CHAPTER 1

INTRODUCTION

1.1 GENERAL

In the present scenario, Brushless Direct Current (BLDC) motors have started replacing conventional Direct Current (DC) motors. Conventional DC motors are highly efficient and their characteristics make them suitable for use as servo motors. However, their main drawbacks are commutator and brushes, which require periodical maintenance.

BLDC motors are, in fact, a type of permanent magnet synchronous motors. They are driven by DC voltage but current commutation is carried out by solid state switches. The commutation instants are determined by the rotor position. The position of the rotor is detected either by position sensors or sensorless techniques. BLDC motors have speed and torque controls which are superior to the traditional brush-type DC motor, along with a very high level of efficiency.

BLDC motors are available in many different power ratings, from very small motors used in Hard Disk Drives (HDD), to larger motors used in electric vehicles. They are used in industrial applications, because of their outstanding performance, long life, and very efficient service.

In this research work, it is proposed to design and implement a digital signal controller for the operation of BLDC motor in all the four quadrants. Emphasis has been given to the regenerative braking mode and
smooth transition between the quadrants of operation. A simple and elegant approach to save energy during the regenerative braking period has been proposed. It is also aimed to study the effect of speed control of the BLDC motor with and without loads.

1.2 ELECTRIC DRIVE

The heart of most industrial processes is electrical drives. These drives are a major contribution in creating high quality products. Electrical drives comprise different types of electrical motors that are utilised in industries. More than 60% of the generated electrical energy is used in electric drives. The application of electrical drives has spread from low fractional horse power applications in instruments to industrial applications. Wide power, torque and speed ranges, adaptability to almost every operating condition, high efficiency, fast response, control simplicity, ability to operate as a generator in braking mode and various mechanical design types make the electrical drive a competitive contender among the other drive types.

An electric drive is a system that performs the conversion of electric energy into mechanical energy at adjustable speeds. The three main components of electric drive are electric motor, power electronic converter and drive controller. The block diagram of an electric drive is shown in Figure 1.1.

![Figure 1.1 Electric Drive System](image-url)
Nowadays, drives make use of power electronic converters to digitally control the electro-mechanical energy conversion process. The digital control unit directly controls the power electronic semiconductor switches of the power electronic converter. To obtain this conversion, suitable control hardware, sensors, high-speed digital logic devices, processors and appropriate control algorithms are required. The power range of modern electric drives ranges from few mW to hundreds of MW.

Variable speed drives in the industry employ electric motors as their drive motors mainly because of their several specific advantages, namely, smooth speed control over a wide range and due to the capability of operating in all the four quadrants of the speed torque plane with overload capacity.

The powerful features of BLDC motors, like absolute speed control regardless of load, incredibly high efficiency, very low maintenance and absolute tracking which enables two motors to work in synchronisation, have resulted in the selection of BLDC motor for this research work.

1.2.1  BLDC Motor

BLDC motor has two main components, namely rotor which is made up of permanent magnets, and stator windings, which are connected to the control electronics. In BLDC motor, there are no brushes and no commutator. The mechanical commutation is replaced by electronic commutation. The cross sectional view of BLDC motor is shown in Figure 1.2.
Figure 1.2 Cross sectional view of BLDC Motor with Hall Sensor

In a typical BLDC motor, the electromagnetic field is created by permanent magnets in the rotor. The rotating magnetic field is generated with a number of electromagnets commutated with electronic switches in the right order at the right speed. The instant when to switch electrical energy in the windings to perpetuate the rotating motion should be known. This is accomplished in BLDC motor by means of feedback arrangements designed to provide an indication of the position of the magnetic poles on the rotor relative to the windings. A Hall Effect sensor is a commonly used means for providing the positional feedback.

1.2.2 Hall Effect Sensor

A Hall Effect sensor also known as Hall sensor is a transducer that varies its output voltage in response to the changes in magnetic field (Figure 1.3). They are used for proximity switching, positioning, speed detection and current sensing applications.
Electric current carried through a conductor will produce a magnetic field that varies with current and a Hall sensor is used to measure the current without interrupting the circuit. Typically the sensor is integrated with a wound core or permanent magnet that surrounds the conductor to be measured. When the N pole passes over a sensor, its output is high or state 1. When the S pole passes over the sensor, its output is low or state 0. Hall sensors thus provide information about polarity and position.

The input from the Hall sensors determine the sequence in which the three-phase bridge is switched. The change in the duty cycle controls the current through the motor winding, thereby controlling motor torque.

1.2.3 Mathematical Model

The three-phase star connected BLDC motor can be described by Equations (1.1) to (1.4). Three-phase voltages are represented by Equations (1.1) to (1.3) and the Equation (1.4) is the motor’s torque equation.
The three-phase back Electro Motive Force (EMF) and the electrical torque are expressed respectively as,

\[ v_{ab} = R (i_a - i_b) + L \frac{d}{dt} (i_a - i_b) + e_a - e_b \quad (1.1) \]

\[ v_{bc} = R (i_b - i_c) + L \frac{d}{dt} (i_b - i_c) + e_b - e_c \quad (1.2) \]

\[ v_{ca} = R (i_c - i_a) + L \frac{d}{dt} (i_c - i_a) + e_c - e_a \quad (1.3) \]

\[ T_m = k_f \omega_m + J \frac{d\omega_m}{dt} + T_L \quad (1.4) \]

The function \( F(.) \) gives the trapezoidal waveform of the back EMF.

\[ e_a = \frac{k_e}{2} \omega_m F(\theta_e) e_b = \frac{k_e}{2} \omega_m F(\theta_e - \frac{2\pi}{3}) \quad (1.5) \]

\[ e_b = \frac{k_e}{2} \omega_m F(\theta_e - \frac{2\pi}{3}) \quad (1.6) \]

\[ e_c = \frac{k_e}{2} \omega_m F(\theta_e - \frac{4\pi}{3}) \quad (1.7) \]

\[ T_e = \frac{k_e}{2} \left[ F(\theta_e) i_a + F(\theta_e - \frac{2\pi}{3}) i_b + F(\theta_e - \frac{4\pi}{3}) i_c \right] \quad (1.8) \]

where \( k_e \) and \( k_t \) are the back EMF constant and the torque constant. The electrical angle is equal to the rotor angle (mechanical angle \( \theta_m \)) times the number of pole pairs.

\[ \theta_e = \frac{p}{2} \theta_m \quad (1.9) \]

The function \( F(.) \) gives the trapezoidal waveform of the back EMF.
1.2.4 Commutation Techniques

Commutation is the process where voltage is applied to the motor phases in such a way that it keeps the motor rotating (magnetic flux vector rotating). In BLDC motors, the electronic commutator is fed by the Hall sensors mounted on the motor. These sensors, to obtain the maximum torque from the motor, make the appropriate transistors to turn ON. This establishes a communication between the motor and its control. The position of the motor shaft is constantly monitored by the Hall sensors and signals are fed back to the digital controller.

1.2.5 Four Quadrant Operation

When an electric machine is required to operate (i) both as a motor and a generator and (ii) in both forward and reverse directions, it is said to be operating in the four quadrant modes of operation. A motor designed for automotive use which must run in both forward and reverse directions and which must provide regenerative braking in both directions needs a four quadrant controller.

There are four possible modes or quadrants of operation using a BLDC Motor which is depicted in Figure 1.4. In an X-Y plot of speed versus torque, Quadrant I is forward speed and forward torque. The torque is propelling the motor in the forward direction. Conversely, Quadrant III is reverse speed and reverse torque. Now the motor is “motoring” in the reverse direction, spinning backwards with the reverse torque.
Figure 1.4 Four quadrants of operation

Quadrant II is where the motor is spinning in the forward direction, but torque is being applied in reverse. Torque is being used to “brake” the motor, and the motor is now generating power as a result. Finally, Quadrant IV is exactly the opposite. The motor is spinning in the reverse direction, but the torque is being applied in the forward direction. Again, torque is being applied to attempt to slow the motor and change its direction to forward again. Once again, power is being generated by the motor.

The BLDC motor is initially made to rotate in clockwise direction, but when the speed reversal command is obtained, the control goes into the clockwise regeneration mode, which brings the rotor to the standstill position. Instead of waiting for the absolute standstill position, continuous energization of the main phase is attempted. This rapidly slows down the rotor to a standstill position. Therefore, there is the necessity for determining the instant
when the rotor of the machine is ideally positioned for reversal. Hall sensors are used to ascertain the rotor position.

1.2.6 Regenerative Braking

Braking of a vehicle, a locomotive or a mass in motion that recovers the kinetic energy and converts it to electric energy is termed as regenerative braking. It is an energy recovery mechanism which slows down a vehicle or object by converting its kinetic energy into another form, which can be either used immediately or stored until needed. This contrasts with conventional braking systems, where the excess kinetic energy is converted to heat by friction in the brake linings and therefore wasted. This braking proves to be more beneficial for driving schedules with frequent starts and stops.

1.2.7 Digital Controller

Digital control plays a vital role in the closed loop control of an electric drive. The feedback signals obtained from the Hall sensors of the BLDC motor are digital pulses. The digital pulses have to be fed back into a digital controller, which in turn will generate Pulse Width Modulation (PWM) pulses for the appropriate switching of the inverter circuit. Hence a digital controller is required to control the BLDC motor, in all the four quadrants. The Digital Signal Controller (DSC) (Microchip 2008) combines the Digital Signal Processor (DSP) features and PIC microcontroller features, making it versatile.

1.3 OBJECTIVES OF THE RESEARCH WORK

The objectives of this research work are to

1. Develop and simulate a BLDC machine
2. Formulate a procedure to operate a BLDC machine in all the four quadrants

3. Implement digital controller for a four-quadrant operation of a BLDC machine based on the simulation results.

It is proposed to consider the speed control with and without load. It is also proposed to conserve energy, during the regenerative braking period that will be stored in a chargeable battery.

1.4 ORGANIZATION OF THESIS

The thesis is organised as follows:

Chapter 1 which is an introduction to the thesis; the role of electrical drives in the industries, the features of BLDC motor with built-in Hall sensors, its mathematical model and the commutation process are described. A discussion about the operation of a motor in all the four quadrants, with a pictorial representation is also presented. A brief introduction about the digital controller which is employed to control the BLDC motor is also specified. A description about the objectives of the proposed work and the structure of the thesis in the forthcoming chapters are explained.

Chapter 2 presents the literature review, which is the basis for the proposed work. The significance of electric drive is surveyed initially. There are plenty of motors available in the market, and selection of BLDC motor among them for the research is justified with the help of the review presented in this chapter. The control of the BLDC motor can be achieved with sensored approach or even without using sensors. Hence, papers relating to both the techniques has been explored. The operation of motor in all of its four quadrants, the conventional braking methods, different PWM techniques, the
selection of switches used in the inverter circuit are also examined. The study on the various digital controllers namely microprocessors, microcontrollers, DSPs and DSCs are expounded.

The development of Simulink model for a closed loop control for the four quadrant operation in BLDC motor is discussed in Chapter 3. The feedback obtained from the simulated Hall sensor signals of BLDC motor is examined. The design of switching sequence of the Metal Oxide Semiconductor Field Effect Transistors (MOSFET) implemented in the inverter, the modelling of the digital controller and the simulated control of the motor in all the four quadrants are analysed in this chapter. Energization of the battery during the regenerative braking mode is also included. The discussions of the simulation results are also presented.

The design modules and implementation of the digital controller in the dsPIC30F4011 for the four quadrant operation of BLDC motor are dealt in Chapter 4. The complete proposed drive system hardware is presented. The implementation of the transition from one quadrant operation to another has been described. The operation of BLDC motor in the regenerative mode is explained briefly. The operation of the relay circuit employed and the battery charging mechanism for no load conditions are explained in detail. Comparative performance analysis of the motor and the charging characteristics of the battery with and without load conditions has also been discussed. The digital storage oscilloscope output of speed control of BLDC motor for no-load and with load conditions of operation has been analysed. Also, the graphs pertaining to the energy conservation in the battery, both during on load and no load conditions has been included.

To conclude, the objectives of the proposed research work and the corresponding results of simulation and hardware implementation are presented in Chapter 5. The scope for further work is suggested.
1.5 CONCLUSION

An introduction of the proposed work, the objectives of the proposed research work and the chapter-wise organization of the thesis were presented in this chapter. The state of art will be reviewed in the next chapter.