"MODELLING, SIMULATION AND HARDWARE IMPLEMENTAION OF SPEED CONTROL OF BRUSHLESS DC MOTOR"

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CANDIDATE DECLARATION

I, Monika Kumari , Roll No. 2k17/C&I/11, student of M.Tech Control & Instrumentation, hereby declare that the project dissertation titled "**Modelling, Simulation And Hardware Implementation of Speed Control of Brushless DC Motor**" which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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I hereby certify that the Project Dissertation titled "**Modelling, Simulation and Hardware Implementation of Speed Control of Brushless DC Motor"** which is submitted by Monika Kumari, Roll No. 2K17/C&I/11, Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part of full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

Permanent Magnet Brushless DC (PMBLDC) motor belongs to the class of special electrical machines. Brushless DC motors offer many attractive features like low maintenance, fast response, noiseless operation, high efficiency, high power density, good reliability and compact construction. The inherent simplicity, ruggedness and high efficiency make it a viable machine for various general purpose adjustable speed drive applications. As a result, the brushless DC motors are increasingly being used in military, industrial and commercial applications. Its market is rapidly expanding.

Performance enhancement of BLDC motor drive is an essential task for the researchers today. Initially a mathematical model of BLDC motor is presented. It is assumed to be a linear model. This project presents developed model of Brushless DC Motor by using MATLAB/Simulink and performance characteristics of motor are observed during various loading conditions. Simulation results obtained from developed model are discussed.

A conventional six switch BLDC motor drive system was studied and simulated. In this research work, various strategies have been adopted to improve the performance of BLDC motor. The different strategies adopted in this research work include design of PI, hysteresis current controller. The hysteresis current controller is implemented with speed feedback loop and it is observed that torque ripples are minimized. In this method the current (or torque) ripple can be restricted within the predefined band-gap Simulation is carried out using MATLAB / SIMULINK. The results show that the performance of BLDCM is quite satisfactory for various loading conditions.

The hardware project is designed to control the speed of a BLDC motor. The objective of this work is to control the BLDC motor automatically through microcontroller. A microcontroller based speed control scheme has been developed. The microcontroller has been programmed in such a way that when the duty cycle is varied, speed is changing. Also the implementation of motoring mode is carried out and the results are shown in digital storage oscilloscope.

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LIST OF SYMBOLS

1. L_s - armature self resistance

2. M - Mutual inductance

3. $R_a = R_b = R_c = R$ - Armature resistance in ohm

4. V_a, V_b ,V_c - Terminal phase voltages in volts.

5. i_a , i_b, i_c - motor input current in amperes

6. e_a , e_b , e_c - motor back emf in volts

7. p - Matrix represents $\dfrac{d}{dt}$ —

8. K_E - constant back emf

9. ω - mechanical speed of the rotor

10. T_E - Resultant Torque

11. T_L - load torque in N-m

12. J - Rotor inertia in [kgm^2]

13. B - Damping constant

14. V_{an} ,V_{bn} ,V_{cn} - Phase voltages

15. Q_1,Q_2,Q_3,Q_4,Q_5,Q_6 - Switches

16. V_{dc} - Dc voltage

17. ia *, ib *, ic* - Reference current

18. ΔI_a , ΔI_b , ΔI_c - Error

LIST OF ABBREVIATIONS

1. H- Upper limits of hysteresis band

2. L -Lower limits of hysteresis band

3. V_{IN} - Input Voltage

4. SRAM- Static Random Access Memory

5. ERPROM- Electrically Erasable Programmable Read Only Memory

6. KB- Kilo Byte

7. MHz- Mega Hertz

8. ESC- Electronic Speed Controller

9. BLDC- Brushless Dc Motor

10. PMBLDC - Permanent Magnet Brushless Dc Motor

11. PMSM - Permanent Magnet Synchronous Motors

12. MLI - Multilevel

13. EV - Electrical Vehicle

14. ECM - Electronically Commutated Motors.

CHAPTER 1

INTRODUCTION

1.1 Background

BLDC motor drives have a permanent magnet excited synchronous motor which is fed with a variable frequency inverter controlled by a shaft position sensor. Construction wise, a brushless dc motor is like a dc motor with an inside out construction, the field is on the rotor and the armature is on the stator. In fact, the brushless dc motor is a permanent magnet ac motor whose torque current characteristics imitate the dc motor. Electronic commutation is used instead of commutation of the armature current using brushes. Thus, Sparking and wearing out of the commutator brush arrangements are eliminated in a brushless dc motor, thus making a BLDC more robust than a dc motor as shown in Figure 1.1.
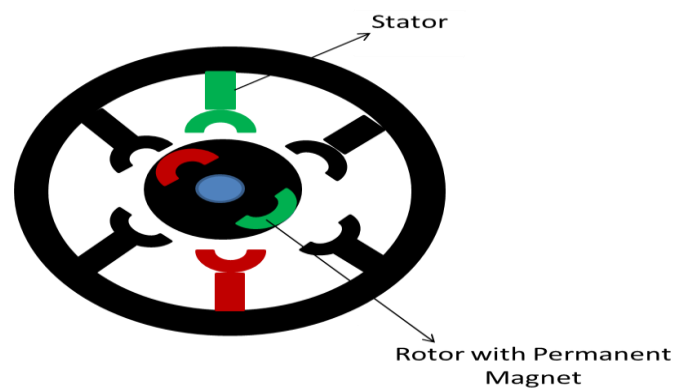
Fig1.1 Cross sectional view of brushless dc motor

In fact, a BLDC is a modified PMSM motor with the change being that the back emf is trapezoidal rather than sinusoidal as in the case of PMSM. The back emf of a BLDC motor's "commutation region" should be as small as possible, while at the same time it should not be so narrow that when driven by a Current Source Inverter it is difficult to switch a phase of that motor. For a smooth torque production, the flat constant portion of the back emf should be 120°.

Using an optical position sensor and its associated logic, the rotor position can be sensed. Phototransistors (sensitive to light), revolving shutters, and a light source are the parts of optical position sensors. An optical position sensor's output is usually a logical signal.

1.2 Construction

In term of construction and working principles, BLDC motors have many similarities with AC induction motors and brushed DC motors respectively. Like all other motors, brushless dc motors also have a rotor and a stator. On the rotor of a BLDC motor, permanent magnets are mounted and stator is wound with a specific number of poles. This is the basic difference between a Brushless dc motor and a typical dc motor.

Stator

The BLDC motor stator is made of laminated steel stacked to carry the windings which are shown in Figure 1.2[25] similar to that of Induction AC motor. Windings can be arranged in two patterns in a stator; i.e. a star pattern(Y) or delta pattern (Δ).The main difference between the two patterns is that the star pattern gives high Torque at low RPM and the delta pattern gives low torque at low RPM. This is because in the delta configuration, half of the voltage is applied across the winding that is not driven, thus increasing losses and, in turn, efficiency and torque.

Fig1.2 Brushless dc motor stator laminated

It is possible to have slotted or slotless steel laminations in the stator as shown in Figure 1.3. There is less inductance in a slotless core, so it can run at very high speeds. Due to the absence of teeth in the lamination stack, the cogging torque requirements also decrease, making them ideal for low speeds too (when permanent magnets on the rotor and the tooth on the stator align with each other, an undesirable cogging torque develops and causes ripples in speed due to the interaction between the two).The main disadvantage of a slotless core is higher cost because it requires more winding to compensate for the larger air gap.
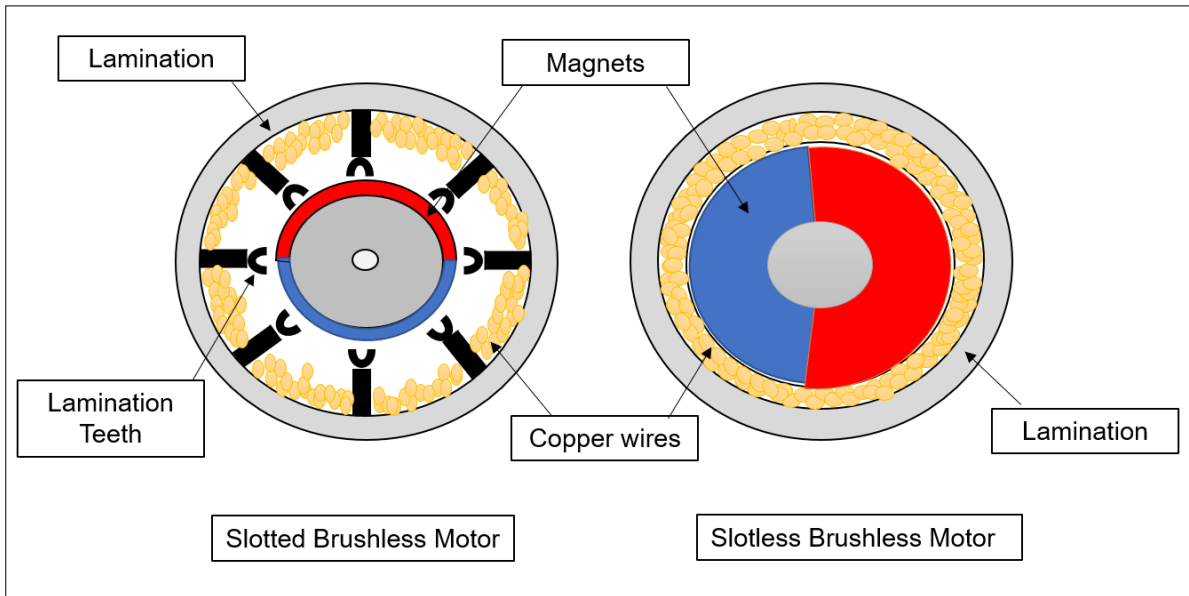
Fig1.3 Slotted and Slotless Brushless Dc motor

Proper choice of the laminated steel and windings for the construction of stator are crucial for motor performance. An improper choice could cause multiple issues, throughout production, resulting in market delays and increased design costs.

Rotor

The rotor of a BLDC motor is made up of permanent magnets. Depending upon applications necessity, the number of poles in the rotor may vary. Increasing the number of poles does give better torque but at the cost of reducing the maximum speed possible. The outer and inner rotor are shown in Figure 1.4[26].
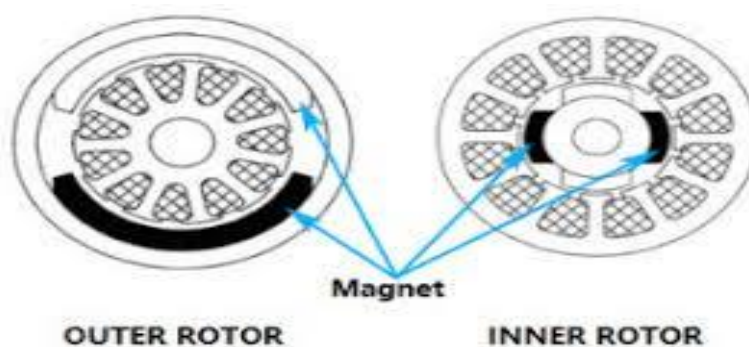
Fig1.4 Outer and Inner Rotor of Brushless Dc motor

Another rotor parameter that impacts the maximum torque is the material used for the construction of permanent magnet; when the flux density of the material is high then the torque is also high[31].

➢ **Inner rotor type bldc motor**

There is an internal rotor type brushless DC motor which is shown in Figure1.5[26] that has the magnet acting as the rotor inside while the winding is arranged outside as the stator. This motor has the following characteristics compared to the outer rotor type:

1.Small moment of inertia of the rotating shaft.
2. High heat dissipation efficiency.

However, to obtain a high magnetic flux density using small magnets, high performance magnets must be used. Creating a large number of coils inside the stator is a more difficult task than winding coils outside the rotor. For this reason, an inner rotor type motor is currently used for applications that require a compact and high-output motor with superior dynamic characteristics [32].
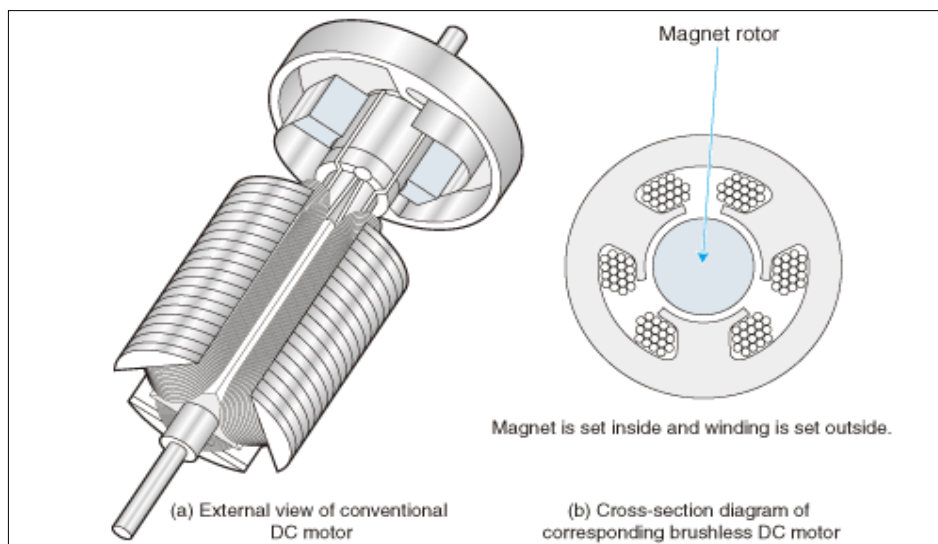
Fig1.5 Inner rotor type of Brushless Dc Motor

➢ **Outer rotor type of bldc**

Outer brushless DC motors which is shown in Figure 1.6[26] is differ from typical brushless DC motors because the rotor is located outside rather than inside the stator. The stator consists of a multiphase winding on a laminated core and the rotor consists of permanent magnet segments or a molded ring attached to the inside surface of a steel cup component attached to the shaft of the motor at one end. The stator windings which are fed with currents controlled in magnitude and sequence (commutated) to effect rotation of the rotor element same as in a typical brushless motor [32].
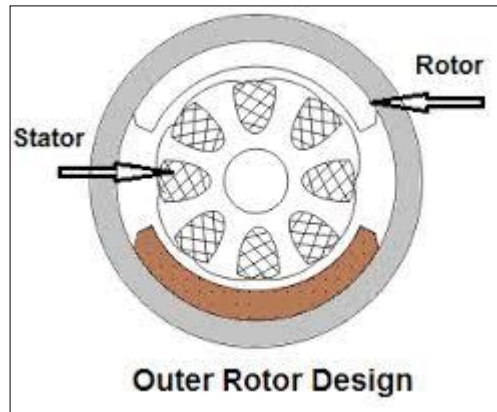
Fig1.6 Outer rotor type of Brushless Dc Motor

1.3 Working Principles and operation of Brushless Dc Motor

The underlying principles for a BLDC motor operation is the same as a brushed DC motor except for the feedback from the internal shaft position. Feedback is implemented using a mechanical commutator and brushes in the case of a brushed DC motor. With a BLDC motor, multiple feedback sensors are used to achieve this. Hall sensors and optical encoders are the most frequently used sensors.

An integrated switching circuit connects stator windings of a BLDC motor to a control circuit. The control circuit energizes proper winding at proper time, in a pattern which rotates around the stator. The rotor magnet attempts to align with the stator's energized electromagnet and the next electromagnet is energized as soon as it aligns .The rotor magnet tries to align with the energized electromagnet of the stator, and as soon as it aligns, the next electromagnet energized. Thus the rotor continues to run as shown un Figure 1.7[33].
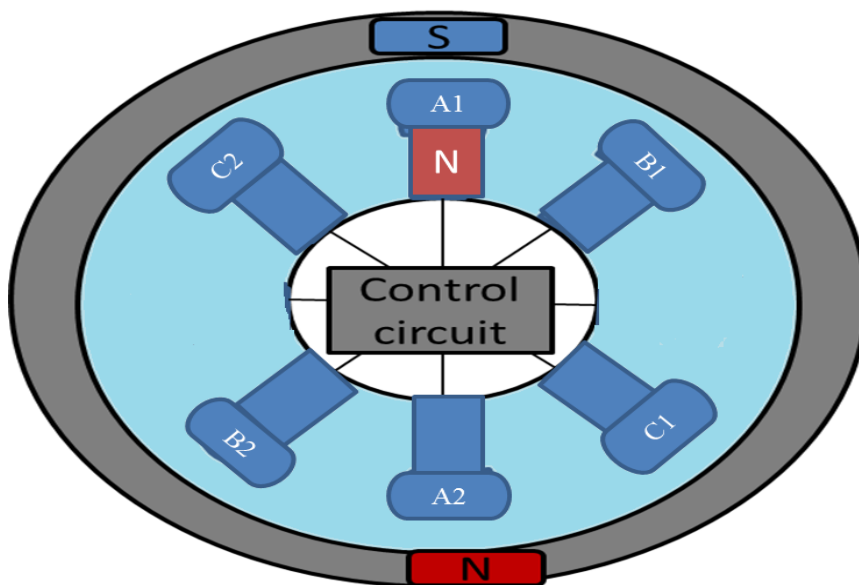
Fig1.7 Working of Brushless Dc motor

Hall sensors are based on the principle of hall-effect, when a current carrying conductor is

exposed to the magnetic field, charge carriers experience a force based on the voltage developed across the two sides of the conductor, If the magnetic field direction is reversed, the voltage developed will also reverse. Whenever rotor magnetic poles (N or S) pass near the hall sensor, they generate a HIGH or LOW level signal that can be used to determine the shaft position. In a commutation system one that is based on the position of the motor identified using feedback sensors – two of the three electrical windings are energized at a time as shown in Figure 1.8**[27].**

In Figure 1.8(A), the GREEN winding labeled "001" is energized as the NORTH pole and the BLUE winding labeled as "010" is energized as the SOUTH pole. Because of this excitation, the SOUTH Pole of the rotor aligns with the GREEN winding and the NORTH pole aligns with the RED winding labeled "100". In order to move the rotor, the "RED" and "BLUE" windings are energized in the direction shown in Figure 1.8(B). This causes the RED winding to become the NORTH pole and the BLUE winding to become the SOUTH pole. This shifting of the magnetic field in the stator produces torque because of the development of repulsion (Red winding – NORTH-NORTH alignment) and attraction forces (BLUE winding – NORTH-SOUTH alignment) that moves the rotor in the direction of clockwise.

Fgure A:Phase 1

Figure B:Phase 2

Figure C:Phase 3

Figure D:Phase 4

Figure E:Phase 5

Figure F:Phase 6
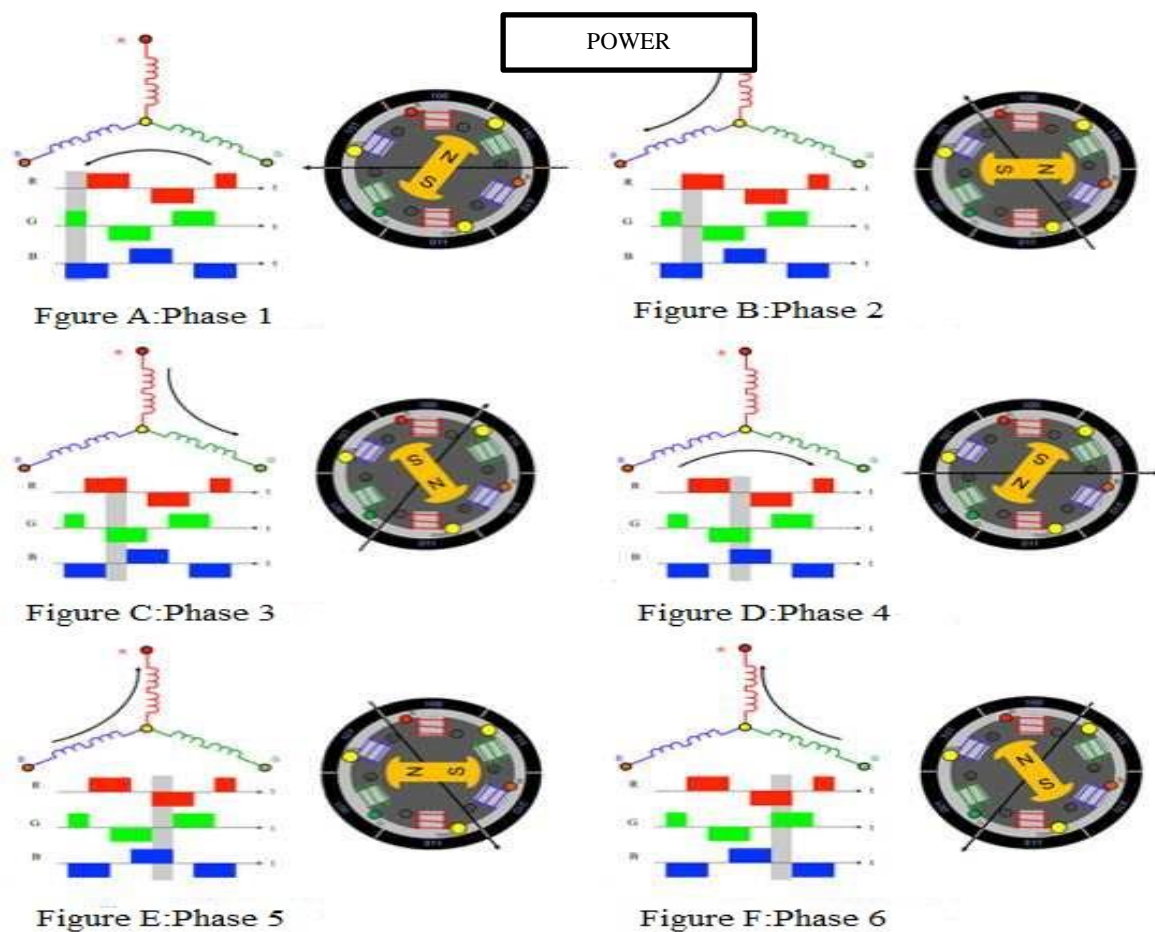
Fig1.8 Operation of Brushless Dc Motor

1.4 Operation Principle of Brushless DC (BLDC) Motor

A brushless dc motor is defined as a synchronous permanent machine with rotor position feedback. The brushless motors are generally controlled by a three phase power semiconductor bridge. To start and provide a proper switching sequence, the motor requires a rotor position sensor to turn on the power devices in the inverter bridge. The power devices are commutated sequentially every 60^0 degrees based on the rotor position. For this reason it is an electronic motor rather than commutating the armature current using brushes. The basic block diagram for the brushless dc motor as shown in Figure 1.9. The brushless dc consists of four main parts power converters, permanent magnet brushless dc motor sensors, and control algorithm. The power converter transforms power from source to BLDC which then convert electrical energy into mechanical energy. One of the salient features of the brushless dc motor is the rotor position sensors, based on rotor position and command signals that can be a torque command, voltage command, speed command, and so on the control algorithms determine the gate signal in the power electronic converter for each semiconductor.
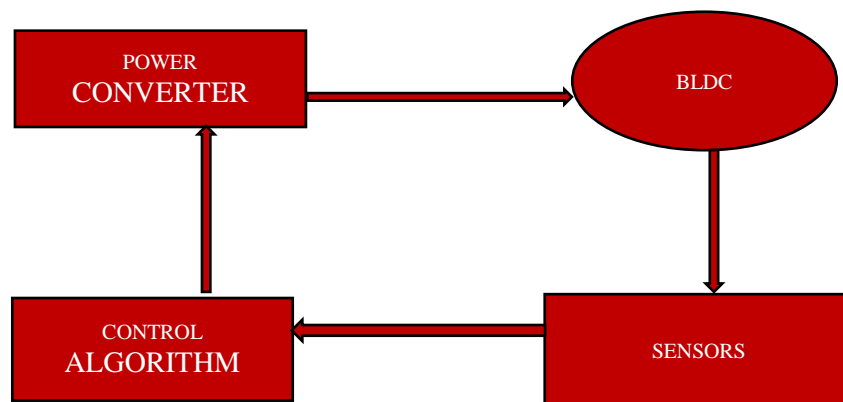
Fig 1.9 Basic block diagram of bldc motor

Based on the inverter used the brushless dc motor, can be classified into two main classes that are the voltage source based drives and the current source based drives. Both the voltage source and the current source based drives used with permanent magnet synchronous machine with either sinusoidal or non sinusoidal back emf waveforms. Machine with sinusoidal back emf shown in Figure.1.10 can be controlled so that almost constant torque can be achieved. However; the offer of a non sinusoidal back emf machine shown in Fig.1.11 reduces inverter sizes and reduces losses for the same level of power level.
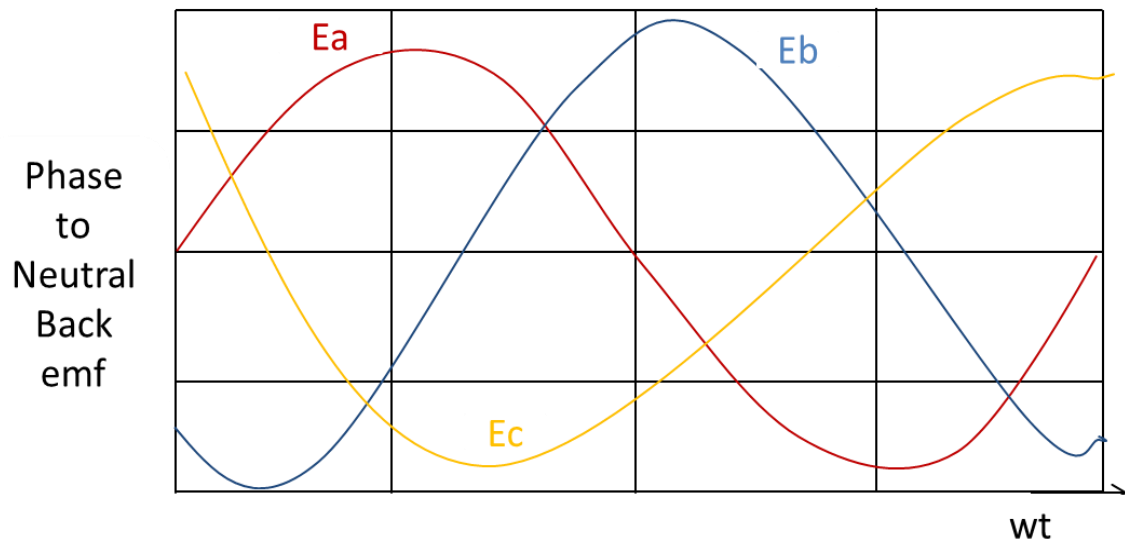
Fig 1.10 Sinusoidal phase back emf of PMSM motor
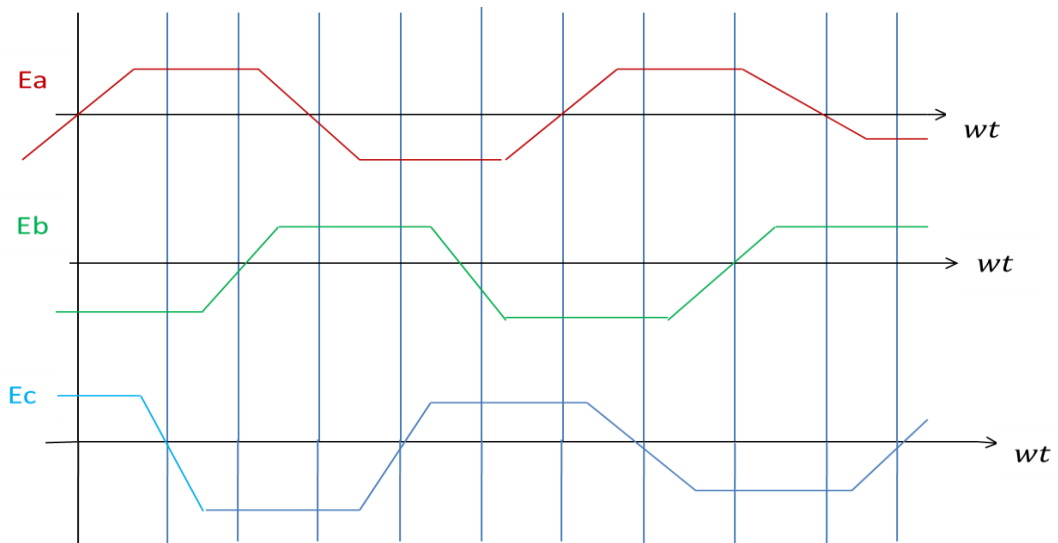
Fig1.11 Trapezoidal back emf of brushless dc motor

1.5 Brushless dc motor operation with inverter

It is essentially an electronic motor and requires the front end of a three phase inverter. The inverter acts as an electronic commutator in self-control mode that receives the logical pulse from the absolute position sensors. Also known as an electronically commutated motor. The inverter can basically operate in the following two modes:

1. 120^0 switch on mode

2. Voltage and current controlled PWM Mode

1.5.1 120^0 Switch on Mode

Inverter operation in this mode is shown in Figure 1.12 with the help of the waveform. The six inverter switches (Q_1 to Q_6) operate in such a way as to place the symmetrical input dc current I_d at the center of each phase voltage waveform for 120^0 angle. The angle shown is the advance angle of current wave with respect to voltage wave in the case zero. It can be seen that two switches are on at a moment, one in the upper group and one in the lower group. At the Instant of time t_1 for example, Q_1 and Q_2 are on when the supply voltage V_{dc} and current I_d is placed across the line a (phase A and phase B in series) so that I_d is positive in phase A. But negative in phase B then after 60^0 interval (the middle of phase A) . Q_2 is switch on and Q_6 is switched off but Q_1 continues conduction for full 120^0 angle. This switching commutates -I_d from the phase A to phase C while phase A carry +I_d the conduction pattern changes every 60^0 angle of switching modes in full cycle. The absolute position sensor dictates the switching or commutation of devices at the precise instants of wave. The inverter mainly operate as a rotor position sensitive electronic commutator.
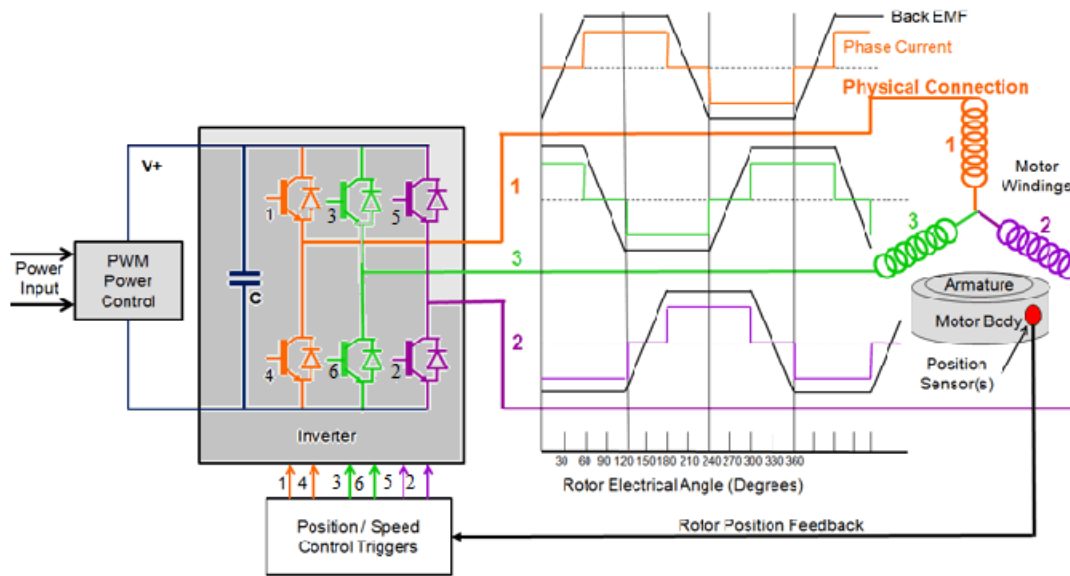
Fig 1.12 Brushless Dc Motor Drive System

1.5.2. Voltage and current control PWM mode

In the previous mode of the inverter, switches were controlled to give commutator function only when the devices were sequentially turned ON and OFF at 120^0 angle duration. In addition to the commutator function, the switches in PWM chopping mode can be controlled continuously at the machine terminal for controlling voltage and current. In essence there are two chopping modes, the inverter's current controlled operation and voltage controlled operation. There are mainly two chopping modes that is feedback mode and freewheeling mode.In both of these modes devices are turned ON and OFF on duty cycle basis to control the machine average current I_{AV} and the machine average voltage V_{AV}.

1.6 Typical applications for BLDC motors

BLDC motors find applications in every segment of market. Such as appliances, industrial control, automation, aviation and so on. The BLDC motor application can be categorized into three types such as

1. Constant load application

2. Varying load application

3. Positioning application

1.6.1. Constant Load Applications

These are the types of applications where a variable velocity is more important than maintaining speed accuracy at a set speed. The load is directly linked to the motor shaft in these types of applications. For example, these types of applications include fans, pumps, and blowers. These applications require low cost controllers, mostly in open loop operation.

1.6.2. Different load applications

These are the types of applications where a speed range over the load on the motor varies. These applications may require accuracy of high speed control and good dynamic responses. Washers, dryers and compressors in home appliances are good examples. Good examples of these are fuel pump control, electronic steering control, engine control and control of electric vehicles in automotive. A number of applications are available in aerospace, such as centrifuges, pumps, robotic arm controls, gyroscope controls, etc. These applications can use speed feedback devices and can run in semi closed loops or in total closed loops. These applications use advanced control algorithms, making the controller more complicated. This also increases the entire system's price of complete control system.

1.6.3 Positioning Applications

Most of the application types of industrial and automation come under this category. Positioning applications have some kind of power transmission that might be mechanical gears or timer belts, or a simple belt driven system. The dynamic response of speed and torque is important in these applications. These applications can also frequently reverse the direction of rotation. A typical cycle will have an accelerating phase, a constant speed phase and a deceleration and positioning phase. During all these phases, the load on the motor may vary, making the controller complex. Most of these systems operate in a closed loop. There could be three control loops functioning simultaneously: Torque Control Loop, Speed Control Loop and Position Control Loop. To measure the actual speed of the motor, optical encoder or synchronous resolves are used. In some case the same sensors are used to obtain information on the relative position. Otherwise, for absolute positions, separate position sensors can be used. A good example of this is computer numeric controlled (CNC) machines.

1.7. A BLDC Motor comparison with conventional Brushed DC motor

The brushes makes mechanical contact with the rotor's asset of electrical contacts (called the commutator) in a conventional type (brushed) DC-motor, forming an electrical circuit between the DC electrical source and the armature coil-windings. The stationary brushes come into contact with various sections of the rotating commutator as the armature rotates on the axis. The commutators and brush system forms a groups of electrical switches, each in sequence firing, so that electrical power always flows through the armature coil closest to the stationary stator (permanent magnet).The electromagnets are not moving in a BLDC motor; instead, the permanent magnets are rotating and the armature is static. Therefore, to transfer current to a moving armature, a smart electronic controller is used in place of the commutator assembly. The controller performs the same power distribution found in a brushed DC motor, but instead of a commutator using a solid-state circuit. There are many advantages for BLDC motors over DC motors. Some of these are the following:

1. High dynamic response.

2. High efficiency.

3. Noiseless operation with long life.

4. Operation at higher speed ranges.

The main disadvantage of the BLDC is the higher cost resulting to a problem that is, complicated electronic speed controllers are required to run BLDC motors. A relatively trivial potentiometer or rheostat that is inefficient but also satisfactory for cost-sensitive applications can be used to regulate brushed DC-motors.

1.8 Review of the modeling of brushless dc motor

Recent analysis has shown that the permanent magnet motor drives, that is the permanent magnet synchronous motor (PMSM) and the brushless dc motor (BLDC), could become one of the serious competitors with the servo induction motor. The back emf of PMSM is sinusoidal which requires sinusoidal stator currents to produce constant torque while the BLDC motor has a trapezoidal back emf and requires rectangular stator currents for constant torque to be produced. There is some confusion about the correct models that should be used in each case, both in the industry and in the university research environment.

The PMSM is similar to the standard wound rotor synchronous machine except that the

PMSM has no damper windings and a permanent magnet provides excitation rather than field winding. The d, q model of the PMSM can therefore be derived from the well known model of the synchronous machine with the equations of the windings of the damper and the dynamics of the field current removed. The transformation of the synchronous machine equations from the abc phase variables to the d, q variables, as is well known, forces all sinusoidal varying inductances in the abc frame to become constant in the d, q framework. In the BLDC motor, since the back emf is not sinusoidal, the inductances in the abc frame do not vary sinusoidally and transforming the equations into the d, q frame does not seem advantageous as the inductances after transformation will not be constant.

It is therefore suggested that the abc phase variables model be used for the BLDC motor drives. This approach in the modelling of the BLDC Motors allows a detailed examination of the machine's torque behaviour that would not be possible if any simplifying assumptions were made. The d, q model of the PMSM has been used to examine the transient behaviour of a high performance vector controlled PMSM servo drive. In addition, the abc phase variable model has been used to examine the behaviour of a BLDC motor speed servo drives.

1.9. Thesis organization

This thesis contains six chapters describing the modelling and control approach of a permanent   magnet brushless dc motor organized as follows:

Chapter 2 includes the literature review.

Chapter 3 discusses the performance of a 3-phase motor fed from a 3-phase balanced power supply. Working principle, mathematical analysis and mathematical modelling of machine in state space form and simulation is carried out using MATLAB SIMULINK model with different loading condition.

Chapter 4 discusses the speed control of brushless dc motor using PI controller and hysteresis current controller and analysis is carried out using MATLAB SIMULINK model. Simulation results show that current ripple and torque ripple are minimized which enhance the performance of the drive.

Chapter 5 describes the hardware implementation of speed control of brushless dc motor

using microcontroller. By using the PWM technique speed of the BLDC was controlled for motoring mode.

Chapter 6 describes the conclusion and further work to be carried out.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

To carry out this research work number of books, research articles and other resources are used. This chapter provides a description and summary of the material used for solving research problem being investigated.

2.2 Importance of Efficient BLDC drive

The Permanent Magnet in electrical machines have so many benefits and advantages than electromagnetic excitation machines, Then are zero excitation losses which result in high efficiency, simple construction, low cost, less maintenance and high torque or high output power per unit volume . Due to high power to weight ratio, high torque, good dynamic control for variable speed applications, absence of brushes and commutator make Brushless dc (BLDC) motor, best choice for high performance applications.

The performance evaluation of the BLDC motor drive underlines the importance of the developing analytical tools for modeling the controller and the permanent magnet machine.

Pillay, R.Krishnan[1] have studied the permanent Magnet Brushless Motors (PMBL) which are available in two types namely Permanent Magnet Synchronous Motor (PMSM) with a sinusoidal flux distribution, and Permanent Magnet Brushless DC motor (BLDC) with trapezoidal flux distribution. In this modeling of the complete drive system consisting of the current controlled voltage source inverter (CC-VSI), PI speed controller, motor and the load. The simulation results are given both for transient and steady state operating conditions of PMSM and BLDC drive systems.

Jahns[2] has discussed a strategy on torque production in permanent magnet synchronous motor drives with rectangular current excitation.

Tashakori, A.Ektesabi, M.Hosseinzadeh[3] have studied electric vehicle which has received more attention as an alternative option to traditional vehicles powered by internal combustion engines running on fossil fuels. In-wheel technology is new concept in which each wheel of EV is driven by separate motor instead of using central drive system. The model of Brushless DC Motor is developed using MATLAB/Simulink and performance characteristics of motor are observed during various loading conditions. Simulation results obtained from developed model are discussed which gives correct performance of model.

S.Baldursson[4] has discussed the performance of a 3-phase motor fed from a 3-phase balanced

power supply. A mathematical model similar to those representing conventional machines has been adopted to reflect the motor operation. In this working principle, mathematical analysis and control of 3-phase BLDC motor by using abc-axis property. The results indicate smooth operation of motor at synchronous speed.

Ektesabi, Laskaris, K.I Kladas [5-6] have described the model of 3-phase BLDC motor with trapezoidal back-EMF and the same has been simulated in MATLAB/Simulink. Simulation results under no-load and for load condition are showing proper performance of model. Output characteristics and simplicity of model make it effectively useful in design of BLDC motor drives with different control algorithms for various applications. A BLDC motor has higher power density, higher efficiency and higher speed range. Therefore it is a good choice for automotive industries.

N.A Patel, J.C Baria[7] have studied the high-performance electronic convertors, emphasizing the always need to reduce the harmonics. Hysteresis current control technique for AC to DC converter is proposed. Where, the upper band limit as well as lower band limit can be defined.

A.Karaarslan, I. Iskender[8] have studied the analysis and simulation of hysteresis band current control technique for model of AC/DC line side converters. Open-loop and closed-loop configurations can be used for reducing harmonics but where variable load is there, closed-loop configuration is applicable. In open-loop, if load is changed, the output voltage becomes low because source current doesn't increase and the output voltage will not be constant. But if being used closed loop system, then variable dc load can be connected. It doesn't need load information for controlling the source current THD. It will produce constant voltage in variable load condition also.

Park, Byoung-Gun[9] the hysteresis current controller and the same is implemented with speed feedback loop and it is observed that torque ripples are minimized. Simulation is carried out using MATLAB / SIMULINK. The results show that the performance of BLDC motor is quite satisfactory for various loading.

G.H. Jang , M.G. Kim[10] have studied the hysteresis current controller fed BLDC drive. Simulation result shows that current ripple are minimized which enhance the performance of the drive. The results show that the dynamic performance of the motor under various loading conditions.

Sudhoff, Krause[11-12] developed an average value model for the 120° mode inverter system of a brushless DC motor and also discussed about the operating modes of brushless DC motors with a 120° inverter system.

Fardoun et al[13] proposed a SPICE model for an electronically commutated permanent magnet machine drive system and evaluated the efficiency of the system in the motoring state.

Lefley, P.L Petkovska, G. Cvetkovski[14] have studied the modeling and simulation of torque hysteresis controller for BLDC motor. Moreover, a new current blocking strategy to prevent the energy wastage from the batteries such that it can prolong the capacity of battery is proposed. From the simulation results obtained, it showed that the hysteresis controller can offer inherent current protection/limitation and is robustness in controlling the motor torque.

Xavier[15] has studied the speed of a BLDC. BLDC motor has various application used in industries like in drilling, lathes, spinning, electric bikes etc. The speed control of the DC motors is very essential and has proposed a very precise and effective speed control system.

Hemalatha et al[16] have studied how to control a BLDC motor up to 250 Watt efficiently with electronic speed controlling unit. Instead PWM signals are used to control the speed of the motor. Such type of motors are used in electric vehicles which are the future of automobile industry. The motto of this study is to build an efficient yet a low cost BLDC controller.

A.Tashakori et al[17] have studied the BLDC motor controller using Arduino and concluded that the smooth functioning of the motor requires appropriate chopping of the current.

Mukherjee et al[18] have studied how to control the speed of a brushless dc motor using low cost pic16f877 microcontroller. To accomplish this, pwm technique is used, which is intrinsic under module of pic. A microcontroller based speed control scheme has been developed. The pic16f877a microcontroller has been programmed to vary the duty cycle.

Qiang Li et al[19] have proposed a method for control which reduces the number of components because the microcontroller can integrate in one package all the functions. Thus, the proposed technique well-matched for industrial applications. This project suggests a durable, accurate, reliable, and efficient way of speed control of Brushless DC motor.

Ward Brown[20-21] has studied that electronic speed controllers are often used on motors essentially providing an electronically-generated three-phase electric power low voltage source of energy for the motor. It also allows much smoother and more precise variation of motor speed in a far more efficient manner than the mechanical type with a resistive coil and moving arm once in common use.

Besse et al[22] have studied the designing a BLDC controller with electronic speed controller that works with the controlling element i.e Arduino,the MOS drivers and the MOSFET commutation circuitry. With the help of this circuit efficient rotation is not yet achieved but current chopping can help for the smooth functioning of the motor.

Jahns et al[23] have studied the four quadrant operation of Brushless Dc Motor and also the hardware which shows the motoring and generating modes.

2.3 Conclusion

Literature review includes the summary of various research papers, books and other material used for performing this research work.

CHAPTER 3
Modelling of Brushless DC Motor

3.1 Introduction

A Brushless DC Motor conserves the characteristics of dc motor but eliminates the brushes and commentators hence known as Brushless DC (BLDC) Motor. DC conventional motors can be replaced by brushless dc motor in many cases. Current commutation is done by solid state switches said to be electronic commutation but motor is driven by dc voltage source. BLDC motors are available in many different power ratings, from large motors used in electric vehicle to very small motors used in hard drives. Three phase motors are common but in many applications two phase motors are also found. Nowadays, electric vehicles are considered as the future for a sustainable automobile industry as they have several benefits over internal combustion engine vehicles. Electric vehicle consist Motor, Controller and Battery. Electric motor plays significant role in electric vehicle. A wide variety of electric motors have been used for integration in electric vehicles. In previous years, DC electric motors were the most probably used, but recent advancements in technology have made AC electric motors much more suitable AC electric motors are characterized by more power density, less need of maintenance, higher efficiency and greater reliability.

BLDC motor is normally powered by conventional three phase inverter which is controlled by the rotor position information obtained from Hall sensors or simply from hall position sensors. Three phase windings use one Hall Sensor for each winding to provide three overlapping signals giving a 60° or 120° wide position range. Whenever the magnetic poles pass near the sensors a high or low signals will produce indicating North or South Pole. The controller has low cost and desirable stability. It can better perceive energy regenerative braking when the vehicle is decelerating and flux weakening control during high speed. Block diagram of electric vehicle and hybrid vehicle structure is shown in Figure 3.1.

(a) Electric Vehicle　　　　　　(b) Hybrid Vehicle
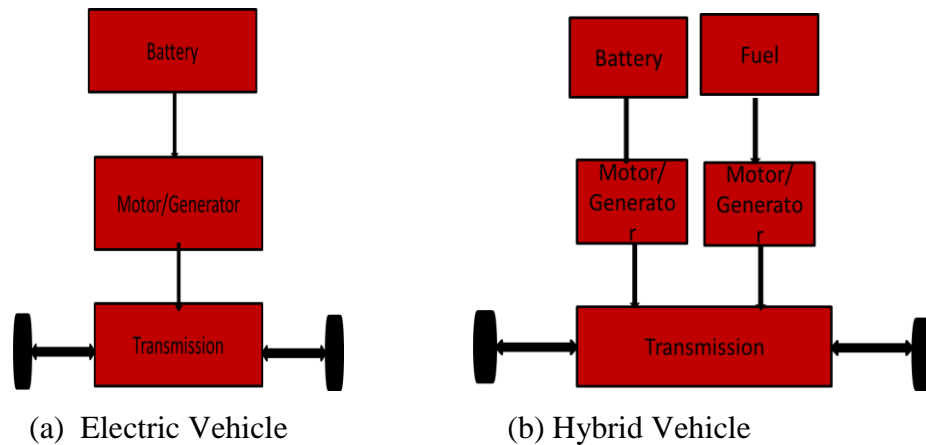
Fig3.1 Block diagram of electric vehicle and hybrid vehicle structure

Due to electronic commutation BLDC Motor have more complex control algorithm as compare to other motors. Hence, for precise and complete control scheme of BLDC accurate model of motor is required. It is necessary to have motor model which gives precise value of torque related to current and back EMF. Wheel technology uses a separate motor mounted inside each wheel instead of one central drive train propelling two or all wheels in conventional electric vehicles. It helps to increase controllability of vehicle and reduces chassis weight. BLDC motor has been used in various applications like aerospace, automotive, industrial automation, instrumentation, medical applications etc. As the brushes are eliminated less maintenance is required by motor also reduces noise susceptibility and sparking. BLDC motor is more advantageous as compared to brushed DC motor and induction motor in electric vehicle application because of its electronic commutation technique and permanent magnet rotor .

3.2 BLDC Motor Control

BLDC motor can be control by using inverter or electronic commutator, and the commutation is done by controlling the order of conduction on the inverter bridge arm. Figure.3.2 shows equivalent block diagram of BLDC motor with typical H-bridge inverter, Shaft position sensing unit and trigger circuit. DC power supply is given to the motor. Hall Effect sensors are used for predicting the position of rotor.

Three-phase Static Inverter

Vdc/2   Q1   Q3   Q5   A   BLDC Motor

Vdc/2   Q4   Q6   Q2   B   C

Trigger Circuit   Shaft position Sensing system
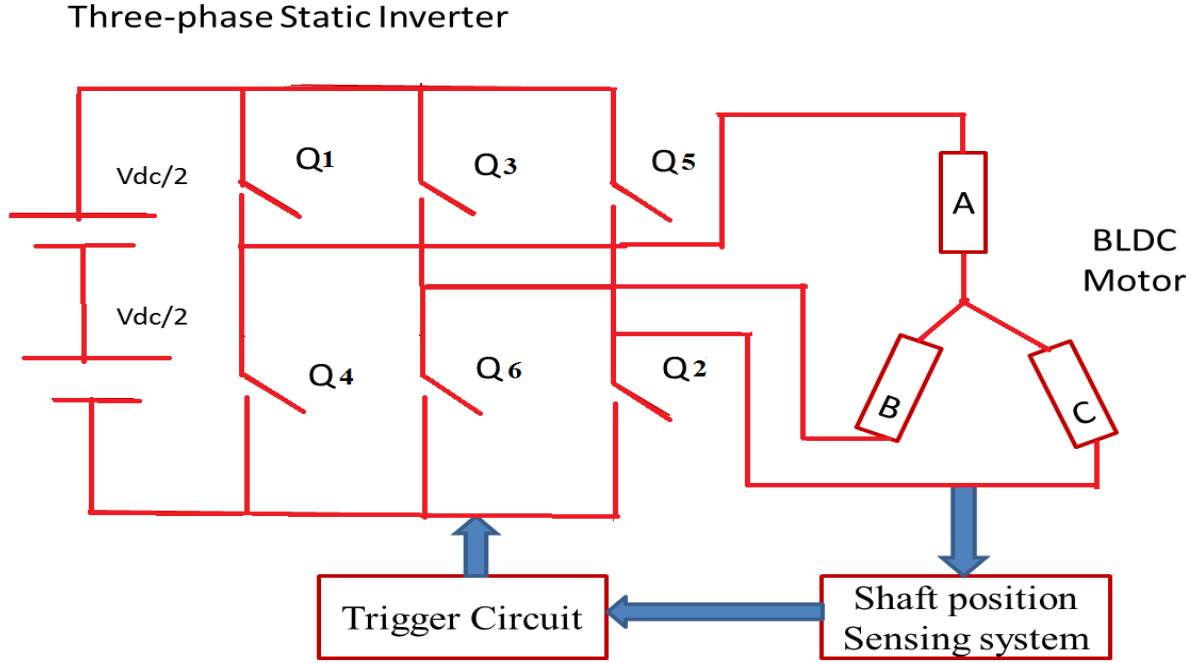
Fig.3.2 Equivalent Block Diagram of BLDC motor

3.3 Mathematical Analysis

A three phase star connected BLDC motor can be described by following electrical and mechanical equations:

$$V_a = R(i_a\text{-}i_b) + L\frac{d(ia-ib)}{dt} + e_a \text{-} e_b \qquad (3.1)$$

$$V_b = R(i_b\text{-}i_c) + L\frac{d(ib-ic)}{dt} + e_b\text{-} e_c \qquad (3.2)$$

$$V_c = R(i_c\text{-}i_a) + L\frac{d(ic-ia)}{dt} + e_c \text{-}e_a \qquad (3.3)$$

$$T_E(t) = T_L(t) + Jd\omega(t)/dt + k_f{}^*\omega(t) \qquad (3.4)$$

Where the symbols V, i and e represents phase to phase voltage (Volt), phase current (Amp) and phase back EMF of phase a, b and c respectively. Rand L are per phase values of resistance(Ω) and inductance(H) respectively. Te is electrical torque (N-m), T_L is load torque (N-m), J is rotor inertia (Kg/m²), K_f is friction constant, ω is rotor speed (rpm).The back EMF and electrical torque is given by

$$e_a(t) = (K_e/2)^*F(\theta_e)^*\omega(t) \qquad (3.5)$$

$$e_b(t) = (K_e/2)^*F(\theta_e\text{-}2\pi/3)^*\omega(t) \qquad (3.6)$$

$$e_c(t) = (K_e/2)^*F(\theta_e\text{-}4\pi/3)^*\omega(t) \qquad (3.7)$$

$T_e=(K_t/2)[F(\theta_e)i_a +F(\theta_e - 2\pi/3)i_b + F(\theta_e-4\pi/3)i_c$ $\qquad\qquad$ (3.8)

Where, K_E is back emf constant, K_t is torque constant

The electrical angle θ_E is equal to the rotor angle times the pole pairs ($\theta_e=p\theta_m/2$).The function F(.) gives trapezoidal waveform of back emf. One period of this function can be written as,

$F(\theta_e) = \{ 1 , \quad 0 \leq \theta_e \leq \pi$ $\qquad\qquad\qquad$ (3.9)

$\qquad$ $1-6(\theta_e - 2/3)/\pi , \ 2\pi/3 \leq \theta_e \leq \pi$

$\qquad$ $-1 , \quad \pi \leq \theta_e \leq 5\pi/3$

$\qquad$ $1+ 6(\theta_e - 2/3)/\pi , \ 5\pi/3 \leq \theta_e \leq 2$

$\qquad\qquad$ $\}$

Equation (3.1)-(3.4) are converted to state-space form for convenient use in MATLAB/Simulink. Each voltage equation is in linear combination of other two voltage equations only two voltages are needed. By eliminating one equation by using current relationship.

$i_a + i_b +i_c =0$

The voltage equations become

$V_{ab} = R(ia-ib) +L\dfrac{d(ia-ib)}{dt} + e_a - e_b$ $\qquad\qquad$ (3.10)

$V_{bc} = R(ia+2ib) +L\dfrac{d(ia+2ib)}{dt} + e_a - e_b$ $\qquad\qquad$ (3.11)

And the complete model is given as,

$$
\begin{bmatrix} ia* \\ ib* \\ ic* \\ wm* \\ \emptyset m* \end{bmatrix} =
\begin{bmatrix} -R/L & 0 & 0 & 0 \\ 0 & -R/L & 0 & 0 \\ 0 & 0 & -Kf/J & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}
\begin{bmatrix} ia \\ ib \\ ic \\ wm \\ \emptyset m \end{bmatrix} +
\begin{bmatrix} 2L/3 & L/3 & 0 \\ -L/3 & L/3 & 0 \\ 0 & 0 & 1/J \\ 0 & 0 & 0 \end{bmatrix}
\begin{bmatrix} Vab-eab \\ Vbc-ebc \\ Te-Tl \end{bmatrix} \quad (3.12)
$$

$$
\begin{bmatrix} ia \\ ib \\ ic \\ wm \\ \emptyset m \end{bmatrix} =
\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\begin{bmatrix} ia \\ ib \\ ic \\ wm \\ \emptyset m \end{bmatrix} \quad (3.13)
$$

Machine models are often transformed to rotating reference frame for improvement and simplification of computational efficiency.Model will get more complex after implementation of final state space equations (3.12)and (3.13).Even though neutral point of motor is not attainable but practically it is possible to approximate it with zero crossing point of back EMF.State space to Laplace transform and vice versa can also be written for zero initial condition systems. Hence final state space equation is divided into two separate and easy mechanical as well as electrical Laplace equations applied by phase to neutral voltages with the help of this BLDC model will become more simple and convenient.For implementation of various control techniques. According to electrical rotation of rotor in each phase separately ideal reference back EMF signal of motor is also produced and applied as negative feedback to phase voltage.

3.4 Simulation of BlDC Motor

Modelling and simulation of Brushless DC Motor with various loading conditions. The technical specification of brushless dc motor is shown in table 1.

Table 1 Parameter of BLDC Motor

Discription	value
Voltage	220V
Rated Frequency	50Hz
Poles	4
Phase Resistance	1.43ohm
Phase Inductance	9.4mH
Back emf	120 V
Moment of Inertia	0.0015
Damping Constant	0.002Nms
Flux	0.2158wb

As shown in Figure 3.3, 3-phase, 4poles trapezoidal back emf BLDC motor is fed with balanced supply of 220V, 50Hz.Trapezoidal back emf is referring that mutual inductance between rotor and stator has trapezoidal shape. Due to trapezoidal back emf abc phase variable model is more applicable than d-q axis. System includes BLDC motor subsystem blocks which shown in Fig3.4 and consists of current, back EMF and speed calculation blocks. Measurement block is connected to give output parameters. Hall Effect signals for the movement of rotor are produced according to electrical degree.
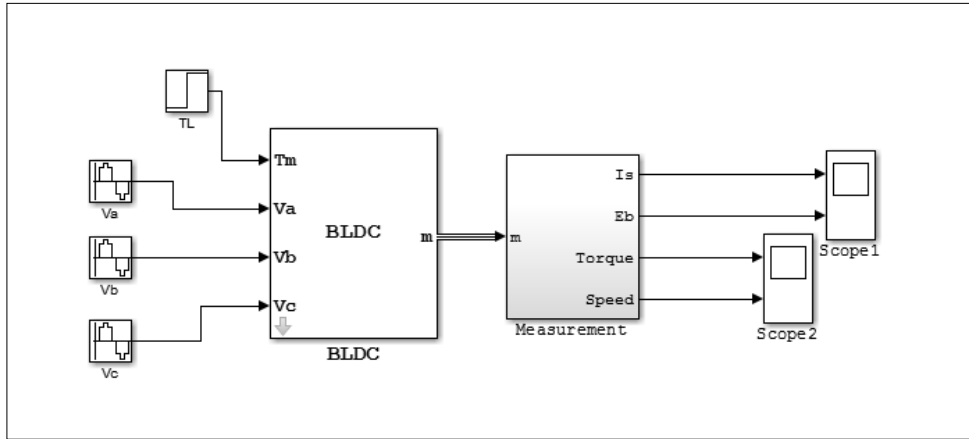
Fig 3.3 Simulink model of Three Phase Brushless Dc motor

Figure.3.4 shows detail Simulink model of 3-phase BLDC motor. Voltage, Current and torque equation, equations are used to implement the model of motor. Current block shows the calculation of current through phase-abc as well as electromagnetic torque, Back-EMF block gives calculation of back-EMF of all phases and electromagnetic speed (w_e). Speed calculation block calculates speed of rotor with the input of load torque (T_L) and electromagnetic torque (T_e).
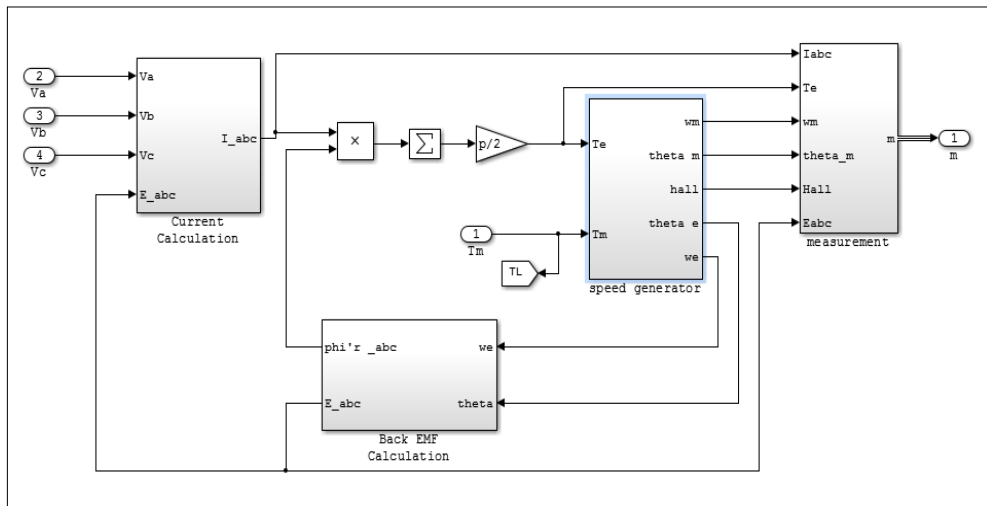
Fig 3.4 Simulink model of BLDC Motor
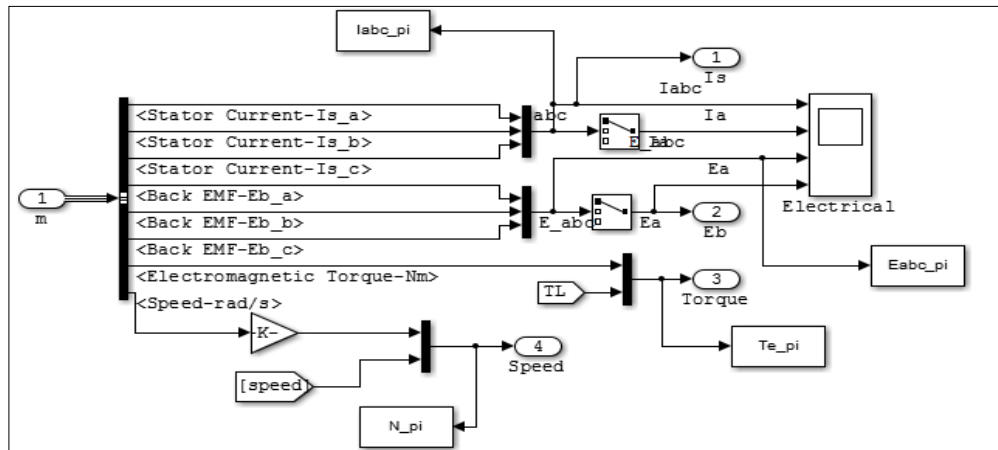
Fig 3.5 Simulink model of measurement

3.5 Simulation Results

The MATLAB model of 3-phase BLDC motor gives following results in terms of current, back emf, torque and speed. Figure3.6 and 3.7 shows the stator current and back-EMF for phase A at no-load condition with respect to time and figure3.8 shows torque with respect to time at no-load condition. Figure 3.9 shows speed of BLDC motor with respect to time is 1500 rpm at no load condition.

Fig3.6 Stator current of phase A at no load is 71.40A

Fig 3.7 Back Emf of phase A at no load is 70V

Fig 3.8 Torque of BLDC Motor at no load
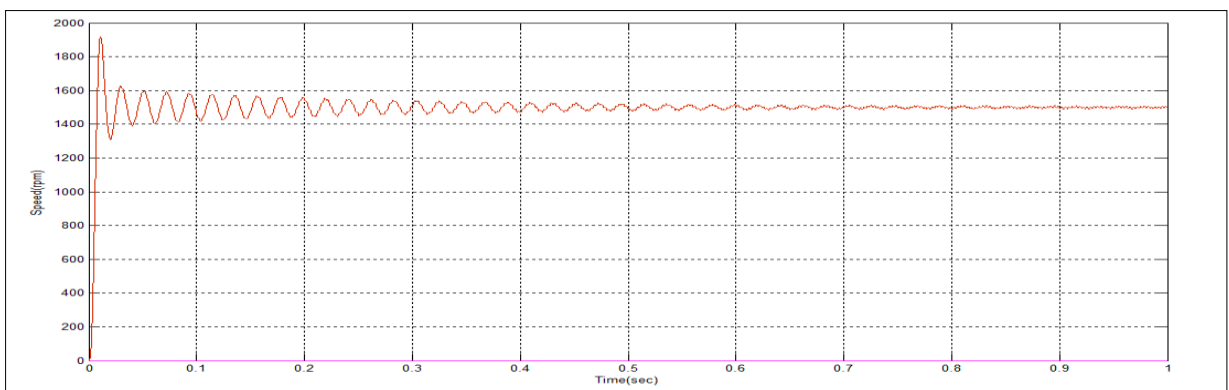
Fig 3.9 Speed of BLDC Motor at no laod

Figure3.10 and 3.11 shows the stator current and back EMF for phase A at 15 Nm load condition with respect to time and figure3.12 shows torque with respect to time at 15 Nm load condition. Figure 3.13 shows speed of BLDC motor with respect to time is 1500 rpm at 15Nm
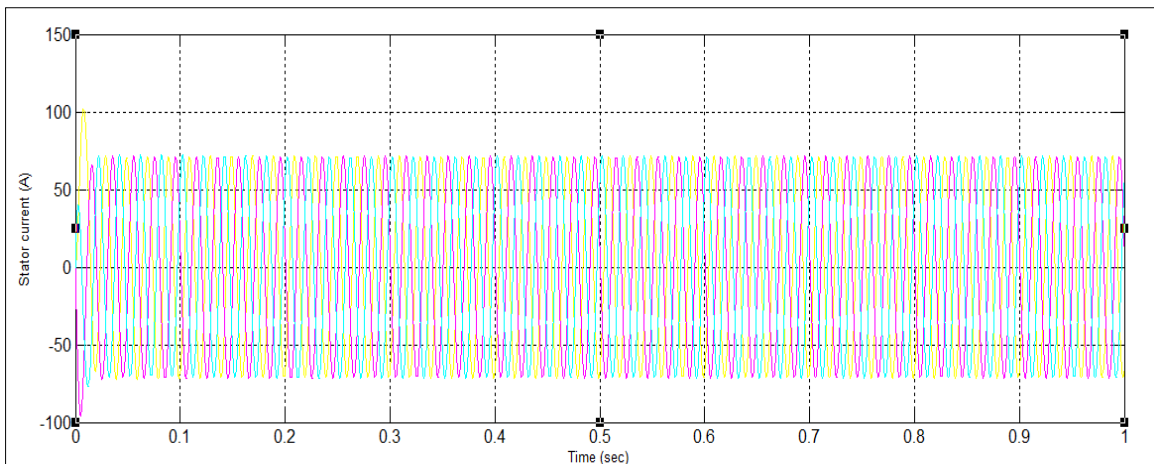
load condition.
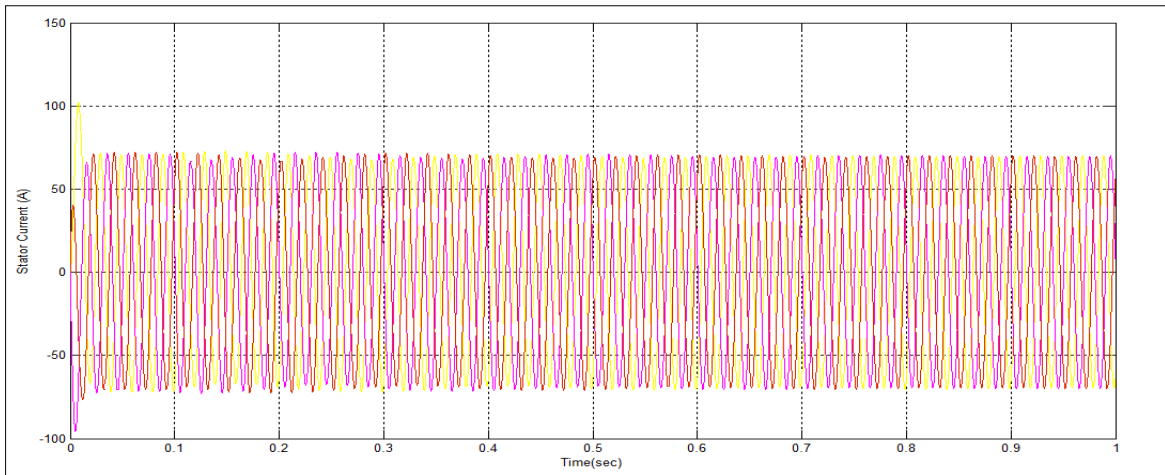
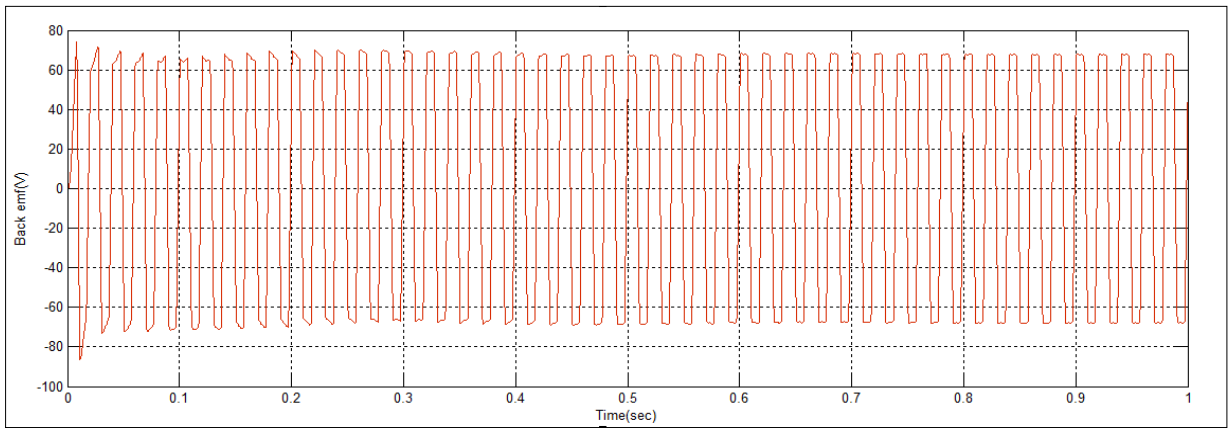Fig3.10 Stator current of phase A at 15 Nm load is 72.8382A
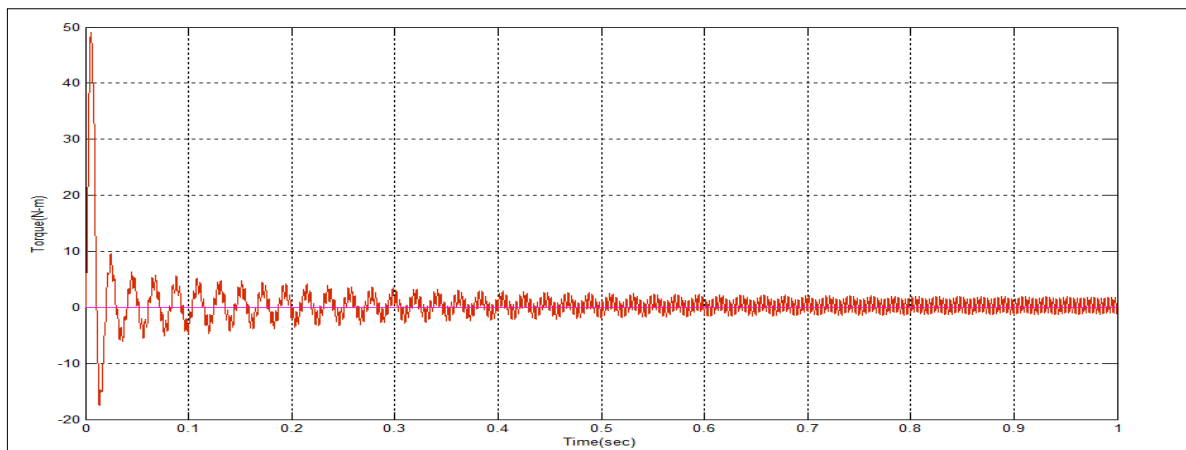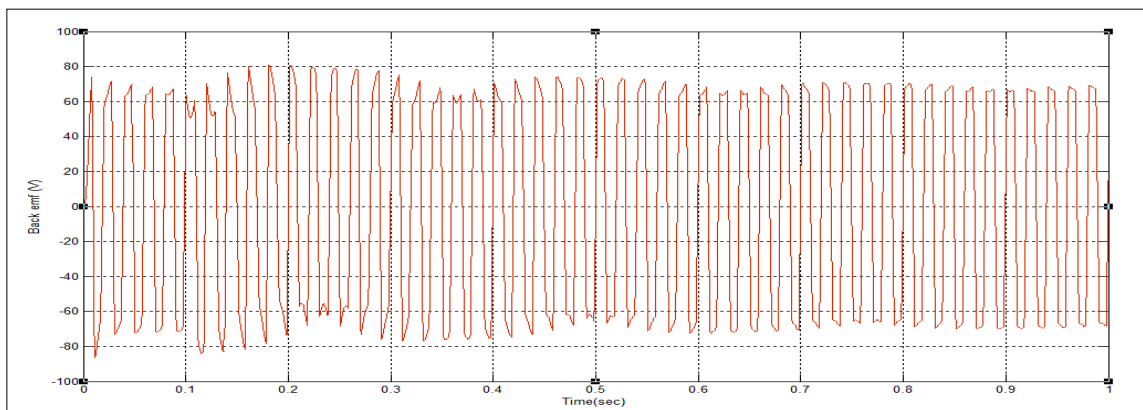

Fig 3.11 Back emf of phase A at 15 Nm load is 79.99V
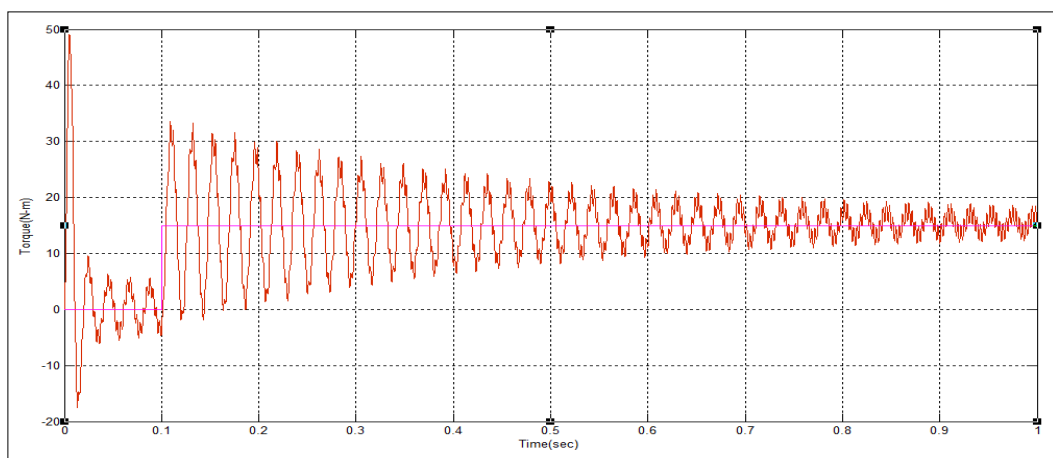
Fig3.12 Torque of BLDC Motor at 15Nm load condition
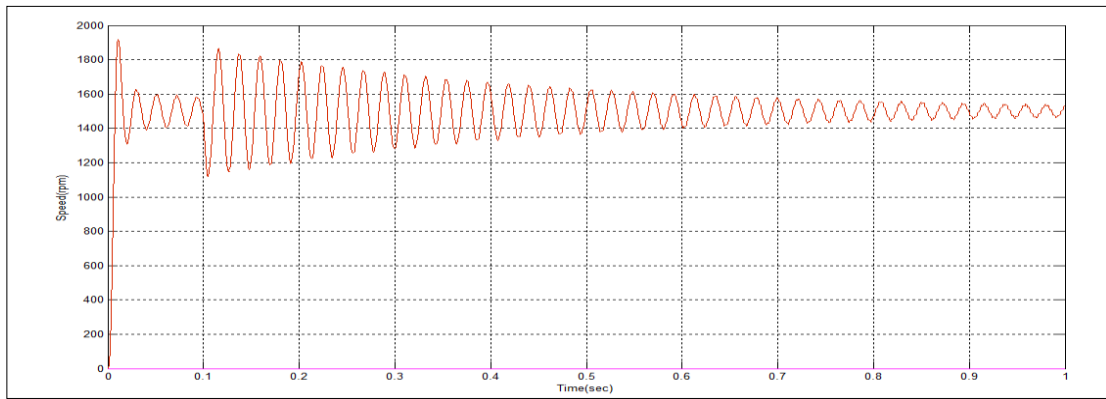
Fig 3.13 Speed of BLDC motor at 15 Nm load condition

3.6 Conclusion

All over the world sustainable transportation is a need of future due to greenhouse gases emission and reduced energy consumption. Electrical and Hybrid vehicles are the good solution for solving global warming issues commonly created by internal combustion engine vehicles. Motor is used to drive the wheels in EV. In this chapter the performance of a 3-phase motor fed from a 3-phase balanced power supply is analysed. A mathematical model similar to those representing conventional machines has been adopted to reflect the motor operation. Working principle, mathematical analysis and control of 3-phase BLDC motor are discussed.

CHAPTER 4

PERFORMANCE IMPROVEMENT OF BLDC MOTOR WITH HYSTERESIS CURRENT CONTROLLER

4.1 Introduction

Uses of Permanent Magnet in electrical machines have so many benefits and advantages than electromagnetic excitation machines. There are zero excitation losses which result in high efficiency, simple construction, low cost, less maintenance and high torque or high output power per unit volume. Due to high power to weight ratio, high torque, good dynamic control for variable speed applications, absence of brushes and commentators make Brushless dc (BLDC) motor, best choice for high performance applications. Due to the absence of brushes and commentators there is no problem of mechanical wear of the moving parts. As well, better heat dissipation property and ability to operate at high speeds make them superior to the conventional dc machine. However, the BLDC motor constitutes a more difficult problem than its brushed counterpart in terms of modeling and control system design due to its multi input nature and coupled nonlinear dynamics. Due to the simplicity in their control, Permanent magnet brushless dc motors are more accepted used in high performance applications.

In many of these applications, the production of ripple free torque is of primary concern. There are three main sources of torque ripple production in BLDCMs: cogging torque, reluctance torque, and mutual torque. Cogging torque is created by the stator slots interacting with the rotor magnetic field and is independent of stator current excitation. Reluctance torque is caused by the variation in phase inductance with respect to position. Mutual torque is created by the mutual coupling between the stator winding current and rotor magnetic field. In general, surface mounted magnets are used in many high performance BLDCM's. Because the permeability of the magnet material is nearly equal to that of air, the effective air gap is enlarged by the magnet. This fact ensures minimum armature effect on the rotor field from the stator currents. If a BLDCM is designed with low saliency and either the stator slots or rotor magnets are skewed by one slot pitch, the effects of the first two torque components can be greatly reduced. Therefore, if the waveforms of the phase back EMF and phase current are perfectly matched, torque ripple is minimized and the mutual torque component is maximized.

4.2 Modelling of Drive System

Fig4.1 shows the schematic BLDC drive system with Hysteresis current control loop.It consists mainly of BLDC motor, Hysteresis Current Controller, Inverter, Speed Controller and hall sensor blocks. Each block is modeled separately and integrated together. Figure4.1 shows the schematic of closed loop Two Level Inverter fed BLDC drive with Hysteresis Current controller loop. BLDC motor, Hysteresis Current Controller, Inverter, Speed Controller and hall sensor blocks. Each block is modeled separately and integrated together.
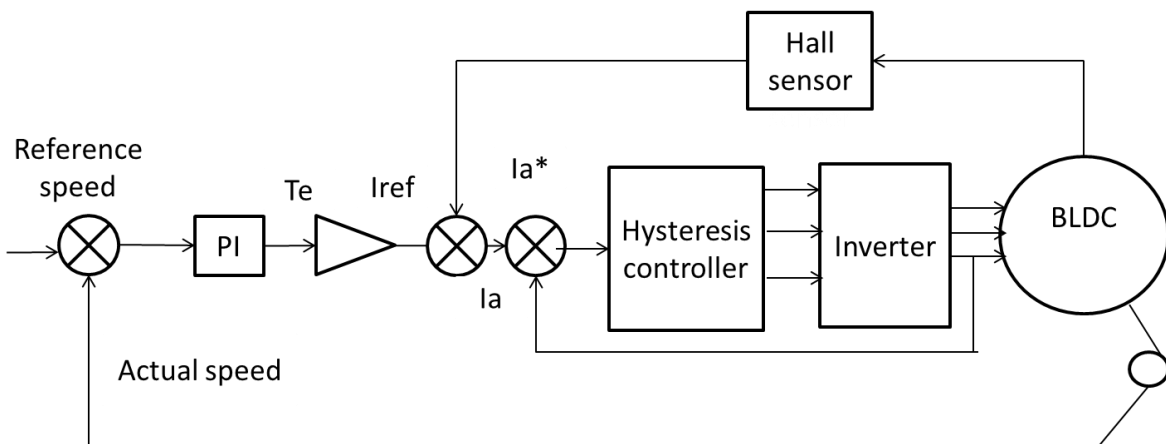
Fig4.1 Closed loop Two Level Inverter fed BLDC drive with Hysteresis Current controller loop

4.3 Modelling of BLDC Drive

A BLDC motor modeling can be developed in the same way as a synchronous three-phase machine. Some dynamic characteristics are different since its rotor is mounted with a permanent magnet. Flux linkage from the rotor is dependent upon the magnet. Therefore, saturation of magnetic flux linkage is typical for this kind of motors. Like any typical three-phase motor, as shown in Figure 4.2 one BLDC motor structure is fed by a three phase voltage source. The source is not necessary to be sinusoidal. Square wave or other wave shape can be applied as long as the peak voltage which does not exceeded the maximum voltage limit of the motor. Similarly, the model of the armature winding for the BLDC motor is expressed as follows. Following assumption is made.

1. Motor is not saturated as it operates within the rated current.

2. There are no changes in the rotor reluctances with angle.

3. Three phases are balanced one.

$$V_a = Ri_a + L\frac{dia}{dt} + e_a \qquad\qquad (4.1)$$

$$V_b = Ri_b + L\frac{dib}{dt} + e_b \qquad\qquad (4.2)$$

$$V_c = Ri_c + L\frac{dic}{dt} + e_c \qquad\qquad (4.3)$$

Compact matrix form are as follows

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} R+pL & 0 & 0 \\ 0 & R+pL & 0 \\ 0 & 0 & R+pL \end{bmatrix} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} ea \\ eb \\ ec \end{bmatrix} \qquad (4.4)$$

Where $L_a = L_b = L_c = L_s$ - M

L_s is the armature self resistance

M is the mutual inductance

$R_a = R_b = R_c = R$ Armature resistance in ohm

V_a, V_b ,V_c are the terminal phase voltages in volts.

i_a , i_b , i_c motor input current in amperes

e_a , e_b , e_c are the motor back emf in volts

Its back emf is trapezoidal because of the permanent magnet mounted on the rotor as shown in Fig 4.3. The back emf expression must be modified as expressed in

$$e_a \,(t) = K_E * \varnothing \,(\theta) * \omega(t) \qquad\qquad (4.5)$$

$$e_b \,(t) = K_E * \varnothing \,(\theta - 2\pi/3) * \omega(t) \qquad\qquad (4.6)$$

$$e_c \,(t) = K_E * \varnothing \,(\theta+2\pi/3) * \omega(t) \qquad\qquad (4.7)$$

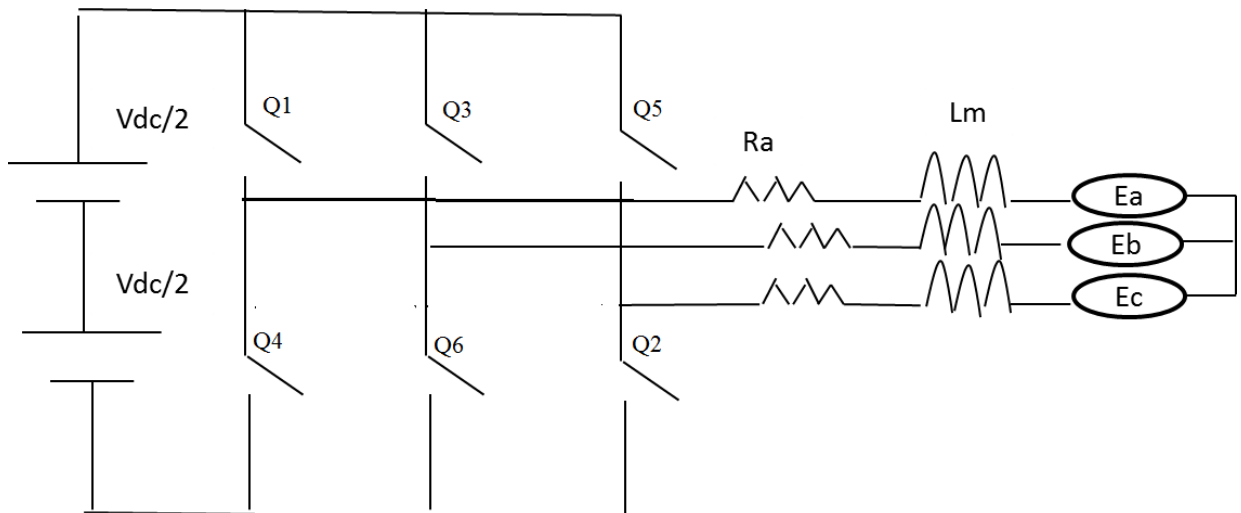Where K_E is the constant back emf and ω is the mechanical speed of the rotor.

Fig4.2 The Brushless Dc motor control system

Due to the trapezoidal flux linkage, the permanent magnet also influences produced torques. Where K_T is the torque constant and the produced torque are:

$T_E = (e_a i_a + e_b i_b + e_c i_c) / \omega$ (4.8)

The resultant torque, T_E can be obtained by the following expressions:

$T_a(t) = K_T * \emptyset (\theta) * i_a(t)$ (4.9)

$T_b(t) = K_T * \emptyset (\theta - 2\Pi/3) * i_b(t)$ (4.10)

$T_c(t) = K_T * \emptyset (\theta + 2\Pi/3) * i_c(t)$ (4.11)

$T_E(t) = T_a(t) + T_b(t) + T_c(t)$ (4.12)
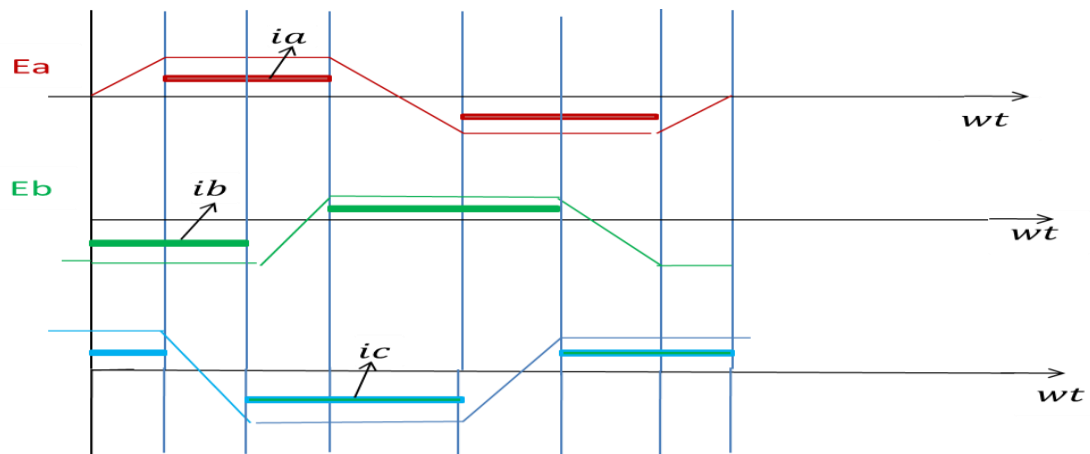
Fig 4.3 The motor phase current and BLDC motor back emf

Back emf and the phase current of BLDC motor with the Newton's second law of motion and the angular motion of the rotor can be written as follows:

$T_E(t) - T_L(t) = J d\omega(t)/dt + B*\omega(t)$ (4.13)

Where T_L is load torque in N-m

J is the rotor inertia in $[kgm^2]$

B is the damping constant

4.4 Closed loop Controller:

The Brushless Dc motor is fed from a three phase two level inverter. The PWM gating signals to fire the power semiconductor devices in the inverter is injected from a hysteresis current controller block, which is required to maintain the current constant within the 60^0 interval of one electrical revolution of the rotor. It regulates the actual current within the hysteresis band

around the reference currents. Depending on the steady state operating mode, the reference current generator generates the reference currents. The reference currents are quasi square wave in shape. From the reference torque, the magnitude of the reference current is calculated. By limiting the output of the PI controller, the reference torque is obtained. Speed error signal i.e. the difference between the reference speed and actual speed of the motor is given to the PI controller which gives the reference torque information. The motor will drive at reference speed, which is nothing but the closed loop control drive system, due to the presence of external speed feedback loop.

4.5 Modelling of Inverter

Figure 4.4 shows the two level inverter which supplies the input voltage for the three phase of the BLDC motor. It generally consists of two power semiconductor devices on each phase leg. Firing of the pair power semiconductor devices is generally based on the hall sensors input. For every 60°, three phases are commuted. Synchronization between stator flux and rotor flux is achieved because as sensors are the direct feedback of the rotor position. The inverter is designed using the below equations .

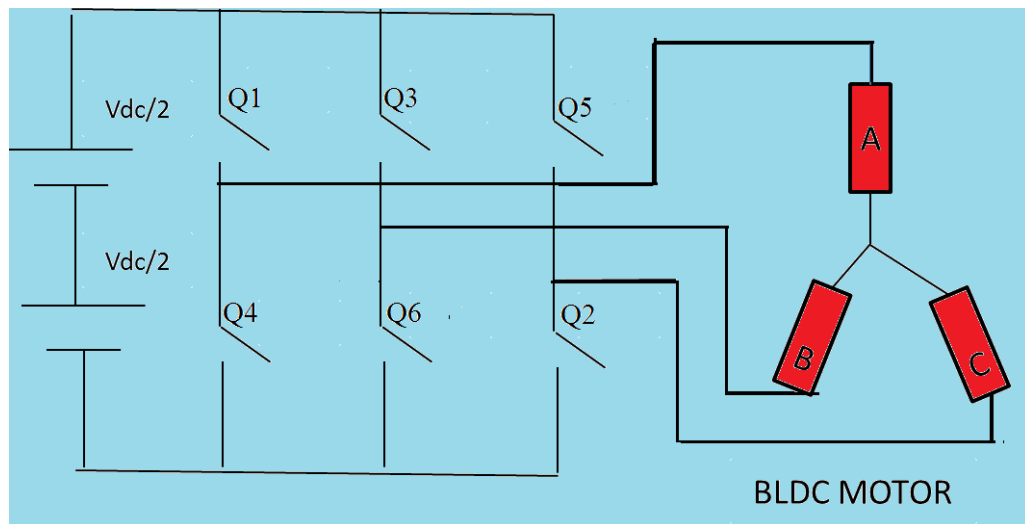Fig 4.4 Two level inverter fed by bldc motor

$$V_{an} = (Q_1)*(\frac{Vdc}{2}) - (Q_4)*(\frac{Vdc}{2}) \qquad (4.14)$$

$$V_{bn} = (Q_3)*(\frac{Vdc}{2}) - (Q_6)*(\frac{Vdc}{2}) \qquad (4.15)$$

$$V_{cn} = (Q_5)*(\frac{Vdc}{2}) - (Q_2)*(\frac{Vdc}{2}) \qquad (4.16$$

4.6 Modeling of Hysteresis current Controller

Figure 4.5 shows the hysteresis current controller block diagram that will generate inverter gating signals, Input currents ia, ib, ic are measured and compared with the reference currents, ia *, ib*, ic*. The error is fed by comparator with a prescribed hysteresis band. Power semiconductor devices (Q_1 ON and Q_4 OFF) switching occurs when current attempts to exceed the set value of the desired current. The reverse switch (Q_1 OFF and Q_4 ON) occurs when the current attempts to be less than i_{aref}. Hysteresis controller is easy to us and produces very good waveform quality.

The disadvantage of this method is that the frequency of switching does not remain constant, but varies with different portions of the desired current. The pattern of switching is as follows:

If ΔI_a >H, Q_1 is on, Q_4 is off   (4.17)

If ΔI_a <L, Q_1 is off, Q_4 is on   (4.18)

If ΔI_b >H, Q_3 is on, Q_6 is off   (4.19)

If ΔI_b <L, Q_3 is off, Q_6 is on   (4.20)

If ΔI_c >H, Q_5 is on, Q_2 is off   (4.21)

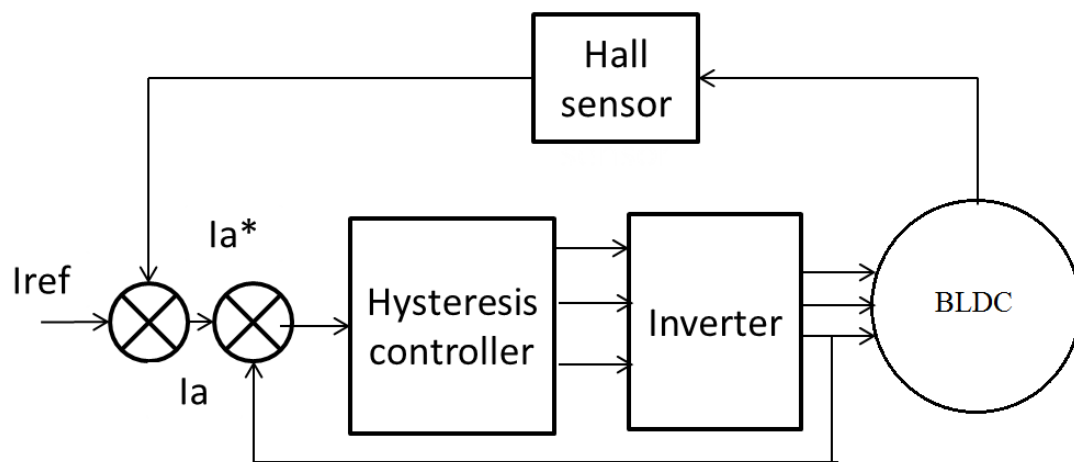If ΔI_c <L, Q_5 is off, Q_2 is on   (4.22)

Fig4.5 Block diagram of hysteresis current controller

Where $\Delta I_a = I_a* - I_a$

H is the upper limits of hysteresis is band

L is the lower limits of hysteresis is band

Thus, it is possible to obtain quasi-square waveforms by regulating the current desired.

4.7 Modeling of speed controller block

Figure4.6 shows the block diagram of the speed controller. In this PI controller is used as a speed controller. Speed error that is the difference between the actual speed and the reference speed of the motor are the inputs signals to the speed PI controller. Where Ki and Kp values are finding out by trial and error method for each set of speed.
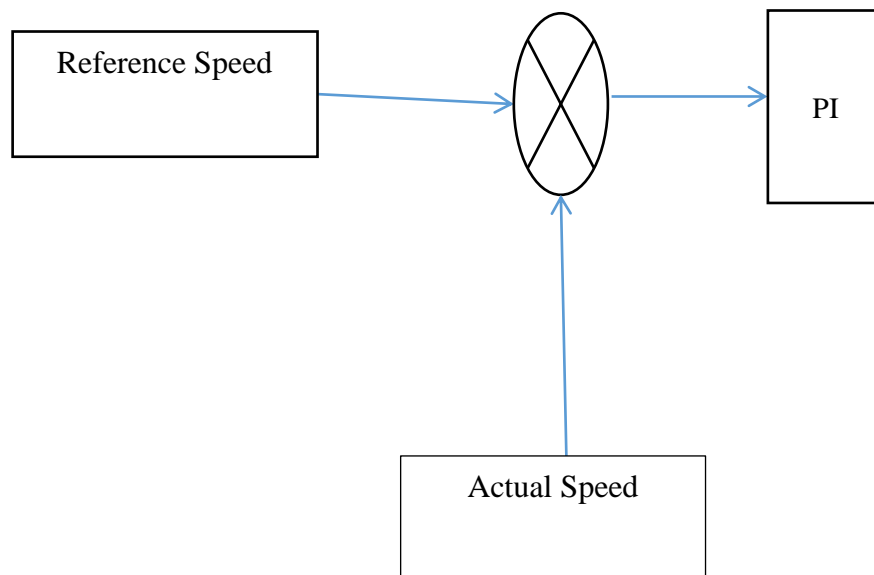

Fig 4.6 Block diagram of speed controller

4.8 Result and discussion

Simulation of BLDC Motor is carried out under various loading condition using PI controller and hysteresis current controller. The dynamic performance of drive for bellow two cases are shown through Fig4.7 to Fig4.24. The technical specification of BLDC motor is given in Table 2.

Table2 The test parameters of the motor taken for simulation

Parameters	Value
Rated voltage	500V
Resistance of the stator (Rs)	2.8750ohm
Inductance of the stator (L)	8.5mh
Moment of inertia (J)	0.0083
Flux	0.175wb
Motor torque constant (kt)	1.4
No. of poles	4

1. Without Hysteresis current control loop

Fig4.7 Show the Simulink block diagram of the closed loop operation of BLDC motor drive without hysteresis current control. Fig4.8 shows that dynamic behaviour of the motor when reference speed is set at 3000 rpm. A current of 5 amps is observed at the time of starting, at t= 0.05 motor taking a current of 0.25 amps at no load. Fig4.9 shows the back emf at no load using PI controller.
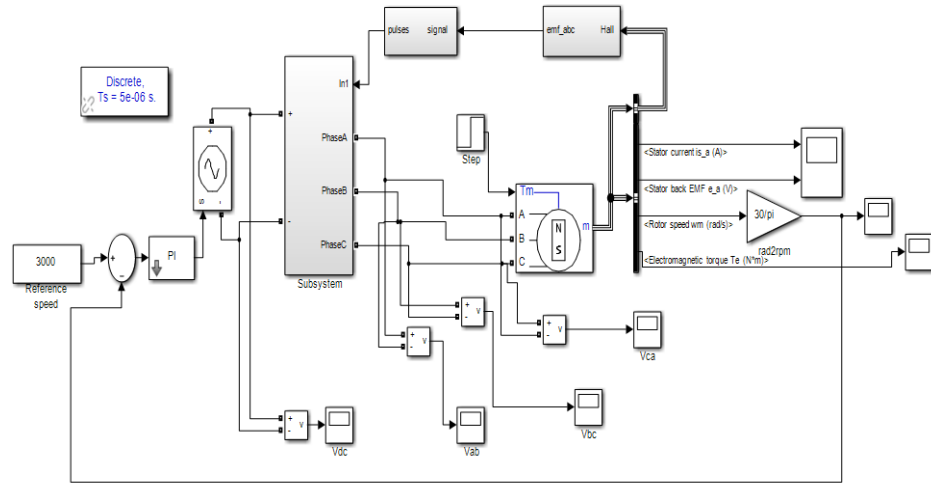
Fig 4.7 Simulink model of BLDC motor drive without Hysteresis current controller

Fig4.8 Stator current of phase A at no load using PI controller
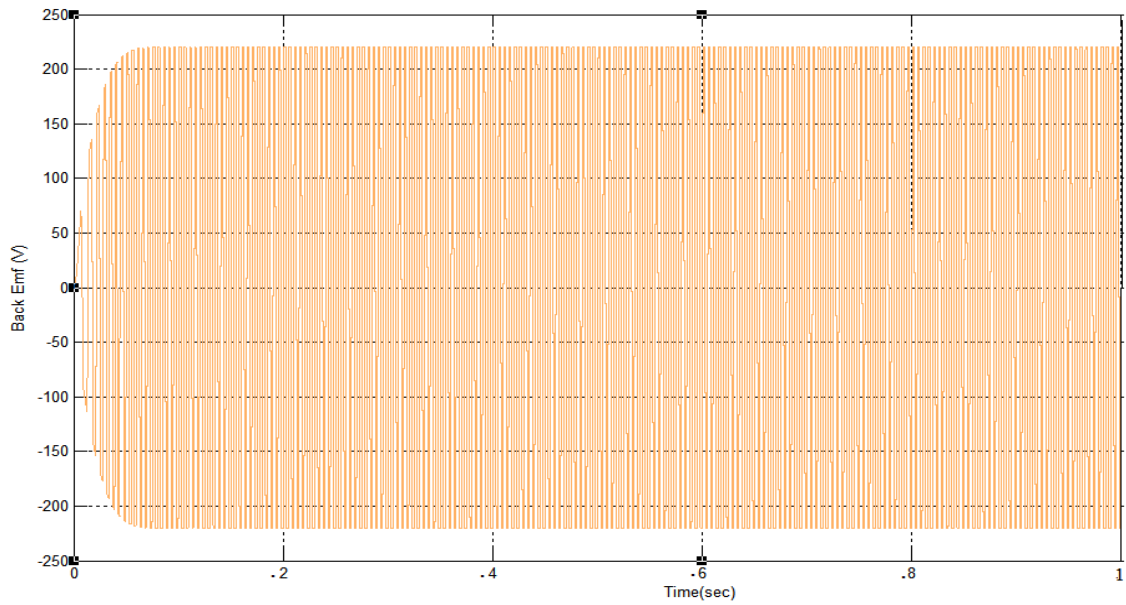
Fig 4.9 Back emf of phase A at no load using PI controller

Fig4.10 shows that a motor is developing a high torque of 17 Nm at the time of starting and develops a torque of 0.1 Nm at no load condition. Fig4.11 shows that the speed is 3000 rpm at no load using PI controller.
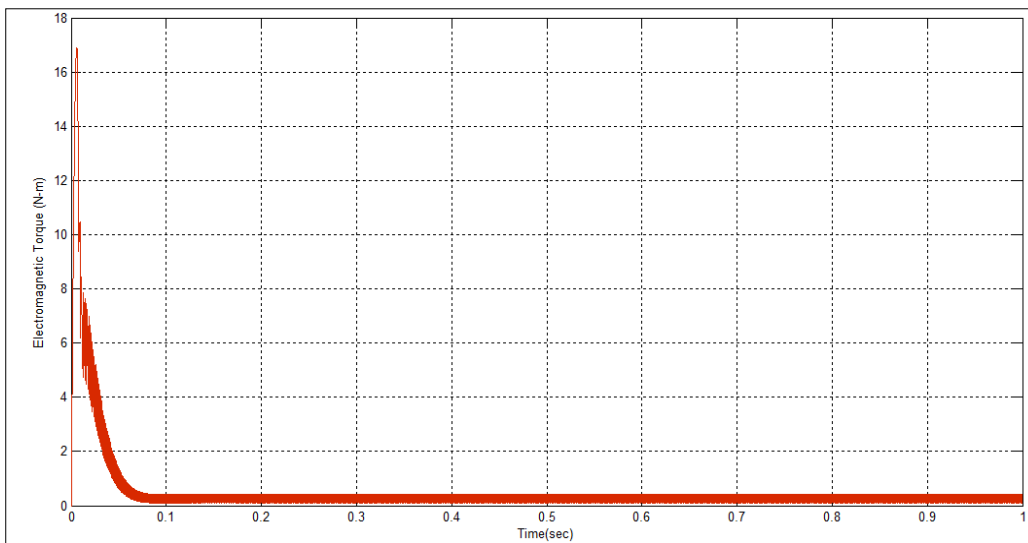
Fig4.10 Torque of the BLDC Motor at no load using PI controller

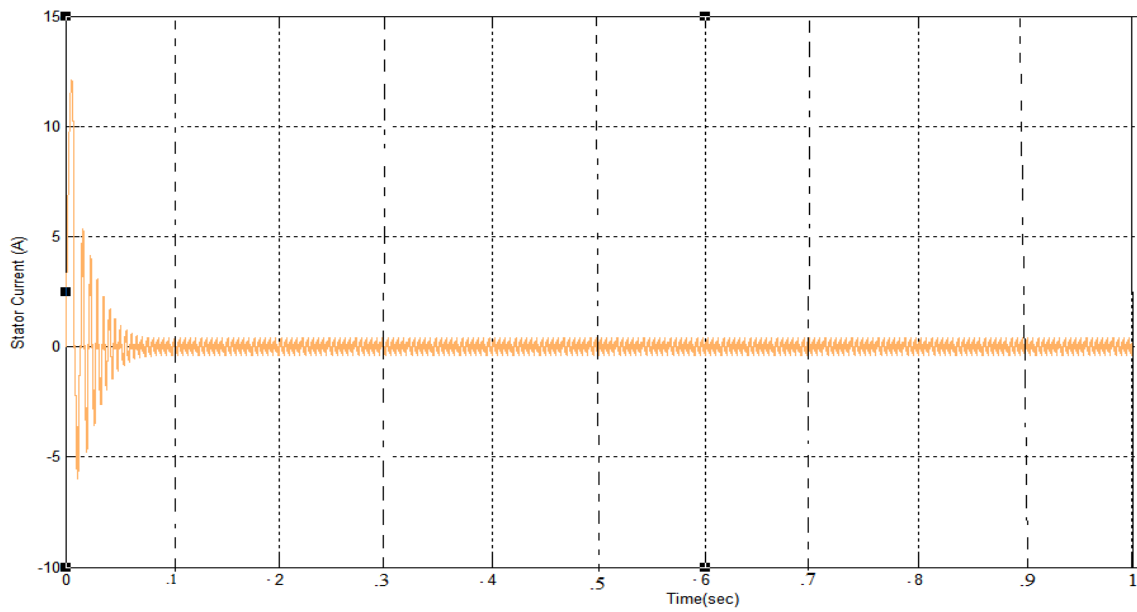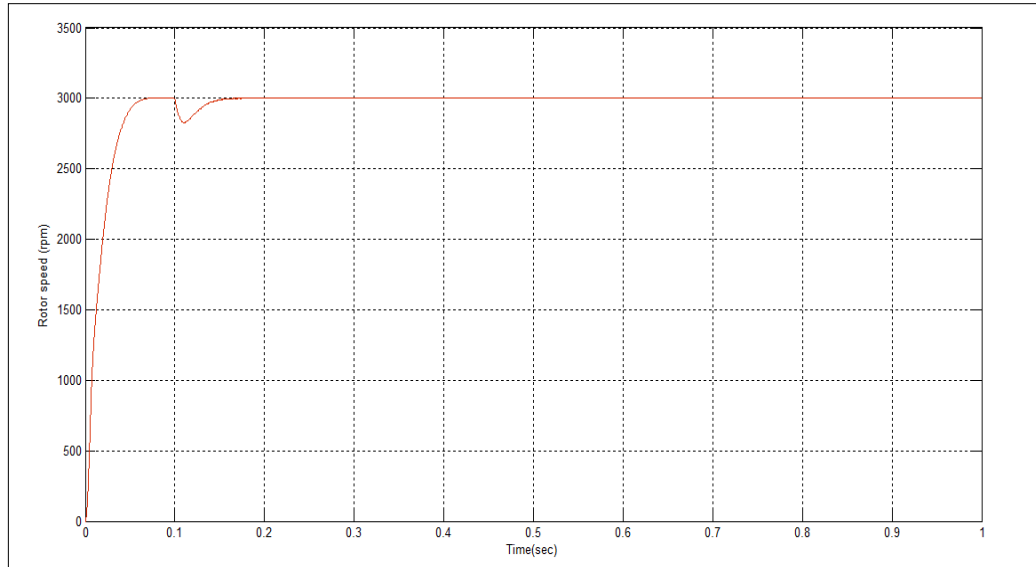Fig 4.11 Speed of BLDC Motor at no load using PI controller

Fig4.12 and Fig4.13 shows the stator current and back emf of phase A at 15Nm load condition using PI controller.

Fig 4.12 Stator current of phase A at 15Nm load condition using PI controller

Fig 4.13 Back emf of phase A at 15Nm load condition using PI controller

Fig 4.14 and Fig 4.15 shows that the torque and speed at 15Nm load condition using PI controller.

Fig4.14 Torque of the BLDC Motor at 15Nm load condition using PI controller
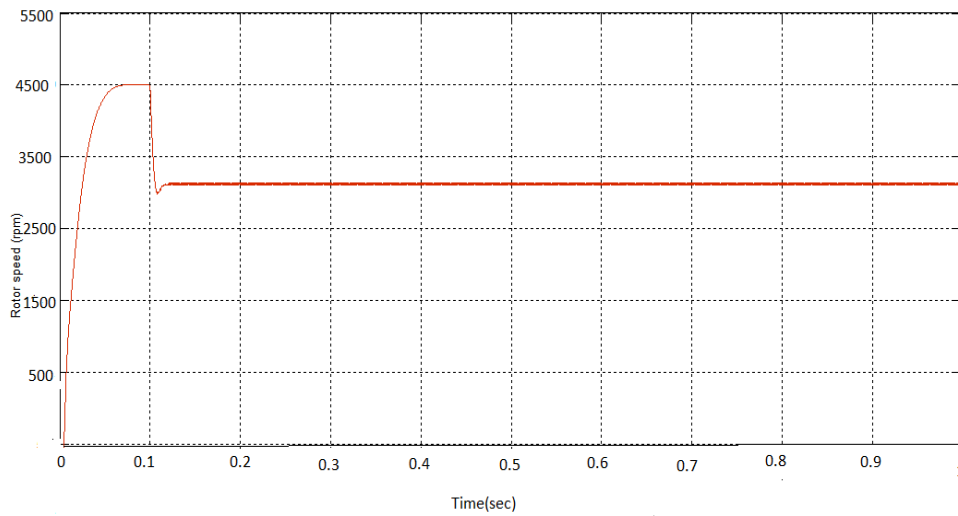
Fig 4.15 Speed of BLDC Motor at 15Nm load condition using PI controller

2. With Hysteresis current control loop

Fig4.16 Show the Simulink block diagram of the closed loop operation of BLDC motor drive with hysteresis current control. Fig4.17 shows the Dynamics of the motor with hysteresis current controller. A current of 12 amps is observed at the time of starting, motor taking a current of 2.75 amps at no load.Fig4.18 shows the back emf at no load using hysteresis current controller.
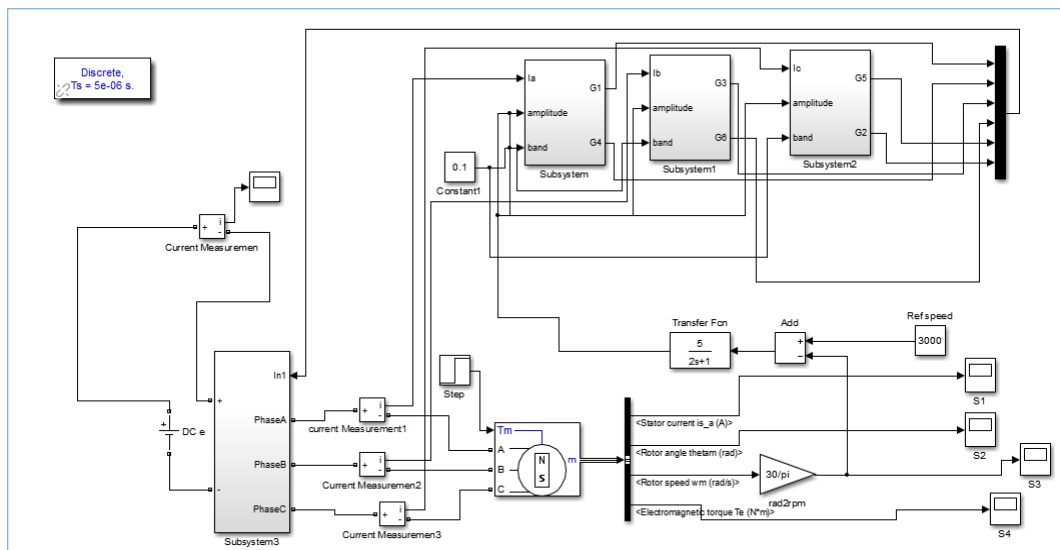
Fig4.16 Simulink model of BLDC motor drive with Hysteresis current controller
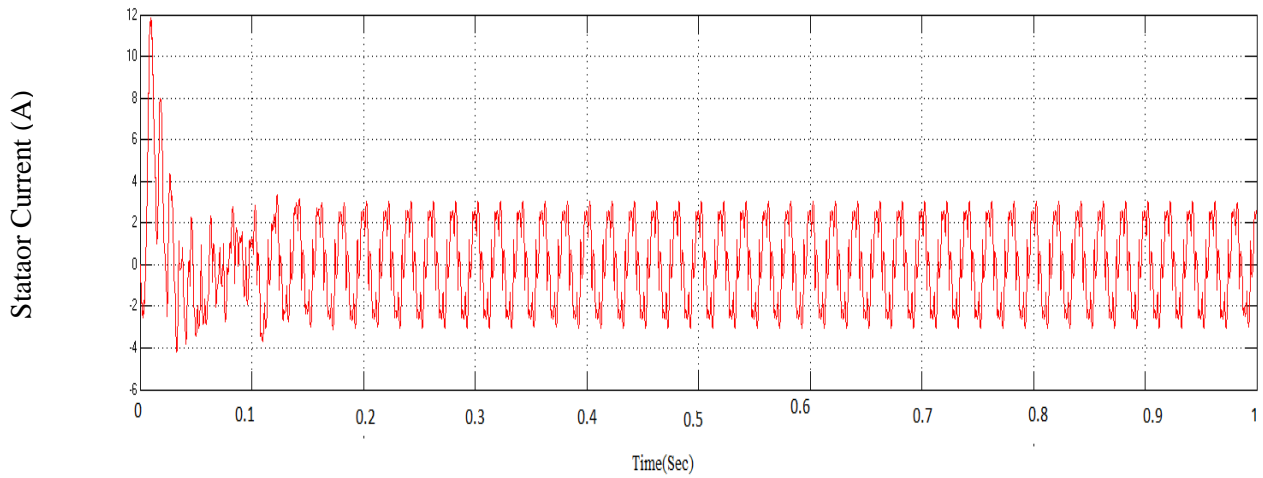
Fig4.17 Stator current of phase A at no load using hysteresis current controller
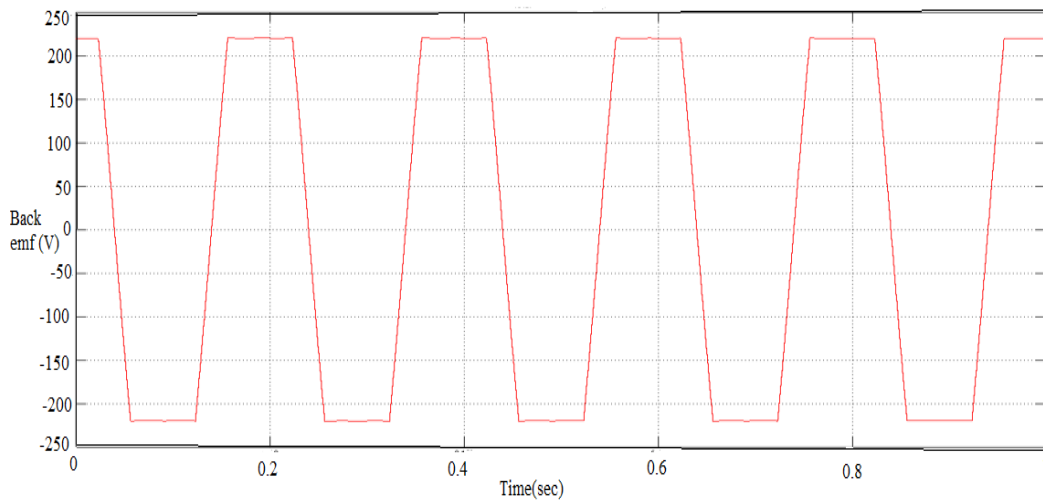
Fig4.18 Back emf of phase A at no load using hysteresis current controller

Fig4.19 shows that the speed is 3000 rpm at no load condition.Fig4.20 shows that a motor is developing a high torque of 4 Nm at the time of starting and develops a torque of 0.1 Nm at no load condition using hysteresis current controller.
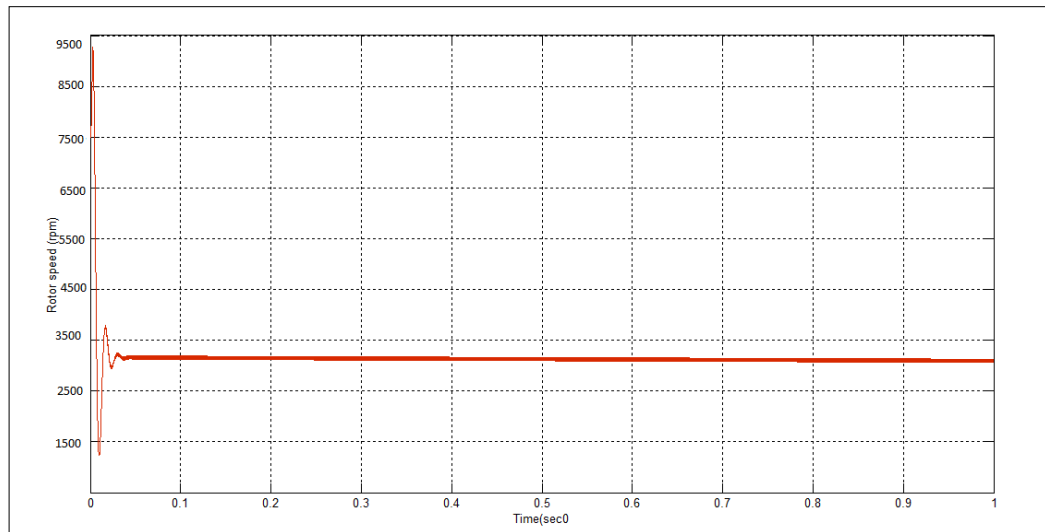
Fig4.19 Speed of BLDC Motor at no load using hysteresis current controller
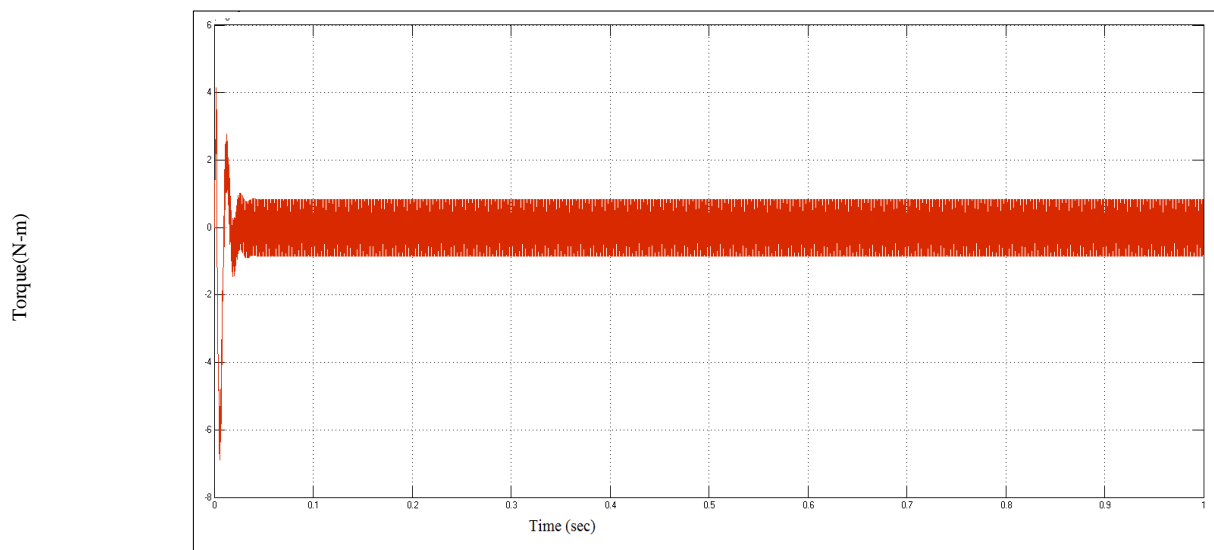
Fig 4.20 Torque of BLDC Motor at no load using hysteresis current controller

Fig4.21 and Fig4.22 shows the stator current of phase A and back emf of phase A at 15Nm load condition using hysteresis current controller.
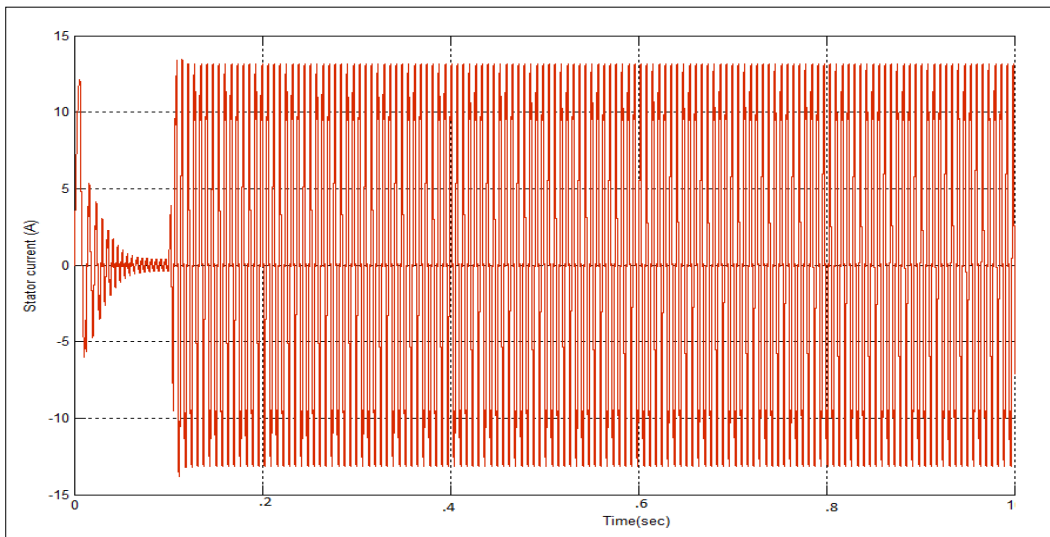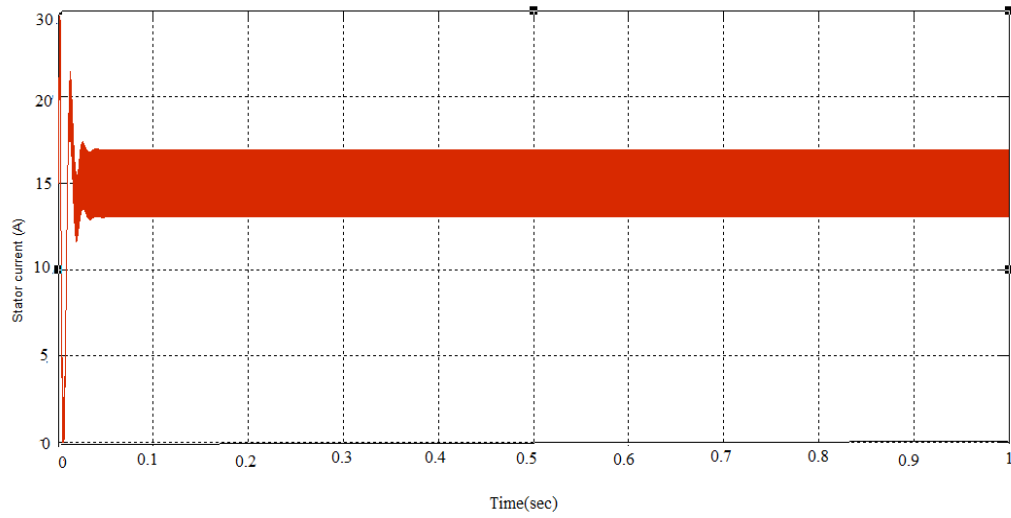
Fig4.21 Stator current of phase A at 15Nm load condition using hysteresis current   controller
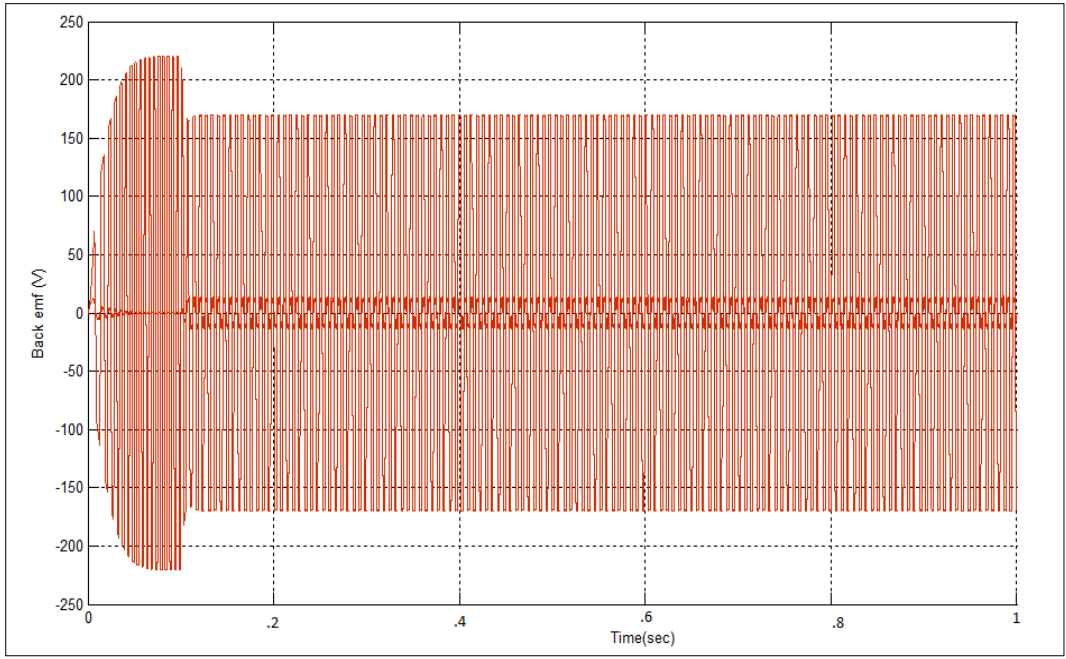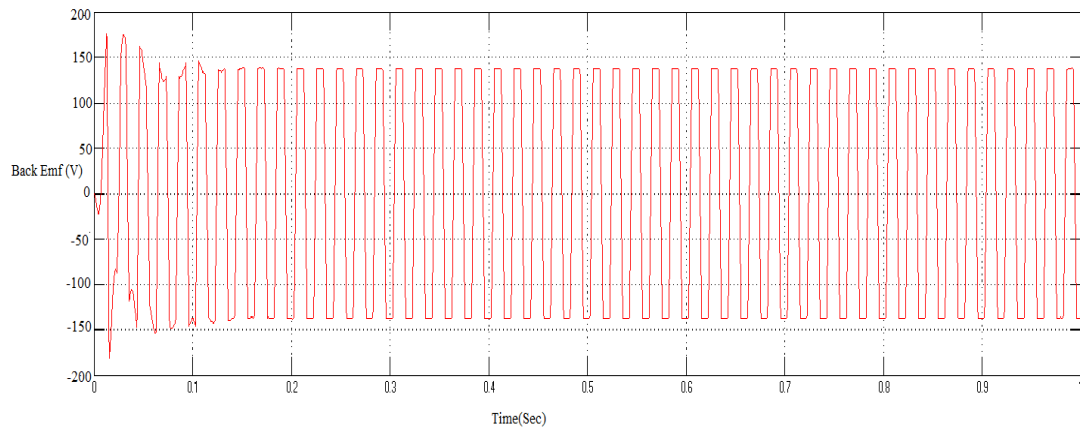

Fig 4.22 Back emf of phase A at 15Nm load condition using hysteresis current controller

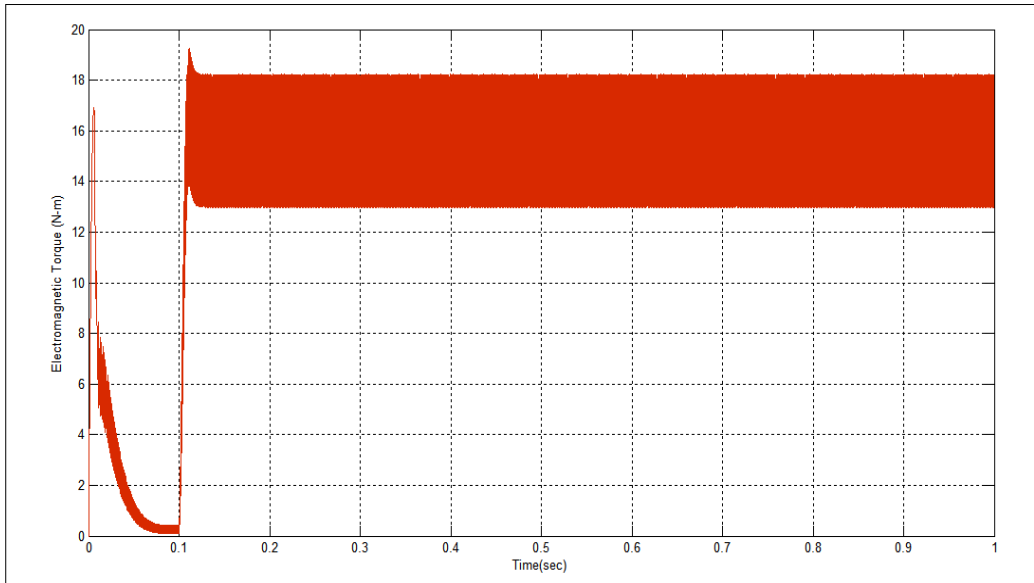Fig 4.1 and Fig 4.15 shows that the torque and speed at 15Nm load condition using hysteresis current controller.
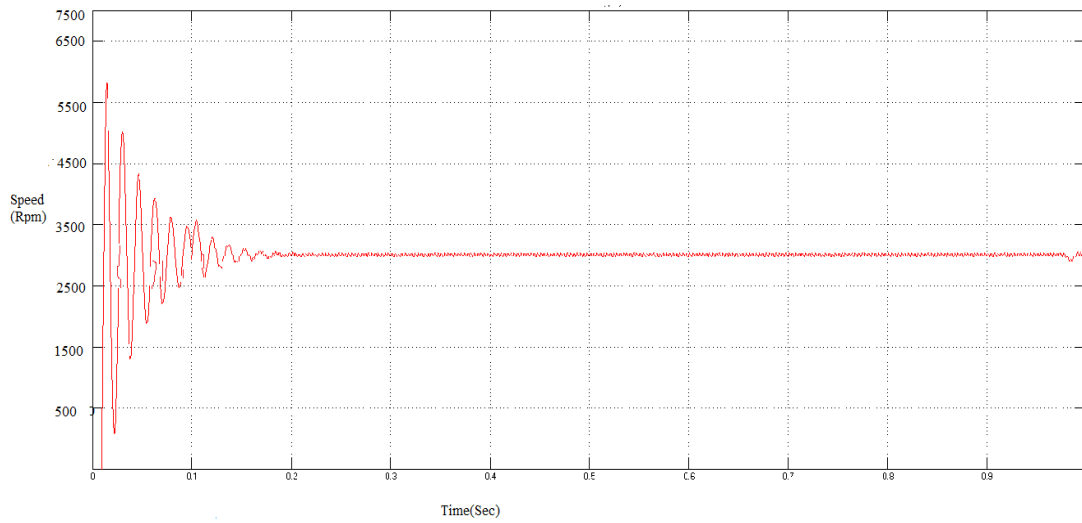
Fig4.23 Speed of BLDC Motor at 15Nm load condition using hysteresis current controller
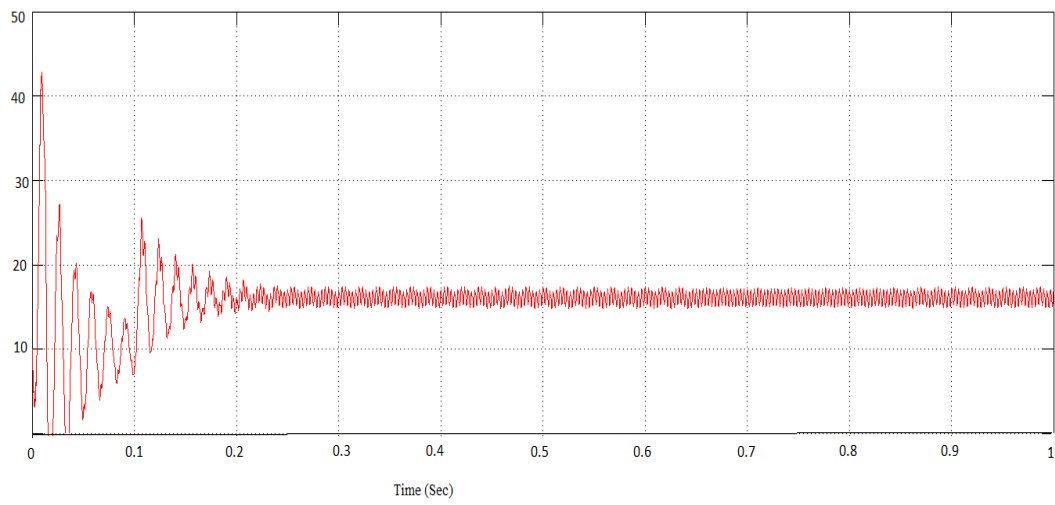
Fig 4.24 Torque of BLDC motor at 15Nm load condition using hysteresis current controller

3. Performance of drive under Loaded Condition

Reference speed is set to 3000 rpm, and motor is subjected to various loads conditions i.e. load torque is equal to 1Nm, 1.5Nm and 2Nm. The time taken to reach the set speed 3000 rpm increases with the increment in load. Table 3 shows the rise time of the load to reach set speed.

Table3 Rise time of the load to reach set speed of 3000rpm

Load torque(Nm)	Rise time
1Nm	0.19
1.5Nm	0.3
2Nm	1.3
2.5Nm	2.5

4. Comparison between with and without hysteresis current controller

Comparison between the magnitudes of ripple variation in stator current with hysteresis current controller and without hysteresis current controller is carried out and it is observed that without hysteresis current controller the current ripples varies between ±1 amps, while with hysteresis current controller, the variation in the ripple is between ±0.20 amps. The magnitude of torque ripples are less in hysteresis current controller when compared with without hysteresis current controller fed BLDC drive as current ripples decreases torque ripples are also minimized or reduced.

4.9 Conclusion

Permanent magnet brushless dc motors are more widely used in high performance applications because of their higher efficiency, higher torque in low speed range, high power density, low maintenance and less noise than other motors. In this chapter closed loop speed control of BLDC motor drive with hysteresis current controller loop is carried out and it is compared with and without hysteresis current controller fed BLDC drive. Simulation results shows that current ripple and torque ripple are minimized which enhance the performance of the drive

CHAPTER 5
HARDWARE IMPEMENTATION

5.1 Introduction

Brushless DC motor(BLDC motors) are also known as synchronous DC motors or electronically commutated motors (ECM).They are powered by DC electricity via an inverter or switching power supply which produces an AC electric current to drive each phase of the motor via a closed loop controller Reduced size and cost, increased torque current ratio, reduced torque ripples, low noises, high efficiency, reduced maintenance and good control characteristics over a wide range in torque speed plane are the various peculiarities of a permanent magnet excited BLDC motor. AC fans using shaded pole or universal motors are bulkier than the BLDC which are smaller in size and weight. The BLDC motors can work with low voltage sources such as 12V DC supply which makes them convenient for use in electronic gadgets like computers, mobiles, spindle drivers for disc memory, because of its high reliability. The speed of the BLDC motor can be controlled by varying the duty cycle. Hence it becomes the need of the hours to design a BLDC motor effectively with low cost and less circuitry. Most of the research papers have included the Electronic Speed control unit to control the speed of the motor. ESCs are often used on motors essentially providing an electronically-generated three phase electric power low voltage source of energy for the motor. It also allows much smoother and more precise variation of motor speed in a far more efficient manner than the mechanical type with a resistive coil and moving arm once in common use. In this designing of BLDC controller with ESC that works with the controlling element i.e Arduino, the MOS drivers and the MOSFET commutation circuitry. With the help of this circuit efficient rotation is achieved but current chopping can help for the smooth functioning of the motor.

5.2 Hardware Components Used

- Arduino UNO Platform
- AVR ATMega328 Controller
- 16 x 2 LCD MATRIX
- Motor Driver Circuit L293D
- Electronic speed controller
- BLDC motor

5.3 Microcontroller

As the name suggests the microcontroller is a small controller. They are like single chip computers that are often embedded as processing /controlling units in other systems. For example, the remote control you are using probably has microcontrollers inside that do decoding and other controlling functions. They are also used where automation used in automobiles, washing machine, microwave oven, toys etc. Here, we are using AVR ATMega328 microcontroller based on Arduino Platform. Platform refers to hardware architecture with software framework on which other software can run.

5.3.1   ARDUNIO UNO

An Arduino board which is shown in fig5.1 [35] is composed of an 8-bit Atmel AVR microcontroller with complementary components to facilitate programming and integration into other circuits. The Arduino Uno is a microcontroller board which is based on the ATmega328 (datasheet) which is shown in table4. It has 14 digital input/output pins (in which 6 can be used as PWM outputs), 6 analog inputs, a 16MHz ceramic resonator, a USB connection, a power jack, an ICS header, and a reset button. It contains everything that needed to support the microcontroller; simply connect it to a computer through USB cable or power it to get started with an AC to DC adapter or battery. The Uno differs from all previous boards because the FTDI USB to serial driver chip is not used. Rather, it features the Atmega16U2 (Atmega8U2 up to version R2) programmed as a USB-to-serial converter. The Board's revision 2 has the following new features:

1.0 pinout: Added SDA and SCL pins which are near to the AREF pin and two other new pins placed near to the RESET pin, the IORE which allows the shield to adapt to the voltage provided from the board. Shields will be compatible with both the board that uses the 5V-operating AVR and the 3.3V-operating Arduino. The second is a non-connected pin, which is reserved for future purposes.

RESET circuit is stronger.

8U is used instead of Atmega 16U2.

Fig 5.1 Arduino Uno

5.3.2.1.A Power

The Arduino Uno can be powered with an external power supply or via a USB connection. The power source is automatically selected. External power (non USB) can come from either an AC to DC adapter or a battery. The adapter can be connected by plug in into the power jack of the board a 2.1 mm center positive plug. Leads from a battery can be inserted into the POWER connector's Gnd and VIN pin headers.

The board can operate on an external supply of the 6 to 20 volts. However, if supplied with less than 7V, the 5V pin could supply less than 5 volts and the board could be unstable. The voltage regulator can overheat and

damage the board when using more than 12V. The recommended range is between 7 and 12 volts.

The power pins are as follows:

VIN: When using an external power source, the input voltage to the arduino board (as opposed to 5 volts from the USB connection or other regulated power source).You can also supply voltage through this pin, or, supplying voltage via from the power jack, access it through this pin.

5V: This pin outputs a regulated 5V from the regulator on the board. The board can be powered either from the board's DC power jack (7-12V), US connector (5V), or board's VIN pin (7-12V). Supplying voltage through the 5V or 3.3V buttons bypasses the regulator and might harm the board.

3.3V: The on-board regulator generates a 3.3volt supply. The maximum draw is 50 mA.

GND: Means ground pin.

5.3.2.1. B Memory

The ATmeg328 has 32 KB (0.5 KB is used for bootloader). It also has 2 KB of SRAM and 1KB of EEPROM (with the help of EEPROM library it can be read and write).

5.3.2.1. C Input and Output

Using pinMode(), digitalWrite(), and digitalRead(), each of the 14 digital buttons or pins on the Uno can be used as an input or output. They are operating at 5 volts. Each pin can supply or obtain up to 40 mA and has a 20-50kOhms internal pull-up resistor (default disconnected). In addition to this, some of pins have specialized functions:

Serial: 0 (RX) and 1 (TX). Which is used to receive (RX) and transmit (TX) TTL serial data. These pins are linked to the ATmega8U2 USB-to-TTL Serial chips.

External Interrupts: 2 and 3. These pins can be configured to trigger an interrupt on a low value, a rising or falling edge, or a change in value. See the attachInterrupt() function for details.

PWM: 3, 5, 6, 9, 10, and11. These pins provide 8-bit PWM output with the analogWrite() function.

SPI: 10 (SS), 11 (MOSI), 12 (MISO), 13 (SCK). These pins generally support SPI communication with the help of SPI library.

LED:B13. There is a built in LED connected to digital pin 13. When the value of pin is HIGH then the LED is on and when the value of pin is LOW than LED is off.

The Uno has 6 analog inputs, marked A0 through A5, each with a resolution of 10 bits (i.e. 1024 distinct values). By default, they measure from ground to 5volts, although the AREF pin and analog Reference () function can be used to change the upper end of their range. Additionally, some of the pins have specialized functionality:

TWI: A4 or SDA pin and A5 or SCL pin. With the help of Wire library it supports TW1 communication. There are a couple of other pins on the board:

AREF: Reference voltage for the analog inputs. Used with the function analog Reference().

Reset: To reset the microcontroller this line should be LOW. Usually used to add shields with a reset button that blocks the one on the board.

5.3.2.1. D Communication

The Arduino Uno has a huge number of facilities for communicating with either a computer or Arduino or with micro controllers. The ATmega328 generally provides UART TTLB (5V) serial communication, which is available on digital pins 0 (RX) and 1 (TX).An ATmega16U2 on the board channels this serial communication via USB and appears on the desktop as a virtual com port. .The 16U2 firmware general uses the standard USB COM drivers, and external no driver is needed. Usually, on Windows, a .inf file is required. The Arduino software involves a serial monitor that enables the transmission of easy textual information from and to the Arduino board. When data is transmitted via the USB to serial chip and USB connection to the computer, the RX and TX LEDs on the board will flash (but not for serial communication on pins 0 and 1).

5.3.2.1. E Programming

It is possible to program the Arduino Uno with the Arduino software. From the Tools > Board menu, select "Arduino Uno" (according to your board microcontroller).

The Arduino Uno ATmega328 comes pre-burned with a bootloader that enables you to upload fresh code to it without using an internal programmer. It communicates with the initial protocol STK500.

5.3.2.1. F USB Over current Protection

The Arduino Uno has a generally resettable polyfuse that protects our computer's USB ports from the overcurrent and the shorts. Most of the computers provide their own internal protection, the fuse which provides us an extra layer of protection. If the current is more than 500mA is given to the USB port, the fuse will automatically break the connection until the short or overload is removed.

5.3.2.1. G Physical Characteristics

The maximum length and width of the Uno PCB are 2.7 and 2.1 inches respectively, with the USB connector and power jack extending beyond the former dimension. Four screw holes allow the board to be attached to a surface or case. Note that the distance between digital pins7 and 8 is 160 mil (0.16"), not an even multiple of the 100 mil spacing of the other pins.
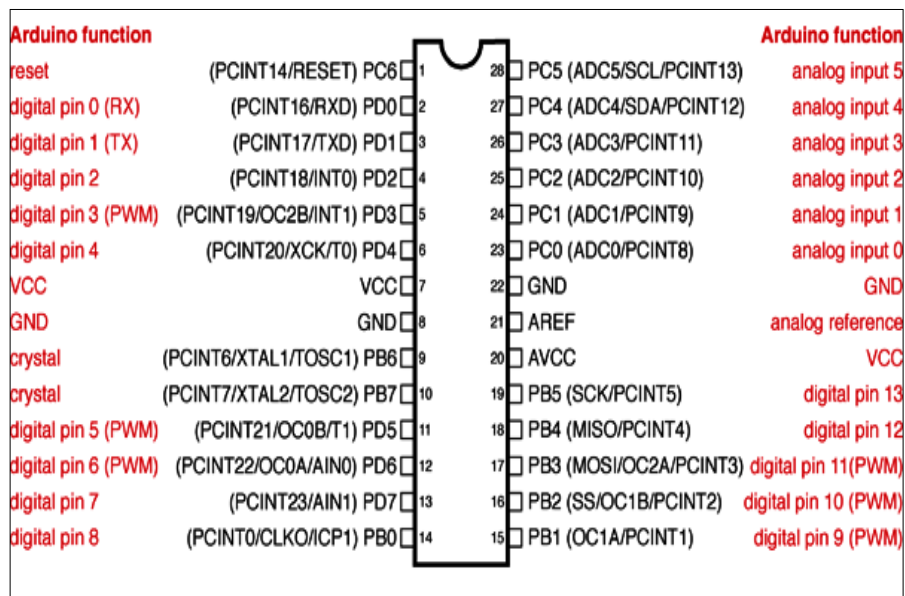

Fig 5.2 Pin Diagram of the Uno

Table 4 Parameter of arduino board

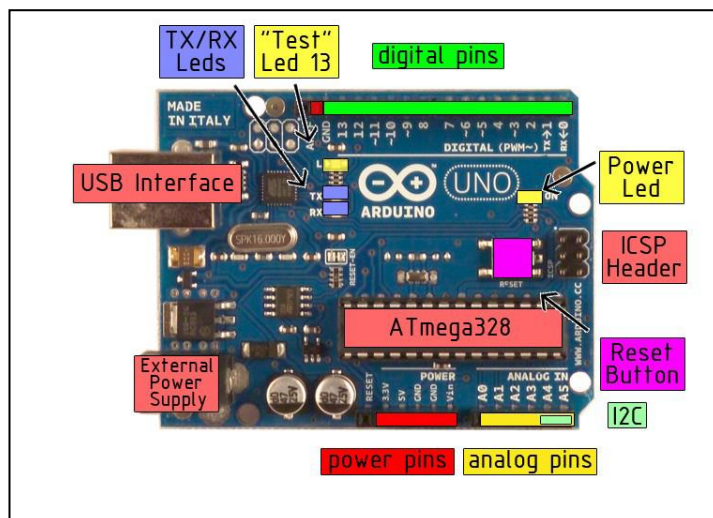| Micro controller	Atmega328
Operating Voltage	5V
Input voltage(recommended)	7-12V
Input voltage(limits)	6-20V
Digital I/O Pins	14(of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	40mA
DC Current for 3.3V Pin	50mA
Flash Memory	32KBB(ATmega328) of which 0.5 KB used by bootloader
SRAM	2KB (ATmega328)
EEPROM	1KB (ATmega328)
Clock Speed	16 MHz

Fig 5.3 Arduino Board

5.4 Accelerometer - ADXL 335

The ADXL335 which is shown in fig5.4[36], is a small, thin, low power, complete 3-axis accelerometer with signal conditioned voltage outputs. The product measures acceleration with a minimum full scale range of ±3*g*.It can also measuring the static acceleration of gravity sensing applications, as well as dynamic acceleration resulting from motion, shock, or vibration.

   Using the CX, CY and CZ capacitors on the XOUT, YOUT and ZOUT pins, the user selects the accelerometer bandwidth. With a range of 0.5Hz to 1600Hz for the YX and YB axes and a range of 0.5Hz to 550Hz for the Z axis, bandwidths can be selected to suit the application. The ADXL335 is generally available in a small, low profile,4mm×4mm×1.45mm,16-lead, plastic lead frame chip scale package. The data sheet of accelerometer is shown in table5.

Table 5 Data sheet of Accelerometer

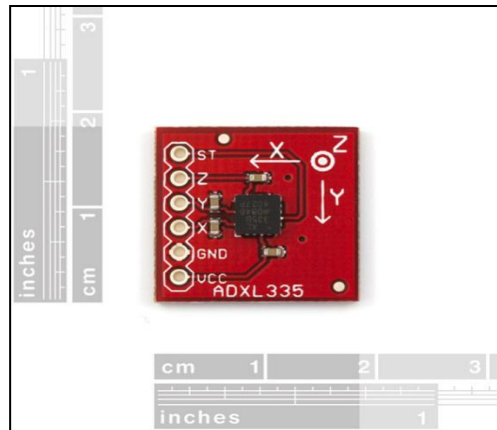|	
Acceleration (Any Axis, Unpowered)	$10,000g$
Acceleration (Any Axis, Powered)	$10,000g$
Vs	−0.3V to +3.6V
All Other Pins	(COM − 0.3V) to (Vs + 0.3V)
Output Short-Circuit Duration Any Pin to Common)	Indefinite
Temperature Range (Powered)	−55°C to +125°C
Temperature Range (Storage)	−65°C to +150°C

Fig 5.4 The ADXL335

5.5 Motor Driver Circuit –L293D

5.5.1 Description

The motor driving circuit which is shown in fig5.6 [37] is made up of monolithic integrated high voltage, high current, four channel driver designed to accept standard DTL or TTL logic levels and drive inductive loads (such as relays solenoids, DC and stepping motors) and switching power transistors. Each pair of channels is equipped with an enable input to simplify the use as two bridges. For the logic, a distinct supply input is given, enabling operation at a reduced voltage and internal clamp diodes are included. This device generally used in switching applications at frequencies up to 5kHz.The L293D is assembled in a 16-lead plastic package with 4 center pins linked together and used for heat sinking. The L293D is assemble in a 20-lead surface mount with 8 center pins linked together and used for heat sinking. Pin description of motor driving circuit is shown in table6.

5.5.2 Features

- 600mA Output Current Capability per channel
- 1.2A Peak Output Current (non repetitive) per channel
- Enable facility
- Over Temperature Protection
  - Logical "0" Input Voltage Up to 1.5 V
  - High Noise Immunity
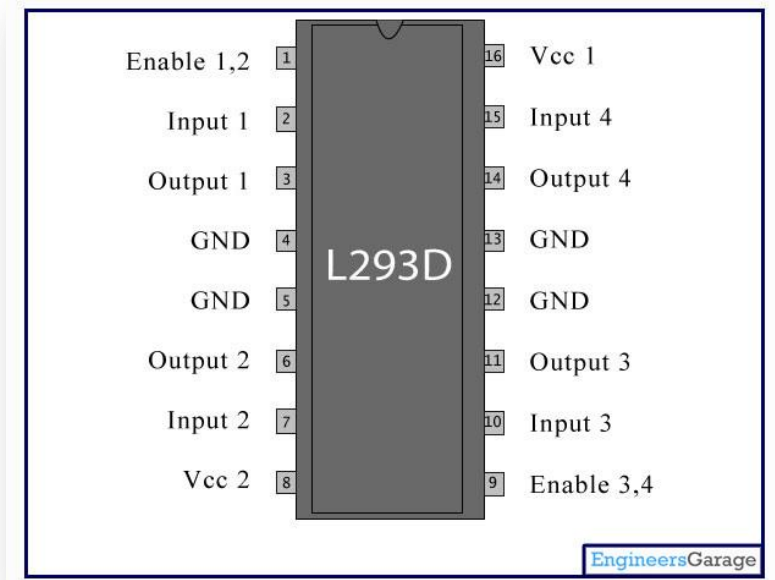 - Internal Clamp Diodes

5.5.3 Pin Diagram
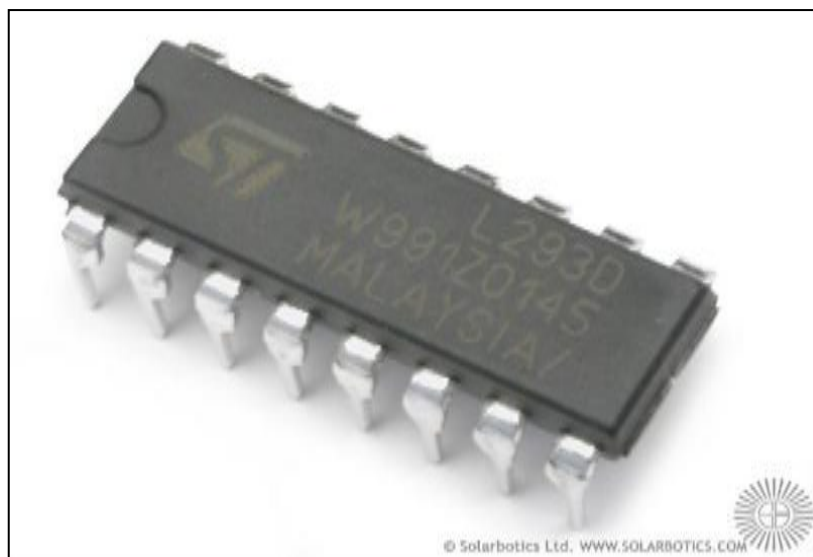

Fig 5.5 Pin Diagram of L293D

Fig 5.6 Motor Driving IC-L293D

Table 6 Pin Description of Motor Driving IC-L293D

Pin No.	Function	Name
1	Enable pin for Motor1; active high	Enable1,2
2	Input1 for Motor1	Input1
3	Output1 for Motor1	Output1
4	Ground(0V)	Ground
5	Ground(0V)	Ground
6	Output2 for Motor1	Output2
7	Input2 for Motor1	Input2
8	Supply voltage for Motors;9-12V(up to 36V)	Vcc $_2$
9	Enable pin for Motor 2; active high	Enable3,4
10	Input1 for Motor1	Input3
11	Output1 for Motor1	Output3
12	Ground(0V)	Ground
13	Ground(0V)	Ground
14	Output2 for Motor1	Output4
15	Input2 for Motor1	Input4
16	Supply voltage; 5V(up to 36V)	Vcc $_1$

5.6 LCD (Liquid Crystal Display)

Frequently, a program must interact with the outside world using input and output devices that communicate directly with a human being. One of a controller's most popular appliances is an LCD display which is shown in fig5.7. Some of the most popular LCDs are 16x2 and 20x2 displays linked to the 8051. This implies 16 characters per line by 2 lines, respectively, and 20 characters per line by 2 lines. Fortunately, there is a very popular standard that enables us to interact with the vast majority of LCDs irrespective of their manufacturer. The standard is called the HD44780U, which relates to the controller chip that gets information from an external source(in this case the UNO) and directly communicates with the LCD.

Fig5.7 LCD Display

5.7 Electronic Speed Controller

This is fully programmable 30A BLDC Electronic Speed Controller with 5V, 3A BEC. It can drive motors with continuous 30Amp load current. It has robust design for Controller and ESC power MOSFETs with 2 distinct PCBs. It can be driven by batteries of 2-4 lithium polymer or 5-12 NiMH / NiCd. It has a distinct microcontroller voltage regulator to ensure excellent anti-jamming capacity.. It is most suitable for UAVs, Aircrafts and Helicopters.

Features:

- For BLDC motor drive, high qualities MOSFETs are used.
- With any standard RC remote control electronic speed controller is fully programmable.
- For better thermal management, heat sink with high-performance heat   transmission membrane.
- 3 start modes that is Normal, Soft and Super-Soft, mostl bcompatible with fixed wing aircrafts and helicopters.
- To be consistent with any remote control available on the market, the throttle range can be configured.

5.8 Brushless Dc Motor

Brushless dc motor which is shown in fig5.8 [38] and data sheet of BLDC motor is shown in table7.

Fig 5.8 Brushless Dc Motor

Table 7 Data sheet of BLDC Motor

No. of cells	2-3 Li-Poly
	6-10 NiCd/NiMH
Kv	1000 RPM/V
Maximum frequency	80%
Maximum Efficiency current	4-10(>75%)
No load current	0.5A@10V
Resistance	0.090ohm
Max current	30A for 60s
Max watts	150W
Weight	52.7g/1.860z
Size	28mm dia × 28mm bell length
Shaft diameter	3.2mm
Poles	14
Model weight	300-800g/10.5-28.20z

5.9 Description of Hardware

Brushless motors have rather more satisfying results as compared to brushed motors. The basic difference between brushless and brushed motor is that in a brushless motor, the rotor contains the permanent magnets and the electromagnets which move to the stator in a quite opposite as seen in the brushed motors. It is more accurate and can also contribute to the speed of the motor in the equation. This makes brushless motors more effective because there is no sparking, less electrical noise and no wear out brushes. Brushless motor has only disadvantage that is it has higher initial cost; cost can recover through the greater efficiency over the life of the motor.

Interfacing of LCD-Microcontroller with Arduino is shown in fig5.9 [39]. ESC that is Electronic Speed Controller. As the name indicates, it control the speed of motor with the use some electronic protocol. To continue working, these ESCs need a command. In this project sending commands using an aurdino, AtMegab328. Most ESCs require a frequency of 50Hz, i.e. a cycle of 20ms, and the speed that is depends on the duty cycle which you provide. 1ms reduces or even stops its (depending on the ESC model) while a 2ms

pulse needed to runs the motor at full speed. The values between them offer you variable speed.

An ESC needs a power source to work with (this source will also provide power to the motor). Lithium Polymer battery (11.1V) is used here. Now at the input side, apart from the battery need, it requires a signal which is connected to the OC1A pin (10). After that output comes with 3 pins that is A, B and C. These pins correspond to the 3 pins of the BLDC motor. The motor in use comes with three wires with in colours: yellow, black and red. Connect A to yellow, B to black and C to the red one. In this case motor is running in opposite direction, just interchange yellow and red wires.

AtMeg328 is a 16 bit timer i.e. it can count up to 65535 starting from zero. The reason using of this timer and not timer0 or timer2 is that these are 8 bit timers and can count up to 255. For 20,000 counts (0-19999) which use 20 ms cycle. As the value cannot be accommodated in any 8 bit timer therefore switched over 16 bit one. One great thing about 16 bit timers is that it can set the top value between 0-65535. Timer 1 is further divided into two individual 16 bit timers A and B. For the 'A' part , timer 1 is used. Also, values corresponding to 1ms and 2 ms are 1000 and 2000 respectively. The circuit diagram is shown in fig5.10 [39].
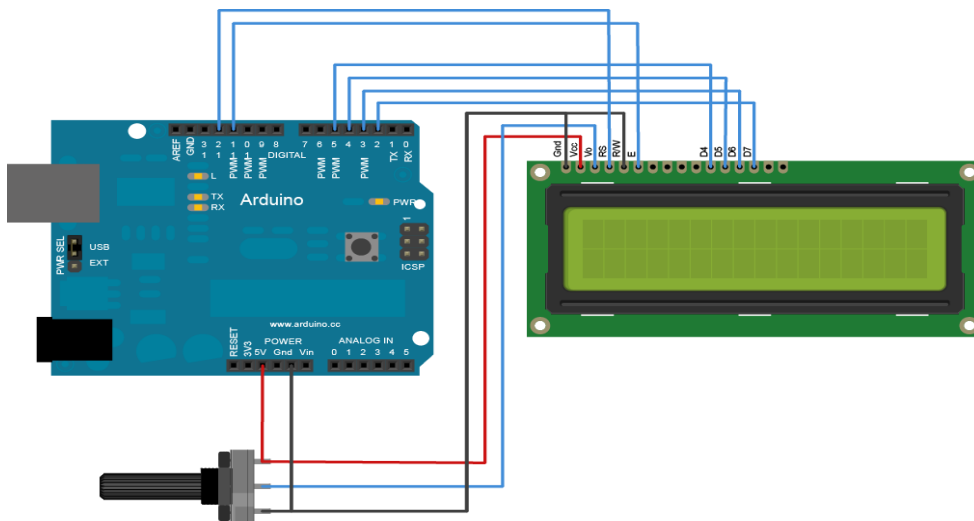

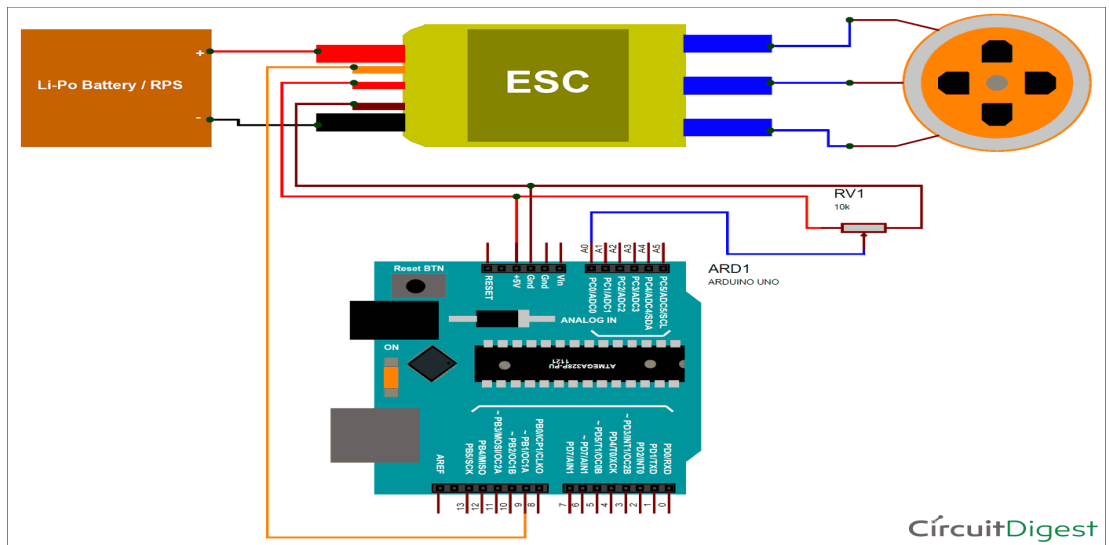Fig 5.9 Interfacing of LCD-Microcontroller with Arduino
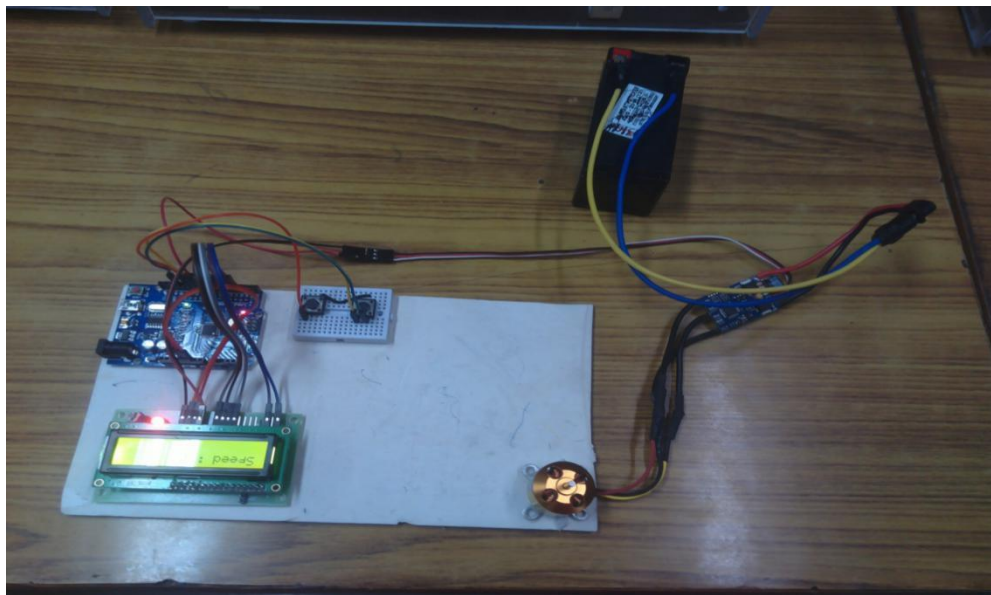
Fig 5.10 Circuit Diagram

Fig 5.11 Hardware setup

5.10 Motoring and generating modes of BLDC Motor

There are four possible quadrants of operation using a brushless DC motor which is shown in figure 5.12.When the brushless DC motor is operating in the first and third quadrant, the supplied voltage is greater than back emf which is known as forward motoring and reverse motoring modes respectively, but the direction of current flow differs. When the motor is operating in the second and fourth quadrant, the back emf generated by motor should be greater than supplied voltage which is forward motoring and reverse motoring modes respectively and here again the direction of current flow is reversed. The motor is initially made to rotate in the clockwise direction and when the speed reversal command is obtained, the control goes into clockwise regeneration mode which brings the rotor to standstill position. Instead of waiting for exact standstill position, continuous energization of main phase is attempted and this rapidly slows down the rotor of the machine to standstill position. Therefore there is the necessity of determining the instant when the rotor is ideally positioned for reversal. Hall Effect sensors are used to obtain the rotor position and from the hall sensor outputs it is determined whether the machine has reversed its direction which is the ideal moment for energizing the stator phase so that machine can start motoring in the counter clockwise direction.
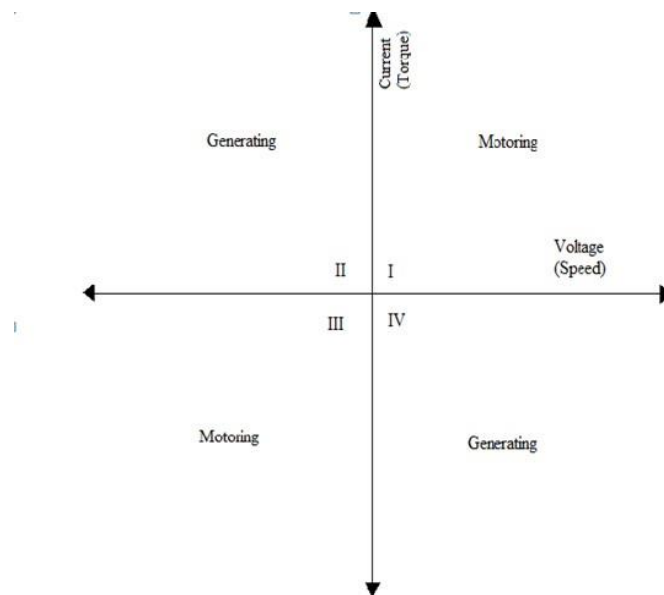

Fig 5.12Four quadrants of operation

Description

Hardware which is shown in fig5.13 has motoring mode. Firstly supply which 12 V is given to the aurdino board through pulses. Aurdino convert 12V to 5V and then 5V through the aurdino is given to the electronic speed controller. Electronic speed controller converts dc to ac which is given to the Brushless dc Motor .BLDC motor converts electrical energy to mechanical energy. Then, first BLDC is connected mechanically to the second BLDC .This is the motoring mode. With the help of first BLDC, second BLDC is rotating that means first BLDC is producing emf, with the help of that emf second BLDC is rotating which means generating mode. The first BLDC is act as a motor and second BLDC is act as generator. The second BLDC which is acting as a generator, converts mechanical energy to the electrical energy. Electrical energy which is coming to the second BLDC is given to the three phase full rectifier that converts ac supply to dc supply.
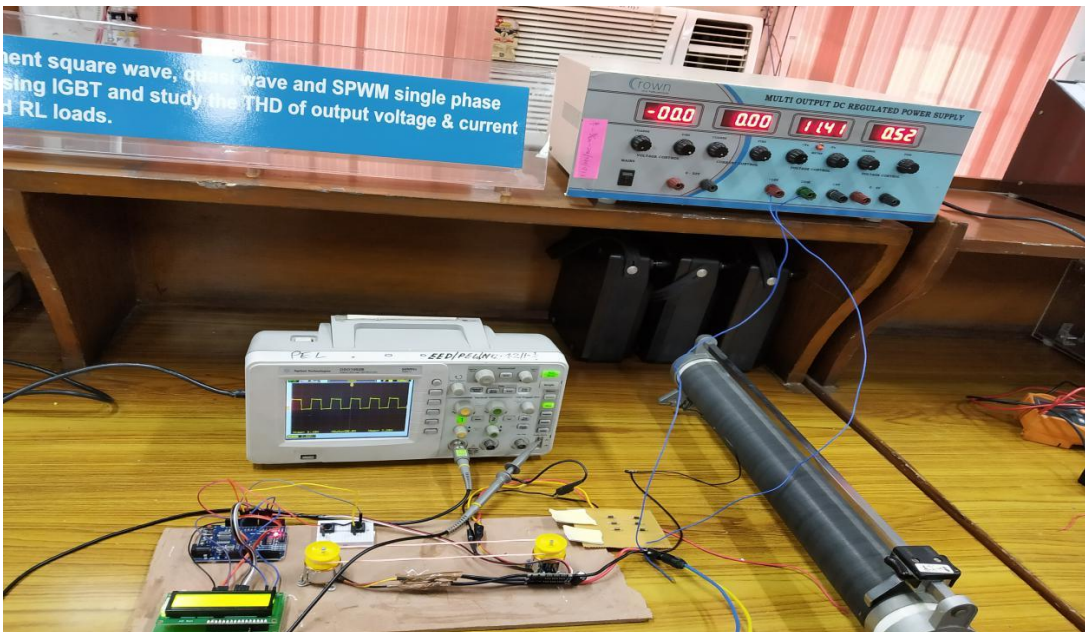

Fig 5.13 Hardware setup of Motoring mode of BLDC Motor

5.11 Software

Connecting the hardware according to the circuit diagram is the first step. Then after there is a need to program the components according to the algorithm you have designed in order to make the project work properly as required. Following is the description of software used.

5.11.1 Arduino IDE

The Arduino IDE is a cross-platform application written in <u>Java</u>, and is derived from the IDE for the <u>Processing programming language</u> and the <u>Wiring</u> project. It is designed to introduce programming to artists and other new comers unfamiliar with software development. It includes a code editor with features such as <u>syntax highlighting</u>, <u>brace matching</u>, and automatic indentation, and is also capable of compiling and uploading programs to the board with a single click. There is typically no need to edit <u>makefiles</u> or run programs on a <u>command-line interface</u>. Although building on command-line is possible if required with some third party tools such as <u>Ino</u>. The Arduino IDE comes with a <u>C</u>/<u>C++</u> library called "<u>Wiring</u>" (from the project of the same name), which makes many common input/output operations much easier.

Key Features

- Cross platform program
- Open Source
- Different instructions for different OS
- Example Programs

5.11.2 Code

```
#include <Servo.h>
#include <LiquidCrystal.h>
LiquidCrystal lcd(4, 5, 6, 7, 8, 9);
Servo esc1;
  int esc1_speed = 0;
  int esc1_val = 60;
  int sw1 = 11;
  int sw2 = 12;
  int relay_pin = 3;
//
void switches_init()
```

```
{
  pinMode(sw1, INPUT);
  pinMode(sw2, INPUT);
  digitalWrite(sw1, HIGH);
  digitalWrite(sw2, HIGH);
}
//
void  lcd_init()
{
  lcd.begin(16, 2);
  lcd.setCursor(0, 0);
  lcd.print("  BLDC Speed   ");
  lcd.setCursor(0, 1);
  lcd.print("  Controller   ");
  delay(5000);
  lcd.clear();
}
//
void lcd_display()
{
 lcd.setCursor(0,0);lcd.print("Speed :");lcd.setCursor(8, 0);lcd.print(esc1_speed);
}
//
void  setup()
{
  Serial.begin(9600);
  Serial.println("Program Started");
  switches_init();
  esc1.attach(10);
  esc1.write(esc1_val);
  lcd_init();
  lcd_display();
}
//
```

```
void loop()
{
 if(digitalRead(sw1)==LOW)
 {
   delay(100);
   if(digitalRead(sw1)==LOW)
   {
    if(esc1_speed<100)
    {
     esc1_speed+=5;
     esc1_val = map(esc1_speed, 0, 100, 60, 150);
     lcd_display();
     esc1.write(esc1_val);
    }
   }
 }
 if(digitalRead(sw2)==LOW)
 {
   delay(100);
   if(digitalRead(sw2)==LOW)
   {
    if(esc1_speed>0)
    {
     esc1_speed-=5;
     esc1_val = map(esc1_speed, 0, 100, 60, 150);
     lcd_display();
     esc1.write(esc1_val);
    }
   }
 }
```
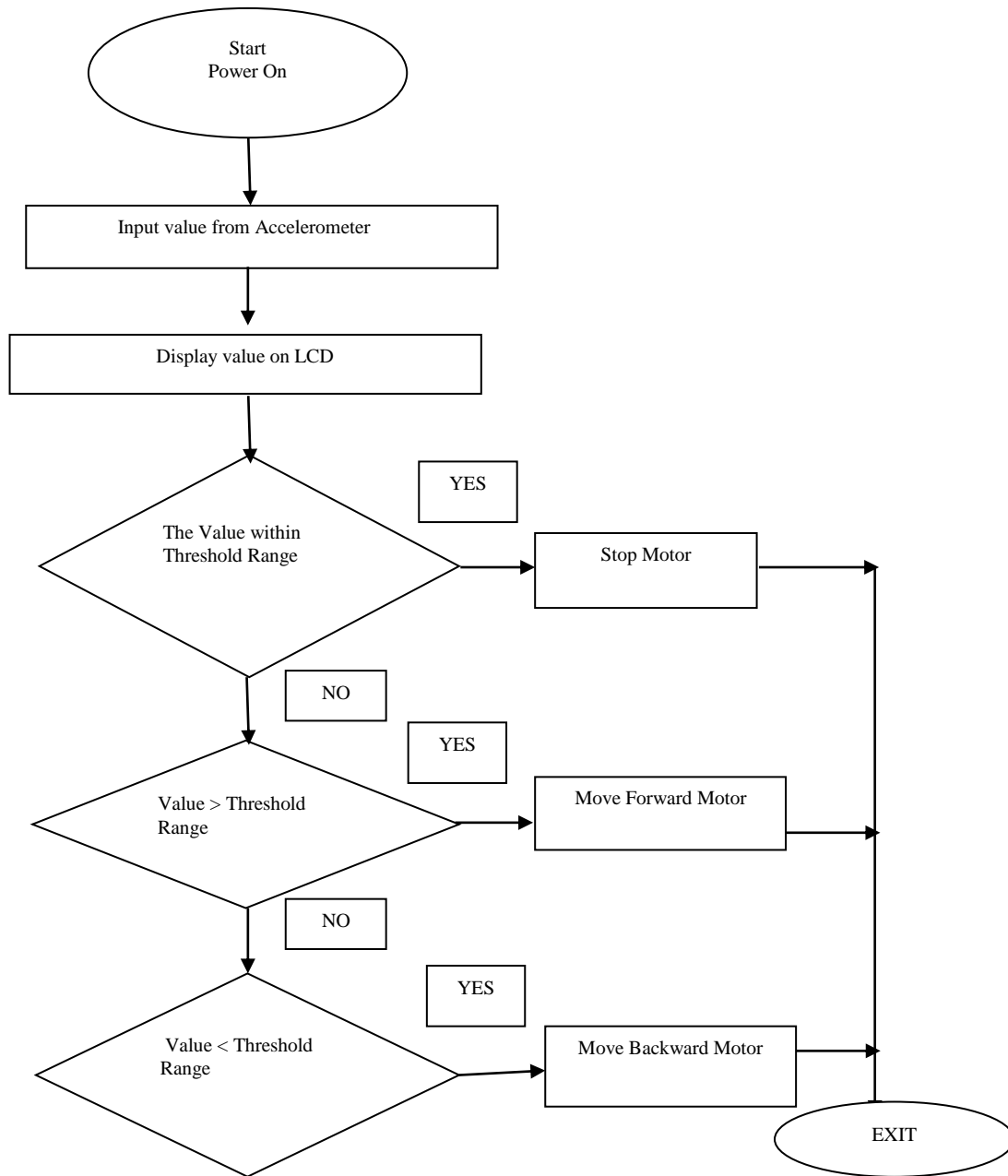
Fig 5.14 Flow chart

5.12 Result and discussion

Hardware implementation of speed control of BLDC motor is carried out using motor has technical specification in table8.

Table 8 Duty cycle Vs Voltage

DUTY CYCLE (%)	Vmax (V)	Vrms(V)
10%	5V	1.58V
20%	5V	2.20V
30%	5V	2.71V
40%	5V	3.13V
50%	5V	3.53V
60%	5V	3.89V
70%	5V	4.20V
80%	5V	4.47V
90%	5V	4.72V
100%	5V	5.0V

1

1 When Duty Cycle is 10%

BLDC motor is coupled to a second BLDC motor of the same rating so that it is being driven by the first BLDC motor. Therefore, the second BLDC motor act as a generator which is electrically loaded with a resistive load. The output of second BLDC is rectified and the load voltage is shown in fig5.17.
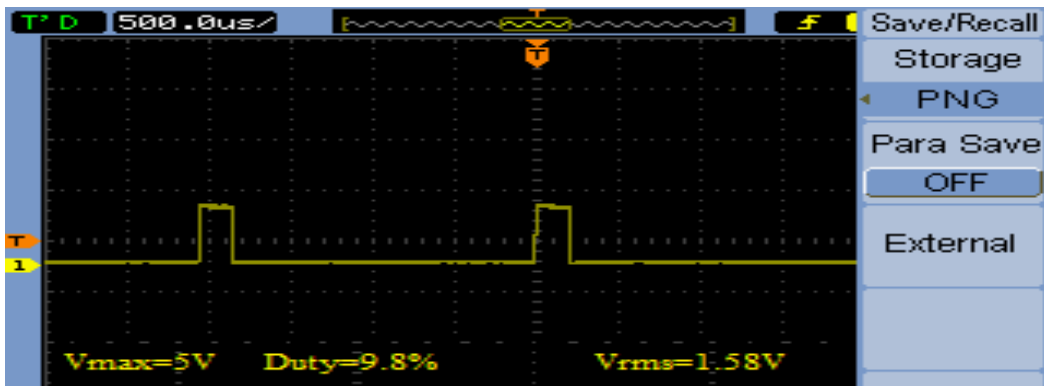
Fig 5.15 PWM output for 10% duty cycle

Fig5.16 Speed for 10% duty cycle, 5014 rpm
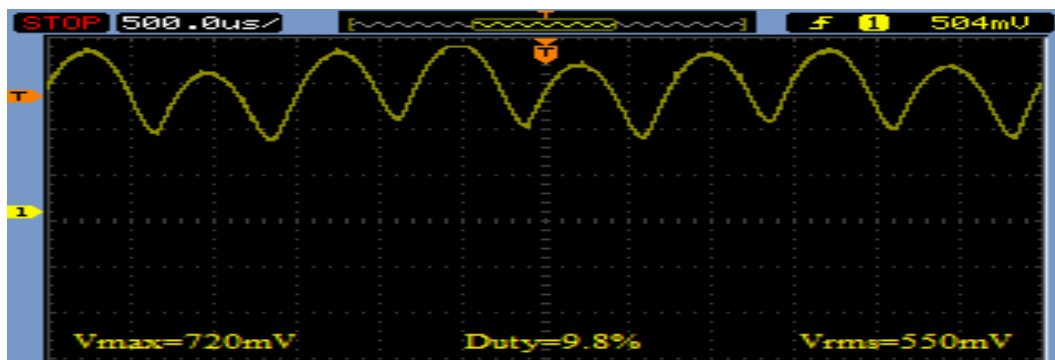
Fig 5.17 Output voltage for 10% duty cycle

2   When Duty Cycle is 20%
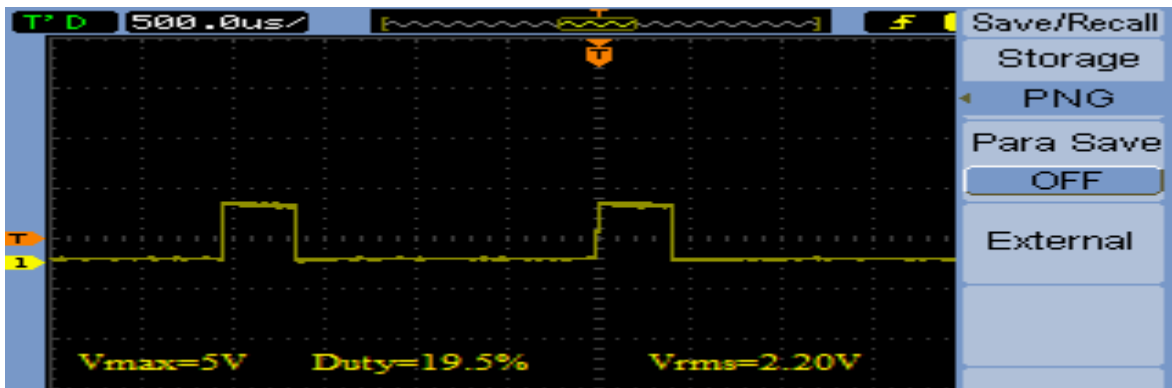
Fig 5.18 PWM output for 20% duty cycle

Fig5.19 Speed for 20% duty cycle, 6984 rpm

The output voltage across the resistive load is shown in fig 5.20
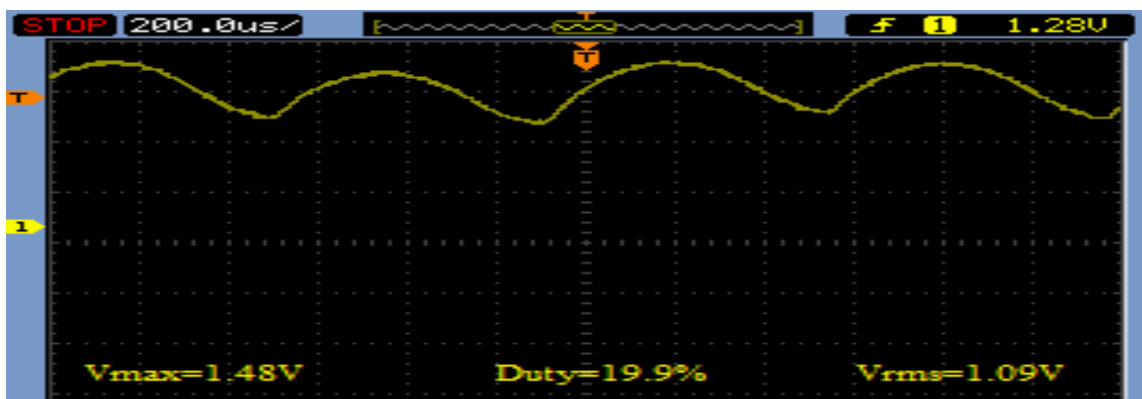
Fig 5.20 Output voltage for 20% duty cycle

3 . When Duty Cycle is 30%
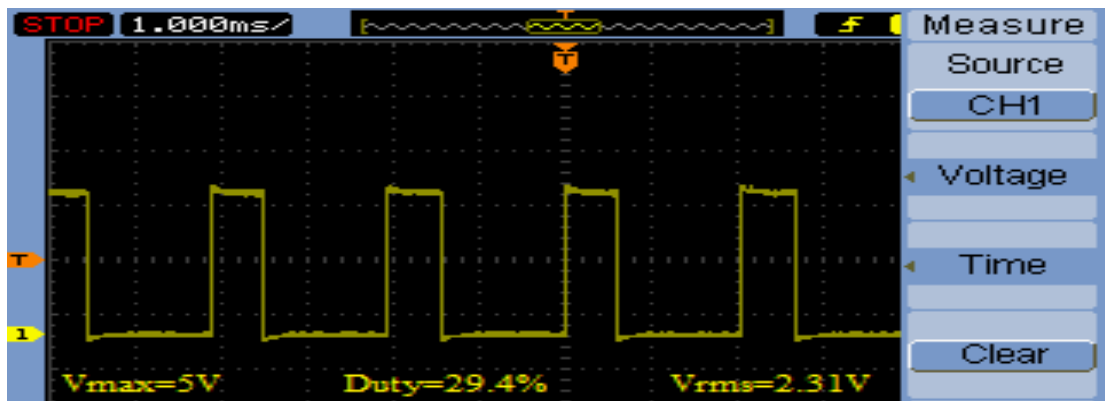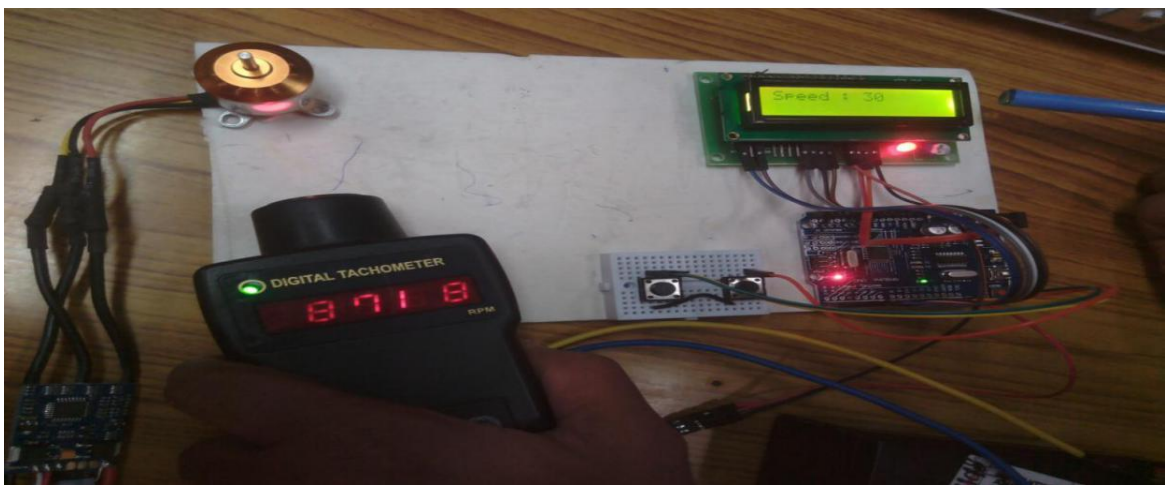

Fig 5.21 PWM output for 30% duty cycle

Fig5.22 Speed for 30% duty cycle, 8718 rpm.

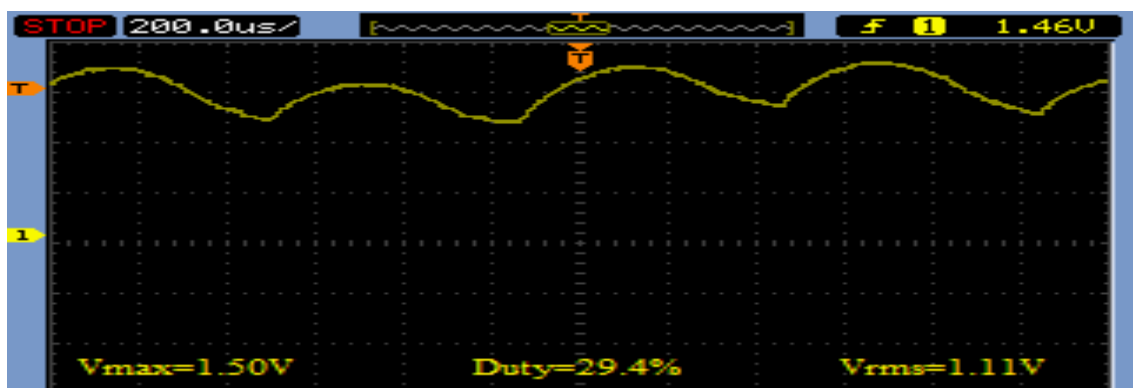The output voltage across the resistive load is shown in fig 5.23

Fig 5.23 Output voltage for 30% duty cycle

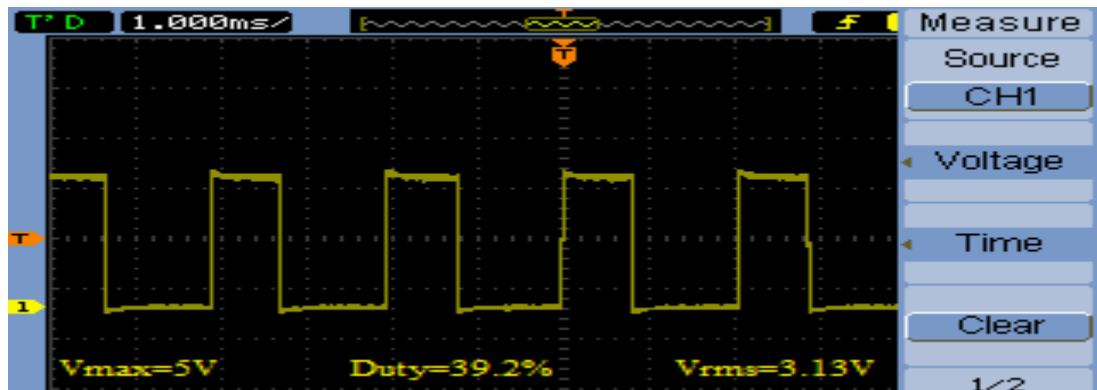**4.When Duty Cycle is 40%**

Fig 5.24 PWM output for 40% duty cycle

Fig5.25 Speed for 40% duty cycle, 9615 rpm

The output voltage across the resistive load is shown in fig 5.26
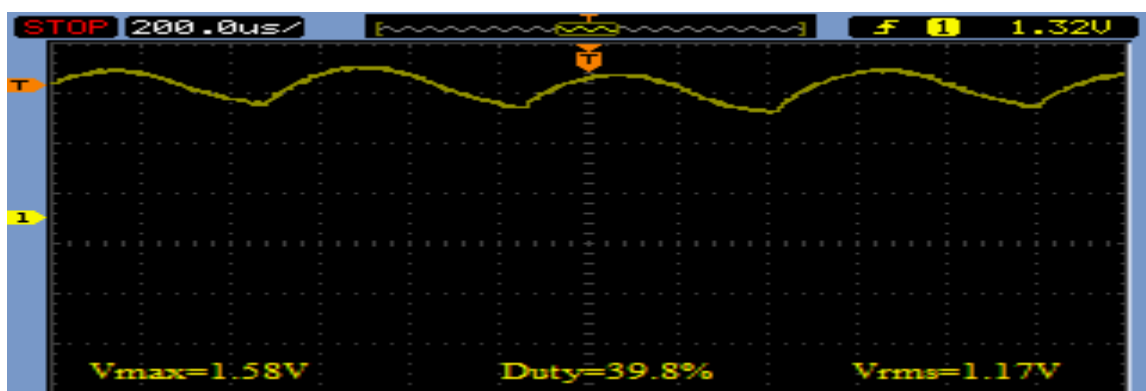

Fig 5.26 Output voltage for 40% duty cycle

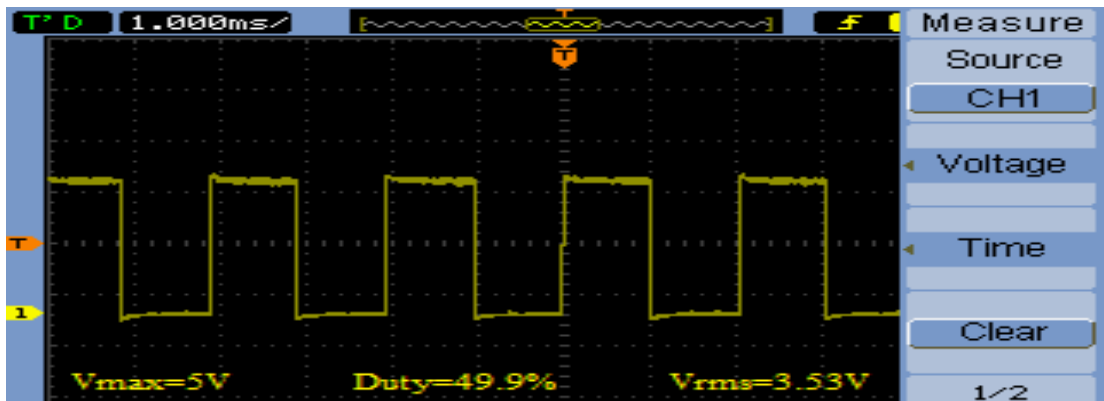**5. When Duty Cycle is 50%**

Fig 5.27 PWM output for 50% duty cycle

Fig5.28 Speed for 50% duty cycle, 10249 rpm

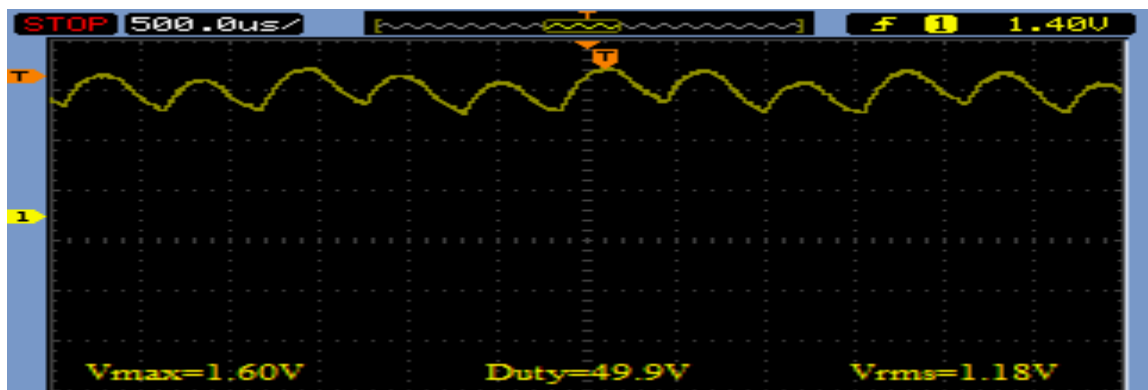The output voltage across the resistive load is shown in fig 5.29

Fig 5.29 Output voltage for 50% duty cycle
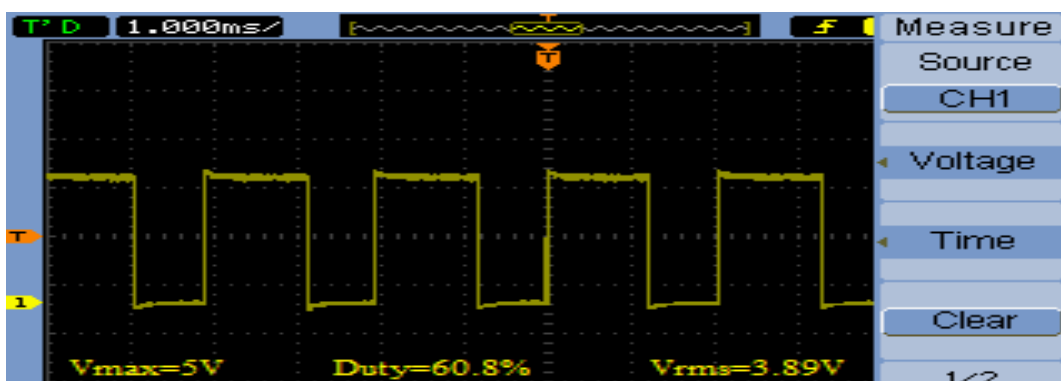
6. When Duty Cycle is 60%
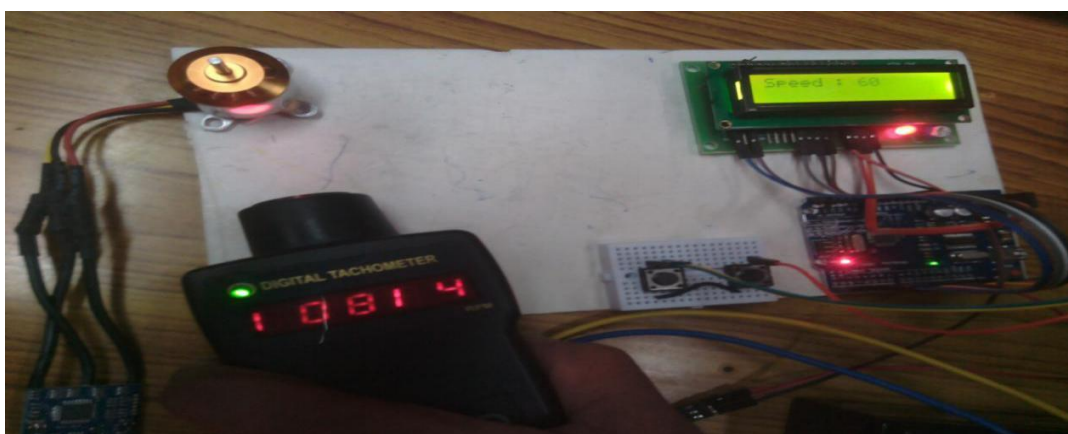

Fig 5.30 PWM output for 60% duty cycle

Fig5.31 Speed for 60% duty cycle, 10814 rpm

The output voltage across the resistive load is shown in fig 5.32
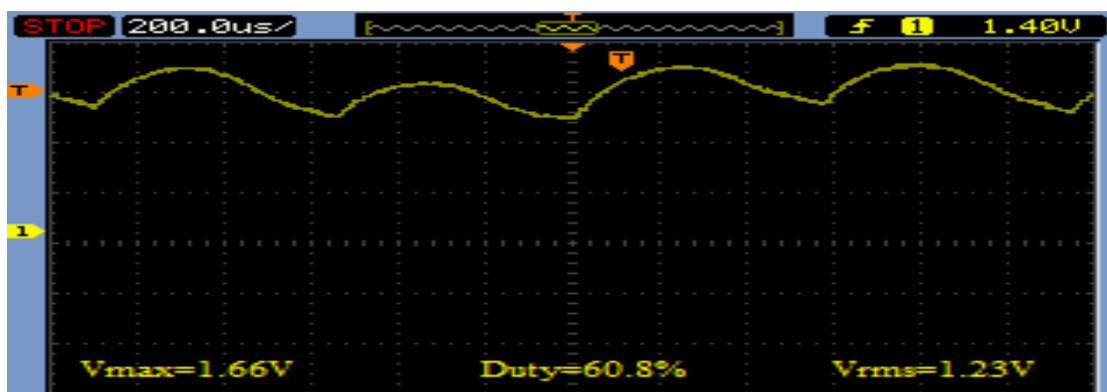

Fig 5.32 Output voltage for 60% duty cycle
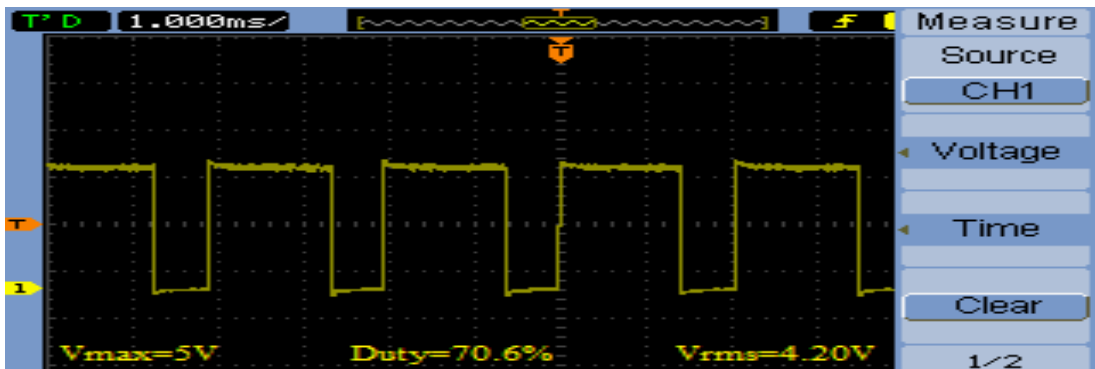
7. When Duty Cycle is 70%

Fig 5.33 PWM output for 70% duty cycle
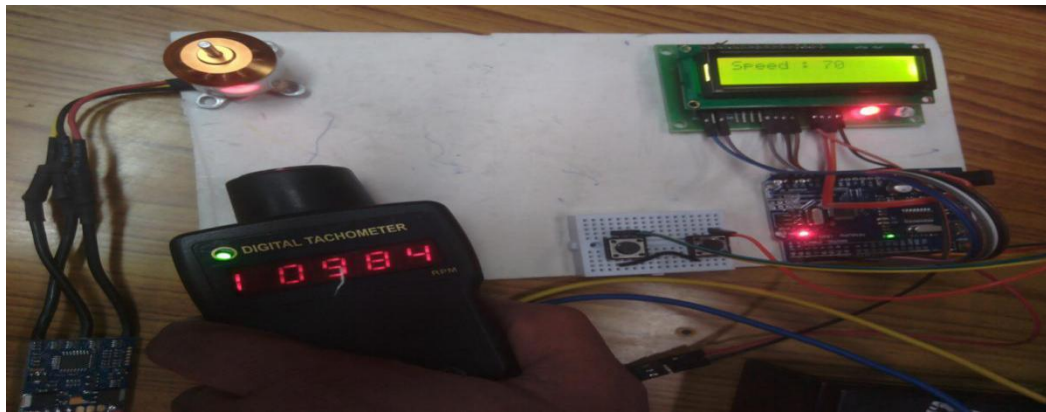

Fig5.34 Speed for 70% duty cycle, 10984 rpm

The output voltage across the resistive load is shown in fig 5.35

Fig 5.35 Output voltage for 70% duty cycle

8. When Duty Cycle is 80%

Fig 5.36 PWM output for 80% duty cycle

Fig5.37 Speed for 80% duty cycle, 11214 rpm

The output voltage across the resistive load is shown in fig 5.38

Fig 5.38 Output voltage for 80% duty cycle

9. When Duty Cycle is 90%

Fig 5.39 PWM output for 90% duty cycle

Fig 5.40 Speed for 90% duty cycle, 11385 rpm

The output voltage across the resistive load is shown in fig 5.41

Fig 5.41 Output voltage for 90% duty cycle

10. When Duty Cycle is 100%
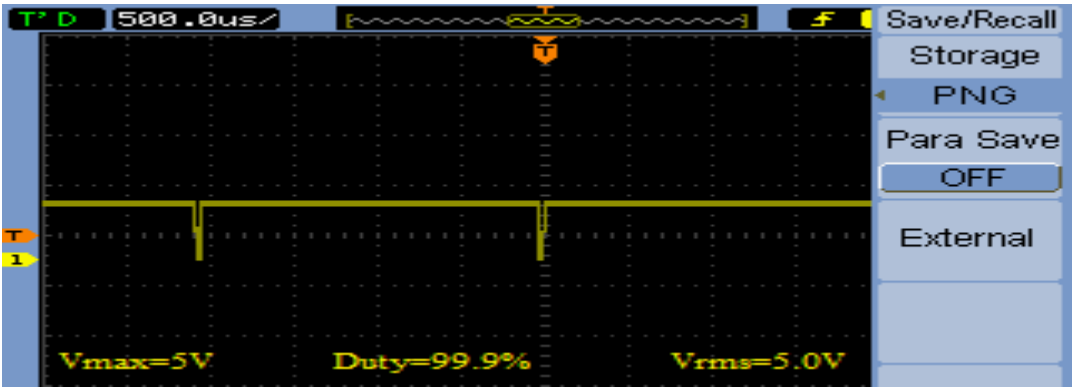
Fig 5.42 PWM output for 100% duty cycle

Fig5.43 Speed for 100% duty cycle, 11904 rpm

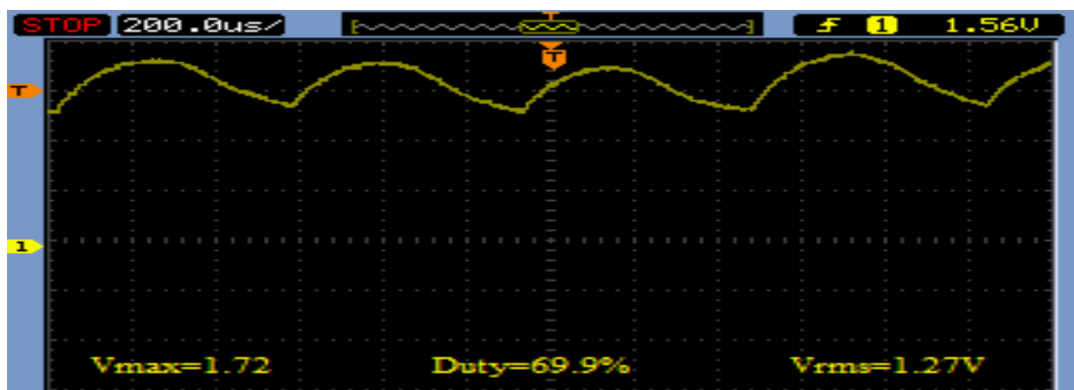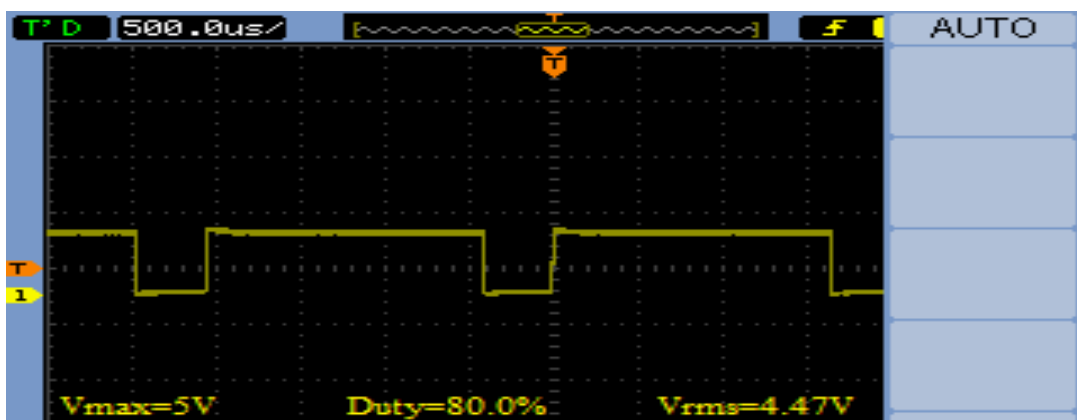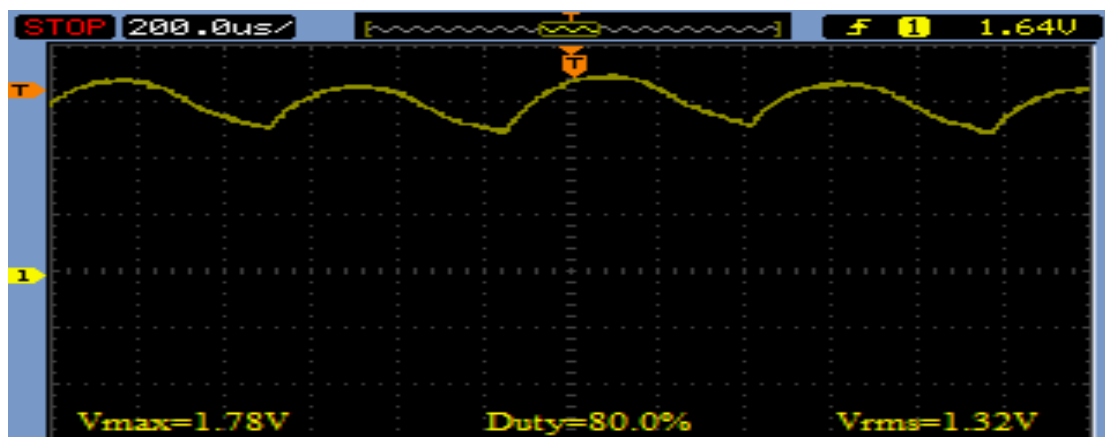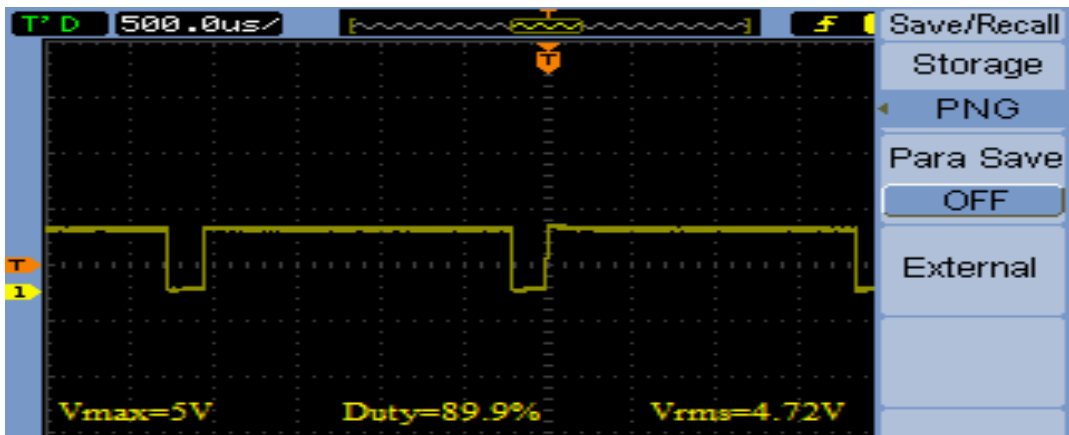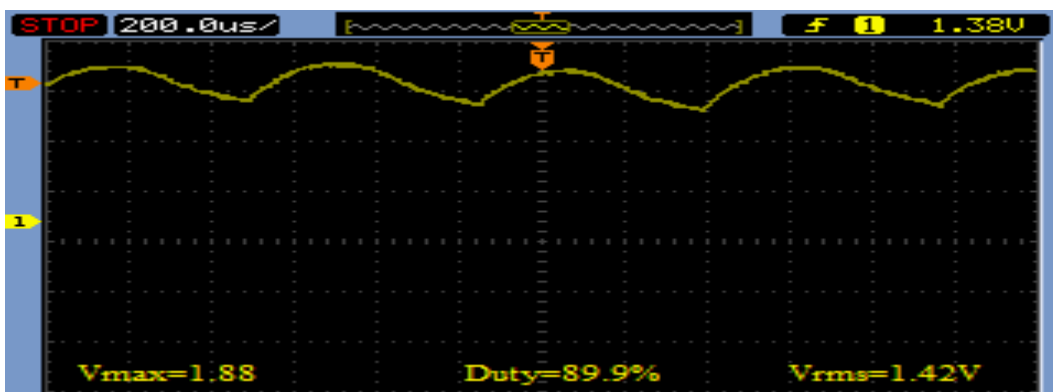The output voltage across the resistive load is shown in fig 5.44
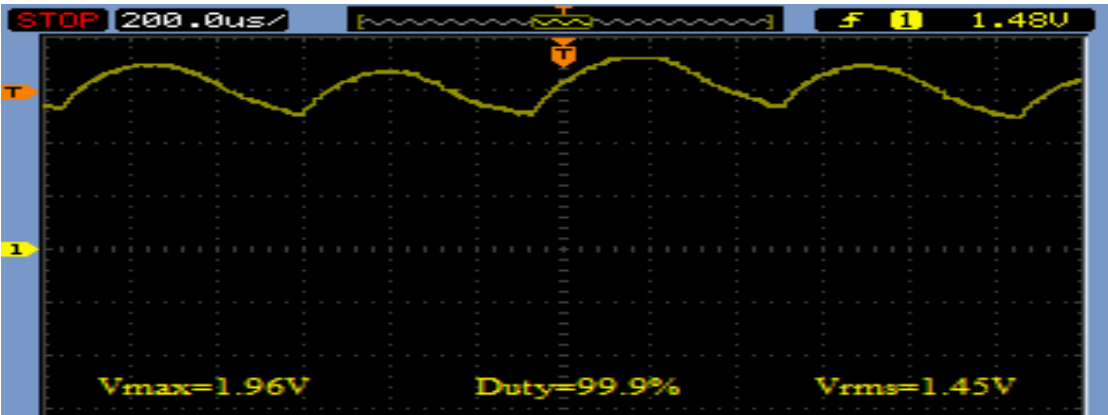
Fig 5.44 Output voltage for 100% duty cycle

The output from the rectifier shows the values of Vmax and Vrms where the load is constant and duty cycle varies from 10% to 100% is shown in Table 9 and thus calculating the current for each duty cycle. Further, Fig5.45 shows the graph between Vmax, Vrms, I and duty cycle and Fig5.46 shows the graph between speed and duty cycle.

Table 9 Output response

DUTY CYCLE (%)	SPEED (Rpm)	Vmax (V)	Vrms (V)	LOAD (Ohm)	CURRENT (A)
10%	5014	0.72	0.55	45	0.016
20%	6984	1.48	1.09	45	0.032
30%	8718	1.50	1.11	45	0.033
40%	9615	1.58	1.17	45	0.035
50%	10249	1.60	1.18	45	0.036
60%	10814	1.66	1.23	45	0.037
70%	10998	1.72	1.27	45	0.038
80%	11214	1.78	1.32	45	0.039
90%	11385	1.88	1.42	45	0.0417
100%	12000	1.96	1.45	45	0.0435

Fig5.45 Graph between Vmax, Vrms, I and Duty Cycle
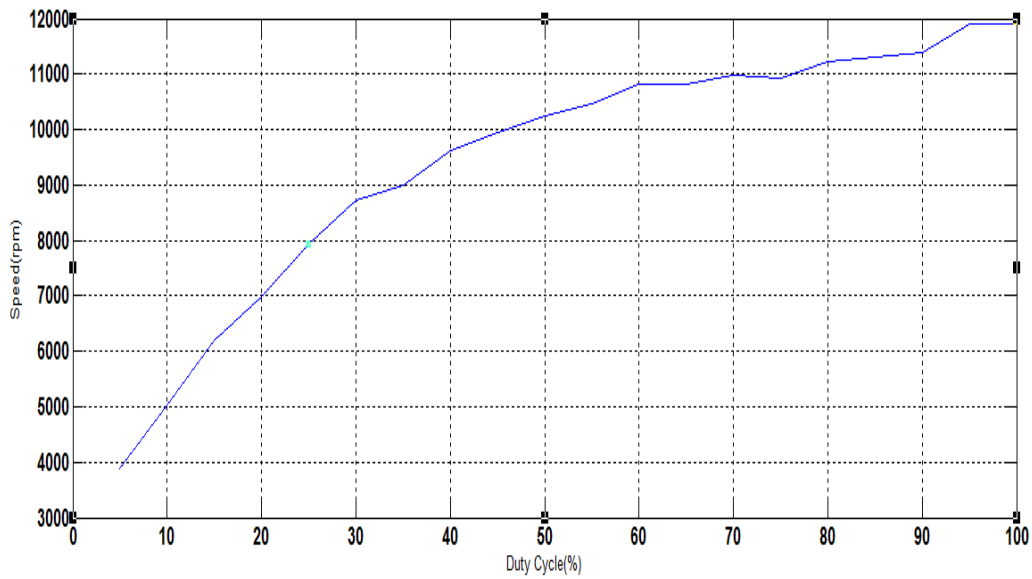
Fig5.46 Graph between speed and duty cycle

5.13 Conclusion

The hardware implementation of speed control of BLDC motor using microcontroller is projected. By using the PWM technique, speed of the BLDC was controlled for motoring mode.

CHAPTER 6

CONCLUSIONS & FUTURE SCOPE

CONCLUSION

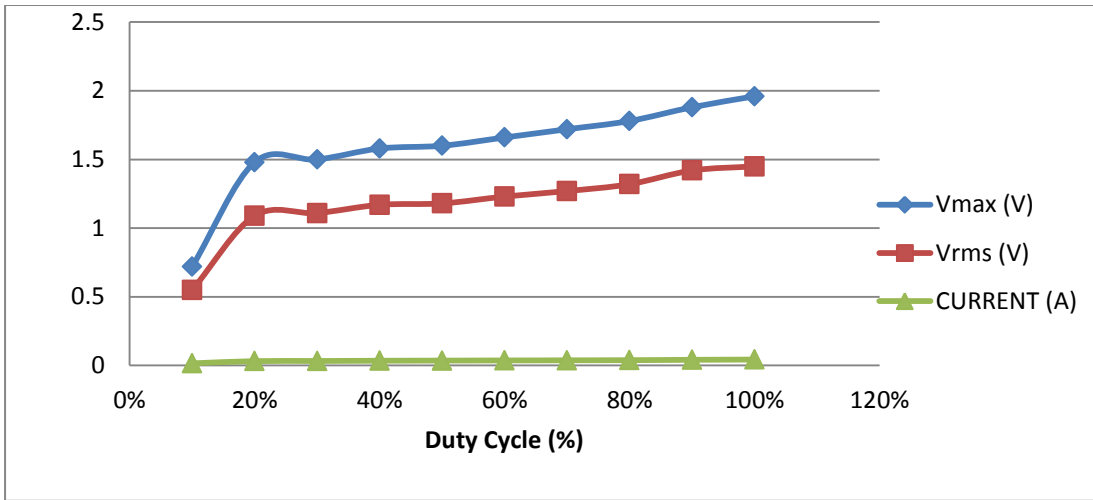The aim of this dissertation is the modeling, simulation and hardware implementation of speed control of Brushless Dc Motor. The performance of a 3-phase motor fed from a 3-phase balanced power supply is analyzed. Mathematical analysis and control of three phase BLDC motor under different loading conditions and also the speed control of BLDC motor using PI controller and hysteresis current controller are achieved. The hardware implementation of speed control of BLDC motor using microcontroller is developed; by using the PWM technique speed of the BLDC was controlled motoring mode.

FUTURE SCOPE

The study can be further enhanced on the following lines.

1. The torque ripple can be minimized by a modified PWM and current control based schemes.

2. The controller implementation may be done with a DSP processor or a VLSI based system.

3. Resonant converters may be used to minimize switching losses for BLDC motor drive.

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[26]https://www.google.com/search?biw=1536&bih=706&tbm=isch&sa=1&ei=v9UuXfugHsemwgOW9 7vQBQ&q=Outer+and+Inner+Rotor+of+Brushless+Dc+motor&oq=Outer+and+Inner+Rotor+of+Brushle ss+Dc+motor&gs_l=img.3...3101470.3106877..3108032...0.0..0.36.65.2......1....1j2..gws-wiz-img.....0.naMl7Tr7VEI#imgrc=QTlz-AfR1RrhCM:

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H4Dw&q=Operation+of+Brushless+Dc+Motor&oq=Operation+of+Brushless+Dc+Motor&gs_l=img.3...
1096219.1104639..1105317...0.0..0.658.1110.1j4-1j1......0....1j2..gws-wiz-img.....0.fTh1CAWVRqY

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[37]https://www.google.com/search?q=5Motor+Driver+Circuit+%E2%80%93BL293D&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjYj9fW9MjjAhUMwI8KHe-gD_IQ_AUIECgB&biw=1536&bih=706

[38]https://www.google.com/search?q=bldc+motor+1000kv&source=lnms&sa=X&ved=0ahUKEwjim-vu9sjjAhWl7XMBHYrADU0Q_AUICygA&biw=1536&bih=706&dpr=1.25

[39]https://www.google.com/search?biw=1536&bih=706&ei=4uE1XdDSOcnnvgSW4YzYAQ&q=Interfacing+of+LCD-Microcontroller+with+Arduino&oq=Interfacing+of+LCD-Microcontroller+with+Arduino&gs_l=psy-ab.3..33i22i29i30.310287.312009..313486...1.0..0.556.793.2-1j5-1......0....1j2..gws-wiz.....10..0i71j35i39.ZmBnfAadQUE&ved=&uact=5