMF $e_a, e_b, and\ e_c$ are have trapezoidal wave from

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \omega_m \lambda_m \begin{bmatrix} f_{as}(\theta_r) \\ f_{bs}(\theta_r) \\ f_{cs}(\theta_r) \end{bmatrix} \tag{2.17}$$

Where -

ω_m the angular rotor speed in radians per seconds, λ_m is the flux linkage,

θ_r is the rotor position in radian and the functions $f_{as}(\theta_r)$ have the same shape $(e_a, e_b, and\ ec$ as with a maximum magnitude of ±1.The induced emfs do not have sharp corners because these are in trapezoidal nature.

The emfs are the result of the flux linkages derivatives and the flux linkages are continuous function.

Fringing also makes the flux density function smooth with no abrupt edges.

The electromagnetic toque in Newton's defined as [12]

$$Te = [e_a i_a + e_b i_a + e_c i_a] / \omega_m \text{ (N-m)} \tag{2.18}$$

It is significant to observe that the phase voltage-equation is identical to armature – voltage equation of dc machine. That is one of reasons for naming this machine the PM brushless dc machine.

The moment of inertia is described as

$$J = J_m + J_l \tag{2.19}$$

The equation of the simple motion system with inertia J, friction coefficient B, and load torque T_l is

$$J\frac{d\omega_m}{dt} + B\omega_m = Te - T_l \tag{2.20}$$

The electrical rotor speed and position are related by

$$\frac{d\theta_r}{dt} = \frac{P}{2}\omega_m \tag{2.21}$$

The damping coefficient B is generally small and often neglected. The above equation is the rotor position θ_r and it repeats every 2π The potential of the neutral point with respect to the zero potential (V_{no}) is required to be considered in order to avoid imbalance in the applied voltage and simulate the performance of the drive [13].

$$V_{ao} + V_{bo} + V_{co} - 3V_{no}$$

$$= Rs((i_a + i_b + i_c) + (L - M)(pi_a + pi_b + pi_c) + (e_a + e_b + e_c\ ) \tag{2.22}$$

Substituting equation (2.14) in (2.22)

$$V_{ao} + V_{bo} + V_{co} - 3V_{no} = e_a + e_b + e_c$$

Thus

$$V_{no} = [V_{ao} + V_{bo} + V_{co} - (e_a + e_b + e_c)]/3 \tag{2.23}$$

The set of differential equations mentioned in equations (2.16), (2.20) and (2.21), combining the all relevant equations, the system in state-space form is [15]

$$\dot{x} = Ax + Bu + Ce \tag{2.24}$$

Where

$$x = [\ i_a \quad i_b \quad i_c \quad \omega_m \quad \theta_r \ ]^t \tag{2.25}$$

$$A = \begin{bmatrix} -\frac{Rs}{L-M} & 0 & 0 & -\frac{\lambda m}{J} f_{as}(\theta_r) & 0 \\ 0 & -\frac{Rs}{L-M} & 0 & -\frac{\lambda m}{J} f_{bs}(\theta_r) & 0 \\ 0 & 0 & -\frac{Rs}{L-M} & -\frac{\lambda m}{J} f_{cs}(\theta_r) & 0 \\ \frac{\lambda m}{J} f_{as}(\theta_r) & \frac{\lambda m}{J} f_{bs}(\theta_r) & \frac{\lambda m}{J} f_{cs}(\theta_r) & -\frac{B}{J} & 0 \\ 0 & 0 & 0 & \frac{P}{2} & 0 \end{bmatrix} \tag{2.26}$$

$$B = \begin{bmatrix} \frac{1}{L-M} & 0 & 0 & 0 \\ 0 & \frac{1}{L-M} & 0 & 0 \\ 0 & 0 & \frac{1}{L-M} & 0 \\ 0 & 0 & 0 & \frac{1}{L-M} \end{bmatrix} \tag{2.27}$$

$$C = \begin{bmatrix} -\frac{1}{L-M} & 0 & 0 \\ 0 & -\frac{1}{L-M} & 0 \\ 0 & 0 & -\frac{1}{L-M} \end{bmatrix} \tag{2.28}$$

$$u = [V_{as}\ V_{bs}\ \ V_{cs}\ T_l\ \ ]\text{^}t \tag{2.29}$$

$$e = [e_a \ \ e_b \ \ e_c]^t \tag{2.30}$$

2.8. Conclusion

From above discussion and results, it is shown that we do not need d-q model of BLDC motor for speed analysis. 120^o mode inverter is more efficient than 180^o mode. Mathematical modelling of machine is simple and only two phase are active at a time for conducting in inverter. Only two thyristor conducts at a time. Inverter shows square waveform.

CHAPTER-3
DESIGN OF PI SPEED CONTROLLER

3.1. Brief review on PI controller

A proportional integral-derivative is control loop feedback mechanism used in industrial control system. In industrial process a PI controller attempts to correct that error between a measured process variable and desired set point by calculating and then outputting corrective action that can adjust the process accordingly. A Proportional-Integral (PI) controller is the most common controller in speed loop feedback system which is widely used in the industries due to its capabilities in controlling linear plants. However, it faces problem in controlling nonlinear plants such as electrical machines. These machines might behave as a nonlinear system, where non-linearity may appear due to armature current limitations, change of load and drive inertia [17].

The step response of the drive system for a given reference speed is one of the performance indicator of the speed controller. It is desired that the step response of the system can achieve fast settling response and without overshoot. However, PI controller cannot be tuned in such a way that the optimum step response is achieved for different inertia, load and speed reference. Thus, an intelligent controller such as fuzzy controller is needed for improving the speed response [18].

Nowadays, there is a tendency to integrate the control algorithms together for better performances. Recently, hybrid systems have increased the potential for intelligent control systems in getting improved performances [19].

The PI controller mainly supports steady-state accuracy and cancels disturbance effects when load torque change while the fuzzy controller acts in the case of sufficiently large reference input changes especially during start-up. In order to obtain control schemes that have good dynamic responses due to parameter variations, a hybrid controller is included in this comparative study.

The hybrid controller contains PI and fuzzy control algorithms. By using switch, the fuzzy controller will be activated in the case of sufficiently large reference input changes or large speed error, while the PI controller will be activated in the case of the small speed error so that it can support steady-state accuracy and cancels disturbance effects.

The PI controller calculation involves two separate modes the proportional mode, Integral mode determines the reaction based recent error. The weighted sum of the two modes output as corrective action to the control element. PI controller is widely used in industry due to its ease in design and simple structure. PI controller algorithm can be implemented as-

$$output = K_p e(t) + K_I \int_0^{\tau} e(\tau) d\tau \qquad (3.1)$$

Where e(t) = set reference value — actual value

The transfer function of the most basic form of PI controller

$$e(s) = K_p + K_I/s \qquad (3.2)$$

If the proportional factor is too high the system will become unstable. If it is too small the system is not able to reach the set point in a given time. So the proportional factor or gain of the PI controller is tuned to maintain the speed at a desired level.

The advantage of both P-controller and I-controller are combined in PI-controller. The proportional action increases the loop gain and makes the system less sensitive to variations of system parameters. The integral action eliminates or reduces the steady state error [21].

Structure of PI controller

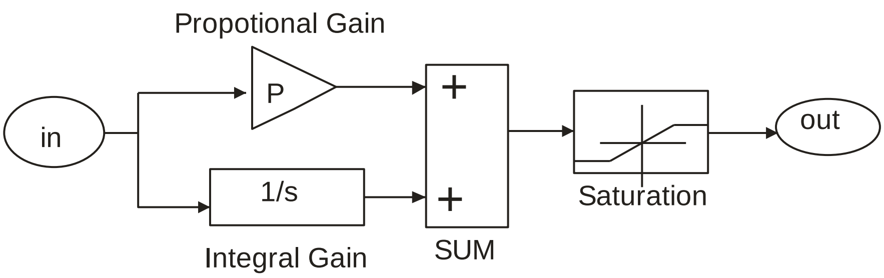


Fig.3.1. PI speed controller structure

3.2. PI speed control of BLDC motor

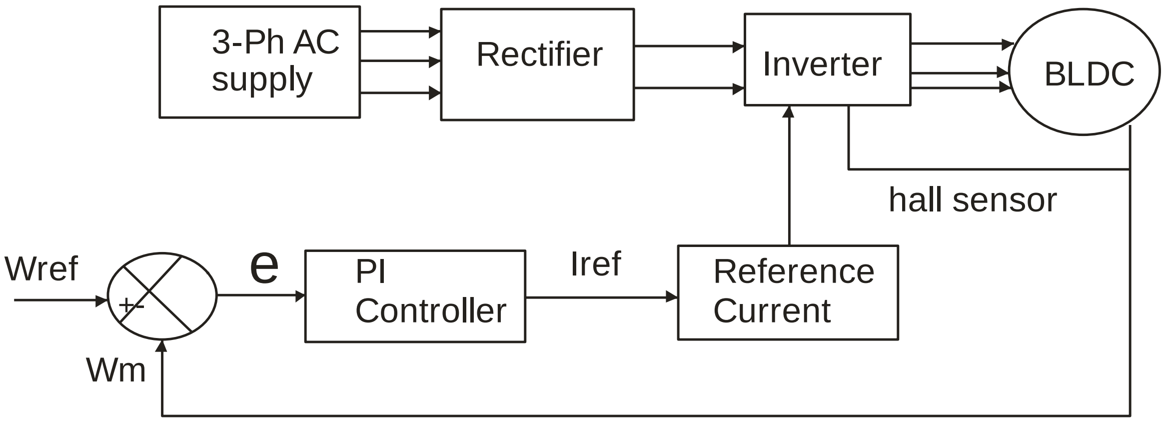


Fig.3.2. BLDC model with PI Controller

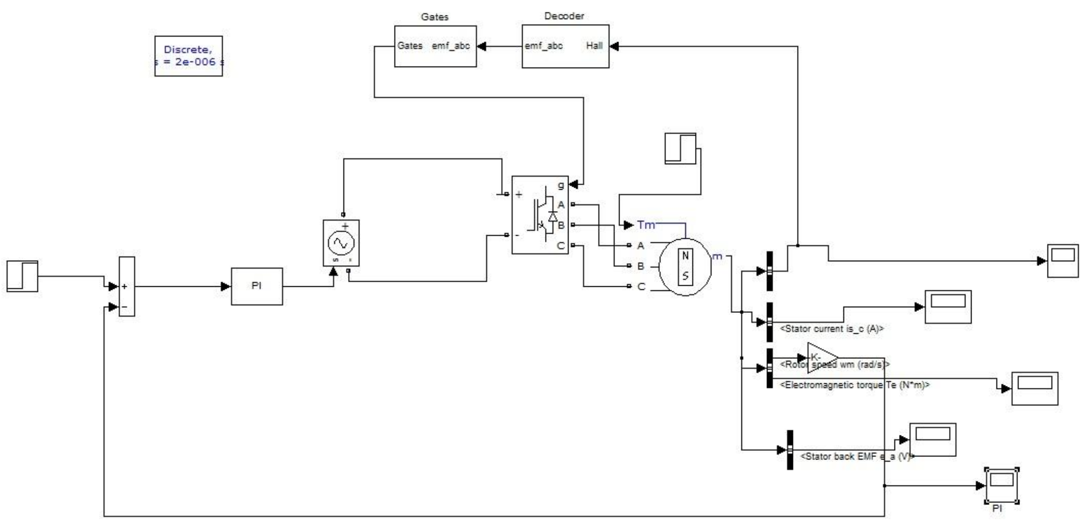


Fig.3.3. BLDC motor model using PI in Simulink

Figure 3.2 shown above describes the basic building blocks of the PBLDC drive. The drive consists of speed controller, reference current generator, position sensor, the motor and IGBT based voltage controlled voltage source inverter.

The speed of the motor is compared with its reference value and the speed error is processed in proportional- integral (PI) speed controller.

$$\mathrm{e(t)} = \omega_{ref} - \omega_m \quad (3.3)$$

ω_m is compared with the reference speed ω_{ref} .

Nth sampling instsnt as-

$$\mathrm{T}_{ref}(t) = T_{rfe}(t-1) + K_P[e(t) - e(t-1)] + K_I e(t) \quad (3.4)$$

Kp and Ki are considered to be proportional and integral gains.

3.3. Modeling of back EMF using Rotor position-

The phase back EMF in the PMBLDC motor is trapezoidal in nature and is the function of the speed ω_m and rotor position angle θ_r. From this, the phase back EMF'S can be expressed as [19]-

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \omega_m \lambda_m \begin{bmatrix} f_{as}(\theta_r) \\ f_{bs}(\theta_r) \\ f_{cs}(\theta_r) \end{bmatrix} \quad (3.5)$$

Where $f_{as}(\theta_r)$, $f_{bs}(\theta_r)$ and $f_{cs}(\theta_r)$ are unit function generator to corresponding to the trapezoidal induced emfs of the of BLDCM as a function of θ_r . The $f_{bs}(\theta_r)$, $f_{cs}(\theta_r)$ are similar to $f_{as}(\theta_r)$, but phase displacement of 120^0.

The back emf functions mathematical model as-

$$f_{as}(\theta_r) = \begin{array}{ll} \theta_r \frac{6}{\pi}, & 0 \le \theta_r < \frac{\pi}{6} \\ 1, & \frac{\pi}{6} \le \theta_r < \frac{5\pi}{6} \\ (\pi - \theta_r)\frac{6}{\pi}, & \frac{5\pi}{6} \le \theta_r < \frac{7\pi}{6} \\ -1, & \frac{7\pi}{6} \le \theta_r < \frac{11\pi}{6} \\ (\theta_r - 2\pi)\frac{6}{\pi}, & \frac{11\pi}{6} \le \theta_r < 2\pi \end{array} \quad (3.6)$$

$$f_{bs}(\theta_r) = \begin{cases} -1, & 0 \le \theta_r < \frac{\pi}{2} \\ \left(-\frac{2\pi}{3} + \theta_r\right)\frac{6}{\pi}, & \frac{\pi}{2} \le \theta_r < \frac{5\pi}{6} \\ 1, & \frac{5\pi}{6} \le \theta_r < \frac{3\pi}{2} \\ \left(-\frac{5\pi}{3} + \theta_r\right)\frac{6}{\pi}, & \frac{3\pi}{2} \le \theta_r < \frac{11\pi}{6} \\ -1, & \frac{11\pi}{6} \le \theta_r < 2\pi \end{cases} \tag{3.7}$$

$$f_{cs}(\theta_r) = \begin{cases} 1, & 0 \le \theta_r \frac{\pi}{6} \\ \left(\frac{\pi}{3} - \theta_r\right)\frac{6}{\pi}, & \frac{\pi}{6} \le \theta_r < \frac{\pi}{2} \\ -1, & \frac{\pi}{2} \le \theta_r < \frac{7\pi}{2} \\ \left(-\frac{4\pi}{3} + \theta_r\right)\frac{6}{\pi}, & \frac{7\pi}{2} \le \theta_r < \frac{\pi}{2} \\ 1, & \frac{3\pi}{2} \theta_r < 2\pi \end{cases} \tag{3.8}$$

3.4. Switching algorithm for BLDC motor with trapezoidal back EMF through Hall effect Sensor

Rotor position is sensed by Hall Effect sensors embedded into the stator which gives the sequence of phases. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high/low signal, indicating the N or S pole is passing near the sensors. The three Hall effect sensors, ha, hb, and hc, are used to detect the rotor position. To rotate the BLDC motor, the stator windings should be energized in a sequence. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined as [20].

The simulink/MATLAB diagram.

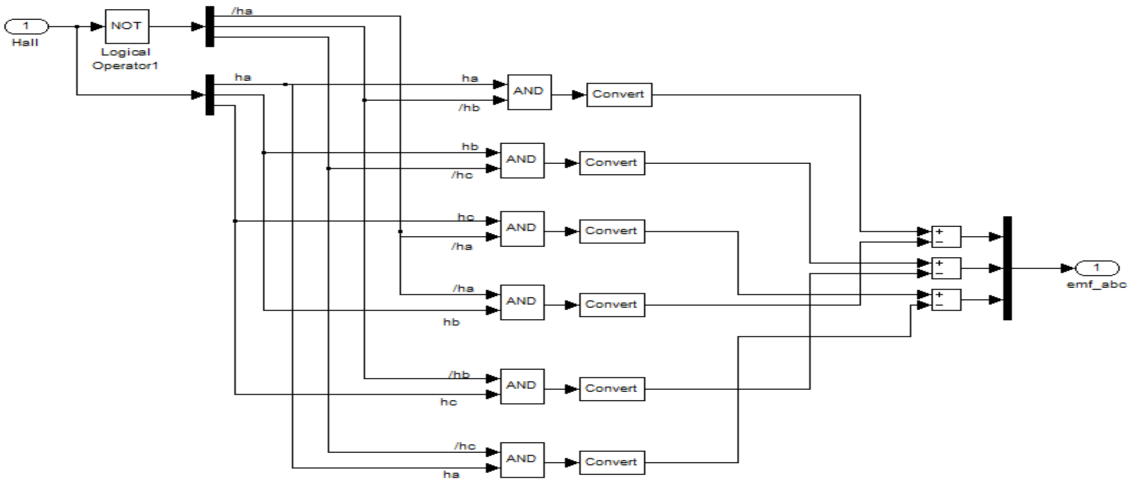


Figure 3.4. Hall decoder

Table No.-3.1.
Switching algorithm for back emf using hall effect sensor

ha	hb	hc	emf_a	emf_b	emf_c
0	0	0	0	0	0
0	0	1	0	-1	+1
0	1	0	-1	+1	0
0	1	1	-1	0	+1
1	0	0	+1	0	-1
1	0	1	+1	-1	0
1	1	0	0	+1	-1
1	1	1	0	0	0

The gate logic is to transform electromagnetic forces to the 6 signal on the gates as given in the Table 3.2.

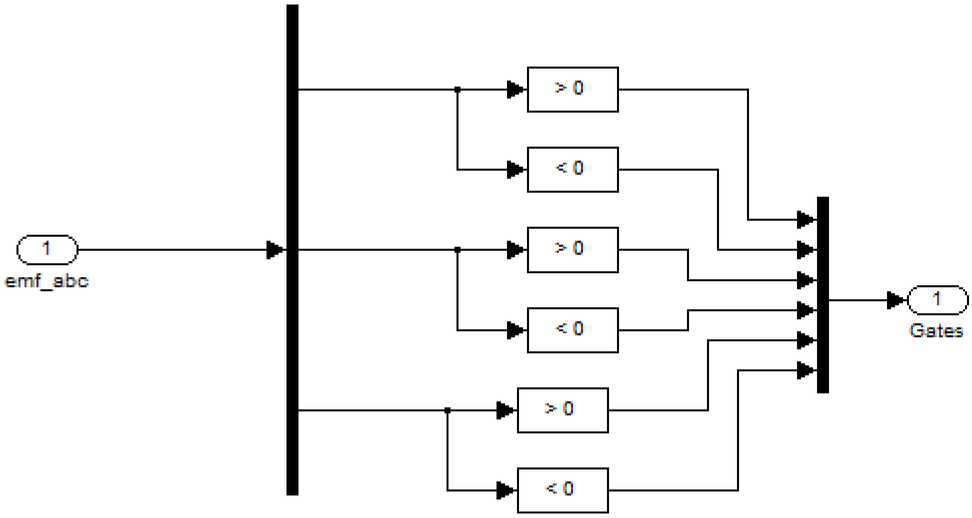


Fig. 3.5. Gate Logic

Table No. - 3.2.
Transistor switching sequence through Gate logic

emf_a	emf_b	emf_c	T1	T2	T3	T4	T5	T6
0	0	0	0	0	0	0	0	0
0	-1	+1	0	0	0	1	1	0
-1	+1	0	0	1	1	0	0	0
-1	0	+1	0	1	0	0	1	0
+1	0	-1	1	0	0	0	0	1
+1	-1	0	1	0	0	1	0	0
0	+1	-1	0	0	1	0	0	1
0	0	0	0	0	0	0	0	0

3.5. Performance analysis with PI (2000rpm, T_L=0)

Speed graph

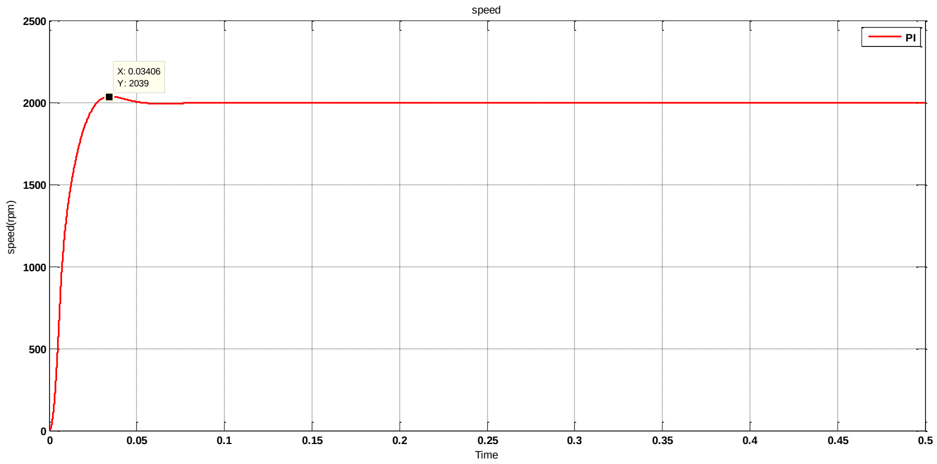


Fig.3.6(a). Speed response with PI (2000rpm, T_L=0)

In above fig.3.6(a). we show the speed response with classical PI controller. At the time of starting PI controller show some kind of spikes in the weveform. The motor is set for the reference speed of 2000 RPM at no load condition. During sartup it shows more overshoot at 0.03397 sec and at this moment the speed crosses the reference speed i.e. 2039 rpm. After 0.05454 sec PI controller settles the speed to its reference speed means it takes much time for settling the speed to its nominal speed. PI controller shows some delay to track the reference speed. PI controller has slow efficiency however shows If the proportional factor is too high the system will become unstable.

If it is too small the system is not able to reach the set point in a given time. So the proportional factor or gain of the PI controller is tuned to maintain the speed at a desired level. The advantage of both P-controller and I-controller are combined in PI-controller. The proportional action increases the loop gain and makes the system less sensitive to variations of system parameters. The integral action eliminates or reduces the steady state error. The proportional controller gives an output directly proportional to the error. If the error goes to zero then output of the controller is zero and the system will slow down with damping. It also causes an overshoot The integral controller reduces the rise time, causes an overshoot, increases the settling time and most importantly eliminates the steady state error. So we need fuzzy contoller for reducing the overshoot and rise tme.

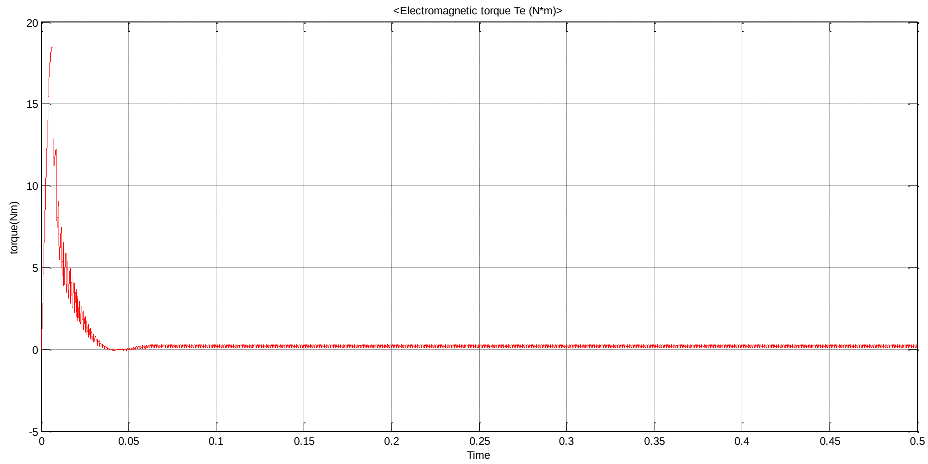


Fig.3.6(b). Electromagnetic torque with PI(2000rpm,T_L=0)

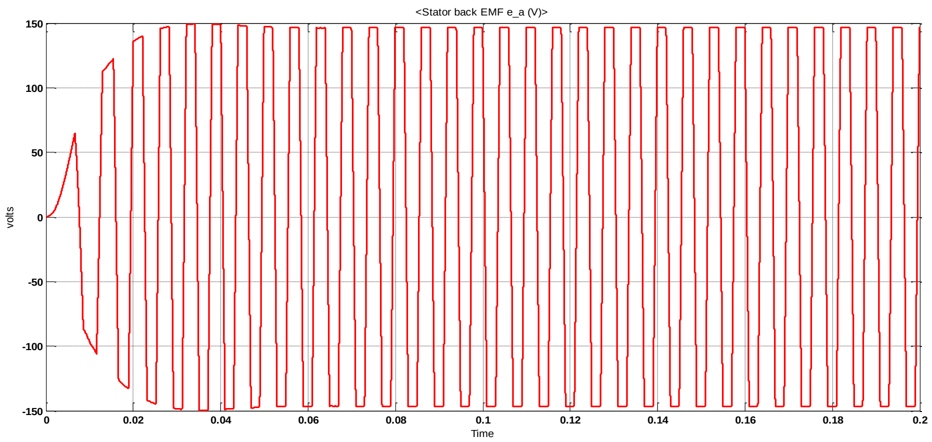


Fig.3.6(c). Stator back emf with PI (2000rpm,T_L=0)

Stator current (amp)

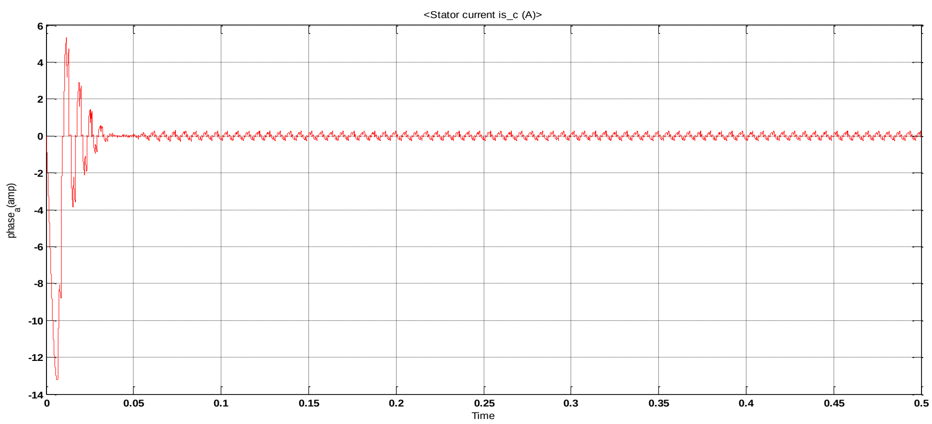


Fig.3.6(d). stator current with PI

3.6. Performance analysis with PI (2000rpm, T_L=4Nm)

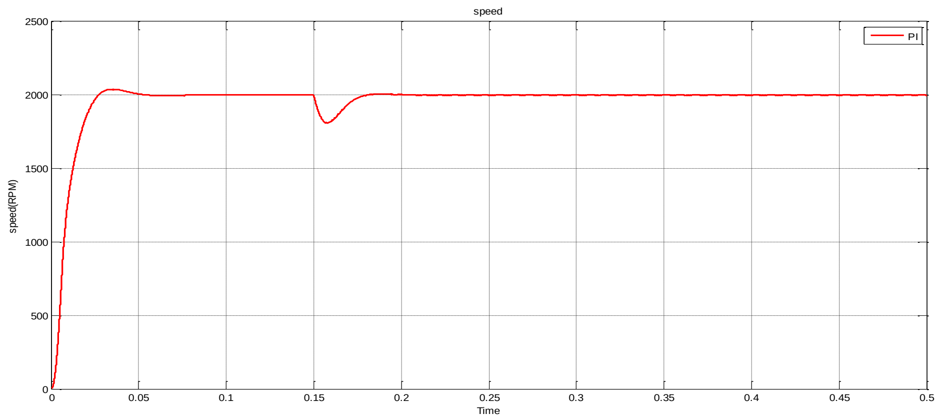


Fig.3.7(a). Speed response with PI (2000rpm, T_L=4)

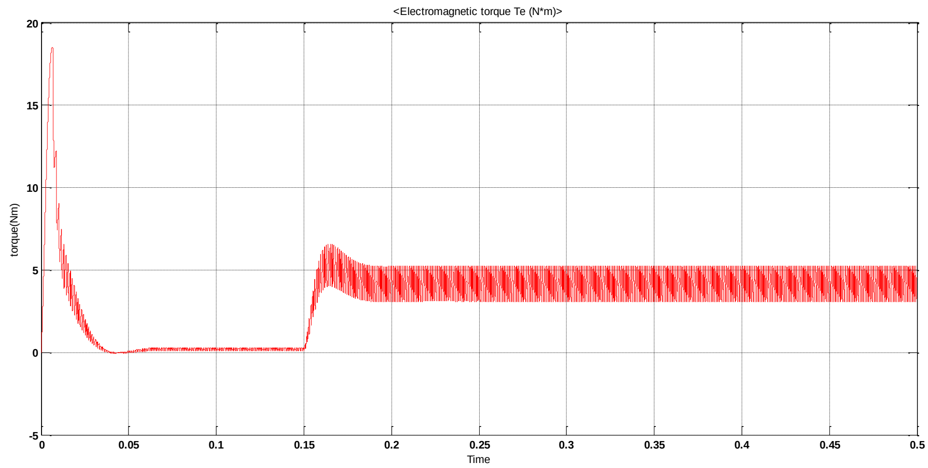


Fig.3.7(b). Electromagnetic torque (2000rpm, T_L=4Nm)

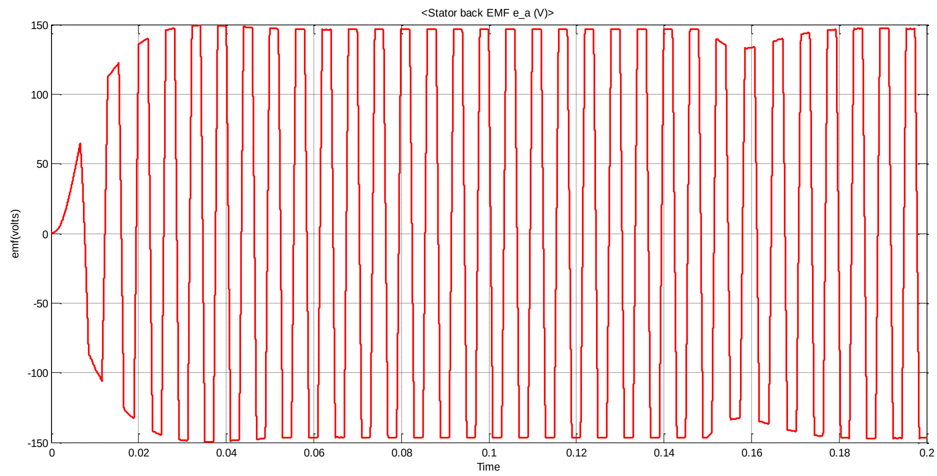


Fig.3.7(c). Stator back emf (2000rpm, T_L=4Nm)

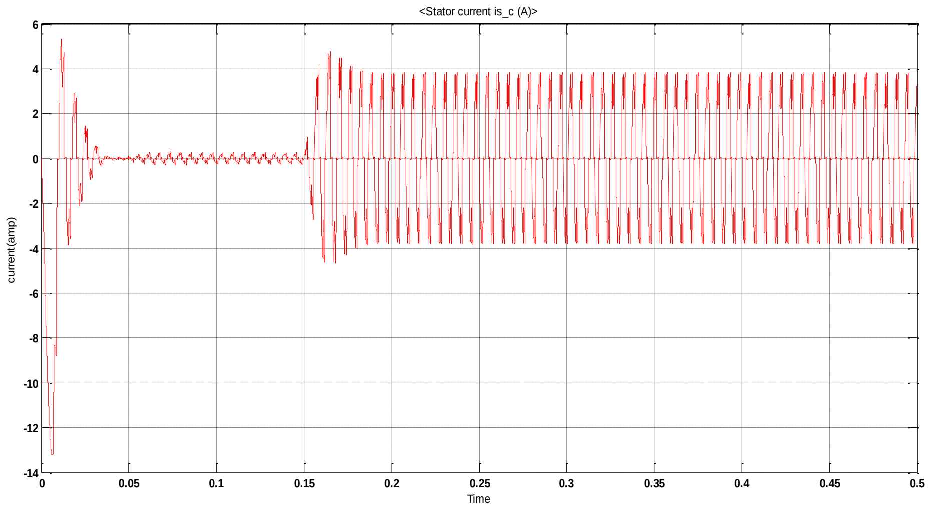


Fig.3.7(d). Stator current (2000rpm, T_L=4Nm)

3.7. Performance analysis with PI (2500rpm,T_L=0Nm)

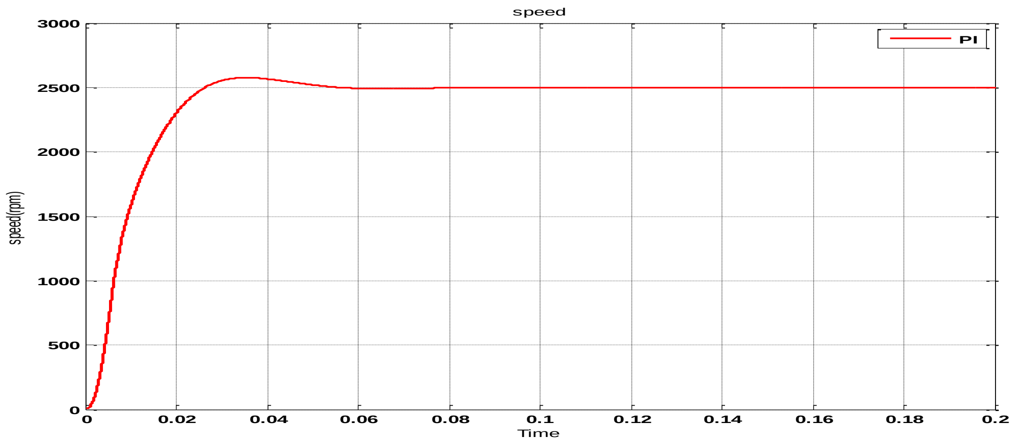


Fig.3.8(a). speed response with PI (2500rpm,T_L=0Nm)

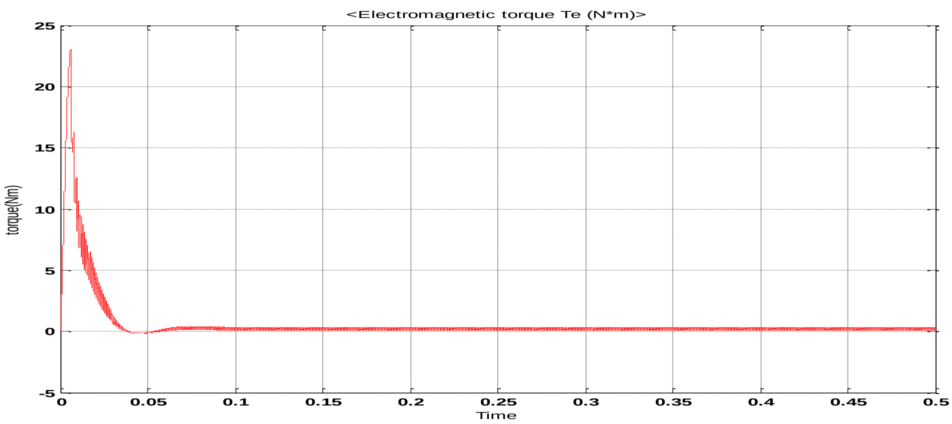


Fig.3.8(b). electromagnetic torque with PI (2500rpm, T_L=0Nm)

3.8. Performance analysis with PI (2500rpm,T_L=4Nm)

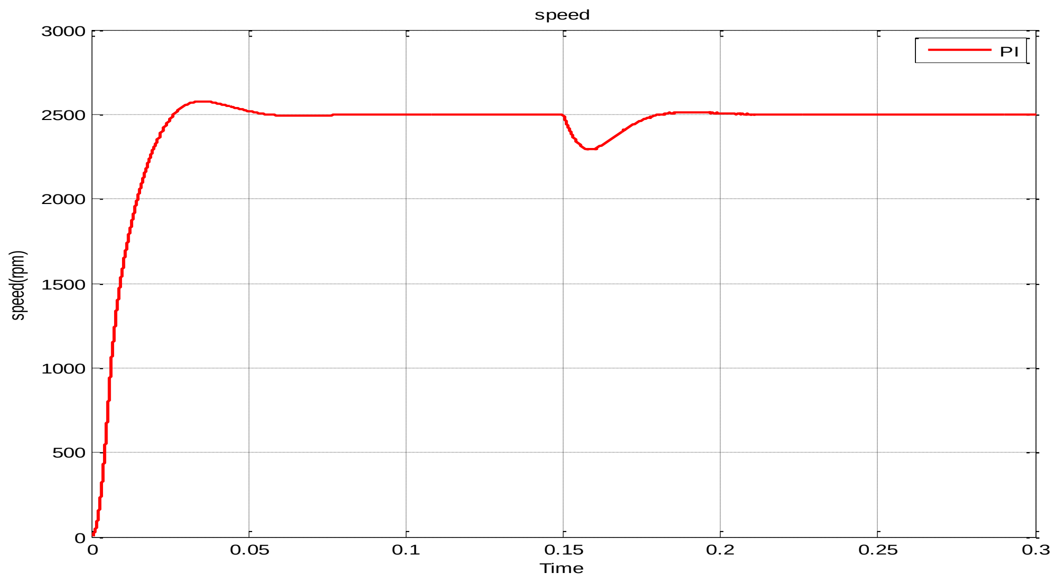


Fig.3.9(a). speed response with PI (2500rpm,T_L=4Nm)

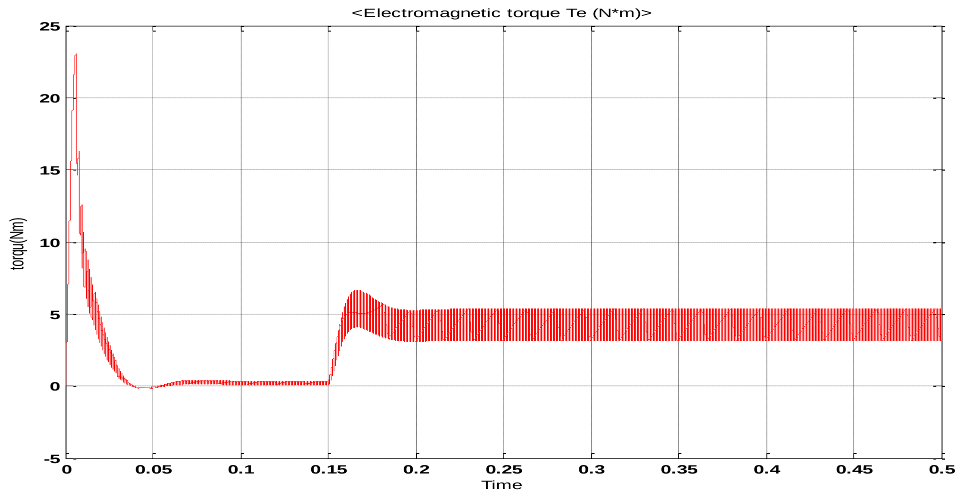


Fig.3.9(b). electromagnetic torque (2500rpm, T_L=4Nm)

3.9. Conclusion

In this chapter discussed above, PI speed controller for controlling the speed of motor is a classical way of controller. The PI controller mainly supports steady-state accuracy and cancels disturbance effects when load torque change. In order to obtain control schemes that has good dynamic responses due to parameter variations.

If the proportional factor is too high the system will become unstable. If it is too small the system is not able to reach the set point in a given time. So the proportional factor or gain of the PI controller is tuned to maintain the speed at a desired level. PI speed Controller shows overshoot. This problem can be eliminated by using another controller known as Fuzzy controller, discussed in next chapter.

CHAPTER-4
DESIGN OF FUZZY LOGIC CONTROLLER

4.1. A brief review on FLC

Fuzzy logic has rapidly become one of the most successful of today's technology for developing sophisticated control system. With it aid complex requirement so may be implemented in amazingly simple, easily minted and inexpensive controllers. The past few years have witnessed a rapid growth in number and variety of application of fuzzy logic.

CLASSICAL control methods can be implemented in well-defined systems to achieve good performance of the systems. To control a system, an accurate mathematical model of the complete system must be obtained. Systems with nonlinear structure cannot be exactly modelled. The nature of fuzzy logic control has adaptive characteristics that can achieve robust response to a system with uncertainty, parameter variation, and load disturbance. Fuzzy logic, or fuzzy set theory, was first presented by Zadeh [22].

Since the introduction of fuzzy logic, many researchers have studied modelling of the complex systems, and fuzzy logic controllers (FLCs) have been broadly used to control ill-defined, nonlinear, or imprecise systems [23], [24]. In the area of the electrical machines' drive systems, fuzzy logic controllers have been applied to switched reluctance motors [25], [26], induction motors [27], brushless direct current motors (BLDC) [28], and other types of alternating current (ac) motors successfully [8]. Many colleges are now offering fuzzy logic courses as a result of successful applications of FLCs in nonlinear systems.

Fuzzy set theory is originally introduced by Lotfi Zadeh in the 1960 [22], resembles approximate reasoning in it use of approximate information and uncertainty to generate decisions.

Several studies show, both in simulations and experimental results, that Fuzzy Logic control yields superior results with respect to those obtained by conventional control algorithms thus, in industrial electronics the FLC control has become an attractive solution in controlling the electrical motor drives with large parameter variations like machine tools and robots.

However, the FL Controllers design and tuning process is often complex because several quantities, such as membership functions, control rules, input and output gains etc must be adjusted. The design process of a FLC can be simplified if some of the mentioned quantities are obtained from the parameters of a given Proportional-Integral controller (PI) for the same application.

4.2. Motivations for choosing fuzzy logic controller (FLC)

Fuzzy logic controller can model nonlinear systems. The design of conventional control system essential is normally based on the mathematical model of plant .if an accurate mathematical model is available with known parameters it can be analysed, for example by bode plots or nyquist plot , and controller can be designed for specific performances .such procedure is time consuming [29].

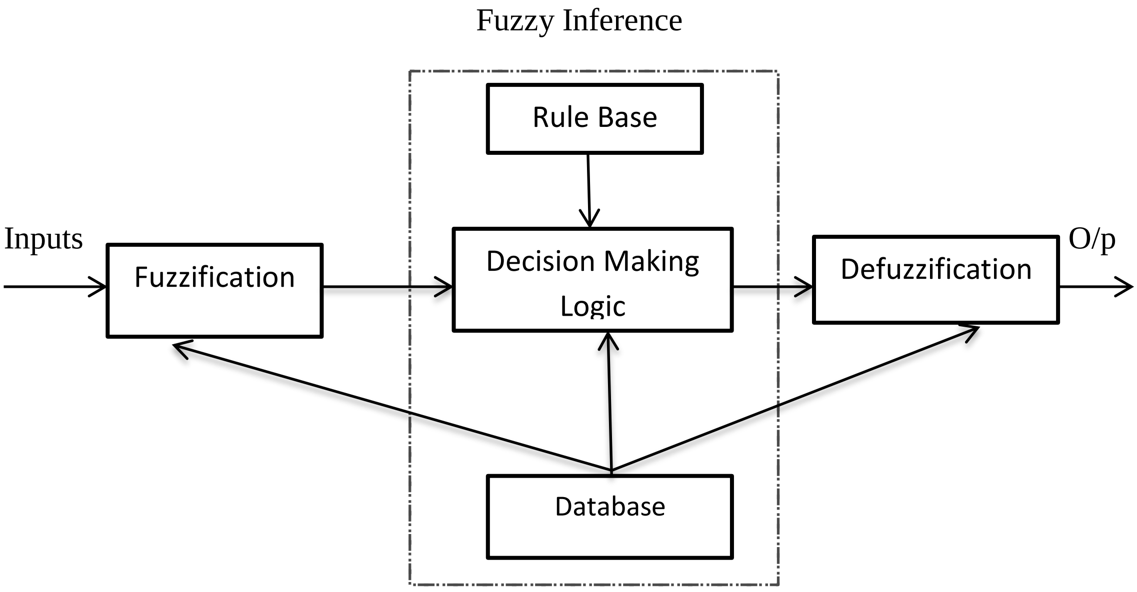


Fig.4.1. Fuzzy logic Controller Block diagram

- Fuzzy logic controller has adaptive characteristics

4.3. The fuzzy logic controller has three main components

1. Fuzzification
2. Fuzzy inference
3. Defuzzification

4.3.1. Fuzzification

1. Multiple measured crisp inputs first must be mapped into fuzzy membership function this process is called fuzzification.

2.. Performs a scale mapping that transfers the range of values of input variables into corresponding universes of discourse.

3.. Performs the function of fuzzification that converts input data into suitable linguistic values which may be viewed as labels of fuzzy sets.

Fuzzy logic linguistic terms are often expressed in the form of logical implication, such as if then rules. These rules define a range of values known as fuzzy member ship functions.

Fuzzy membership function may be in the form of a triangular, trapezoidal, bell shape (as shown in fig.4.2.).

I. Triangular membership Function defined as-

$$\mu(u_i) = \begin{cases} \frac{u_i - V_{al1}}{V_{al2} - V_{al1}}, V_{al1} \leq u_i \leq V_{al2} \\ \frac{V_{al3} - u_i}{V_{al3} - V_{al2}}, V_{al2} \leq u_i \leq V_{al2} \\ 0, \quad otherwise \end{cases} \quad (4.1)$$

II. Trapezoidal membership function defined in

$$\mu_i = \begin{cases} \frac{u_i - V_{al1}}{V_{al2} - V_{al1}}, V_{al1} \leq u_i \leq V_{al2} \\ 1, \quad V_{al2} \leq u_i \leq V_{al3} \\ 0, \quad otherwise \end{cases} \quad (4.2)$$

III. The bell membership functions are defined by parameters X_P , w and m as follows-

$$\mu_i = \frac{1}{1+\left(\frac{|u_i - X_P|}{w}\right)^{2m}} \tag{4.3}$$

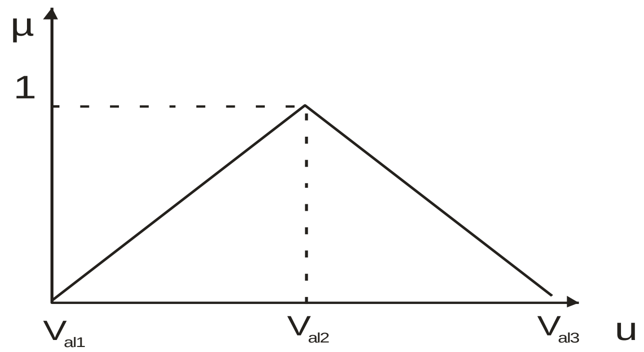


Fig. 4.2.(a)- triangular membership

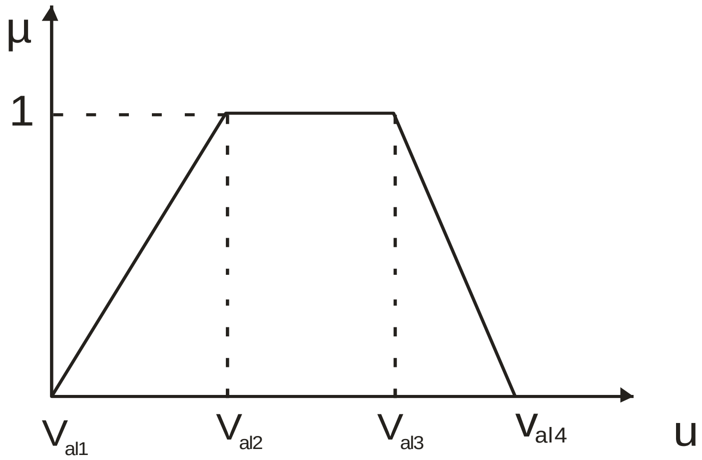


Fig.4.2.(b)- trapezoidal membership

4.3.2. Fuzzy Inference

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. There are two types of fuzzy inference systems that can be implemented in the Fuzzy Logic Toolbox:

Mamdani- type and Sugeno -type. These two types of inference systems vary somewhat in the way outputs are determined.

Fuzzy inference systems have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems, and computer vision. Because of its multidisciplinary nature, fuzzy inference systems are associated with a number of names, such as fuzzy-rule-based systems, fuzzy expert systems, fuzzy modeling, fuzzy associative memory, fuzzy logic controllers, and simply (and ambiguously) fuzzy Mamdani's fuzzy inference method is the most commonly seen fuzzy methodology.

Mamdani's method was among the first control systems built using fuzzy set theory. It was proposed in 1975 by Ebrahim Mamdani as an attempt to control a steam engine and boiler combination by synthesizing a set of linguistic control rules obtained from experienced human operators. Mamdani's effort was based on Lotfi Zadeh's 1973 paper on fuzzy algorithms for complex systems and decision processes.

The second phase of the fuzzy logic controller is its fuzzy inference where the knowledge base and decision making logic reside .The rule base and data base from the knowledge base. The data base contains the description of the input and output variables. The decision making logic evaluates the control rules .the control-rule base can be developed to relate the output action of the controller to the obtained inputs.

4.3.3. Defuzzification

The output of the inference mechanism is fuzzy output variables. The fuzzy logic controller must convert its internal fuzzy output variables into crisp values so that the actual system can use these variables. This conversion is called defuzzification. One may perform this operation in several ways. The commonly used control fuzzification strategies are

(a).The max criterion method (MAX)

The max criterion produces the point at which the membership function of fuzzy control action reaches a maximum value.

(b) The height method

The centroid of each membership function for each rule is first evaluated. The final output U_0 is then calculated as the average of the individual centroids, weighted by their heights as follows

$$U_0 = \frac{\sum_{i=1}^{n} u_i \mu(u_i)}{\sum_{i=1}^{n} \mu(u_i)} \tag{4.4}$$

(c) The centroid method or centre of area method (COA)

The widely used centroid strategy generates the centre of gravity of area bounded by the Membership function -

$$\bar{y} = \frac{\int \mu_Y(y).y dy}{\int \mu_Y(y) dy} \tag{4.5}$$

Based on the nature of fuzzy human thinking, Lotfi Zadeh, a computer scientist at the University of California, Berkeley, originated the "fuzzy logic," or fuzzy set theory, in 1965. In the beginning, he was highly criticized by the professional community, but gradually, FL captured the imagination of the professional community and eventually emerged as an entirely new discipline of Al. The general methodology of reasoning in FL and ES by "IF... THEN..." statements or rules is the same; therefore, it is often called "fuzzy expert system." For example, an ES rule for speed control in a variable-speed drive may be

IF speed of the motor is <u>greater than 1500 rpm</u> AND the machine stator temperature is <u>between 60°F and 100°F</u>

THEN set the stator current iq, <u>less than 10 amps</u>

The same rule in FL may read as

IF speed of the motor is high and stator temperature is medium THEN set the stator current i_{ces} low

4.4. Membership Functions

A fuzzy variable has values that are expressed by the natural English language. For example, as shown in Fig, the stator temperature of a motor as a fuzzy variable can be defined by the qualifying linguistic variables Cold, Mild, or Hot, where each is represented by a triangular or straight-line segment membership function (MF). These linguistic variables are defined as fuzzy sets or fuzzy subsets. An MF is a curve that defines how the values of a fuzzy variable in a certain region are mapped to a membership value ,u (or degree of membership) between 0 and 1. The fuzzy sets can have more subdivisions such as Zero, Very Cold, Medium Cold, Medium Hot, Very Hot. etc [30].

In Fig.4.3, if the temperature is below 40° F, it belongs completely to the set Cold, that is, the MF value is l ; whereas for 55° F. it is in the set Cold by 30 percent (MF = 0.3) and to the set Mild by 50 percent (MF = 0.5). At temperature 60° F, it belongs completely to the set Mild (MF = I) and not in the set Cold and Hot (MF = 0). If the temperature is above 80° F, it belongs completely to the set Hot (MF = 1), where MF = 0 for Cold and Mild. For the temperature range below 55° F, it belongs to the set Cold (MF = 1); between 55° F to 65° F, it belongs to the set Mild (MF = 1); and above 65° F, it belongs to the set Hot only (MF = l). The sets are not members (MF = 0) beyond the defined ranges. The numerical interval (20° F to 90° F) that is relevant for the description of a fuzzy variable is defined as the universe of discourse .

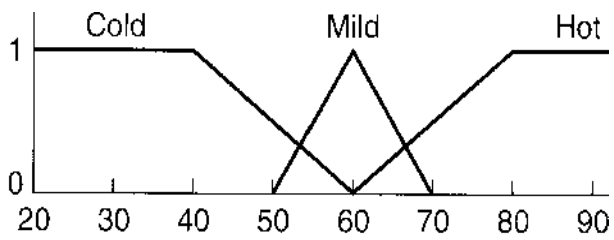


Fig.4.3. Membership function

Fig. 4.3.membership function, an MF can have different shapes, as shown in fig.4.4 below. The simplest and most commonly used MF is the triangular-type, which can be symmetrical or asymmetrical in shape. A trapezoidal MF (symmetrical or unsymmetrical) has the shape of a truncated triangle. Two MFs are built on the Gaussian distribution curve: a simple Gaussian curve and a two-sided composite of two different Gaussian curves.

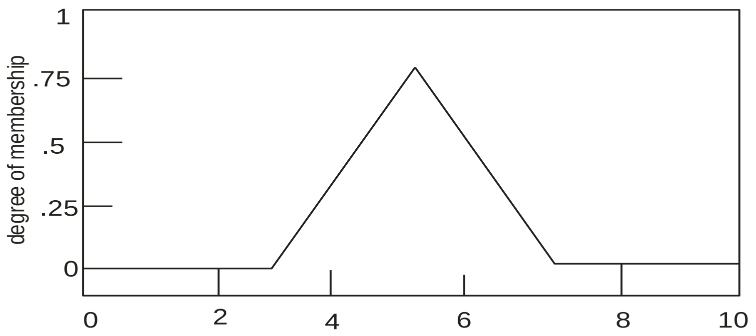


Fig. 4.4(a) Triangular Membership

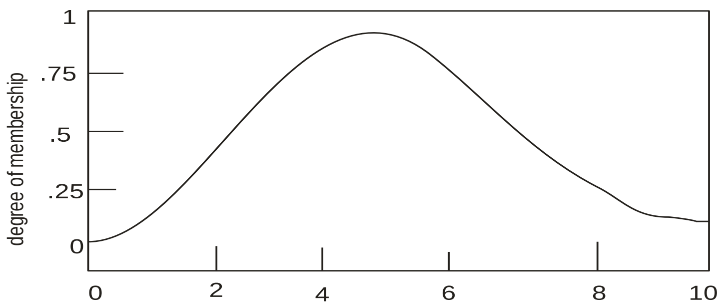


Fig.4.4(b). Gaussian Membership

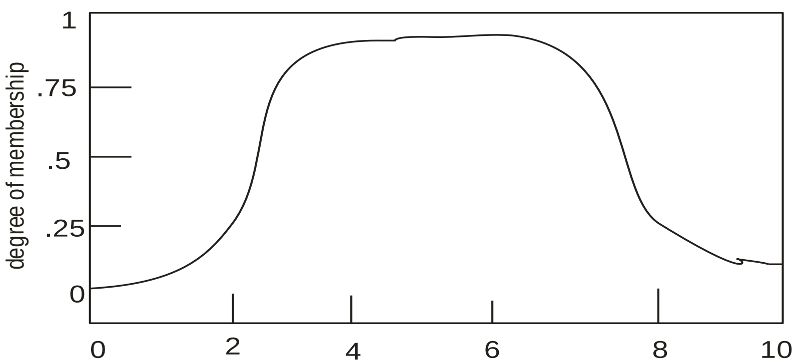


Fig.4.4(c). Bell shaped Membership

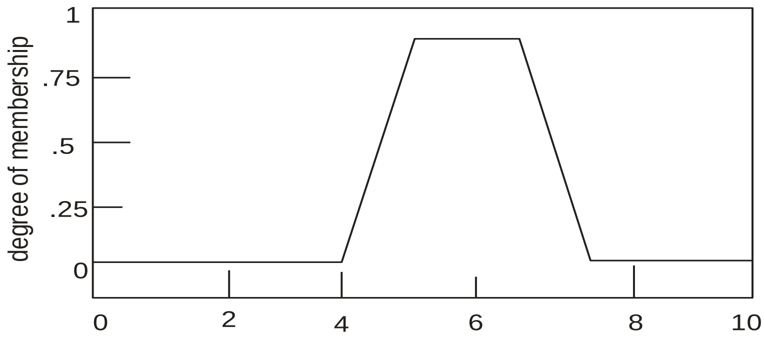


Fig.4.4.(d). Trapezoidal membership

The bell MF with a flat top is somewhat different from a Gaussian function. Both the Gaussian and bell functions are smooth and non-zero at all points. A sigmoidal-type MF can be open to the right or left. Asymmetrical and closed (not open to the right or left) MFs can be synthesized using two sigmoidal functions, such as difference sigmoidal (difference between two sigmoidal functions) and product sigmoidal (product of two sigmoid).

4.5. Operations on Fuzzy Sets

The basic properties of Boolean logic are also valid for FL. logical operations of OR, AND, and NOT on fuzzy sets A and *B* using triangular MFs and compares them with the corresponding Boolean operations on the right. Let $U_A(x)$, $P_B(x)$ denote the degree of membership of a given element x in the universe of discourse X (denoted by xEX

Union: Given two fuzzy sets A and *B*, defined in the universe of discourse X, the union (AU B) is also a fuzzy set of X, with the membership function given**.**

$$\mu_{AUB}(x) = max\ [\mu_A(x), \mu_B(x)]$$

$$= \mu_A(x)\ \ V\ \ \mu_B \qquad (4.6)$$

Intersection: The intersection of two fuzzy sets A d *B* in he universe of discourse X. denoted by A n B, has the membership function given by

$$\mu_{A\cap B} = \min[\mu_A, \mu_B]$$
$$= \mu_A \wedge \mu_B \quad (4.7)$$

where " Λ " is a minimum operator. This is equivalent to Boolean AND logic

Complement or Negation- The complement of a given set A in the universe of discourse X is denoted by A and has the membership function

$$\mu_{\bar{A}}(x) = 1 - \mu_A \quad (4.8)$$

This is equivalent to the NOT operation in Boolean logic.

Product of two fuzzy sets: The product of two fuzzy sets A and B defined in the same universe of discourse X is a new fuzzy set, $A.B$, with an MF that equals the algebraic product of the MFs of A and B

$$\mu_{A.B}(x) = \mu_A * \mu_B \quad (4.9)$$

Multiplying Fuzzy Set by a Crisp Number: The MF of fuzzy set A can be multiplied by a crisp number k to obtain a new fuzzy set called product $k.A$. Its MF is

$$\mu_{kA(x)} = k\mu_A(x) \quad (4.10)$$

Power of a Fuzzy Set: We can raise fuzzy set A to a power m (positive real number) by raising its MF to m. The m power of A is a new fuzzy set, A^{i}", with MF

$$\mu_{A^m(x)} = [\mu_A(x)]^m \quad (4.11)$$

4.6. Fuzzy logic control of the BLDC motor

The fuzzy logic controller was applied to the speed loop by replacing the classical Proportional integral (PI) controller. The fuzzy logic controlled BLDC drive system block diagram is shown in Fig.4.5.

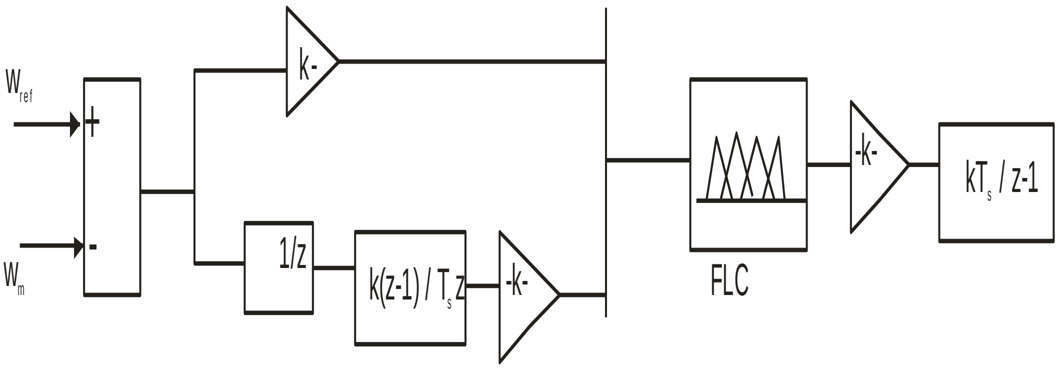


Fig.4.5. FLC speed controller structure

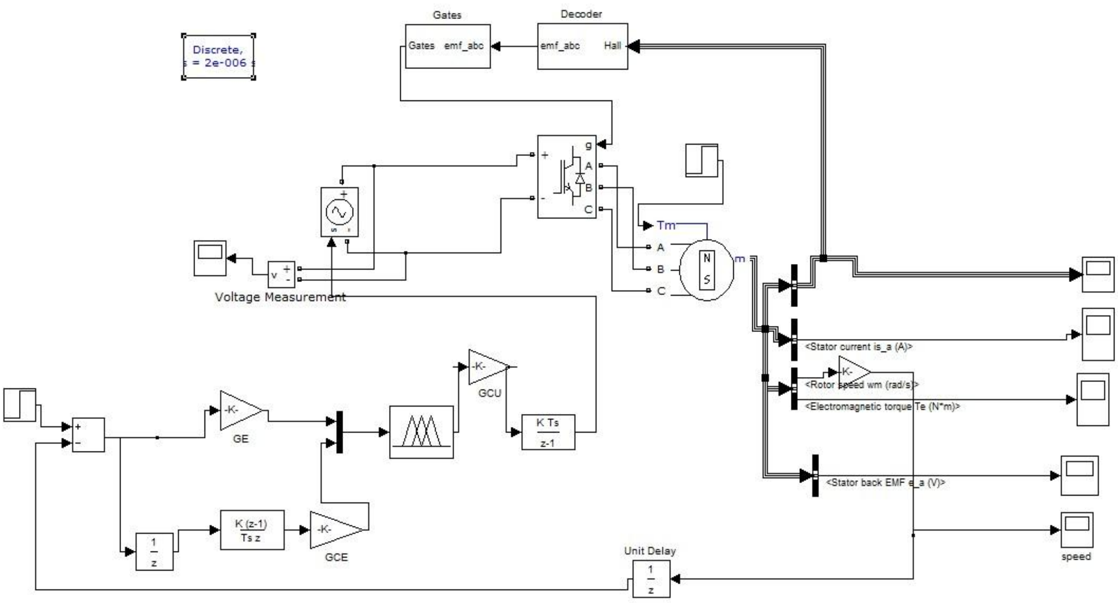


Fig.4.6. BLDC model With FLC in Simulink

The input variable is speed error (E), and change in speed error (CE) is calculated by the controller with E.

The fuzzy member's ship function for the input variable and output variable are chosen as follows:

Positive Big: PB Negative Big: NB

Positive Medium: PM Negative Medium: NM

Positive Small: PS Negative Small: NS

And zero: Z

The input variable speed error and change in speed error is defined in the range of

$$-1 \leq \omega_{e\leq} + 1 \quad (4.12)$$

And

$$-1 \leq \omega_e \leq +1 \quad (4.13)$$

The triangular shaped functions are chosen as the membership functions due to the resulting best control performance and simplicity. The membership functions for the speed error and the change in speed error and the change in error.

Table No.- 4.1

7×7 Rule base

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

The steps for speed controller are as

- Sampling of the speed signal of the BLDC.
- Calculations of the speed error and the change in speed error.
- Determination of the fuzzy sets and membership function for the speed error and Change in speed error.
- Determination of the control action according to fuzzy rule.
- Calculation of the current by centre of area defuzzyfication method.

• Sending the control command to the system after calculation of current.

FLC has two inputs and one output. These are error (e), error change (de) and control signal, respectively. A linguistic variable which implies inputs and output have been classified as: NB, NM, NS, Z, PS, PM, PB. Inputs and output are all normalized in the interval of [-10,10], [31]. As shown in fig. 4.7.

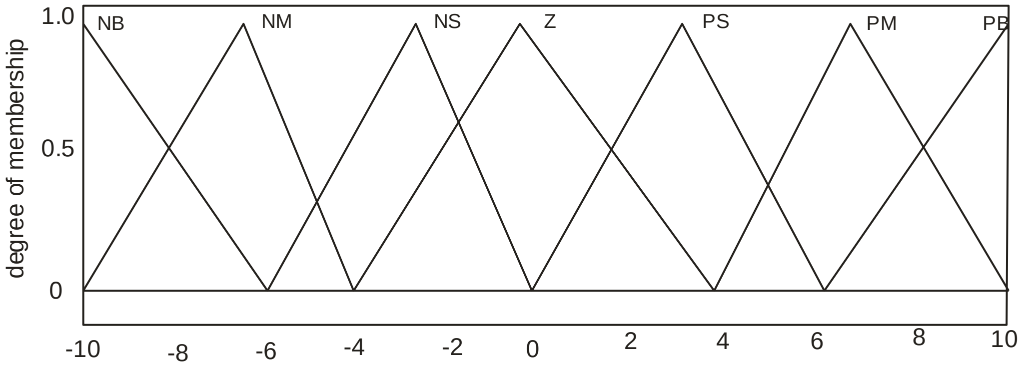


Fig.4.7.(a)- Fuzzy membership function for the speed error(e)

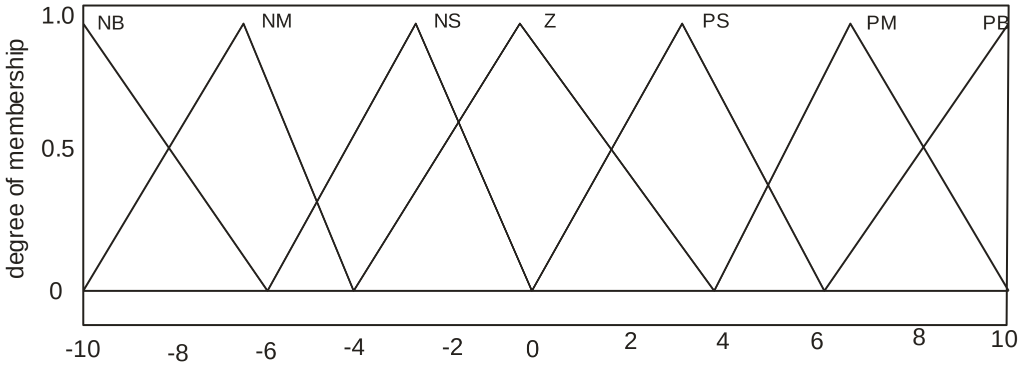


Fig.4.7.(b)- Change in error (ce) membership function

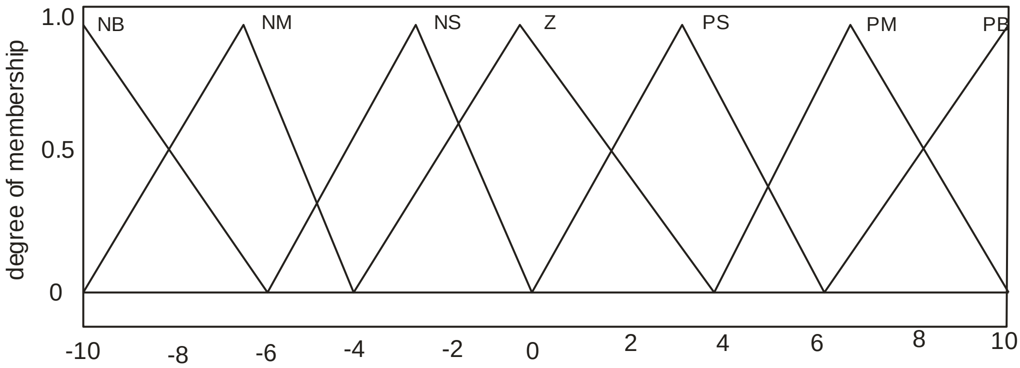


Fig.4.7(c)- Output membership function

4.7. Performance analysis with Fuzzy controller.

Performance with FLC

The type and characteristics of the FLC we have designed are as follows.

FLC Type=Mamdani.

Number of Inputs=2.

Number of outputs=1.

Number of Rules=49.

AND Method=min.

OR Method=max.

Defuzzification Method= height defuzzification

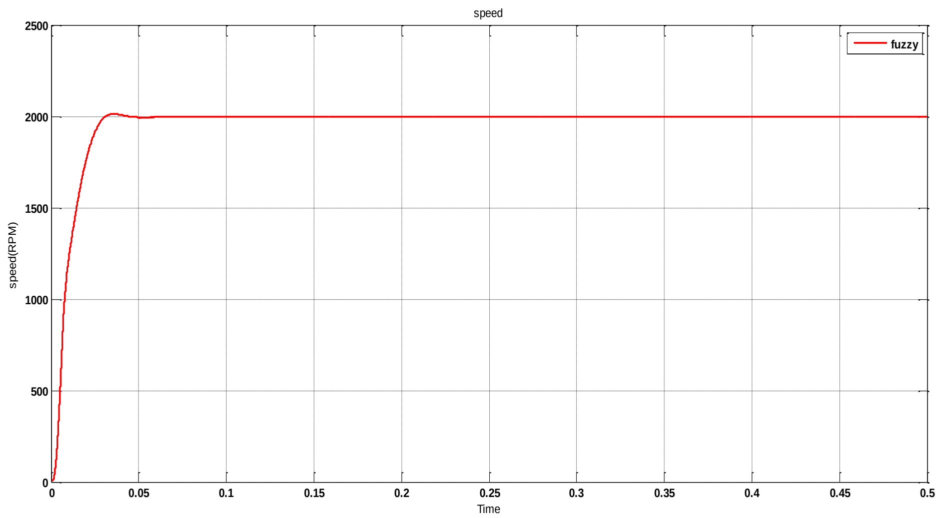


Fig.4.8(a). speed performance with fuzzy (2000rpm, T_L=0Nm)

The speed response of BLDC motor shown here with FLC. Here the speed reaches to 2016 rpm initially in 0.03543sec which is less than that of PI controller. However the fuzzy controller obtained its reference speed much faster than that of PI controller in 0.04359. The response of fuzzy controller is smooth and less variation occurred during load changes. Fuzzy controller reduces the overshoot and settling time as required. For improving overshoot and settling time we implement hybrid fuzzy PI controller.

Torque (no load).

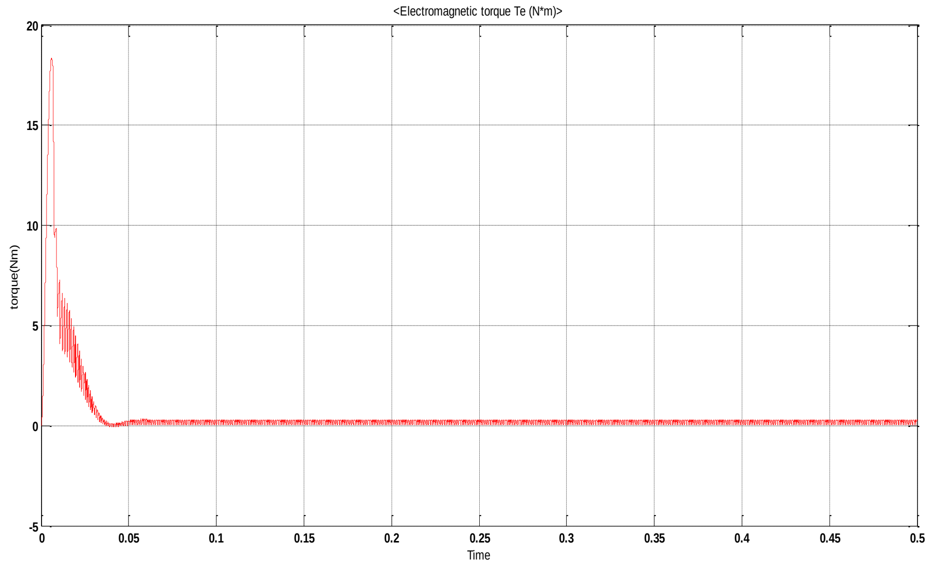


Fig.4.8(b). electromagnetic torque with fuzzy (2000rpm,T_L=0Nm)

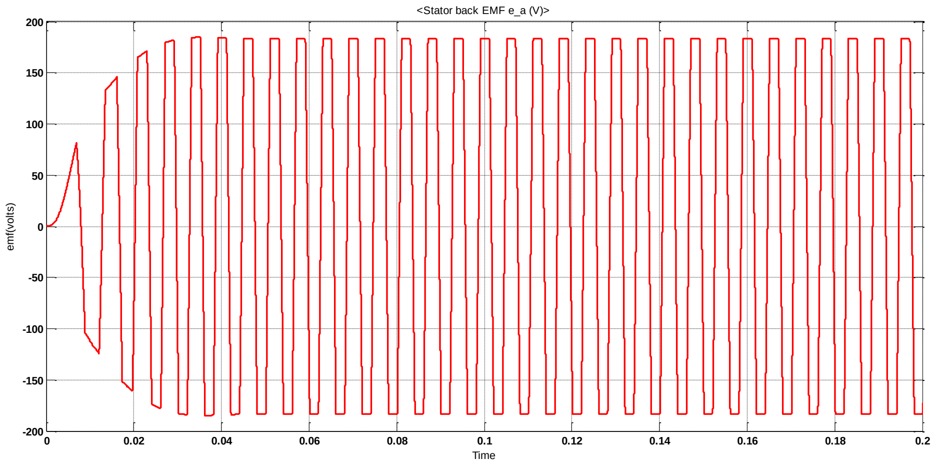


Fig.4.8(c). stator back emf with fuzzy (2000rpm,T_L=0Nm)

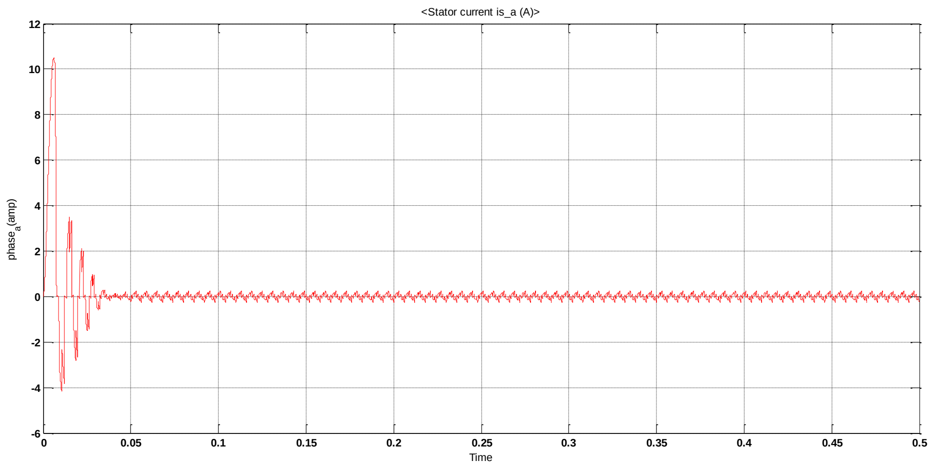


Fig.4.8(d). stator current (2000rpm, T_L=0Nm)

4.8. Performance analysis with Fuzzy (2000rpm,T_L=4Nm)

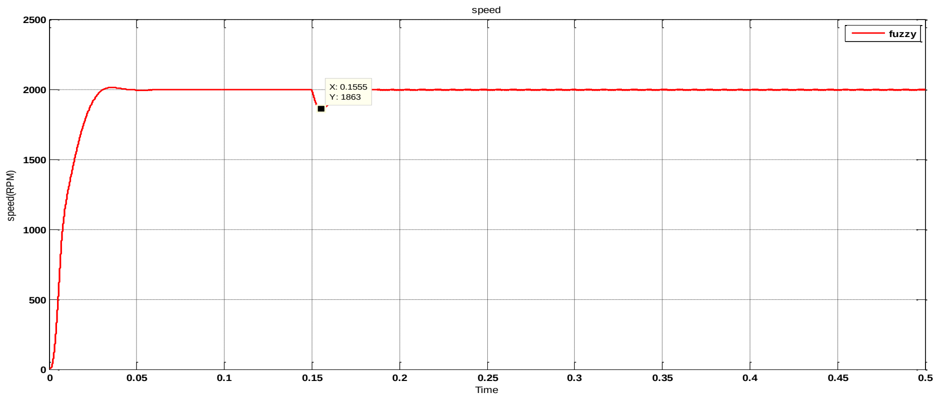


Fig.4.9(a). speed performance with fuzzy (2000rpm, T_L=4Nm)

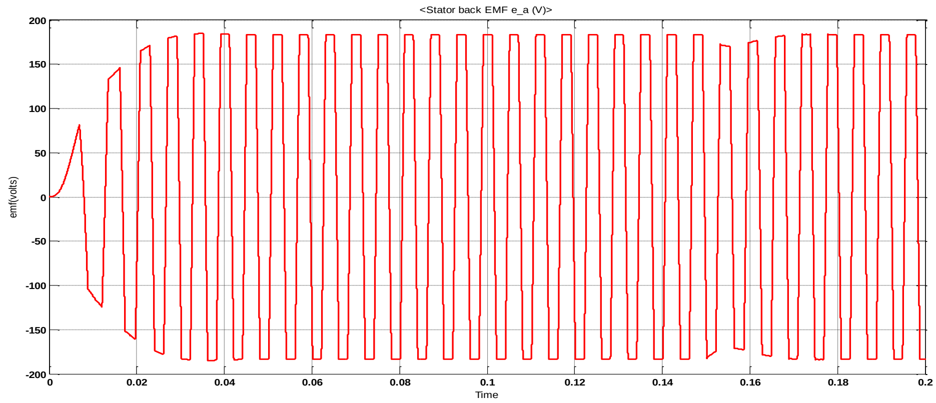


Fig.4.9(b). stator back emf with load T_L=4Nm

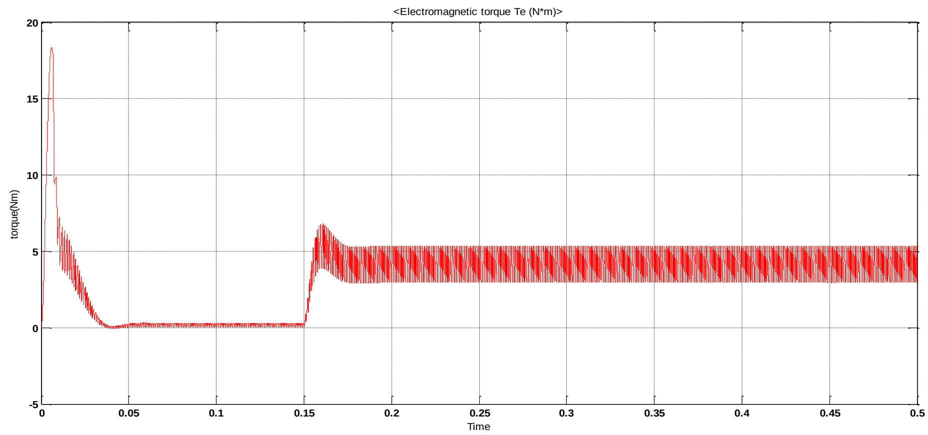


Fig.4.9(c). electromagnetic torque wih load T_L= 4Nm

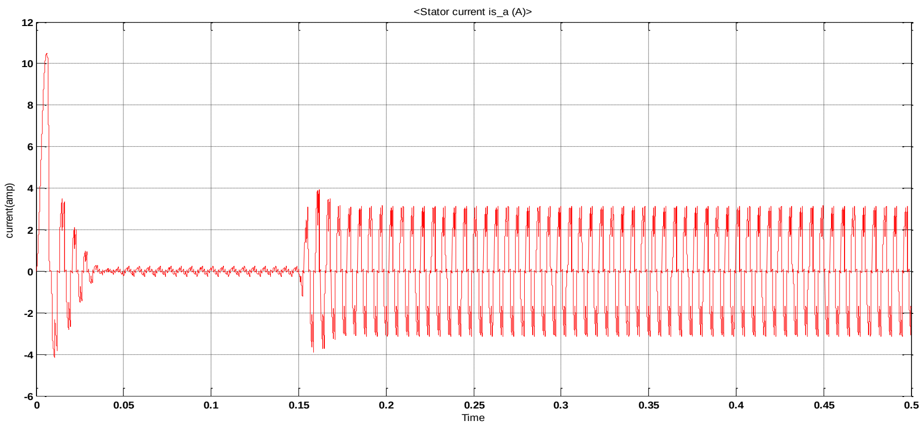


Fig.4.9(d) stator current with load T_L=4Nm

4.9. Performance analysis with fuzzy (2500 rpm, T_L=0Nm)

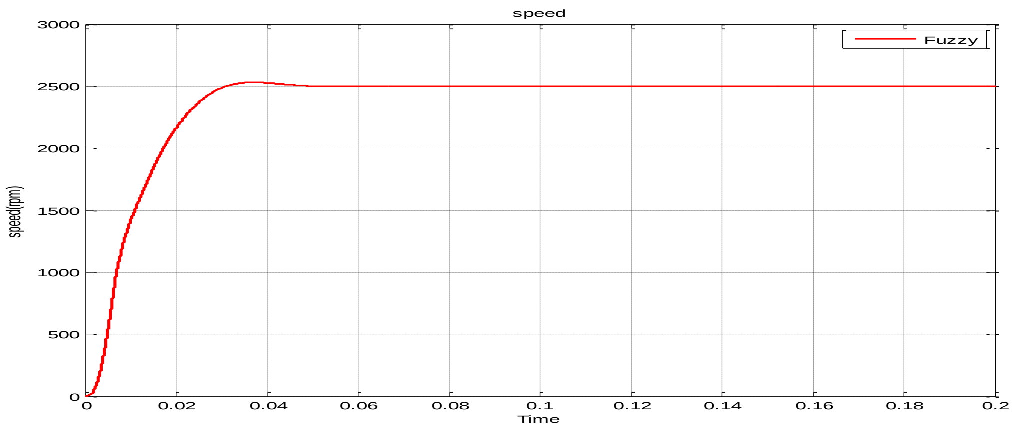


Fig.4.10(a). speed with fuzzy (2500 rpm, T_L=0Nm)

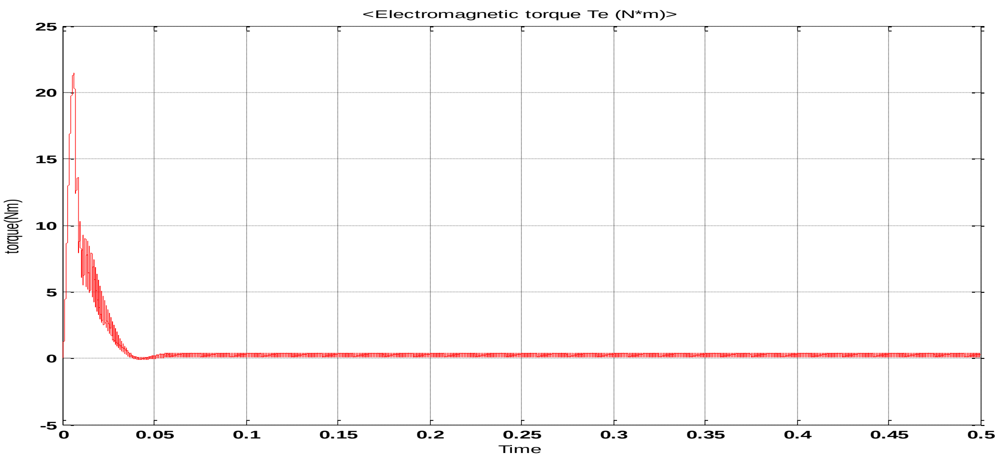


Fig.4.10(b). electromagnetic torque with fuzzy (2500 rpm,T_L=0Nm)

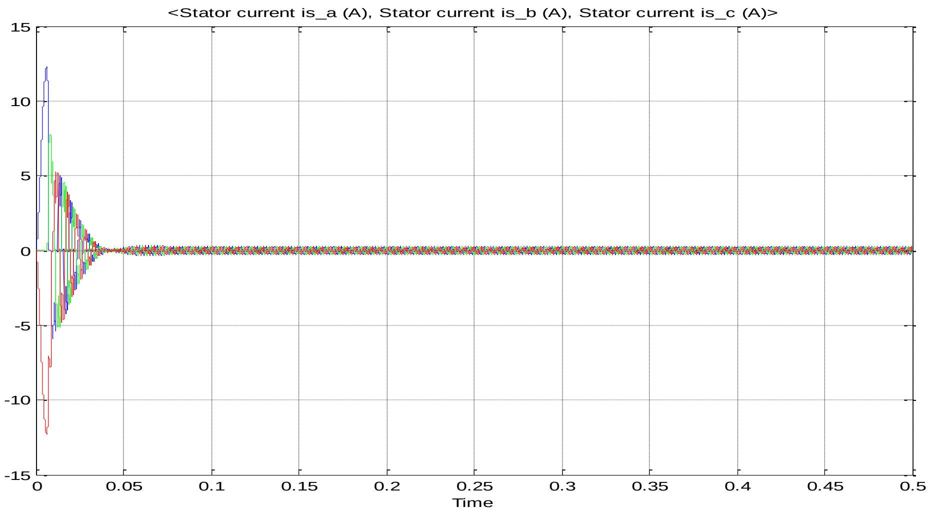


Fig.4.10(c). stator phase a,b,c currents (amp)

4.10. Performance analysis with fuzzy (2500rpm,T_L=4Nm)

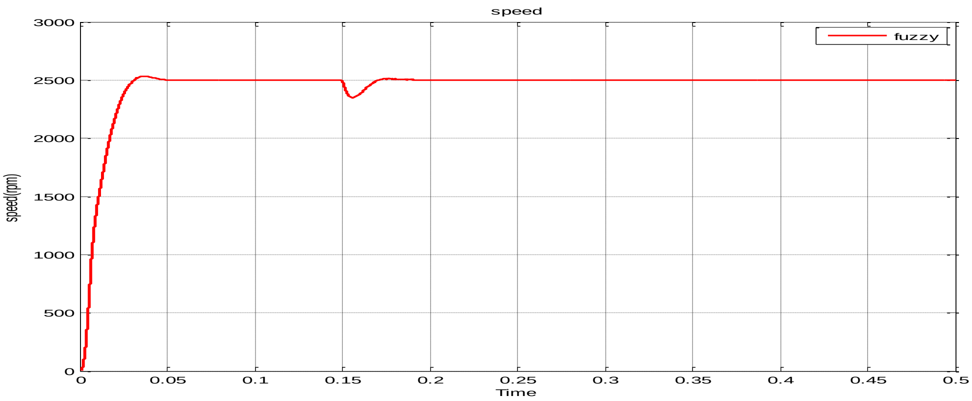


Fig.4.11(a). speed with fuzzy (2500rpm, T_L=4Nm)

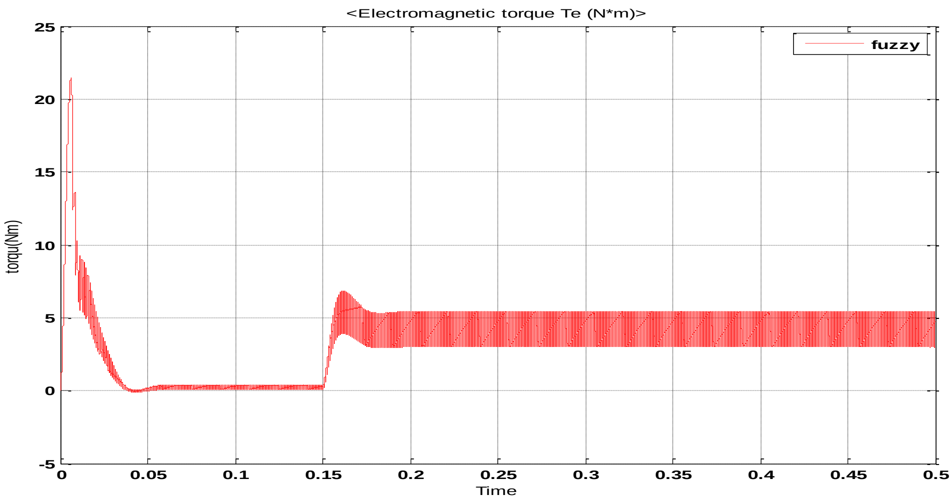


Fig.4.12(b). electromagnetic torque with fuzzy (2500rpm, T_L=4Nm)

CHAPTER-5

DESIGN OF HYBRID FUZZY PI CONTROLLER

5.1. BLDC model with hybrid fuzzy PI Controller

Two control loops are used. The inner loop synchronises the inverter gates signals with the electromotive forces. The outer loop controls the motor's speed by varying the DC bus voltage. Observe the saw tooth shape of the motor currents. That's caused by the DC bus which applies a constant voltage during 120 electrical degrees to the motor inductances.

The initial current is high and decreases during the acceleration to the nominal speed. When the nominal torque is applied, the stator current increases to maintain the nominal speed. The saw tooth waveform is also observed in the electromagnetic torque signal Te. However, the motor's inertia prevents this noise from appearing in the motor's speed waveform. Change the "Back EMF flat area" of the motor from 120 to 0 and observe the waveform of the electromotive force [32].

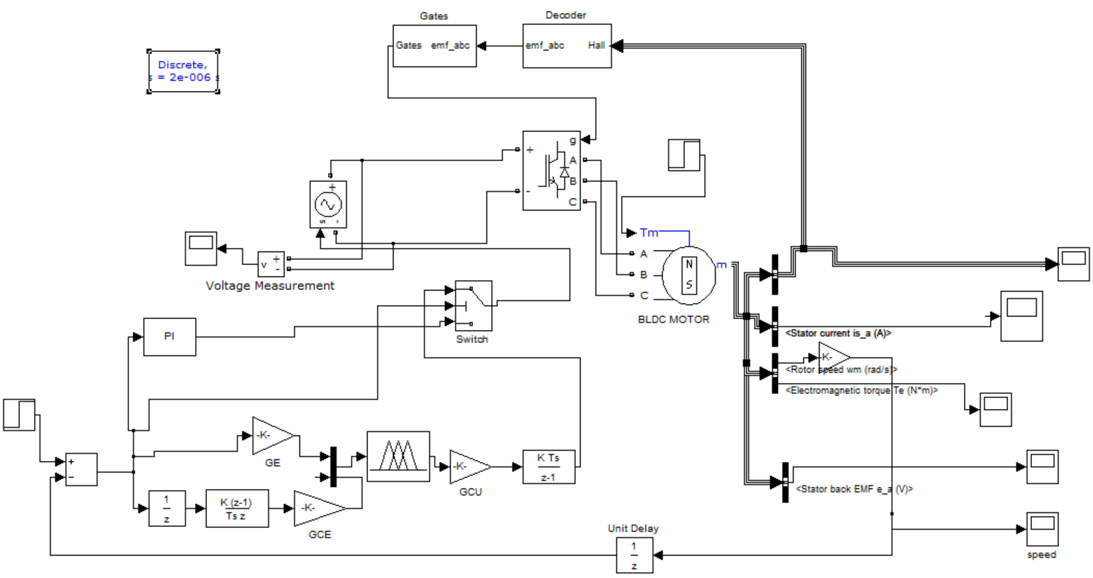


Fig.5.1. Hybrid Fuzzy PI speed controller BLDC Motor in Simulink/MATLAB

5.2. Performance analysis with hybrid fuzzy PI controller (2000 rpm, T_L=0)

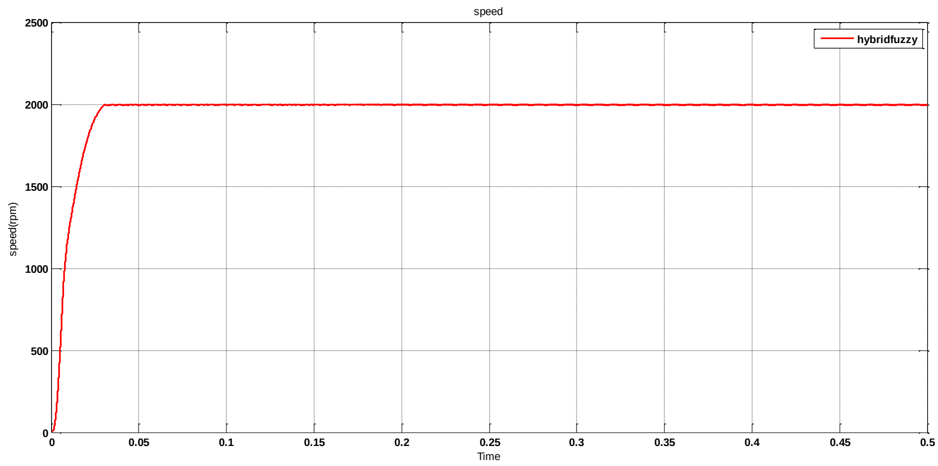


Fig.5.2(a). speed response with hybrid controller (2000rpm, T_L=0Nm)

Fig.5.2(a). shows the speed response with hybrid fuzzy + PI controller. The motor obtained its desired speed 2000 rpm in 0.03083 sec which is much lesser than fuzzy as well as PI controller. The hybrid fuzzy controller incorporated with PI and Fuzzy controller.

The Fuzzy controller offers a better speed response for start-up and large reference input changes (large speed error) whereas the PI controller has good adaptability over load torque variation and supports steady state accuracy. The superiority of both fuzzy and PI controller are integrated together by using a switch and steady state of PI controller [33].

Electromagnetic Torque (T_e)

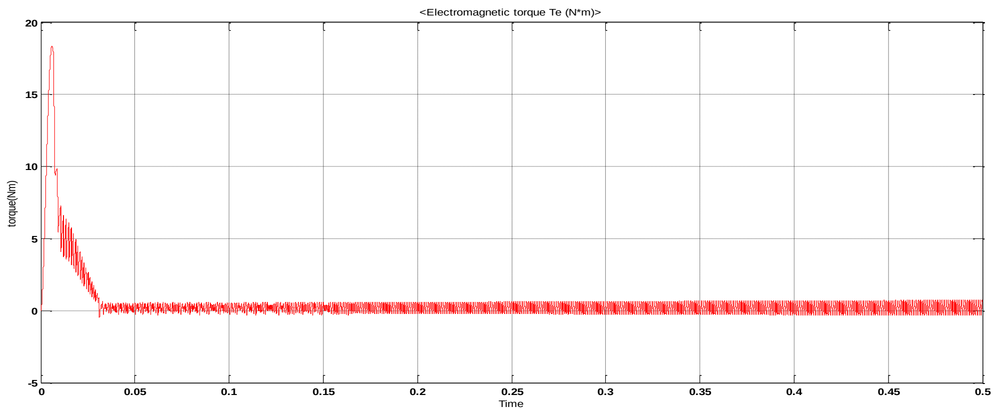


Fig.5.2(b). Electromagnetic torque with hybrid controller (2000rpm, T_L=0Nm)

Stator back Emf (Volts)

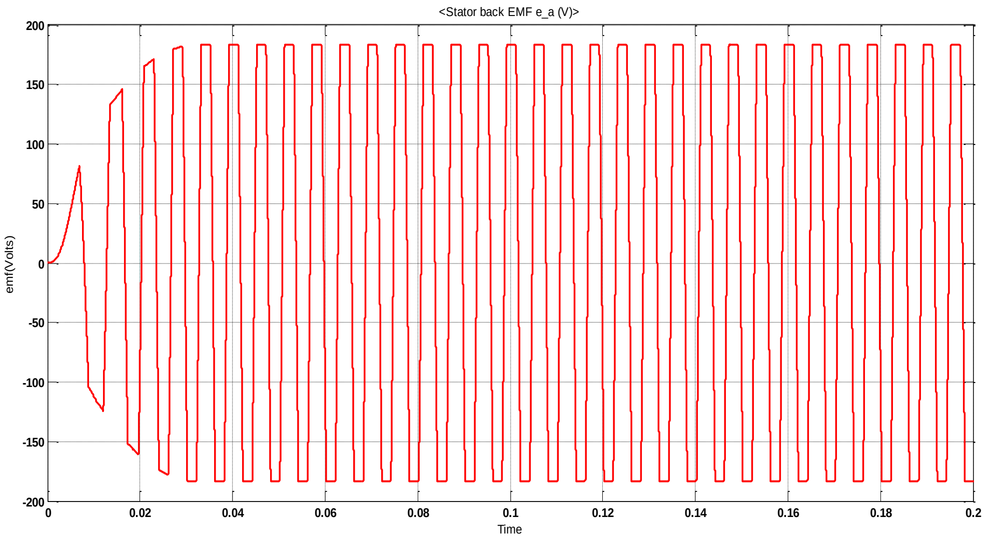


Fig.5.2(c). stator back emf with hybrid controller

Stator Current (amp)

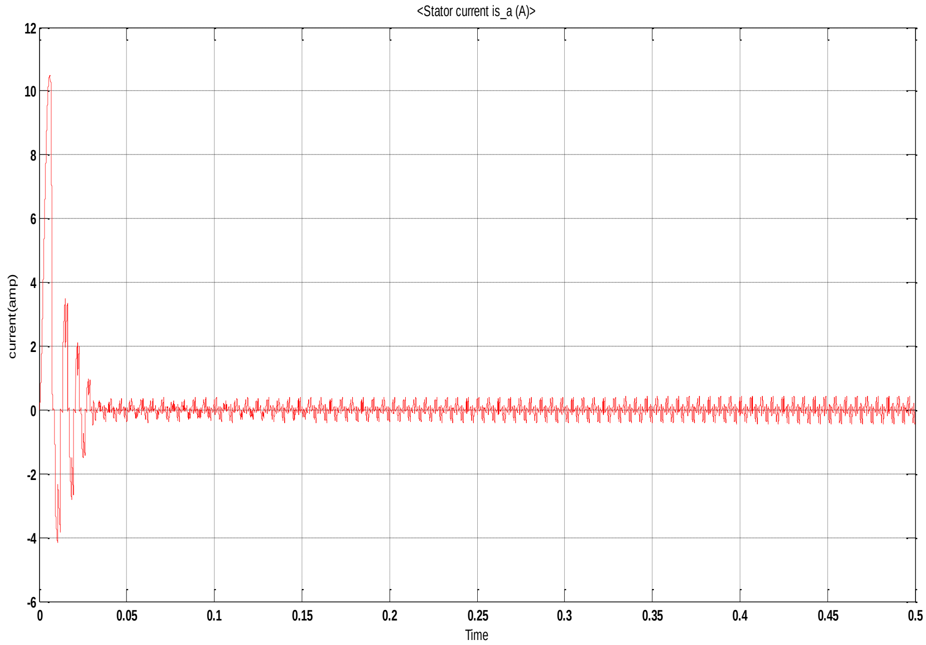


Fig.5.2(d). stator Current (amp)

5.3. Performance analysis with hybrid fuzzy PI controller (Speed 2000rpm, TL=4Nm)

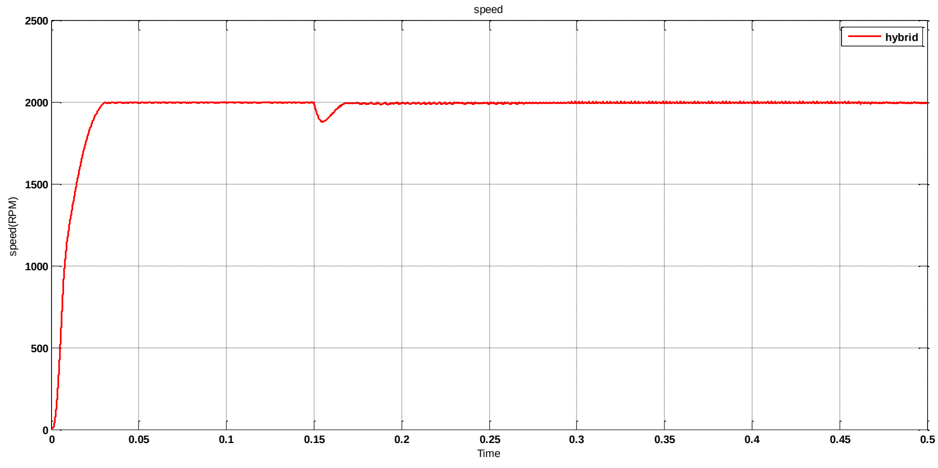


Fig.5.3. speed at load with hybrid controller.

5.4.(a). Performance analysis with hybrid fuzzy PI contoller (Speed 2500rpm, TL=0Nm)

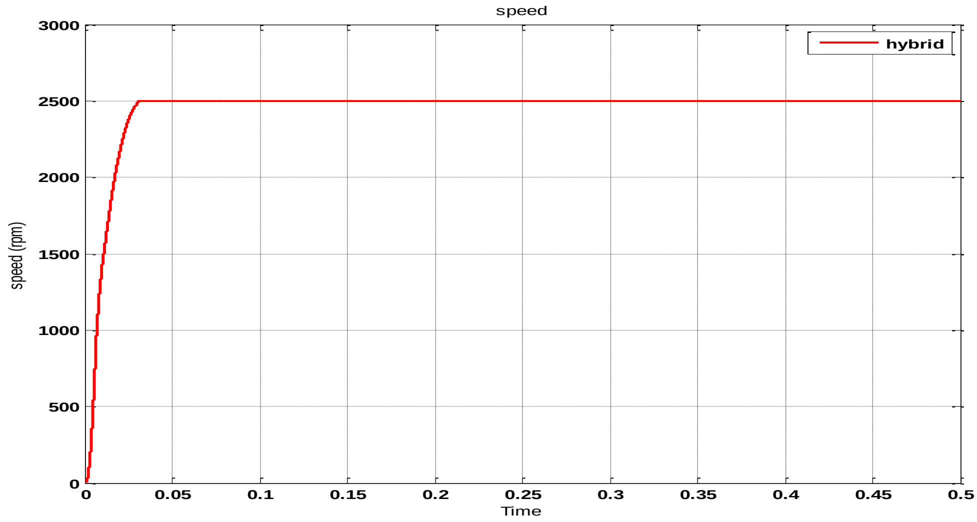


Fig.5.4. speed response with hybrid (2500rpm, T_L=0Nm)

5.4.(b). Performance analysis with hybrid fuzzy PI controller (Speed 2500rpm, T_L=4Nm)

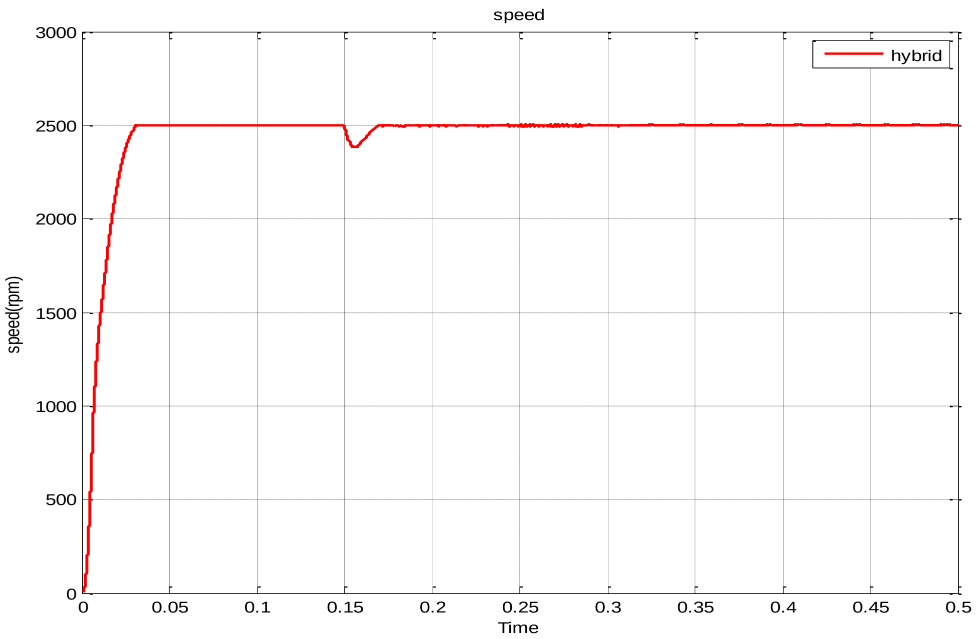


Fig.5.5. speed response with hybrid (2500 rpm, T_L=4Nm)

CHAPTER-6

CONCLUSION AND FUTURE WORK

6.1. Conclusion

6.1.1. Speed performance with hybrid, fuzzy and PI controller (speed 2000 rpm, T_L=0Nm)

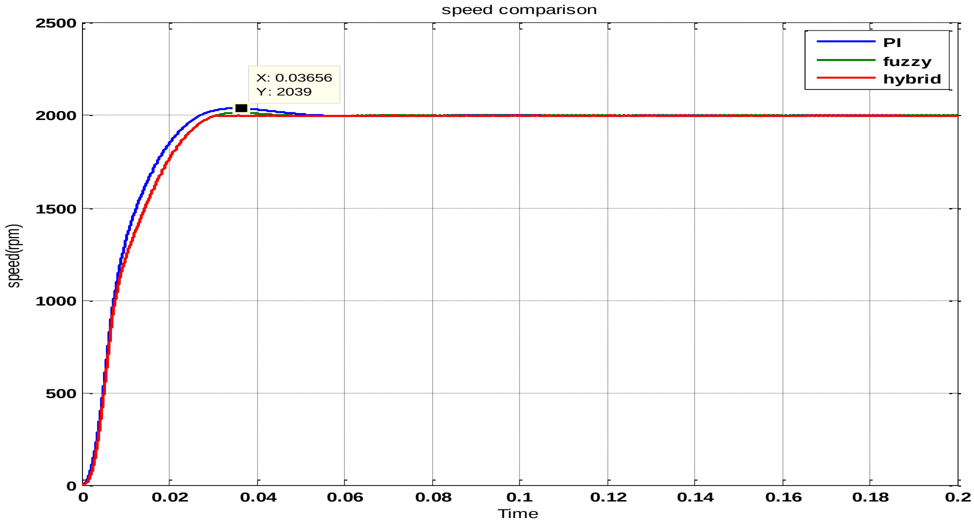


Fig.6.1. speed comparison among hybrid, fuzzy and PI (2000rpm,T_L=0Nm)

In this figure speed comparison of different controller has been brought. As shown in the figure the blue line shows the response with PI controller, green with fuzzy controller and red with hybrid fuzzy controller. We observe from figure that during start up PI controller takes much time for obtaining its actual speed that is 0.03556 and its behaviour is more overshoot in nature while when we analyse fuzzy controller response it shows less overshoot in comparison to PI controller but more with respect to hybrid fuzzy controller i.e. 0.03543 sec. moreover the hybrid fuzzy controller shows no sign of overshoot and attains the reference speed very rapidly in 0.03083 secs which is much faster than of both fuzzy and PI controller. So we can say for controlling speed of BLDC motor we use hybrid fuzzy + PI controller for utilising best attributes of the Fuzzy controller offers a better speed response for start-up and large reference input changes (large speed error) whereas the PI controller has good adaptability over load torque variation and supports steady state accuracy. The superiority of both fuzzy and PI controller exhibited in hybrid controller [34].

6.1.2. Speed performance PI, Fuzzy and Hybrid Fuzzy PI (Speed 2000 Rpm, T_L= 4Nm)

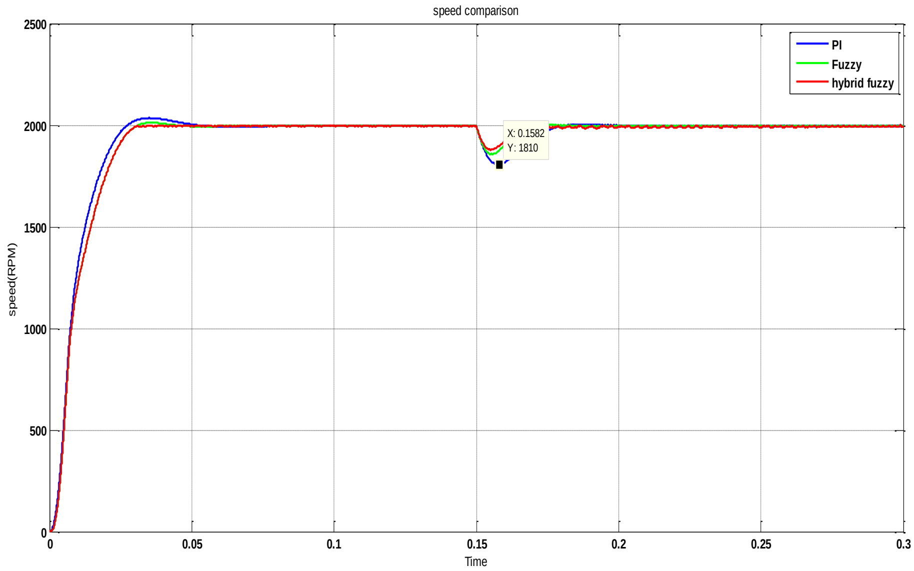


Fig.6.2. speed comparison among hybrid, fuzzy and PI (2000rpm, TL=4Nm)

As shown in figure above different speed controller comparison is initiated during the load torque of 4Nm which is step at 0.15 sec. From figure it is cleared that PI controller has more undershoot and setting time among three controllers while fuzzy controller has less undershoot and settling time to PI while more to hybrid fuzzy controller. In load condition PI controller speed dip to 1810 rpm in 0.1581 sec and settles in 0.194 sec to its reference speed which is more. While fuzzy controller dips to 1886 rpm in .156 sec and settles in 0.175 sec. Hybrid fuzzy dips less than that of fuzzy and PI controller it dips to 1886 rpm in 0.155 sec which means it observed the load change very early and settles in 0.1689 sec which is lesser than both PI and fuzzy controller. We can conclude that PI controller is more sensitive to load change and cause the system to instability [35].

6.1.3. Speed performance with Hybrid, Fuzzy and PI (at 2500 rpm, T_L=0)

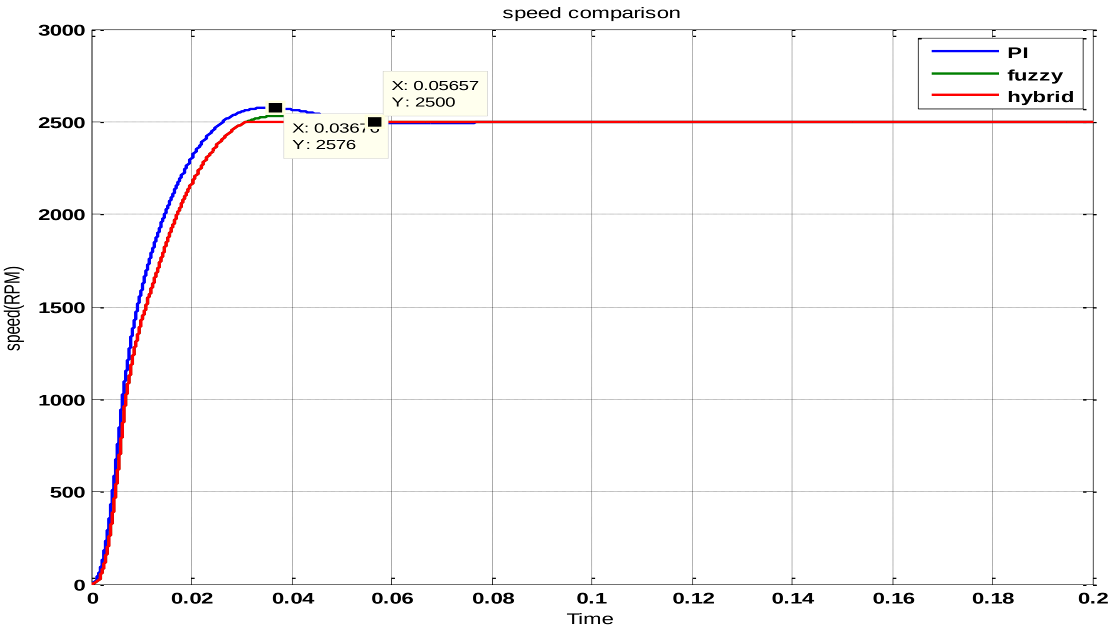


Fig.6.3. Speed comparison hybrid, fuzzy and PI controller

Now increasing speed from 2000 rpm to 2500 rpm. During this process PI controller takes much time to settle to its reference value 2500. It means when we increase the speed of machine the PI speed controller shows sluggish behaviour towards speed response it takes 0.03676 sec to reach 2576 during at this moment overshoot is maximum among all speed controller. For reaching its reference speed i.e. 2500 rpm it takes 0.05657 sec as shown in figure above.

In contrast to PI controller the fuzzy speed controller reaches to 2530 rpm in 0.03751 sec which is much less than PI controller but more than hybrid fuzzy controller, fuzzy speed controller settles in 0.04863 sec which is also much lesser than PI speed controller but more than to hybrid fuzzy controller. However PI speed controllers have good speed response but lagging due to sluggish settling time and overshoot. Hybrid fuzzy controller reaches to its reference speed without any overshoot and settling time for this controller is almost negligible. Ultimately we can say that as soon as we increase the speed of BLDC machine, PI speed controller becomes more sluggish and shows much settling time. So for higher speed response we consider fuzzy or hybrid speed controller.

Based on the developed model simulation studies are performed in MATLAB /Simulink environment. BLDC model is designed using hybrid controller which combines both PI controller and Fuzzy Logic Controller

It is seen that hybrid controller has more advantage compare to both Fuzzy Logic and PI controller. This project combines both the fuzzy and the PI controller principles efficiently and provides a highly efficient speed control. Ripple in the output is very much reduced with low rms value, the output curve will be smooth, has low peak overshoot value and has fast response time

From simulation results, it was shown that PI controller maintained the steady state accuracy while the fuzzy controller performed well in the case of sufficiently large reference input changes with shorter settling time. The hybrid controller has integrated both fuzzy controller and PI controller. During the large speed error, the fuzzy controller will be selected by switch. When the speed error is less than 0.28 rpm, the PI controller will be selected to maintain the high steady-state accuracy. The simulation results showed that the hybrid controller has incorporated advantage of both fuzzy and PI controller. As a conclusion, the hybrid controller has improved the dynamic performance of BLDC motor.

The most commonly used controller for dc motor controller system is Proportional- Integral (PI) controller. However, the PI controller has some disadvantages such as: high starting overshoot, sensitivity to controller gains and sluggish response due to sudden load disturbance. Further, fuzzy control is proposed and the performance of fuzzy controller was compared with PI controller. Simulation result are presented and analysed for both fuzzy and PI controllers.

It is observed that fuzzy logic based controlled give better responses than traditional PI controller for the speed control of dc motor drives. Among PI, fuzzy and hybrid fuzzy PI the later one gives the much better speed response among all speed controller discussed above. And we adopt the hybrid fuzzy PI speed controller for controlling the speed of motor. In hybrid fuzzy PI controller both fuzzy and PI speed controller are incorporated for getting the best of both. During start up fuzzy controller gives better response while in steady state condition PI controller gives much better response. Fuzzy speed controller may reduce the transient at the starting point and make it constant in short time of period.

6.1.4. Speed performance with hybrid, fuzzy and PI (Speed 2500 rpm, T_L=4Nm)

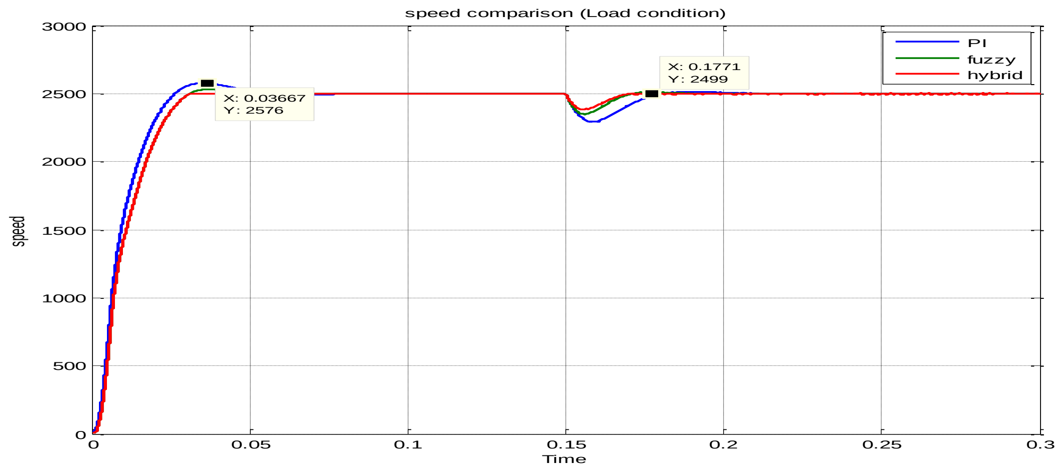


Fig.6.4. Speed comparison With T_L=4Nm, 2500rpm

However we can also see the different performance in all the controllers from the speed response as shown in Fig. During start-up, fuzzy controller has smaller settling time compared to PI controller while hybrid controller took similar path of fuzzy controller. At t = 0.15s, the load was increased from 0 Nm to 4 Nm that caused the speed to undershoot for a while. PI controller has bigger amount of undershoot and managed to follow the reference speed with greater settling time. Although fuzzy controller has smaller undershoot but it has constant speed error which results in having lower actual speed than reference speed. On the other hand, hybrid controller shows the smallest amount of undershoot and shorter settling time to follow the reference speed very quickly.

6.2. Future work and scope

1. BLDC motors can be used in various types of actuators in advance aircraft and satellite systems. Integral hp brushless dc motors can be developed for propulsion and servo applications in unmanned submarines.
2. The hybrid integrator back stepping controller is proposed for robotic manipulators actuated with brushless dc motors in the presence of arbitrary uncertain inertia parameters of the manipulator and the electrical parameters of the actuators. However, the study of the control of robots actuated by the BLDCM was relatively recent .In a robust feedback linearizing control was proposed. By using integrator back stepping techniques, robust and adaptive controllers are proposed, respectively.
3. To improve the performance, genetic algorithm (GA), fuzzy neural controllers can be implemented to optimize the motor design.

   It should be noted however that all those results are suitable only for a single-link manipulator (an inertial load). The objective of this study is to develop a control scheme for a rigid n-link manipulator where the joint actuators are driven by BLDCM's. Based on the integrator back stepping techniques, a hybrid integrator back stepping controller (i.e., adaptive and robust adaptive) is proposed. The proposed controller has the following features

- It does not require joint acceleration feedback.
- Knowledge of the robot or any of the BLDC motor uncertain parameters is not required.
- A semi global asymptotic stability result is obtained in the Lyapunov sense.

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Appendix A

BLDC Motor Parameters

Stator phase resistance Rs (ohm)	2.8750ohm
Stator phase inductance Ls (H)	8.5e-3
Voltage Constant (V_ peak L-L / krpm)	183.2596
Back EMF flat area (degrees)	120
Inertia(J)	0.8e-3(kg.m^2)
friction factor(F)	1e-3 (N.m.s)
No. of pole pair	5
Rated power	1 kw
Nominal Torque	11Nm
Vdc	300V