# MODELING AND CONTROL OF A BRUSHLESS DC MOTOR

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

**Master of Technology**

**In**

**Power Control and Drives**

By

**S.Rambabu**

**Department of Electrical Engineering**

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**Under the Guidance of**

**Dr. B. D. Subudhi**

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**Rourkela**

**CERTIFICATE**

This is to certify that the thesis entitled, **"Modeling and Control of a Brushless DC Motor"** submitted by **S.Rambabu** in partial fulfillment of the requirements for the award of MASTER of Technology Degree in **Electrical Engineering** with specialization in **"Power Control and Drives"** at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him/her under my/our supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma.

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# ABSTRACT

Permanent magnet brushless DC motors (PMBLDC) find wide applications in industries due to their high power density and ease of control. These motors are generally controlled using a three phase power semiconductor bridge. For starting and the providing proper commutation sequence to turn on the power devices in the inverter bridge the rotor position sensors required. Based on the rotor position, the power devices are commutated sequentially every 60 degrees. 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 (PI) controller. 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.

This thesis presents a Fuzzy Logic Controller (FLC) for speed control of a BLDC by using. The Fuzzy Logic (FL) approach applied to speed control leads to an improved dynamic behavior of the motor drive system and an immune to load perturbations and parameter variations. The FLC is designed using based on a simple analogy between the control surfaces of the FLC and a given Proportional-Integral controller (PIC) for the same application. Fuzzy logic control offers an improvement in the quality of the speed response, compared to PI control. This work focuses on investigation and evaluation of the performance of a permanent magnet brushless DC motor (PMBLDC) drive, controlled by PI, and Fuzzy logic speed controllers. The Controllers are for the PMBLDC motor drive simulated using MATLAB soft ware package. Further, the PI controller has been implemented on an experimental BLDC motor set up.

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I would like to articulate my profound gratitude and indebtedness to my thesis guide **Dr. B. D. Subudhi** who has always been a constant motivation and guiding factor throughout the thesis time in and out as well. It has been a great pleasure for me to get a opportunity to work under him and complete the project successfully.

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An undertaking of this nature could never have been attempted with our reference to and inspiration from the works of others whose details are mentioned in references section. I acknowledge my indebtedness to all of them. Last but not the least, my sincere thanks to all of my friends who have patiently extended all sorts of help for accomplishing this undertaking.

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## LIST OF ACRONYMS

- PMBLDCM — Permanent magnet brushless dc motor
- PI — Proportional integral
- FLC — Fuzzy logic controller
- PMSM — Permanent magnet synchronous motor
- PWM — Pulse width modulation
- CC-VSI — Current controlled voltage source inverter
- IPM — Intelligent power module
- DSP — Digital signal processor
- ADC — Analog to digital converter
- DAC — Digital to analog converter

## LIST OF SYMBOLS

| | | |
|---|---|---|
| $R_s$ | - | Stator resistance per phase |
| L | - | Stator inductance per phase |
| M | - | Mutual inductance between phases |
| $\omega_m$ | - | Angular speed of the motor |
| $\theta$ | - | Angular position of the rotor |
| $\lambda_m$ | - | Flux linkages |
| $J$ | - | Moment of inertia |
| B | - | Damping constant |
| $T_e$ | - | Electro magnetic torque |
| $T_l$ | - | Load torque |
| $K_p$ | - | Proportional constant |
| $K_i$ | - | Integral constant |
| $e(t)$ | - | Speed error |
| $\mu$ | - | Member ship function |
| $i_a, i_b, i_c$ | - | Motor phase currents |
| $e_a, e_b, e_c$ | - | Motor phase back emfs |
| $v_{as}, v_{bs}, v_{cs}$ | - | Stator phase voltages |

| | | |
|---|---|---|
| $\frac{d}{dt}$ | - | Derivative Operator |
| $f_{as}(\theta_r), f_{bs}(\theta_r), f_{cs}(\theta_r)$ | - | Trapezoidal unit functions |
| $i_a^*, i_b^*, i_c^*$ | - | Reference phase currents |

## 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 [4]. 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

- 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 a brushed DC-motor, but using a solid-state circuit rather than a commutator. BLDC motors have many advantages over DC motors. A few of these are:

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

BLDC's main disadvantage is higher cost which arises from two issues. First, BLDC motors require complex electronic speed controllers to run. Brushed DC-motors can be regulated by a comparatively trivial variable resistor (potentiometer or rheostat), which is inefficient but also satisfactory for cost-sensitive applications.

### 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 (BDCM) 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 BDCM 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 [4] 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 BDCM motor, since the back emf is no sinusoidal, the inductances do not vary sinusoidally 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 BDCM. In addition, this approach in the modeling of the BDCM allows a detailed examination of the machine's torque behavior 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 behavior of a high-performance vector controlled PMSM servo drive [5]. In addition, the *abc* phase variable model has been used to examine the behavior of a BDCM speed servo drive [6]. Application characteristics of both machines have been presented in [7]. The purpose of this paper is to present these two models together and to show that the *d*, *q* model is sufficient to study the PMSM in detail while the *abc* model should be used in order to study the BDCM.

## 1.5. A brief review 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 (BDCM) [8]. The BDCM 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 values. Although some steady-state analysis has been done [9], [10],the modeling, detailed simulation, and experimental verification of this servo drive has been neglected in the literature.

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 modeling 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 BLDCM servo system usually requires time consuming trial and error process, and fail to optimize the performance. In practice, the design of the BLDCM drive involves a complex process such as model, devise of control Scheme, simulation and parameters tuning. In a PI controller has been proposed for BLDCM. 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 (PI) controller. 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 PMBLDC 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 behavior 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 seven 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 and PWM voltage and current operation, Hall position sensors, mathematical modeling of machine in state space form.

Chapter 3 describes the design of PI speed controller, PI speed controller of brushless dc motor and modeling of PI control of brushless dc motor drive elements are references current generator, back emf function modeling and Hysteresis current controller**.**

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 for experimental system of brushless dc motor are IPM module. Current advocate sensors, DSP processor, signal conditioners and overview of software development of speed of brushless dc motor.

Chapter 6 describes the results and discussion for the PI speed control performance and fuzzy speed control performance with simulation results are discussed.

Chapter 7 describes the conclusion of the speed control strategies of the brushless dc motor and further work to be carried out.

## 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 NC 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. Modeling 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.

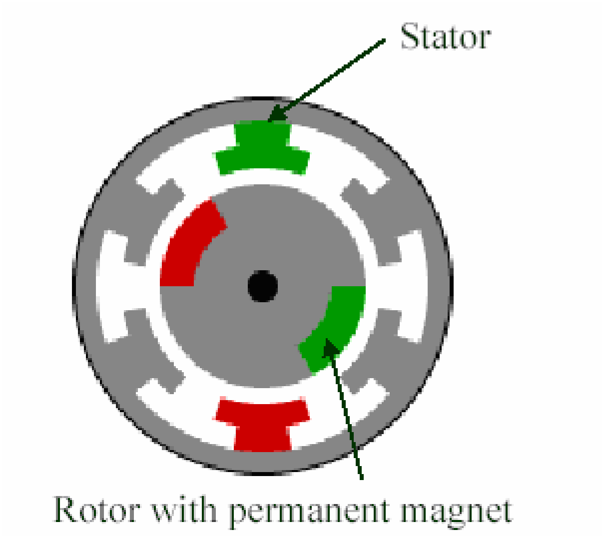



**Fig 2.1 Cross-section view of a brushless dc motor**

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. Principle operation of Brushless DC (BLDC) Motor

A brush less dc motor is defined as a permanent synchronous machine with rotor position feed back. 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.

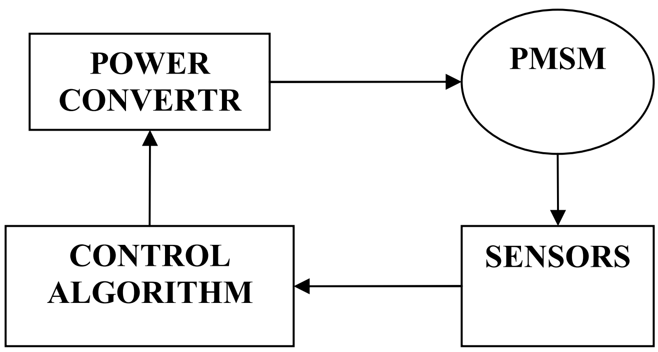



**Fig.2.2.Basic block diagram of BLDC motor**

The basic block diagram brushless dc motor as shown Fig.2.1.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 (Fig.2.3) may be controlled so as to achieve nearly constant torque. However, machine with a non sinusoidal back emf (Fig.2.4) offer reduces inverter sizes and reduces losses for the same power level.

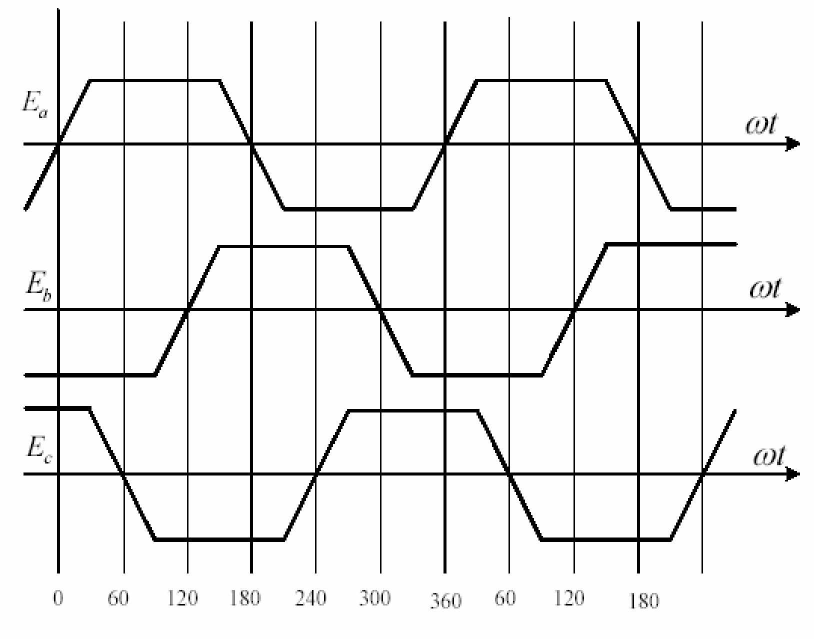



**Fig.2.3.Trapezoidal back emf of three phase BLDC motor**

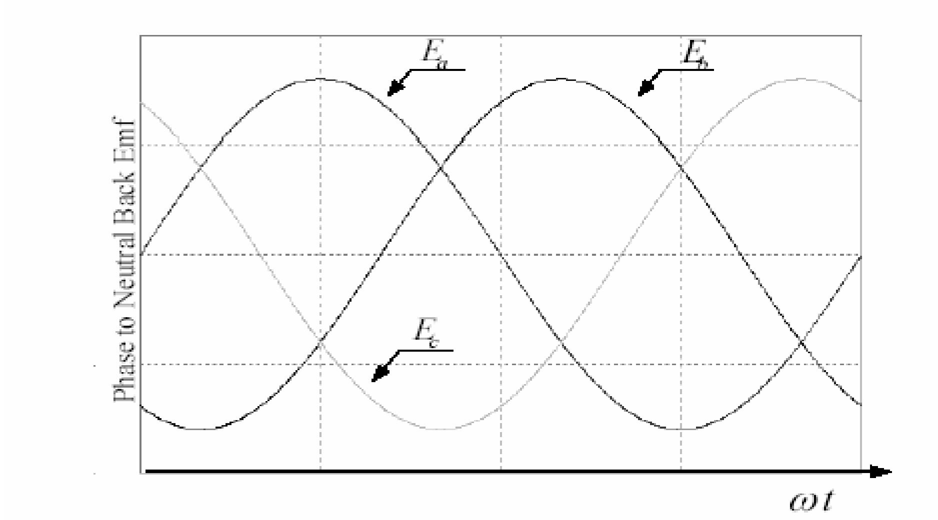



**Fig.2.4.Sinusoidal phase back emf of BLDC motor**

## 2.3. BLDC drives operation with inverter

Basically it is an electronic motor and requires a three-phase inverter in the front end as shown in Fig. 2.5. 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.

Basically the inverter can operate in the following two modes.

- $\frac{2\pi}{3}$ angle switch-on mode
- Voltage and current control PWM mode

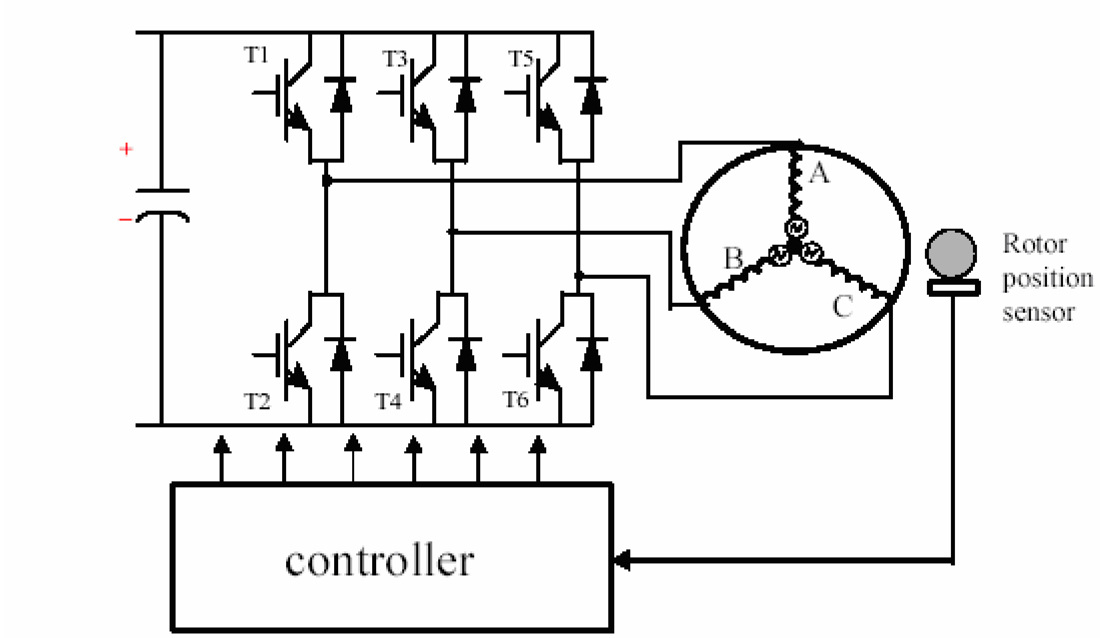



**Fig.2.5. Brushless dc motor drive system**

### 2.3.1. $\frac{2\pi}{3}$ Angle switch-on mode

Inverter operation in this mode with the help of the wave from shown on Fig.2.6.The six switches of the inverter ($T_1 - T_6$) operate in such way so as to place the input dc current $I_d$ symmetrical for $\frac{2\pi}{3}$ angle at the center of each phase voltage wave. The angle $\alpha$ shown is the advance angle of current wave with respect to voltage wave in the case $\alpha$ is zero. It can be seen that any instant, two switches are on, one in the upper group and anther is lower group. For example instant $t_1$ ,$T_1$ and $T_6$ are on when the supply voltage $V_{dc}$ and current $I_d$ are placed across the line ab (phase A and phase B in series) so that $I_d$ is positive in phase a. But negative in phase b then after $\frac{\pi}{3}$ interval (the middle of phase A). $T_6$ Is turned off and $T_2$ is turned on but $T_1$ continues conduction of the full $\frac{2\pi}{3}$ angle. This switching commutates $-I_d$ from phase b to phase c while phase a carry $+I_d$ the conduction pattern changes every $\frac{\pi}{3}$ angle indication switching modes in full cycle. The absolute position sensor dictates the switching or commutation of devices at the precise instants of wave. The inverter basically operating as a rotor position sensitive electronic commutator.

### 2.3.2. Voltage and current control PWM mode

In the previous mode the inverter switches were controlled to give commutator function only when the devices were sequentially ON, OFF $\frac{2\pi}{3}$ - angle duration .In addition to the commutator function. It is possible to control the switches in PWM chopping mode for controlling voltage and current continuously at the machine terminal. There are essentially two chopping modes, current controlled operation of the inverter. There are essentially two chopping modes feedback (FB) mode and freewheeling mode. In both these modes devices are turned on and off on duty cycle basis to control the machine average current $I_{AV}$ and the machine average voltage $V_{AV}$.

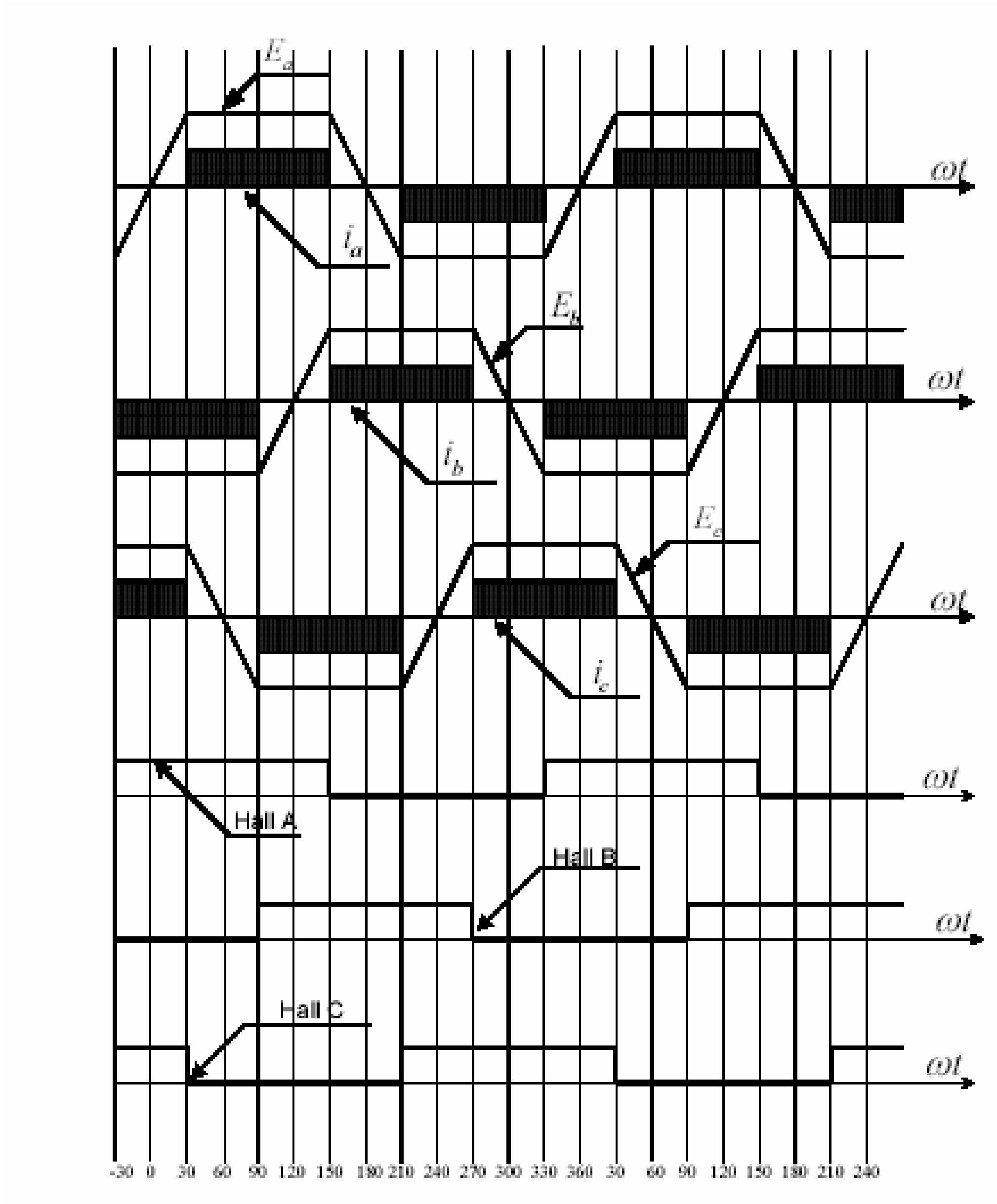



**Fig.2.6. Back-emfs, current waveforms and Hall position sensors for BLDC**

## 2.4. Rotor position sensors

Hall Effect sensors provide the portion of information need to synchronize the motor excitation with rotor position in order to produce constant torque. It detects the change in magnetic field. The rotor magnets are used as triggers the hall sensors. A signal conditioning circuit integrated with hall switch provides a TTL-compatible pulse with sharp edges. Three hall sensors are placed 120 degree apart are mounted on the stator frame. The hall sensors digital signals are used to sense the rotor position.

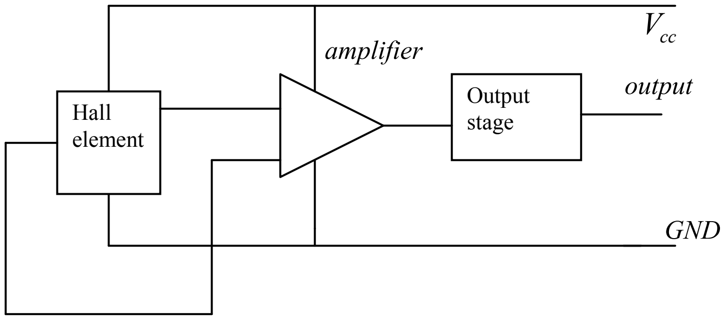



**Fig.2.7. Hall position sensors**

## 2.5. Machine Dynamic Model

The BLDCM 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 modeled the circuit equation of the three windings in phase variables are obtained.

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad (2.1)$$

where $v_{as}$, $v_{bs}$ and, $v_{cs}$ are the stator phase voltages; $R_s$ 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; $L_{ab}$, $L_{bc}$ ,and $L_{ac}$ 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

$$L_{aa} = L_{bb} = L_{cc} = L \qquad (2.2)$$

$$L_{ab} = L_{ba} = L_{ac} = L_{ca} = L_{bc} = L_{cb} = M \qquad (2.3)$$

Substituting equations (2.2) and (2.3) in equation (2.1) gives the PMBDCM model as

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2.4)$$

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

$$v_{as} = v_{ao} - v_{no},\ v_{bs} = v_{bo} - v_{no} \text{ and, } v_{cs} = v_{co} - v_{no} \quad (2.5)$$

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.

$$i_a + i_b + i_c = 0 \quad (2.6)$$

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

$$Mi_b + Mi_c = -Mi_a \quad (2.7)$$

There fore in state space from

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_v \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2.8)$$

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

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \omega_m \lambda_m \begin{bmatrix} f_{as}(\theta_r) \\ f_{bs}(\theta_r) \\ f_{cs}(\theta_r) \end{bmatrix} \quad (2.9)$$

where $\omega_{m_r}$ the angular rotor speed in radians per seconds, $\lambda_m$ is the flux linkage, $\theta_r$ is the rotor position in radian and the functions $f_{as}(\theta_r)$, $f_{bs}(\theta_r)$, and $f_{cs}(\theta_r)$ have the same shape as $e_a$, $e_b$ and , $e_c$ with a maximum magnitude of $\pm 1$.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

$$T_e = [e_a i_a + e_b i_b + e_c i_c] / \omega_m \text{ (N-m)} \tag{2.10}$$

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

$$J = J_m + J_l \tag{2.11}$$

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

$$J\frac{d\omega_m}{dt} + B\omega_m = (T_e - T_l) \tag{2.12}$$

The electrical rotor speed and position are related by

$$\frac{d\theta_r}{dt} = \frac{p}{2}\omega_m \tag{2.13}$$

The damping coefficient B is generally small and often neglected thus the system. The above equation is the rotor position $\theta_r$ and it repeats every $2\pi$. 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. This is obtained by substituting equation (2.6) in the volt-ampere equation (2.8) and adding then give as

$$v_{ao} + v_{bo} + v_{co} - 3v_{no} = R_s(i_a + i_b + i_c) + (L - M)(pi_a + pi_b + pi_c) + (e_a + e_b + e_c) \tag{2.14}$$

Substituting equation (2.6) in equation (2.14) we get

$$v_{ao} + v_{bo} + v_{co} - 3v_{no} = (e_a + e_b + e_c)$$

Thus

$$v_{no} = [v_{ao} + v_{bo} + v_{co}] - (e_a + e_b + e_c)]/3 \tag{2.15}$$

The set of differential equations mentioned in equations (2.8), (2.12), and (2.13). Defines the developed model in terms of the variables $i_a, i_b, i_c, \omega_m$ and, $\theta_r$ time as an independent variable.

Combining the all relevant equations, the system in state-space form is

$$\dot{x} = Ax + Bu + Ce \tag{2.16}$$

where

$$x = \begin{bmatrix} i_a & i_b & i_c & \omega_m & \theta_r \end{bmatrix}^t \tag{2.17}$$

$$A = \begin{bmatrix} -\frac{R_s}{L-M} & 0 & 0 & -\frac{\lambda_m}{J} f_{as}(\theta_r) & 0 \\ 0 & -\frac{R_s}{L-M} & 0 & -\frac{\lambda_m}{J} f_{bs}(\theta_r) & 0 \\ 0 & 0 & -\frac{R_s}{L-M} & -\frac{\lambda_m}{J} f_{cs}(\theta_r) & 0 \\ \frac{\lambda_m}{J} f_{as}(\theta_r) & \frac{\lambda_m}{J} f_{bs}(\theta_r) & \frac{\lambda_m}{J} f_{cs}(\theta_r) & -\frac{B}{J} & 0 \\ 0 & 0 & 0 & \frac{P}{2} & 0 \end{bmatrix} \tag{2.18}$$

$$B = \begin{bmatrix} \frac{1}{L-M} & 0 & 0 & 0 \\ 0 & \frac{1}{L-M} & 0 & 0 \\ 0 & 0 & \frac{1}{L-M} & 0 \\ 0 & 0 & 0 & \frac{1}{L-M} \end{bmatrix} \tag{2.19}$$

$$C = \begin{bmatrix} -\frac{1}{L-M} & 0 & 0 \\ 0 & -\frac{1}{L-M} & 0 \\ 0 & 0 & -\frac{1}{L-M} \end{bmatrix} \tag{2.20}$$

$$u = \begin{bmatrix} v_{as} & v_{bs} & v_{cs} & T_l \end{bmatrix}^t \tag{2.21}$$

$$e = \begin{bmatrix} e_a & e_b & e_c \end{bmatrix}^t \tag{2.22}$$

### 3.1. PI speed controller design

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.

The PI controller calculation involves two separate modes the proportional mode, integral mode. The proportional mode determine the reaction to the current error, 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

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

where *e(t)* = set reference value – actual calculated

### 3.2. PI speed control of the BLDC motor

Fig. 3.1 describes the basic building blocks of the PMBLDCM drive. The drive consists of speed controller, reference current generator, PWM current controller, position sensor, the motor and IGBT based current controlled voltage source inverter (CC-VSI).

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

$$e(t) = \omega_{ref} - \omega_m(t) \tag{3.2}$$

$\omega_m(t)$. is compared with the reference speed $\omega_{ref}$ . and the resulting error is estimated at the nth sampling instant as.

$$T_{ref}(t) = T_{ref}(t-1) + K_P[e(t) - e(t-1)] + K_I e(t)$$

where $K_p$ and, $K_I$ are the gains of PI speeds controller

The output of this controller is considered as the reference torque. A limit is put on the speed controller output depending on permissible maximum winding currents. The reference current generator block generates the three phase reference currents $i_{a}, i_{b}, i_{c}$ using the limited peak current magnitude decided by the controller and the position sensor.

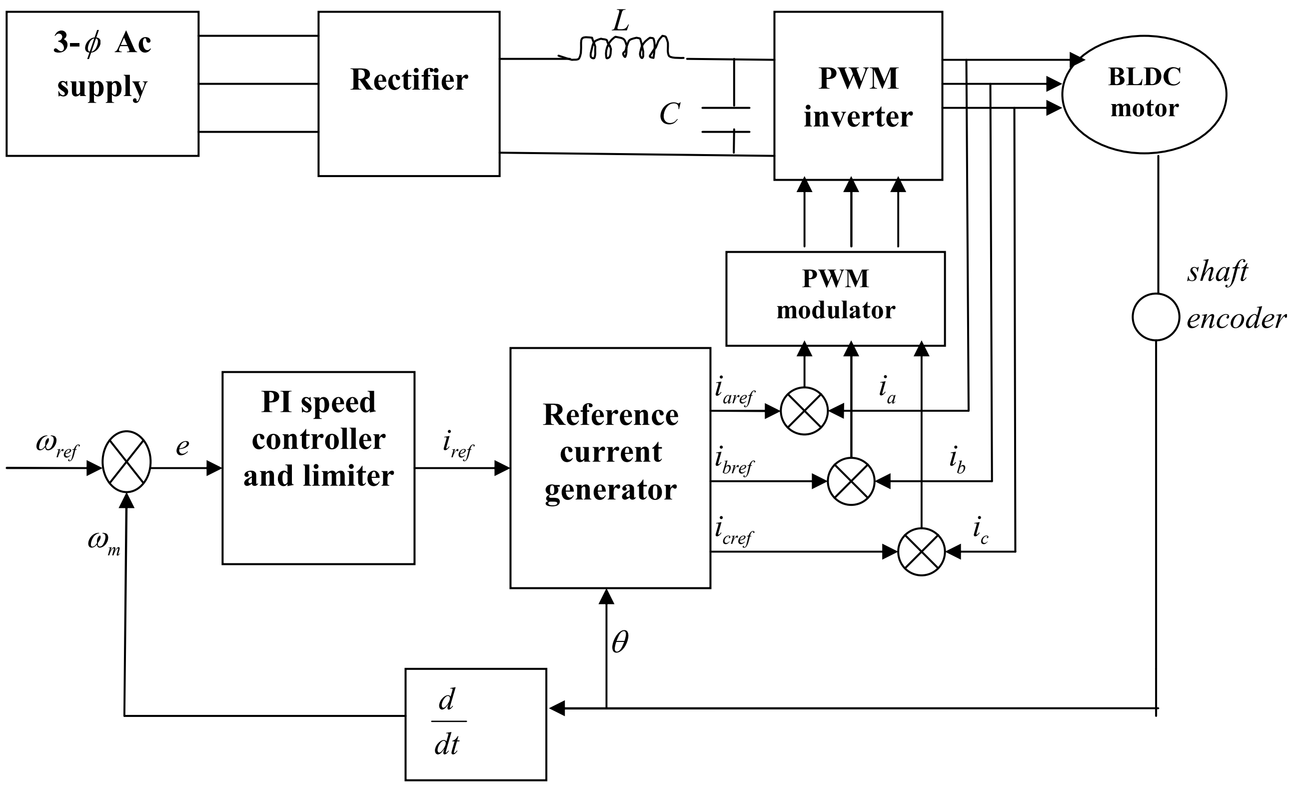



**Fig.3.1.PI speed controller of the BLDCM drive**

The reference currents have the shape of quasi-square wave in phase with respective back EMF develops constant unidirectional torque as. The PWM current controller regulates the winding currents $i_a$ , $i_b$ , $i_c$ with in the small band around. The reference currents $i_a$ , $i_b$ $i_c$ the motor currents are compared with the reference currents and the switching commands are generated to drive the inverter devices.

## 3.3. Modeling of speed control of BLDC motor drive system

The drive system considered here consists of PI speed controller, the reference current generator, PWM current controller, PMBLDC motor and an IGBT inverter. All these components are modeled and integrated for simulation in real time conditions

### 3.1.1. Reference Current Generator

The magnitude of the three phase current $i_{ref}$. is determined by using reference torque $T_{ref}$

$$i_{ref} = \frac{T_{ref}}{Kt} \tag{3.4}$$

where $K_t$ is the torque constant. $K_t$ Depending on the rotor position, the reference current generator block generates three-phase reference currents ($i_a^*$ , $i_b^*$ , $i_c^*$)by taking the value of

Reference current magnitude as $i_{ref}$.The reference currents are fed to the PWM current controller. The reference current for each phase $i_a^*$ $i_b^*$ $i_c^*$ f are function of the rotor position. These reference currents are fed to the PWM current controller Rotor position signal and Reference currents shown in Table.3.1.

**Table.3.1.Rotor position signal and Reference currents**

| **Rotor Position** $\theta_r$ | $i_a^*$ | $i_b^*$ | $i_c^*$ |
|---|---|---|---|
| 0-60 | $i_{ref}$ | $-i_{ref}$ | 0 |
| 60-120 | $i_{ref}$ | 0 | $-i_{ref}$ |
| 120-180 | 0 | $i_{ref}$ | $-i_{ref}$ |
| 180-240 | $-i_{ref}$ | $i_{ref}$ | 0 |
| 240-300 | $-i_{ref}$ | 0 | $i_{ref}$ |
| 300-360 | 0 | $-i_{ref}$ | $i_{ref}$ |

### 3.3.2. Hysteresis current controller

The Hysteresis current controller contributes to the generation of the switching signals for the inverter. hysteresis-band PWM is basically an instantaneous feedback current control method of PWM where the actual current continually tracks the command current continually tracks the command current within hyssteresis-band.Fig.3.2 explains the operation principle of hysteresis-band PWM for half-bridge inverter. The control circuit generates the sine reference current and it's compared with actual phase current wave.

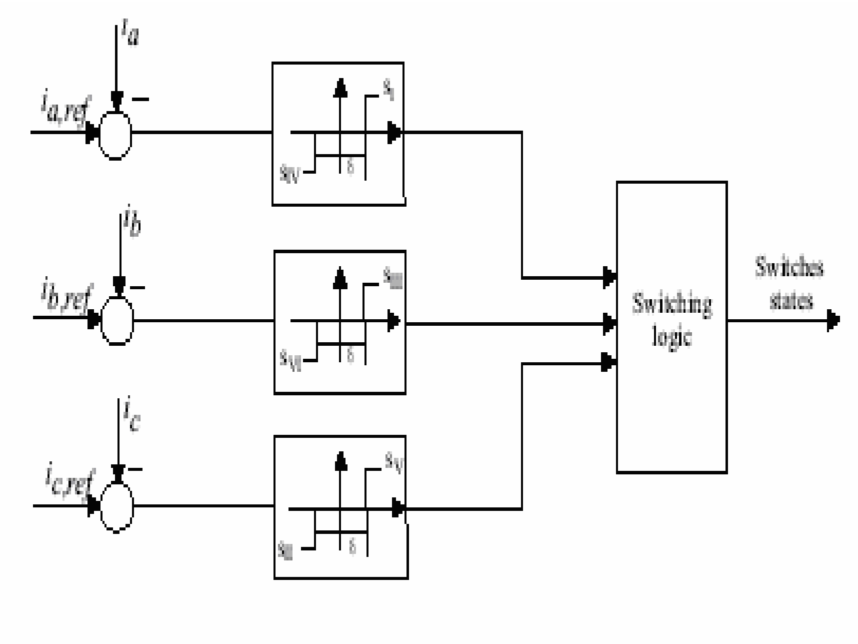



**Fig.3.2.The structure of PWM current controller**

The current exceed upper band limit the upper switch is off and lower switch is on. as the current exceed lower band limit upper switch is on and lower switch is off like this control of the other phase going on.

The switching logic is formulated as given below.

If $i_a < (i_a^* - h_b)$ switch 1 ON and switch 4 OFF $S_A = 1$

If $i_a < (i_a^* + h_b)$ switch 1 OFF and switch 4 ON $S_A = 0$

If $i_b < (i_b^* - h_b)$ switch 3 ON and switch 6 OFF $S_B = 1$

If $i_b < (i_b^* + h_b)$ switch 3 OFF and switch 6 ON $S_B = 0$

If $i_c < (i_c^* - h_b)$ switch 5 ON and switch 2 OFF $S_C = 1$

If $i_c < (i_c^* + h_b)$ switch 5 OFF and switch 2 ON $S_C = 0$

where, $h_b$ is the hysteresis band around the three phase's references currents, according to above switching condition of the inverter output voltage are given below

$$v_a = \frac{1}{3}[2S_A - S_B - S_C]$$
$$v_b = \frac{1}{3}[-S_A + 2S_B - S_C] \tag{3.5}$$
$$v_c = \frac{1}{3}[-S_A - S_B + 2S_C]$$

### 3.3.3. 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 $\omega_m$ and rotor position angle $\theta_r$ as shown in Fig3.3. From this, the phase back EMF'S can be expressed as.

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \omega_m \lambda_m \begin{bmatrix} f_{as}(\theta_r) \\ f_{bs}(\theta_r) \\ f_{cs}(\theta_r) \end{bmatrix} \tag{3.6}$$

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 $\theta_r$. The $f_{bs}(\theta_r)$, $f_{cs}(\theta_r)$ is similar to $f_{as}(\theta_r)$ but phase displacement of $120^0$.

The back emf functions mathematical model as

$$f_{as}(\theta_r) = \begin{cases} \theta_r \dfrac{6}{\pi}, & 0 \le \theta_r < \dfrac{\pi}{6} \\ 1, & \dfrac{\pi}{6} \le \theta_r < \dfrac{5\pi}{6} \\ (\pi - \theta_r)\dfrac{6}{\pi}, & \dfrac{5\pi}{6} \le \theta_r < \dfrac{7\pi}{6} \\ -1, & \dfrac{7\pi}{6} \le \theta_r < \dfrac{11\pi}{6} \\ (\theta_r - 2\pi)\dfrac{6}{\pi}, & \dfrac{11\pi}{6} \le \theta_r < 2\pi \end{cases} \tag{3.7}$$

$$f_{bs}(\theta_r) = \begin{cases} -1, & 0 \le \theta_r < \dfrac{\pi}{2} \\ (-\dfrac{2\pi}{3} + \theta_r)\dfrac{6}{\pi}, & \dfrac{\pi}{2} \le \theta_r < \dfrac{5\pi}{6} \\ 1, & \dfrac{5\pi}{6} \le \theta_r < \dfrac{3\pi}{2} \\ (-\dfrac{5\pi}{3} + \theta_r)\dfrac{6}{\pi}, & \dfrac{3\pi}{2} \le \theta_r < \dfrac{11\pi}{6} \end{cases} \tag{3.8}$$

$$-1, \qquad \frac{11\pi}{6} \le \theta_r < 2\pi$$

$$f_{cs}(\theta_r) = \begin{cases} 1, & 0 \le \theta_r < \frac{\pi}{6} \\ (\frac{\pi}{3} - \theta_r)\frac{6}{\pi}, & \frac{\pi}{6} \le \theta_r < \frac{\pi}{2} \\ -1, & \frac{\pi}{2} \le \theta_r < \frac{7\pi}{2} \\ (-\frac{4\pi}{3} + \theta_r)\frac{6}{\pi}, & \frac{7\pi}{2} \le \theta_r < \frac{3\pi}{2} \\ 1, & \frac{3\pi}{2} \le \theta_r < 2\pi \end{cases} \qquad (3.9)$$

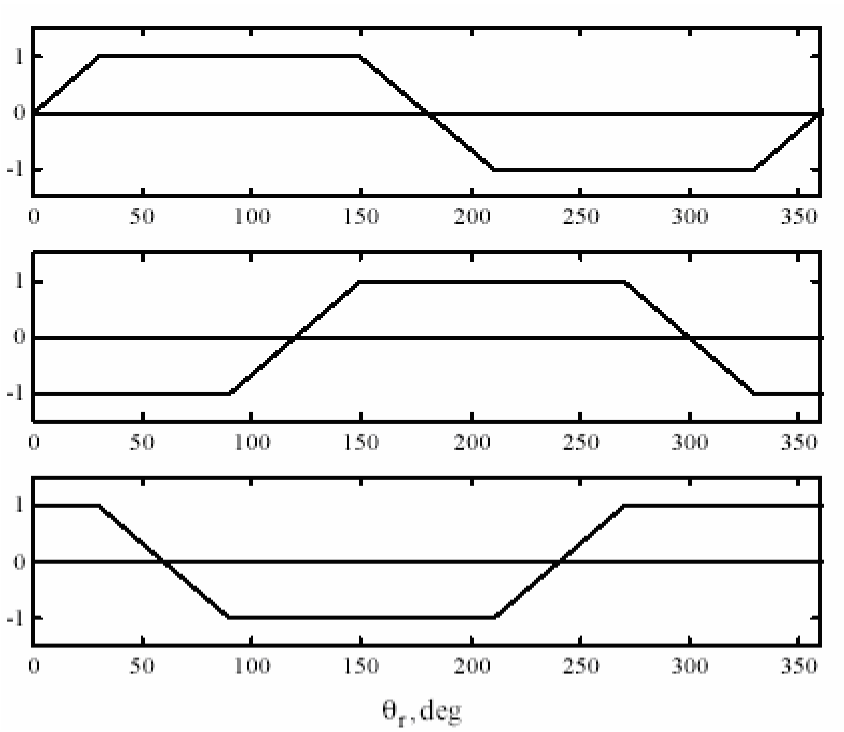



**Fig.3.3. Plots back emfs $f_{as}(\theta_r)$, $f_{bs}(\theta_r)$ and, $f_{cs}(\theta_r)$.**

## 4.1 Introduction to 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. The application range from consumer products such as cameras ,camcorder ,washing machines and microwave ovens to industrial process control ,medical instrumentation ,and decision-support system .many decision-making and problem solving tasks are too complex to be understand quantitatively however ,people succeed by using knowledge that is imprecise rather than precise . fuzzy logic is all about the relative importance of precision .fuzzy logic has two different meanings .in a narrow senses ,fuzzy logic is a logical system which is an extension of multi valued logic .but in wider sense fuzzy logic is synonymous with the theory of fuzzy sets . Fuzzy set theory is originally introduced by Lotfi Zadeh in the 1960,s[15] 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 (PIC) 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 analyzed., for example by bode plots or nyquist plot , and controller can be designed for specific performances .such procedure is time consuming.

- Fuzzy logic controller has adaptive characteristics.

The adaptive characteristics can achieve robust performance to system with uncertainty parameters variation and load disturbances.

## 4.3. Fuzzy logic controller (FLC)

Fuzzy logic expressed operational laws in linguistics terms instead of mathematical equations. Many systems are too complex to model accurately, even with complex mathematical equations; therefore traditional methods become infeasible in these systems. However fuzzy logics linguistic terms provide a feasible method for defining the operational characteristics of such system.

Fuzzy logic controller can be considered as a special class of symbolic controller. The configuration of fuzzy logic controller block diagram is shown in Fig.4.1

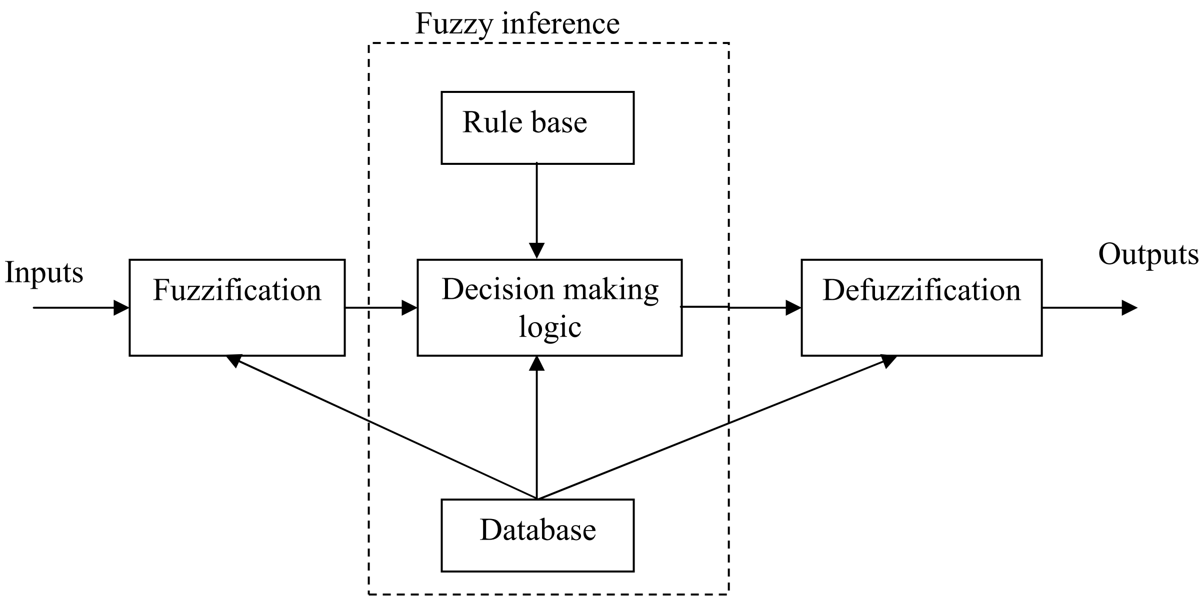



**Fig.4.1.Structure of Fuzzy logic controller**

The fuzzy logic controller has three main components

1. Fuzzification
2. Fuzzy inference
3. Defuzzification

### 4.3.1. Fuzzification

The following functions:

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, a trapezoidal, a bell (as shown in Fig.4.2) or another appropriate from.

The triangle membership function is defined in (4.1).Triangle membership functions limits defined by $V_{al1}$, $V_{al2}$ and $V_{al3}$.

$$\mu(u_i) = \begin{cases} \dfrac{u_i - V_{al1}}{V_{al2} - V_{al1}}, V_{al1} \le u_i \le V_{al2} \\ \dfrac{V_{al3} - u_i}{V_{al3} - V_{al2}}, V_{al2} \le u_i \le V_{al2} \\ 0, \qquad othetrwise \end{cases} \tag{4.1}$$

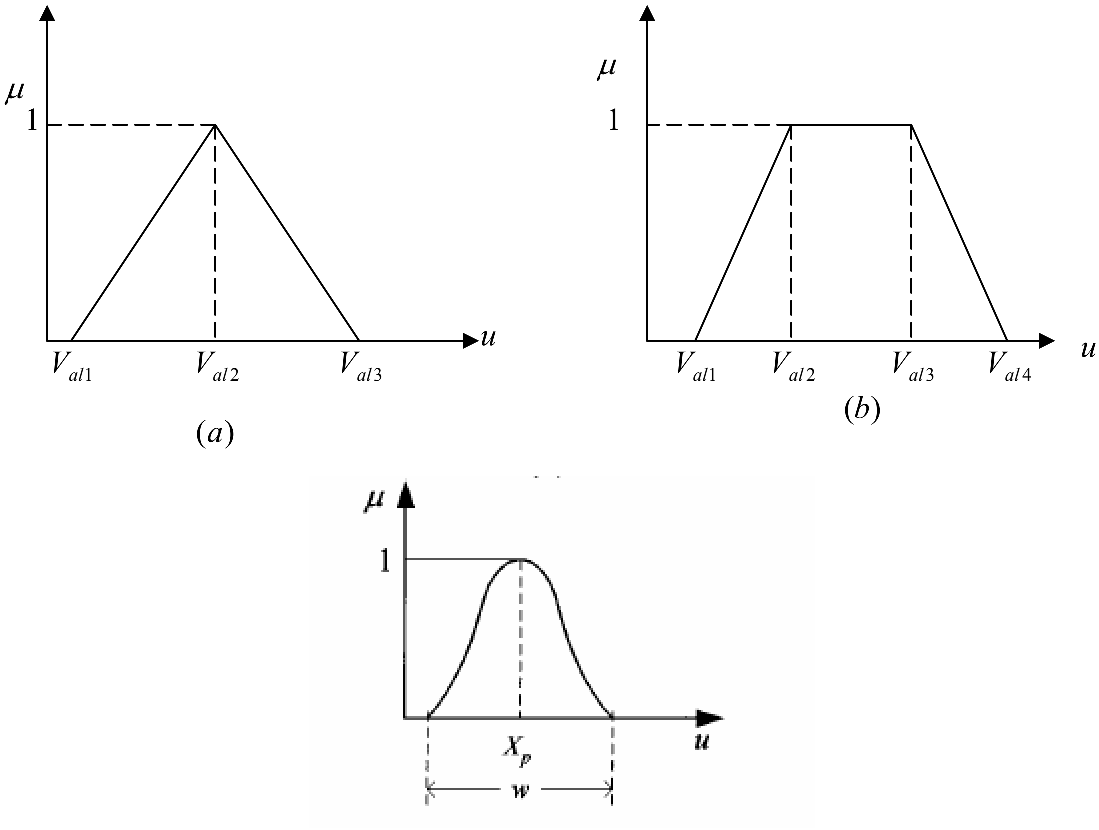
Trapezoid membership function defined in (4.2) .Trapezoid membership functions limits are defined by $V_{al1}$, $V_{al2}$, $V_{al3}$ and $V_{al4}$.

$$\mu_i(u_i) = \begin{cases} \dfrac{u_i - V_{al1}}{V_{al2} - V_{al1}}, V_{al1} \le u_i \le V_{al2} \\ 1, \qquad , V_{al2} \le u_i \le V_{al3} \\ \dfrac{V_{al4} - u_i}{V_{al4} - V_{al3}}, V_{al3} \le u_i \le V_{al4} \\ 0, \qquad otherwise \end{cases} \tag{4.2}$$

The bell membership functions are defined by parameters $X_p$, $w$ and $m$ as follows

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

where $X_p$ the midpoint and w is the width of bell function. $m \ge 1$, and describe the convexity of the bell function.




(c)

**Fig.4.2. (a) Triangle, (b) Trapezoid, and (c) Bell membership functions.**

The inputs of the fuzzy controller are expressed in several linguist levels. As shown in Fig.4.3 these levels can be described as Positive big (PB), Positive medium (PM), Positive small (PS) Negative small (NS), Negative medium (NM), Negative big (NB) or in other levels. Each level is described by fuzzy set.

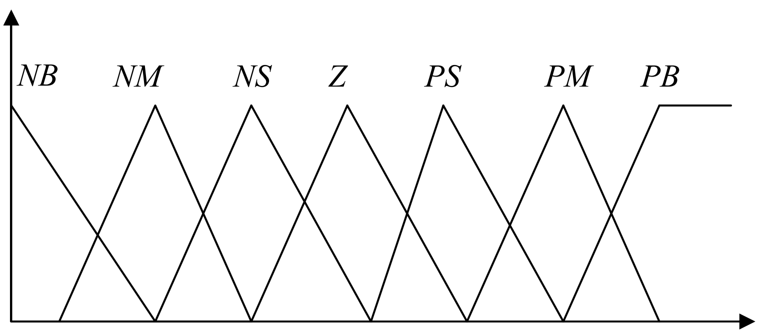



**Fig.4.3. Seven levels of fuzzy membership function**

### 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 M amdani [Mam75] 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 [Zad73].

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 defuzzification 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:

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

(c) .The centroid method or center of area method (COA)

The widely used centroid strategy generates the center of gravity of area bounded by the Membership function cure.

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

## 4.4. Fuzzy logic control of the BLDC motor

The fuzzy logic controller was applied to the speed loop by replacing the classical polarization index (PI) controller. The fuzzy logic controlled BDCM drive system block diagram is shown in Fig 4.4.

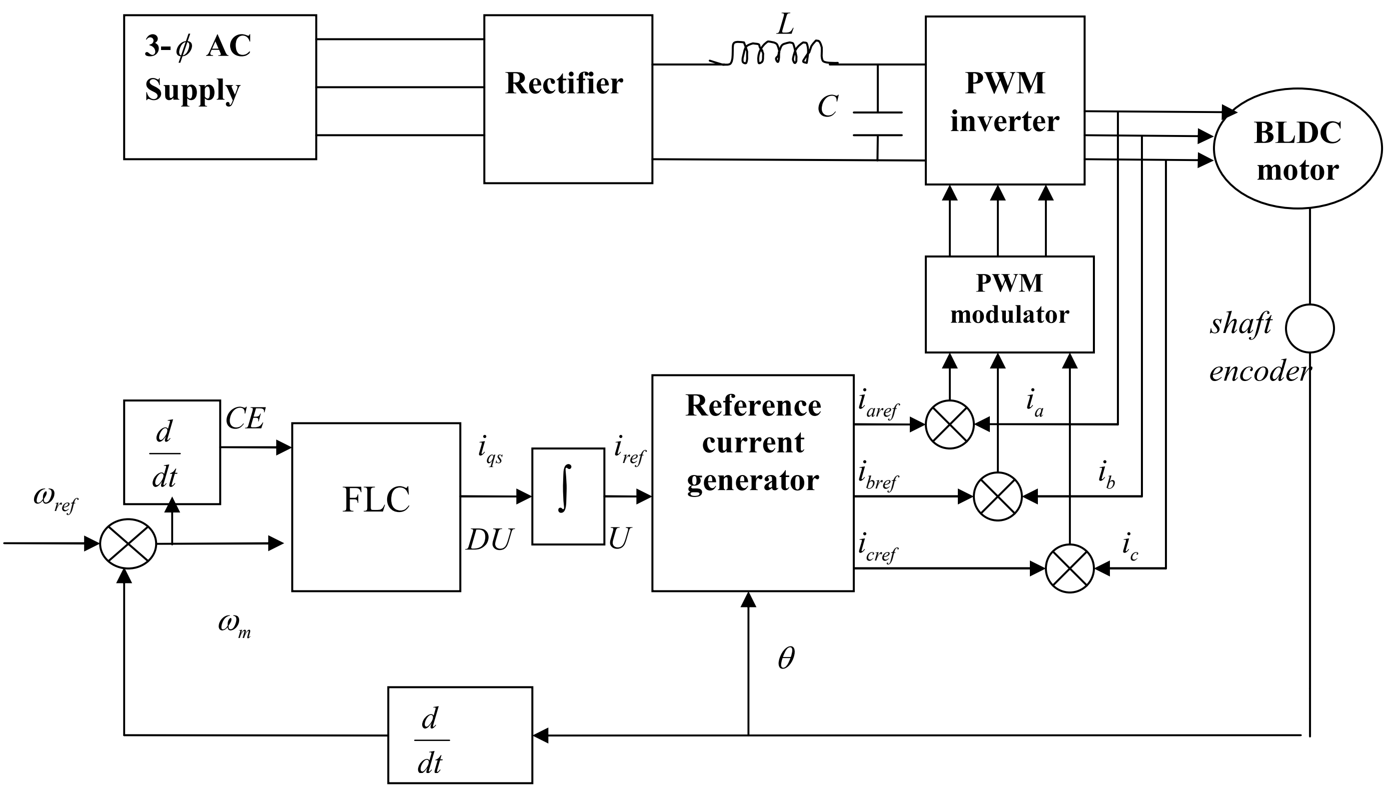



**Fig.4.4. Fuzzy speed control block diagram of the BLDC motor**

The input variable is speed error (E), and change in speed error (CE) is calculated by the controller with E .The output variable is the torque component of the reference ($i_{ref}$) where $i_{ref}$ is obtained at the output of the controller by using the change in the reference current.

The controller observes the pattern of the speed loop error signal and correspondingly updates the output DU and so that the actual speed $\omega_m$ matches the command speed $\omega_{ref}$. There are two inputs signals to the fuzzy controller, the error $E = \omega_{ref} - \omega_m$ and the change in error CE, which is related to the derivative $\frac{dE}{dt} = \frac{\Delta E}{\Delta t} = \frac{CE}{T_s}$, where $CE = \Delta E$ in the sampling Time $T_S$, CE is proportional to $\frac{dE}{dt}$. The controller output DU in brushless dc motor drive is $\Delta i^*_{qs}$ current. The signal is summed or integrated to generate the actual control signal U or current $i^*_{qs}$ .where $K_1$ and $K_2$ are nonlinear coefficients or gain factors including the summation process shown in Fig 4.4. We can write

$$\int DU = \int K_1 E dt + \int K_2 CE dt \tag{4.6}$$

$$U = K_1 \int E dt + K_2 E \tag{4.7}$$

which is nothing but a fuzzy P-I controller with nonlinear gain factors. The non linear adaptive gains in extending the same principle we can write a fuzzy control algorithm for P and P-I-D.

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: ZO | |

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

$$-1 \le \omega_e \le +1 \tag{4.8}$$

and

$$-1 \le \omega_{ce} \le +1 \tag{4.9}$$

and the output variable torque reference current change $\Delta i_{qs}$ is define in the range of

$$-1 \le \Delta i_{qs} \le +1 \tag{4.10}$$

The triangular shaped functions are chosen as the membership functions due to the resulting best control performance and simplicity. The membership function for the speed error and the change in speed error and the change in torque reference current are shown in Fig. 4.5 .For all variables seven levels of fuzzy membership function are used .Table .II show the $7 \times 7$ rule base table that was used in the system.

**Table 4.1.7×7 Rule base table used in the system**

| **e/ce** | **NB** | **NM** | **NS** | **ZO** | **PS** | **PS** | **PB** |
|---|---|---|---|---|---|---|---|
| **NB** | NB | NB | NB | NB | NM | NS | ZO |
| **NM** | NB | NB | NB | NM | NS | ZO | PS |
| **NS** | NB | NB | NM | NS | ZO | PS | PM |
| **ZO** | NB | NM | NS | ZO | PS | PM | PB |
| **PS** | NM | NS | ZO | PS | PM | PB | PB |
| **PM** | NS | ZO | PS | PM | PB | PB | PB |
| **PB** | ZO | 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 $\Delta i_{qs}$ by centre of area defuzzyfication method.
- Sending the control command to the system after calculation of $\Delta i_{qs}$

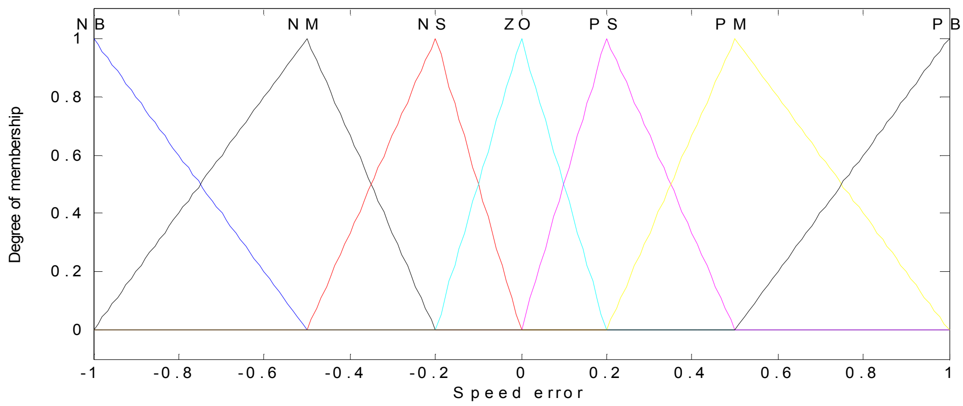



**Fig. 4.5.a. Fuzzy membership function for the speed error**

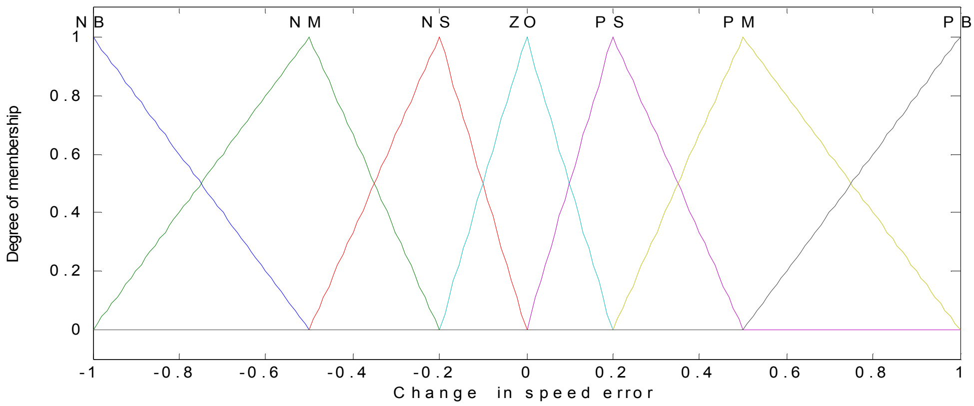



**Fig. 4.5.b.Fuzzy membership function for the change in speed error**

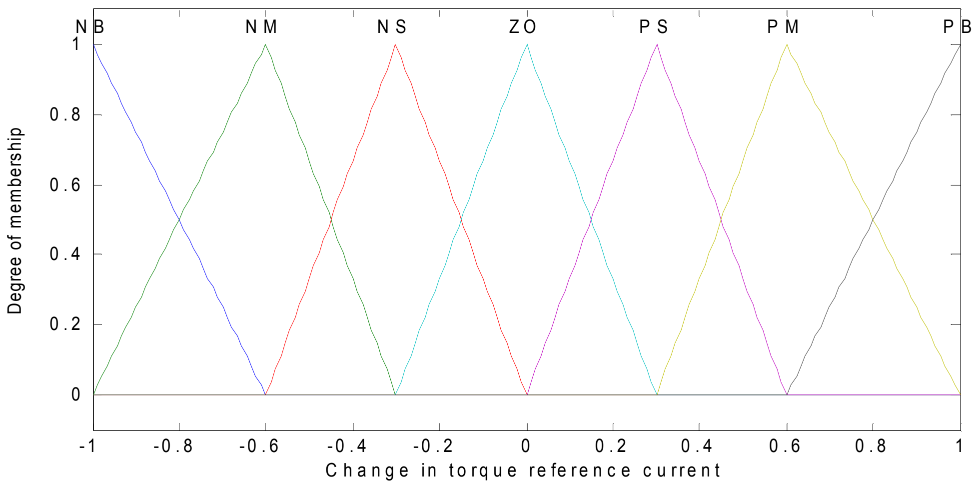



**Fig. 4.5.c. Fuzzy member ship function for the change in torque reference current**

**5.1. Experimental system**

Instead of using an analog PI controller for the proposed drive, a digital controller was implemented on a TMS320LF2407 DSP processor from Texas Instruments. Although the analog PI controller may have a greater bandwidth than a digital PI controller, it is subject to deviation due to the drifts in nominal values of its components. Another fact is that it is much more difficult to adapt an analog PI controller to changes in the system parameters, for example, replacement of the motor by other BLDC motor and other factors. For a digital PI controller, all that needs to be done in order to adapt it to a new system is to change the parameters of the controller by reprogramming the DSP.

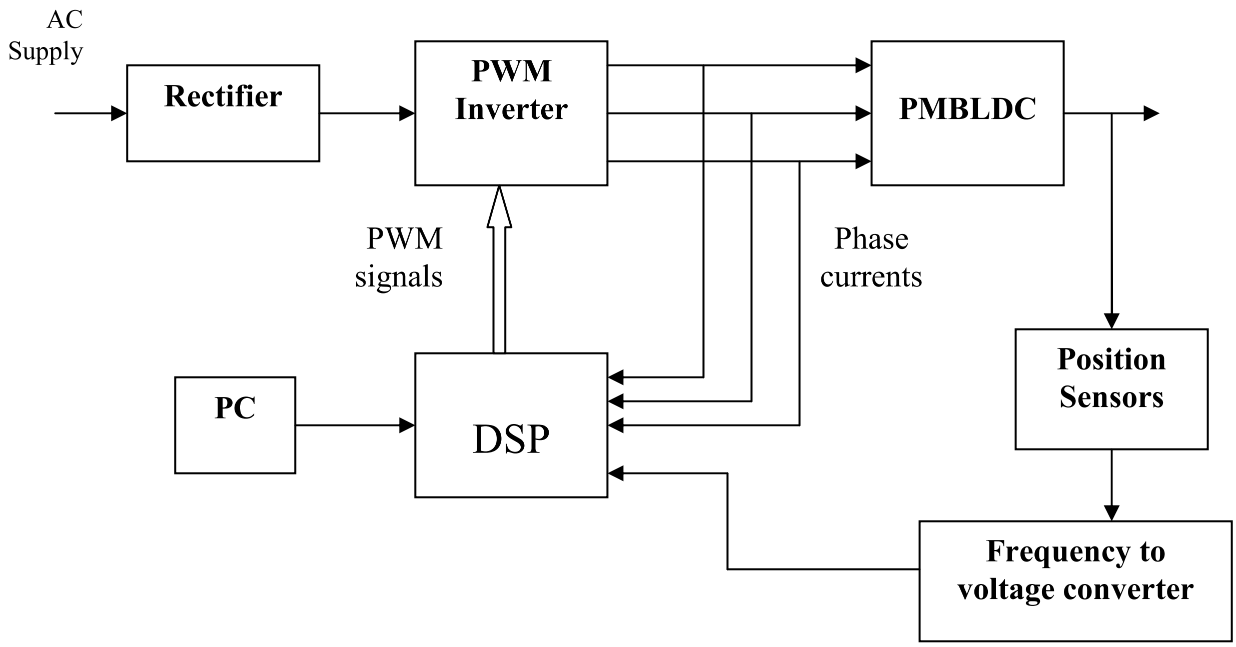



**Fig.5.1.A simple structure diagram of experimental setup**

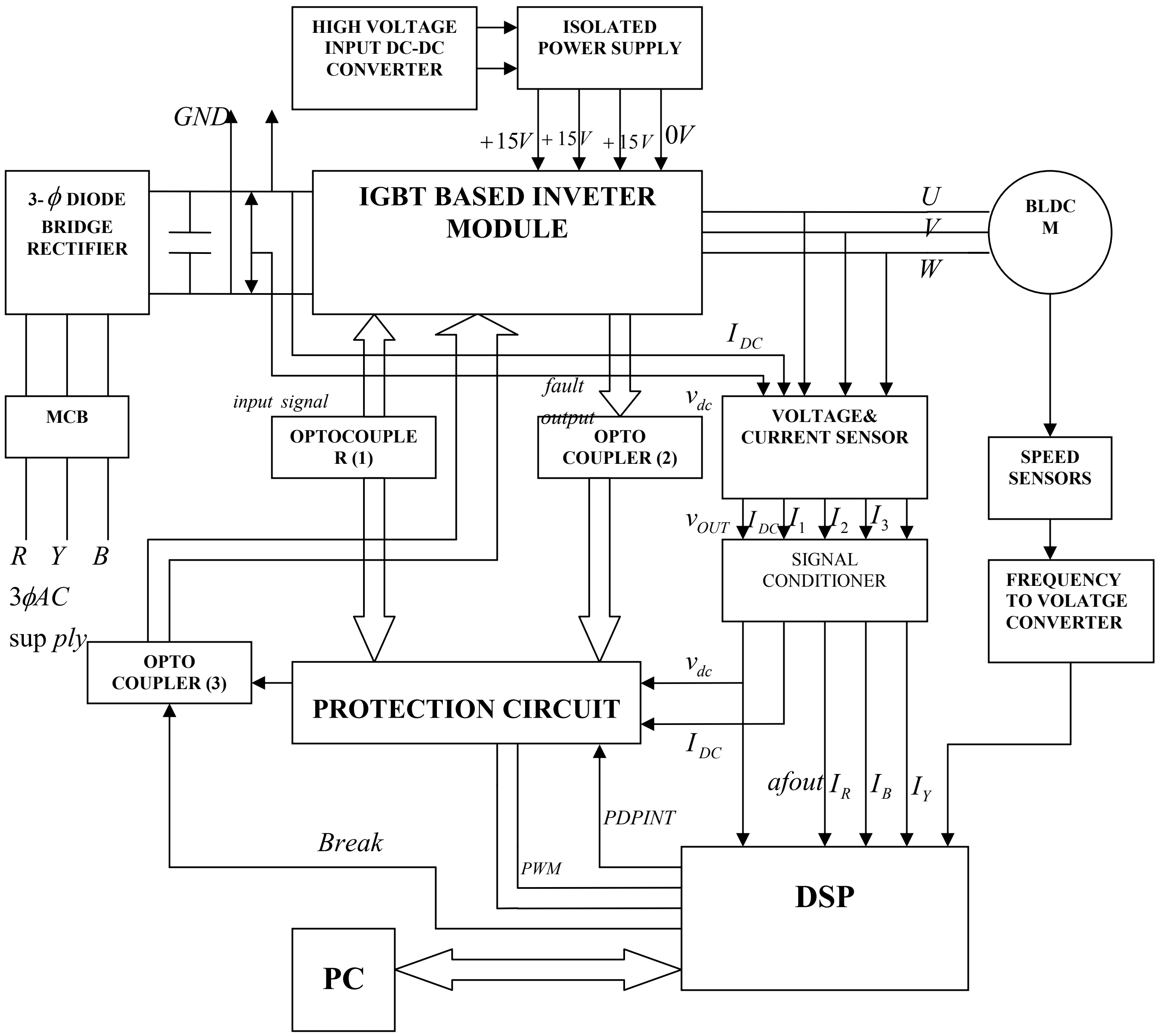



**Fig. 5.2.The over all system block diagram of experimental setup**

The IPM type used in these studies is PEC16DSM01, its rated voltage is 1200V, rated current is 25A, the control voltage is 20V and the switching frequency is 20 KHz. The experimental setup block diagram of BLDC motor diagram as show in Fig.5.12 and it consists of following systems.

1. Intelligent power module
2. Voltage and current sensor
3. Signal conditioner
4. Protection circuit
5. Opt coupler
6. $3\phi$ diode bridge rectifier

7. Speed sensor
8. Frequency to voltage converter

**5.1.1. Intelligent power module**

Intelligent power module as work as DC-DC converter (chopper) or DC-AC converter. It works using an IGBT based IPM and works on basis of software from DSP processor .The power module can be used for studying the operation of chopper, three phase inverter.

Intelligent power modules are advanced hybrid power devices that combine high speed, low loss IGBT with optimized gate drive and protection circuitry. Highly effective over current and short-circuit protection is realized through the use of advanced current sense IGBT chips that allows continuous monitoring of power device current. System reliability is further enhanced by the IPM integrated over temperature and under voltage lock out protection.

**5.1.2. Voltage and current sensor**

Intelligent power module output voltage and current is not directly feed to control circuits. intelligent power module output voltage is very high but control circuit operate in minimum voltage .So necessary for IPM output high voltage is convert in to very low voltage and current transducer sense from high voltage and output of transducer low voltage (max 5v). The sensors used for sensing current and voltage are work on the principle of hall effect hence the sensors is called hall effect transducer hall effect transducer output voltage and currents depends upon transducer primary and secondary winding ratio. A hall effect current transducer sense the current $I_{dc}$ ,$I_1(U)$ ,$I_2(V)$ $I_3(W)$ and one hall effect voltage transducer sense the dc link voltage $V_{DC}$ .

**5.1.3. Signal conditioner**

Signal conditioner is used to give the reference signals of current and voltage to the protection circuit as well as to the ADC of the DSP processor.

**5.1.3.1. DC link voltage**

Dc link voltage is sensed using a hall effect voltage sensor and output of that transducer is given to non-inverting amplifier .Then the output of that amplifier is given to non inverting amplifier can be adjusted using a trim pot(TR9). Then the output is compared with reference voltage which his already set, then the output is given to hardware protection unit as well as to ADC channel of the DSP processor through a 5v voltage regulator.

#### 5.1.3.2. DC link current

Dc link current is feed from a Hall Effect current transducer, it is given to non-inverting amplifier here the offset voltage can be adjusted using the trim pot (TR4). Then the gain can be adjusted using trim pot (TR1). The $I_1$ current is given to active filter. Active filter output is connected to ADC channel of the DSP processor. $I_1$ Current is compared with reference value by using comparator and it is given to the protection unit.

#### 5.1.3.3. R, Y, B phase current

The phase current are sensed by using 3 separate hall effect transducer then these current is given to the non inverting here the offset voltage can be set. Then the outputs is given to inverting amplifier here the gain can be set. Finally outputs are given to the ADC channel of DSP.

### 5.1.4. Protection circuit

The schematic diagram of protection circuit of IPM based power module is as shown in Protection circuit is used to prevent the over voltage, over current and under voltage. The current and voltage from signal conditioners are given to input of master/slave JK flip-flop. Master/slave JK flip-flop output is connected to transistors $Q_1$ and $Q_2$ .Transistor $Q_1$ output C1 terminal is given to input of AND gates and AND gate anther input is feed from PWM output of DSP. These output AND gates depends upon transistor $Q_1$ output, then AND gates output is given to input of opto coupler(1), then opto coupler(1) output signal is feed input of IPM . IPM is generate to fault output signals, when over current/voltage occurs an IPM. This signal is feed to opto coupler (2) and opto coupler (2) output is AND with DSP PDP INT signal.

### 5.1.5. OPTO coupler

The function of the opto coupler is isolate to the control circuit from power circuit .pulse width modulation signal (PWM1 to PWM6) comes from DSP processor. This signal is not directly feed through a power circuit. Suppose control circuit is connected to power circuit without isolation circuit the control circuit may get affect so needed to isolation circuit interface between power circuit and control circuit.

### 5.1.6. Three Phase bridge rectifier

The rectifier provides the rectified DC voltage to intelligent power module.$3\phi$ AC supply is connected to input of $3\phi$ bridge rectifier module. 3 phase bridge rectifier convert the AC voltage in to DC voltage with AC ripples. Capacitor is connected across the bridge rectifier .capacitor is used to neglect the ac ripples. $3\phi$ diode bridge rectifier module output is connected to input of intelligent power module**.**

### 5.1.7. Speed sensor

Circular windows around the circular disk mounted on the motor shaft such that it rotates with the shaft. A LED is mounted on the one side of disk and photo transistor is mounted on the other side disk opposite to LED. During rotation when circular window come across the LED. The light passes to the photo transistor. As result photo transistor conducts and produces low output at its collector. Each time when light passes through window to the photo transistor; it conducts and output goes low other wise photo transistor is off and output is high.

As disk rotates the train of pulses is generated .the number of pulses in one rotation equal number of circular window on the disk. Counting the number of pulses in specific time this pulse convert frequency to voltage by using frequency to voltage converter.

### 5.1.8. Frequency to voltage converter

The square wave of speed sensor output is feed frequency to voltage converter circuit. The XR4151 can be used as a frequency to voltage converter. The voltage applied comparator input should not be allowed to go below ground by more then 0.3V. The input frequency range 0 to 20kHz and corresponding voltage output level is -10mv to -10v.

## 5.2. DSP processor

The DSP Controller is a16-bit fixed point TMS320LF2407 from Texas Instruments, and that is enclosed in a block responsible for all the control functions. As observed, the DSP processor is very powerful, compact and multi-functional, containing many inbuilt modules like the Analog-to-Digital converter, Capture Units for sensing the change in rotor field position, and the computations performed on it implement the hysteresis current control and the PI speed regulator. The TMS320LF2407A contains a C2xxDSP core along with useful peripherals such as ADC, Timer, PWM Generation are integrated onto a signal piece of silicon.

Although a traditional micro-controller/microprocessor has a CPU, the corresponding arithmetic and logic functions as well as some non-volatile memory on-board, many peripherals ICs and components have to be added in order that a suitable system for motor control is built. The TI family of DSPs for motor control has incorporated many functions that were previously performed by off-chip ICs and components by integrating various modules on the chip, thereby, greatly increasing the speed and reliability of the overall system.

TMS320LF2407 is a fixed-point DSP processor, meaning that the DSP does not have an inbuilt architecture for handling non-integer parts of decimal numbers. That is, the system designer has to interpret the non-integer parts by means of using scaled numbers. An added precaution when using fixed point processors is to protect against numerical overflows that may lead to errors, while at the same time, not to scale down each number so small that precision is lost. This is explained in greater detail in the section on current control and PI regulators.

The TMS320LF2407 can be operated in two modes. In the mode: 1 (serial mode) the trainer is configured to communicate with PC through serial port. In the mode: 2 (stand alone mode), the user can interact with trainer through the IBM PC keyboard and 16×2 LCD display.

The DSP board contains the following modules:

1. TMS320C/F2*xx* core CPU
    - 32-bit central arithmetic unit.
    - 32-bit accumulator.
    - 16-bit x 16-bit parallel multiplier with a 32-bit product capability.
    - Eight 16-bit auxiliary registers with a dedicated arithmetic unit for indirect addressing of data memory.
2. MEMORY
    - 64K words program memory space.
    - 64K words data memory space.
    - 64K I/O space.
3. SPEED
    - 25-ns (40MIPS) instruction cycle time, with most instruction single cycle.
4. Event Manager
    - Two event managers A&B.
    - Four 16-bit general-purpose timers with six modules including continuous up counting and continuous down counting.
    - Six 16-bit full compare units with dead band capability in each event managers.
    - Two 16-bit timer PWMs in each event manager.
5. Dual 10-bit analog- to –digital converter (ADC).

6. 40 individually programmable multiplexed I/O pins.
7. Phase-locked loop (PLL) based clock module.
8. Serial communication interface (SCI).
9. Serial peripheral interface (SPI).
10. CAN controller module.
11. Watchdog Timer, to bring the CPU to reset in case of a fault that causes either CPU Disruption or the execution of an improper loop.

**5.2.1. Analog-to-Digital converter**

Many of the real-world input signals are in the analog domain whereas the CPU does all the processing in the digital domain. In order that the CPU get the analog domain signals for processing, it is essential to translate them into a format that makes sense to the CPU. This is achieved by using an Analog-to-Digital converter (ADC) that does the required Translation. The analog input signals are buffered using ICs 3403. Each buffer IC consists of four buffer. The ADC out put signal is given to protection section to the processor.

**5.2.2. Digital-to-analog converter**

The digital output from the processor is converted into analog using IC AD8582 (U32). It is a 2 channel DAC IC. The output from the DAC is of low voltage hence IC TL084 is placed at the output of the DAC to amplify the DAC output.

**5.2.3. PWM section**

In the PWM section three number of 74LS14 ICs are provided. The default PWM output of the processor is high signal. The 74LS14 is provided to invert the PWM outputs to avoid shoo through fault.

## 5.3. Overview of the system and software development process

The development of the necessary software required for the proposed speed control BLDC drive. C language is used to develop the necessary code for the TMS320LF2407. The Digital-to-Analog converter (DAC) for ease of testing and development, a XDS 510 PP emulator pod for interfacing the PC, making it possible to develop code using a PC based environment. The compiler used is Code Composer Version 3.12. Real-Time monitor, a utility from TI is added to enable online tuning of various control parameters.

Since it is a fixed point DSP, the only way to handle fractional and non-integral Quantities is to scale them to some range and then work with the scaled quantities as if they Were integers and then correctly interpret the obtained results (in the integer formats). Formats are used to represent non-integer numbers.

The program is divided into two Categories, namely the 'main' program and its various functions. The various functions are nothing but various interrupt service routines, each having its designated priority. The Real-Time monitor is, in fact, a lowest priority interrupt that keeps track of the global variables during the spare time between interrupt request processing, and it displays these variables in a watch window on the computer screen. The complete flowcharts are described as shown below.

**Fig.5.3. A Photo of experimental setup of brushless dc motor**

**Fig.5.4. A Photo of DSP processor.**

## 6.1. Performance with PI controller

The simulation of speed control characteristics PI speed control is based on the system configuration shown in Fig.3.1. The governing equations of the BDCM are listed in chapter 2.The inverter output terminal voltages are generated according to the PWM switching algorithm.

A program is developed using MATLAB to simulate the PMBLDC drive model with both the FLC speed controller and the fixed gain PI controller [enclosed as annexure1]. The equations governing the model of the drive system are given in the above section. A numerical technique namely Fourth order Rung-Kutta method was used to get the solution of these equations for the variables such as $i_a, i_b, and\ \ i_c$ and $T_e$. The speed controller and switching logic of current controller are used in this simulation.

**Table.6.1. BLDC motor specifications**

| | |
|---|---|
| HP | 2 |
| No. of Poles | 4 |
| No. of Phases | 3 |
| Type of connection | Star |
| Vdc | 160V |
| Resistance/Ph | 0.7Ω |
| flux linkages constant | 0.105wb |
| Self Inductance | 2.72$m$H |
| Mutual inductance | 1.5$m$H |
| Moment of Inertia | 0.000284 kg-m/sec2 |
| Damping constant | 0.02 N-m/rad/sec |

The simulation result for speed reference input of 700 rpm with a load torque of 0.7 N-m are shown Fig 5.1. The controller gains are $K_P$ =0.8, $K_I$ = 0.02 and current controller bandwidth is 0.3A.The rotor is standstill at time zero with onset of the speed reference, the speed error, torque reference, and attains maximum value. The current is made to follow the reference by the current controller. There fore electromagnetic follows the reference value.

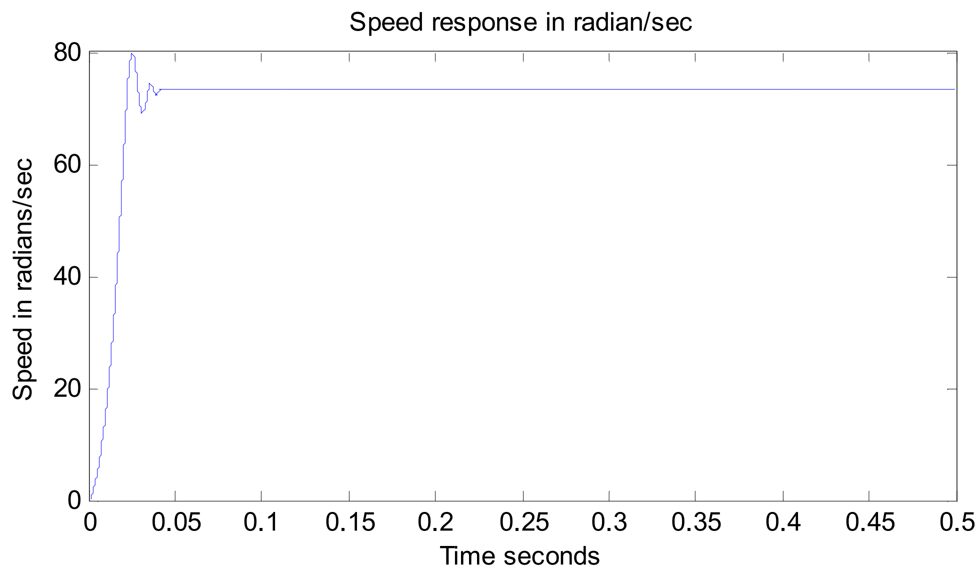



**Fig.6.1. Speed response radians /seconds versus time**

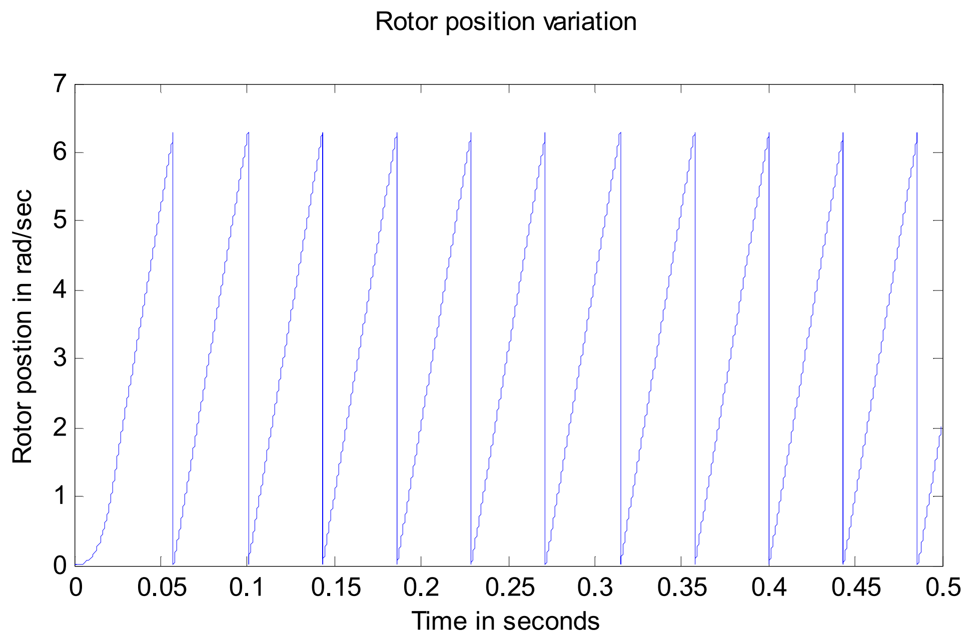



**Fig.6.2 Rotor position in radians versus time**

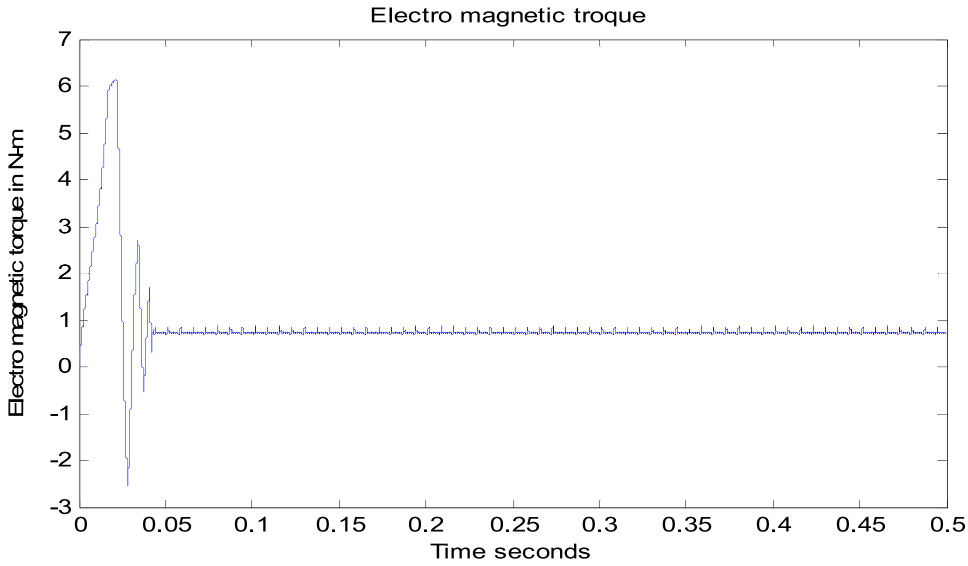



**Fig.6.3. Electromagnetic torque developed in N-m**

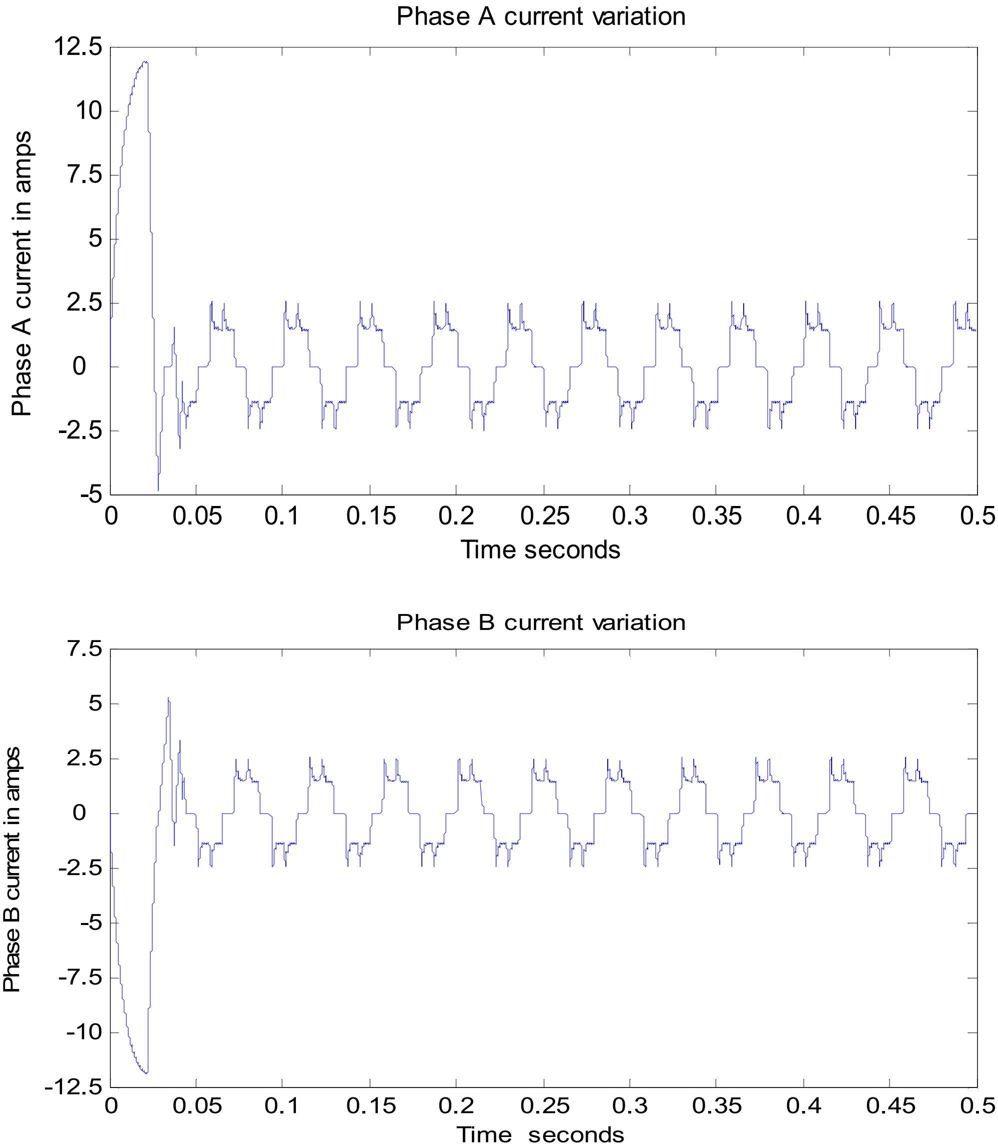



**Fig.6.4.Phase currents variation of motor**

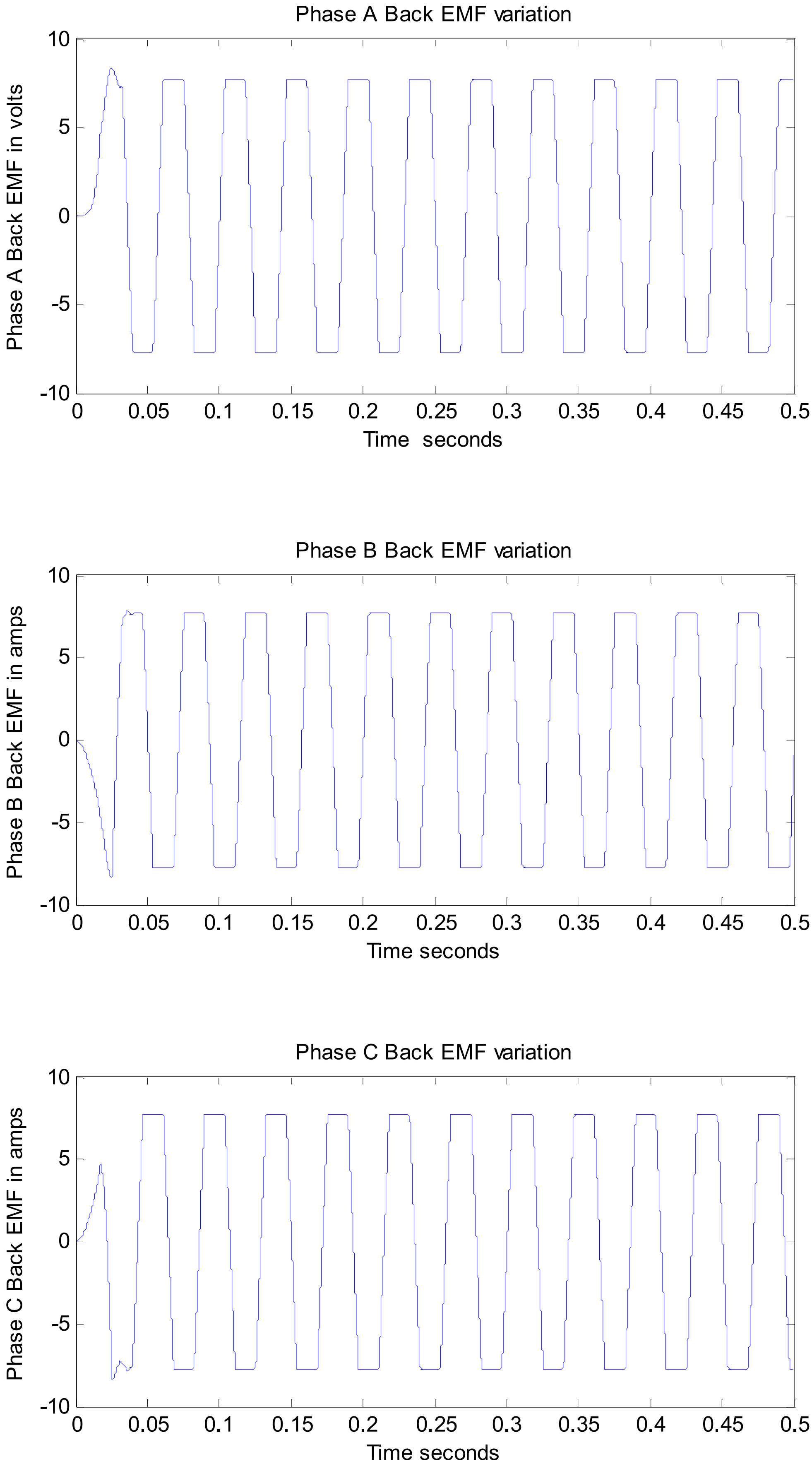



**Fig.6.5: Phase Back EMF s variation of Motor**

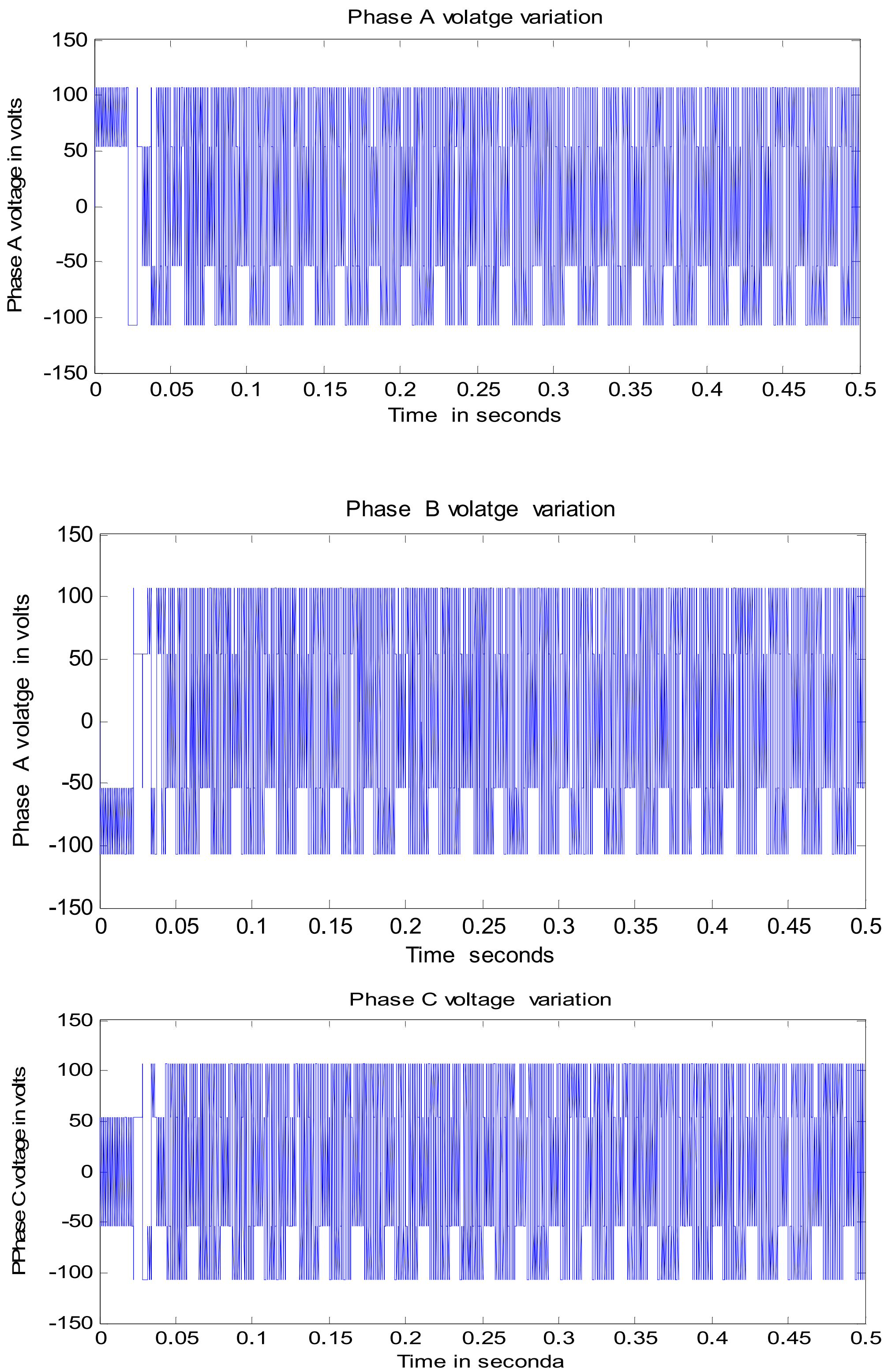



**Fig.6.6: Phase voltages variation of Motor**

## 6.2. Performance with FLC

The speed control performance achieved by using the fuzzy logic controller (described in chapter 4) is presented here. The type and characteristics of the FLC we have designed are as follows.

FLC Type=Mamdani.

Number of Inputs=2.

Num of outputs=1.

Num of Rules=49.

AND Method=min.

OR Method=max.

Defuzzification Method= height defuzzification

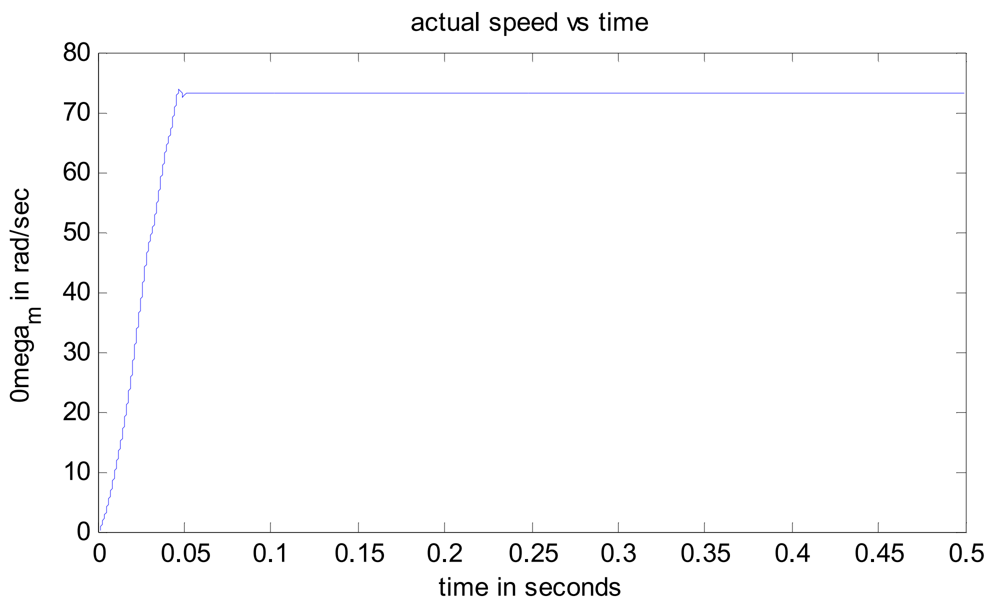



**Fig.6.7. Speed response radians /seconds versus time**

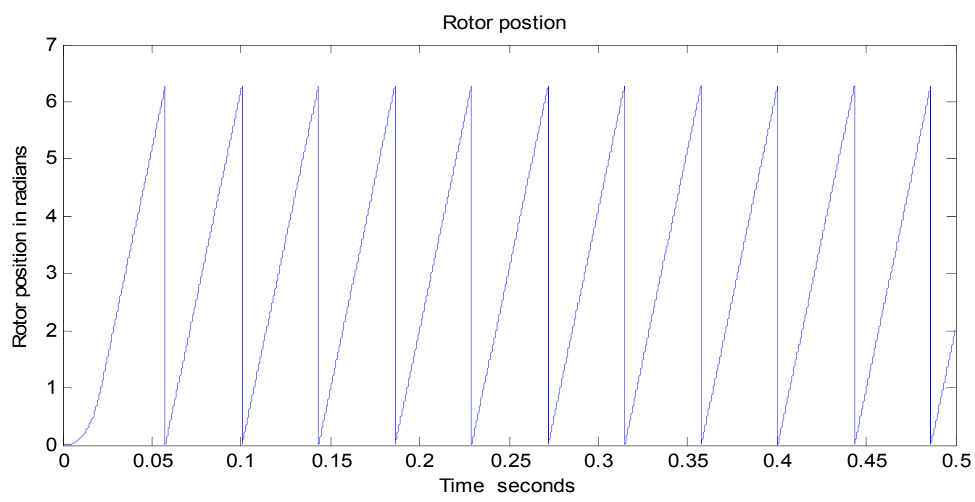



**Fig.6.8. Rotor position in radians versus time**

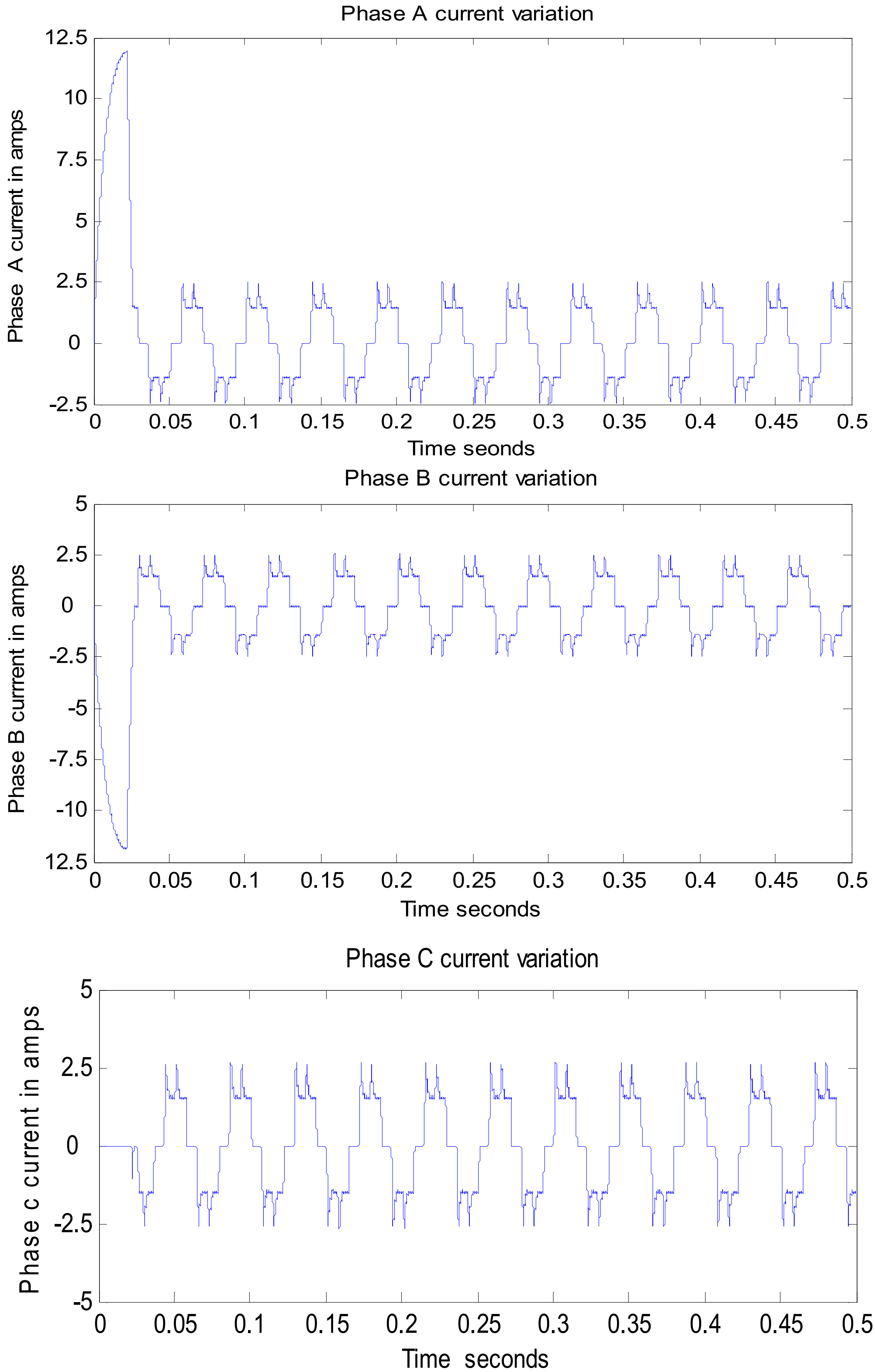



**Fig.6.9.Phase currents variation of motor**

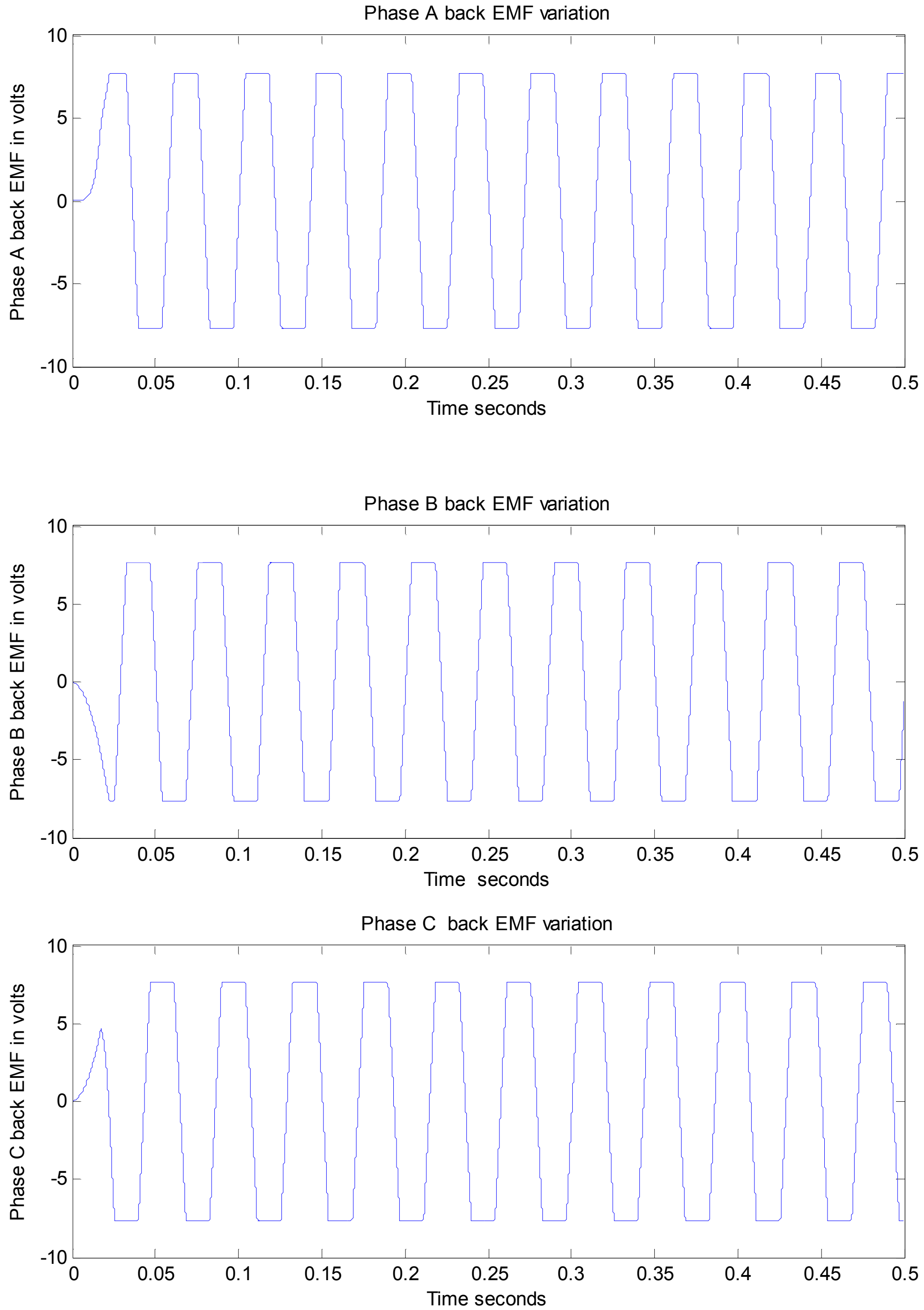



**Fig.6.10.Phase Back EMF s variation of Motor**

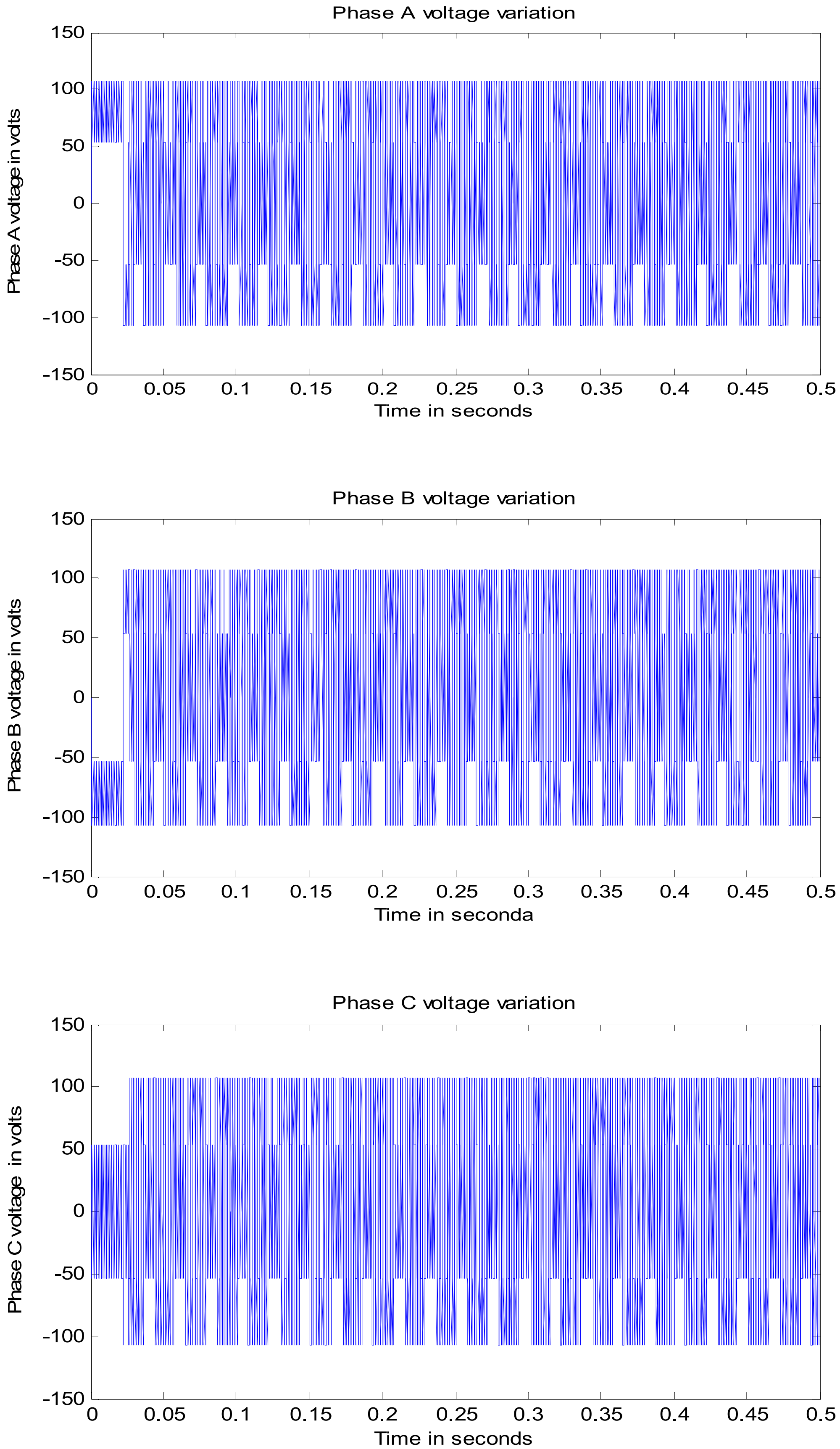



**Fig.6.11: Phase voltages variation of Motor**

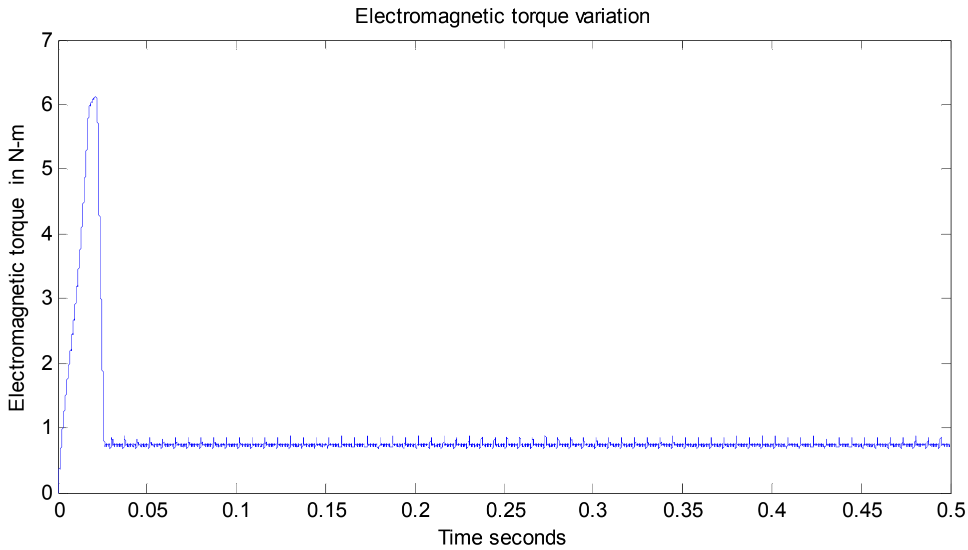
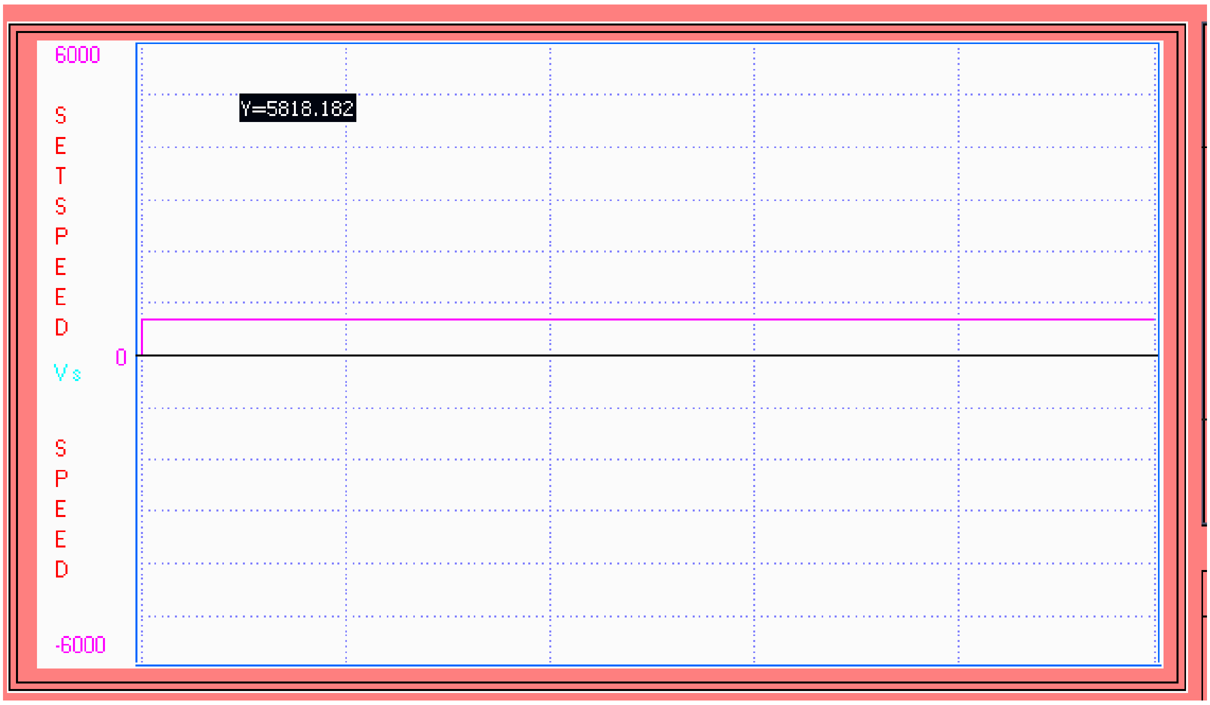



**Fig.6.12. Electromagnetic torque developed in N-m**

## 6.3. Experimental results

The experimental setup of speed control of brushless dc motor shown in Fig.5.1. The experimental and simulation results with a speed reference input of 700rpm with a load torque of 0.6 N-m .In experimental are shown in Fig 6.13 and Fig 6.14. The rotor is standstill at time zero with onset of the speed reference, the speed error, torque reference, and attains maximum value. The current is made to follow the reference by the current controller




**6.13. Speed response of machine obtained from experiment**

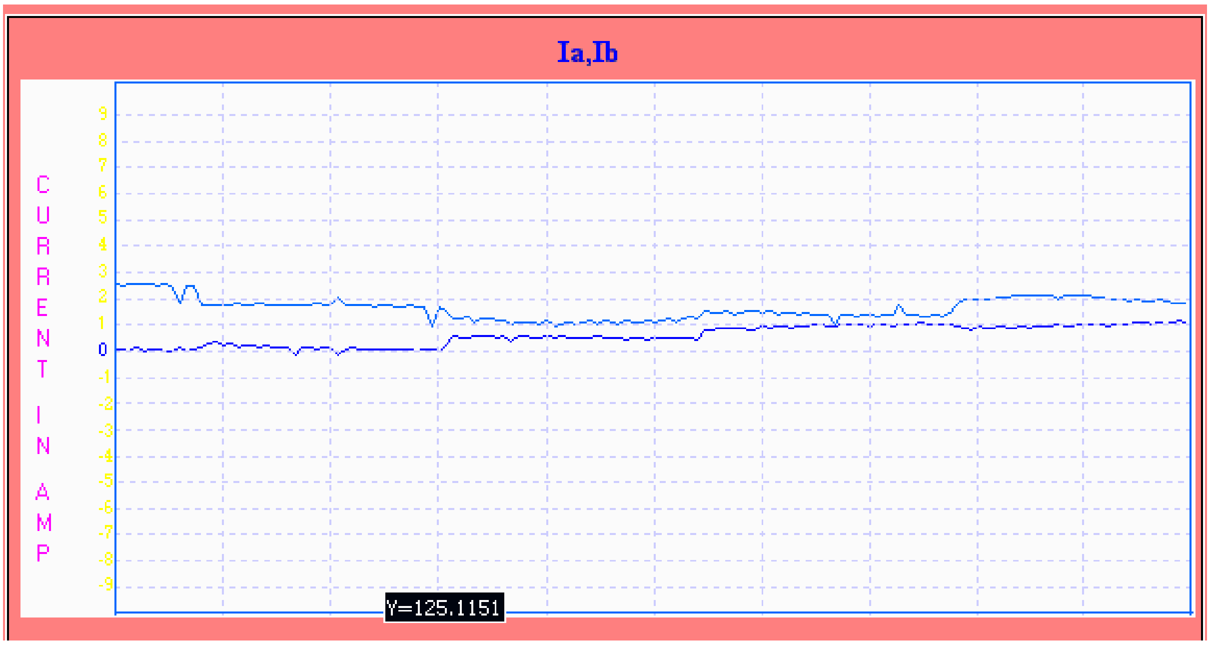



**Fig.6.14. Phase current response of machine obtained from experiment**

## 6.4. Discussions

The speed response of the BLDC drive system using and PI controller and fuzzy logic controller is shown in Fig.6.1 and Fig.6.8. With the motor at rest, the reference speed is set at 75rad/s (700rpm) with a settling time 0.05 seconds the motor speed reaches the reference speed with a percentage overshoot of 6.667 with PI speed controller. The phase currents at the time starting getting transient due to initial phase back emfs machine are zero. After the speed reaching reference speed, phase currents are reaches the reference current. Phase currents are conduction with 120 angle duration shown in Fig 6.4.

For FLC the motor speed reaches reference speed with settling time of 0.03 seconds, out any appreciable overshoot and zero steady state error in speed shown in Fig. 6.7. And phase currents are settling to steady state, when actual current reaches the reference current.

From the above shows the speed response of the BLDC drive with conventional PI controller response of the drive is slower than that of FLC speed controller. The former controller shows an overshoot in speed response, which is undesirable. The drive takes maximum permissible current to start the motor from standstill. The results prove that the response of the drive is faster with FLC controller than the conventional PI controller. Improved response in case of FLC controller is of immense help to industrial applications.

The speed response of the BLDC drives system using PI controller experimental results are shown in Fig 6.13, the reference speed is set at 700rpm with load torque of 0.6N-m.In experimental results machine speed response as reaches as 688 rpm. And the phase currents are shown in Fig 5.14.The currents are reaching reference current by the current controller. For comparing of experimental results with simulation results of PI controller are with percentage speed error of 1.71.

## 7.1. Conclusions

A fuzzy logic controller (FLC) has been employed for the speed control of PMBLDC motor drive and analysis of results of the performance of a fuzzy controller is presented. The modelings and simulation of the complete drive system is described in this thesis. Effectiveness of the model is established by performance prediction over a wide range of operating conditions. A performance comparison between the fuzzy logic controller and the conventional PI controller has been carried out by simulation runs confirming the validity and superiority of the fuzzy logic controller for implementing the fuzzy logic controller to be adjusted such that manual tuning time of the classical controller is significantly reduced. The performance of the PMBLDCM drive with reference to PI controller, FLC controller and experimental verified with conventional PI controller using DSP processor. Fuzzy logic speed controller improved the performance of PMBLDC Drive of the fuzzy logic speed controller.

## 7.2. Further work

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 linearzing control was proposed. By using integrator back stepping techniques, robust and adaptive controllers are proposed, respectively. 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 backstepping techniques, a hybrid integrator backstepping 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 BLCDM uncertain parameters are not required
- A semiglobal asymptotic stability result is obtained in the Lyapunov sense.

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