

# **DESIGN AND SIMULATION OF CONTROLLER FOR SENSORED BRUSHLESS DC MOTOR**

A Thesis submitted in partial fulfillment of the  
requirements for the award of degree of

**Master of Engineering  
in  
Electronics Instrumentation and Control**



**Submitted by**

**Umesh Chugh**  
Roll No. 801251025

**Under the Guidance of**

**Mr. Sivadas A.**  
Assistant General Manager  
&  
**Mr. Nirbhow Jap Singh**  
Assistant Professor

**Department of Electrical and Instrumentation Engineering  
Thapar University**

(Established under the section 3 of UGC act, 1956)

Patiala-147004, Punjab, India

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## DECLARATION

I hereby certify that the work presented in this thesis entitled "**Design and Simulation of controller for sensored brushless DC motor**" in partial fulfillment of the requirements for the award of Master of Engineering in Electronics Instrumentation and Control Engineering submitted at Electrical & Instrumentation Engineering Department Thapar University, Patiala. It is an authentic record of my own work carried out under the supervision and guidance of Mr. Sivasdas A., Assistant General Manager, Crompton Greaves Limited and Mr. Nirbhaw Jap Singh, Assistant Professor, Department of Electrical & Instrumentation Engineering, Thapar University, Patiala. To the best of 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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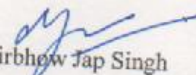
Unesh Chugh

(Roll No: 801251025)

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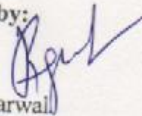


Mr. Sivasdas A.  
Assistant General Manager  
Crompton Greaves Limited, Mumbai



Mr. Nirbhaw Jap Singh  
Assistant Professor, EIED  
Thapar University, Patiala

Countersigned by:



Dr. Ravinder Agarwal  
Head, Electrical and Instrumentation  
Engineering Department  
Thapar University Patiala



Dr. S.K. Mohapatra  
Dean of Academic Affairs  
Thapar University, Patiala

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**Umesh Chugh**

**Roll No 801251025**

## **ABSTRACT**

Brushless dc motor (BLDC) is very popular in wide variety of applications. In comparison to conventional dc motor, the brushless dc motor uses an electronic commutator rather than mechanical commutator, so it is more reliable than the dc motor. A BLDC motor has same torque-speed characteristic as a conventional dc motor even though the principle of operation is more complex. BLDC motors are commonly used in high end white goods (refrigerator, washing machine, dish washer etc.), high end pump applications which require higher reliability and efficiency.

Another important and very common application of BLDC motor is fans. This document simulates the open loop control and closed loop control of BLDC motor drive for ceiling fan. In open loop speed regulation is possible by varying applied voltage or regulating duty cycle manually whereas in closed loop speed control is possible using various types of controllers like proportional integral controller, fuzzy logic controller which regulate the duty cycle on receiving an error signal.

The aim of this thesis is to investigate and evaluate the performance of permanent magnet brushless dc motor driven by open loop and closed loop control system. The speed control by varying applied voltage in open loop system and by using proportional integral in closed loop system for permanent magnet brushless dc motor are simulated using MATLAB software package. Further, for practical implementation point of view open loop Controller has been designed, implemented for 24 V, 40W brushless dc motor based ceiling fan.

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## LIST OF SYMBOLS AND ABBRIVATIONS

Abbreviation	Description
BLDC	Brushless direct current
CNC	Computer numeric controller
PMSM	Permanent magnet synchronous motor
DC	Direct current
AC	Alternating current
MOSFET	Metal oxide semiconductor field effect transistor
IGBT	Insulated gate bipolar transistor
PWM	Pulse width modulation
PMBLDC	Permanent Magnet Brushless DC
DC	Direct Current
EMF	Electromotive Force
PI	Proportional Integral
RPM	Revolution per minute
R	Winding resistance
L	Winding inductance
J	Moment of Inertia
P	Proportional
I	Integral
N	North
S	South
Nd	Neodymium
SmCo	Samarium Cobalt
NdFeB	Neodymium Ferrite and Boron

# CHAPTER 1

## INTRODUCTION

---

### 1.1 BACKGROUND

A Brushless dc (BLDC) motor is a rotating self synchronous machine [1] as shown in Fig.1.1, whose stator is similar to that of an induction motor and the rotor has surface mounted permanent magnet [2].



**Fig. 1.1** Brushless dc motor

In BLDC motor, winding is placed on stator which is stationary and permanent magnets are placed on rotor which is rotating [1]. In the dc motor, the current polarity is altered by commutator and brushes. However in brushless dc motor there are no brushes and commutator. The current polarity reversal is controlled by switches (MOSFET, IGBT) in synchronization with rotor position. Therefore sensored BLDC motor uses position sensors to sense the actual rotor position or the position can be detected without sensors. Brushless dc motors are preferred over conventional dc motor due to their high efficiency, silent operation, compact form, reliability and low maintenance. But the speed control of these motors is not an easy task, the advancements in microcontroller, power electronics and electrical drives over the decade have made reliable and cost effective solution for adjustable speed application. The BLDC motors are used in home appliances, replacing the conventional motor applications, everywhere there is a fast growing market for BLDC motors for several years to come because everyone wants reliable and cost effective solution. The major application includes washing machines, room air conditioner, refrigerator, vacuum cleaner, dish washer etc. House hold appliance have traditionally relied on

classic electric motor technology such as single phase AC induction, induction split phase, capacitor start, capacitor run types and universal motor. There is demand for low operating cost, high performance, reduced acoustic noise and more convenience features. Those conventional technologies cannot provide cost effective solution. One of the ways to get higher efficiency is by selecting the right hall sensor which can significantly affect reliability and performance of many critical applications including robotics, medical equipment, heating, ventilation and air conditioning (HVAC) system fans. These applications all call for a highly efficient and quiet motor. BLDC motors are electronically commutated motors, also known as synchronous motors because stator flux and rotor flux both rotate at same frequency that are powered by a DC supply through an inverter .

## **1.2 OVERVIEW OF BLDC MOTOR**

In a conventional DC motor, the carbon brushes make contact with commutators on the rotor forming an electrical circuit between the DC electrical source and armature coil windings. As the armature rotates, the stationary carbon brushes come into contact with different sections of the rotating commutator. When commutator comes in contact with brushes the current reversal take place in that armature so that torque continue to act in one direction thus rotor continue to rotate.

In a BLDC motor, the electromagnets do not move, instead the permanent magnet rotates and the armature remains static. The permanent magnets are mounted on surface of rotor and armature winding is placed on stator. In BLDC the commutator assembly is replaced by an intelligent electronic controller. The advantages of BLDC motors are summarized below [2]:

- a) High dynamic response
- b) High efficiency
- c) Long operating life
- d) Noiseless operation
- e) Higher speed range
- f) High output power
- g) Low maintenance
- h) Compact volume

The major disadvantage of BLDC motor is higher cost because of permanent magnet and electronic commutator. The permanent magnet synchronous motor (PMSM) and the brushless dc (BLDC) motor have many similarities [3]. The differences in these two machines are:

BLDC	PMSM
Torque generated will have more ripples.	Torque generated is almost ripple free.
Coil span is less than 180 degree electrical and coil pitch is 1.	Coil span is 180 degree electrical and coil pitch is greater than 1.
Two phases are conducting at a time.	Three phases are conducting at a time.
Concentrated winding.	Distributed winding.
Back EMF is of trapezoidal fashion.	Back EMF is of sinusoidal fashion.

**Table 1.1** A comparison of BLDC with PMSM

### 1.3 APPLICATIONS

For single speed application, induction motors are more suitable. Because of flat speed torque curve, BLDC motor becomes more suitable for adjustable speed application. Sinusoidal BLDC motor use optical encoder or hall sensors and complex controller to monitor speed and position. BLDC motor used in application with constant load application require open loop control, cheaper controller while those used in varying load application, require closed loop control, complicated and advance controller which are expensive. Further BLDC motors used in Position control application require more complex controller, optical encoders or High resolution resolvers to calculate speed of motor, two or more closed loop are operated simultaneously. BLDC motor finds applications in every segment of the market. Some of the applications are described below:

- a) Consumer: hard drives, CD/DVD drives, PC cooling fans, dish washer, washing machine, vacuum cleaner, air conditioner, refrigerator, toys.
- b) Medical: artificial heart, microscopes, centrifuges, dental surgical tools, organ transport pump system.
- c) Automobile: automotive applications, electric and hybrid vehicle etc.

### 1.4 OBJECTIVE OF THESIS WORK

There are three main objective of thesis work: simulation of open loop system and closed loop system for speed control of sensored brushless dc motor based ceiling fan in MATLAB software. Design, implemented and testing of open loop controller hardware for 24V, 40W brushless dc motor based ceiling fan. The objective can be summarized as follows: To check the performance

of BLDC motor based ceiling fan using open loop control system on Matlab platform, To check the performance of BLDC motor based ceiling fan using proportional integral controller in closed loop control system on Matlab platform, Design, implementation and testing of controller hardware for BLDC motor based ceiling fan on general purpose printed circuit board, Compare the performance of BLDC motor driven by open loop control and closed loop control system.

## **1.5 THESIS ORGANISATION**

The work done to achieve the above stated objectives consists of designing, testing and simulation of controller for sensored BLDC motor. The complete thesis is organized as follows: In Chapter 1, the background of BLDC motor, comparison of BLDC with conventional DC motor and PMSM (sinusoidal BLDC motor) is introduced. In Chapter 2, the detailed literature review of BLDC motor, Construction, working principle, and operation of BLDC motor. In this chapter Hall effect sensor, 120° conduction inverter, driving circuit of BLDC motor and switching elements of driving circuit are discussed. Further the methods to control speed and torque of BLDC motor using pulse width modulation (PWM) technique, torque versus speed curves are discussed based on literature survey. In Chapter 3, the open loop operation and closed loop operation for BLDC motor are discussed. Further simulation results of controller for BLDC motor based ceiling fan are analyzed. In Chapter 4, the hardware components used to implement the open loop controller for brushless dc motor are discussed. Hall sensor A3207, BLDC motor controller MC 33035, mosfet IRF530, mosfet IRF9530 and their circuit diagram are discussed. In Chapter 5, the conclusion of thesis work based on open loop control and closed loop control of BLDC motor and future scope of thesis work are discussed.

## **CHAPTER 2**

### **LITERATURE SURVEY**

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The brush DC motor was invented all the way back in 1856 by famed German inventor and industrialist Ernst Werner von Siemens. Von Siemens's brush DC motor was fairly rudimentary and was enhanced upon by Harry Ward Leonard, who nearly perfected the first effective motor control system near the end of the 19th century. Once the Electronic Regulator Company maximized the efficiency of the brush DC motor, the door was opened for an even more efficient motor device. Brushless DC motors first made the scene in 1962, when T.G. Wilson and P.H. Trickey unveiled what they called a DC machine with solid state commutation. Remember that the key element of brushless dc motors as opposed to brush DC motors is that the brushless dc motor requires no physical commutator, a innovative difference. As the device was sophisticated and developed, it became a popular choice for special applications such as computer disk drives, robotics and in aircraft. In fact, brushless DC motors are used in these devices today, fifty years later, so great is their effectiveness. The reason these motors were such a great choice for these devices is that in these devices brush wear was a big problem, either because of the extreme demands of the application or, for example, in the case of aircraft because of low humidity. Because brushless dc motors had no brushes that could wear out, they represented a great leap forward in technology for these types of devices. The problem was that as consistent as they were, these early brushless dc motors were not able to generate a great deal of power. That all changed in the 1980s, when permanent magnet materials became readily available. The use of permanent magnets, combined with high voltage transistors, enabled brushless dc motors to generate as much power as the old brush DC motors, if not more. Near the end of the 1980s, Robert E. Lordo unveiled the first large brushless dc motors, which had at least ten times the power of the former brushless dc motors.

#### **2.1 CONSTRUCTION AND OPERATION OF BLDC MOTOR**

BLDC motors are type of self synchronous motors [1] because the magnetic field generated by the stator and magnetic field generated by the rotor rotate at the same frequency. Hence BLDC motors do not experience the slip that is normally seen in induction motor. The stator looks a lot like that of an induction motor, however the windings are distributed in different manners [2]. BLDC motors come in single phase, 3 phase configuration, 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 they generate high torque and mostly used in high power applications. The brushless motor has surface mounted magnet on the rotor unlike the DC brushed motor; the stator of the motor is composed of stationary electromagnets. The major advantage of brushless motor is that the rotor carries only the permanent magnets, it needs no power at all. No connections need to be done with rotor, thus no brush commutator pair needs to be made. Just because it requires no brushes so it is called brushless motor. One of the advantages of BLDC motor is that it does not require carbon brushes which wear off very fast hence it can perform noiseless and spark free operation. Moreover brushless motors are more competent in terms of power consumptions. There is difference in the theory of operation of brushed DC motors with permanent magnets like how the commutator is made, and how the coils changes polarity during rotation. But brushless motor has no commutator no brushes. Thus there is need to know where each time the rotor is, but there are several ways to find out where the rotor is. Sometimes using rotary encoders, along with their controllers and know exactly the angle the rotor is, others use hall sensor. The hall sensor is placed in suitable position. Usually three hall sensors are used which are placed at  $120^\circ$  electrical apart from each other. It can sense if in front of it is the North or South Pole correspondingly the hall sensor will give high or low signal to the controller of the motor. The controller will then switch on or off the appropriate coils needed in order to produce rotating flux and provide torque.

Any BLDC motor has two primary parts, the rotor as shown in Fig. 2.1 and Fig. 2.2 the rotating part having permanent magnet and the stator the stationary part having armature coils [3]. There are two basic BLDC motor design inner rotor and outer rotor design.



**Fig. 2.1** Inner rotor



**Fig. 2.2** Outer rotor

## **2.2 STATOR**

The stator of BLDC motor consists of stacked steel laminations with windings placed in the slots of the teeth. The stator of BLDC motor is similar to that of an induction motor however the windings are distributed in different manner. Most of BLDC motors have three stator winding connected in star fashion. There are two types of winding which is done in BLDC motor the concentrated and the distributed winding. The concentrated winding gives trapezoidal back EMF where as distributed winding gives sinusoidal back EMF. 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 inner connected to make a winding. Each of these windings is distributed over the stator periphery to form an even number of poles. In addition to the back EMF, the phase current also has trapezoidal and sinusoidal variation in the respective types of motor. This makes the torque output by a sinusoidal motor smoother than that of trapezoidal motor. The sinusoidal motors are expensive than same rating of trapezoidal motor as the sinusoidal motors take extra winding interconnections because of the coils distribution on the stator periphery there by increasing the copper intake by motor winding. For selecting a BLDC motor its stator voltage rating is given, 24 V to 50 V rating BLDC motor are used in Fans. BLDC motor with stator rating above 100V is used in industrial application. Another advance of BLDC motor is its compact size, which make it reliable for home appliances. Fig. 2.3 shows the cross sectional view of BLDC motor.

## **2.3 ROTOR**

The rotor as shown in Fig.2.4 is made of permanent magnet and can vary from two to many pole pairs with alternate north and south poles. Based on the required magnetic field density in the

rotor, the proper magnetic material is chosen to make the rotor. Most commonly used permanent magnet is a Ferrite magnet which is cheaper and easily available but gives low magnetic flux for same size as compare to artificial alloy magnets. As the alloy material has high magnetic density per volume and enables the rotor to compress further for the same torque. They are used in high precision application. Also these alloy magnets improve the size to weight ratio and give higher torque for same size motor using ferrite magnets.



**Fig. 2.3** Cross sectional view of brushless dc motor

The Neodymium (Nd), Samarium Cobalt (SmCo) and the alloy of neodymium, ferrite and boron (NdFeB) are some examples of rare earth alloy magnets. In an outer rotor design, the windings are located in the core of motor for example Fan. Disadvantage of outer rotor is that rotor magnet surrounds the stator winding. The rotor magnets act as an insulator, thereby reducing the rate of heat dissipation from the motor. Hence motor gets more heating so can not be used in high power application. The outer rotor BLDC motor gives relatively low torque. In an inner rotor design, the stator winding surrounds the rotor and are affixed to the motor's housing. The primary advantage of an inner rotor construction is its ability to dissipate heat and so they can be used in high power application. A motor's ability to dissipate heat directly impacts its ability to produce torque. For this reason, the majority of BLDC motors use an inner rotor design. Another advantage of inner rotor design is its lower rotor inertia.

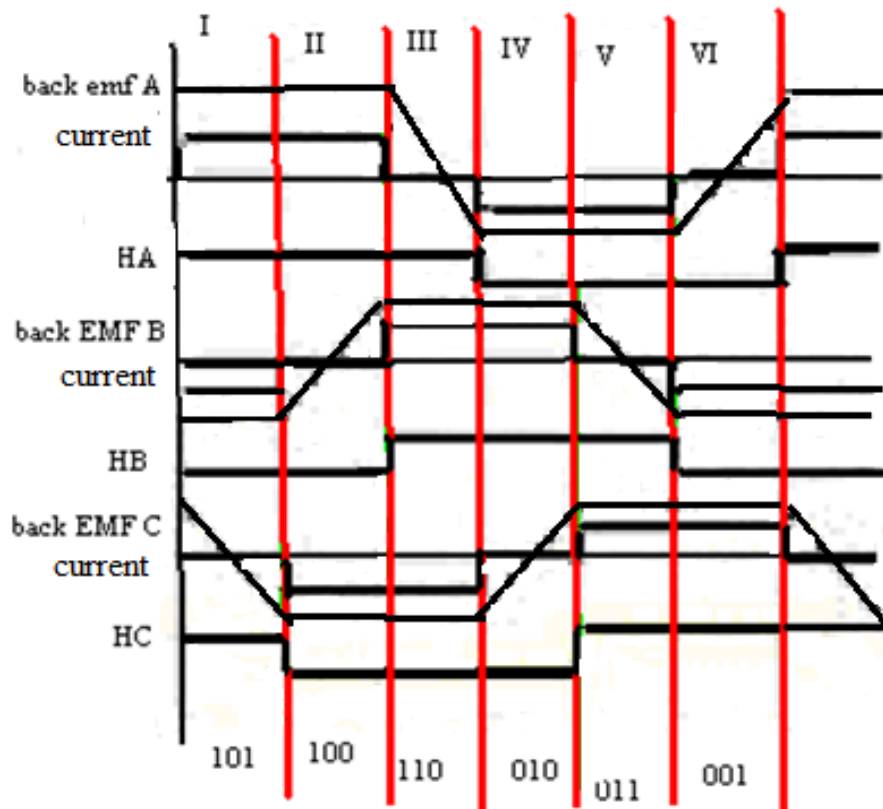
## **2.4 WORKING PRINCIPLE AND OPERATION**

The Working Principle of BLDC motor is same as for brushed DC motor i.e. internal shaft position feedback. In case of brushed DC motor, feedback is implemented using a mechanical commutator and brushes. While in BLDC motor, it is achieved using multiple feedback sensors. The most commonly used sensors are Hall Effect sensors.



**Fig. 2.4** Rotor

In the commutation system, one that is based on the position of motor identified using feedback sensors: two of three electrical windings are energized at a time, Fig. 2.5 shows the back EMF, Phase current, and Hall signal for one complete electrical revolution.



**Fig. 2.5** Back EMF, Current, Hall Effect signal waveforms

From above figure, Table 2.1 and Table 2.2 are derived which shows phase excitation corresponding to Hall signals [5]. If the phases are excited in given sequence rotating magnetic field will be produced in clockwise and counter clock wise direction respectively.

HA	HB	HC	Phase A	Phase B	Phase C
1	0	1	+	-	NC
1	0	0	+	NC	-
1	1	0	NC	+	-
0	1	0	-	+	NC
0	1	1	-	NC	+
0	0	1	NC	-	+

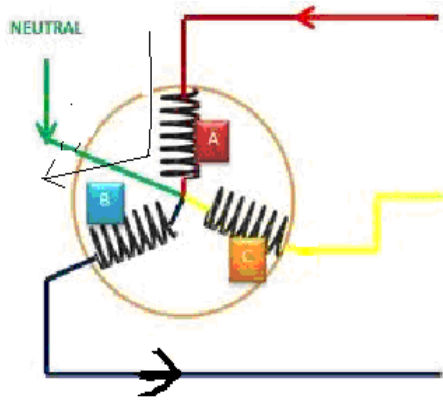
**Table 2.1** Hall Sequence for Counter Clockwise Rotation of Magnetic Field

HA	HB	HC	Phase A	Phase B	Phase C
0	0	1	NC	-	+
0	1	1	-	NC	+
0	1	0	-	+	NC
1	1	0	NC	+	-
1	0	0	+	NC	-
1	0	0	+	-	NC

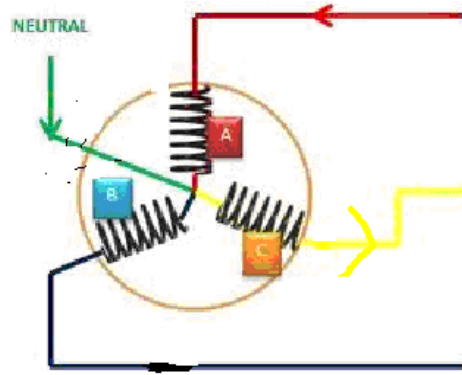
**Table 2.2** Hall Sequence for Clockwise Rotation of Magnetic Field

Fig. 2.6 shows the commutation corresponding to Hall signals. There are total six possible outcomes of Hall signals, corresponding to each signal there is a fixed excitation of phases. This figure also gives information about star connected three phase system, which two phases are excited corresponding to given Hall signal. Change of excitation of phase current is called commutation. For BLDC motor commutation takes place whenever there is change in Hall signal hence there are six possible excitation sequence which are shown below:

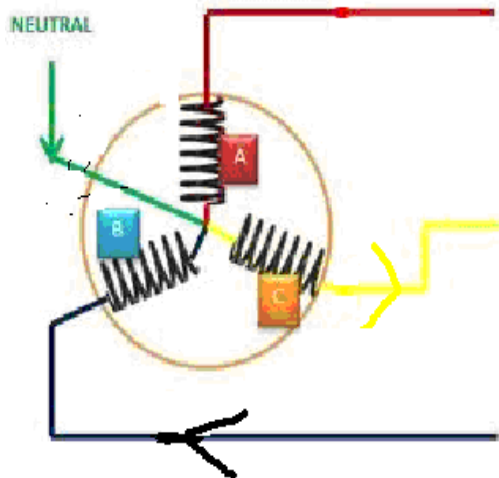
I. Hall signal 101



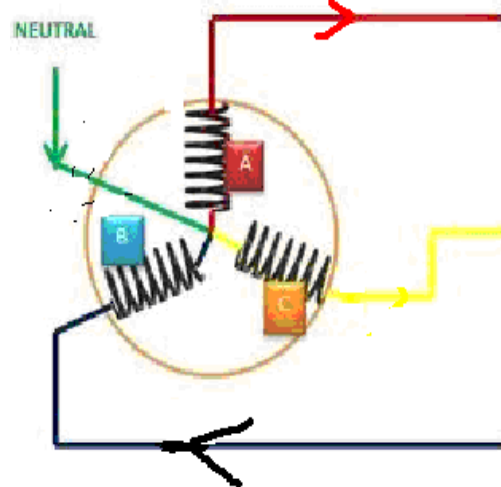
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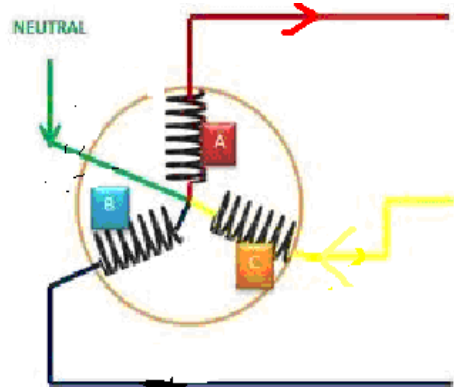
III. Hall signal 110



IV. Hall signal 010



V. Hall signal 011



VI. Hall signal 001

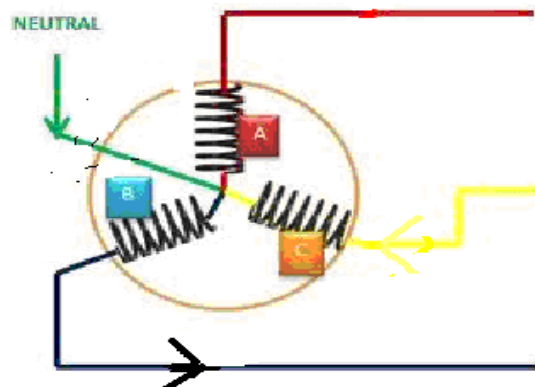
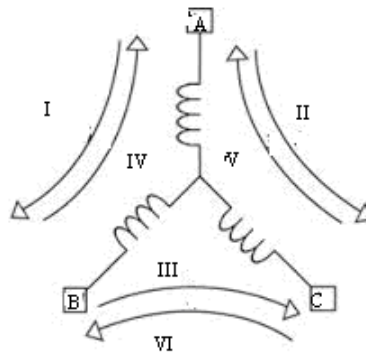


Fig. 2.6 Commutation corresponding to Hall signals

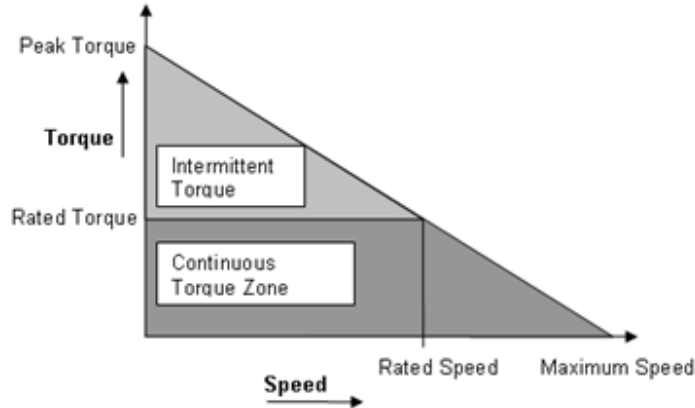
Fig. 2.7 shows how the rotating magnetic field is produced in three phase star connected BLDC motor.



**Fig. 2.7** Generation of rotating flux

The brushless DC motor is the combination of permanent excited synchronous motor and frequency inverter. The inverter replaces the commutator of conventional DC motor. In BLDC motor electronic commutation sequentially energizes the stator coils generating a rotating magnetic field that drags the rotor around with it. In BLDC motor the hall sensors are attached to the stator that act as a position sensor. It faces magnets perpendicularly and can distinguish if the north or south pole is in front of it. The brushless motors are generally controlled using three phase power semiconductor bridge. Power semiconductor bridge is nothing but a three phase inverter. The three phase inverter with  $120^\circ$  conduction mode VSI (voltage source inverter) is used in trapezoidal BLDC while  $180^\circ$  conduction mode VSI (voltage source inverter) is used in sinusoidal BLDC. In sinusoidal BLDC optical encoders are used as position sensor. 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 rotor position, the power devices are commutated sequentially every  $60^\circ$  electrical [6]. In BLDC motor electronic commutation is done unlike the mechanical commutation as done in conventional DC motor. This eliminates the problems associate with the brush and commutator arrangement for sparking and wearing out of the cummutator brush arrangement, thereby making BLDC more reliable and durable as compare to DC motor. The torque is at its maximum when the angle between rotor flux and stator flux is  $90^\circ$  i.e. the rotor starts to move, but it reduces as the two fields align to each other or we can say torque is zero when angle between stator flux and rotor flux is zero. The stator produces the rotating magnetic flux and rotor tries to catch up with the field generated by the stator the rotor will keep rotating. Since the magnetic field of the stator and rotor both rotate at same frequency,

they come under the category of synchronous motor. This switching of the stator to build up the rotation is known as commutation or the change of current excitation in stator. For three phase winding, there are 6 six steps in the commutation i.e. 6 unique combination in which the motor windings will be energized which are nothing but six possible outcomes of hall sensors. Fig. 2.8 shows torque versus speed characteristic of BLDC motor.

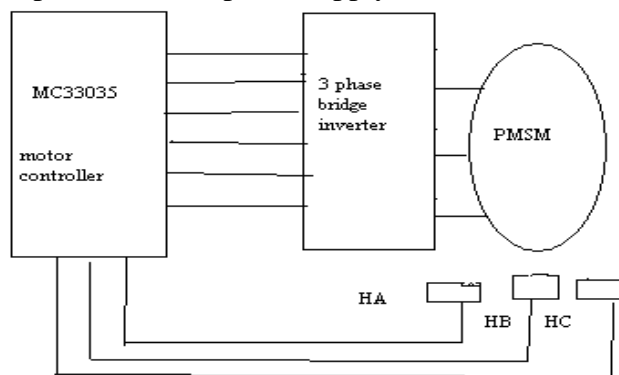


**Fig. 2.8** Torque versus speed Curve

- a) With an increase in speed, the torque reduces (considering the input power is constant).
- b) Maximum power can be delivered when speed is half of the no load speed and torque is half of start torque.
- c) output power of motor = torque × angular velocity (1)
- d) input power of motor = voltage × current (2)
- e) Efficiency of motor =  $\frac{\text{output power}}{\text{input power}}$  (3)

## 2.5 DRIVING CIRCUIT OF BLDC MOTOR

Fig. 2.9 shows the driving circuit of BLDC motor. HA, HB, HC are three hall sensors placed at 120° electrical from each other. MC33035 is motor controller followed by three phase 120° conduction inverter which provides three phase supply to brushless dc motor.



**Fig. 2.9** Driving Circuit of BLDC Motor

## 2.6 THREE PHASE BRIDGE INVETER (120° conduction)

Three phase inverters are more common than single phase inverters because they provide adjustable frequency [7]. Three phase inverter, like single phase inverter take their dc supply from battery or more usually from rectifier. A rectifier converts AC voltage into dc voltage which fed to inverter. A three phase inverter is a six step bridge inverter [6]. It uses a minimum of six switches, switches can be thyristor, IGBT and MOSFET depends upon firing frequency and power supply. Turning ON or OFF these switches is controlled externally. Each step would be 60° interval for a six step inverter. These switches are gated at 60° interval in proper sequence to produce 3 phase AC at output of inverter. A large capacitor connected at the input terminal tends to make the input DC voltage constant also suppresses the harmonics fed back to the dc source. There are two types of three phase bridge inverter one is 120° conduction mode another is 180° conduction mode, in 120° each switch conducts for 120° cycle and in 180° each switch conducts for 180° cycle. But in both these modes commutation take place every 60° electrical for completing one electric cycle of voltage at output.

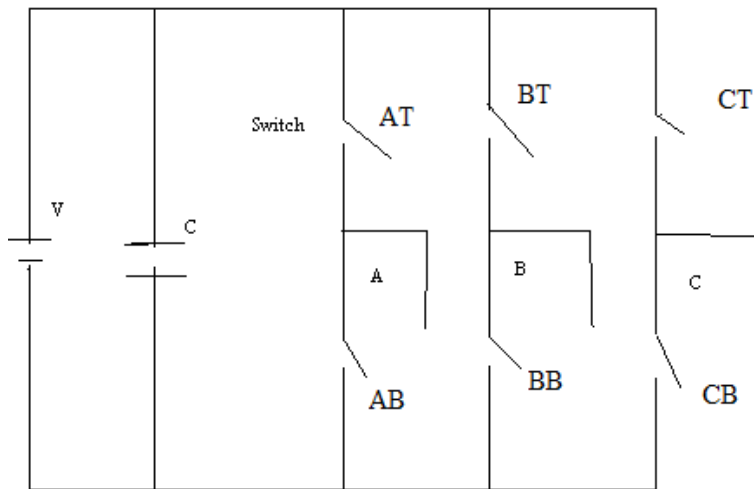


Fig. 2.10 Three Phase Bridge Inverter

## 2.7 HALL SENSORS

BLDC motor use electronic commutation, it uses Hall Effect sensor to measure the motor's position [5]. Hall sensors work on principle of Hall Effect which states that when magnetic field is applied to current carrying device perpendicularly then voltage will appear across its two terminals [7]. It can be easily derived, the force acting on a moving charge when placed in magnetic field is:

$$F = Q(V \times B) \quad (4)$$

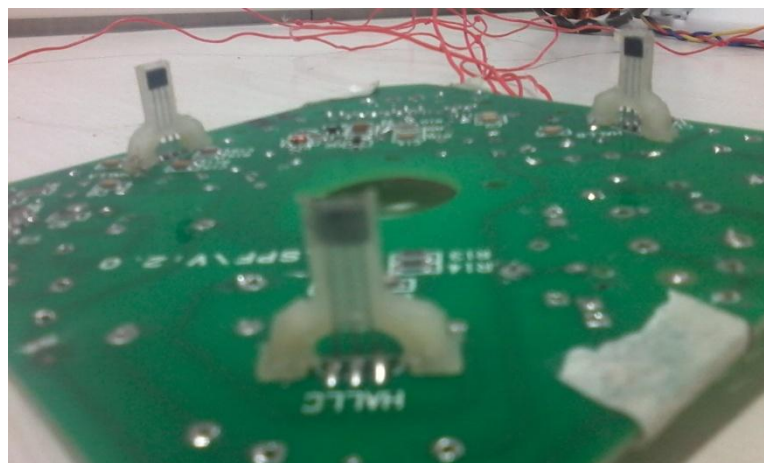
Where,  $Q$  is the moving charge

$V$  is the velocity of charged particle

$B$  is the magnetic field applied

The term  $V \times B$  is the vector product hence force will appear perpendicular to plane of  $V$  and  $B$ . So magnetic field is required to activate the hall sensor. These hall sensors are operated by magnetic field from the permanent magnet, responding to south and north poles by giving high or low signal respectively. Selecting the right hall sensor is must for higher efficiency because it tells about time of commutation, and also through which coil the current should flow to continue the rotation. The parameters that should be considered while selecting the hall sensor is sensitivity, repeatability, and stability over temperature and response time [8].

Sensitivity level is based on the placement of sensor to the magnet, the air gap and magnet strength. Higher Sensitive sensors can response if air gap is more, magnetic field strength is low, and this allows the sensor to be placed away from magnet. The magnetic field strength required to make hall sensor change state is given in the data sheet. The high sensitivity sensors are typically rated at less than 60 gauss, allow for the use of smaller magnets or less expensive magnetic materials. Higher is the sensitivity, higher is the reliability, which providing some design flexibility for the same air gap. This means a hall sensor with higher sensitivity or a lower magnetic switch point delivers more efficient motor performance. Fig. 2.11 shows the position of Hall effect sensors on controller designed for three phase BLDC motor.



**Fig. 2.11** Position of Hall Effect sensors

Repeatability refers to the hall sensor latching time. As the magnet rotates past the sensor, a high repeatable sensor changes state at the same angular position each time the magnet passes by. A

high repeatable sensor is one that has steady response time, which will maintain all of angular measurements very close to the same value. To produce the maximum amount of torque on the shaft, the timing between current flowing through the coil and the position of shaft must be as precise as possible. If there is a delay in the sensor's reaction to change in the magnetic field, this slower response can lead to errors. Any error in the switching point of the Hall Effect sensor will reduce the torque of the motor, which results in lower motor efficiency.

Response time is the time it takes for the output of the sensor to change state. For example if a sensor has an operating point of 40 gauss and 40 gauss magnetic field level is applied to the sensor, the response time is measure from the point when the 30 gauss field is applied to when the output state changes. A faster response time to a change in magnetic field delivers greater efficiency in commutating a BLDC. If a sensor switches at a different magnetic field level than what is required, will result in precision errors. Motor needs to switch at a very specific point to achieve the highest efficiency. Miss-commutation results in lower effective torque constant and higher torque ripple that can cause additional noise as well as impact efficiency and system performance.

## **2.8 SWITCHING ELEMENTS**

The most commonly used switching elements are SCR, BJT, MOSFET, and IGBT. Depending upon switching frequency [10] and application these elements are chosen.

### **Insulated gate bipolar transistor (IGBT):**

IGBT is a semiconductor device with three terminals known as emitter, collector and gate. It is a type of transistor which can handle sophisticated amount of power and has a lower switching speed making it higher efficient. IGBT was introduced in 1980s. IGBT has the combined features of both MOSFET and Bipolar junction transistor (BJT). It is gate driven like MOSFET and has current voltage characteristics like bipolar junction transistor (BJT). Therefore it has the advantage of both high current handling capability and ease of control. IGBT modules can handle KW of power. The advantages of IGBT are summarized below. They are preferred devices under these conditions:

- a) Low duty cycle
- b) Low frequency
- c) Narrow or small line or load variation
- d) High voltage application

- e) Operation at high function temperature is allowed
- f) Above 5 kW output power

The typical IGBT application includes:

- a) Motor control : frequency less than 20 kHz
- b) Uninterruptible power supply: constant load, typically low frequency
- c) Welding : high average current, low frequency
- d) Low power lighting : low frequency

### **Metal oxide semiconductor field effect transistor (MOSFET):**

MOSFET is a type of field effect transistor which is made of three terminals known as gate, source, and drain. Here drain current is controlled by gate voltage. Therefore MOSFETS are voltage controlled devices. MOSFETS are available in four different types such as n-channel or p-channel with either in depletion or enhancement mode. Drain and source are made of n type semiconductor for n-channel MOSFETS and similarly for p-channel devices. Gate is made of metal and separate from source and drain using metal oxide. This insulation causes low power consumption and it is an advantage in MOSFET. Therefore MOSFET is used in digital CMOS logic where p-channel and n-channel MOSFETS are used as building blocks to minimize power consumption. The advantages of MOSFET are summarized below. They are ideal devices under these conditions:

- a) High frequency application
- b) Wide line or load variation
- c) Long duty cycle
- d) Low voltage application
- e) Output power less than 500W

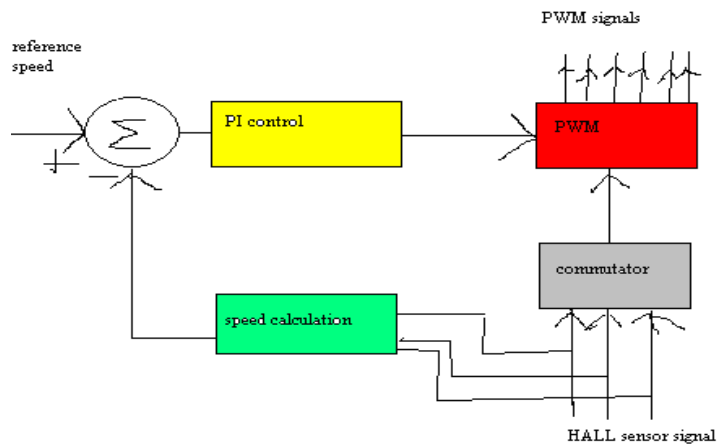
The typical MOSFETS application includes:

- a) Switched mode power supply (SMPS): Hard switching above 200kHz
- b) Battery charging

## **2.9 SPEED CONTROL OF BRUSHLESS DC MOTOR**

When properly commutation is established which results in production of rotating stator flux, ensuring the proper rotation of the motor then the motor speed can be regulated by regulating the amplitude of the applied voltage. There are two modes to control the applied voltage either by open loop control or by closed loop control. In open loop control speed is regulated by changing

the supply voltage. In closed loop control conventional PI controller is used as a speed controller for recovering the actual motor speed to the reference speed. The reference and the measured speed are the input signals to the PI controller. The  $K_p$  and  $K_i$  values of the controller are determined by trial and error method for set speed [8]. In closed loop control the amplitude of the applied signal is adjusted by pulse width modulation (PWM) technique using PI controller [11] as shown in Fig. 2.12. The proportional action increases the loop gain and makes the system less sensitive to variations of system parameters while integral action eliminates or reduces the steady state error [9]. By controlling the duty cycle of pulse width modulation (PWM) signal, the amplitude of applied voltage can be controlled, which in turn will control the speed of the motor. The PWM signal logically ANDED with the switch control signal is used to control the power applied to the motor. It can either control the voltage on the motor with fixed PWM duty cycle or the current by means of an integrated current control circuitry. Speed control of brushless dc motor is accomplished by the pulse width modulation of the stator coil voltage [16]. When the PWM signal controls the voltage, the motor is driven in voltage mode, when it is controlling the current; the motor is driven in current mode. Voltage mode controls the speed easily by changing the motor reference voltage. It does not give fine control of current but current can be limited externally using resistor divider and consequently torque to the maximum value. The voltage control is done by the PWM duty cycle. Current mode permanently controls the torque by changing the motor reference current because torque is proportional to current. The current in the winding is regulated in real time and there is a true DC current flowing through DC bus. Current mode also allows the current for each of the 6 steps to be finally controlled as the current control is done during PWM cycle.



**Fig. 2.12** Closed loop speed control

$$\text{Duty cycle} = \frac{T_{\text{on}}}{T_{\text{on}} + T_{\text{off}}} \quad (5)$$

$$\alpha = \frac{T_{\text{on}}}{T} \quad (6)$$

The difference between the required speed and actual speed is input to the PI controller, which then modulates the duty cycle of the PWM based on error signal obtained by the difference between the actual speed and required speed. Fig. 2.13 shows the change in applied voltage by applying pulse width modulated signals.

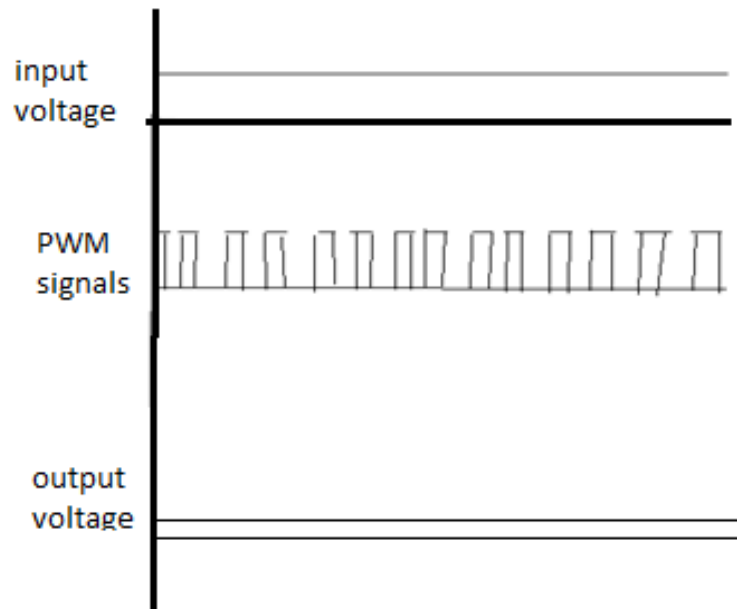


Fig. 2.13 Pulse width modulated signals

## 2.10 TORQUE CONTROL OF BRUSHLESS DC MOTOR

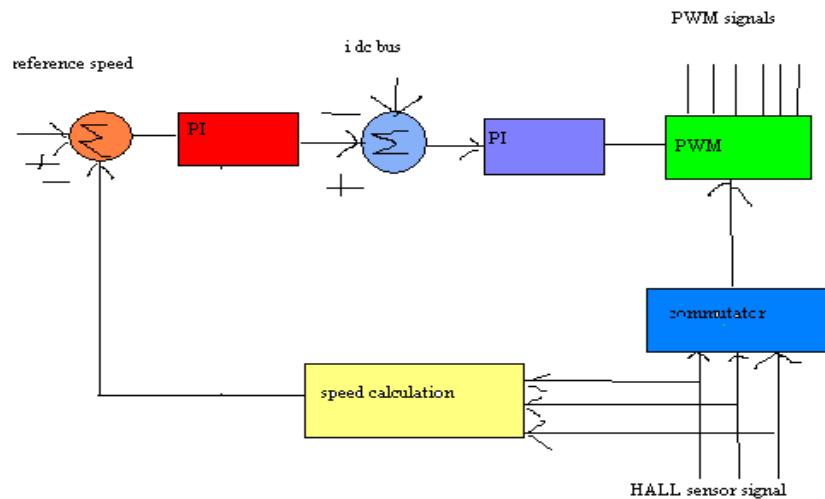


Fig. 2.14 Closed loop torque control

Torque is another important parameter of the electric machine. Torque of fan motor is constant as the fan is running [5]. Torque can be controlled by adjusting the magnetic flux. However magnetic flux is dependent upon the current flowing through the winding. Thus by controlling current, torque of a motor can be controlled as shown in Fig. 2.14. A PI loop similar to that used to control speed can be implemented to smooth the torque response curve with changes in load.

## CHAPTER 3

### CONTROLLER SIMULATION

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#### 3.1 INTRODUCTION

Those systems in which the output has no effect on the control action are called open loop control system. In other words in an open loop control system the output is neither measured nor feedback for evaluation with the input. Example is a washing machine. Soaking, washing, and rinsing in the washer operate on a time basis. The machine does not measure the output signal that is the cleanliness of the clothes. In any open loop control system the output is not compare with the reference input [17]. Thus to each reference input there corresponds a fixed operating condition, as a result the correctness of the system depends on calibration. In the presence of disturbances, an open loop control system will not perform the preferred task. Open loop control can be used inside practice only if the connection between input and output is known and if there are neither internal nor external disturbances. Clearly, such systems are not feedback control system. For example traffic control by means of signal operated on a time basis is another example of open loop control. A system that maintains a prescribed connection between the output and the reference input by comparing them and using the difference as a means of control is called feedback control system. An example would be a room temperature control system. By measuring the actual room temperature and comparing it with the reference temperature (desire temperature), the thermostat turns the heating or cooling equipment on or off in such a way as to make sure that room temperature remains at a comfortable level regardless of outside condition. Feedback control system is not limited to engineering but can be found in various non engineering fields as well. The human body for instance is a highly advanced feedback control system. Both body temperature and blood pressure are kept constant by means of physiological feedback. Feedback control system is often referred to as closed loop control system. In practice, the term feedback control and closed loop control are used interchangeably. In a closed loop control system the actuating error signal, which is the difference between the input signal and the feedback signal, is fed to the controller so as to reduce the error and bring the output of the system to a desired value. The term closed control always implies the use of feedback control action in order to reduce error system error. An advantage of the closed loop control system is the fact that the use of feedback makes the system response relatively insensible to external

disturbances and internal deviation in system parameters. It is thus possible to use relatively inaccurate and inexpensive components to obtain the accurate control of a given plant, where as doing are impossible in open loop case. From the point of view of steadiness, the open loop control system is easier to build because system stability is not a major problem. On the other hand, stability is a major problem in the closed loop control system. This may tend to overcorrect errors and thereby can cause oscillations of constant or changing amplitude. It should be highlighted that for system in which the inputs are known ahead of time and in which there are no disturbances, it is advisable to use open loop control. Closed loop control systems have advantages only when unpredictable turbulence and/or unpredictable deviations in the system components are present. The number of components used in a closed loop control system is more than that for a corresponding open loop control system. Thus, the closed loop control system is generally higher in cost [17]. Advantages of open loop control system are Simple construction, ease of protection and less expensive that corresponding closed loop system. Disadvantages of open loop system are disturbances and changes in calibration cause errors, the output may be different from what is preferred and to maintain the required quality in the output, recalibration is necessary from time to time. In this chapter open control and closed loop system for brushless dc motor is discussed and controller simulation is done in matlab software.

### 3.2 OPEN LOOP CONTROL OF BLDC MOTOR

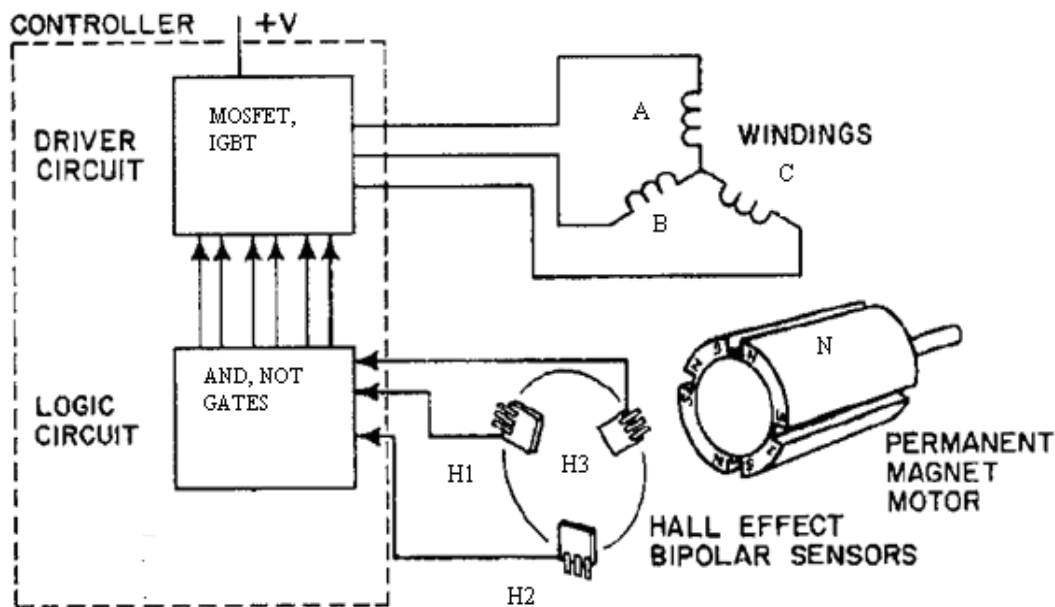


Fig. 3.1 Open loop control system for brushless dc motor

In Open loop control system Hall effect sensor senses the North Pole or South Pole in front of it by giving high signal or low signal respectively as shown in Fig. 3.1. These hall sensors are placed at 120° electrical apart to complete one 360° electrical revolution. There are total six possible combinational outcomes of hall sensor 100,101,011,001,010,110. These signals tell when commutation will take place also sequence in which stators should be energized to produce rotating magnetic field. Commutation occurs when these signal changes. These signal changes every 60° electrical revolution, Hence the commutation take place every 60° electrical revolution. Once hall signals are received the gate logic circuit tells which two switches will be turn on. Gate logic is nothing but combination of AND gates and NOT gates. The gate logic can be derived from Karnaugh map. As we know there are total six switches of inverter each switch is on for 120° electrical revolution .Corresponding to hall signal these switches signals are drawn which is nothing but gate signals. The logic of gate signals is derived from Karnaugh map as shown below.

### 3.3 GENERATION OF GATE LOGIC

Fig. 3.2 shows the hall signals, phase current, and back EMF voltage waveforms for one complete electrical cycle. From this figure it can be seen that gate signals remains ON for 120° electrical for each switching element as shown in Fig. 3.3. For each switching element K-map is drawn as shown in Fig. 3.4.

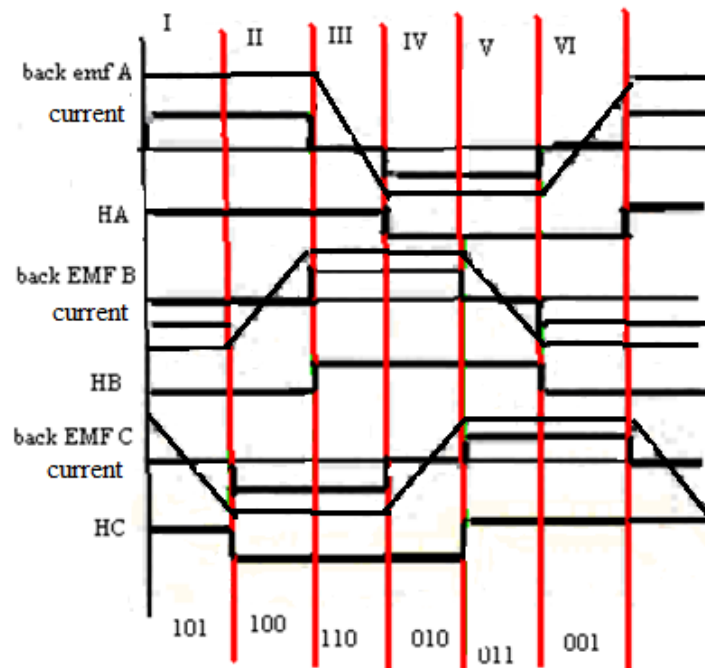


Fig. 3.2 Back EMF, Current and Hall sensor waveforms

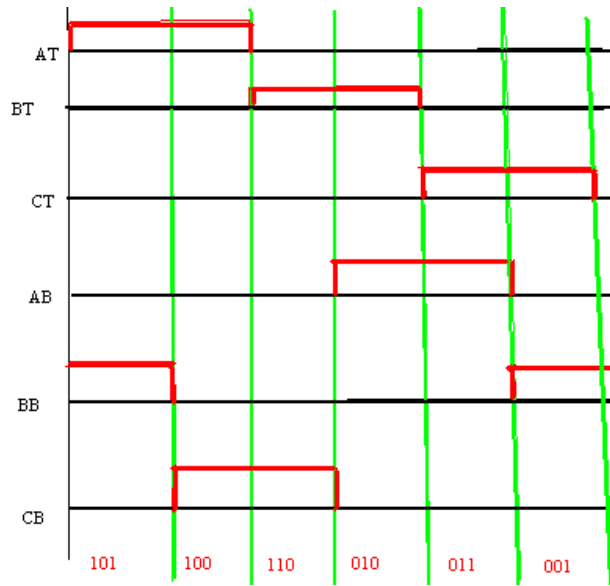


Fig. 3.3 Gate Signals

AT

		HC	
		0	1
HA	HB		
	00		
	01		
	11		
	10	1	1

BT

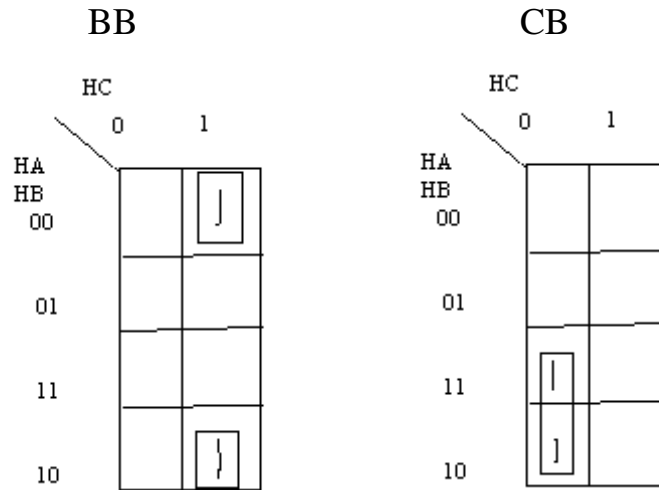
		HC	
		0	1
HA	HB		
	00		
	01	1	
	11	1	
	10		

CT

		HC	
		0	1
HA	HB		
	00		
	01		1
	11		
	10		

AB

		HC	
		0	1
HA	HB		
	00		
	01	1	1
	11		
	10		



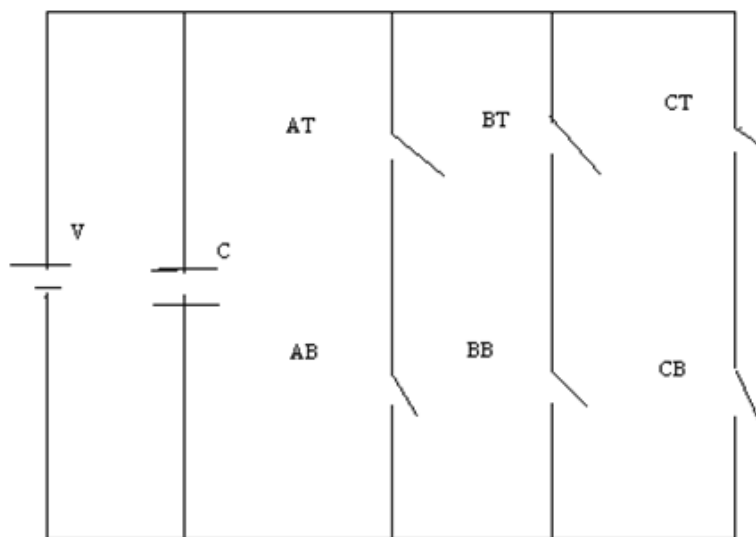
**Fig. 3.4** Karnaugh map of Hall signals

From karnaugh map we derive the gate logic which will turn on the corresponding MOSFET.

Table 5.1 shows hall signals to turn ON corresponding MOSFET.

$AT = HA * \text{not } HB$	A top
$BT = HB * \text{not } HC$	B top
$CT = \text{not } HA * HC$	C top
$AB = \text{not } HA * HB$	A bottom
$BB = \text{not } HB * HC$	B bottom
$CB = HA * \text{not } HC$	C bottom

**Table 3.1** Sequence of Hall signals



**Fig. 3.5** Sequence of Hall signals

### 3.4 MATLAB SIMULATION (SIMULINK)

The whole system is comprised of following parts:

- The main power circuit: Constant DC voltage source which provide 24V to driver circuit.
- The motor: The module “Permanent magnet synchronous motor” is selected with the waveform of air gap magnetic flux density being trapezoidal and the width of its flux part is 120 electrical.
- Measurement unit: this unit consists of bus selecting module “Bus selector,” which is used to measure the variables of the motor when it operating such as back EMF, current, rotor speed, torque etc.
- Logic unit: This unit consists of logical operator AND/NOT which are used for generating gate pulse signals for driving circuit.

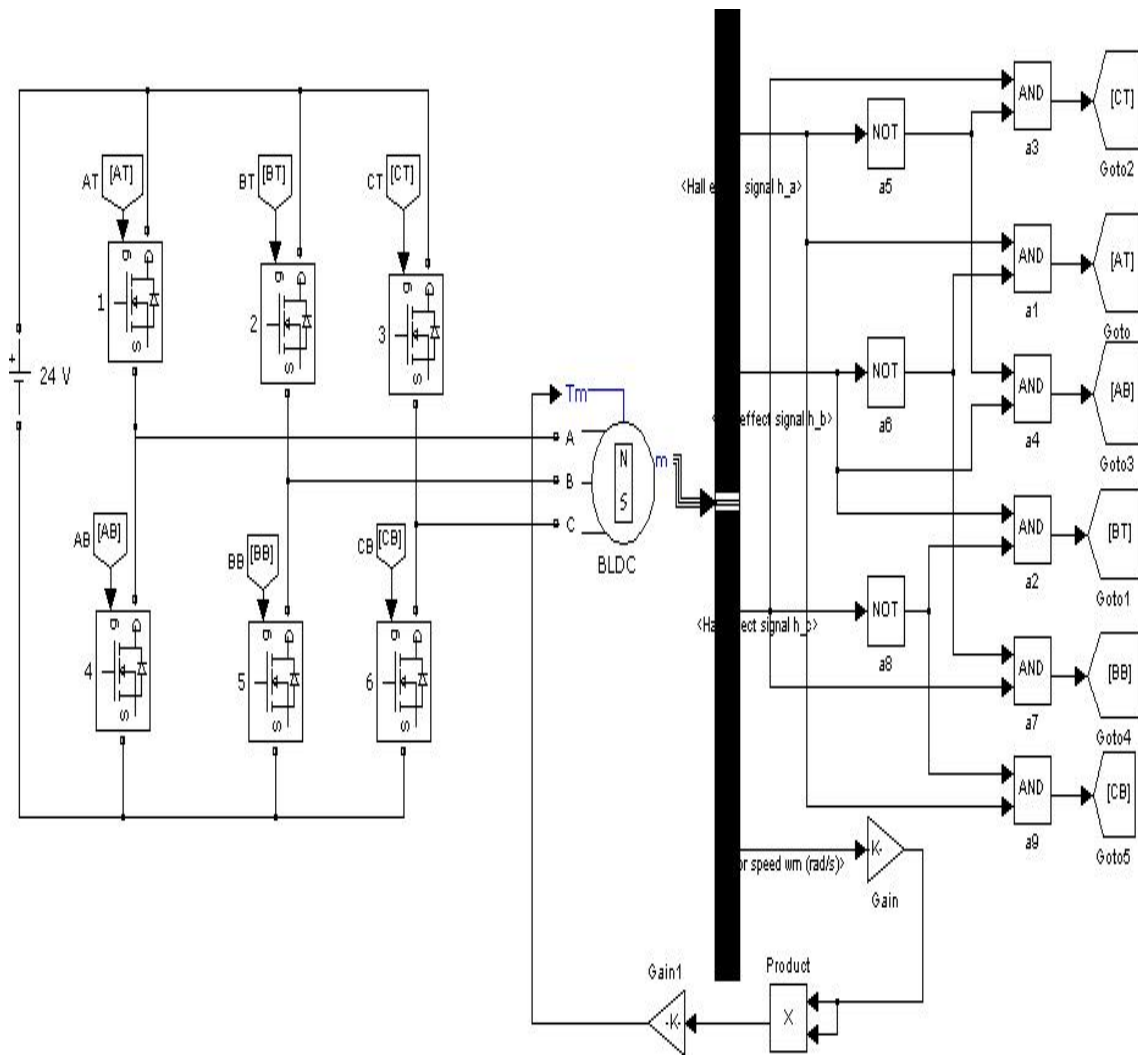


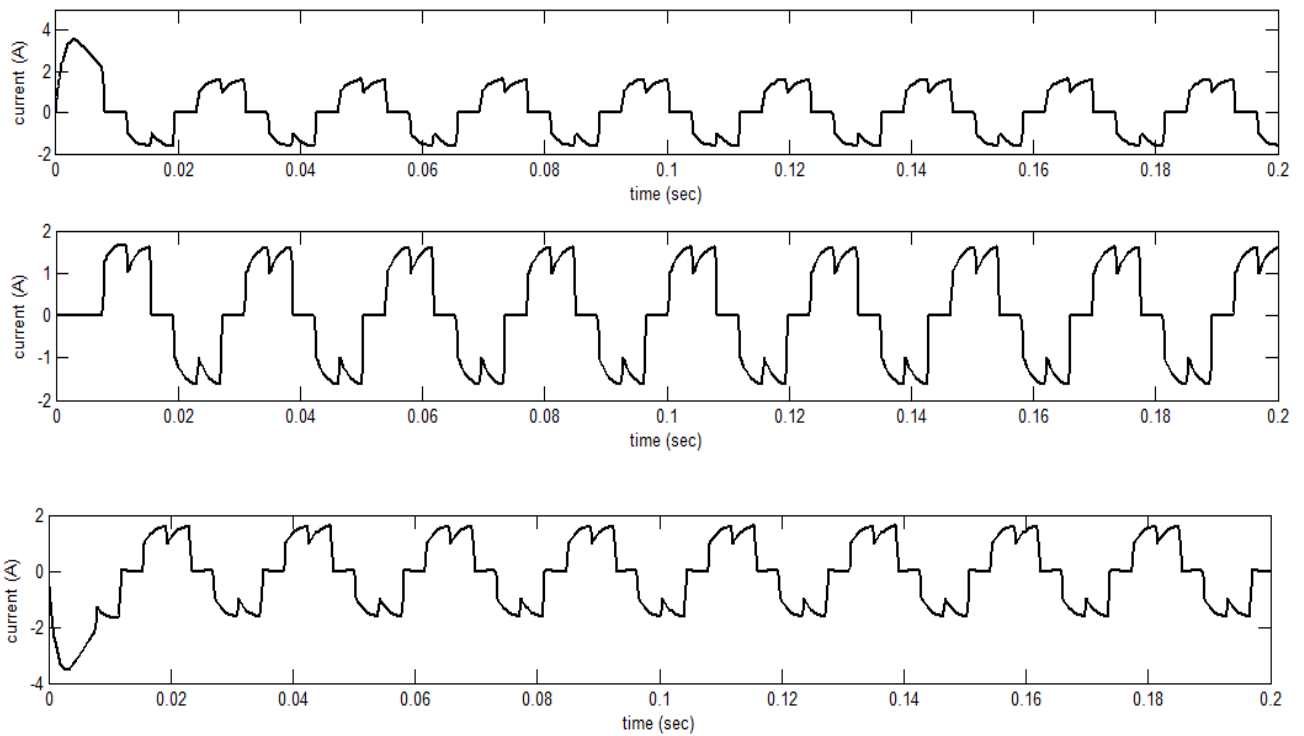
Fig. 3.6 Open Loop Control Simulation

Table 3.2 shows the input parameters of BLDC motor for simulation.

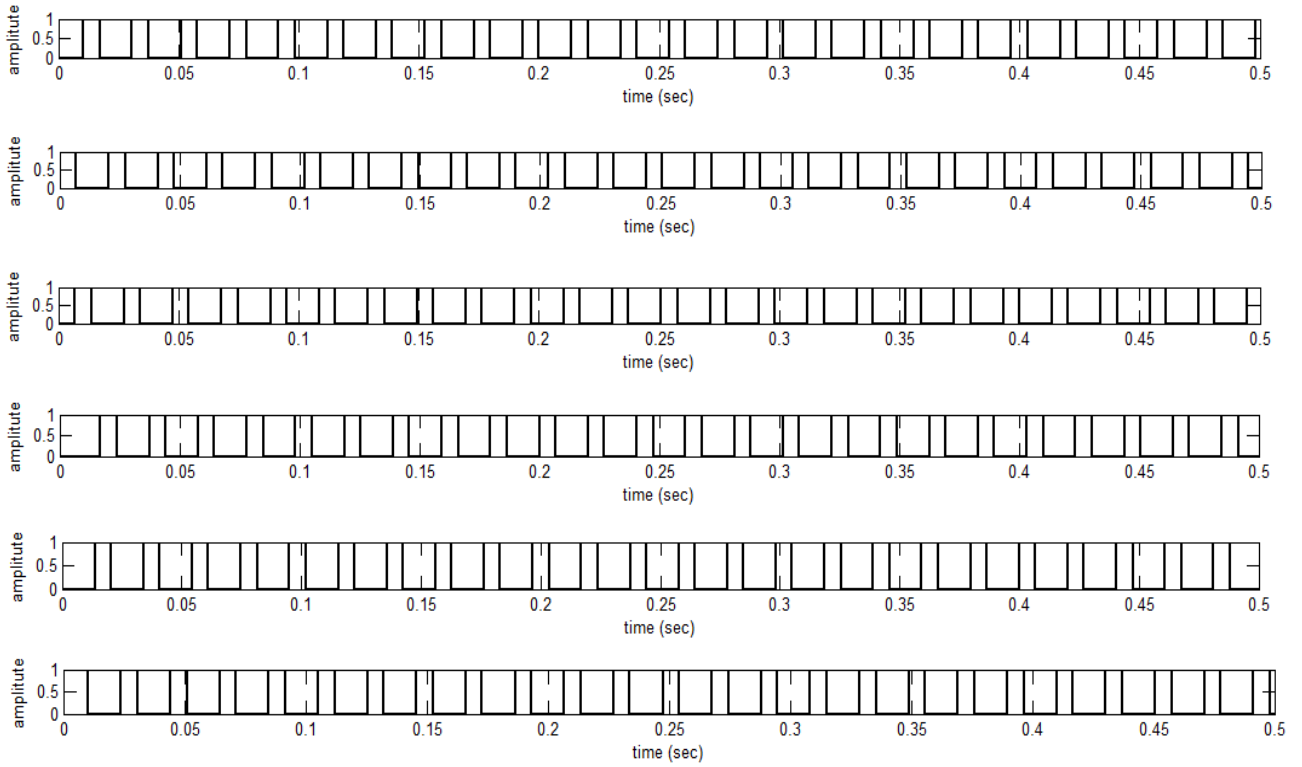
Phase resistance	2 ohm
Phase inductance	3 mH
Number of slots	18
Voltage constant	40 V/Krpm
Number of poles	16
Number of phases	3
Voltage input	24 V
Power input	40 W

**Table 3.2** BLDC Motor Specification

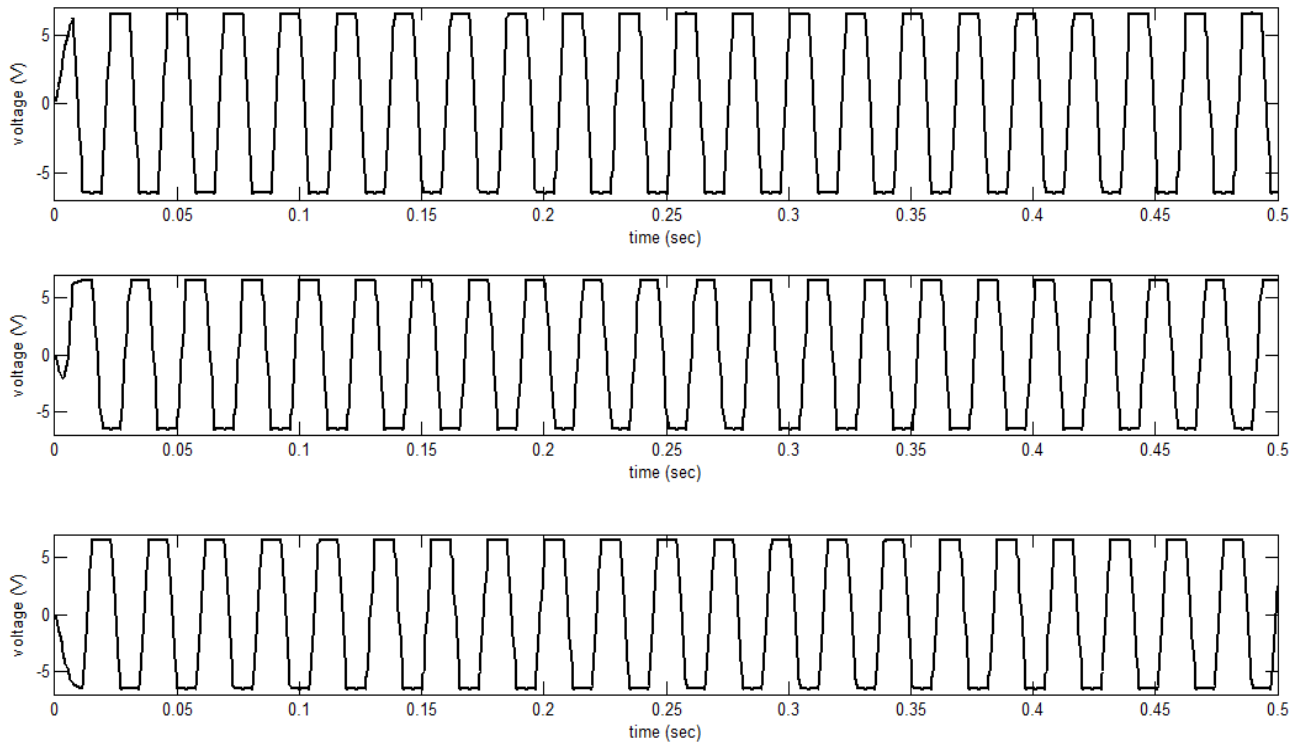
The simulation is performed in MATLAB. The simulation results for open loop operation of the motor are shown below:



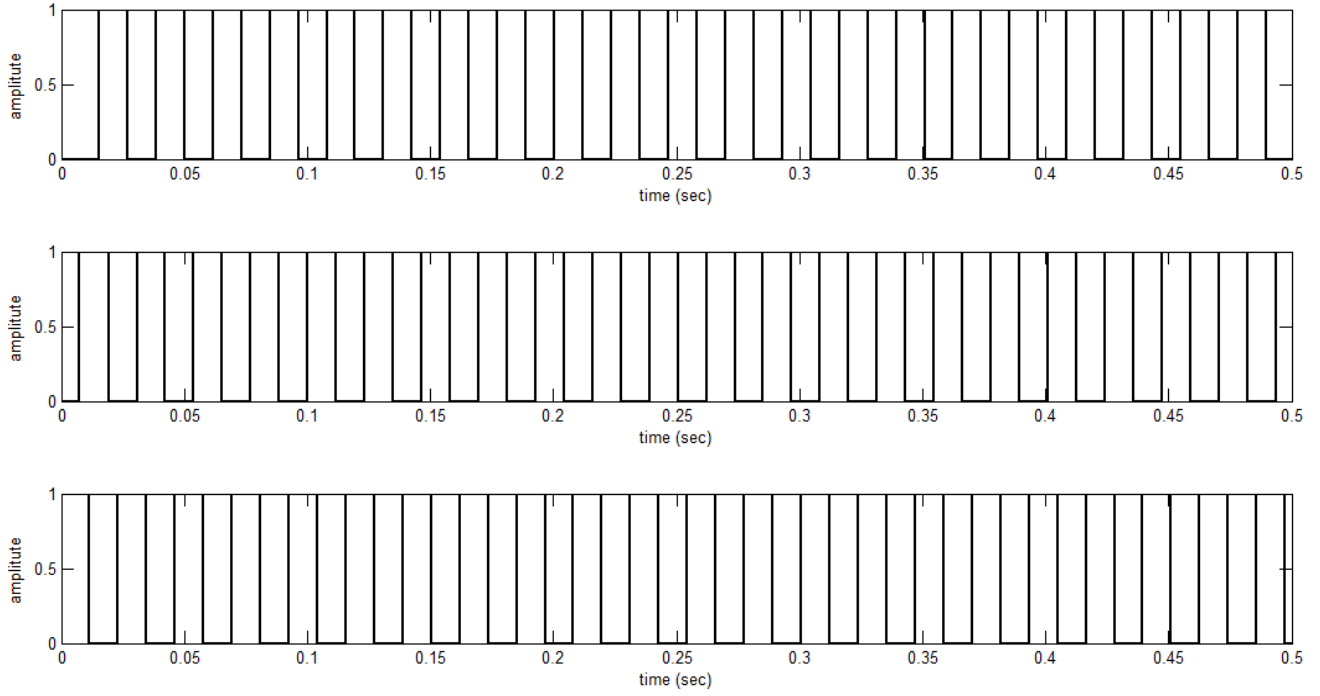
**Fig. 3.7** Stator Current versus time



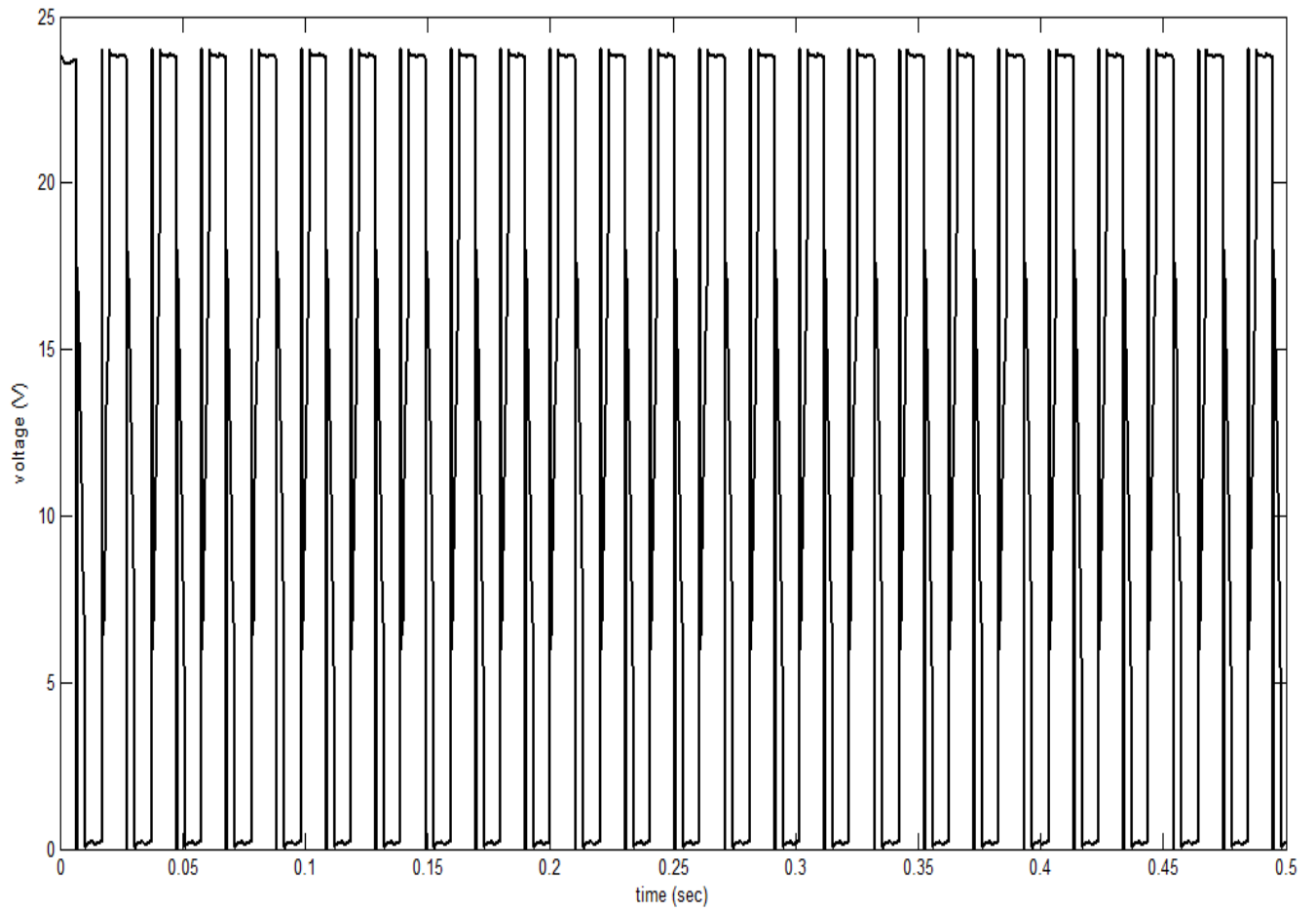
**Fig. 3.8** Gate signals versus time



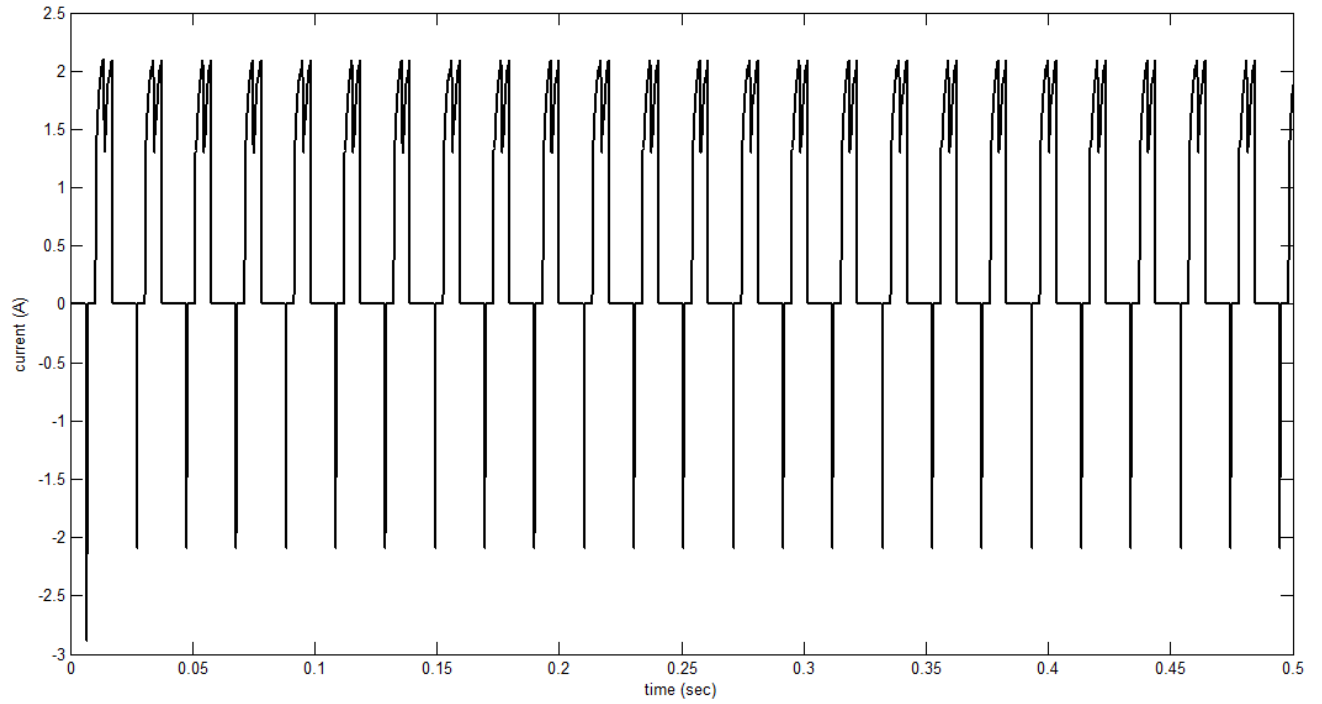
**Fig. 3.9** Phase Back EMF versus time



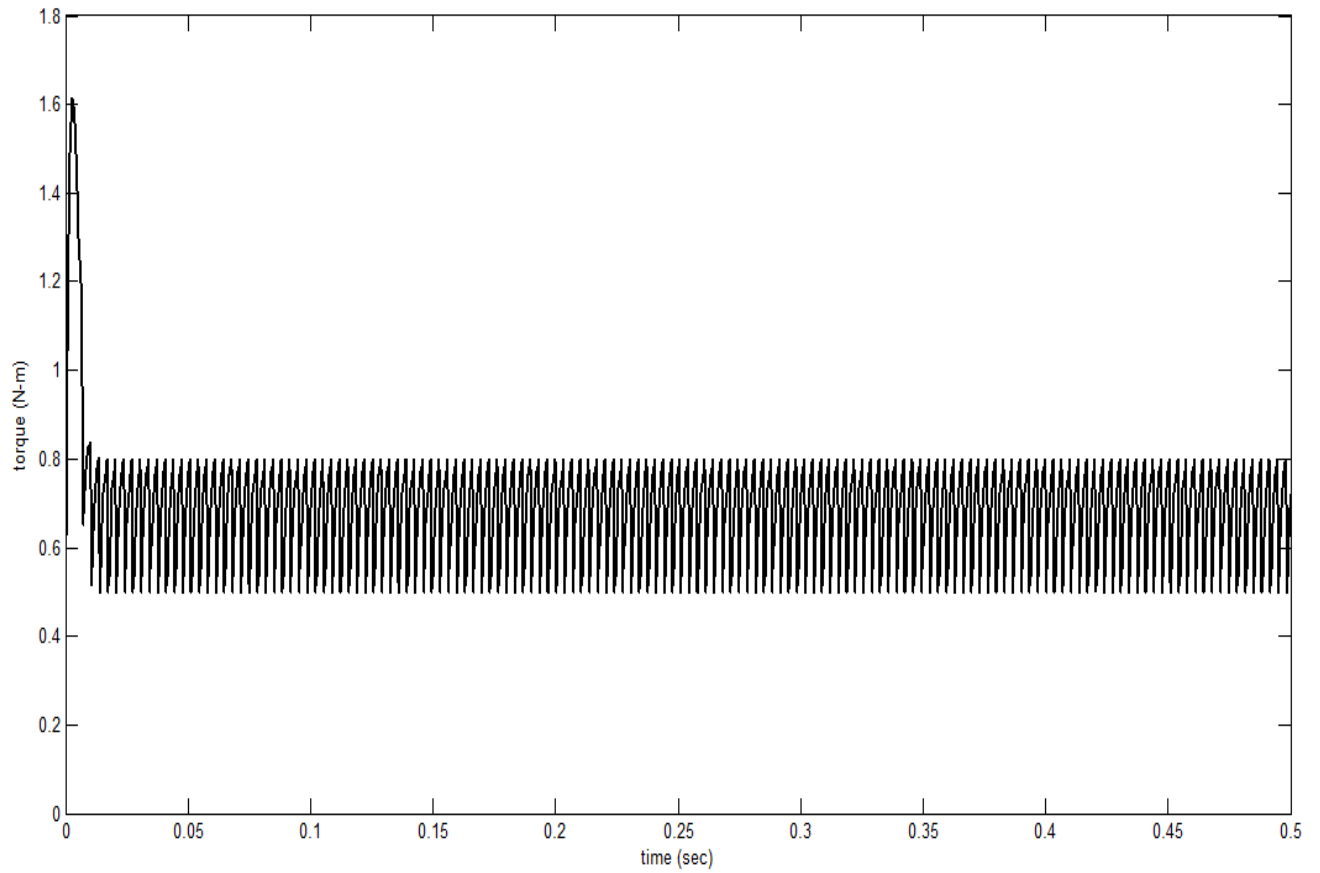
**Fig. 3.10** Hall Signals versus time



**Fig. 3.11** MOSFET voltage versus time



**Fig. 3.12** MOSFET current versus time



**Fig. 3.13** Torque versus time

As seen from the waveforms: The back EMF is of trapezoidal type, stator current is not pure quasi square wave because of commutation. Response of BLDC motor for different input voltage for open loop system is shown below:

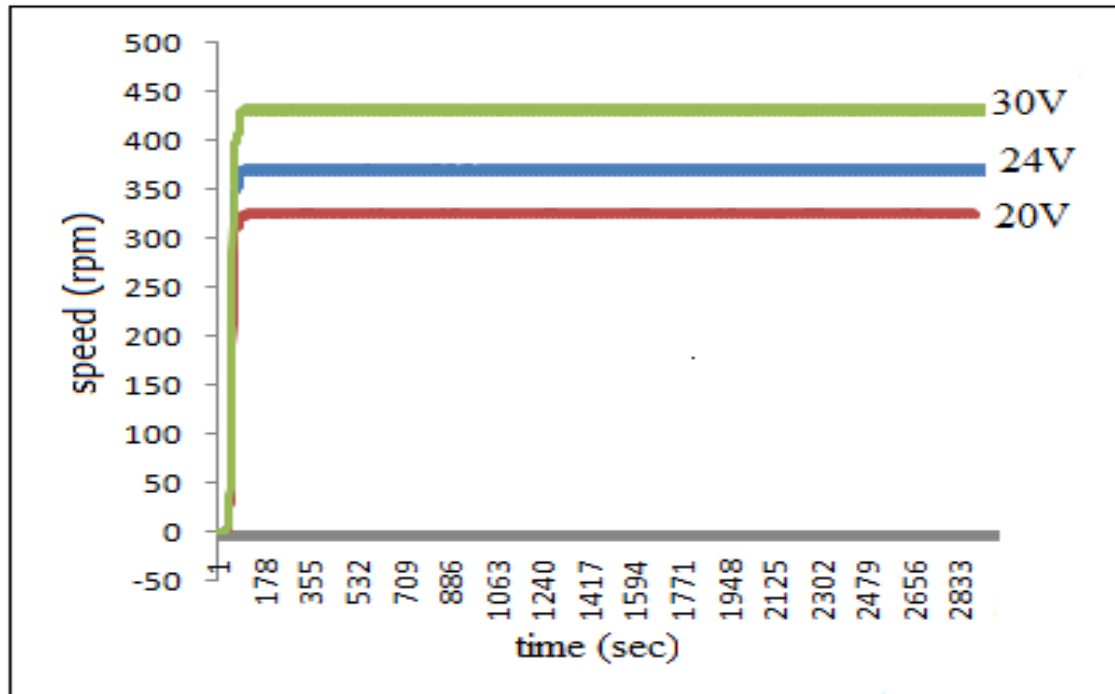


Fig. 3.14 Motor speed versus time

From speed time waveform it can be seen that speed of motor is directly proportional input voltage. Speed is a function of voltage. Speed of BLDC motor can be controlled by applied voltage. Fig. 3.13 shows the speed of motor for three different input voltage.

### 3.5 CLOSED LOOP CONTROL OF BLDC MOTOR

In closed loop control the speed of BLDC motor can be controlled using proportional integral (PI) controller, PI controller can regulate the duty cycle hence control the voltage applied to BLDC motor. Speed of BLDC motor is directly proportional to applied voltage. Speed of BLDC motor can be set to reference speed. Any diversion from this speed will be given as an error signal to PI controller. PI controller will take appropriate signal on receiving of this error signal, it can increase as well as decrease the duty cycle of applied gate signal.

### 3.6 MATLAB SIMULATION (CLOSED LOOP)

The whole system is comprised of following parts:

- a) The main power circuit: constant DC voltage source which provide 24V to driver circuit.

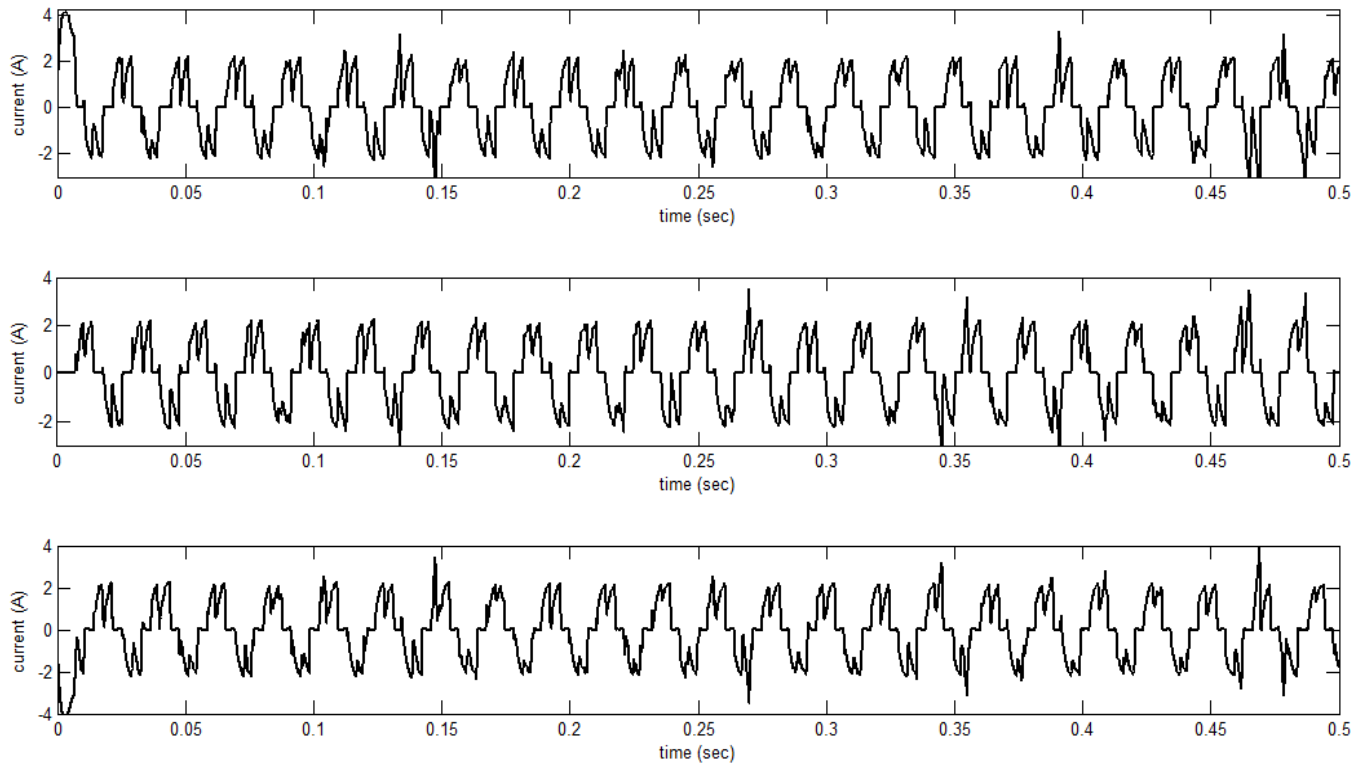


Table 3.2 shows the input parameters of BLDC motor for simulation

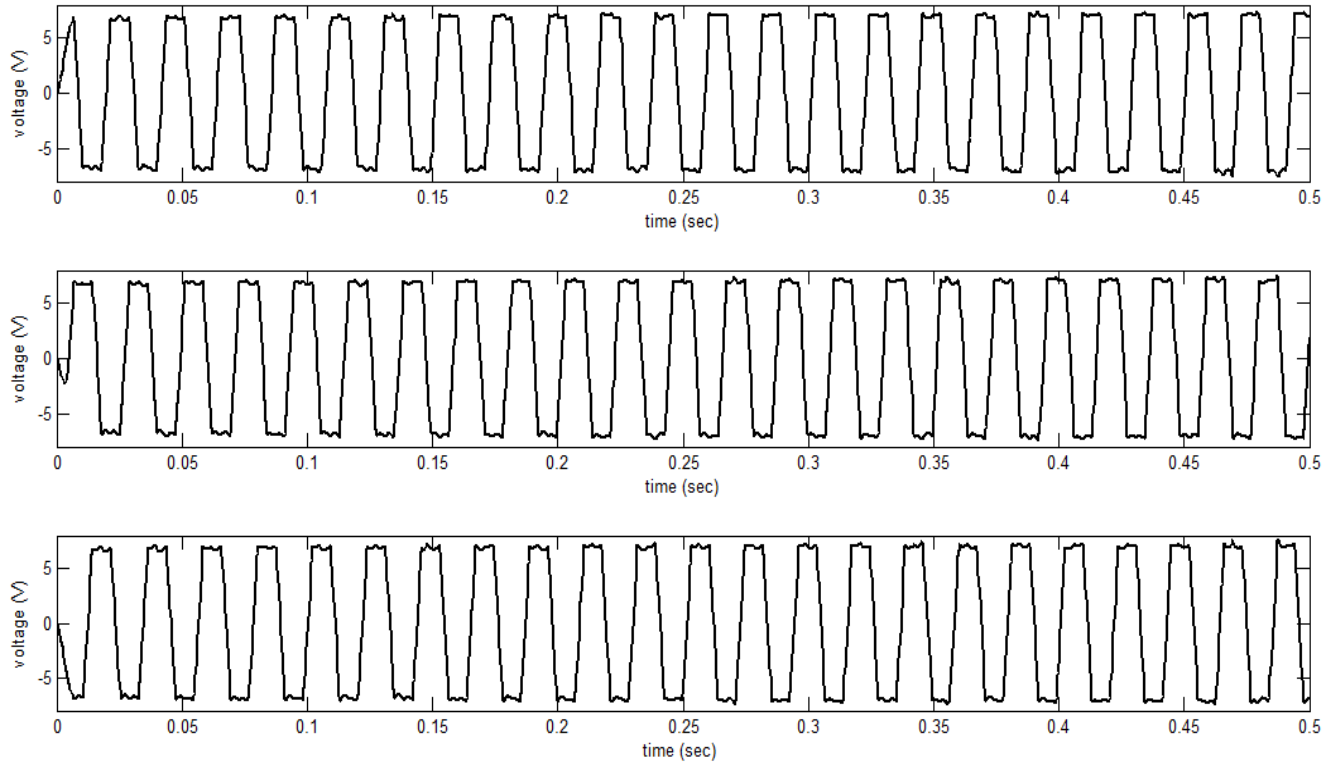
Phase resistance	2 ohm
Phase inductance	3 mH
Number of Slots	18
Voltage constant	40 V/Krpm
Number of poles	16
Number of phases	3
Voltage input	24 V
Power input	40 W
Proportional constant	0.0015
Integral constant	0.25

**Table 3.2** BLDC Motor Specifications

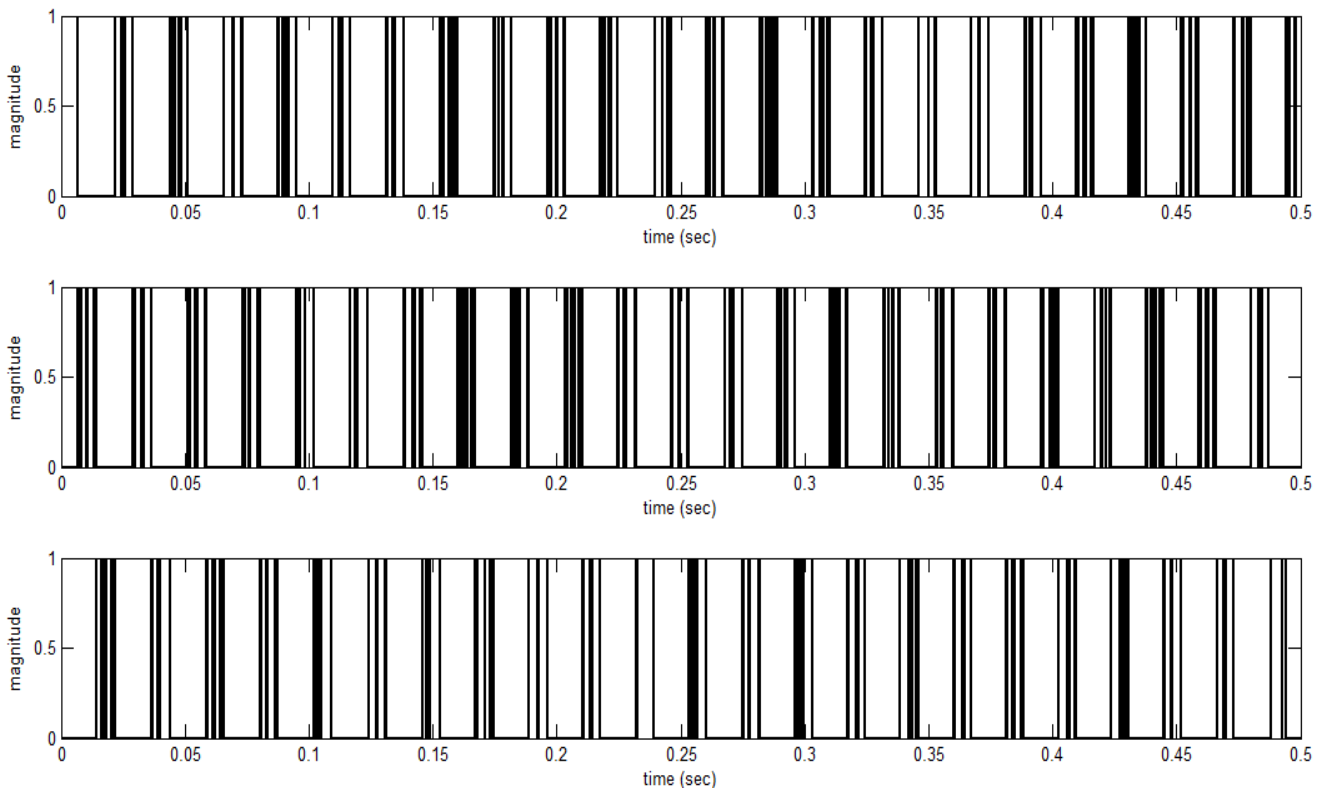
The simulation is performed in MATLAB. The simulation results for closed loop operation of the motor are shown below:



**Fig. 3.16** Stator Current versus time



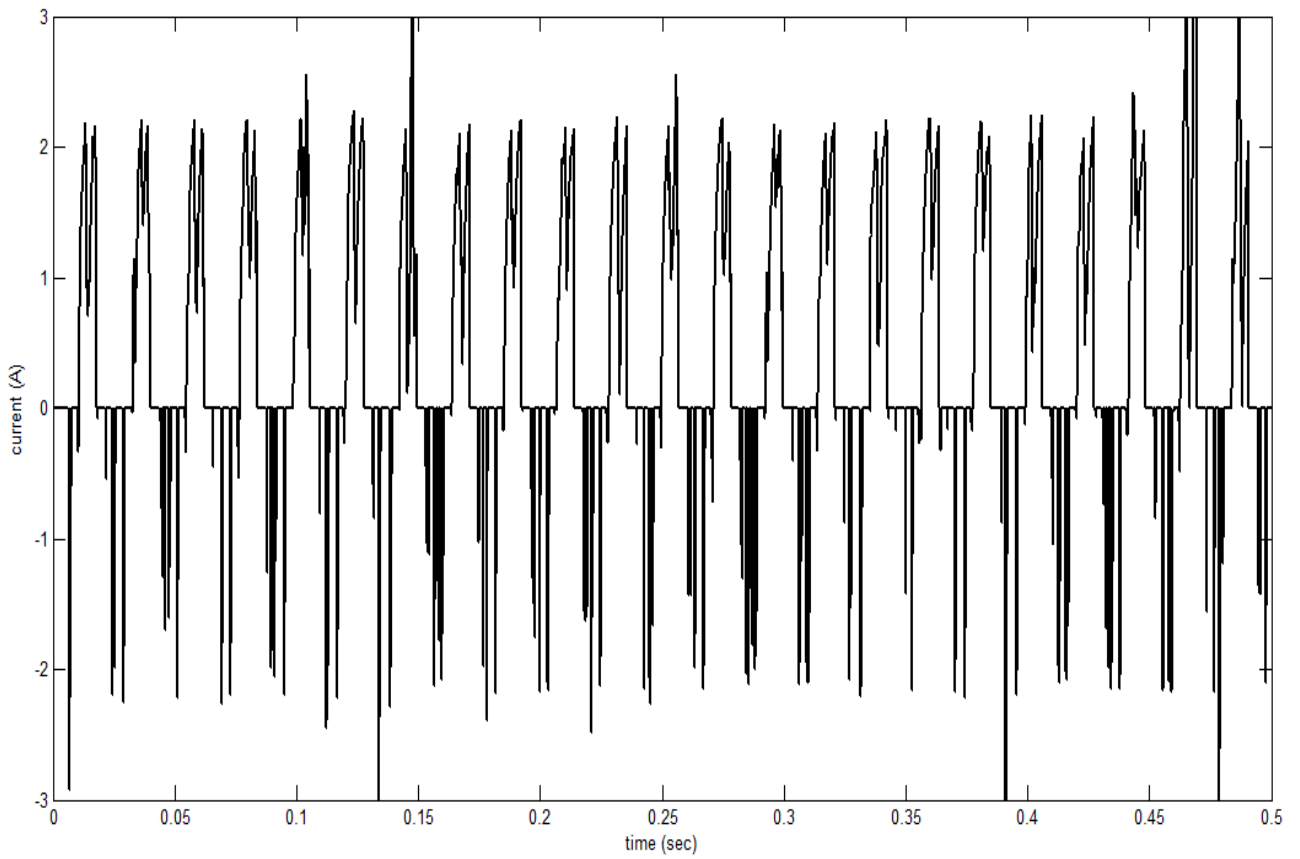
**Fig. 3.17** Back EMF versus time



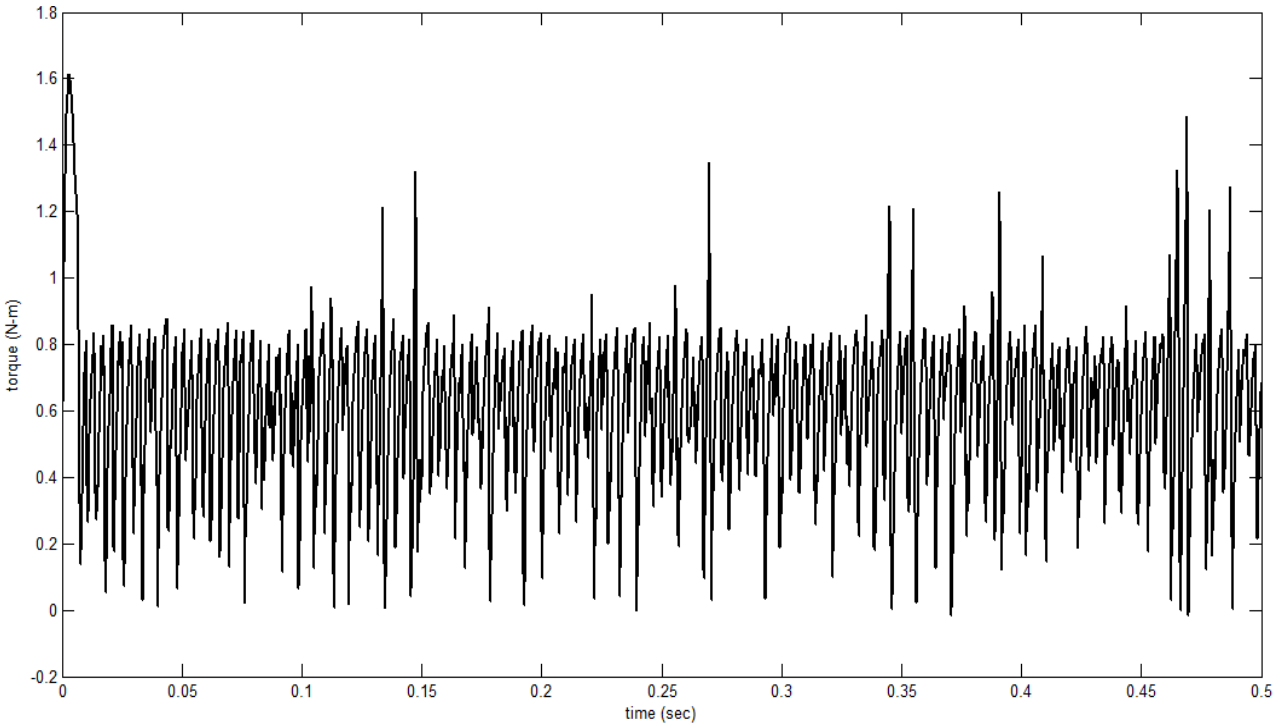
**Fig. 3.18** Gate signals versus time



**Fig. 3.19** MOSFET voltage versus time



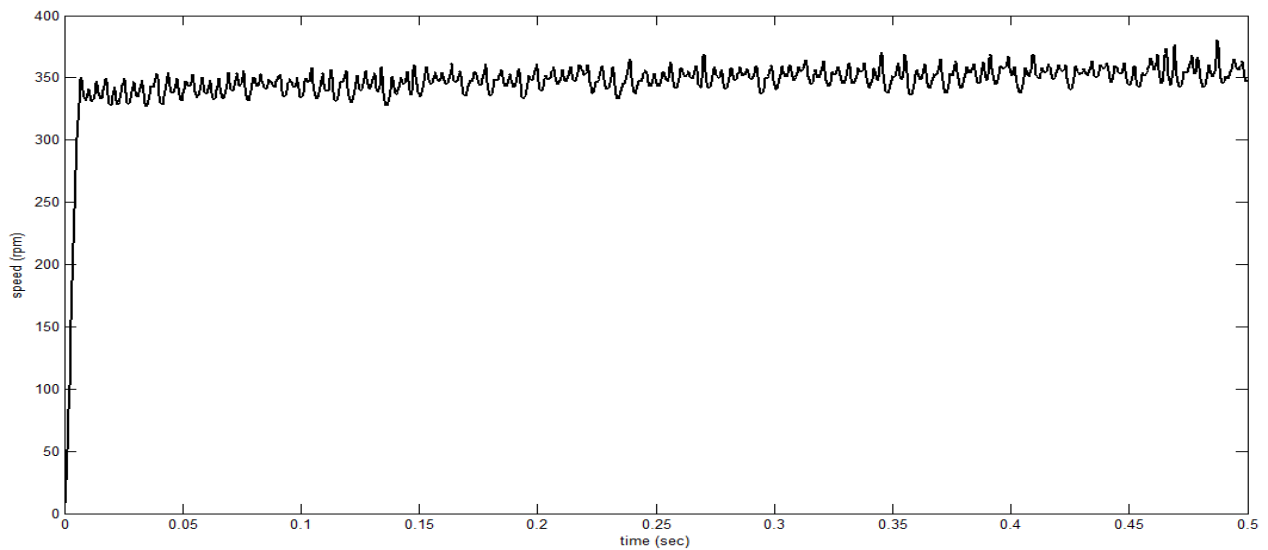
**Fig. 3.20** MOSFET CURRENT versus time



**Fig. 3.21** Torque versus time

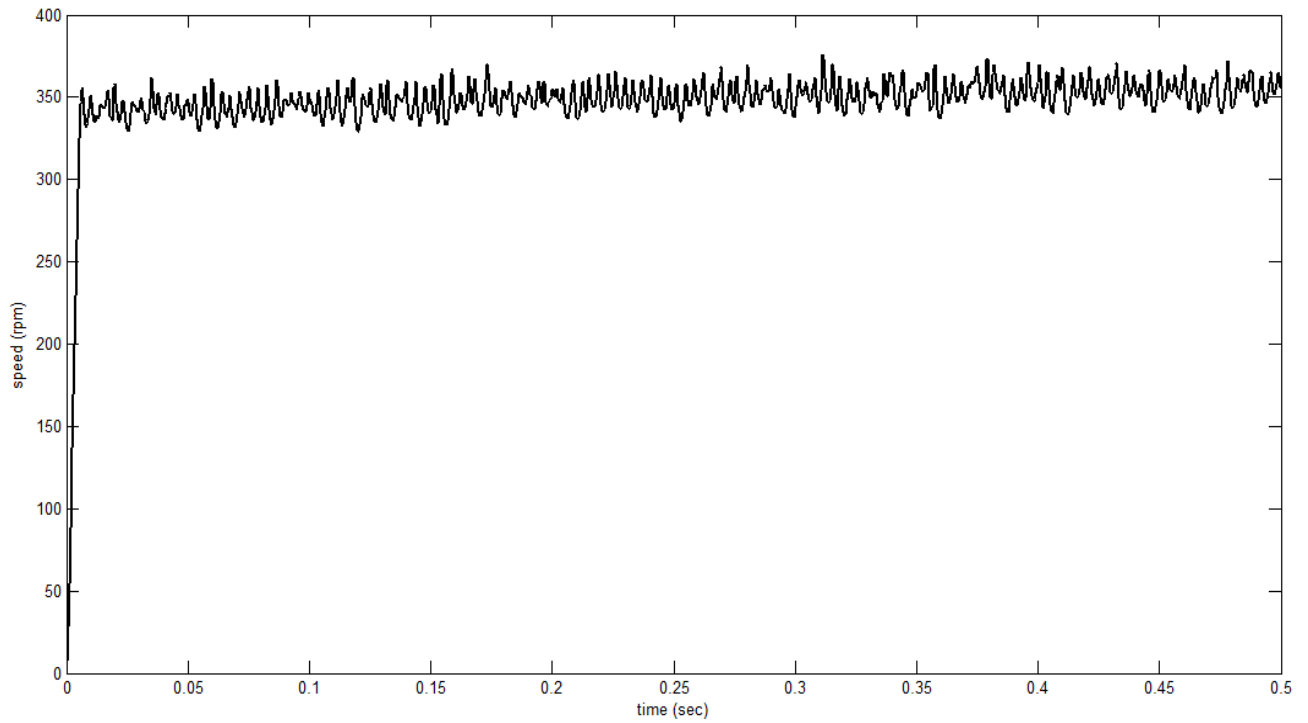
It can be seen from figure that back EMF is of pure trapezoidal type, mosfet voltage , current is not similar to open loop simulation because of introducing pulse width modulation by proportional integral controller. The response of motor for different input voltage but fixed reference speed is shown below:

a) Input Voltage 24V reference speed 360 rpm



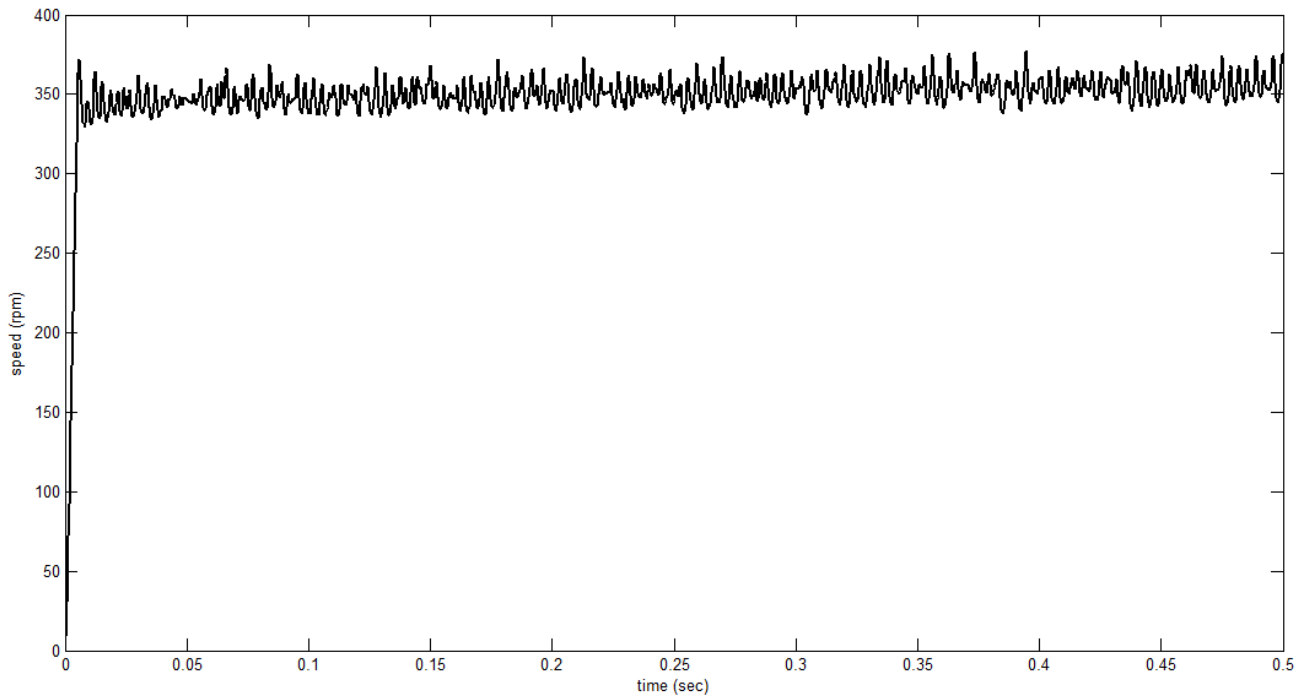
**Fig. 3.22** Speed versus time at 24V

b) Input Voltage 26V reference speed 360 rpm



**Fig. 3.23** Speed versus time at 26V

c) Input Voltage 30V reference speed 360 rpm



**Fig. 3.24** Speed versus time at 30V

From speed versus time graph it can be shown that control loop system is insensitive to parameter variation or disturbances. The speed maintained by motor is the reference speed. The simulation is done for three different input voltages 24V, 26V, 30V keeping the same reference speed. Initial response may be different for different input voltage but final speed of motor is the reference speed this is because of using proportional integral controller which regulates the duty cycle of gate pulse on receiving the error signal.

## CHAPTER 4

### DESIGN OF CONTROLLER HARDWARE

This chapter demonstrates the concepts presented in the preceding chapters. The results presented here utilize the equations and procedure developed in the previous chapters. The controller hardware is designed, implemented and tested for 24V, 40W BLDC motor based ceiling fan. The layout of controller circuit is drawn in ORCAD. The following components are used:

Component	Purpose	IC	Rating
Hall sensor	To detect rotor position	A3290	$V_{in} = 4.2V - 24V$
MOSFET	As a switching element	IRF530	Max. $V_{ds} = 100V$ Max. $V_{gs} = 20V$
MOSFET	As a switching element	IRF9530	Max. $V_{ds} = -100V$ Max. $V_{gs} = -20V$
Voltage Regulator	To provide constant voltage	7812	Max. $V_{in} = 35V$ Min. $V_{in} = 19V$ $V_{out} = 12V$
Motor controller	Generate gate pulses and Regulate the speed of motor	MC33035	$V_{in} = 10V - 30V$ $V_{out} = 6.25V$

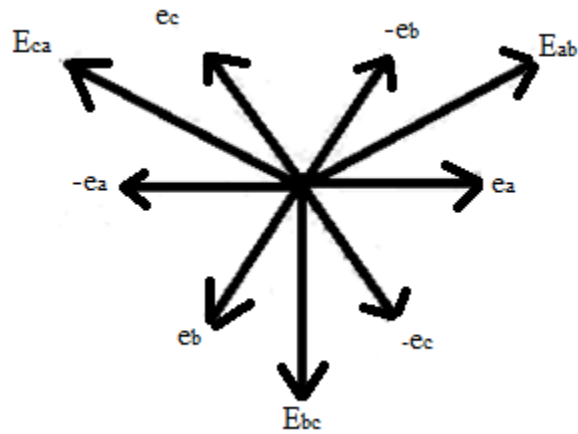
**Table 4.1** Components used in controller

#### 4.1 IDENTIFICATION OF PHASES AND THEIR CORRESPONDING HALL SENSORS

There are three wires of hall sensors output and three wires of phases A, B, C. Here purpose is to identify which one is HA, HB, HC and phase A, phase B, phase C. It can be easily find out by drawing phasor diagram of phase voltage and line voltage. From phasor diagram Fig. 4.1 the following observations are taken. Here line voltage is leading  $30^\circ$  than corresponding phase voltage i.e.

- a) Line voltage  $E_{ab}$  is  $30^\circ$  leading than phase A voltage

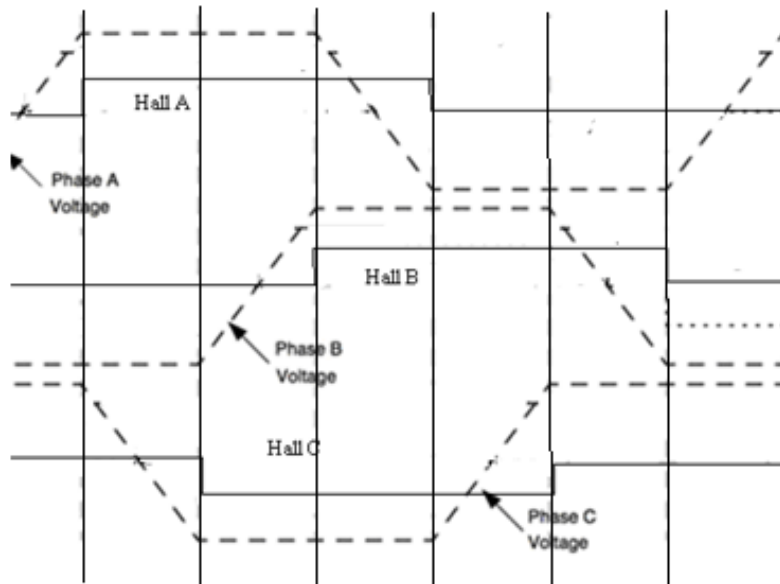
- b) Line voltage  $E_{bc}$  is  $30^\circ$  leading than phase B voltage
- c) Line voltage  $E_{ca}$  is  $30^\circ$  leading than phase C voltage



**Fig. 4.1** Phasor diagram

The Hall Effect sensor output is also leading  $30^\circ$  than their corresponding phases as shown in Fig. 4.2. If hall sensors are placed at zero degree displace from reference phase A.

- a) Hall signal A is leading  $30^\circ$  phase A
- b) Hall signal B is leading  $30^\circ$  phase B
- c) Hall signal C is leading  $30^\circ$  phase C



**Fig. 4.2** Hall Effect sensors and Back EMF waveforms

Hence it is proven that line voltage will be in phase with corresponding Hall sensor output. Using oscilloscope the output waveform of line voltages and hall sensors are matched. Once the

HA, HB, HC and phases A, B, C are determine they are connected with corresponding wires of controller.

#### 4.2 ORCAD LAYOUT OF CONTROLLER

The layout of controller is drawn in ORCAD software. It include physical wire connection of various components such resistors, diodes, mosfets, voltage source, voltage regulator, Hall Effect sensors and motor controller. The connections of components are shown in Fig. 4.4.

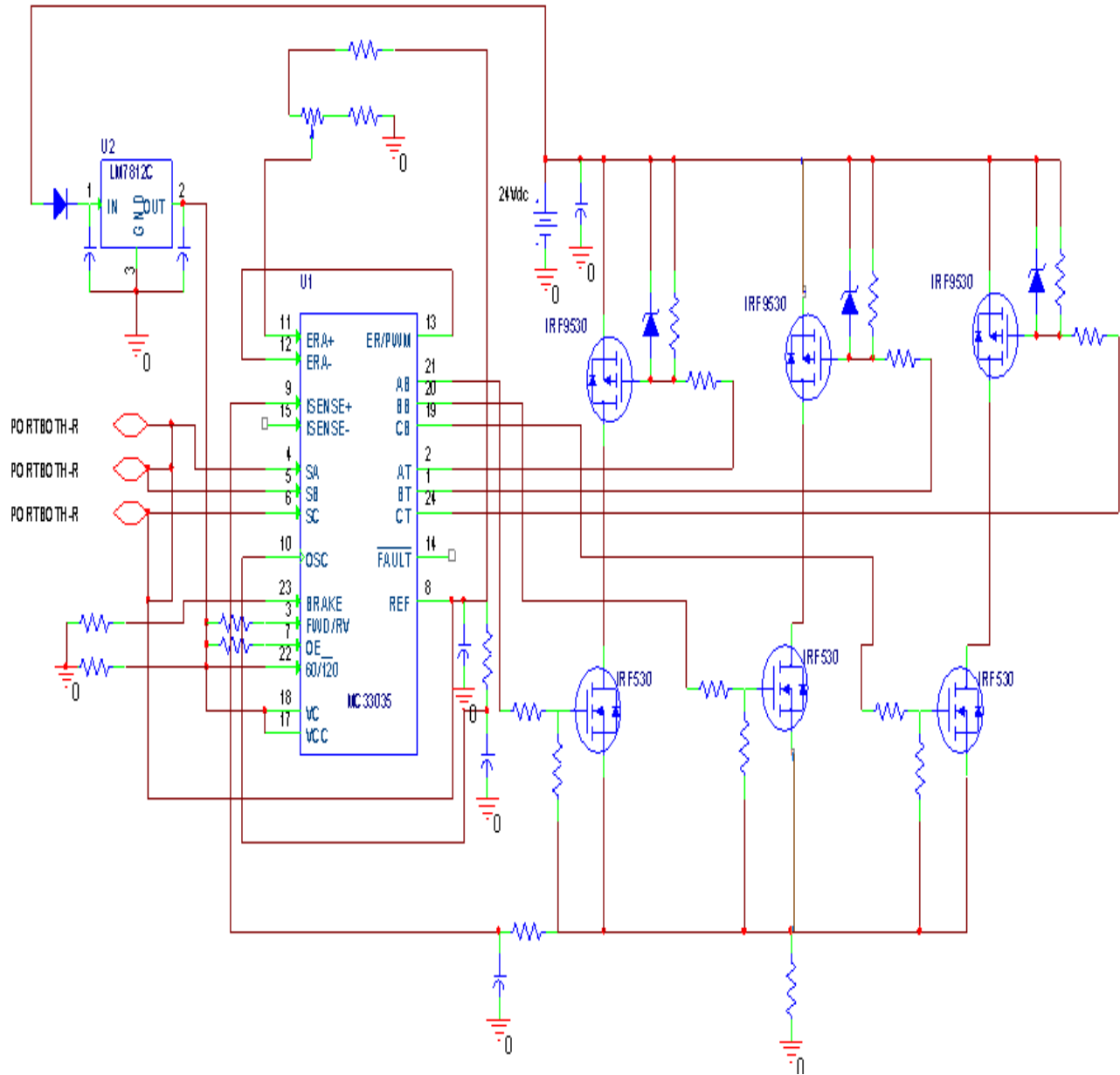
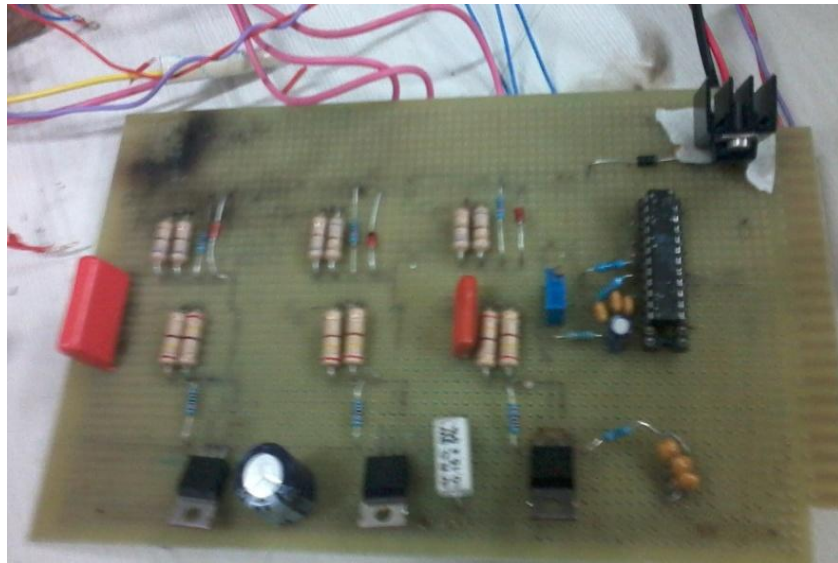


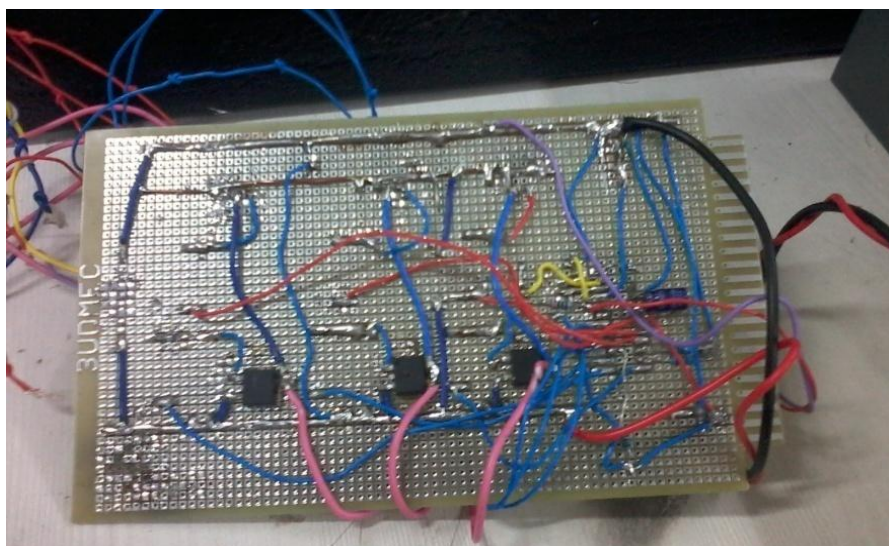
Fig. 4.3 Layout of Controller

### 4.3 CONTROLLER HARDWARE

For practical implementation the controller is designed on general purpose printed circuit board (PCB). The devices are either surface mounted or through hole. One common 24V supply line is made and one common ground is made on PCB. These devices are connected in the same fashion as shown in ORCAD layout. The front side and back side of PCB are shown in Fig. 4.3 and Fig. 4.5. Further assembling of ceiling fan along with diagram is shown pictorially in Fig. 4.6.



**Fig. 4.4** A photo of front side of controller



**Fig. 4.5** A photo of back side of controller



**Fig. 4.6** A photo of assembling of ceiling fan

#### **4.4 TESTING OF CONTROLLER**

Three hall sensors are mounted on printed circuit board (PCB) which is kept along the stator. There are total five output wires coming out, one is  $V_{CC}$ , Common ground, three outputs of hall sensors. These wires are connected with corresponding wires of motor controller IC. The constant DC voltage is provided by DC power supply. The waveforms are analyzed on cathode ray oscilloscope (CRO). Fig. 4.7 shows the experimental setup for testing of controller.



**Fig. 4.7** A photo of experimental setup

The results for open loop operation of the motor are shown below:

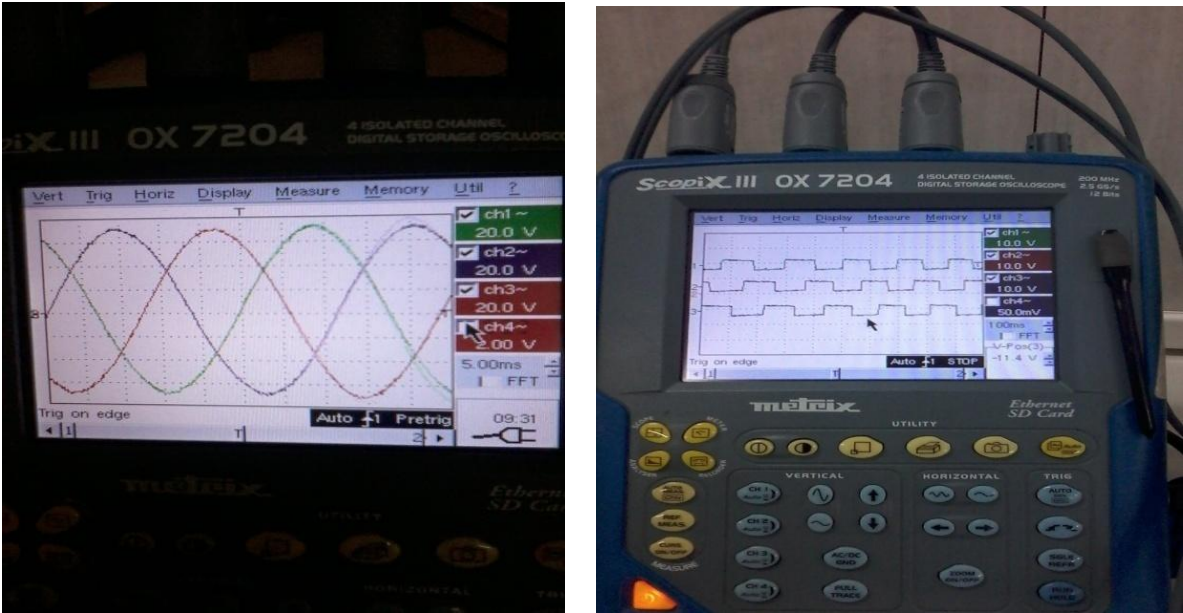


Fig. 4.8 A photo of Back EMF and Hall signal waveforms

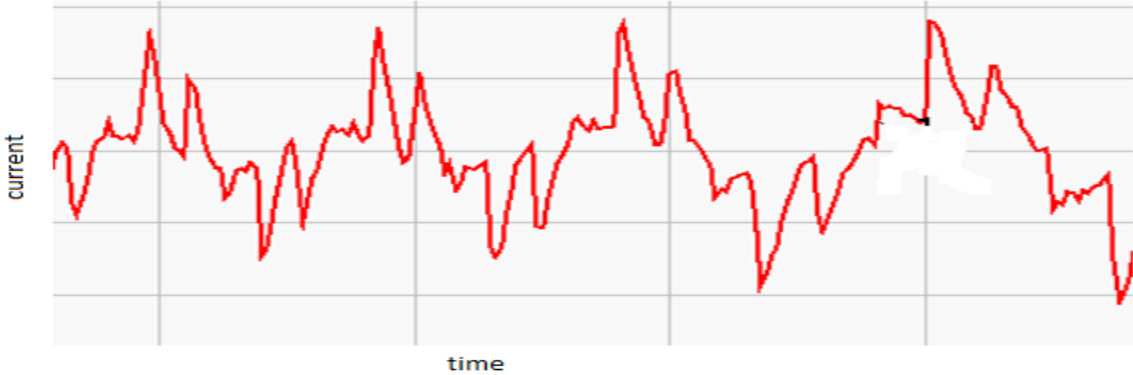
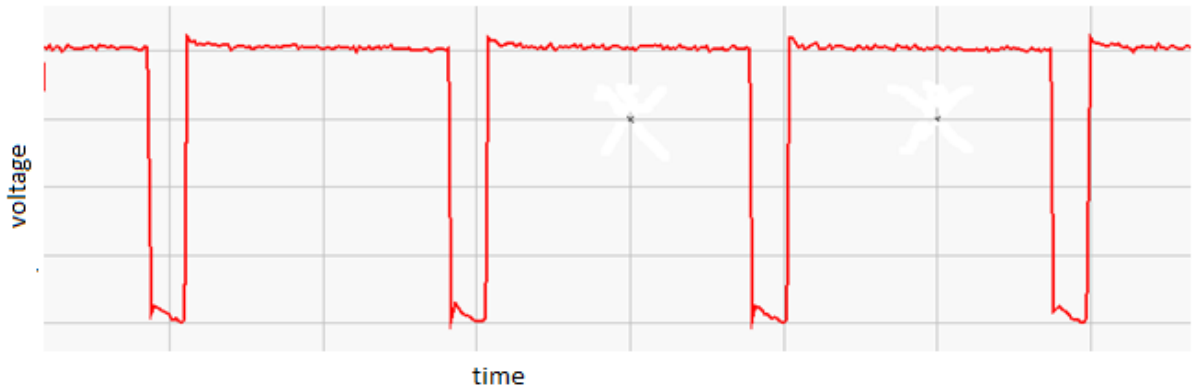


Fig. 4.9 Phase current versus time



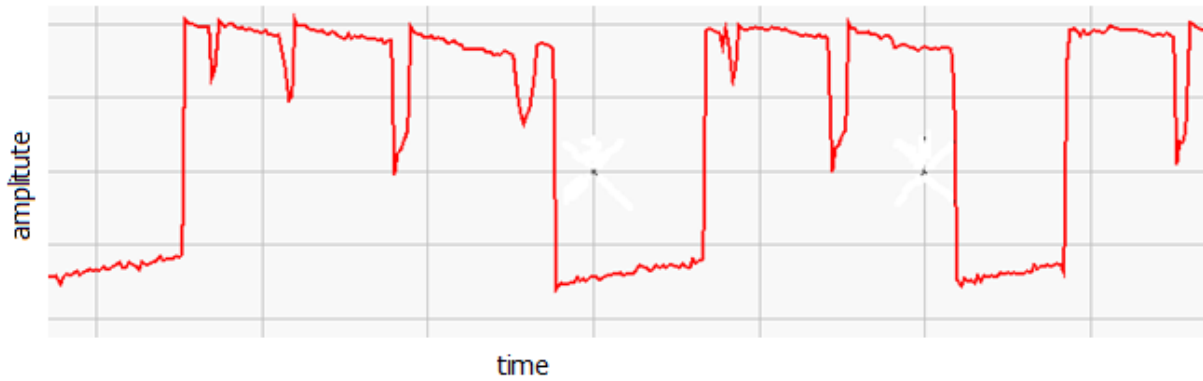
Fig. 4.10 MOSFET current versus time



**Fig. 4.11** MOSFET voltage versus time



**Fig. 4.12** Hall signal versus time



**Fig. 4.13** Gate signal versus time

It can be seen from diagram that waveforms of brushless dc motor by controller hardware are similar to waveform of simulated open loop controller.

**5.1 CONCLUSION**

BLDC motor achieves high efficiency than conventional dc motor and induction motor. It has surface mounted permanent magnet on rotor which rotates at synchronous speed. High dynamic response, long operating life, noiseless operation, higher speed range, high output power, low maintenance make it more reliable than other motors. BLDC motors are used in CD/DVD drives, PC cooling fans, dish washer, washing machine, vacuum cleaner, air conditioner, refrigerator, toys. Another major application of BLDC motor is ceiling/pedestal fan. In Crompton greaves limited BLDC motors are manufacture and assembled for fan application.

In this thesis design and simulation of controller for BLDC motor based ceiling fan is carried out. The open loop speed control and closed loop speed control (using proportional integral controller) is implemented and simulated in matlab/simulink. The output waveforms of phase current, back EMF voltage, hall effect sensor, gate signal, mosfet voltage, mosfet current, motor speed, electromagnetic torque are analyzed for open loop and closed loop system.

For open loop system speed is 325 rpm, 370 rpm and 430 rpm at input voltage of 20V, 24V and 30V respectively. From this data it can be concluded that speed is directly to input voltage in open loop system. For closed loop system (using proportional integral controller) speed is 360 rpm at reference speed of 360 rpm for different input voltages 24V, 26V and 30V. From this observation it can be concluded that for closed loop system speed is independent of input voltage but is a function of reference speed i.e. output speed is same as reference speed. Closed loop control is an efficient way to regulate the speed of brushless dc motor because it keeps the actual speed closed to reference speed and is insensitive to parameter variation or disturbances. Closed loop system is more complex and expensive then corresponding open loop system.

Finally the hardware of controller is designed, implemented and tested for 24V, 40W BLDC motor based ceiling fan. Controller hardware is designed for BLDC motor using motor controller, mosfets, voltage regulator on printed circuit board and waveforms are analyzed. The waveforms are similar to waveforms of open loop system simulated in simulink.

## **5.2 FUTURE SCOPE**

Speed Control of BLDC motor using fuzzy logic controller, tuning of proportional integral derivative controller, using Genetic algorithm (GA), using neural network can be implemented to check the performance of brushless dc motor.

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**BLDC MOTOR PARAMETERS**

S.No.	Motor Specifications: 24V, 40W	
1	Number of phases	3
2	Back EMF waveform	Trapezoidal
3	Mechanical input	Torque $T_m$
4	Stator phase resistance $R_s$ (ohms)	2
5	Stator phase inductance $L_s$ (Henry)	$3e^{-3}$
6	Voltage constant ( $V_{peak}$ /rpm)	40
7	Torque constant (N.m/ $A_{peak}$ )	0.38197
8	Back EMF flat area (degree)	120
9	Inertia ( $J\text{kgm}^2$ )	$0.2e^{-3}$
10	Friction factor $F$ (N.m-s)	$1e^{-3}$
11	Pole pairs	8
12	Initial condition [ $w$ (rad/sec) $\Theta$ (deg) $i_a, i_b$ (A)]	[0,0,0]
13	Flux linkage established by magnets	0.023873