SPEED TORQUE CHARACTERISTICS OF BRUSHLESS DC MOTOR UNDER DIFFERENT LOAD VARIATION

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by

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JUNE 2020

DECLARATION

I hereby declare that the work, which is being presented in the dissertation entitled **"Speed Torque Characteristics of Brushless DC Motor Under Different Load Variation**" in partial fulfillment for the award of degree of **Master of Technology** in Department of Electrical Engineering with Specialization in **Power System & Control** is submitted to the **Department of Electrical Engineering, Babu Banarasi Das University** is a record of my own investigations under the guidance of **Prof. Akash Varshney, Assistant Professor, Department of Electrical Engineering, Babu Banarasi Das University, Lucknow.** I have not submitted the matter presented in this dissertation anywhere for the award of any other degree.

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CERTIFICATE

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ABSTRACT

Permanent magnet brushless DC motors (PMBLDC) find wide applications in industries due to their high-power density and ease of control. These motors are generally controlled using a three-phase power semiconductor bridge.

To achieve desired level of performance the motor requires suitable speed controllers. In case of permanent magnet motors, usually speed control is achieved by using proportional-integral (PI) controller. Although conventional PI controllers are widely used in the industry due to their simple control structure and ease of implementation, these controllers pose difficulties where there are some control complexity such as nonlinearity, load disturbances and parametric variations. Moreover, PI controllers require precise linear mathematical models.

In this dissertation, the speed response characteristics analysis of brushless dc motor under different load variations. BLDC drive are widely used motors now a days due to its good speed control characteristics and high efficiency which improves the performance of motor. PI controller is used in motor operation to maintain the constant speed. The analysis is carried out in three different type of load condition which are given as under-load, rated load and overload conditions. The performance of BLDC motor is observed through speed, current, back emf and torque response. To evaluate the result appropriate value of Kp and Ki of controller has been taken in order to get the better result for characteristics parameter of the speed response of BLDC motor. The result are then calculated mathematically and analysed according to the load variations. The required model has been developed using Simulink/Matlab and speed torque characteristics graph is also analyzed using PI controller.

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LIST OF ABBREVIATIONS

ABBREVIATIONS	DESCRIPTION
DC	Direct current
AC	Alternating current
BLDC	Brushless Direct Current
MATLAB	MATrix-LABoratry
PI	Proportional, Integral
MPP	Maximum power point
PWM	Pulse width modulation
RMS	Root mean square
RPM	Revolution per minute
NM	Newton Meter
PF	Power factor
R_s	Stator resistance per phase
L	Stator inductance per phase
M	Mutual inductance between phases

LIST OF SYMBOLS

SYMBOL	DISCRIPTION
K_e	The line back-emf constant.
K_p	Proportional gain
K_i	Integral gain
K_t	The line torque constant.
T_e	The electrical torque.
T_L	The load torque.
i_a, i_b, i_c	The phase current.
v_a, v_b, v_c	The line-to-line voltages.
θ_e	The electrical angle.
θ_m	The rotor angle.
w_m	Rotor speed
e_a, e_b, e_c	The phase back-emf's.
e_{ab}, e_{bc}, e_{ca}	The line back-emf's.
e_{ss}	Steady state error.
J	The rotor inertia
K_f	The friction constant
Ka	Armature constant
$\emptyset$	Flux of the machine
Ia	Armature current
Ea	Back- EMF
Vt	Terminal voltage

CHAPTER 1

INTRODUCTION

1.1 Project Background

The increasing trend towards usage of green and eco-friendly electrical devices has lead to research development in Brushless DC (BLDC) motors. In electric traction, a wide range in speed and torque control for the electric motor is desired. In 1962, the model of BLDC motors had been invented as “a DC machine with solid state commutation” [1]. The DC machine fulfils these requirements but these machines needs periodic maintenance. The term “Brushless DC motor” is used to identify the combination of AC machine, solid state inverter and rotor position sensor that results in a drive system having a linear torque – speed characteristic as in a conventional DC machine [2][3][4]. As the name suggest, BLDC does not have brushes, and their rotors are robust because commutator and / or rings do not exist. That means very low maintenance. This also increases the power to weight ratio and efficiency [5]. The term “Brushless DC motor” is used to identify the combination of AC machine, solid state inverter and rotor position sensor that results in a drive system having a linear torque – speed characteristic as in a conventional DC machine.

The BLDC motors exhibit better performance in terms of higher efficiency, higher torque under low speed range, higher power density, lower maintenance and lesser noise than other motors. BLDCM can act as acceptable alternative as against the conventional motors like Induction Motors, Switched Reluctance Motors etc. The nature of back emf in BLDC motor is trapezoidal [5][6]. The BLDC motors are gaining grounds in the industries, especially in the areas of appliances production, aeronautics, medicine, consumer and industrial automations and so on. Recent trend in automobile industry is using these BLDC motors as electric vehicles as these are energy efficient and pollutant free.

Some of the many advantages of a brushless dc motor over the conventional “brushed dc motors are highlighted below [7]:

1. Better speed versus torque characteristics
2. High dynamic response
3. High efficiency
4. Long operating life
5. Noiseless operation
6. Higher speed ranges

7. Low maintenance (in terms of brushes cleaning; which is peculiar to the brushed dc motors). Another vital advantage is that the ratio of torque delivered to the size of the motor is higher, and this contributes to its usefulness in terms of space and weight consideration.

However, the problems are encountered in these motors for variable speed operation over last decades continuing technology development in power semiconductors, microprocessors, adjustable speed drivers control schemes and permanent-magnet brushless electric motor production have been combined to enable reliable, cost-effective solution for a broad range of adjustable speed applications.

Household appliances are expected to be one of fastest-growing end-product market for electronic motor drivers over the next five years. The major appliances include clothes washer's room air conditioners, refrigerators, vacuum cleaners, freezers, etc. Household appliance have traditionally relied on historical classic electric motor technologies such as single-phase AC induction, including split phase, capacitor-start, capacitor–run types, and universal motor. These classic motors typically are operated at constant-speed directly from main AC power without regarding the efficiency. Consumers now demand for lower energy costs, better performance, reduced acoustic noise, and more convenience features. Those traditional technologies cannot provide the solutions.

1.2 Objective and scope of Work

This work aims at studying the performance analysis of BLDC drive under varying loads. The main focus of this work is to compare the three types of load that is half load, full load and overloading conditions at constant speed under the effect of PI Controller and required speed torque characteristics is also performed. These types of variations in the load have been considered as they are the most commonly encountered ones in real life. The scope of this work signifies that the performance is better if the load is applied and removed gradually as against sudden load variations.

1.3 Thesis Outline

This dissertation contains five chapters describing the mathematical model of Brushless DC Motor and load variations in BLDC Motor organized as follows

Chapter 1: Summarizes the overview of the dissertation, literature review, motivation of work organization of the project.

Chapter 2: Presents an introduction and demonstrates the principal and operation of brushless dc motor working of Brushless DC motor (BLDC) is described. Comparison of BLDC to other motors is also presented.

Chapter 3: This chapter presents the mathematical model of BLDC and its transfer function is determined. Also, it discusses state space form of BLDC motor.

Chapter 4: This chapter discusses the design of PI controller and performance analysis of BLDC Motor during different loading conditions.

Chapter 5: Shows the simulation results of BLDC motor drive system and conclusions of the research work presented in this thesis in addition to some recommendations for future work and further work to be carried out.

Finally, a list of references and some appendices of the thesis are included.

CHAPTER 2

LITERATURE REVIEW

In 1962, T.G. Wilson and P.H. Trickey [1] invented the model of BLDC motors. They called BLDC motor as “a DC machine with solid state commutation” and said that the key element of brushless DC motors as opposed to brush DC motors is that the brushless DC motor requires no physical commutator, a revolutionary difference. In 2002, B. K. Bose [2] explained that a trapezoidal PM machine is basically a surface magnet non salient pole machine that includes three phase trapezoidal voltage waves at the machine terminal due to concentrated full pitch windings in the stator. Between sinusoidal and trapezoidal PM machines with self control, the latter gives performance closer to that of a dc motor. For this reason, it is widely known as a brushless dc motor (BLDM or BLDC).

In 1997, P. C. Sen [3] defines multi-machine systems, brushless motors, and switched reluctance motors are covered, as well as constant flux and constant current operation of induction motors. Additional material is included on new solid state devices such as Insulated gate bipolar transistors and MOS-controlled thyristors. In 1988, P. Pillay and R. Krishnan [5], presented PM motor drives and classified them into two types such as permanent magnet synchronous motor drives (PMSM) and brushless dc motor (BDCM) drives. The PMSM has a sinusoidal back emf and requires sinusoidal stator currents to produce constant torque while the BDCM has a trapezoidal back emf and requires rectangular stator currents to produce constant torque. In 2010, G. K Dubey [6] describes the operation, features and applications of Brushless dc (or Trapezoidal PMAC) motor drives. In 2003, Padmaraja Yedamale [7] concluded that BLDC motors have advantages over brushed DC motors and induction motor.

In 2009, Bhim Singh and Sanjeev singh [8] did an exhaustive overview of PMBLDCM drives. This paper presents state of the art PMBLDC motor drives with an emphasis on sensorless control of these motors. In 2010, Bhim Singh et al [9] presented a new speed control strategy of a PMBLDC motor drive. In this paper, a buck half-bridge DC-DC converter is used as a single-stage power factor correction (PFC) converter for feeding a voltage source inverter (VSI) based permanent magnet brushless DC motor (PMBLDCM) drive. The VSI is operated only as an electronic commutator of the PMBLDCM. The stator current of the PMBLDCM during step change of reference speed is controlled by a rate limiter for the reference voltage at DC link. The proposed PMBLDCM drive with voltage control based PFC converter is designed, modeled and its performance is simulated in Matlab-Simulink environment.

In 2004, Yen-Shin Lai et al [10] presented a novel PWM technique for BLDCM drives fed by MOSFET inverters, which significantly reduces the conduction losses, and thereby dramatically reduces the heat dissipation. Comparative results with conventional PWM technique will be fully explored to highlight the advantages of the presented novel technique. Experimental results derived from spindle drive will be presented to confirm the theoretical analysis. In 2014, A. J. Varghese and R. Roy [11] concluded that BLDC motors have the capacity to replace induction motors, but the major setback is the implementation of its drive system which should be efficient as well as low cost and can be implemented easily and try to implement a improved speed control system for a BLDC motor using sensors and easily available controllers which can be utilized for operating under various conditions directly for many applications which will help in the replacement of induction motors with BLDC motor systems. The response of the system has been studied for various speed and load conditions using MATLAB simulation tools.

In 2009, Oludayo John Oguntoyinbo [12] presented a PID model of a brushless dc (BLDC) motor and a robot trajectory planning and simulation. A short description of the brushless dc motor is given. For this work, mathematical models were developed and subsequently used in getting the simulation parameters. The operational parameters of the specific BLDC motor were modelled using the tuning methods which are used to develop subsequent simulations.

In 2012, A. Purna Chandra Rao, Y. P. Obulesh and Ch. Sai Babu [17] presented a mathematical model of BLDC motor and show the values of various technical parameters using MATLAB/SIMULINK. In this paper the simulation is carried out for 120 degree mode of operation. The test results show the performance of BLDCM which are highly acceptable. Finally a PID controller is applied for closed loop speed control under various loading conditions.

In 2013, K. Shivanarayana et al [13] evaluated the BLDC model using MATLAB/ SIMULINK and the modeling of Brushless DC motor drive system along with control system for speed and current has been presented. In 2014, S. Dinesh Kumar [14] has been designed a speed control system to control the Brushless DC motor speed at desired speed through the technique of soft computing based self tuning of PID controller. In 2001, Dorf, C. Richard and H. Robert Bishop [15] described the three-term controller is known as a PID controller because it contains a proportional, an integral, and a derivative term and gives transfer function of PID controller.

In 2013, Pooja Agarwal, Arpita Bose [18] demonstrated the detailed analysis of Proportional-Integral (PI) controller and Fuzzy Logic controller for speed control of a Permanent Magnet Brushless DC (PMBLDC) motor for different speed commands and varying load torque conditions. Implementation of PI controller in closed loop conditions is done. Analysis of classical tuning methods to obtain best PI parameters for speed control is calculated. Fuzzy controller is also implemented for the same and the simulation results obtained for both PI and Fuzzy control in MATLAB/Simulink are compared. PI controllers have poor response due to overshoot, more drop in speed and oscillations

In 2015, Ahmed M. Ahmed, Mohamed S. Elksasy, Amr Ali-Eldin, Faiz F. Areed [19] proposed the PI and Fuzzy PI speed controllers for the BLDC motors . A simulation study is conducted to evaluate the efficiency of the proposed speed controllers. Further, a comparative study is performed to validate the system effectiveness.

2.1 Brushless DC Motor

A BLDC motor is a type of permanent magnet synchronous motor. According to the shape of their induced electromotive force it is further categorized into two types: sinusoidal and trapezoidal [4][5]. In trapezoidal motor the back-emf induced in the stator windings has a trapezoidal shape and its phases must be supplied with quasi-square currents for ripple-free torque operation.

The sinusoidal motor on the other hand has a sinusoidally shape backemf and require sinusoidal phase currents for ripple-free torque operation. The shape of back-emf is determined by the shape of the rotor magnets and the stator winding distribution. The sinusoidal motor need high resolution position sensor because the rotor position must be known at every time instant for optimal operation. It also requires more complex software and hardware.

The trapezoidal motor is a more attractive alternative for most industrial applications due to its simplicity, lower price and higher efficiency [1]. This type of motor also offers good compromise between precise control and the number of power electronic devices needed to control the stator currents. Position detection is usually implemented using three Hall effect sensors that detects the presence of small magnets that are attached to the BLDC motor shaft. The sinusoidal induced electromotive force waveform is associated with permanent synchronous motor and the trapezoidal electromotive force waveform is associated with brushless DC motor.

Permanent magnet (PM) DC brushed and brushless motors incorporate a combination of PM and electromagnetic fields to produce torque (or force) resulting in motion. This is done in the DC motor by a PM stator and a wound armature or rotor. Current in the DC motor is automatically switched to different windings by means of a commutator and brushes to create continuous motion where as in BLDC, brushes are absent so force of commutation is implemented electronically with a power electronic amplifier that uses semiconductor switches to change current in the windings situated on the rotor [4][5]. In this respect, the reverse working phenomena of DC motor is being depicted and its equivalent to BLDC motor, in which the magnet rotation is a continuous process while conductor remains stationary. Therefore, BLDC motors often incorporate either internal or external position sensors to sense the actual rotor. In a brushless motor, the rotor incorporates the magnets, and the stator contains the windings.

2.2 Construction

BLDC motors have many similarities to AC induction motors and brushed DC motors in terms of construction and working principles respectively. Like all other motors, BLDC motors also have a rotor and a stator. The transverse view of BLDC motor is shown in fig. 2.1.

2.2.1 Stator

Similar to an Induction AC motor, the BLDC motor stator is made out of laminated steel stacked up to carry the windings. Windings in a stator can be arranged in two patterns; i.e. a star pattern (Y) or delta pattern (Δ). The major difference between the two patterns is that the Y pattern gives high torque at low RPM and the Δ pattern gives low torque at low RPM. This is because in the Δ configuration, half of the voltage is applied across the winding that is not driven, thus increasing losses and, in turn, efficiency and torque.

A slot less core has lower inductance, thus it can run at very high speeds. Because of the absence of teeth in the lamination stack, requirements for the cogging torque also go down, thus making them an ideal fit for low speeds too (when permanent magnets on rotor and tooth on the stator align with each other then, because of the interaction between the two, an undesirable cogging torque develops and causes ripples in speed). The main of a slot less core is higher cost because it requires more winding to compensate for the larger air gap. Proper selection of the laminated steel and windings for the construction of stator are crucial to motor. An improper selection may lead to multiple problems during production, resulting in market delays and increased design costs.

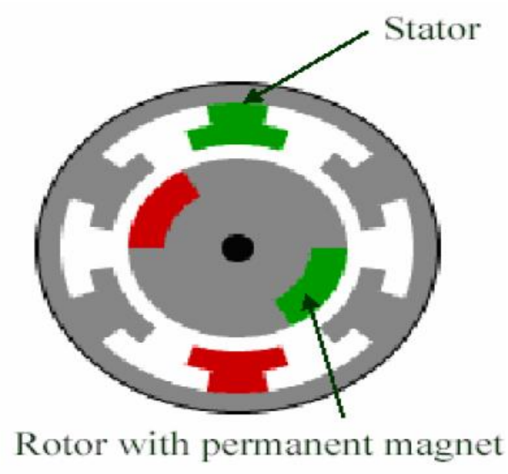

Fig 2.1 Cross-section view of a brushless dc motor

2.2.2 Rotor

The rotor of a typical BLDC motor is made out of permanent magnets. Depending upon the application requirements, the number of poles in the rotor may vary. Increasing the number of pole gives higher torque and higher speed but it increases the cost.

Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are traditionally used to make permanent magnets. As the technology advances, rare earth alloy magnets better are gaining popularity. The ferrite magnets are less expensive but they have the disadvantage of low flux density for a given volume. In contrast, the alloy material has high magnetic density per volume and enables the rotor to compress further for the same torque. Also, these alloy magnets improve the size-to-weight ratio and give higher torque for the same size motor using ferrite magnets. Neodymium (Nd), Samarium Cobalt (SmCo) and the alloy of Neodymium, Ferrite and Boron (NdFeB) are some examples of rare earth alloy magnets. Continuous research is going on to improve the flux density to compress the rotor further. Another rotor parameter that impacts the maximum torque is the material used for the construction of permanent magnet; the higher the flux density of the material, the higher the torque.

2.2.3 Hall Sensors

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall sensors embedded into the stator. Most BLDC motors have three Hall sensors embedded into the stator on the non-driving end of the motor. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the Nor S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.

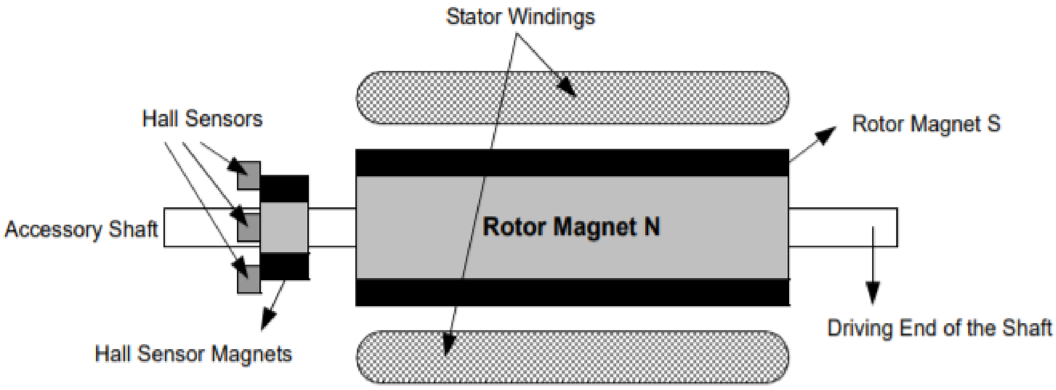

Fig 2.2: BLDC Motor Transverse Section

Hall sensors are embedded into the stationary part of the motor. Embedding the Hall sensors into the stator is a complex process because any misalignment in these Hall sensors, with respect to the rotor magnets, will generate an error in determination of the rotor position. To simplify the process of mounting the Hall sensors onto the stator, some motors may have the Hall sensor magnets on the rotor, in addition to the main rotor magnets. These are a scaled down replica version of the rotor. Therefore, whenever the rotor rotates, the Hall sensor magnets give the same effect as the main magnets.

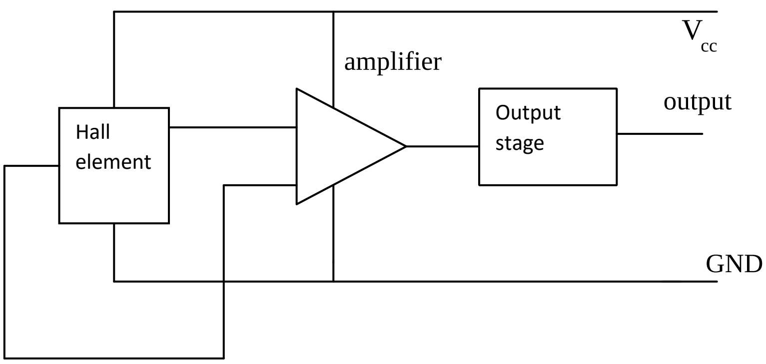

Fig 2.3: Hall position sensors

The Hall sensors are normally mounted on a PC board and fixed to the enclosure cap on the non-driving end. This enables users to adjust the complete assembly of Hall sensors, to align with the rotor magnets, in order to achieve the best performance. Based on the physical position of the Hall sensors, there are two versions of output. The Hall sensors maybe at 60° or 120° phase shift to each other. Based on this, the motor manufacturer defines the commutation sequence, which should be followed when controlling the motor.

2.3 Principle Operation of Brushless DC (BLDC) Motor

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

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

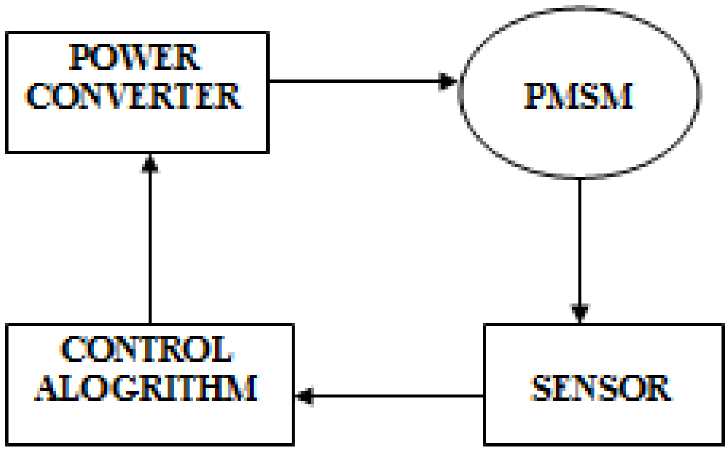

Fig.2.4: Basic block diagram of BLDC motor

The basic block diagram brushless dc motor as shown Fig.2.4. The brushless dc motor consist of four main parts power converter, permanent magnet-synchronous machine (PMSM) sensors, and control algorithm. The power converter transforms power from the source to the PMSM which in turn converts electrical energy to mechanical energy.

One of the salient features of the brush less dc motor is the rotor position sensors , based on the rotor position and command signals which may be a torque command ,voltage command speed command and so on the control algorithms determine the gate signal to each semiconductor in the power electronic converter. The structure of the control algorithms determines the type of the brush less dc motor of which there are two main classes voltage source based drives and current source based drives.

Both voltage source and current source based drive used with permanent magnet synchronous machine with either sinusoidal or non-sinusoidal back emf waveforms. Machine with sinusoidal back emf may be controlled so as to achieve nearly constant torque. However, machine with a non-sinusoidal back emf offer reduces inverter sizes and reduces losses for the same power level.

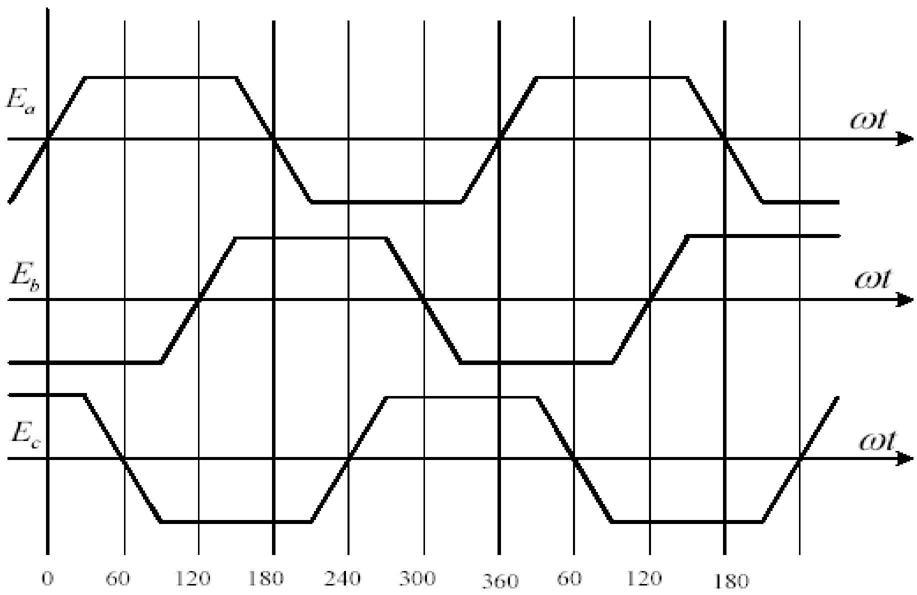

Fig.2.5: Trapezoidal back emf of three phase BLDC motor

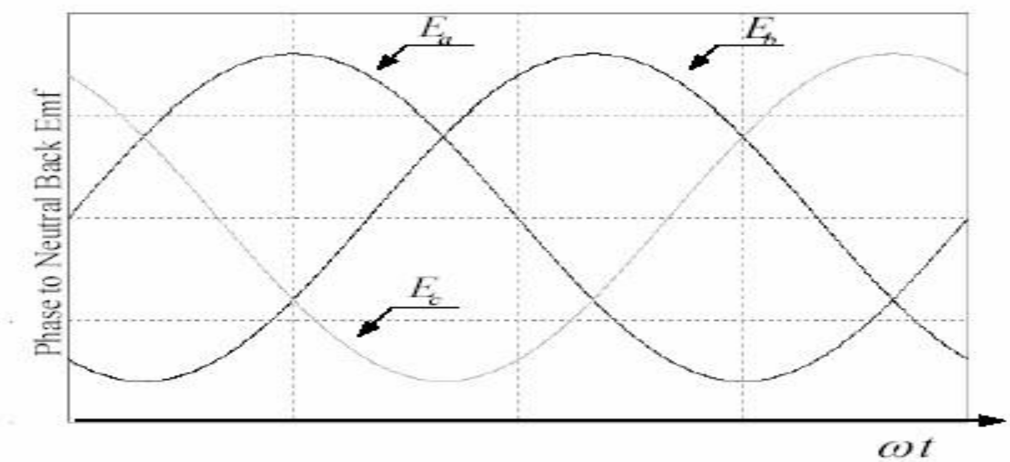

Fig.2.6: Sinusoidal phase back emf of BLDC motor

2.4 Commutation

Commutation provides the creation of a rotation field. As previously explained, it is necessary to keep the angle between stator and rotor flux close to 90° for a BLDC motor to operate properly. Six-step control creates a total of six possible stator flux vectors. The stator flux vector must be changed at a certain rotor position. The rotor position is usually sensed by Hall sensors [3][5].

The Hall sensors generate three signals that also comprise six states. Each of Hall sensors' states corresponds to a certain stator flux vector. The simplified drive model for BLDC motor is shown in Fig 2.4. The actual voltage pattern can be derived from Table 2.1. Phase A is connected to the positive DC Bus voltage by the transistor Q1; Phase B is connected to the ground by transistor Q4; Phase C is unpowered.

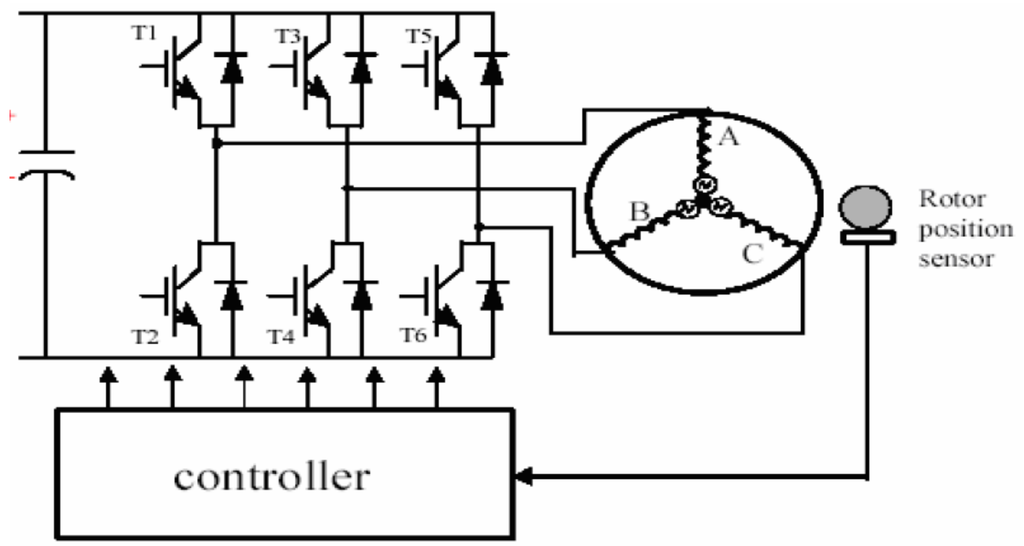

Fig.2.7: BLDC motor drive

As soon as the rotor reaches a certain position the Hall sensors' state changes its value from ABC [100] to ABC [001]. A new voltage pattern is selected from Table 2.1and applied to the BLDC motor. As shown, when using a six-step control technique, it's impossible to keep the angle between the rotor flux and the stator flux precisely at 90°. The actual angle varies from 60° to 120°. Commutation is repeated every 60° electrical. The commutation event is critical for its angular (time) accuracy. Any deviation causes torque ripples, leading to a variation in speed.

Table 2.1 Switching Sequence

Switching Interval	Sequence No	Position Sensor			Switch Closed		Phase Current		
		H1	H2	H3			A	B	C
0-60	0	1	0	0	T1	T4	+	-	off
60-120	1	1	1	0	T1	T6	+	off	-
120-180	2	0	1	0	T3	T6	off	+	-
180-240	3	0	1	1	T3	T2	-	+	off
240-300	4	0	0	1	Q5	Q2	-	off	+
300-360	5	1	0	0	Q5	Q4	off	-	+

2.4.1 Commutation Methods

The driving performance of the motor may vary depending on the voltage waveforms applied to the motor windings. Two commutation methods, trapezoidal and sinusoidal, are used in BLDC motor drives as follows.

1. Trapezoidal Commutation

This method is also called six-step commutation. In this method, two of the three windings are energized at the same time. The remaining winding which is left floating gives position information by using BEMF signal in sensorless control. Each one of the six-steps is equivalent to 60 electrical degree rotation. So, these six steps make one complete electrical cycle. In trapezoidal method, steps are applied properly in order to generate a rotating field in the stator. Electrical repetition frequency in the stator is proportional to the mechanical rotor speed depending on number of magnetic pole pairs on the rotor. Mechanical rotation speed is equal to the electrical frequency divided by the number of pole pairs.

2. Sinusoidal Commutation

In this method, all three phases of the motor are energized with sinusoidal voltages at the same time. This allows generation of smoother torque and ability of controlling the motor more precisely. In order to obtain a precise sinusoidal waveform, one degree or better resolution of position information is necessary. In addition, precise generation of a smooth torque profile also requires BEMF waveform matching.

2.5 Types of BLDC motor

BLDC motor is classified on the basis of number of phase windings and the number of pulses given to the devices during each cycle.

(i) One phase winding one pulse BLDC motor

(ii) One phase two pulse BLDC motor

(iii) Two phase winding and two pulse BLDC motor

(iv) Three phase winding and three pulse BLDC motor

(v) Three phase six pulse BLDC motor

2.5.1 One phase winding one pulse BLDC motor

It is connected to the supply through a power semiconductor switch. When the rotor position sensor is influenced by say n pole flux, the stator operates and the rotor developed a torque. When the RPS is under the influence of S pole, the transistor is in off state. The rotor gets torque whenever the rotor position is under the influence of n pole.

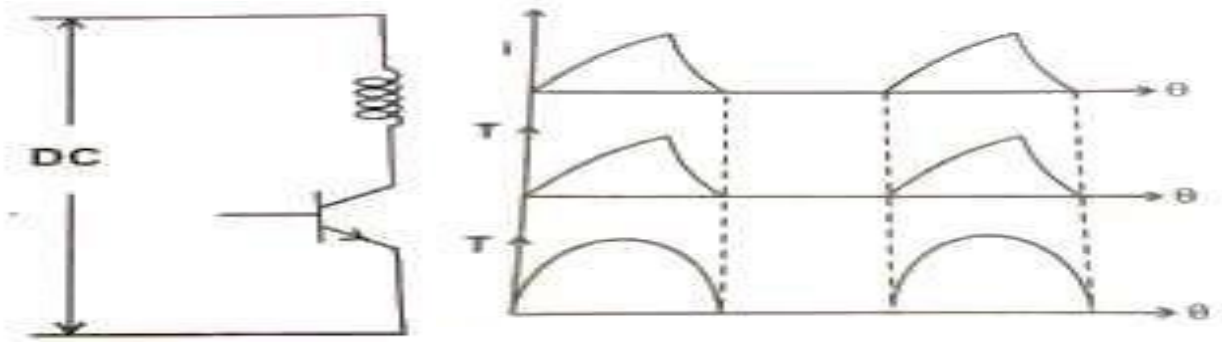

Fig.2.8: One phase one pulse BLDC motor and required Current and torque waveform

2.5.2 One phase two pulse BLDC motor

Stator has only one winding. It is connected to DC three wire supply through two semiconductor devices. There is only one position sensor. The position sensor is under the N-pole influence, T1 is in on-state and T2 is in off-state. When it is under the influence of S-pole, T2 is on and T1 is off. In the first case, the winding carries current from A to B and when T2 is on, the winding carries current from B to A. The polarity of the flux setup by the winding gets alerted depending upon the position of the rotor.

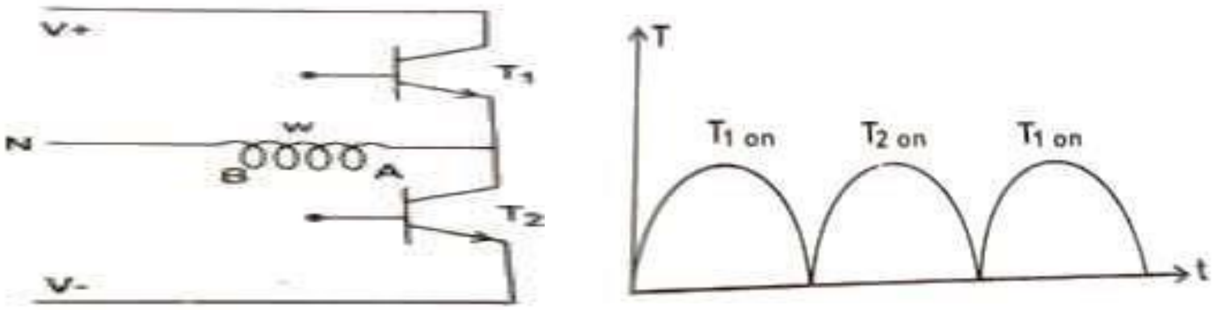

Fig.2.9: One phase two pulse BLDC motor and Torque waveform

2.5.3 Two phase winding and two pulse BLDC motor

Stator has two phase windings which are displaced by 180° electrical. It makes use of two semiconductor switches. Performance of this type is similar to one phase 2 pulse BLPM motor. However, it requires two independent phase windings. Torque developed is uniform and utilization of transistors and windings are less.

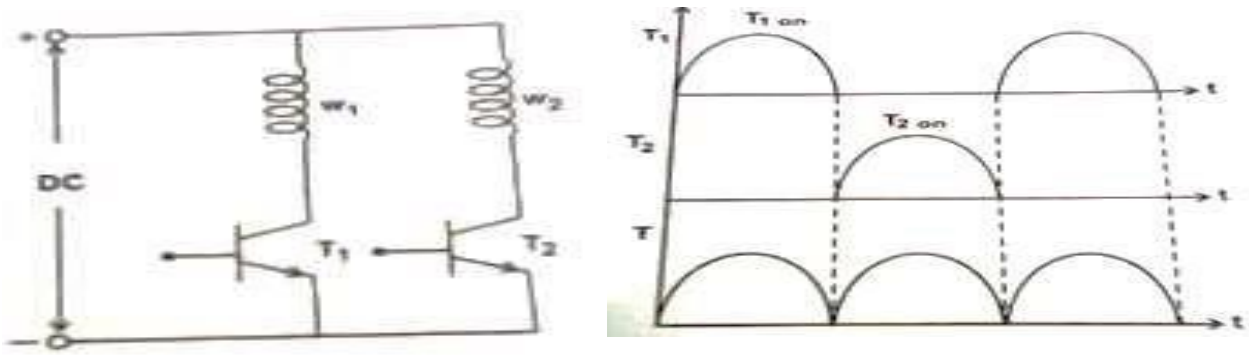

Fig.2.10: Two phase two pulse BLDC motor and Torque waveform

2.5.4 Three phase winding and three pulse BLDC motor

The stator has 3Φ windings as shown in fig. Whose areas are displaced by 120°elec. apart. Each phase windings is controlled by a semiconductor switch which is operated depending upon the position of the rotor. Three position sensors are required for this purpose.

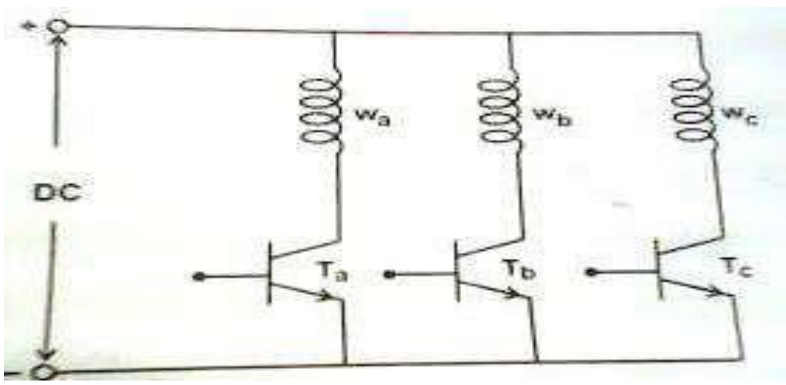

Fig.2.11: Three phase winding and three pulse BLDC motor

2.5.5 Three phase six pulse BLDC motor

The stator has 3Φ windings as shown in fig. Whose areas are displaced by 120°elec. apart. phase windings are controlled by a 6-semiconductor switch which is operated depending upon the position of the rotor. 6 position sensors are required for this purpose Usually 120^o and 180^o conduction is adopted. This circuit produces unidirectional torque in all the 3 phase winding.

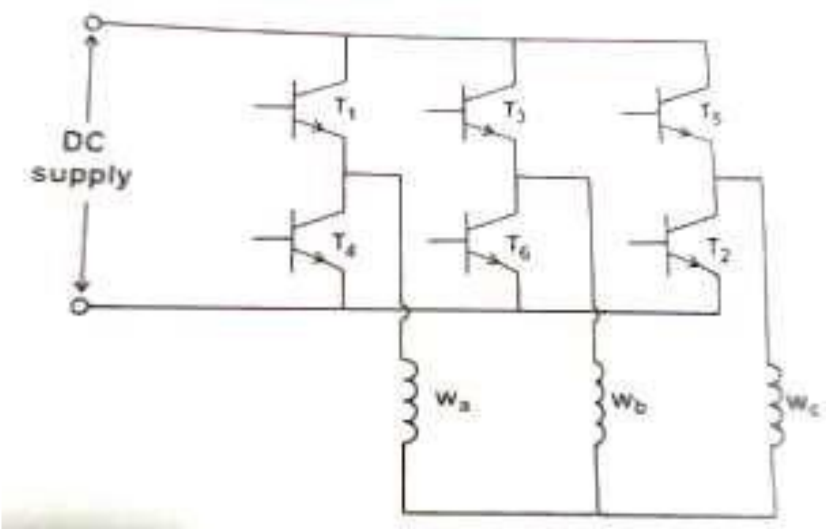

Fig.2.12: Three phase six pulse BLDC motor

2.6 Speed-Torque Relationship of the BLDC

BLDCs have been introduced to replace DC motors to provide more efficiency and lower cost. The speed vs. torque relationship for the BLDC is linear, but speed decreases as the load torque increases. In comparison, the speed of separately excited DC motor decreases only gradually as load torque increases. A velocity control loop is used in some BLDC controllers to provide constant speed over the torque range.

This chapter has two objectives:

(i) To understand the speed vs. torque characteristics of BLDCs

(ii) To understand the principles and design of a control loop using a proportional integral (PI) controller.

2.6.1 Torque-Speed Characteristics

For the study of electric motors, it is important to understand the term torque. By definition, torque is the product of force and radius to rotate an object about its axis [15]

$$Torque(N, m) = Force(N) X \ Radius\ (m) \tag{4.1}$$

Therefore, for a BLDC, torque can be increased by either increasing the force or the radius. The force can be increased by using stronger magnets or increasing the currents in 26 the phases. A typical speed- torque characteristic graph of a BLDC is shown in Figure 4-1.

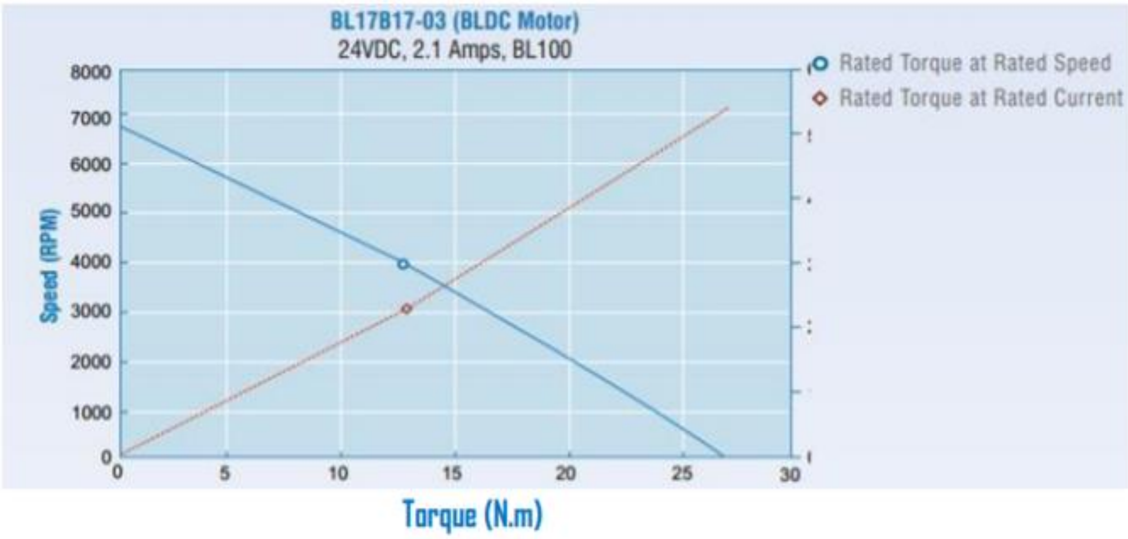

Fig.2.13: Speed vs. Torque of a BLDC

The torque of a separately excited DC motor shown in Figure 4.2 is provided by equation

$$Torque = Ka\emptyset Ia\ (N.\text{m}) \tag{4.2}$$

Where: Ka- Armature constant

$\emptyset$- Flux of the machine (Weber)

Ia- Armature current (Ampere)

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Ia- Armature current (Ampere)

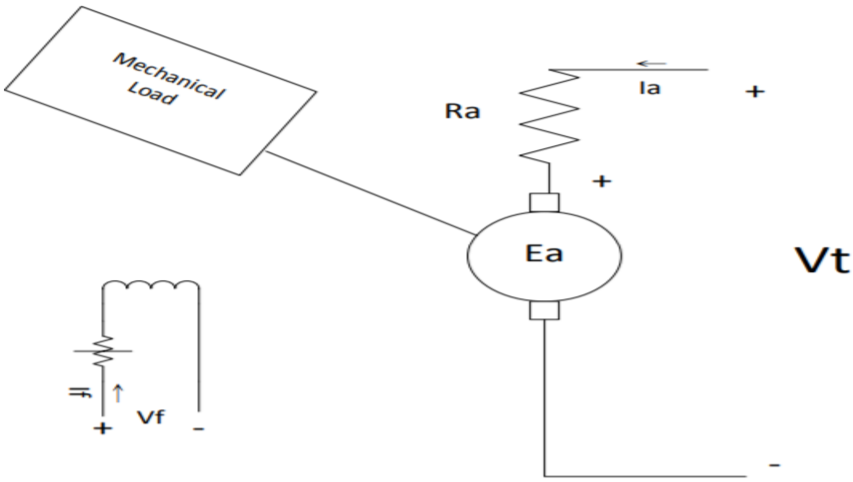

Fig.2.14: Separately Excited DC Motor

The Back- EMF of a separately excited DC motor is:

$Ea = Ka\emptyset\ \omega m = Vt - IaRa$ (4.3)

Where,

Ea- Back- EMF (Volts)

ωm - Speed (Radians/second)

Vt - Terminal voltage (Volts)

From Figure 2.9, Vf and If are the field voltage and field current respectively.

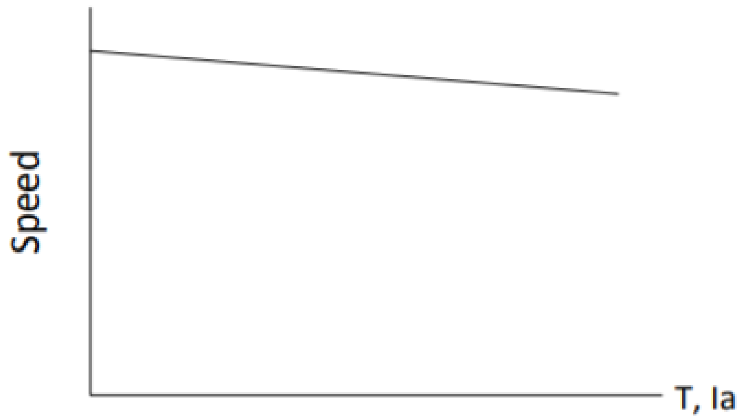

Fig 2.15: Speed vs. Torque of a Separately Excited DC Motor

The speed- torque characteristic graph of a separately excited DC motor is shown in Figure 2.10. As shown in the figure, the speed drop over the torque range is very small, hence providing good speed regulation, unlike the BLDC.

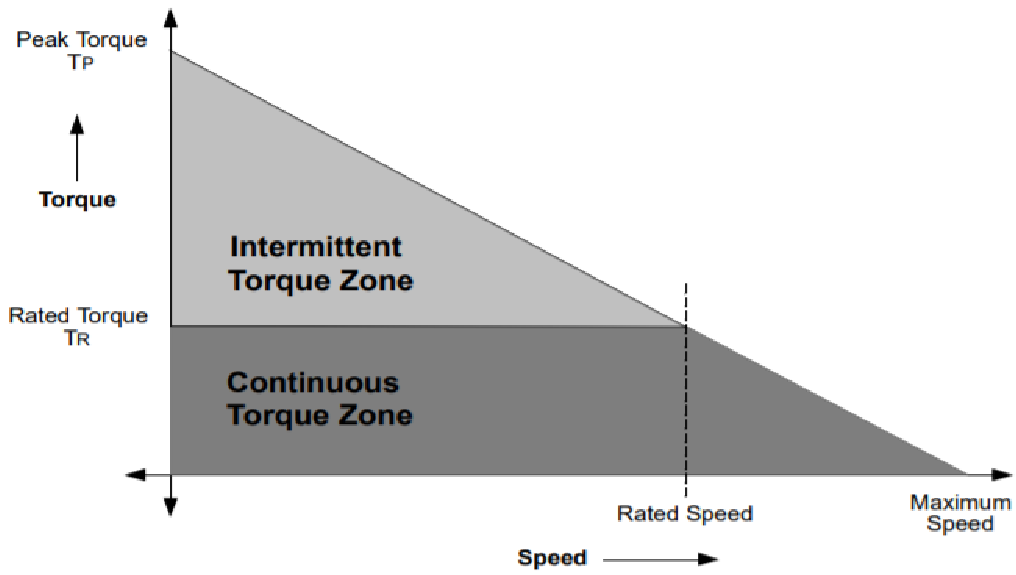

Fig 2.16: Torque/Speed Characteristics

Speed in a DC machine increases as the terminal voltage increases. By adding a velocity loop to a BLDC control system, speed can be held constant across varying torque. This velocity control loop uses a Proportional Integral (PI) Controller for speed regulation. A PI controller corrects the error between a measured process variable and desired set point by calculating and then outputting corrective action that can adjust the process accordingly.

Figure 2.11 shows an example of torque/speed characteristics. There are two torque parameters used to define a BLDC motor, peak torque (TP) and rated torque (TR). During continuous operations, the motor can be loaded up to the rated torque. As discussed earlier, in a BLDC motor, the torque remains constant for a speed range up to the rated speed. The motor can be run up to the maximum speed, which can be up to 150% of the rated speed, but the torque starts dropping.

Applications that have frequent starts and stops and frequent reversals of rotation with load on the motor, demand more torque than the rated torque. This requirement comes for a brief period, especially when the motor starts from a standstill and during acceleration. During this period, extra torque is required to overcome the inertia of the load and the rotor itself. The motor can deliver a higher torque, maximum up to peak torque, as long as it follows the speed torque curve.

2.7 Comparing BLDC Motors to other Motor types

Compared to Brushed DC motors and induction motors, BLDC motors have many advantages and few disadvantages. Brushless motors require less maintenance, so they have a longer life compared with brushed DC motors. BLDC motors produce more output power per frame size than brushed DC motors and induction motors [11].

Because the rotor is made of permanent magnets, the rotor inertia is less, compared with other types of motors. This improves acceleration and deceleration characteristics, shortening operating cycles [3][5]. Their linear speed/torque characteristics produce predictable speed regulation. With brushless motors, brush inspection is eliminated, making them ideal for limited access areas and applications where servicing is difficult.

BLDC motors operate much more quietly than brushed DC motors, reducing Electromagnetic Interference (EMI). Low-voltage models are ideal for battery operation, portable equipment or medical applications [11].

Table 2.2 Comparison between BLDC Motor and INDUCTION Motor

Feature	BLDC Motor	AC INDUCTION MOTOR
Speed/Torque Characteristics	Flat – Enables operation at all speeds with rated load.	Nonlinear – Lower torque at lower speeds.
Output Power/ Frame Size	High – Since it has permanent magnets on the rotor, smaller size can be achieved for a given output power	Moderate – Since both stator and rotor have windings, the output power to size is lower than BLDC.
Starting Current	Rated – No special starter circuit required.	Approximately up to seven times of rated – Starter circuit rating should be carefully selected. Normally uses a Star-Delta starter.
Slip	No slip is experienced between stator and rotor frequencies.	The rotor runs at a lower frequency than stator by slip frequency and slip increases with load on the motor.
Control Requirements	A controller is always required to keep the motor running. The same controller can be used for variable speed control.	No controller is required for fixed speed; a controller is required only if variable speed is desired.

Table 2.3 Comparison between Mechanical and Electronic commutator

Mechanical Commutator	Electronic commutator
Commutator is made up of commutator segment and mica insulation. Brushes are made up of carbon.	Power electronic switching devices are used in the commutator.
Shaft position sensing is inherent in the arrangements.	It requires a separate rotor position sensor.
Commutator arrangement is located in the rotor.	Commutator arrangement is located in the stator.
Sliding contact between commutator and brushes.	No sliding contacts
Sparking takes place.	There is no sparking.
It requires regular maintenance.	It requires less maintenance.
Number of commutator segment are very high.	Number of switching devices is limited to 6.
Difficult to control the voltage available across tapping.	Voltage available across armature tappings can be controlled by PWM techniques.
Highly Reliable	Reliability depends on the switching devices.

Table 2.4 Comparison between BLDC Motor and BRUSHED DC Motor

Feature	BLDC Motor	Brushed DC Motor
Commutation	Electronic commutation based on Hall position sensors.	Brushed commutation.
Maintenance	Less required due to absence of brushes.	Periodic maintenance is required.
Speed/Torque Characteristics	Flat – Enables operation at all speeds with rated load	Moderately flat – At higher speeds, brush friction increases, thus reducing useful torque.
Efficiency	High – No voltage drop across brushes.	Moderate.
Output Power/ Frame Size	High – Reduced size due to superior thermal characteristics. Because BLDC has the windings on the stator, which is connected to the case, the heat dissipation is better.	Moderate/Low – The heat produced by the armature is dissipated in the air gap, thus increasing the temperature in the air gap and limiting specs on the output power/frame size
Rotor Inertia	Low, because it has permanent magnets on the rotor. This improves the dynamic response.	Higher rotor inertia which limits the dynamic characteristics.
Electric Noise Generation	Low	Arcs in the brushes will generate noise causing EMI in the equipment nearby.
Control	Complex and expensive.	Simple and inexpensive.
Control Requirements	A controller is always required to keep the motor running. The same controller can be used for variable speed control.	No controller is required for fixed speed; a controller is required only if variable speed is desired.

2.8 Typical BLDC Motor Applications

BLDC motors find applications in every segment of the market. Automotive, appliance, industrial controls, automation, aviation and so on, have applications for BLDC motors.
Out of these, we can categorize the type of BLDC motor control into three major types:
(i) Constant load
(ii) Varying loads
(iii) Positioning applications

2.7.1 Applications with Constant Loads

These are the types of applications where variable speed is more important than keeping the accuracy of the speed at a set speed. In addition, the acceleration and deceleration rates are not dynamically changing. In these types of applications, the load is directly coupled to the motor shaft. For example, fans, pumps and blowers come under these types of applications. These applications demand low-cost controllers, mostly operating in open-loop. A brushless DC motor built in a compressor of air conditioner is a typical application and it confirms the feasibility and the validity of some sensorless algorithms, such as a variation of the back-EMF zero crossing detection method. It is necessary to modulate the capacity of room air conditioners in proportion to the load results in energy saving and a comfortable environment. The speed of the brushless motor with a permanent magnet rotor can be easily controlled over a wide range by changing the motor voltage. Nevertheless, this type of motor needs a rotor position sensor, and this reduces the system ruggedness and complicates the motor configuration. In particular, the motor speed control and elimination of mechanical sensors are the main points of the sensorless methods, which contribute to the motor built in a completely sealed compressor and make it possible to mass produce. Mechanical sensors have low reliability in high-temperature and the need of a extra hermetic terminal of the sensor signal lead wires, and can be substituted by low-pass filters and voltage comparators.

An example of the Terminal Voltage Sensing algorithm can be implemented to drive an IPM BLDC motor which is in a completely sealed compressor of air conditioner. The drive works from about 500 to 7,500 rpm and at low speed, where the amplitude of back-EMF is nearly zero, taking into account that the variation of neutral voltage includes the information of rotor position. Also, the control implementation of a brushless motor, which consists of a three-phase star-connected stator and a four-pole permanent magnet rotor, can be commutated using a 120-electrical-degree type inverter with a capacity of 1.5 kVA, a single-chip microcomputer and comparators. This system has been used for the drive of brushless motor in compressors, and the room air conditioners that contain these control systems have been mass-produced since 1982 without any particular problem since then.

2.7.2 Applications with Varying Loads

In these applications the load on the motor varies over a speed range and may demand high-speed control accuracy and good dynamic responses. Home appliances such as washers, dryers and refrigerators are good examples. Also, fuel pump control, electronic steering control, engine control and electric vehicle control are examples of these in the automotive industry. In aerospace, there are a number of applications, such as centrifuges, pneumatic devices with electroactuators, pumps, robotic arm controls, gyroscope controls and so on. These applications may use speed feedback devices and may run in semi-closed loop or in total closed loop by using advanced control algorithms which complicates the controller and increases the price of the complete system.

The brushless DC motor is well suited for automotive returnlees fuel pump applications today, because they are inherently more reliable, more efficient, and with current electronics technology, more cost effective than the standard brush-type fuel-pump motor and controller. In a returnless fuel system, the fuel pump speed is adjusted to maintain constant fuel pressure over the fuel demand/load range. It uses a sensing method that detects the true back-EMF zero crossing point, which requires neither a manufactured neutral voltage nor a great amount of filtering, and provides a wider speed range from startup to full speed. Taking into account that over the last decade, there has been a steady improvement in electronics, control algorithms, and motor technologies, BLDC motors are the preferred solution in not just automotive fuel pumps but also in a broad range of applications using adjustable speed motors, such as home appliances for compressors, air blowers, vacuum cleaners or engine cooling fans. For instance, a brush type fuel pump motor is designed to last 6,000 h, so in certain fleet vehicles this can be expended in less than one year. A BLDC motor life span is typically around 15,000 h, extending the life of the motor by almost three times. Also, because of a microcontroller is used to perform the brushless commutation other features can be incorporated into the application, such as electronic returnless fuel system control, fuel level processing, and fuel tank pressure. These added features simplify the vehicle systems as well as drive overall system cost down.

Another important application of BLDC motors is the aerospace field. The implementation of any new technology in the aerospace industry makes strict demands on the safety and reliability of on-board equipment. A fundamental element that drives the EHA/EMA actuator is the DC motor. Nowadays, BLDC motors are widely used, mainly because of their better characteristics and performance. In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors, especially in aerospace. The operation of an actuator is safety critical and thus the actuator requires a reliable control algorithm that ensures safe start-up and operation of the BLDC motor that drives the actuator. Intelligent EHA/EMA actuators and smart actuation systems promising technologies for future power optimised aircraft, adding important benefits in energy consumption, weight savings, easy assembly procedures.

2.7.3 Positioning Applications

Most of the industrial and automation types of application come under this category. The applications in this category have some kind of power transmission, which could be mechanical gears or timer belts, or a simple belt driven system. In these applications, the dynamic response of speed and torque are important. Also, these applications may have frequent reversal of rotation direction. A typical cycle will have an accelerating phase, a constant speed phase and a deceleration and positioning phase. The load on the motor may vary during all of these phases, causing the controller to be complex. These systems mostly operate in closed loop. There could be three control loops functioning simultaneously: Torque Control Loop, Speed Control Loop and Position Control Loop. Optical encoder or synchronous resolvers are used for measuring the actual speed of the motor. In some cases, the same sensors are used to get relative position information. Otherwise, separate position sensors may be used to get absolute positions. Computer Numeric Controlled (CNC) machines are a good example of this. Process controls, machinery controls and conveyer controls have plenty of applications in this category.

Hydraulic systems are commonly used in automotive applications, since they allow developing higher forces and torques compared with purely electric actuators. For example, passenger cars are equipped with hydraulically-assisted brakes, clutches and power steering systems, while in commercial vehicles hydraulic power is used to operate also lifting systems and other auxiliary machineries. If a variable speed electric motor is coupled to the hydraulic pump, a flow control valve is always necessary, and the possibility to regulate the rotational speed of the pump *i*ndependently from the engine speed allows a significant reduction of parasitic losses. However, this solution requires the design of a specific electronic controller, capable of motor speed regulation according to the hydraulic load dynamic requirements. Moreover, since the power supply of these electro-hydraulic systems must be the battery of the vehicle, to allow operation even when the engine is switched off, electric motors and power electronics must be designed for low-voltage and high-current ratings, especially in commercial vehicle applications. Then, a brushless motor are the appropriate device to this purpose.

Another important application in this category is the hard disk drives. HDDs tend to have high spin speeds in order to reduce the access time in data reading and writing. The highest spin speed of commercial HDDs has reached 15,000 rpm and will be higher in the near future. However, for the small form factor HDDs, the back-EMF amplitudes of their spindle motors are becoming low even at the rated speed, and some methods based on the zero-crossing detection of back EMFs does not work well when the terminal voltage spikes last relatively longer at higher spin speed or the phase back- EMF amplitude is very small. Recently, due to HDDs being widely used in mobile applications, the power-supply voltage has been reduced and the detection of the rotor position from the back EMF is difficult at low speed. Thus, the stable starting and acceleration to nominal operating speed, regardless of severe mechanical disturbance is the utmost concern in these applications.

2.9 Advantages and Disadvantages of BLDC Motor

Table.3.1.1 will compare the advantages and disadvantages of each type of motor and summarizes the comparison between BLDC motor and other types of motor.

Comparing brushed DC motors and induction motors to BLDC motors, BLDC motors have many advantages over disadvantages. Brushless DC motors require less maintenance and therefore have a longer life span as compared to brushed DC motors. BLDC motors produce more output power per frame size than brushed DC motors and induction motors. Because the rotor is made of permanent magnets, the rotor inertia is less, comparing with other types of motors. This low rotor inertia improves acceleration and deceleration characteristics, shortening operating cycles. Their linear speed/torque characteristics produce predictable speed regulation. With brushless motors, brush inspection is eliminated, making them ideal for areas with limited access and applications where servicing is difficult. BLDC motors operate much more quietly than brushed DC motors, reducing Electromagnetic interference (EMI). Low-voltage models are ideal for battery operation, portable equipment or medical applications. It also reduces the risk of electric shock.

Table.2.5. Advantages and Disadvantages of different types of motor

Type	Advantage	Disadvantage	Typical Application	Typical Drive
AC Induction (Shaded Pole)	Least expensive Long life High Power	Rotation slips from frequency Low starting torque	Fans	Uni/Ply-phase AC
AC Induction (Split-Phase Capacitor)	High Power High starting torque	Rotation slips from frequency	Appliance Power Tools	Uni/Ply-phase AC
Brushed DC	Low initial cost Simple speed control	Maintenance(brushes) Medium life span	Treadmill exercises Automotive motors (seats, blowers, windows)	Direct DC or PWM
Brushless DC	Long life span Low maintenance High efficiency	High initial cost Requires a controller	Hard drives CD/DVD Rom Electric Vehicles	Direct DC or PWM

CHAPTER 3

SYSTEM DESCRIPTION AND MODELING OF BLDC MOTOR

3.1 Theory Of Operation

For each of the commutation sequence, one of the winding is fed to positive power (current enters into the winding), the second winding is fed to negative power (current exit the winding) and the third is in a non-energized condition. The interaction of magnetic field generated by the stator coils and the permanent coils produces torque. In order to keep the motor in running condition, the magnetic field produced by the windings should shift position, so that the rotor synchronizes with the stator field.

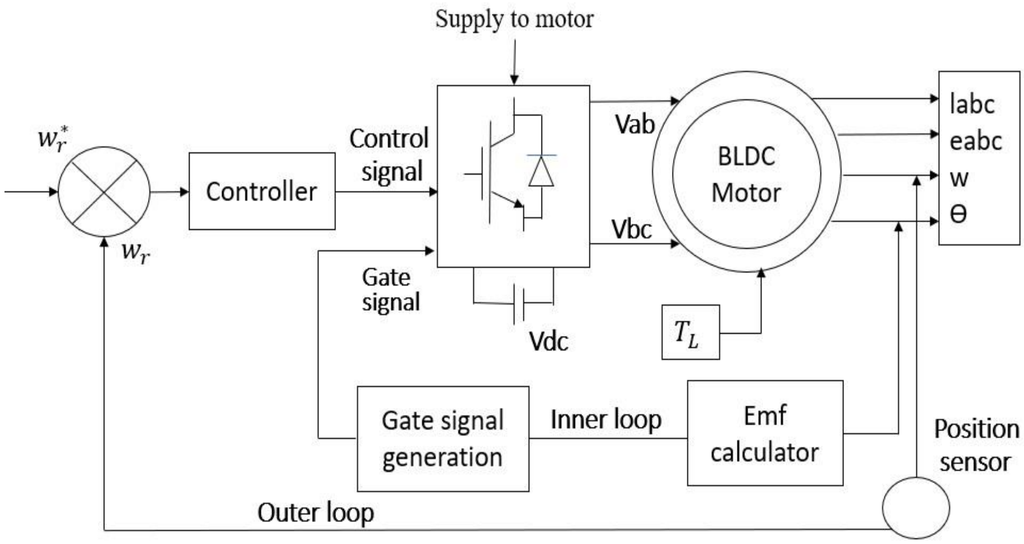

Fig.3.1. Block Diagram of BLDC Motor

BLDC motors are also known as electronically commutated motors which are powered by direct-current (DC) electricity and commutation is controlled electronically by the drive amplifier. Fig.3.1 shows the block diagram of the BLDC motor drive system used in the paper. The speed of the motor is compared with its reference value and the speed error is processed in proportional- integral controller. The outer loop is designed to improve the static and dynamic characteristics of the system. The disturbance caused by the inner loop can be limited by the outer loop. The rotor position information supplied by the Hall Effect sensors of the BLDC motor. To control motor current, a proportional controller is used to supply proper switching pattern for inverter where three hall sensors are used.

To control a BLDC motor the following five assemblies are incorporated:

1) DC power supply

The fixed DC voltage is derived from either a battery supply, low voltage power supply or from a rectified mains input. The input voltage may be 12V or 24V as used in many automotive applications, 12V-48V for applications such as disc drives or tape drives, or 150V-550V for single-phase or three-phase mains-fed applications such as domestic appliances or industrial servo drives or machine tools.

2) Inverter

The inverter bridge is the main power conversion stage and it is the switching sequence of the power devices which controls the direction, speed and torque delivered by the motor. The power switches can be either bipolar devices or, more commonly, Power MOS devices. Mixed device inverters, for example system using p-n-p Darlingtons as the high side power switches and MOSFETs as the low side switches are also possible. The freewheel diodes in each inverter leg may be internal to the main power switches as in the case of FREDFETs or may be separate discrete devices in the case of standard MOSFETs or IGBTs.

The inverter switching speed may be in the range 3 kHz to 20 kHz and above. For many applications operation at ultrasonic switching speeds (>15-20 kHz) is required in order to reduce system noise and vibration, reduce the amplitude of the switching frequency currents and to eliminate switching harmonic pulsations in the motor. Because of the high switching speed capability of Power MOS devices they are often the most suitable device for BLDC motor inverters.

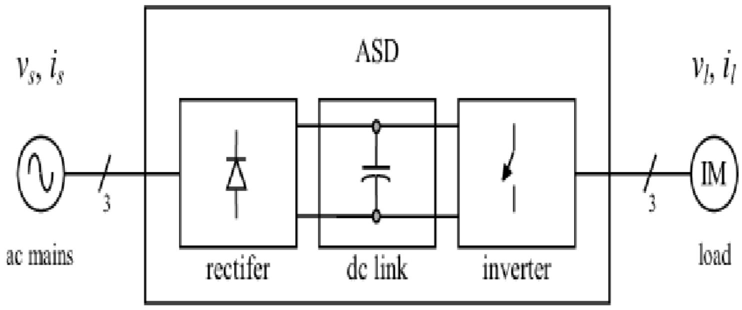

Fig.3.2. Basic inverter circuit

3) Power electronic switches

For the ‘inside out’ BLDC motor it is still necessary to switch the armature current into successive armature coils as the rotor advances. As the coils are now on the stator of the machine the need for a commutator and brush gear assembly has disappeared. The development of high voltage and high current power switches, initially thyristors and bipolar power transistors but more recently MOSFETs, FREDFETs, Sensor FETs and IGBTs, has meant that motors of quite large powers can be controlled electronically, giving a feasible BLDC motor drive system.

4) Motor

A two pole BLDC motor with the field magnets mounted on the surface of the rotor and with a conventional stator assembly was shown in Fig.2.1. Machines having higher numbers of poles are often used depending upon the application requirements for motor size, rotor speed and inverter frequency. Alternative motor designs, such as disc motors or interior magnet rotor machines, are also used for some applications. Rotor position sensors are required in order to control the switching sequence of the inverter devices. The usual arrangement has three Hall Effect sensors, separated by either 60° or 120°, mounted on the stator surface close to the air gap of the machine. As the rotor advances the switching signals from these Hall Effect latches are decoded into rotor position information in order to determine the inverter firing pattern.

In order to minimize torque ripple the EMF induced in each motor phase winding must be constant during all instants in time when that phase is conducting current. Any variation in the motor phase EMFs while it is energized results in a corresponding variation in the torque developed by that phase.

5) Controller

The inverter is controlled in order to limit the device currents, and hence control the motor torque, and to set the direction and speed of rotation of the motor. The average output torque is determined by the average current in each phase when energized. As the motor current is equal to the DC link current then the output torque is proportional to the DC input current, as in a conventional DC motor. The motor speed is synchronous with the applied voltage waveforms and so is controlled by setting the frequency of the inverter switching sequence. Rotor position feedback signal are derived from the Hall Effect devices as discussed earlier or from optic transducers with a slotted disc arrangement mounted on the rotor shaft. It is also possible to sense rotor position by monitoring the emfs in the motor phase windings but this is somewhat more complex. In some applications the Hall Effect sensor outputs can be used to provide a signal which is proportional to the motor speed. This signal can be used in a closed loop controller if required.

3.2 Mathematical Model

3.2.1 Overview

Typically, the mathematical model of a Brushless DC motor is not totally different from the conventional DC motor. The major thing addition is the phases involved which affects the overall results of the BLDC model [12]. The phases peculiarly affect the resistive and the inductive of the BLDC arrangement. For example, a simple arrangement with a symmetrical 3-phase and "wye" internal connection could give a brief illustration of the whole phase concept.

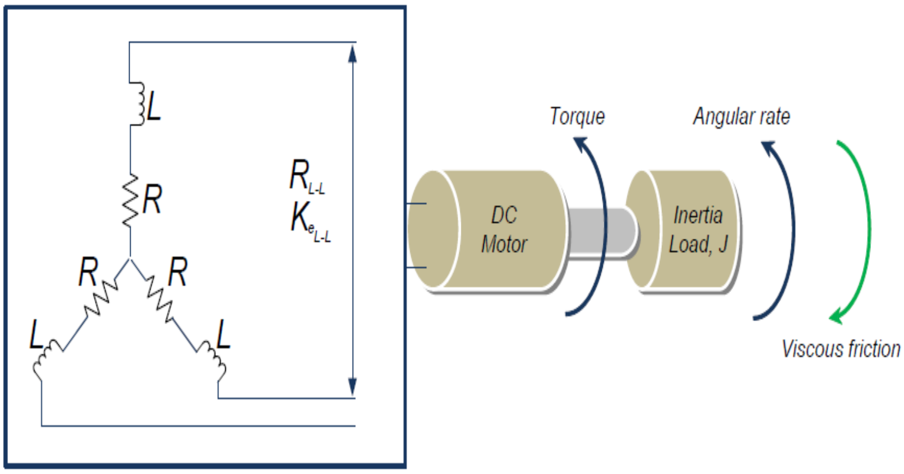

Fig.3.3. Brushless DC motor schematic diagram

The model equations of a BLDC motor are composed of a voltage equation, a torque equation and a motion equation. The stator of a general BLDC motor has three windings like an induction motor [1]. Equations (2.1) through (2.9) represents the dynamical model of BLDC motor. These equations are based on the following [42]:

i. The stator has a Y-connected concentrated full-pitch winding.
ii. The inner rotor has a non-salient pole structure.
iii. Three hall sensors are placed symmetrically at 120^{o} interval.

$$v_{ab} = R(i_a - i_b) + (L - M)\frac{d}{dt}(i_a - i_b) + e_a - e_b$$

$$v_{ca} = R(i_c - i_a) + (L - M)\frac{d}{dt}(i_c - i_a) + e_c - e_a$$

$$v_{bc} = R(i_b - i_c) + (L - M)\frac{d}{dt}(i_b - i_c) + e_b - e_c$$

$$T_e = J\frac{dw_m}{dt} + B_v w_m + T_L$$

$$e_a = \frac{K_e}{2} w_m F(\theta_e)$$

$$e_b = \frac{K_e}{2} w_m F(\theta_e - \frac{2\pi}{3})$$

$$e_c = \frac{K_e}{2} w_m F(\theta_e - \frac{4\pi}{3})$$

$$T_e = \frac{K_t}{2}[F(\theta_e)i_a + F\left(\theta_e - \frac{2\pi}{3}\right)i_b + F\left(\theta_e - \frac{4\pi}{3}\right)i_c] \qquad (2.8)$$

$$F(\theta_e) = \left\{\begin{matrix} 1 & 0 \le \theta_e \le \frac{2\pi}{3} \\ 1 - \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right) & \frac{2\pi}{3} \le \theta_e \le \pi \\ -1 & \pi \le \theta_e \le \frac{5\pi}{3} \\ -1 + \frac{6}{\pi}\left(\theta_e - \frac{5\pi}{3}\right) & \frac{5\pi}{3} \le \theta_e \le 2\pi \end{matrix}\right\} \qquad (2.9)$$

where:

B_v:	the friction constant.
K_e:	the line back-emf constant.
K_t:	the line torque constant.
T_L:	the load torque.
T_e:	the electrical torque.
e_a, e_b, e_c:	the phase back-emf's.
i_a, i_b, i_c:	the phase current.
θ_m:	the rotor angle.
ω_m:	rotor speed.
J:	the rotor inertia.
L:	the phase inductance.
P:	the number of pole pairs.
R:	the phase resistance.

Two mathematical models will be presented in this section based on these differential equations. The first is transfer function model and the second is state space model.

3.2.2 Transfer function of BLDC Motor

Transfer functions are usually used to study the systems such as single-input single-output filters, typically within the fields of signal processing, communication theory, and control theory. The term is often used exclusively to refer to linear, time-invariant systems (LTI). Most real systems have non-linear input/output characteristics, but many systems, when operated within nominal parameters its behaviour will near enough to linear that LTI system theory is an acceptable representation of the input/output behaviour.

To simplify the proposed transfer function model of BLDC motor the following assumptions are made:

(i) Neglect the core saturation, as well as the eddy current losses and the hysteresis losses.

(ii) Neglect the armature reaction, and the distribution of air-gap magnetic field is thought to be a trapezoidal wave with a flat-top width of 120 0 electrical angle.

(iii) Neglect the cogging effect and suppose the conductors are distributed continuously and evenly on the surface of the armature.

(iv) Power switches and flywheel diodes of the inverter circuit have ideal switch features. Implementing such assumption leads to the following linearized model.

The parameters of BLDC Motor are given in Appendix 1. Using the Kirchhoff's Voltage Law for single phase DC motor,

$$V_s = Ri + L\frac{di}{dt} + e \tag{2.1}$$

Therefore, for the non steady-state, equation 2.1 is rearranged to make provision for the back emf, as shown in equation 2.2 below:

$$e = -Ri - L\frac{di}{dt} + V_s \tag{2.2}$$

Where,

V_s = the DC Source voltage

i= the armature current

Similarly, considering the mechanical properties of the dc motor, from the Newton's second law of motion, the mechanical properties relative to the torque of the system arrangement would be the product of the inertia load, J and the rate of angular velocity, ω_m is equal to the sum of all the torques [13] [14]; these follow with equation 2.3 and 2.4 accordingly.

$$J\frac{dw_m}{dt} = \sum T_i \tag{2.3}$$

$$T_e = k_f w_n + J\frac{dw_m}{dt} + T_L \tag{2.4}$$

Where,

Te = the electrical torque

kf = the friction constant

J = the rotor inertia

w_m= the angular velocity

T_L = mechanical load,

Where the electrical torque and the back emf could be written as:

$$e = k_e d w_m \tag{2.5}$$

$$T_e = k_t w_m \tag{2.6}$$

Where,

ke = the back emf constant

kt= the torque constant

Therefore, re-writing equations 2.2 and 2.3, the equation 2.7 and 2.8 are obtained

$$\frac{di}{dt} = -i\frac{R}{L} - \frac{k_e}{L}w_m + \frac{1}{L}V_s \tag{2.7}$$

$$\frac{dw_m}{dt} = -i\frac{k_t}{J} - \frac{k_f}{J}w_m + \frac{1}{J}T_L \tag{2.8}$$

Using Laplace transform to evaluate the two equations 2.7 and 2.8,

$$si = -i\frac{R}{L} - \frac{k_e}{L}w_m + \frac{1}{L}V_s \tag{2.9}$$

$$sw_m = -i\frac{k_t}{J} - \frac{k_f}{J}w_m + \frac{1}{J}T_L \tag{2.10}$$

At no load (for TL = 0); equation 2.10 becomes

$$sw_m = -i\frac{k_t}{J} - \frac{k_f}{J}w_m \tag{2.11}$$

$$i = \frac{sw_m + \frac{k_f}{J}w_m}{\frac{k_t}{J}} \tag{2.12}$$

From equation 2.1 and 2.12,

$$V_s = \left\{\frac{s^2JL+sk_fL+sRJ+k_fR+k_ek_t}{k_t}\right\} w_m \quad (2.13)$$

The transfer function is therefore obtained as follows using the ratio of and the angular velocity, $w_m$to source voltage, V_s.

$$G(s) = \frac{w_m}{V_s}\left\{\frac{k_t}{s^2JL+(k_fL+RJ)s+k_fR+k_ek_t}\right\} \quad (2.14)$$

Considering the following assumptions:

1. The friction constant is small, that is, k_f tends to 0, this implies that;
2. $R \gg k_f L$, and
3. $k_e k_t \gg Rk_f$And the negligible values zeroed, the transfer function is finally written as [9];

$$G(s) = \frac{w_m}{V_s}\left\{\frac{k_t}{s^2JL+RJs+k_ek_t}\right\} \quad (2.15)$$

$$G(s) = \left\{\frac{1/k_e}{s^2\tau_m\tau_e+\tau_m s+1}\right\} \quad (2.16)$$

The mechanical (time constant),

$$\tau_m = \sum\frac{RJ}{k_ek_t} = \frac{J\sum R}{k_ek_t} \quad (2.17)$$

Therefore, since there is a symmetrical arrangement and a three phase, the mechanical (known) and electrical constants become [12]:

$$\tau_m = \frac{3JR}{k_ek_t} \quad (2.18)$$

$$\tau_e = L/3R \quad (2.19)$$

Considering the phase effects

$$\tau_m = \frac{3JR_\emptyset}{K_ek_t} \quad (2.20)$$

Where,

$$K_e = k_{e(L-L)}/\sqrt{3} \quad (2.21)$$

Electrical time constant,

$$\tau_e = L/3R_\emptyset \quad (2.22)$$

Also, there is a relationship between K_e and k_t, using the electrical power (left hand side) and mechanical power (right hand side) equations; that is [12],

$$K_e = k_t \times 0.0605 \tag{2.23}$$

$$G(s) = \frac{1/K_e}{s^2\tau_m\tau_e+\tau_m s+1} \tag{2.24}$$

$$k_t = 0.42863\ Nm \tag{2.25}$$

$$\tau_e = 1.546 \times 10^{-3} \tag{2.26}$$

$$K_e=0.02593 \tag{2.27}$$

$$\tau_m = 0.06038 \tag{2.28}$$

Thus the calculated Transfer Function of BLDC motor is given by

$$\boldsymbol{G(s)} = \frac{\mathbf{38.565}}{\boldsymbol{s^2}(\mathbf{9.335}\times\mathbf{10^{-5}})+(\mathbf{0.06038})\boldsymbol{s}+\mathbf{1}} \tag{2.29}$$

3.2.3 State Space Model

State space equation method is one of the most important analysis method in modern control theory. The state-space method is becoming more and more popular in designing control systems with the fast development of computer techniques. Especially in recent years, computer online control systems such as optimal control, Kalman filters, dynamic system identification, self-adaptive filters and self- adaptive control have been applied to motor control. All these control techniques are based on the state space equation [22]. Using the current relationship :

$$v_{ab} = R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_{ab} \tag{2.30}$$

$$v_{bc} = R(i_a + 2i_b) + L\frac{d}{dt}(i_a + 2i_b) + e_{bc} \tag{2.31}$$

$$i_a + i_b + i_c = 0 \tag{2.32}$$

The voltage equations will become as follows.

Subtract Equation (2.30) from Equation (2.31)

$$\dot{i_b} = -\frac{R}{L} i_b - \frac{1}{3L}(v_{ab} - e_{ab}) + \frac{1}{3L}(v_{bc} - e_{bc})$$

$$v_{ab} = R(2i_a + i_b) + L\frac{d}{dt}(2i_a + i_b) + e_{ab} \tag{2.33}$$

$$v_{ca} = R(i_c - i_a) + L\frac{d}{dt}(i_c - i_a) + e_{ca} \tag{2.34}$$

$$v_{ab} - v_{bc} = -3Ri_b - 3L\frac{d}{dt}i_b + e_{ab} - e_{bc} \tag{2.35}$$

Subtract Equation (2.33) from Equation (2.34).

$$(v_{ab} - e_{ab}) - (v_{ca} - e_{ca}) = 3Ri_a + 3L\frac{d}{dt}i_a \tag{2.36}$$

$$\dot{i_a} = -\frac{R}{L} i_a + \frac{1}{3L}(v_{ab} - e_{ab}) - \frac{1}{3L}(v_{ca} - e_{ca}) \tag{2.37}$$

$$v_{ab} = v_{bc} \tag{2.38}$$

$$e_{ab} = e_{bc} \tag{2.39}$$

$$v_{ca} = -(v_{ab} + v_{bc}) \quad e_{ca} = -(e_{ab} + e_{bc}) = -2e_{ab}$$

(2.40)

Substituting (2.34), (2.35), (2.36), (2.37) into (2.33) will become.

$$\dot{i_a} = -\frac{R}{L} i_a + \frac{1}{3L}(v_{bc} - e_{bc}) + \frac{2}{3L}(v_{ab} - e_{ab}) \tag{2.41}$$

$$\dot{\omega_m} = \frac{-B_v}{J}\omega_m + \frac{1}{J}(T_e - T_L) \tag{2.42}$$

where $T_e = K_t i$ (2.43)

$$\begin{bmatrix} \dot{i_a} \\ \dot{i_b} \\ \dot{\omega_m} \\ \dot{\theta_m} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & 0 & 0 \\ 0 & -\frac{R}{L} & 0 & 0 \\ 0 & 0 & \frac{-B_v}{J} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ \omega_m \\ \theta_m \end{bmatrix} + \begin{bmatrix} \frac{2}{3L} & \frac{1}{3L} & 0 \\ \frac{-1}{3L} & \frac{1}{3L} & 0 \\ 0 & 0 & \frac{1}{J} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ab} - e_{ab} \\ v_{bc} - e_{bc} \\ T_e - T_L \end{bmatrix}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \\ \omega_m \\ \theta_m \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ \omega_m \\ \theta_m \end{bmatrix} \tag{2.44}$$

CHAPTER 4

SIMULATION OF BLDC MOTOR USING MATLAB / SIMULINK

4.1 Modelling of Brushless DC Motor

A model is developed to study the performance analysis of the motor during different load variation condition (free running condition, half load, rated load, full load). The motor carries of 1KW rated power with 500V dc voltage supply. The reference speed of 3000 rpm is used in the model and is compared with a feedback path and is then connected to a controller i.e. PI controller. This type of controller can be used to control the linear application motor. The brushless dc motor is fed by a MOSFET bridge inverter. A speed regulator is used to control the DC bus voltage. The inverter gate signal are produced by decoding the hall effect signal of the motor. The outputs of the bridge inverter is applied to the permanent magnet synchronous motor (PMSM). The load torque provided to the machine shaft is step input of 3Nm. The system is first set to zero and then steps to its nominal value of 3Nm at time 0.1sec. The output of PMSM in terms of back emf, rotor speed and electromagnetic torque are taken out for measurements.

The required values of proportional and integral gain are given as 0.013 and 16.6 respectively. The simulation result of brushless motor are given in the form of time response curve graph.

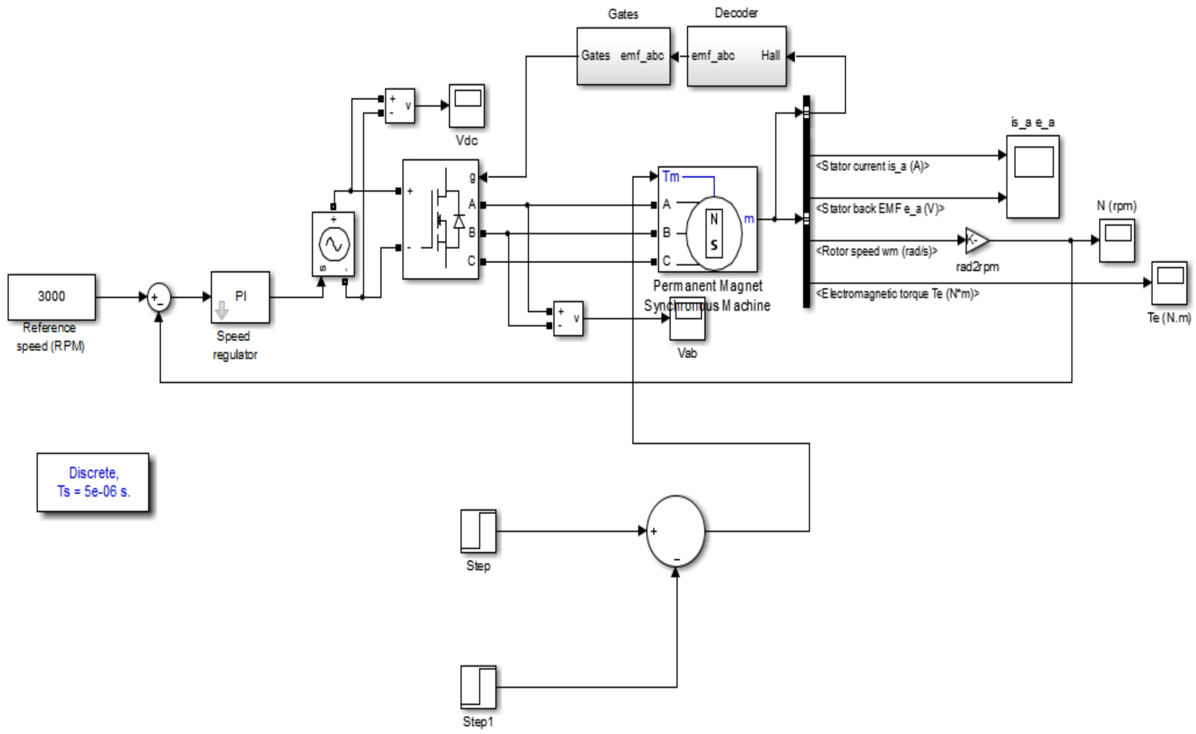

Fig.4.1. BLDC SIMULINK Model

The high-level schematic shown below is built from six main blocks. The PMSM, the three-phase inverter, and the three-phase diode rectifier models are provided with the SimPower Systems library. The speed controller, the braking chopper, and the current controller models are specific to the Electric Drives library. It is possible to use a simplified version of the drive containing an average-value model of the inverter for faster simulation. The speed controller, the braking chopper, and the current controller models are specific to the Electric Drives library. It is possible to use a simplified version of the drive containing an average-value model of the inverter for faster simulation.

4.2. PI controller design

A proportional integral-derivative is control loop feedback mechanism used in industrial control system. In industrial process a PI controller attempts to correct that error between a measured process variable and desired set point by calculating and then outputting corrective action that can adjust the process accordingly.

The PI controller calculation involves two separate modes the proportional mode, integral mode. The proportional mode determine the reaction to the current error, integral mode determines the reaction based recent error. The weighted sum of the two modes output as corrective action to the control element. The block diagram of a PI controller in fig 4.2 is shown below.

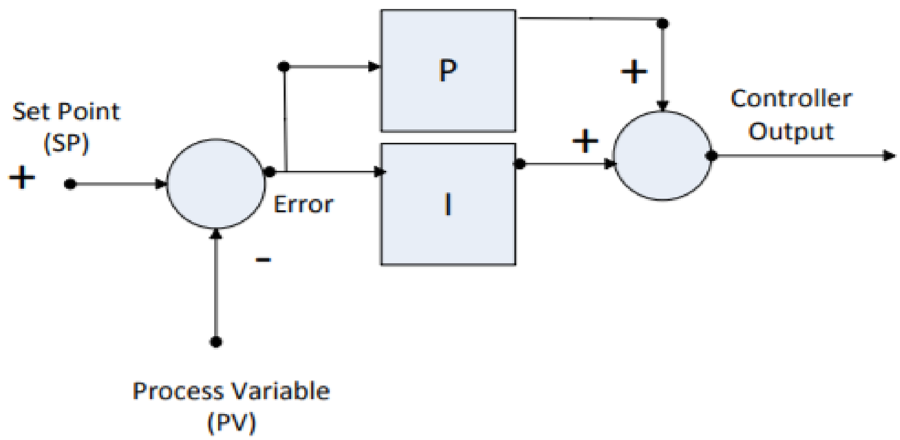

Fig.4.2. Block Diagram of a PI Controller

PI controller is widely used in industry due to its ease in design and simple structure. PI controller algorithm can be implemented as:

$$\text{output}\ (t) = K_p\ e\ (t) + K_i \int e(\tau)\ d\tau$$

Where:

e(t) = set reference value – actual calculated

K_p - Proportional gain

K_i - Integral gain

t- Time

The proportional gain, by design, also changes the net integration mode gain, but the integration gain, can be independently adjusted. It is understood that the proportional offset occurred, when a load change required a new nominal controller output, and this could not be provided except by a fixed error from the set point. In the present mode, the integral function provides the required new controller output, thereby allowing the error to be zero after a load change. The integral feature effectively provides a 'reset' of the zero error output, after the load change occurs. At time t1 a load change occurs, that produces the error. The accommodation of the new load condition requires a new controller output. The controller output is provided through a sum of proportional plus integral action that finally leaves the error at zero. The proportional part is obviously just an image of the error.

4.2.1 CHARACTERISTICS OF THE PI MODE

(i) When the error is zero, the controller output is fixed at the value that the integral term had, when the error reduced to zero. This output is given by pt(0) simply because we choose to define the time at which observation starts, as t = 0.

(ii) If the error is not zero, the proportional term contributes a correction and the integral term begins to increase or decrease the accumulated value [initial pt(0)], depending on the sign of the error and its direct or reverse direction. The integral term cannot become negative; thus it will saturate at zero, if the error and the action try to drive the area to a net negative value.

(iii) The transfer function is given by

Kp + (Ki/s)

The integral action adjustment is the integral time T1 (=KI). For a step deviation 'e', the integral time or reset time is the time for proportional action. 'Reset rate' is defined as the number of times per minute that the proportional part of the response is duplicated. Reset Rate is therefore called 'repeats per minute', and is the inverse of integral type.

During the design of the PI controller for the buck and boost converter, a closed loop operation is performed. The open loop operation is insensitive to load and line disturbances. So this operation is ineffective. Therefore, the closed loop operation is selected. The closed loop control uses a feedback signal from the process, a desired value or set point (output voltage) and a control system that compares the two and derives an error signal. The error signal is then processed and used to control the converter to try to reduce the error. The error signal processing can be very complex because of delays in the system. The error signal is usually processed using a Proportional - Integral (PI) controller whose parameters can be adjusted to optimize the performance and stability of the system. Once a system is set up and is stable, very efficient and accurate control can be achieved.

(i) Input is the voltage error (reference voltage subtracted from the actual voltage)

(ii) Output is the incremental duty ratio.

The controller specifications of a converter are:

(i) Minimum steady state error

(ii) Less settling time.

4.3 Basic control techniques of a BLDC motor

The techniques discussed below are some of the motor control options available for the reliable operation and protection of motors. Based on the functions served, motor control can be classified into following categories:

(i) Speed control

(ii) Torque control

Implementation of these control functions requires monitoring of one or more motor parameters and then taking corresponding action to achieve the required functionality. Before getting into the details of these control function implementations, it is important to understand the implementation of logic and hardware required to build up the rotation of the motor or to establish commutation.

4.3.1. Speed control

Following the commutation sequence in a given order helps in ensuring the proper rotation of the motor. Motor speed, then, depends upon the amplitude of the applied voltage. The amplitude of the applied signal is adjusted by using pulse width modulation (PWM).

It can be noted from the above diagram that the higher side transistors are driven using PWM. By controlling the duty cycle of the PWM signal, the amplitude of the applied voltage can be controlled, which in turn will control the speed of the motor.

The difference between the required speed and the actual speed is input into the PI controller, which then modulates the duty cycle of the PWM based on the error signal obtained by the difference between the actual speed and required speed.

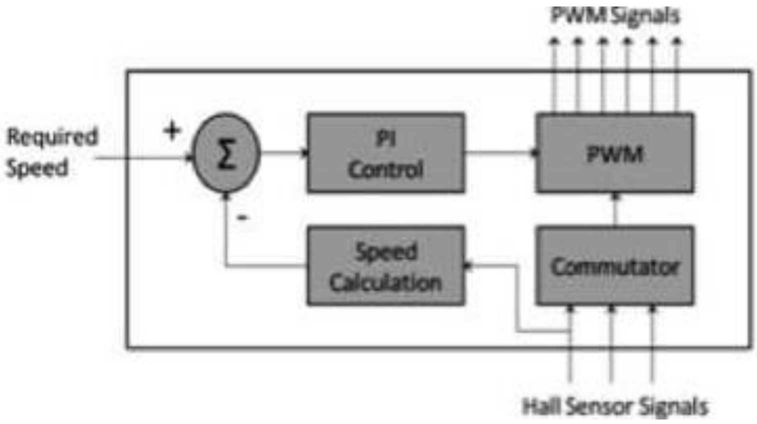

Fig.2.8: Speed Control Loop

4.3.2. Torque control

Torque control is important in various applications where at a given point of time, the motor needs to provide a specific torque regardless of the change in load and speed at which the motor is running. Torque can be controlled by adjusting the magnetic flux; however flux calculations require complex logic. However, magnetic flux is dependent upon the current flowing through the windings.

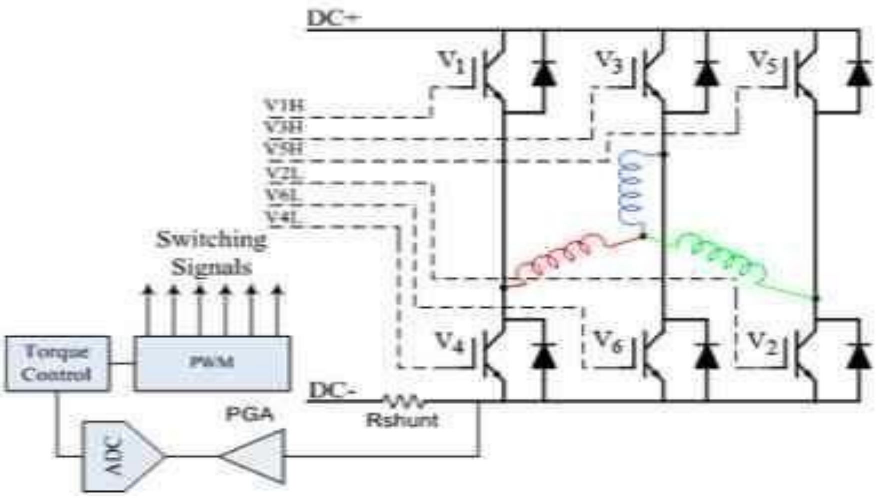

Fig.2.9: Torque Control

Thus, by controlling current, torque of a motor can be controlled. logic. By maintaining the current flowing through the windings, torque can be controlled. A PI loop similar to that used to control speed can be implemented to smooth the torque response curve with changes in load.

4.4. Modelling of speed control of BLDC motor drive system

The drive system considered here consists of PI speed controller, current control and hysteresis current controller. All these components are modelled and integrated for simulation in real time conditions.

4.4.1. Current Control

The power converter in a high-performance motor drive used in motion control essentially functions as a power amplifier, reproducing the low power level control signals generated in the field orientation controller at power levels appropriate for the driven machine.

High-performance drives utilize control strategies which develop command signals for the AC machine currents. The basic reason for the selection of current as the controlled variable is the same as for the DC machine; the stator dynamics (effects of stator resistance, stator inductance, and induced EMF) are eliminated. Thus, to the extent that the current regulatory functions as an ideal current supply, the order of the system under control is reduced and the complexity of the controller can be significantly simplified.

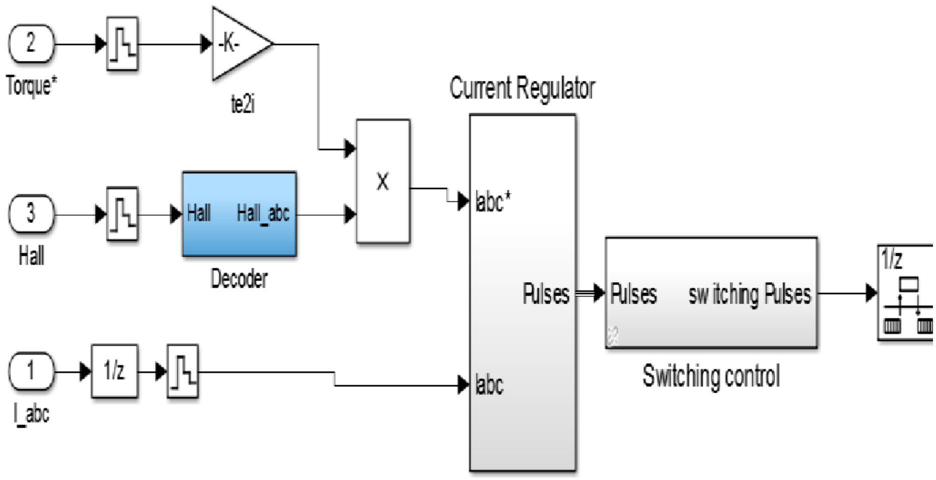

Fig.4.3. Current Controller

4.4.2. Current Regulator

In the current regulator block the individual phase currents signals are compared with each other, then this signal is given to the relay to set the saturation limits for applied signal, from this one signal two signals are generated by not gate as shown in the figure4.4 like six signals are generated given to the switching control block.

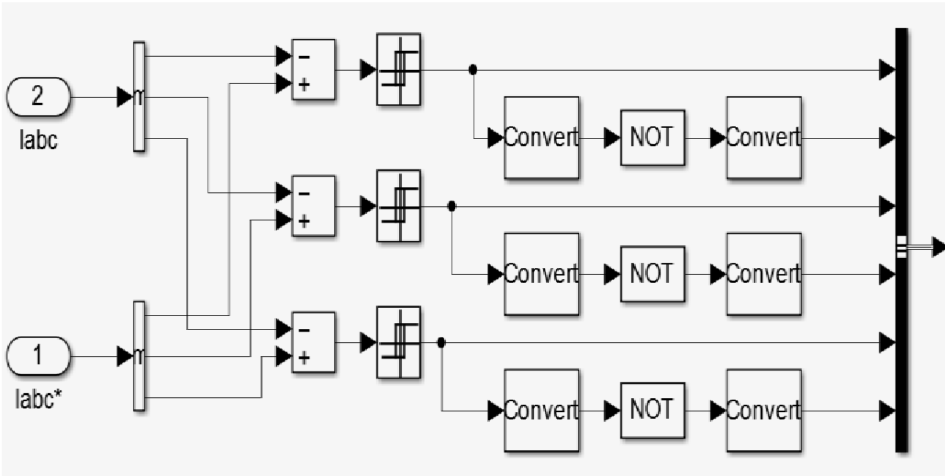

Fig.4.4. Current Regulator

4.4.3. Hysteresis current controller

Hysteresis current controller can also be implemented to control the inverter currents. The controller will generate the reference currents with the inverter within a range which is fixed by the width of the band gap. In this controller the desired current of a given phase is summed with the negative of the measured current.

The error is fed to a comparator having a hysteresis band. When the error crosses the lower limit of the hysteresis band, the upper switch of the inverter leg is turned on. But when the current attempts to become less than the upper reference band, the bottom switch is turned on. The hysteresis band with the actual current and the resulting gate signals. This controller does not have a specific switching frequency and changes continuously but it is related with the band width.

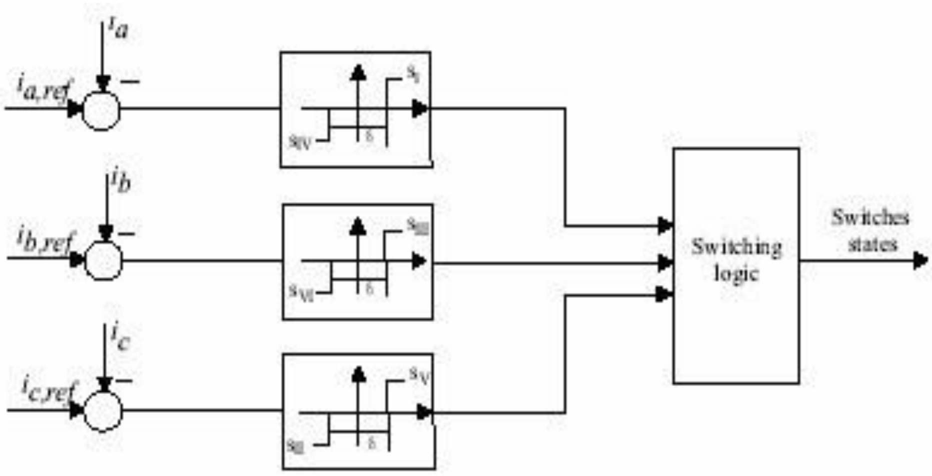

Fig.4.5. Hysteresis Current Controller

4.4.4. Speed Control of PM Motor

Many applications, such as robotics and factory automation, require precise control of speed and position. Speed Control Systems allow one to easily set and adjust the speed of a motor. The control system consists of a speed feedback system, a motor, an inverter, a controller and a speed setting device. A properly designed feedback controller makes the system insensible to disturbance and changes of the parameters.

The purpose of a motor speed controller is to take a signal representing the demanded speed, and to drive a motor at that speed. Closed Loop speed control systems have fast response, but become expensive such as robotics and factory automation, require due to the need of feedback components such as speed sensors. C(c) Implementation of the Speed Control Loop for a PM motor drive system with a full speed range the system will consist of a motor, an inverter, a controller (constant torque and flux weakening operation, generation of reference currents and PI controller) as shown in figure 4.6.

The operation of the controller must be according to the speed range. For operation up to rated speed it will operate in constant torque region and for speeds above rated speed it will operate in flux weakening region. In this region the d-axis flux and the developed torque are reduced.

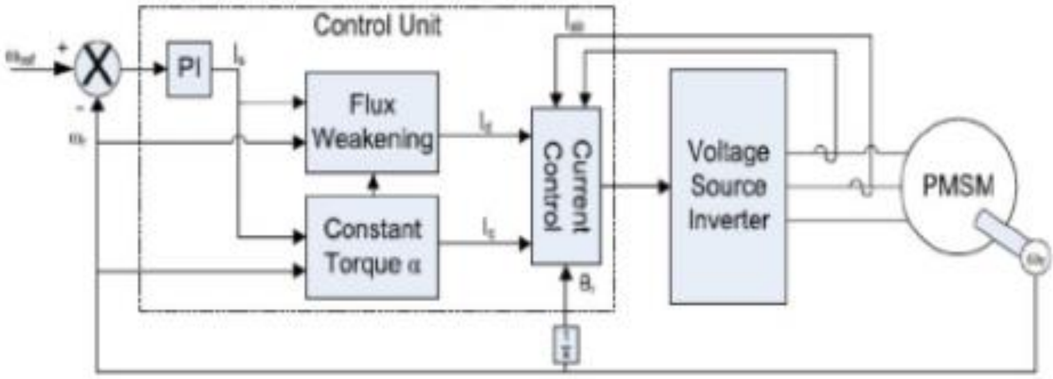

Fig.4.6. Speed Controller

4.4.5. Switching Control

Fig.4.7 gives the block for switching control. The six signals generated from the current regulator are given to the switching control block. The first two signals generated from the switching control block are given to the SR flip-flop to generate the gating signals for the first leg of the inverter Likewise other four signals are generated for other two legs; the output of this switching block is given to the gate terminals of the 3-phase inverter.

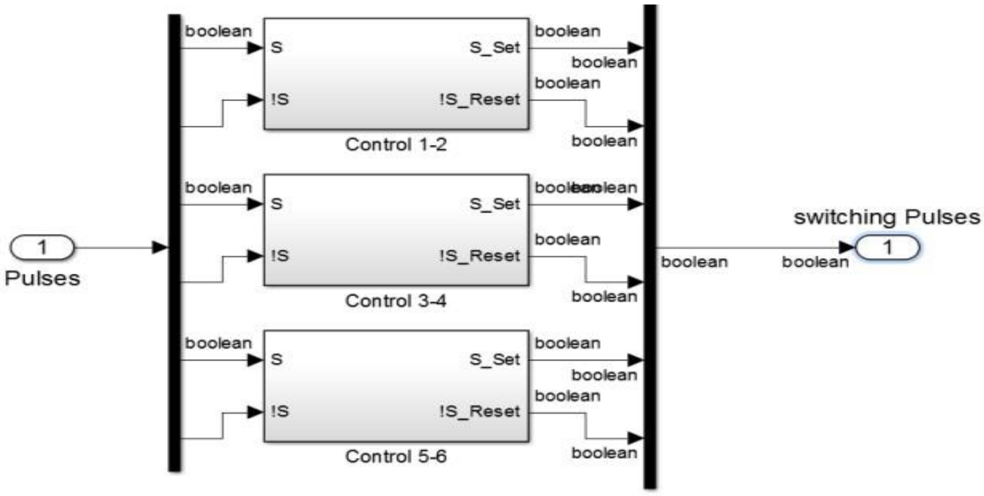

Fig.4.7. Switching Control

4.4.6. Decoding of Hall Effect sensor signal

Fig.4.8 gives the decoding of Hall Effect sensor signal. The above block diagram shows the decoding of Hall Effect signals and generation of back EMF, which is multiplied with torque reference to generate the reference current in the current controller block.

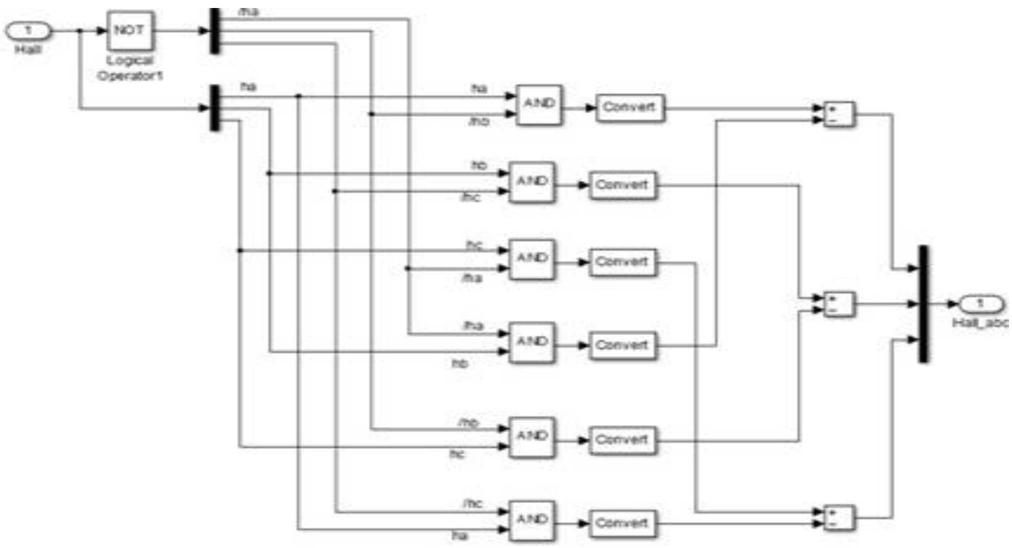

Fig.4.8. Decoding of Hall Effect sensor signal

CHAPTER 5

SIMULATION RESULT OF BLDC MOTOR USING MATLAB

5.1. Result Analysis of BLDC Motor under different loading conditions

In this the analysis of BLDC motor is done through MATLAB software which is used to analyse the speed response of motor under different load variations. A load torque of 3Nm is given to the brushless dc motor at two different step load condition with two different time interval of 0.1 sec and 0.2 sec at the input of unit step. The result analysis is carried out by basically four transient speed response characteristics which are shown in the following table.

5.1.1 At Rated Load Condition

The model has been run at a given step load of 3 Nm. During the time interval of 0 sec to 0.1sec the motor at starting is running at no load condition, the maximum overshoot percentage is 2.83%, peak time is 0.0356 sec, rise time is 0.026 sec and the settling time is given by 0.081sec. During the time of load application between the time interval of 0.1sec-0.2sec maximum overshoot percentage is -5.21%, peak time is 0.1089 sec, rise time is 0.101 sec.

At the time of load removal i.e. after 2 sec the peak time is 0.209 sec, rise time is 0.2001 sec and max. overshoot is 5.23% with settling time of 0.5 sec. After 0.2sec there is gradual increase in load and after 0.25sec become constant at 3 Nm.

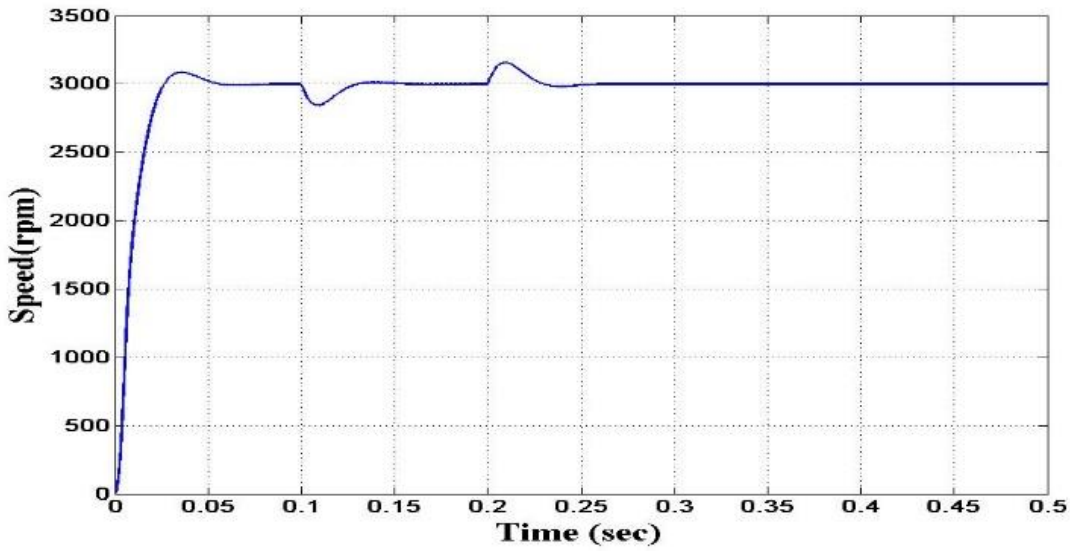

Fig.5.1. a) Speed Response Curve of BLDC motor at rated load condition

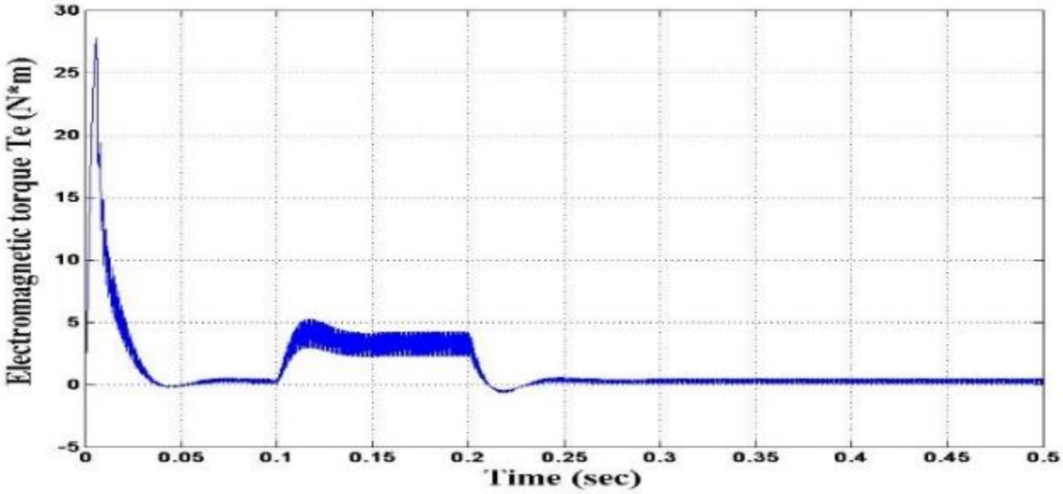

Fig.5.1 b) Torque Response Curve of BLDC motor at rated load condition

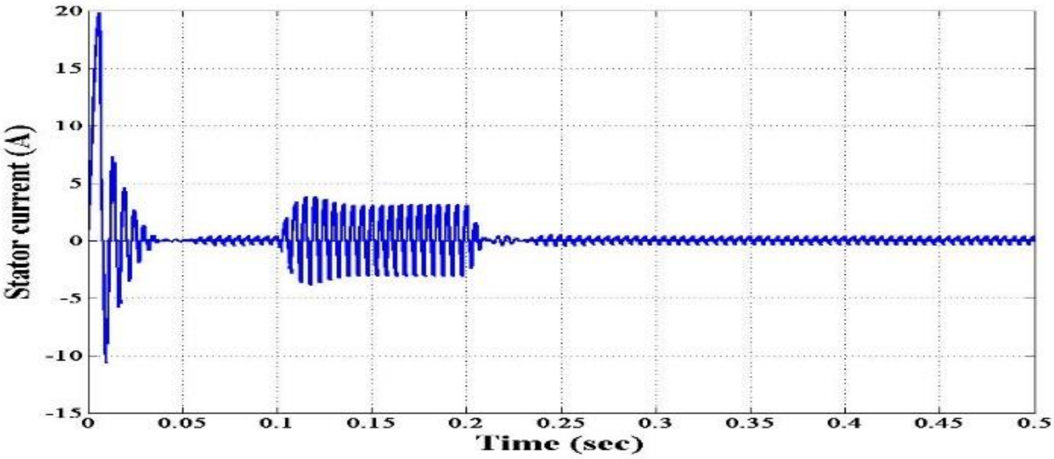

Fig.5.1. c) Current Response Curve of BLDC motor at rated load condition

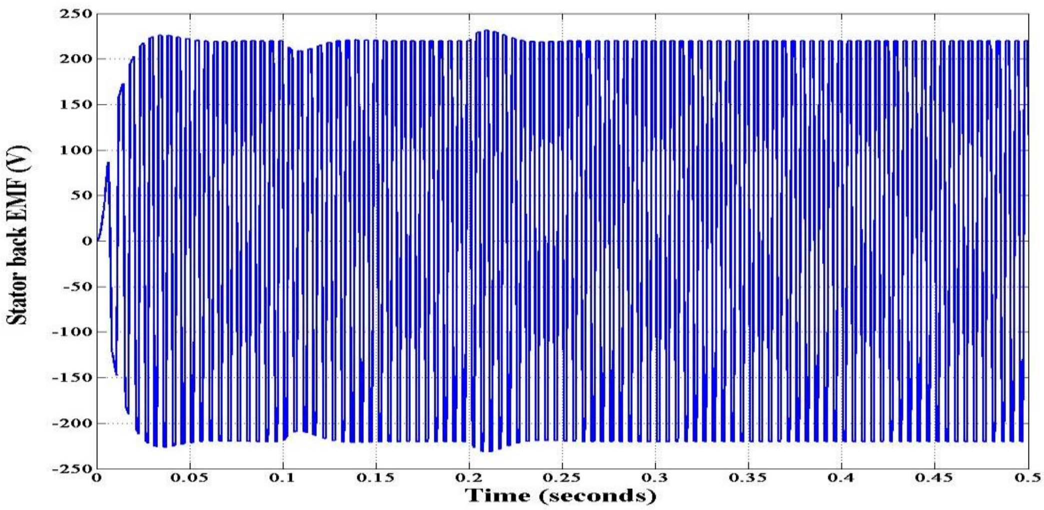

Fig.5.1. d) Emf Response Curve of BLDC motor at rated load condition

5.1.2. At Overload Condition

The result at overload condition is analysed with three different increase in load condition at different increase in percentage. The motor has been provided with 150% increase in load variation and result is carried out in form of table.

With the increase of 150% of the load, the load torque of 4.5Nm is applied and at the time of no-load condition the peak time is 0.035sec, rise time is 0.0266sec and maximum overshoot is 2.83% with settling time of 0.086sec.

At the time of load application during time interval of 0.1-0.2sec maximum overshoot is -7.7%, peak time is 0.108sec with the rise time of 0.10 sec. At 0.2sec when the load is removed the overshoot become 10.46% with peak time 0.2157sec, rise time of 0.2sec and settling time is 0.396sec.

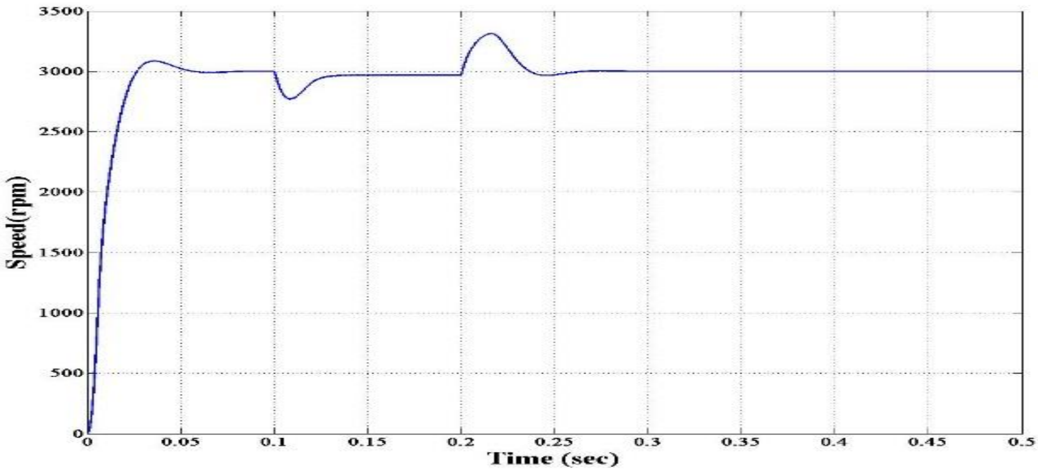

Fig.5.2. a) Speed Response Curve of BLDC motor at overload condition

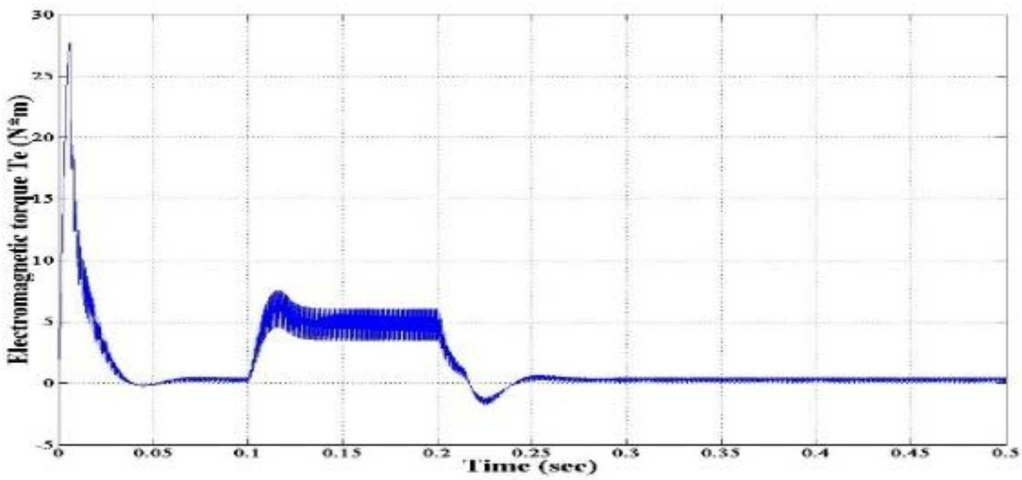

Fig.5.2. b) Torque Response Curve of BLDC motor at overload condition

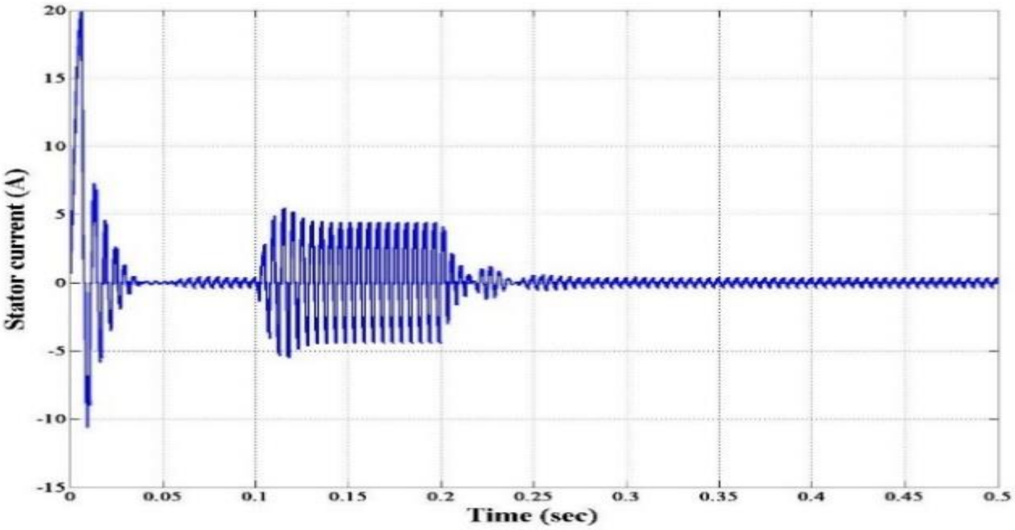

Fig.5.2. c) Current Response Curve of BLDC motor at overload condition

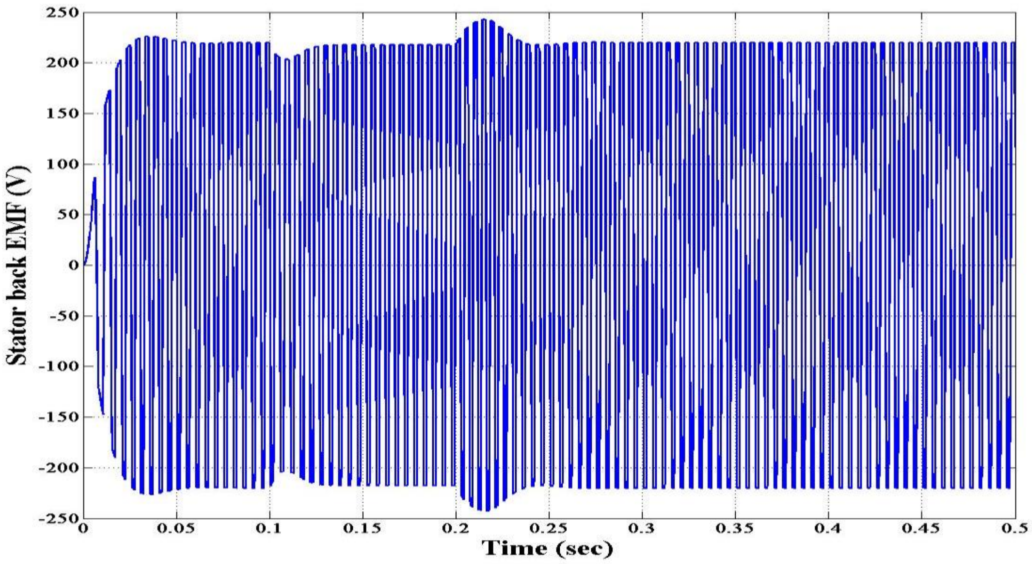

Fig.5.2 d) Emf Response Curve of BLDC motor at overload condition

5.1.3 At Underload Condition

The result has been carried out with the decrease in load variation at different decrease in percentage of 50% and presented in the form of table.

At 50% decrease of the underload condition the load torque of 1.5Nm is applied. In this the starting condition at no load between 0-0.1sec is same as the overload condition when the motor is applied at no-load.

During the time interval of 0.1-0.2sec when the load is applied the overshoot percentage is -3.94%, rise time is 0.102sec and peak time is 0.1088sec with settling time of 0.155sec.
At 0.2sec the overshoot is 3.94% with peak time of 0.2093sec, rise time is 0.201sec and settling time of 0.276sec.

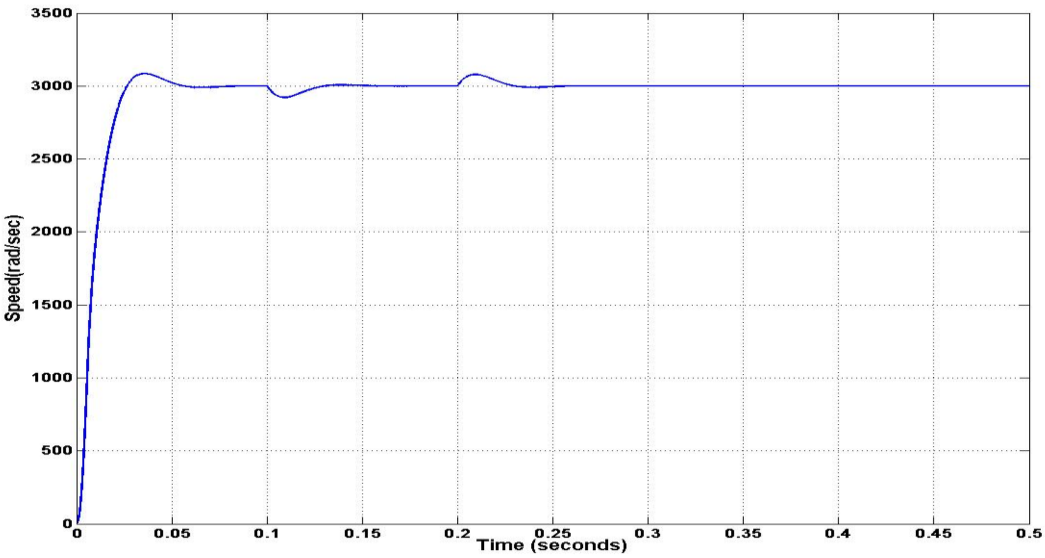

Fig.5.3. a) Speed Response Curve of BLDC motor at underload condition

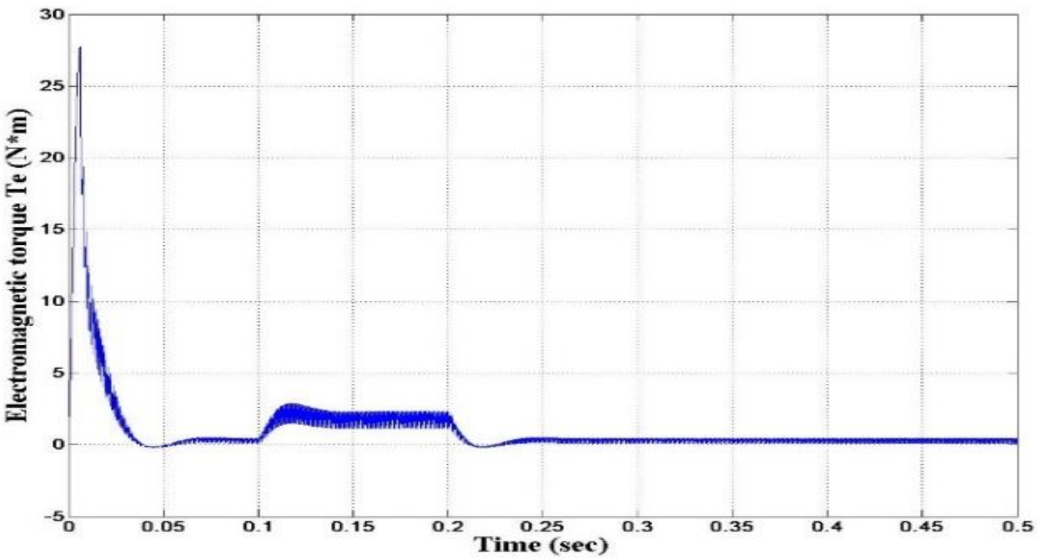

Fig.5.3 b) Torque Response Curve of BLDC motor at underload condition

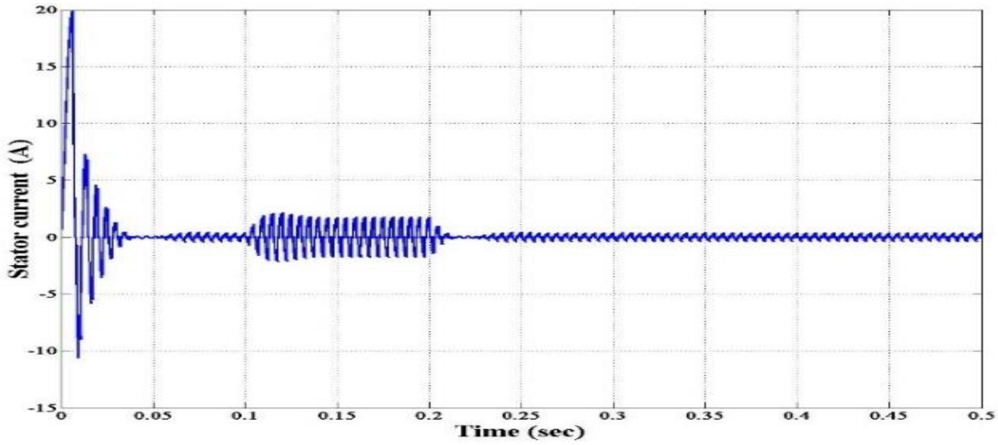

Fig.5.3. c) Current Response Curve of BLDC motor at underload condition

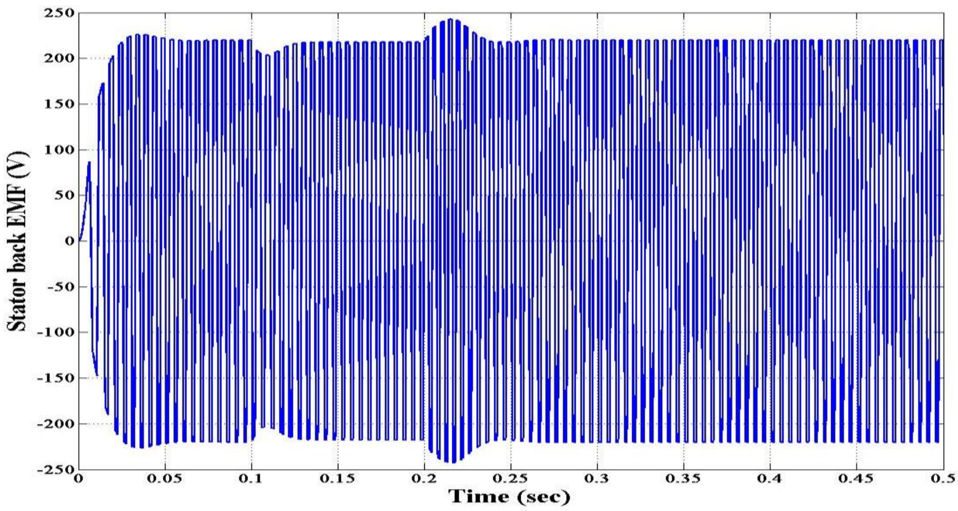

Fig.5.3 d) Emf Response Curve of BLDC motor at underload condition

Table 2.4: Time Response Characteristics at Different Load Conditions

SR.No	Load Applied	Characteristics	Time Interval (sec)	Rise Time (sec)	Peak Time (sec)	Settling Time (sec)	Max. Overshoot (%)
1.	Full-Load (At 3 Nm)	No Load	0-0.1sec	0.0266	0.035	0.081	2.83
		Load Application	0.1-0.2sec	0.101	0.1089	0.162	-5.21
		Load Removal	After 0.2sec	0.2001	0.209	0.485	5.21
2.	Half-Load (At 1.5 Nm)	No Load	0-0.1sec	0.0266	0.035	0.067	2.83
		Load Application	0.1-0.2sec	0.102	0.1088	0.155	-3.94
		Load Removal	After 0.2sec	0.201	0.2093	0.276	3.94
3.	Over-Load (At 4.5 Nm)	No Load	0-0.1sec	0.0266	0.035	0.086	2.83
		Load Application	0.1-0.2sec	0.10	0.108	0.16	-7.7
		Load Removal	After 0.2sec	0.2	0.2157	0.396	10.46

5.2 Result Analysis of Speed-Torque Characteristics

The speed-torque characteristics of BLDC motor under loading includes half full-load, full-load, and overloading are shown in Fig.1,2 and3. It is also cleared that the machine has induced self-torque in the negative region after load removal which provides braking condition for BLDC motor.

In case of loading conditions, the non-linearity behaviour of speed-torque characteristics of BLDC motor is maintained but machine shows erratic behaviour at the time of load removal.

As the overloading exist, the speed-torque plot of BLDC reaches in the negative region with drastically change in the characteristics as shown in Fig.1-3. In the overloading conditions large oscillations has observed and BLDC motor shows jerky operation.

This opens up a new scope for exploring the reasons for the jerky operation of the machine while removing the load; and to suggest mitigation technique for the same.

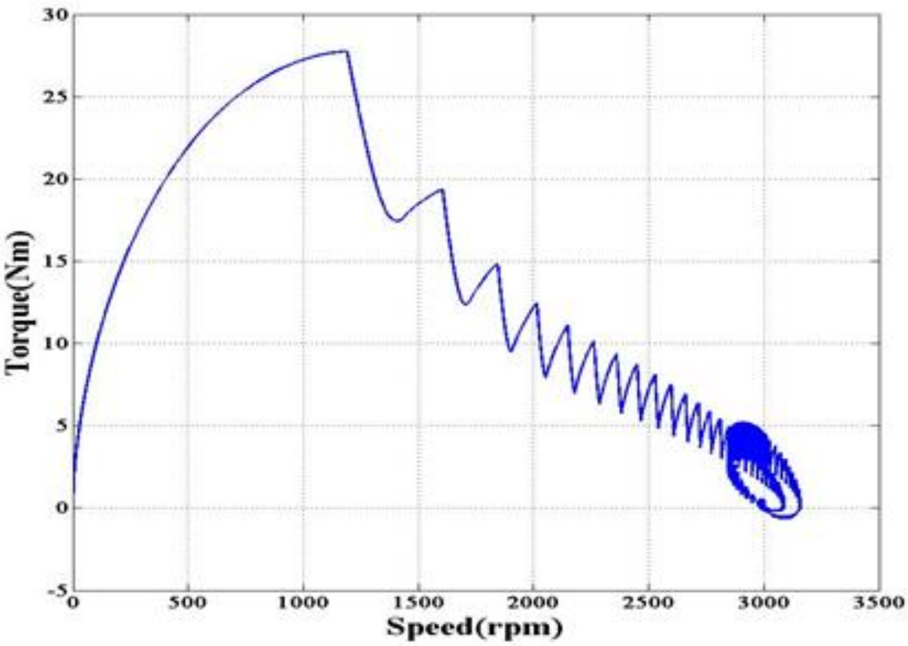

Fig.5.4. Speed-Torque Characteristics Under Full Load Condition

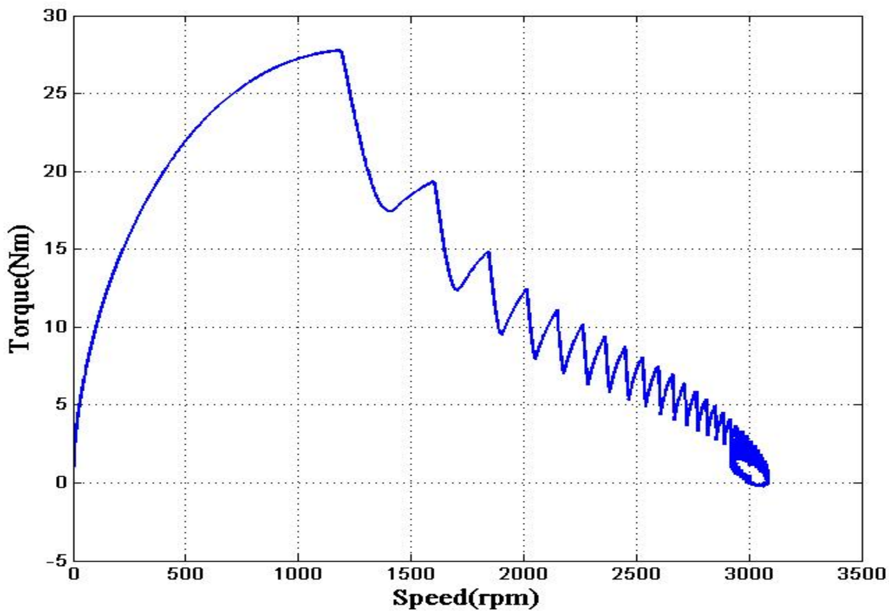

Fig.5.5. Speed-Torque Characteristics Under Half Load Condition

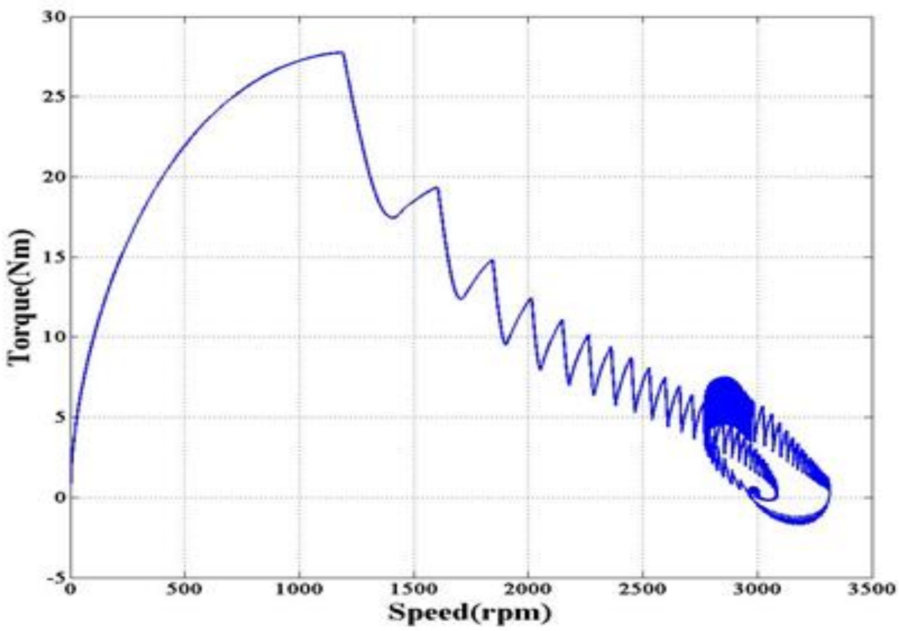

Fig.5.6. Speed-Torque Characteristics Under Over Load Condition

Further, a significant observation is made through the speed-torque characteristics of BLDC motor under the three types of load conditions. It is seen in Fig. 5.4, Fig. 5.5 and Fig. 5.6 that the performance of the motor is better when the load is applied at half load condition than the full load and overload condition.

CONCLUSION

In this thesis, the performance analysis and study of BLDC motor has been carried out. From the analysis a mathematic model of the brushless dc motor has been presented. To achieve a desired level of performance in various applications that require the motor to operate at constant speed over various loads, the motor has been operated using PI controller.

First, in order to achieve better time response on BLDC motor, a PI controller has been designed and performance analysis is done in this work. The PI controller improves the performance of BLDC motor drive. The simulation results depict that BLDC motor show better performance in the case of underloading condition as compared to rated loading condition or overloading condition in terms of rise time, delay time, settling time, peak time and overshoot.

Further, a significant observation is made through the speed-torque characteristics of BLDC motor under the three types of load conditions. It is seen that the performance of the motor is better when the load is applied at half load condition than the full load and overload condition.

FUTURE RESEARCH

To extend the research work presented in this thesis, future work may consider the following possibilities:

(i) Various other controller apart from the proportional-integral controller mentioned in this thesis report can be researched and applied to BLDCs.

(ii) Various other techniques can be tested for speed vs. torque characteristics of BLDCs and can be compared to the speed vs. torque characteristics of a separately excited DC motor.

(iii) Stall torque of various techniques can be measured and compared.

(iv) A feedback control loop can be applied and speed vs. torque characteristics can be tested.

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APPENDIX

Appendix – A

TABLE A -1

Specification of BLDC Motor

S. N.	Parameter	Specification
1.	No. of poles	4
2.	Rated Speed	3000 rpm
3.	Rated Voltage	500 V
4.	Rated Current	4.52 A
5.	Phase	3

Appendix – B

TABLE A -2

S.I. Unit of Electrical Parameter

S.N.	Electrical Parameter	Unit	Abbreviation
1	Reference Voltage	Voltage	V
2	Rated Current	Ampere	A
3	Peak Current (stall)	Ampere	A
4	No Load Current	Ampere	A
5	Back EMF Constant	Volt/rpm	V/rad/s
6	Resistance	Ohms	Ὠ
7	Inductance	Henry	mH
8	Motor Constant	Newton meter	N-m

Appendix - C

TABLE A -3

S.I. Unit of Mechanical Parameter

S.N.	**Mechanical Parameter**	**Unit**	**Abbreviation**
1	Speed	Revolution per minute	rpm
2	Continuous Torque	Newton meter	N-m
3	Peak Torque	Newton meter	N-m
4	Torque Constant	Newton meter/Ampere	N-m/A
5	Friction Torque	Newton meter	N-m-s^2
6	Rotor Inertia	Newton meter second square	N-m-s^2
7	Viscous Damping	Newton meter	N-m-s
8	Temperature	Farad	°F or °C
9	Damping Constant	Newton meter second	N-m-s
10	Thermal Impedance	Farad/Watt	°F/W or °C/W

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I hereby declare that the information furnished above is true to the best of my knowledge and belief.

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