

# **Position Control of Permanent Magnet Brushless DC Motor using PID Controller**

*A Thesis*

*Submitted towards the partial fulfillment of  
the requirements for the award of degree of*

**Master of Engineering**

**in**

**Electronics Instrumentation and Control Engineering**

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## CERTIFICATE

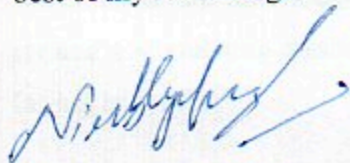
This is to certify that the work presented in this thesis entitled "Position Control of Permanent Magnet Brushless DC Motor using PID Controller" submitted in the partial fulfillment of the requirement for the award of the degree of Master of Engineering in Electronics Instrumentation and Control Engineering at Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Mr. Nirbhow Jap Singh, Assistant Professor and Mr. Vikram, Lecturer. The matter embodied in this thesis has not been submitted for the award of any other degree to any other university.

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## **Abstract**

Growing need of industry for higher productivity is placing new demands on mechanisms connected with electrical motors. This is leading to different problems in work operation due to fast dynamics and instability. The stability of the system is essential to work at desired set targets. The non-linear effects caused by a motor frequently reduce stability, which reduces the controller's ability to maintain speed or position at set points. Hence number of the industrial process applications requires position control of DC motor.

A brushless DC motor described as magnet being the rotor and its stationary windings forming the stator. This design provides many advantages over the brush DC motor. Brushless DC (BLDC) motor drives are becoming widely used in various consumer and industrial systems, such as servo motor drives, home appliances, computer peripherals, and automotive applications in recent years because of their high efficiency, silent operation, compact form, reliability, and low maintenance.

The aim of the thesis is to design a simulation model of Permanent Magnet Brushless DC (PMBLDC) motor and to control its position. In the developed model, the characteristics of the speed, torque, back EMF, voltages as well as currents are effectively monitored and analyzed. The PID controller is used to control the position of a Permanent magnet brushless DC motor by changing the current flow to control the average voltage and thereby the average current. Most useful application is in controlling of CNC machines.

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## List of Abbreviations

PMBLDC	Permanent Magnet Brushless DC
BLDC	Brushless DC
DC	Direct Current
V	Voltage
$V_a, V_b, V_c$	Phase Voltage
I	Current
$I_a, I_b, I_c$	Phase Current
$\theta$	Rotor Position
EMF	Electromotive Force
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
AC	Alternating Current
N	North
S	South
Nd	Neodymium
SmCo	Samarium Cobalt
NdFeB	Neodymium Ferrite and Boron
$T_e$	Generated Torque
$T_l$	Load Torque
$T_p$	Peak Torque

Tr	Rated Torque
Ls	Self Inductance of the winding
$K_e$	Back EMF constant
$K_t$	Torque constant
J	Moment of Inertia
B	Motor Damping Constant
R	Winding resistance
EMI	Electromagnetic Interference
CNC	Computer Numeric Controlled
PMAC	Permanent Magnet Alternating Current
PMSM	Permanent Magnet Synchronous Motor
PID	Proportional Integral Derivative
P	Proportional
I	Integral
D	Derivative
MV	Manipulated variable

## **CHAPTER-1**

### **INTRODUCTION**

#### **1.1 Introduction**

The economic constraints and new standards legislated by governments place increasingly higher requirements on electrical systems. New generations of equipment must have higher performance parameters such as better efficiency and reduced electromagnetic interference. System flexibility must be high to facilitate market modifications and to reduce development time. All these improvements must be achieved while, at the same time, decreasing system cost. Brushless motor technology makes it possible to achieve these specifications. Such motors combine high reliability with high efficiency, and for a lower cost in comparison with brush motors. The Brushless DC Motor (BLDC) motor is conventionally defined as a permanent magnet synchronous motor with a trapezoidal back Electro Motive Force (EMF) waveform shape.

A system based on the Direct Current (DC) motor provides a good, simple and efficient solution to satisfy the requirements of a variable speed drive. Although DC motors possess good control characteristics and ruggedness, their performance and applications in wider areas is inhibited due to sparking and commutation problems. Induction motor do not possess the above mentioned problems, they have their own limitations such as low power factor and non-linear speed torque characteristics. With the advancement of technology and development of modern control techniques, the Permanent Magnet Brushless DC (PMBLDC) motor is able to overcome the limitations mentioned above and satisfy the requirements of a variable speed drive.

Electric motors influence almost every aspect of modern living. Refrigerators, vacuum cleaners, air conditioners, fans, computer hard drives, automatic car windows, and multitudes of other appliances and devices use electric motors to convert electrical energy into useful mechanical energy. In addition to running the common place appliances that we use every day, electric motors are also responsible for a very large portion of industrial processes.

## 1.2 Permanent Magnet Brushless DC Motor

Conventional DC motors are highly efficient and their characteristics make them suitable for use as servomotors [1, 12]. However, their only drawback is that they need a commutator and brushes which are subject to wear and require maintenance. When the functions of commutator and brushes were implemented by solid-state switches, maintenance free motors were realized. These motors are now known as brushless DC motors. The construction of modern brushless motors is very similar to the AC motor, known as the permanent magnet synchronous motor. The stator windings are similar to those in a poly-phase ac motor, and the rotor is composed of one or more permanent magnets. 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 in Fig.1.1. The most common position/pole sensor is the Hall element, but some motors use optical sensors.

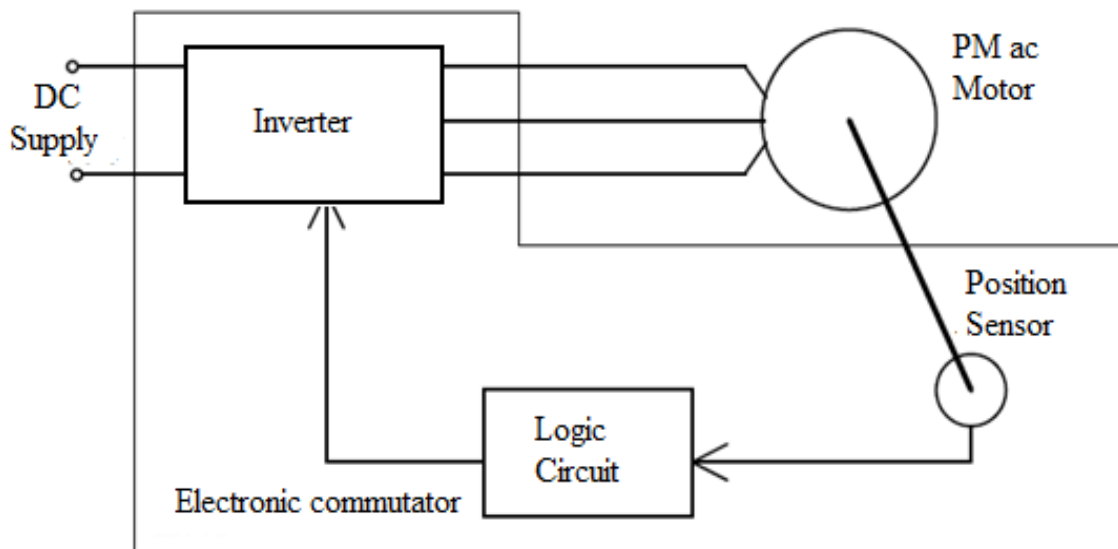


Figure1.1 Permanent Magnet Brushless DC motor

The brushless DC motor is essentially configured as a permanent magnet rotating part a set of current carrying conductors. In this respect, it is equivalent to an inverted DC

commutator motor, in that the magnet rotates while the conductors remain stationary. In both cases, the current must reverse polarity every time a magnet pole passes by, in order that the torque is unidirectional. In the DC commutator motor, the commutator and brushes perform the polarity reversal.

Brushless DC motors usually come in fixed voltage types, such as 5V, 6V, 12V, 24V, 48Vetc, with one of the most common ones in use being the 12V type. When the rated voltage is applied to the motor it will rotate with maximum speed, but by changing this applied voltage the motor speed can be controlled. Naturally, the voltage is higher and then speed is higher and vice versa

In the brushless DC motor, the polarity reversal is performed by power MOSFETS, which must be switched in synchronism with the rotor position. The brushless DC motors are generally controlled using a three-phase inverter, requiring a rotor position sensor for starting and for providing the proper commutation sequence to control the inverter. These position sensors can be Hall sensors, resolvers, or absolute position sensors. Those sensors will increase the cost and the size of the motor, and a special mechanical arrangement needs to be made for mounting the sensors. These sensors, particularly Hall sensors, are temperature sensitive, limiting the operation of the motor to below about 75 degree.

Brushless DC motors usually consist of three main parts:

- Stator
- Rotor
- Hall Sensors.

All the above main parts are mentioned below in short for the understanding of the subject in context of this thesis work.

### 1.2.1 Stator

The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery [13]. Traditionally, the stator resembles that of an induction motor; however, the windings are distributed in a different manner. Most BLDC motors have three stator windings connected in star fashion. Each of these windings is constructed with numerous coils interconnected to form a winding. One or more coils are placed in the slots and they are interconnected to make a winding. Each of these windings is distributed over the stator periphery to form an even numbers of poles.

There are two types of stator windings variants: trapezoidal and sinusoidal motors. This differentiation is made on the basis of the interconnection of coils in the stator windings to give the different types of back Electromotive Force (EMF). As their names indicate, the trapezoidal motor gives a back EMF in trapezoidal fashion and the sinusoidal motor's back EMF is sinusoidal. In addition to the back EMF, the phase current also has trapezoidal and sinusoidal variations in the respective types of motor. This makes the torque output by a sinusoidal motor smoother than that of a trapezoidal motor. However, this comes with an extra cost, as the sinusoidal motors take extra winding interconnections because of the coils distribution on the stator periphery, thereby increasing the copper intake by the stator windings.

Depending upon the control power supply capability, the motor with the correct voltage rating of the stator can be chosen. Forty-eight volts, or less voltage rated motors are used in automotive, robotics, small arm movements and so on. Motors with 100 volts, or higher ratings, are used in appliances, automation and in industrial applications.

Figure 1.2 below shows the electrical schematic of the stator. It consists of three coils each including three elements in series, an inductance, a resistance and one back electromotive force.

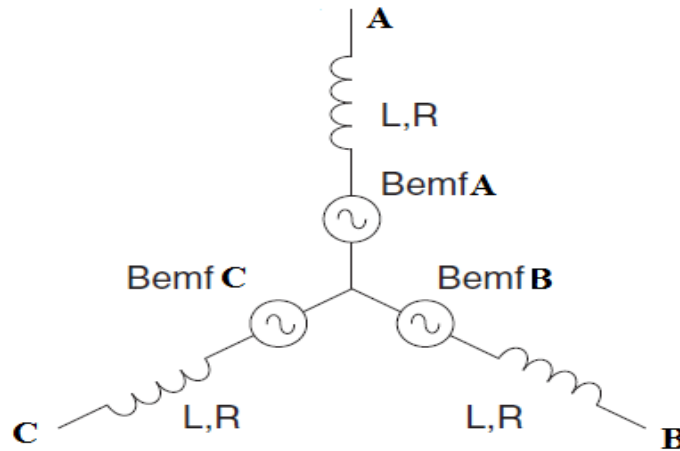


Figure 1.2: Stator Electrical Configuration (Three phases, three coils)

### 1.2.2 Rotor

The rotor is made of permanent magnet and can vary from two to eight pole pairs with alternate North (N) and South (S) poles. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are traditionally used to make permanent magnets. As the technology advances, rare earth alloy magnets are gaining popularity. The ferrite magnets are less expensive but they have the disadvantage of low flux density for a given volume. In contrast, the alloy material has high magnetic density per volume and enables the rotor to compress further for the same torque. Also, these alloy magnets improve the size-to-weight ratio and give higher torque for the same size motor using ferrite magnets.

Neodymium (Nd), Samarium Cobalt (SmCo) and the alloy of Neodymium, Ferrite and Boron (NdFeB) are some examples of rare earth alloy magnets. Continuous research is going on to improve the flux density to compress the rotor further. The rotor magnet comes in different cross section

- Circular core with magnets on the periphery
- Circular core with rectangular magnets embedded in the rotor
- Circular core with rectangular magnets inserted into the rotor core

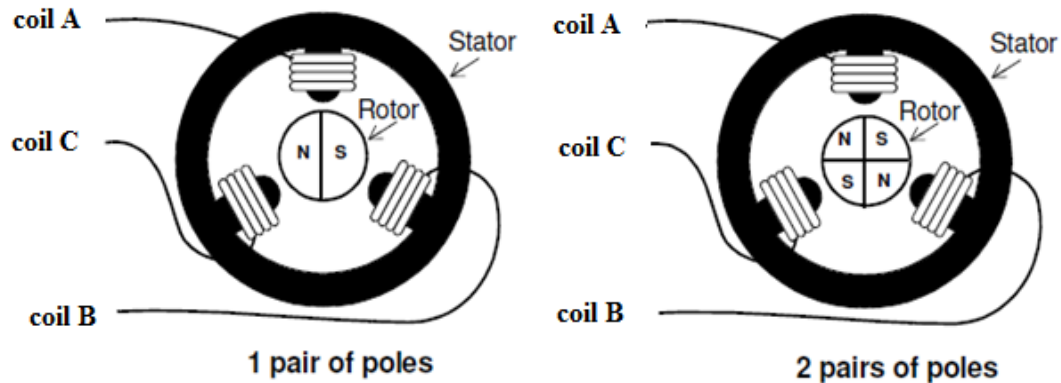


Figure 1.3: Three phase three coil BLDC motor stator and rotor

### 1.2.3 Hall Sensor

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall effect sensors embedded into the stator [13]. Most BLDC motors have three Hall sensors embedded into the stator on the non-driving end of the motor. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.

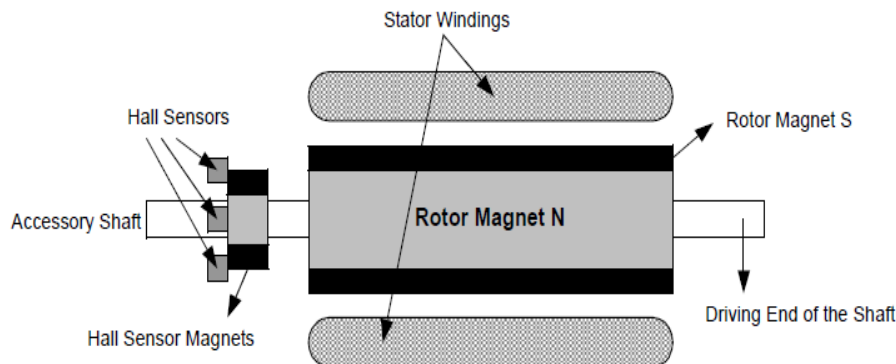


Figure 1.4: Transverse Section of BLDC

Figure 1.4 above shows a transverse section of a BLDC motor with a rotor that has alternate N and S permanent magnets. Hall sensors are embedded into the stationary part of the motor. Embedding the Hall sensors into the stator is a complex process because any misalignment in these Hall sensors, with respect to the rotor magnets, will generate an error in determination of the rotor position. To simplify the process of mounting the Hall sensors onto the stator, some motors may have the Hall sensor magnets on the rotor, in addition to the main rotor magnets. These are a scaled down replica version of the rotor. Therefore, whenever the rotor rotates, the Hall sensor magnets give the same effect as the main magnets. The Hall sensors are normally mounted on a PC board and fixed to the enclosure cap on the non-driving end. This enables users to adjust the complete assembly of Hall sensors, to align with the rotor magnets; in order to achieve the best. Based on the physical position of the Hall sensors, there are two versions of output. The Hall sensors may be at 60° or 120° phase shift to each other. Based on this, the motor manufacturer defines the commutation sequence, which should be followed when controlling the motor performance.

BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are:

- Better speed versus torque characteristics
- High dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges
- Compact size
- Low moment of inertia
- High torque to volume ratio

Due to above advantages, BLDC motors are used in variety of applications. Few of the applications are in computers, CNC machines etc.

### 1.3 Theory of operation of PMSM Motor

Each commutation sequence has one of the windings energized to positive power (current enters into the winding), the second winding is negative (current exits the winding) and the third is in a non-energized condition. Torque is produced because of the interaction between the magnetic field generated by the stator coils and the permanent magnets. Ideally, the peak torque occurs when these two fields are at  $90^\circ$  to each other and falls off as the fields move together. In order to keep the motor running, the magnetic field produced by the windings should shift position, as the rotor moves to catch up with the stator field.

### 1.4 Torque/Speed Characteristics

Figure 1.5 shows an example of torque/speed characteristics. There are two torque parameters used to define a BLDC motor, peak torque ( $T_p$ ) and rated torque ( $T_r$ ). During continuous operations, the motor can be loaded up to the rated torque. In a BLDC motor, the torque remains constant for a speed range up to the rated speed [13]. The motor can be run up to the maximum speed, which can be up to 150% of the rated speed, but the torque starts dropping. Applications that have frequent starts and stops and frequent reversals of rotation with load on the motor, demand more torque than the rated torque. This requirement comes for a brief period, especially when the motor starts from a standstill and during acceleration. During this period, extra torque is required to overcome the inertia of the load and the rotor itself. The motor can deliver a higher torque, maximum up to peak torque, as long as it follows the speed torque curve. Because the rotor is made of permanent magnets, the rotor inertia is less, compared with other types of motors. This improves acceleration and deceleration characteristics, shortening operating cycles. Their linear speed/torque characteristics produce predictable speed regulation. With brushless motors, brush inspection is eliminated, making them ideal for limited access areas and applications where servicing is difficult. BLDC motors operate much more quietly than brushed DC motors, reducing Electromagnetic Interference (EMI). Low-voltage models are ideal for battery operation, portable equipment or

medical applications. This linear torque/speed characteristic causes brushless DC motor used in various numerous applications.

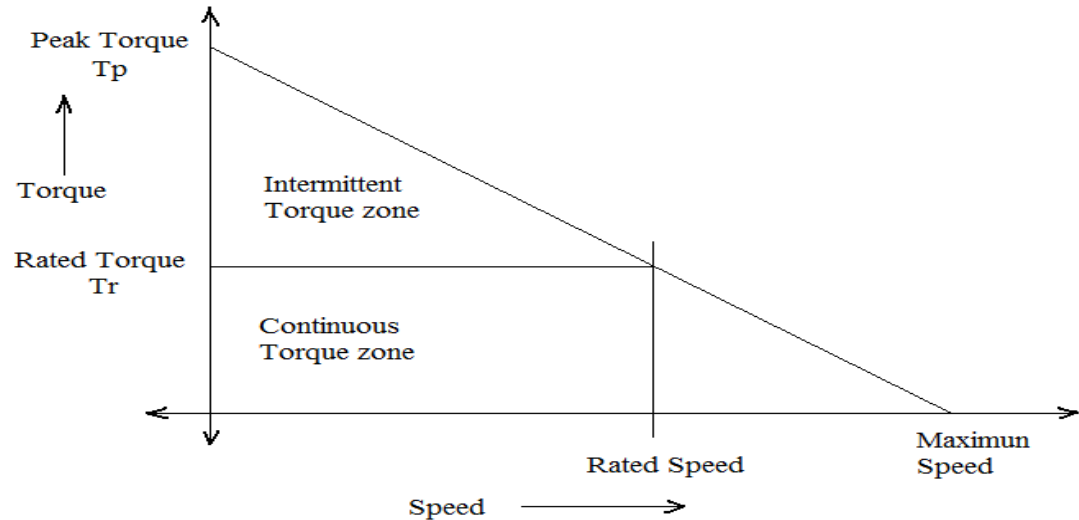


Figure 1.5: Torque Vs Speed Characteristic of BLDC Motor

## 1.5 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. 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 resolvers 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. Process controls, machinery controls and conveyer controls have plenty of applications in this category.

## **1.6 Literature Survey**

T.J.E. Miller [1] introduced the permanent magnet materials and characteristics, B-H loop and demagnetization characteristics, applications of permanent magnets in motors. He discussed the square wave permanent brushless motor, sine wave permanent magnet brushless motor and their torque, e.m.f equations and torque/speed characteristics.

A Kusko and S.M. Peeran [2] presented definitions of a brushless DC motor are inadequate to distinguish it from other types of brushless motors in the industry. A formal definition of a brushless DC motor is described. The definition includes the components of the motor and the types of circuits to energize the stator windings.

M.A.Jabbar, M.A.Rahman [3] discussed the design considerations for permanent-magnet motors intended for brushless operation. Two rotor configurations are described - the imprecated rotor and the segmented rotor. The segmented rotor is designed especially for high speed operation. A brushless DC drive system is also described an the performance of a neodymium-iron-boron excited p.m. motor with an imprecated rotor in a BLDC drive is presented.

A new simulation model of the BLDC motor with nearly real back EMF waveform is proposed by the Jeon, Y.S., Mok, H.S [4]. The torque characteristic of a BLDC motor is a very important factor in the design of the motor drive system, so it is necessary to predict the precise value of torque, which is determined by the back EMF waveform.. The real back EMF waveform is to some degree deviant from the ideal trapezoidal waveform. As a result, when using the ideal trapezoidal waveform, the error occurs. As a consequence, in order to lessen such an error, the model of the BLDC motor with a real back EMF waveform is needed instead of its approximation model.

Byoung-Hee Kang, choel-Ju kim, Hyung-Su Mok [5] described about the reduction of torque ripple which is the main drawback of the brushless DC motor. Torque ripple reduction was considered at the point of current control, which means that if current can be controlled properly, the BLDC motor does not produce any torque ripple. That torque

ripple in the commutation period of a BLDC motor is inevitable, even if the current control is successful.

An advanced simulation model for brushless DC (BLDC) motor drives using Matlab is presented by the Byoung-kuk lee & Mehrdad Ehsani [6]. In the developed model, the dynamic characteristics of speed and torque as well as voltages and currents of pwm inverter components can be effectively monitored and analyzed. The developed simulation model can be an easy-to-design tool for the development of BLDC motor drives including control algorithms and topological variations with reduced computation time and memory size.

Mehdi Nasri, Hossein Nezamabadi-pour, and Malihe Maghfoori [7] presents a particle swarm optimization (PSO) method for determining the optimal proportional-integral derivative (PID) controller parameters, for speed control of a linear brushless DC motor. The proposed approach has superior features, including easy implementation, stable convergence characteristic and good computational efficiency. The brushless DC motor is modelled in Simulink and the PSO algorithm is implemented in MATLAB. Comparing with Genetic Algorithm (GA) and Linear quadratic regulator (LQR) method, the proposed method was more efficient in improving the step response characteristics such as, reducing the steady-states error; rise time, settling time and maximum overshoot in speed control of a linear brushless DC motor.

N. Muruganatham & Dr. S Palani [8] proposed the state space modeling and simulation of sensorless permanent magnet BLDC motor. In this, Brushless DC (BLDC) motor simulation are simply implemented with the required control scheme using specialized simulink built-in tools and block sets such as simpower systems toolbox. By taking reading of the instantaneous position of the rotor as an output, different variables of the motor are controlled without the need of any external sensors or position detection techniques. Simulink is utilized with the assistance of MATLAB to give a very flexible and reliable simulation. With state space model representation, the motor performance can be analyzed for variation of motor parameters.

The position control of four switch three phase BLDC motor using PWM control, in which direct current controlled PWM method for control of four-switch, three phase BLDC motor was presented by D.D.Dhawale, J.G.Chaudhari & Dr.M.V.Aware [9]. The main features of this converter are twofold: the first is the reduction of switches and freewheeling diode count; the second is the reduction of conduction losses. For effective utilization of the developed system, a novel direct current controlled pwm scheme is designed and implemented to produce the desired dynamic and static speed–torque characteristics.

The method of measuring rotor position using analog Hall effect sensors to measure the magnetic field of the rotor magnets to create an absolute position measurement of the electrical cycle, which can be used efficiently to create a computationally simple motor control scheme introduced by Alex Simpkins and Emanuel Todorov [10]. However, ripple-free precision control of brushless motors requires precision position measurement. It can be difficult to mount encoders directly to the shafts of these motors, and for precision position control, a sensorless configuration may be inappropriate. The Hall effect sensors are mounted directly to the motor and are highly compact, have high bandwidth, are extremely low cost, and have high precision, providing position measurements with insignificant increases to motor size.

The hybridization between two optimization methods that are Genetic Algorithm (GA) and Artificial Immune System (AIS) is presented for determining the optimal proportional-integral derivative (PID) controller parameters, for speed control of a linear brushless DC motor presented by Mohammed Obaid Ali, S. P. Koh & K. H. Chong [11]. The brushless DC motor is modeled in Simulink and the Hybrid GA-AIS algorithm is implemented in MATLAB. The capability of overcoming the shortcomings of individual algorithms without losing their advantages makes the hybrid techniques superior to the stand-alone ones based on the dominant purpose of hybridization. The Hybrid GA-AIS method has superior features, stable convergence characteristic and good computational efficiency. The results that get it from hybridization are improved compares with that results can get from GA and AIS alone.

## **1.7 Objective of the Thesis**

In modern electrical machines industry productions the brushless direct current (BLDC) motors are rapidly gaining popularity. BLDC motors are used in industries such as Appliances, HVAC industry, medical, electric traction, road vehicles, aircrafts, military equipment, hard disk drive.

Motivated by these observations, the objective of this thesis is:

- Modeling and analysis of the PMSM motor.
- Implementation of mathematical model in MATLAB/SIMULINK.
- Controlling the position of the PMSM motor using PID controller.

## **1.8 Organization of the Thesis**

The present thesis is organized in five chapters. Some of these chapters are based on developments from former chapters, but in general, all of them can be read independently as self contained entities.

Chapter 2 covers the mathematical modeling of the brushless DC motor.

Chapter 3 covers the concept of the position control, the PID controller and its tuning method.

Chapter 4 presents the simulation results of PMSM motor for position control.

Chapter 5 covers conclusion and suggestions for future work.

## CHAPTER-2

### MATHEMATICAL MODELLING

#### 2.1 Introduction

Brushless DC Motors are permanent magnet motors where the function of commutator and brushes were implemented by solid state switches. BLDC motors come in single-phase, 2-phase and 3-phase configurations. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motors are the most popular and widely used. Because of the special structure of the motor, it produces a trapezoidal back electromotive force (EMF) and motor current generate a pulsating torque.

#### 2.2 Mathematical Modeling of Brushless DC Motor

A three phase BLDC motor equation can be represented as

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + M_{ab} \frac{di_b}{dt} + M_{ac} \frac{di_c}{dt} + e_a \quad (2.1)$$

$$v_b = R_b i_b + L_b \frac{di_b}{dt} + M_{ba} \frac{di_a}{dt} + M_{bc} \frac{di_c}{dt} + e_b \quad (2.2)$$

$$v_c = R_c i_c + L_c \frac{di_c}{dt} + M_{ca} \frac{di_a}{dt} + M_{cb} \frac{di_b}{dt} + e_c \quad (2.3)$$

$R$  : Stator resistance per phase, assumed to be equal for all phases

$L$  : Stator inductance per phase, assumed to be equal for all phases.

$M$  : Mutual inductance between the phases.

$i_a, i_b, i_c$ : Stator current/phase.

$V_a, V_b, V_c$ : are the respective phase voltage of the winding

The stator self inductances are independent of the rotor position, hence:

$$L_a = L_b = L_c = L$$

And the mutual inductances will have the form:

$$M_{ab} = M_{ac} = M_{ba} = M_{bc} = M_{ca} = M_{cb} = M$$

Assuming three phase balanced system, all the phase resistances are equal:

$$R_a = R_b = R_c = R$$

Rearranging the above equations

$$v_a = Ri_a + L \frac{di_a}{dt} + M \frac{di_b}{dt} + M \frac{di_c}{dt} + e_a \quad (2.4)$$

$$v_b = Ri_b + L \frac{di_b}{dt} + M \frac{di_a}{dt} + M \frac{di_c}{dt} + e_b \quad (2.5)$$

$$v_c = Ri_c + L \frac{di_c}{dt} + M \frac{di_a}{dt} + M \frac{di_b}{dt} + e_c \quad (2.6)$$

Neglecting mutual inductance

$$v_a = Ri_a + L \frac{di_a}{dt} + e_a \quad (2.7)$$

$$v_b = Ri_b + L \frac{di_b}{dt} + e_b \quad (2.8)$$

$$v_c = Ri_c + L \frac{di_c}{dt} + e_c \quad (2.9)$$

### 2.3 Trapezoidal Back EMF

When a BLDC motor rotates, each winding generates a voltage known as back Electromotive Force or back EMF, which opposes the main voltage supplied to the windings according to Lenz's Law [13]. The polarity of this back EMF is in opposite direction of the energized voltage. Back EMF depends mainly on three factors:

- Angular velocity of the rotor
- Magnetic field generated by rotor magnets
- The number of turns in the stator windings

Once the motor is designed, the rotor magnetic field and the number of turns in the stator windings remain constant. The only factor that governs back EMF is the angular velocity or speed of the rotor and as the speed increases, back EMF also increases. The potential difference across a winding can be calculated by subtracting the back EMF value from the supply voltage. The motors are designed with a back EMF constant in such a way that when the motor is running at the rated speed, the potential difference between the back EMF and the supply voltage will be sufficient for the motor to draw the rated current and deliver the rated torque. If the motor is driven beyond the rated speed, back EMF may increase substantially, thus decreasing the potential difference across the winding, reducing the current drawn which results in a drooping torque curve.

In general, Permanent Magnet Alternating current (PMAC) motors are categorized into two types. The first type of motor is referred to as PM synchronous motor (PMSM). These produce sinusoidal back EMF and should be supplied with sinusoidal current / voltage. The second type of PMAC has trapezoidal back EMF and is referred to as the Brushless DC (BLDC) motor. The BLDC motor requires that quasi-rectangular shaped currents are to be fed to the machine.

When a brushless dc motor rotates, each winding generates a voltage known as electromotive force or back EMF, which opposes the main voltage supplied to the windings. The polarity of the back EMF is opposite to the energized voltage. The stator has three phase windings, and each winding is displaced by 120 degree.

The windings are distributed so as to produce trapezoidal back EMF. The principle of the PMBLDC motor is to energize the phase pairs that produce constant torque. The three phase currents are controlled to take a quasi-square waveform in order to synchronize with the trapezoidal back EMF to produce the constant torque. The back EMF is a function of rotor position ( $\theta$ ) and has the amplitude  $E = K_e \cdot \omega$  ( $K_e$  is the back EMF constant).

The instantaneous back EMF in BLDC is written as:

$$e_a = f_a(\theta)K_e\omega(2.10)$$

$$e_b = f_b(\theta) K_e \omega \quad (2.11)$$

$$e_c = f_c(\theta) K_e \omega \quad (2.12)$$

Where, “ $\omega$ ” is the rotor mechanical speed and “ $\theta$ ” is the rotor electrical position,

The modeling of the back EMF is performed under the assumption that all three phases have identical back EMF waveforms. Based on the rotor position, the numerical expression of the back EMF can be obtained. Therefore, with the speed command and rotor position, the symmetric three-phase back EMF waveforms can be generated at every operating speed.

The respective back EMF in the windings is represented by the equation (2.13), (2.14), (2.15).

$$e_a = \begin{cases} (6E / \pi)\theta & (0 < \theta < \pi / 6) \\ E & (\pi / 6 < \theta < 5\pi / 6) \\ -(6E / \pi)\theta + 6E & (5\pi / 6 < \theta < 7\pi / 6) \\ -E & (7\pi / 6 < \theta < 11\pi / 6) \\ (6E / \pi)\theta - 12E & (11\pi / 6 < \theta < 2\pi) \end{cases} \quad (2.13)$$

$$e_b = \begin{cases} -E & (0 < \theta < \pi / 2) \\ (6E / \pi)\theta - 4E & (\pi / 2 < \theta < 5\pi / 6) \\ E & (5\pi / 6 < \theta < 9\pi / 6) \\ -(6E / \pi)\theta + 10E & (9\pi / 6 < \theta < 11\pi / 6) \\ E & (11\pi / 6 < \theta < 2\pi) \end{cases} \quad (2.14)$$

$$e_c = \begin{cases} E & (0 < \theta < \pi / 6) \\ -(6E / \pi)\theta + 2E & (\pi / 6 < \theta < \pi / 2) \\ -E & (\pi / 2 < \theta < 7\pi / 6) \\ (6E / \pi)\theta - 8E & (7\pi / 6 < \theta < 9\pi / 6) \\ E & (9\pi / 6 < \theta < 2\pi) \end{cases} \quad (2.15)$$

By putting  $E=1$  in the above back EMF equations a back EMF function is obtained. The back EMF function is a function of the rotor position which is represented as  $f_a(\theta), f_b(\theta)$  &  $f_c(\theta)$  with limit values between -1 & 1 is defined as

$$f_a(\theta) = \begin{cases} (6/\pi)\theta & (0 < \theta < \pi/6) \\ 1 & (\pi/6 < \theta < 5\pi/6) \\ -(6/\pi)\theta + 6 & (5\pi/6 < \theta < 7\pi/6) \\ -1 & (7\pi/6 < \theta < 11\pi/6) \\ (6/\pi)\theta - 12 & (11\pi/6 < \theta < 2\pi) \end{cases} \quad (2.16)$$

$$f_b(\theta) = \begin{cases} -1 & (0 < \theta < \pi/2) \\ (6/\pi)\theta - 4 & (\pi/2 < \theta < 5\pi/6) \\ 1 & (5\pi/6 < \theta < 9\pi/6) \\ -(6/\pi)\theta + 10 & (9\pi/6 < \theta < 11\pi/6) \\ 1 & (11\pi/6 < \theta < 2\pi) \end{cases} \quad (2.17)$$

$$f_c(\theta) = \begin{cases} 1 & (0 < \theta < \pi/6) \\ -(6/\pi)\theta + 2 & (\pi/6 < \theta < \pi/2) \\ -1 & (\pi/2 < \theta < 7\pi/6) \\ (6/\pi)\theta - 8 & (7\pi/6 < \theta < 9\pi/6) \\ 1 & (9\pi/6 < \theta < 2\pi) \end{cases} \quad (2.18)$$

The induced EMFs do not have sharp corners, but rounded edges.

The quasi-square trapezoidal back EMF waveform and the phase current of the PMBLDC motor with respect to the rotor position is shown in the figure 2.1. The graph is presented for one complete cycle rotation of 360 degrees.

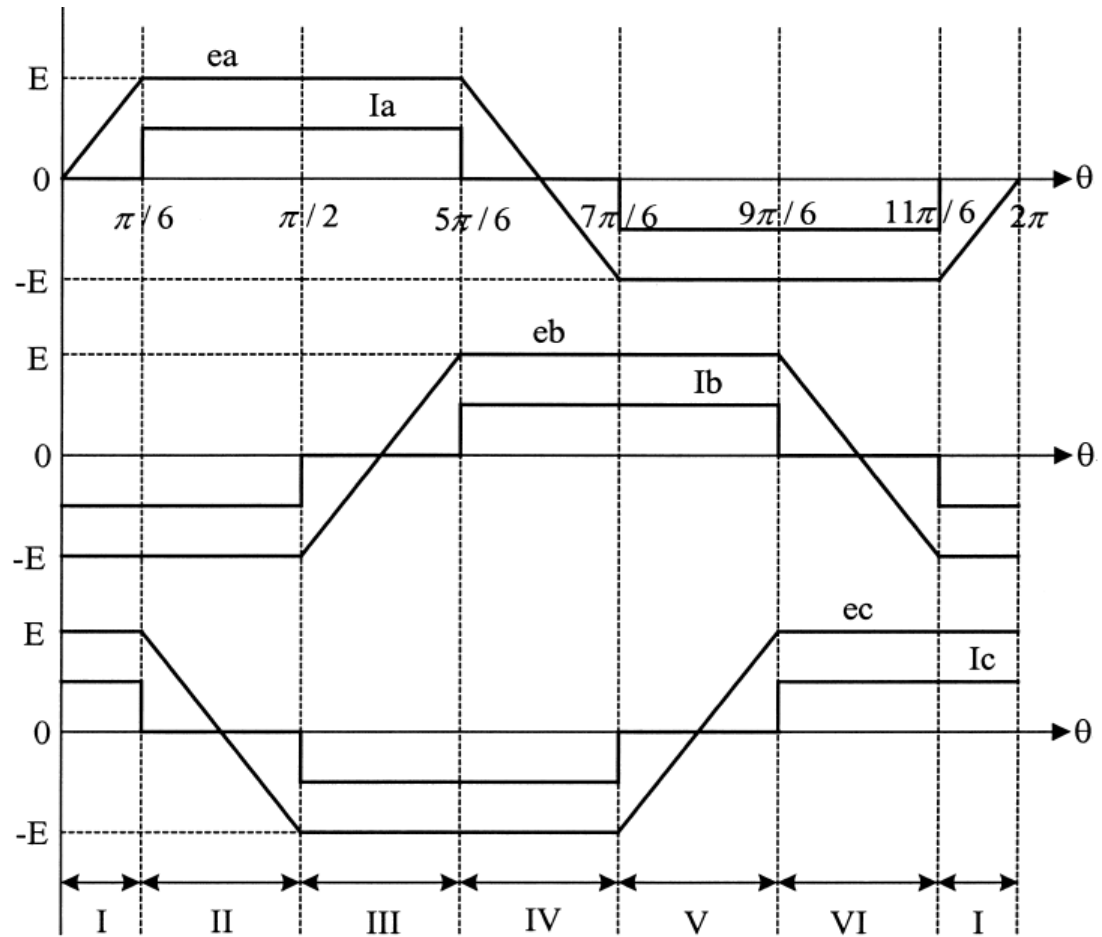


Figure 2.1: Back EMF and phase current waveforms of BLDC Motor

## 2.4 Torque Generation

The Torque is the product of the theoretical motor constant ‘ $K_t$ ’ the supplied current’  $I$ ’. In a single pole system, usable torque is only produced for 1/3 of the rotation. To produce useful torque throughout the rotation of the stator, additional coils, or “phases” are added to the fixed stator. The developed torque by each phase is the product of the motor constant ‘ $k_t$ ’ and the current ‘ $I$ ’.

The sum of the torques is

$$T_a + T_b + T_c$$

Assumption made is all the phases are perfect symmetry

$$K_{t(motor)} = K_{t(a)} = K_{t(b)} = K_{t(c)}$$

$$i_{motor} = i_a = i_b = i_c$$

At any given angle  $\theta$ , the applied torque as measured on the rotor shaft is

$$T_{motor} = 2 * K_{t(motor)} * i_{motor} \quad (2.19)$$

The key to effective torque and speed control of a BLDC motor is based on relatively simple torque and back EMF equations, which are similar to those of the DC motor. The generated electromagnetic torque is given by

$$T_e = [ e_a i_a + e_b i_b + e_c i_c ] / \omega \quad (\text{in N.m}) \quad (2.20)$$

The electromagnetic torque is also related with motor constant and the product of the current with the electrical rotor position which is given as

$$T_e = K_t \{ f_a(\theta) i_a + f_b(\theta) i_b + f_c(\theta) i_c \} \quad (2.21)$$

The equation of motion for simple system is,

$$J(d\omega/dt) + B\omega = T_e - T_l \quad (2.22)$$

Where,

$T_l$  is the load torque,  $J$  is motor inertia,  $B$  is damping constant.

The relation between angular velocity and angular position (electrical) is given by

$$d\theta/dt = (P/2) * \omega \quad (2.23)$$

Where,  $P$  is numbers of Poles,

The simulink diagram based on the mathematical equations as described above is designed in MATLAB/SIMULINK as shown in the figure 2.2. The matlab function block in the figure is described the back EMF function. The equations of back EMF function is to be fed into “S-Function Block” in Matlab Simulink which passes the program written in M-file to the Matlab workspace.

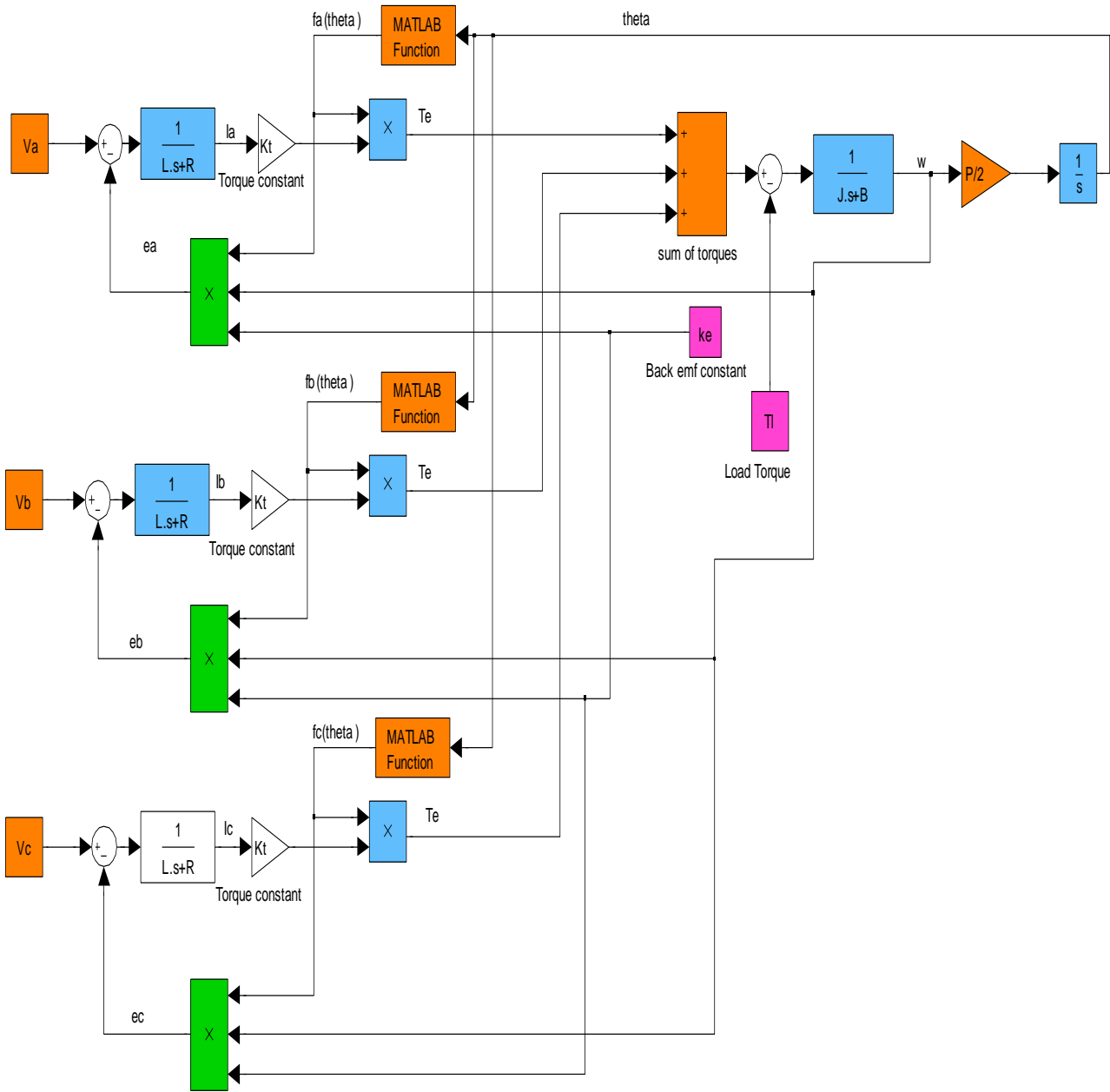


Figure 2.2: Mathematical Model Representation of BLDC Motor

## **CHAPTER-3**

### **POSITION CONTROL**

#### **3.1 Introduction**

In most of the industrial processes like electrical, mechanical, construction, petroleum industry, iron & steel industry, power sectors, development sites, paper industry, beverages industry the need for higher productivity is placing new demands on mechanisms connected with electrical motors. They lead to different problems in work operation due to fast dynamics and instability. That is why control is needed by the system to achieve stability and to work at desired set targets. The position control of electrical motors is most important due to various non linear effects like load and disturbance that affects the motor to deviate from its normal operation. The position control of the motor is to be widely implemented in machine automation.

The position of the motor is the rotation of the motor shaft or the degree of the rotation which is to be controlled by giving the feedback to the controller which rectifies the controlled output to achieve the desired position. The application includes robots (each joint in a robot requires a position servo), computer numeric control (CNC) machines, and laser printers [23]. The common characteristics of all such systems is that the variable to be controlled (usually position or velocity) is fed back to modify the command signal. The BLDC motor employs a dc power supply switched to the stator phase windings of the motor by power devices, the switching sequence being determined from rotor position. The phase current of BLDC motor, in typically rectangular shape, is synchronized with the back EMF to produce constant torque at a constant speed. The mechanical commutator of the brush dc motor is replaced by electronic switches, which supply current to the motor windings as a function of the rotor position.

To control the position of motor shaft, the simplest strategy is to use a proportional controller with gain  $K$ . Figure 3.1 shows the position control of PMSBLDC motor in which the motor output angular velocity is integrated to obtain the actual position of the motor. The output is feedback to the input and the error signal which is the difference between set point and actual motor position acts as the command signal for the PID controller.

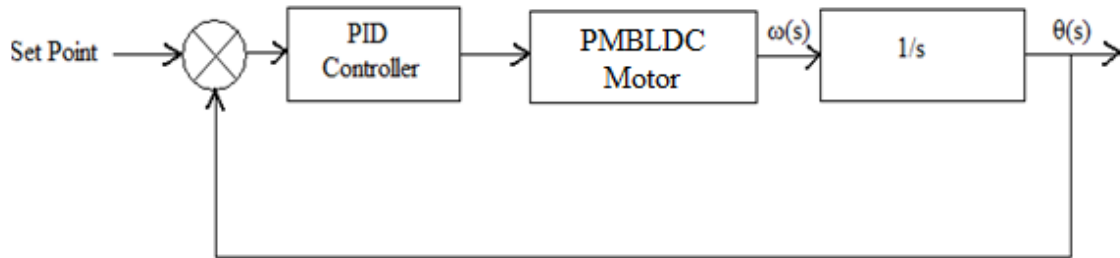


Figure 3.1: Position Control of PMBLDC Motor

### 3.2 PID Controller

A proportional–integral–derivative controller (PID controller) is a control loop feedback mechanism (controller) widely used in industrial control systems[25]. The PID is the most commonly used feedback controller. A PID controller calculates an "error" value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs. The PID controller calculation (algorithm) involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted as P, I, and D respectively. These values can be interpreted in terms of time: *P* depends on the present error, *I* on the accumulation of past errors, and *D* is a prediction of future errors, based on current rate of change. The weighted sum of these three actions is used to adjust the process. By tuning the three parameters in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation. Note that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability. PID control is a very useful method used in feed-back control systems. The error generated after the comparison between the measured signal and the target signal is proportionally multiplied (proportional), integrated (integral) and differentiated (derivative) and the outputs of the three operators are linearly summed to generate the signal applied to the actuator.

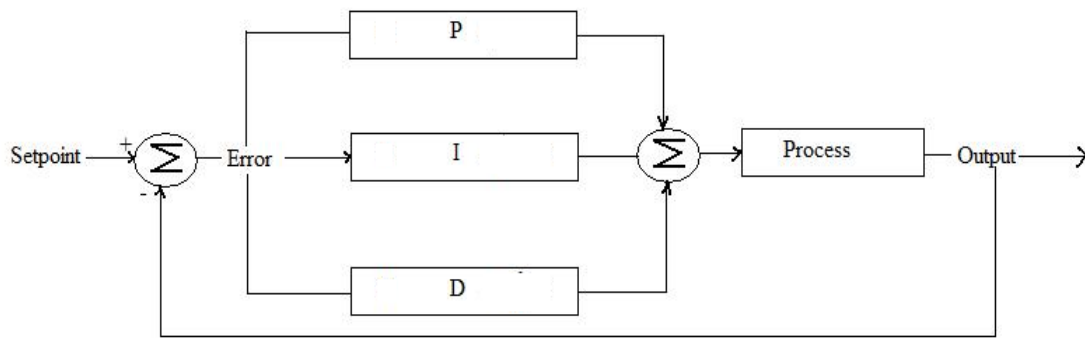


Figure3.2: Basic block diagram of PID controller

Some applications may require using only one or two actions to provide the appropriate system control. This is achieved by setting the other parameters to zero. A PID controller will be called a PI, PD, P or I controller in the absence of the respective control actions. PI controllers are fairly common, since derivative action is sensitive to measurement noise, whereas the absence of an integral term may prevent the system from reaching its target value due to the control action.

### 3.3 PID controller theory

The PID control scheme is named after its three correcting terms, whose sum constitutes the manipulated variable (MV). The proportional, integral, and derivative terms are summed to calculate the output of the PID controller [27]. Defining  $u(t)$  as the controller output, the final form of the PID algorithm is:

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{d}{dt} e(t)$$

Where:

$K_p$  : Proportional gain, a tuning parameter

$K_i$  : Integral gain, a tuning parameter

$K_d$  : Derivative gain, a tuning parameter

$e$  : error = SP – PV

$t$  : Time or instantaneous time (the present)

### 3.3.1 Proportional term

The proportional term makes a change to the output that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant  $K_P$  called the proportional gain. The proportional term is given is given by:

$$P_{out} = K_p e(t)$$

A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is too high, the system can become unstable. In contrast, a small gain results in a small output response to a large input error, and a less responsive or less sensitive controller. If the proportional gain is too low, the control action may be too small when responding to system disturbances. Tuning theory and industrial practice indicate that the proportional term should contribute the bulk of the output change.

### 3.3.2 Integral term

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. The integral in a PID controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain ( $K_i$ ) and added to the controller output. The integral term is given by

$$I_{out} = K_i \int_0^t e(t) dt$$

The integral term accelerates the movement of the process towards set point and eliminates the residual steady-state error that occurs with a pure proportional controller. However, since the integral term responds to accumulated errors from the past, it can cause the present value to overshoot the set point value.

### 3.3.3 Derivative term

The derivative of the process error is calculated by determining the slope of the error over time and multiplying this rate of change by the derivative gain  $K_d$ . The magnitude of the contribution of the derivative term to the overall control action is termed the derivative gain,  $K_d$ . The derivative term is given by:

$$D_{out} = K_d \frac{d}{dt} e(t)$$

The derivative term slows the rate of change of the controller output. Derivative control is used to reduce the magnitude of the overshoot produced by the integral component and improve the combined controller-process stability. However, the derivative term slows the transient response of the controller. Also, differentiation of a signal amplifies noise and thus this term in the controller is highly sensitive to noise in the error term, and can cause a process to become unstable if the noise and the derivative gain are sufficiently large. Hence an approximation to a differentiator with a limited bandwidth is more commonly used. Such a circuit is known as a phase-lead compensator.

## 3.4 Loop Tuning

Tuning a control loop is the adjustment of its control parameters (gain/proportional band, integral gain/reset, derivative gain/rate) to the optimum values for the desired control response [29]. Stability (bounded oscillation) is a basic requirement, but beyond that, different systems have different behavior, different applications have different requirements, and requirements may conflict with one another. Some processes have a degree of non-linearity and so parameters that work well at full-load conditions don't work when the process is starting up from no-load; this can be corrected by gain scheduling (using different parameters in different operating regions). PID controllers often provide acceptable control using default tunings, but performance can generally be improved by careful tuning, and performance may be unacceptable with poor tuning. PID tuning is a difficult problem, even though there are only three parameters and in principle is simple to describe, because it must satisfy complex criteria within the limitations of

PID control. There are accordingly various methods for loop tuning, and more sophisticated techniques are the subject of patents; this section describes some traditional manual methods for loop tuning. If the PID controller parameters (the gains of the proportional, integral and derivative terms) are chosen incorrectly, the controlled process input can be unstable, i.e. its output diverges, with or without oscillation, and is limited only by saturation or mechanical breakage. Instability is caused by *excess* gain, particularly in the presence of significant lag. Generally, stability of response is required and the process must not oscillate for any combination of process conditions and set points, though sometimes marginal stability (bounded oscillation) is acceptable or desired.

The optimum behavior on a process change or set point change varies depending on the application. Two basic requirements are regulation (disturbance rejection – staying at a given set point) and command tracking (implementing set point changes) – these refer to how well the controlled variable tracks the desired value. Specific criteria for command tracking include rise time and settling time. Some processes must not allow an overshoot of the process variable beyond the set point if, for example, this would be unsafe. Other processes must minimize the energy expended in reaching a new set point. There are several methods for tuning a PID loop. The most effective methods generally involve the development of some form of process model, then choosing P, I, and D based on the dynamic model parameters. Manual tuning methods can be relatively inefficient, particularly if the loops have response times on the order of minutes or longer. The choice of method will depend largely on whether or not the loop can be taken "offline" for tuning, and the response time of the system. If the system can be taken offline, the best tuning method often involves subjecting the system to a step change in input, measuring the output as a function of time, and using this response to determine the control parameters.

### **3.4.1 Manual tuning**

If the system must remain online, one tuning method is to first set  $K_i$  and  $K_d$  values to zero. Increase the  $K_p$  until the output of the loop oscillates, then the  $K_p$  should be set to

approximately half of that value for a "quarter amplitude decay" type response. Then increase  $K_i$  until any offset is correct in sufficient time for the process. However, too much  $K_i$  will cause instability. Finally, increase  $K_d$ , if required, until the loop is acceptably quick to reach its reference after a load disturbance. However, too much  $K_d$  will cause excessive response and overshoot. A fast PID loop tuning usually overshoots slightly to reach the set point more quickly; however, some systems cannot accept overshoot, in which case an over-damped closed-loop system is required, which will require a  $K_p$  setting significantly less than half that of the  $K_p$  setting causing oscillation.

Effects of increasing the parameters independently:

<b>Parameter</b>	<b>Rise Time</b>	<b>Overshoot</b>	<b>Settling Time</b>	<b>Steady state error</b>	<b>Stability</b>
<b><math>K_p</math></b>	Decrease	Increase	Small Change	Decrease	Degrade
<b><math>K_i</math></b>	Decrease	Increase	Increase	Decrease significantly	Degrade
<b><math>K_d</math></b>	Minor decrease	Minor decrease	Minor decrease	No effect in theory	Improve if $K_d$ is small

Table 3.1: Recommended PID value Setting

## CHAPTER-4

### Simulation and Results

#### Introduction

This chapter details MATLAB simulink model of Permanent Magnet Brushless DC Motor and its position control using PID controller.

#### 4.1.1 Simulink Model of PMSM Motor

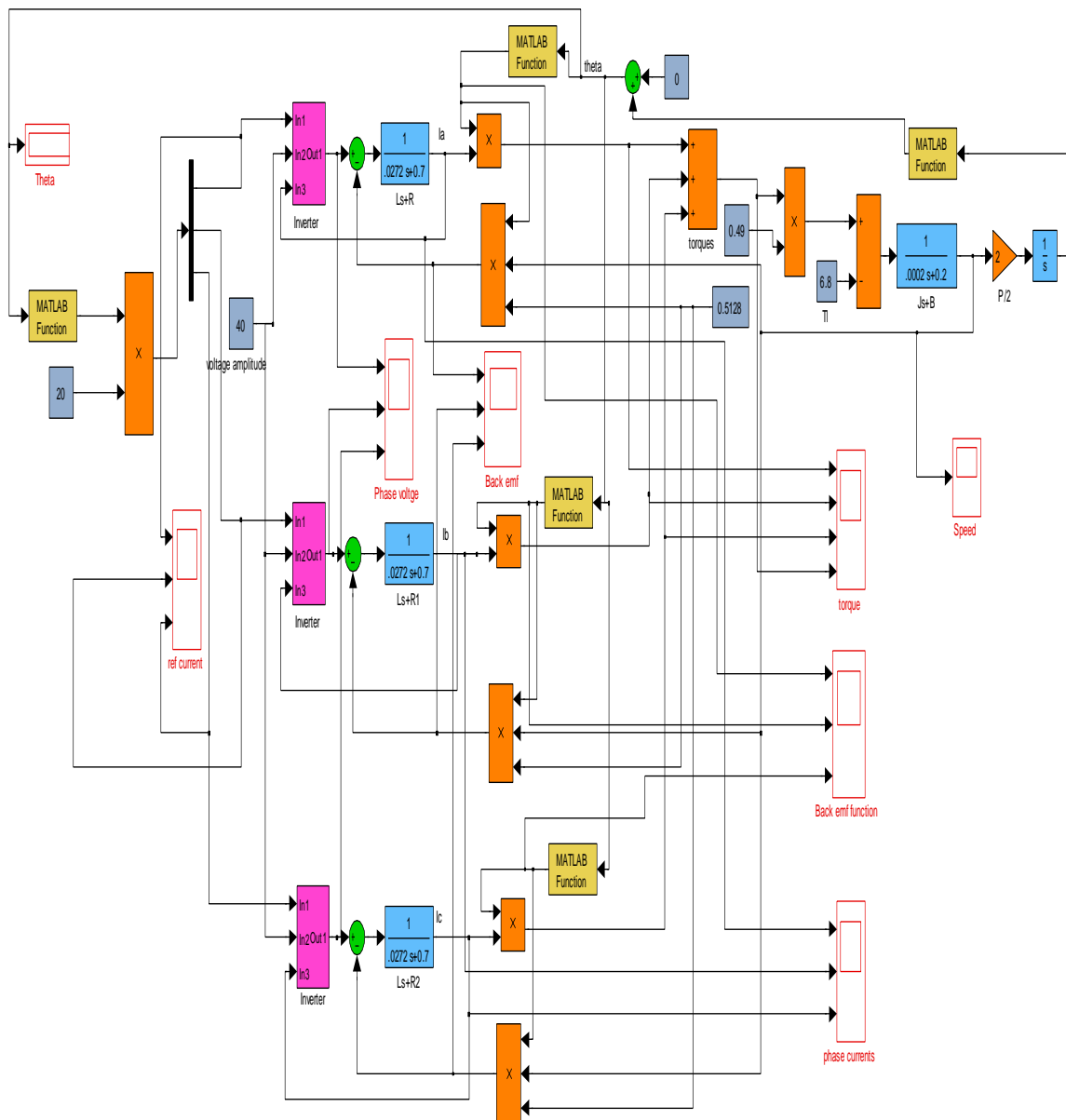


Figure 4.1: Simulink Model of PMSM Motor

The figure 4.1 shows an entire simulation model of PMBLDC motor based on the mathematical modeling. In this model, the trapezoidal back EMF waveforms are modeled as a function of rotor position. The three phase currents are controlled to take a type of quasi square waveform in order to synchronize with the trapezoidal back EMF to produce the constant torque according to the rotor position. By varying the current flow through the coils, the speed and torque of the motor can be adjusted. The most common way to control the current flow is to control the average current flow through the coils. The reference current as shown in the table is compared with the motor phase current in the inverter block of the simulink diagram to obtain the desired voltage. In simulink model the reference current for the three phase is  $I=20A$ . The subsystem of the inverter block is shown in figure 4.2. The waveform output for the voltage, current, EMF, torque and speed taken from the model is shown subsequently.

Rotor position ( $\theta$ – Degree)	Reference current (A)		
	$I_{a\_ref}$	$I_{b\_ref}$	$I_{c\_ref}$
0-30	0	I	I
30-90	I	-I	0
90-150	I	0	-I
150-210	0	I	-I
210-270	-I	I	0
270-330	-I	0	I
330-360	0	-I	I

Table 4.1 Reference currents of BLDC motor

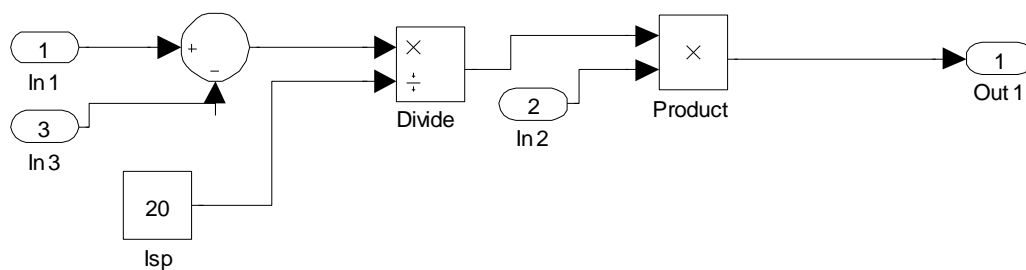


Figure 4.2 Inverter Subsystem

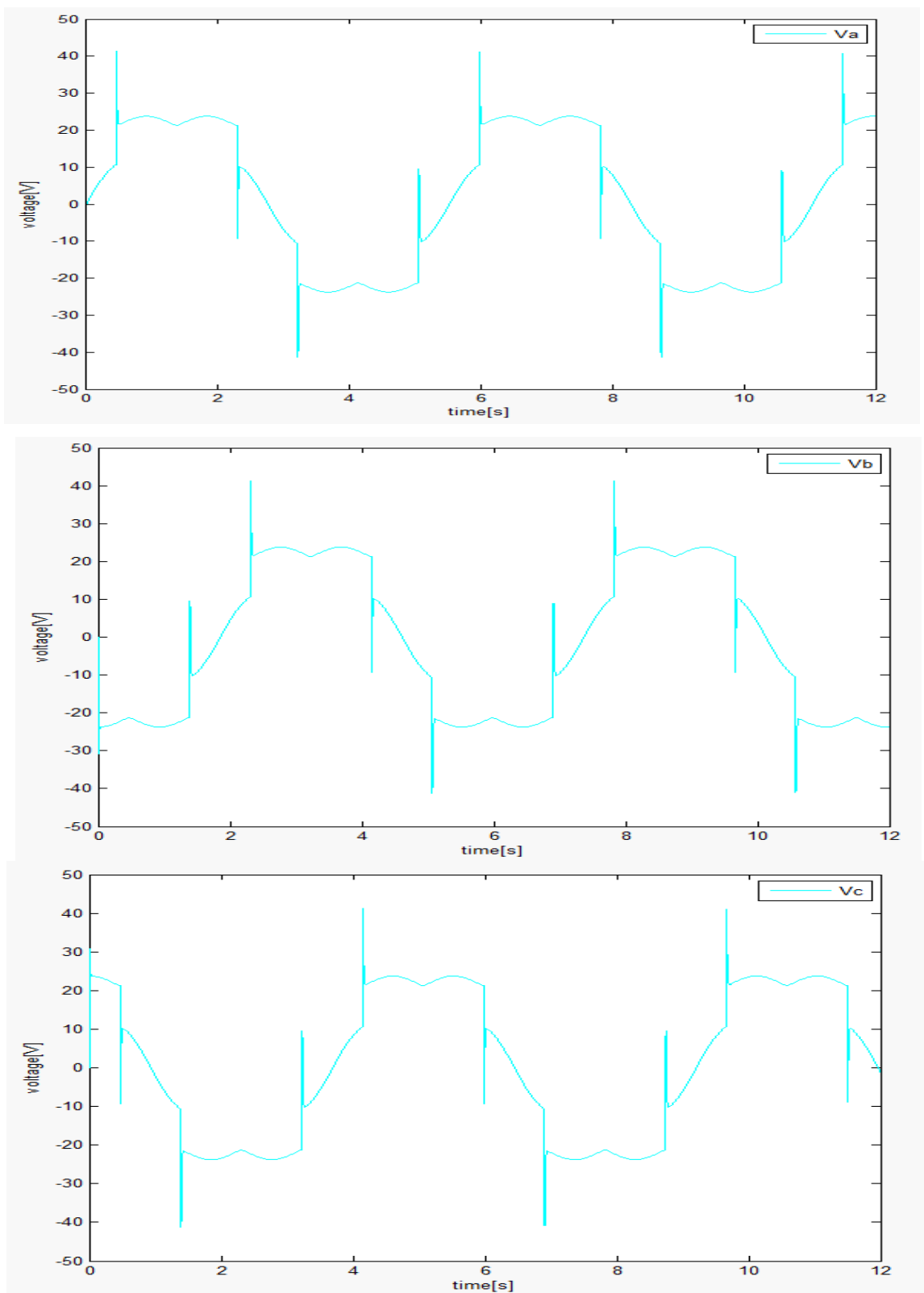


Figure 4.3: Phase voltages

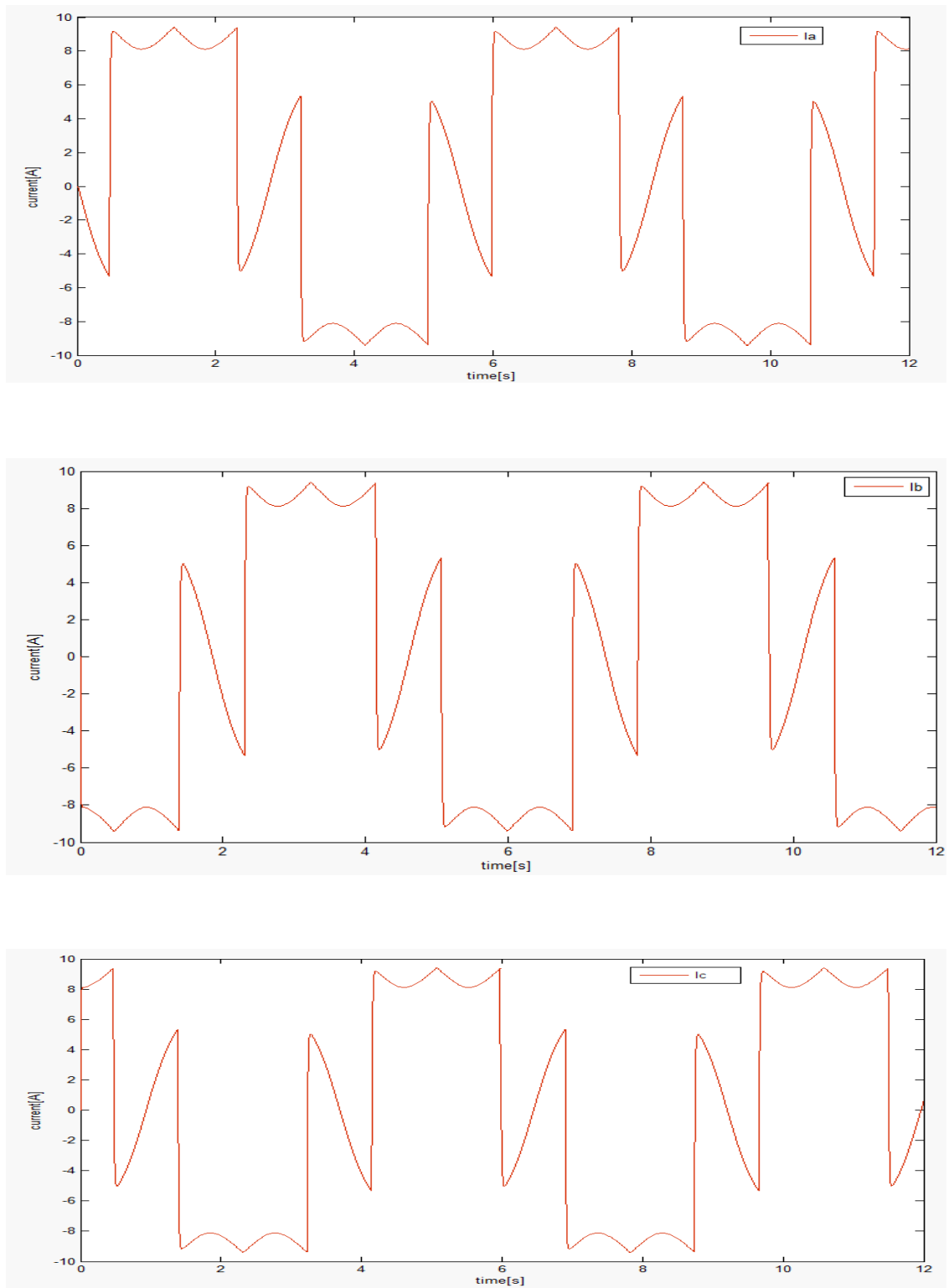


Figure 4.4: Phase currents

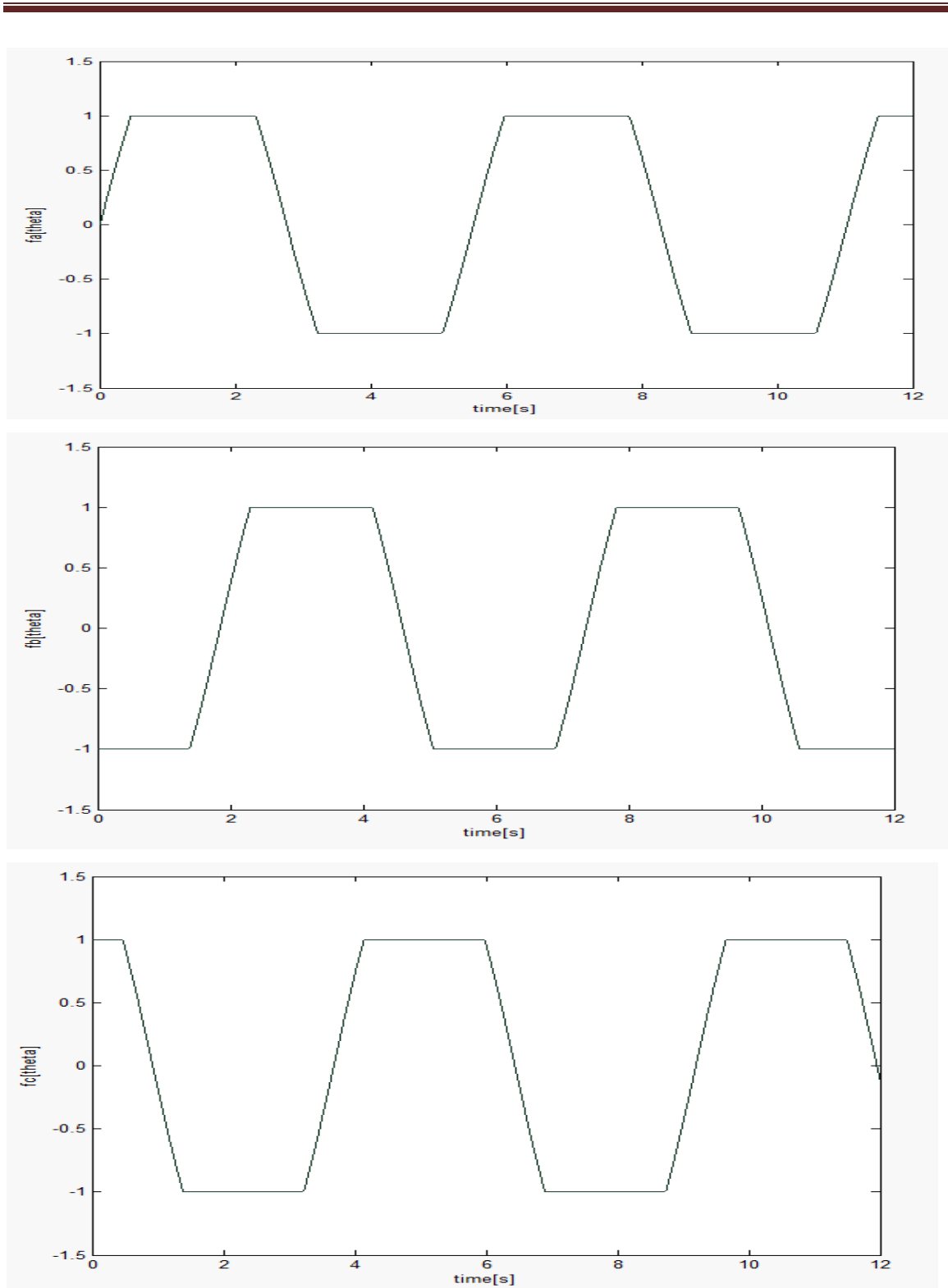


Figure 4.5: Plot of the back EMF functions

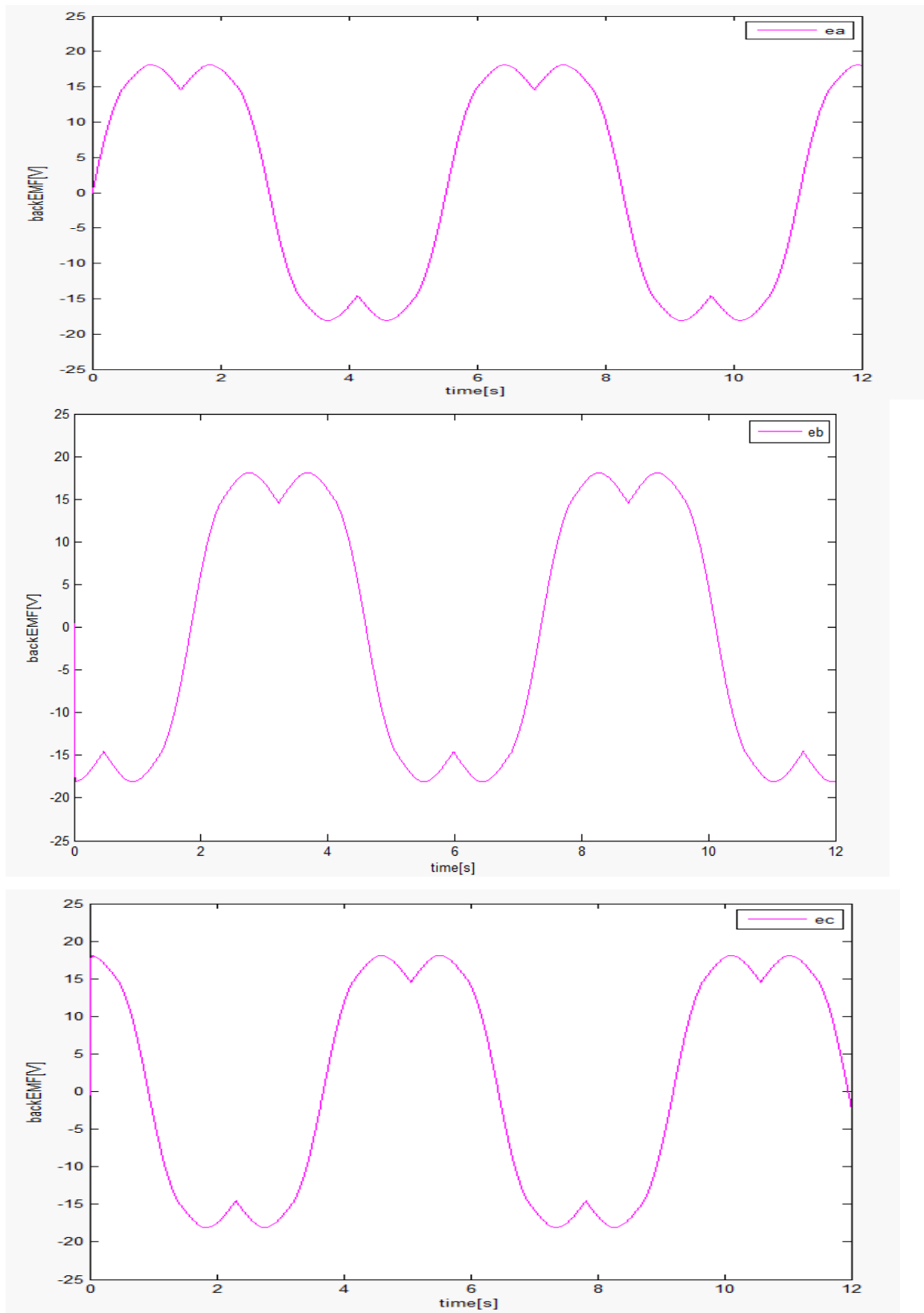


Figure 4.6: Back EMFs

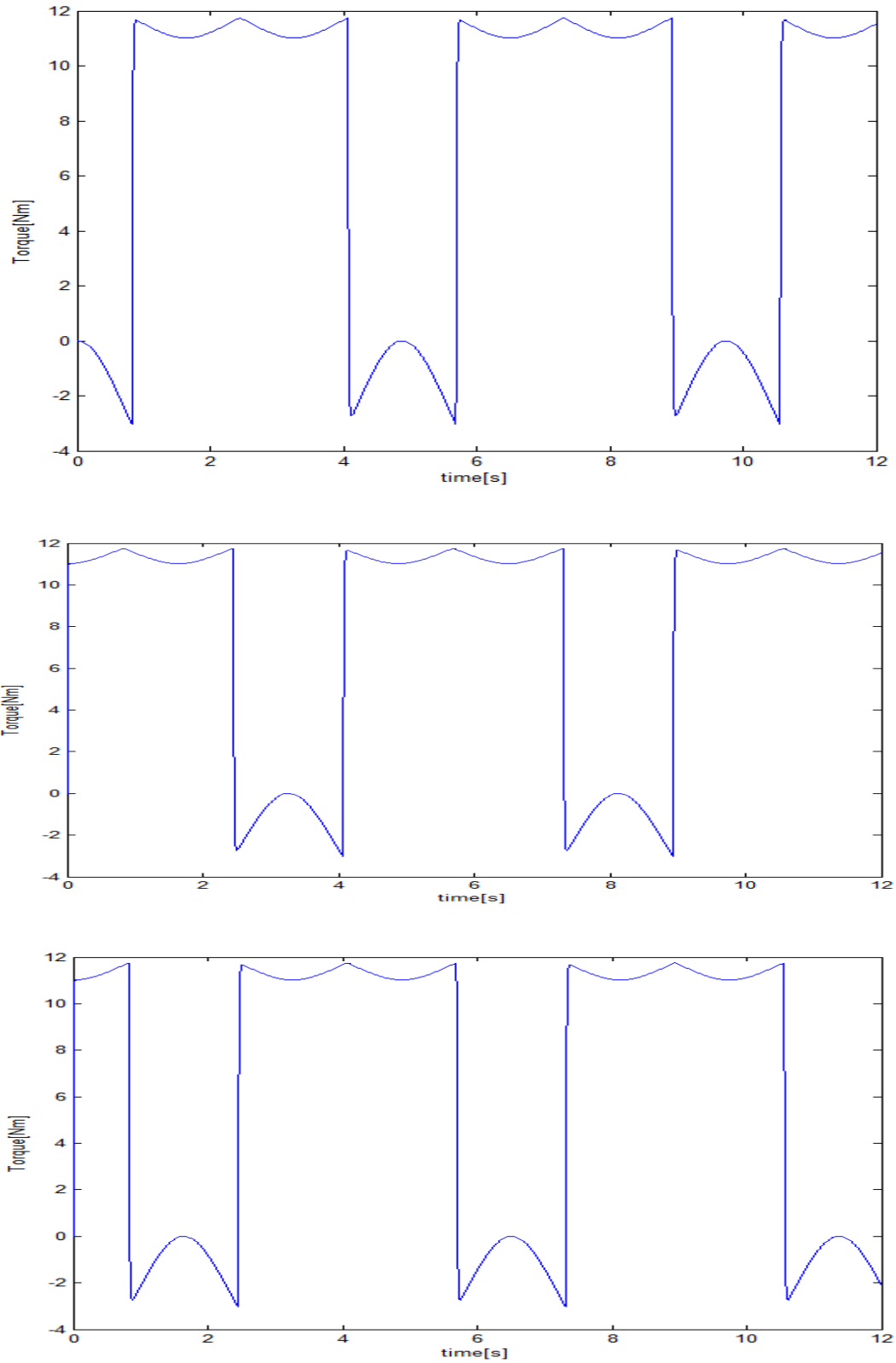


Figure 4.7: Torque generated by three windings

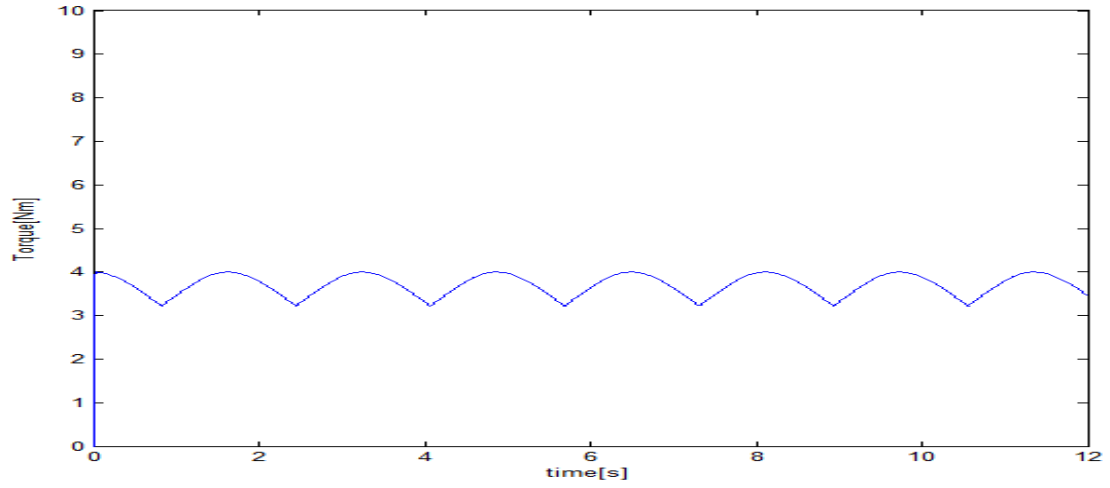


Figure4.8: Output Torque

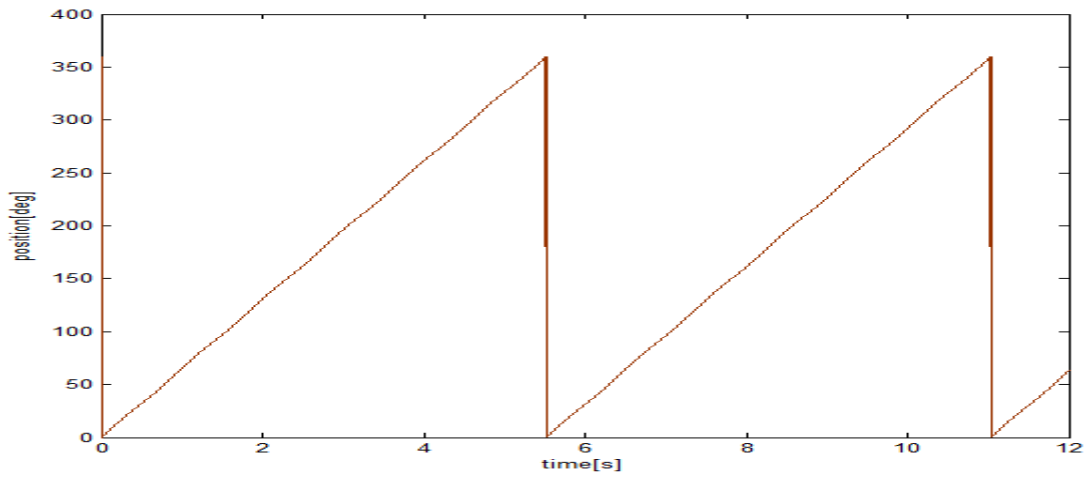


Figure4.9: Rotor Position

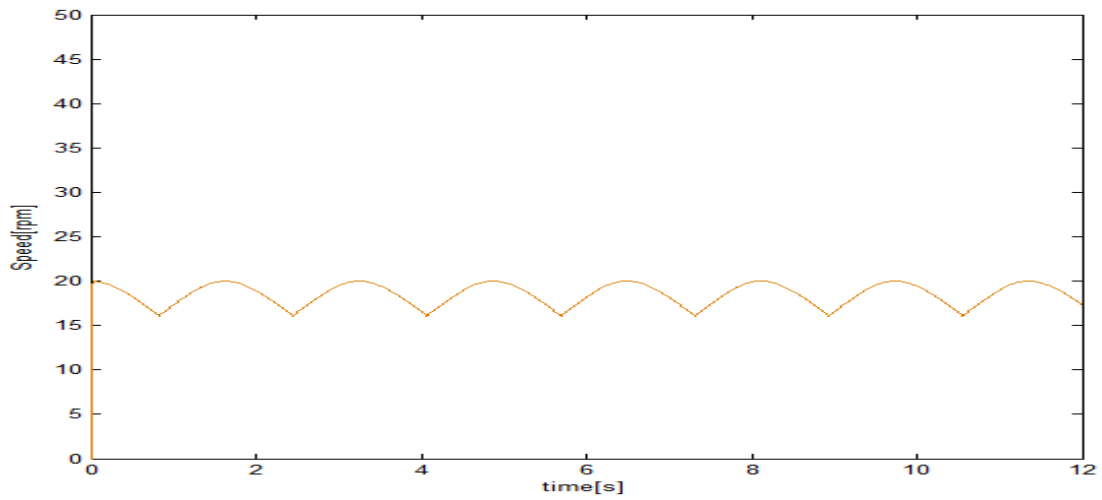


Figure 4.10 Speed

#### 4.1.2 Simulink Model of Position Control of PMBLDC Motor

Figure 4.11 below shows the position control of PMBLDC motor with PID controller which is manually tuned to obtain the desired rotor position. The PID values used is to average the current which is fed to the inverter. The value at which the position is obtained at  $K_p=0.89$ ,  $K_i=0.02$  and  $K_d=0.03$ . Subsequently graphical rotor position with time is shown in figure 4.12 below for the various angles.

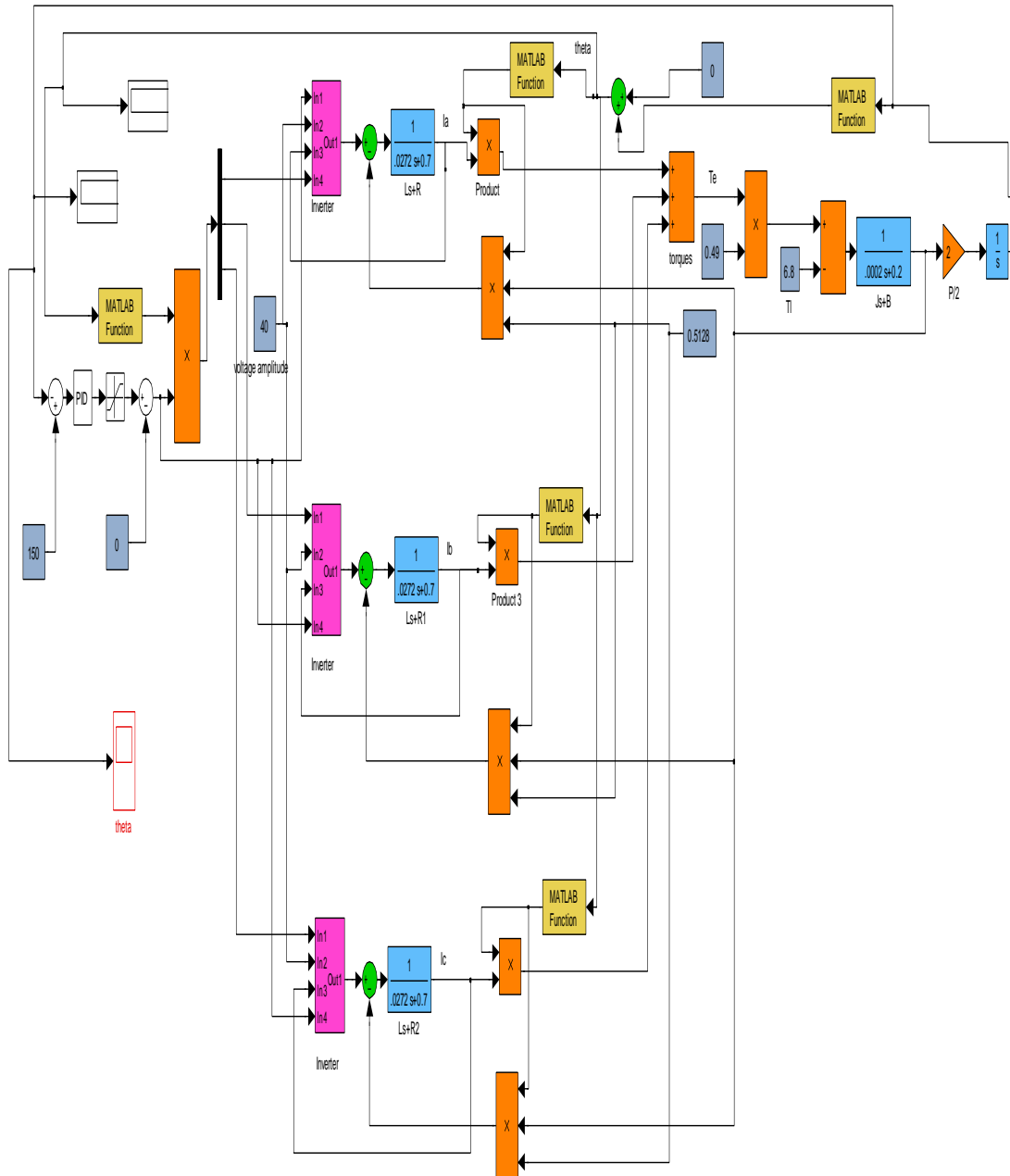
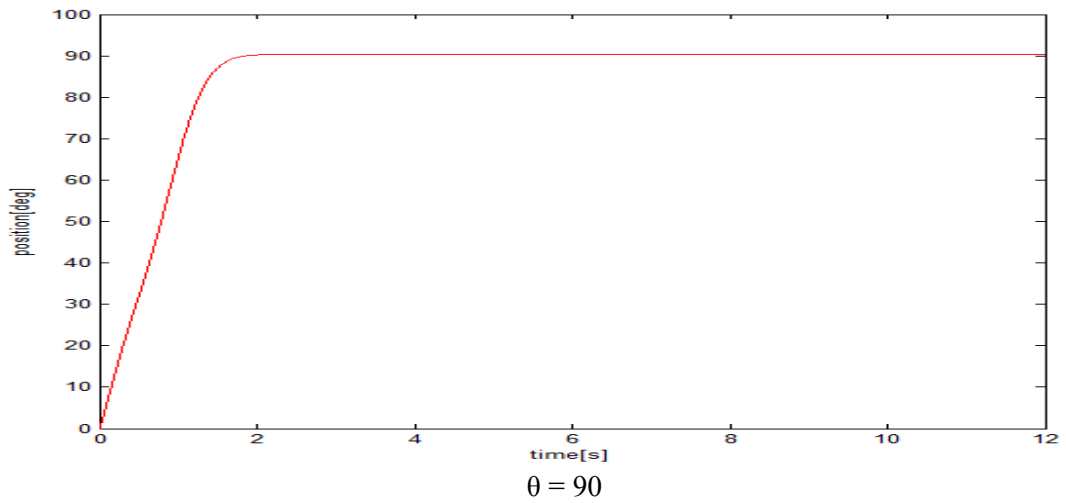
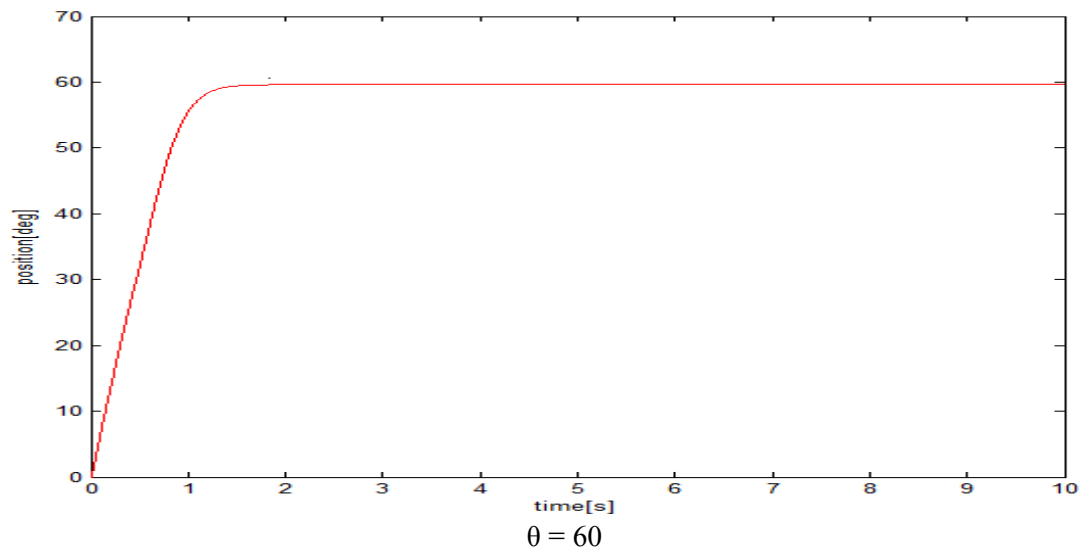
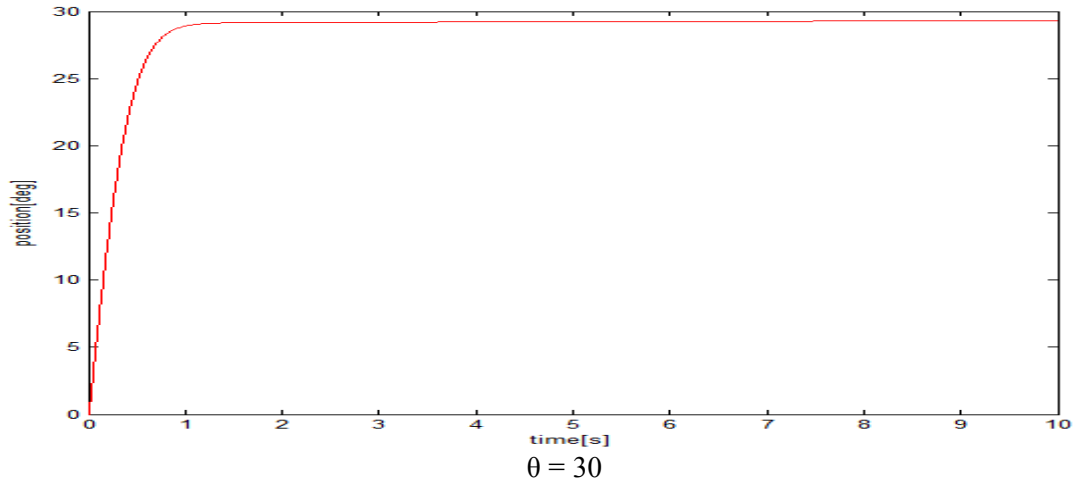
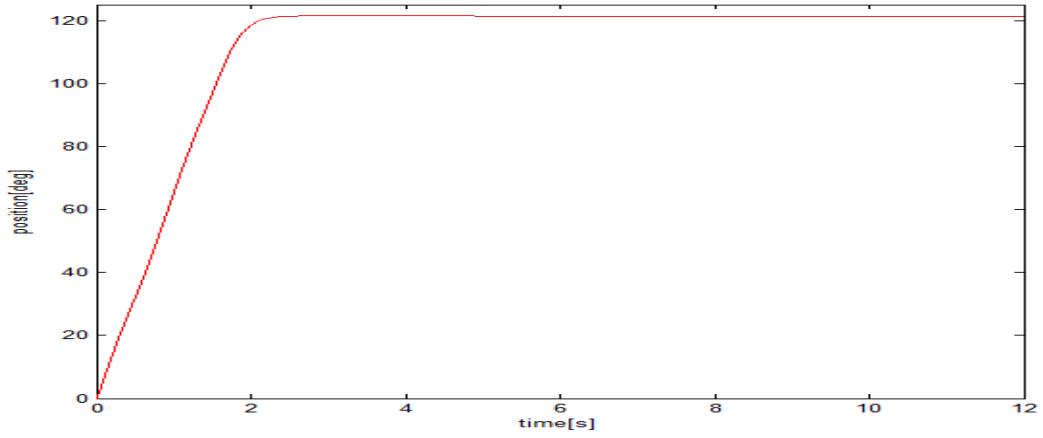
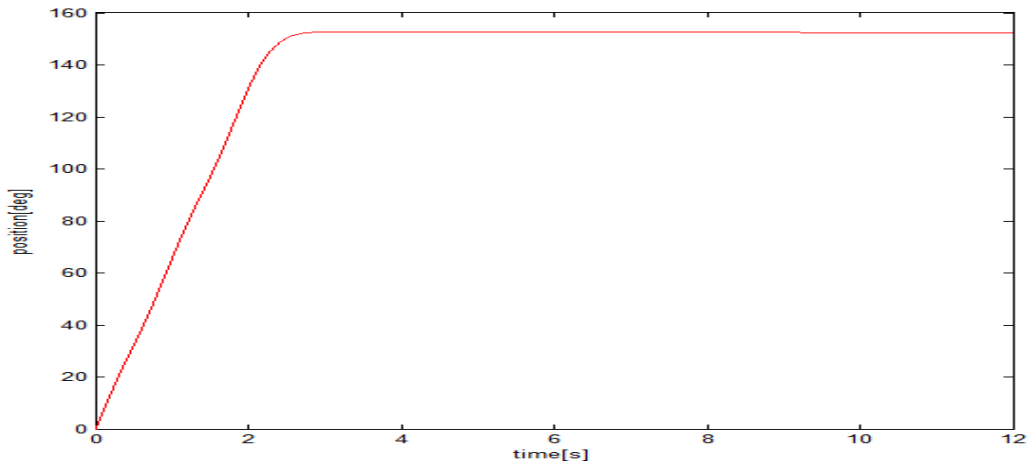


Figure 4.11: Simulink model for Position Control of PMBLDC Motor

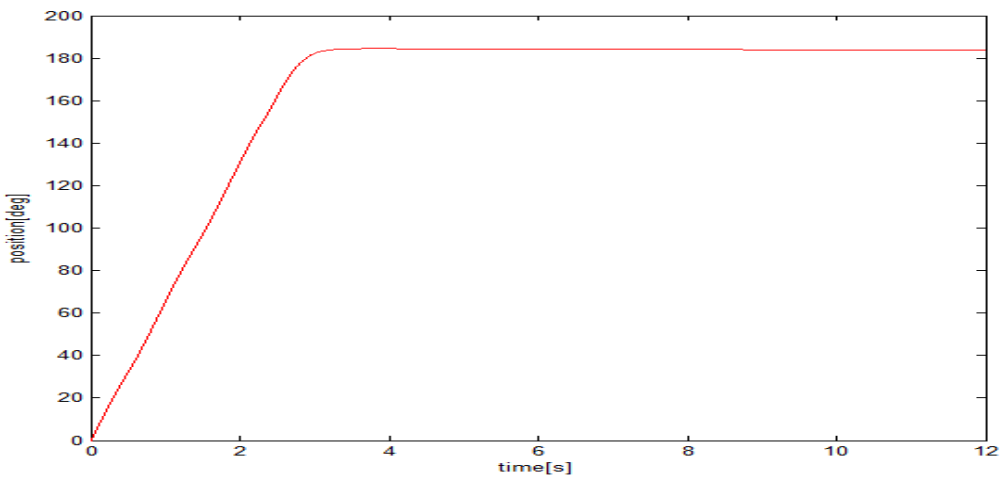




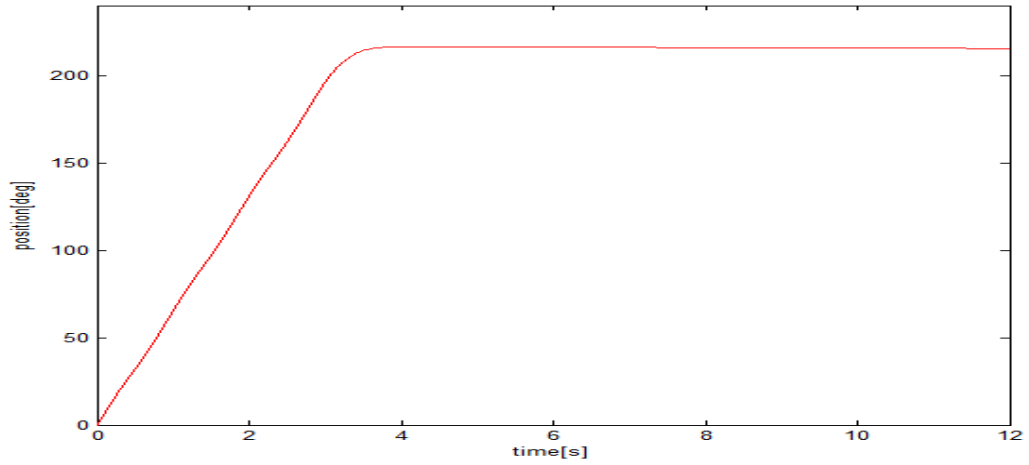
$\theta = 120$



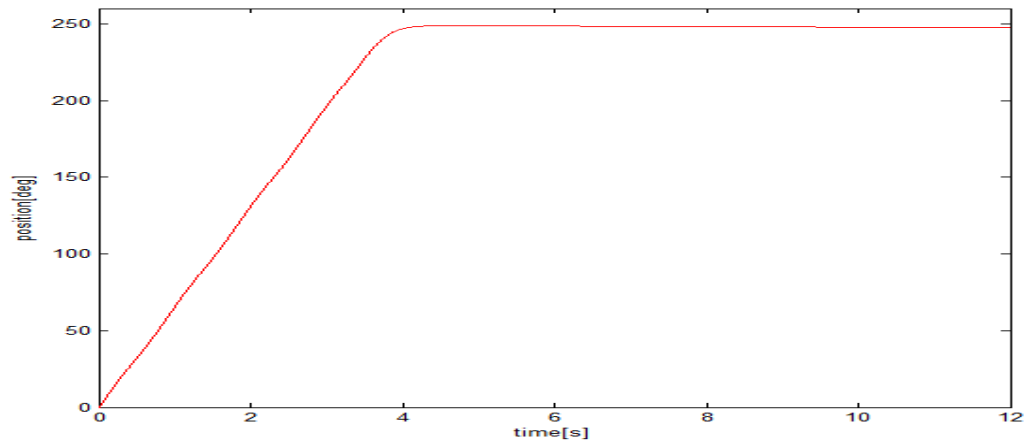
$\theta = 150$



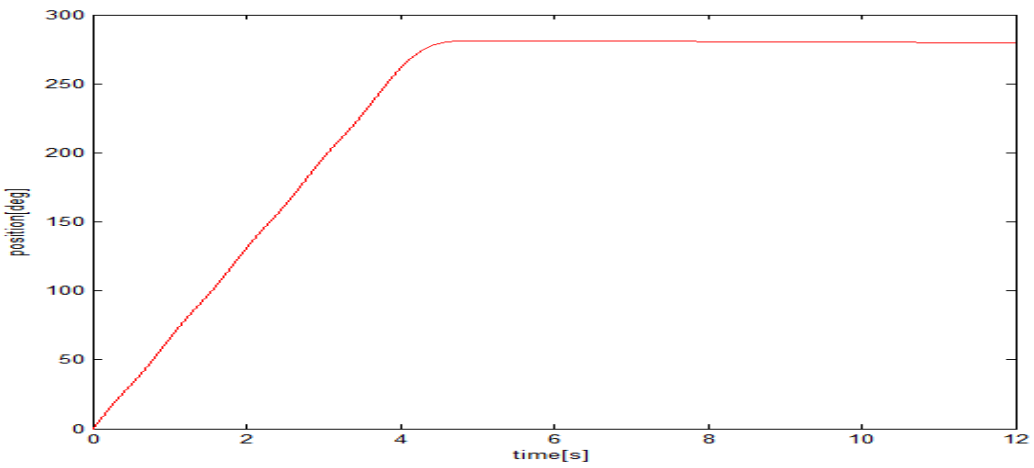
$\theta = 180$



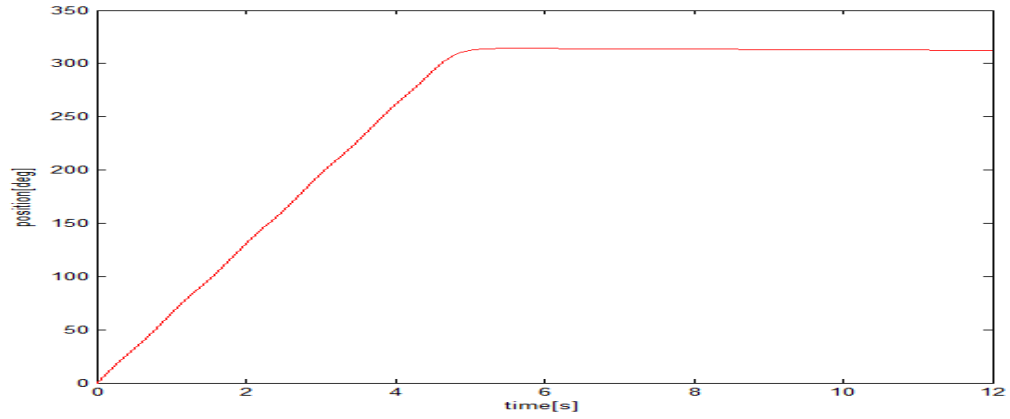
$\theta = 210$



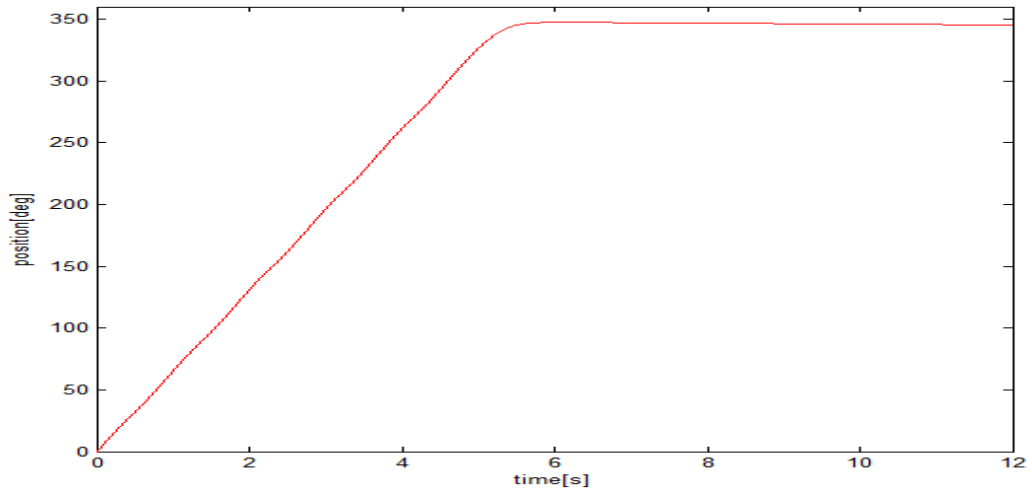
$\theta = 240$



$\theta = 270$



$\theta = 300$



$\theta = 330$



$\theta = 360$

Figure 4.12: Rotor Position at various angles

## **CHAPTER-5**

### **CONCLUSION & FUTURE SCOPE**

#### **5.1 Conclusion**

Electric machines are used to generate electrical power in power plants and provide mechanical work in industries. The DC machine is considered to be a basic electric machine. The Permanent Magnet Brushless DC (PMBLDC) motors are one of the electrical drives that are rapidly gaining popularity, due to their high efficiency, good dynamic response and low maintenance. The brushless DC (BLDC) motors and drives have grown significantly in recent years in the appliance industry and the automotive industry. BLDC drives are very preferable for compact, low cost, low maintenance, and high reliability system.

In this thesis work, a mathematical model of brushless DC motor is developed. The mathematical model is presented in block diagram representation form. The simulation of the Permanent Magnet Brushless DC motor is done using the software package MATLAB/SIMULINK and its phase voltage, phase current, back emf and torque waveform are analyzed. A PID controller has been employed for position control of PMBLDC motor. Effectiveness of the model is established by performance prediction over a wide range of operating conditions. The position controller has been designed successfully for closed loop operation of the PMBLDC motor and the motor runs nearly to the reference position. The results show that MATLAB paired with simulink is a good simulation tool for modeling and analyze PID controlled PMBLDC motor.

#### **5.2 Future Scope**

- Tuning of PID controller for position control using Artificial Intelligence techniques.
- Implementation of real time hardware system for PMBLDC motor position control.

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## Motors Parameters

Voltage	$V=40V$
Current	$I=20A$
Load Torque	$T_l=6.8N\cdot m$
Self Inductance of the winding	$L_s=0.0272H$
Back EMF constant	$K_e=0.5128V/rad/s$
Torque constant	$K_t=0.49\text{ Nm/A}$
Motor inertia	$J=0.0002\text{ kg}\cdot m^2$
Winding resistance per phase	$R=0.7\Omega$
Motor damping constant	$B=0.2\text{ N}\cdot m/rad/s$
Numbers of poles	$P=4$