COMMUTATION STRATEGIES OF BLDC MOTOR

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I, **Ranjani Kamma**, Roll No. 2K20/PES/11 student of M.Tech (Power Electronics & Systems), hereby declare that the project Dissertation titled **"Commutation strategies of BLDC motor"** which is submitted by me to the Department of Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously submitted for the award of any Degree, Diploma.

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It is certified that the Project Dissertation titled **"Commutation strategies of BLDC motor"** which is submitted by Ms. Ranjani Kamma, Roll No 2K20/PES/11 Electrical Engineering Department, Delhi Technological University in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge, this has not been submitted in part or fulfilment for any degree or diploma to this university or elsewhere.

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ABSTRACT

Improved efficiency and dependability have been resulted from the development of sophisticated motor drives. Conventional drives utilizes AC motors, such as induction motor and DC series motors, which needs frequent maintenance and difficult to control. A Brushless DC (BLDC) motor drives, on the other hand, are more efficient, require less maintenance, and are more expensive. Brush-less DC motors (BLDC) will be used to replace these inefficient motors, resulting in significant energy savings. As a result, a low-cost but effective BLDC motor controller is required.

Brushless DC (BLDC) motor is used with hall sensors for many applications like in electric vehicles and robotics. Certain working environments of the motor can affect the functionality of hall sensors and can even cause complete failure. If the hall sensors functionality is affected, it would affect the whole working of system and can make system unstable depending upon the fault that incurred in hall sensors due to their effect on switching pattern timing. So, here hall signals have been deduced, making the operation sensor-less. This paper presents a sensor-less method of BLDC motor operation using 120^o trapezoidal commutation method. Further, a Matlab Simulink model is developed where, the hall equivalent signals are deduced from phase voltages in the proposed method. Finally, simulation analysis is carried out for the proposed method by starting the motor using original hall sensor values and then suddenly shifting to the proposed deduced hall signal method. This work explores the possible application of this method in case of any hall sensor failure also.

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LIST OF ABBREVIATIONS

S No	Abbreviated Name	Full Name
1	DC	Direct current
2	AC	Alternating current
3	BLDC	Brushless direct current motor
4	PMSM	Permanent magnet synchronous motor
5	EMF	Electromotive force
6	PWM	Pulse width modulation
7	PM	Permanent magnet
8	SRM	Switched reluctance motor
9	IPM	Interior permanent magnet
10	SPM	Surface permanent magnet
11	ECPM	Electronically Commutated Permanent Magnet motors
12	GND	Ground
13	IC	Integrated circuits
14	MCU	Micro-controller unit
15	EV	Electric vehicle
16	ADC	Analog to digital converter
17	DSP	Digital signal processing
18	IGBT	Insulated gate bipolar transistor
19	MOSFET	Metal oxide semiconductor field effect transistor

LIST OF SYMBOLS

S. NO.	SYMBOLS	DESCRIPTION
1	φ_m	Flux linkage
2	M_s	Mutual inductance of stator in henry
3	K_E	Back emf constant
4	L_{Mn}	mutual-inductance in henry
5	L_{Sn}	self-inductance of armature of stator in henry
6	R_{an} , R_{bn} , R_{cn}	Phase resistances of armature in ohm
7	v_{an}, v_{bn} and v_{cn}	Phase voltages of motor in volts
8	i_{an}, i_{bn} , i_{cn}	Phase currents of motor in amperes
9	e_{an} , e_{bn} , e_{cn}	Back EMFs of motor in volts
10	τ_E	Electromagnetic torque in N-m.
11	ω	Angular speed of motor in radians per second.
12	τ_{L}	Load torque in N-m.
13	J	Rotor’s inertia in [kgm^2],
14	B	Damping constant
15	V_{ab}, V_{bc}, V_{ca}	line voltages from inverter
16	ω_m	Rotor speed in radians per second
17	K_t	Torque constant in N-m/A
18	$f(\theta_e)$	Function for trapezoidal back emf
19	p	Number of pole pairs
20	Δt	Hall transition time

CHAPTER 1

INTRODUCTION

1.1 Introduction

Motors are becoming increasingly important as residential appliances become more energy efficient and vehicle electrification increases. Traditional motor drive technologies are used in residential such as refrigerators and air conditioning systems and commercial applications. These drives are also suitable electric vehicles. Brushed DC machines or single-phase induction motors are used for above mentioned applications, and both have low efficiency and require a lot of maintenance [1]. Brushed DC motors, for example, are extensively used in automotive applications, toy railroads, and other similar applications. The phenomenal expansion of cost-effective and dependable inverter and converter systems has been accelerated by power electronics devices and their efficient topologies. The art of digital control of BLDC motor drives has been progressed due to software-controlled online deployment of sophisticated robust controllers [2][3]. The DC motor fulfill these needs, but it requires maintenance regularly.

1.2 Brushed DC Motor and BLDC Motor

In brushed DC motor, the permanent magnets acts as stator, the stationary part. The rotating part is armature, which contains an electromagnet. This motor works on electromagnetic induction principle, which states that a conductor carrying current, generates an electro-magnetic field. When such conductor is placed in between the poles of strong magnet, it will experience a force. In brushed DC motor, operation is based on concept of electromagnetism.

Magnetic interaction between a current-carrying conductor and an external magnetic field leads to generate rotational motion. The following are the advantages of a brushed DC motor:

Starting torque is high: Brushed motor's characteristic of having high starting torque is ideal for applications that require rapid acceleration i.e., for the applications which need to quick pick up of speed. A strong starting torque is required in some applications such as caravan movers, for example.

- Cost is low.
- Suitable for industrial environment

The main drawback of this motor is that they require high maintenance because of the presence of brushes and commutators.

AC machines without brushes, like Induction motors and brushless DC motors, have durable rotors since no commutator or rings are present, which means very little maintenance. This improves the power-to-weight ratio as well as efficiency. Flux control for induction motors is designed, which provides great dynamic performance for traction applications, but it is a difficult and sophisticated control type. The discovery of BLDC allowed for significant hardware simplification in electric traction control.

Because of the similar operating principle, brushed and BLDC motors have nearly identical voltage-to-rpm relationships and current-to-torque and hence can be used in electric vehicles as well by choosing size appropriately with proper specifications [4]. The speed-toque characteristics of BLDC motor is given as shown below:

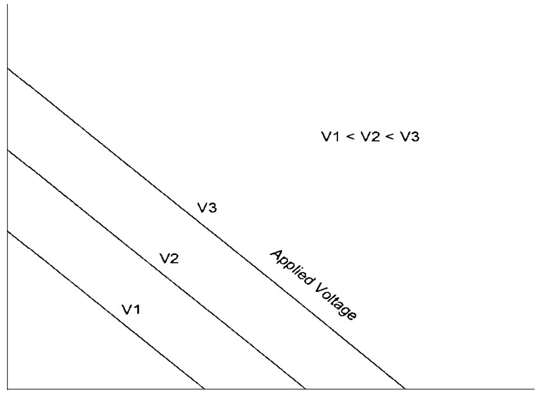

Fig.1.1 Speed-Torque characteristics of BLDC motor

With increasing applications due to small size and several advantages compared to conventional dc motor, BLDC motor is getting popular now-a-days. Because of its inherent satisfactory dynamic features, these motors are particularly useful for many applications such as industrial, medical, robotics, aerospace, tiny electric vehicles, and household applications. In applications where weight and dimensions are critical variables in motor selection, such as aerospace, medical, robotics, and electric vehicles, their reduced size relative to other motors makes them a desirable choice.

It has high efficiency and hence less energy consumption. These motors have a long operating life, are noiseless, and have lower dimensions due to the absence of a collector and brush mechanism and by effective controlling techniques [5]. Hence, Maintenance is less. As a result, Cost of operation is less. Hence, reliability is more with other benefits. So, now-a-days, Electronically Commutated Permanent Magnet motors (ECPMs) are popular in automobile industry instead of using conventional DC motors. Variable speed permanent magnet motor driving applications have grown in popularity as energy costs have increased. Further, the demand for highly efficient permanent magnet (PM) brushless motor drives has risen as a result of hybrid drives in the vehicle industry. Due to the absence of brush and commutator segments, it is called as brushless. Because of electronic commutation, BLDC motors do not require maintenance. As a result, this motor is:

- Simpler in terms of maintenance
- Durability is more
- Small in size
- Less noise compared to other motors.
- 85%–90% better in terms of efficiency
- Ability of responding faster and can work at high operating speed
- Simple to control with respect to reversal and speed control
- Precise in control
- Light in weight
- Less prone to failures
- Low cost

1.3 Working & commutation of BLDC Motor

The BLDC motor is a machine with it’s stator similar to that of an induction motor and permanent magnets installed on the rotor surface (or spinning assembly). Stator consists of a polyphase winding. The stator phase windings can be placed into slots (distributed winding) or wound on the magnetic pole as a single coil. Permanent magnets generate the air gap magnetic field, while the rotor magnetic field is constant. Rotor’s magnets and magnetic poles generated by current through windings of stator attract each other with opposite poles and repel each other with the same poles. This causes rotation in motor. An external inverter controls a brushless motor by applying current to the windings for each phase of stator, based on the detected speed of rotation (rotor position).

When supply is provided to windings of motor, current passing through the windings generates magnetic field. BLDC motors has a rotor made out of permanent magnets that surrounds the stator's electromagnetic coils and related power semiconductor switches for control. Hence, poles are created when current passes through windings of stator and these interact with the permanent magnet poles of the rotor. The rotor of the motor spins because of attraction and repulsion of magnetic fields of stator by magnets of rotor. The direction of motor spinning could be changed by changing the electric current’s direction passing through the windings.

The permanent magnet’s displacement and magnetization of them of the rotor are selected such that the back-EMF has a quasi-square wave form or to have maximum back EMF [13]. This enables the use of a DC voltage shape to generate a rotating field with minimum torque ripples. The rectangular shape of the applied voltage, which is easy to create ensures control and drive simplicity. However, in order to align the applied voltage with the Back-EMF, the rotor position must be known at particular angles. It's critical that Back-EMF and commutation events are in sync. In this state, the motor behaves like a DC motor and operates at its best efficiency. As a result of its ease of use and outstanding performance, this motor is an excellent choice for low-cost, high-efficiency applications. Each phase of the motor can contain many pole pairs. The ratio between the electrical and mechanical revolutions is defined by the number of pole pairs per phase. The BLDC motor depicted, for example, has three pole pairs each phase, corresponding to three electrical revolutions per mechanical revolution.

Windings of stator must be energized depending on position of rotor using switches of inverter to assure continuous rotation of motor. This is what basically the electronic commutation means and position of rotor must be detected for synchronizing of stator and rotor.

1.3.1 Commutation

In BLDC motors, commutation can be done using sensor-less [6][7][8] or sensored approach [9]. Brushed DC motors utilize collector and brush system for commutation. When the brushes of a common DC motor comes in contact with commutator of an another coil, motor continues to rotate. The relationship between the rotor and the stator in terms of position is mechanically detected in case of a brushed DC motor and the currents in the windings of stator are switched using commutator and brush system. Commutator acts as a reversing switch. Its action in motor and generator is as below:

- In a DC generator, the emf induced in the coil's armature is alternating in nature. So, the current flowing in the armature coil is also alternating current. Commutator reverses the current of motor at the instant when the armature coil crosses the magnetic neutral axis. Therefore, the load gets a unidirectional current or DC current.
- In case of a DC motor, commutator reverses the current at the instant when the armature coil crosses the magnetic neutral axis and this is needed to maintain a unidirectional torque. Thus, the commutator alters direct current into alternating current.

Because the BLDC motor lacks a mechanical component for switching electric currents in the stator windings, it is necessary to sense the rotor-stator positional connection in order to control the electric currents applied to the stator windings. so that a magnetic field can be applied which forces the rotor to move in the desired direction. As a result, the BLDC motor requires a semiconductor inverter circuit to create AC currents for commutation of windings of stator. Based on the position of the rotor's permanent magnet, BLDC motors are split into two groups and they are, Interior permanent magnet (IPM) motors and Surface permanent magnet (SPM) motors.

Commutation is carried out via electronic switches, which require the rotor position. The name itself suggests the fact that these motors commute electronically instead of doing it mechanically which makes these motors more precise in control [10]. Hence, these motors are used in various motion control applications using advanced electronics and recent microcontrollers [11]. There are prominently two types of motors under the category of ECPMs on the basis of shape of back electromotive force (emf). One is

Brushless DC (BLDC) motor and the other is Permanent Magnet Synchronous Motor (PMSM). Back emf shape of the BLDC motor is trapezoidal and hence, sensing is easy using hall sensors. Whereas, back emf shape of PMSM is sinusoidal [12]. A high-resolution and expensive rotor position sensor is required to excite the phase windings of the PMSM with sinusoidal current. Because a BLDC motor's phase current has a quasi-square waveform, it requires a low-cost, low-resolution rotor position sensor, which is often a Hall-effect sensor.

1.4 Controlling strategies of BLDC Motor

Control approaches for three-phase BLDC motors are primarily divided as two categories: 120-degree square-wave control and 180-degree sine-wave control. In terms of efficiency, control precision and acoustic noise, sine-wave commutation is better than square-wave commutation. Sine-wave commutation, on the other hand, increases system complexity and so incurs additional expenditures. If poorer control precision, lower efficiency, and higher acoustic noise are allowed, a motor system powered by square-wave commutation is less difficult and cheaper. In general, 120-degree square wave commutation is used since it is easier to regulate and takes up less board space.

It can be used with robust controllers and can be combined with speed controllers with PWM [14], effective torque ripple reducing techniques, by using controllers like hysteresis current controller, which controls torque by controlling currents through windings. to improve overall efficiency [15][16]. Each phase is linked to the power supply for 120 electrical degrees, then off for 60 degrees, then connected to GND for 120 degrees, then off again for 60 degrees in this switching scheme where as in 180-degree conduction mode, each phase is linked to power supply for 180 degrees and then gets connected to ground for other 180 degrees. In 120 Degree commutation, two switches are ON at any instant of time, whereas in 180-degree commutation, three switches are ON at any instant of time as shown in Fig.1.2. and Fig. 1.3.[17].

Furthermore, there are two types depending on the technique for detection of position of rotor: sensor-based detection (Hall sensors or Hall IC) and sensor-free or sensor-less detection. Sensored control implies using physical sensors on the motor in the desired position. Sensor-less control means using other methods to estimate the exact position of the rotor without using any physical sensors.

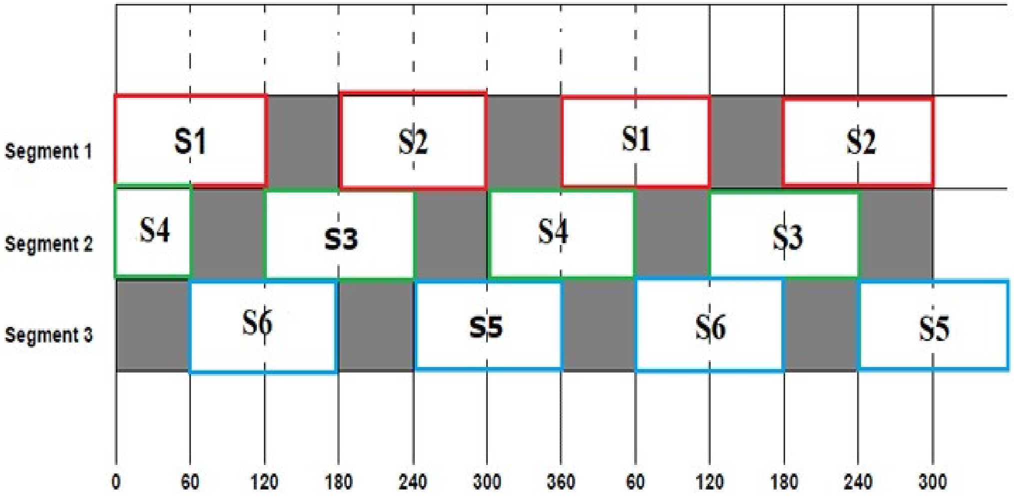

Fig.1.2. switching sequence in 120-degree commutation of BLDC motor

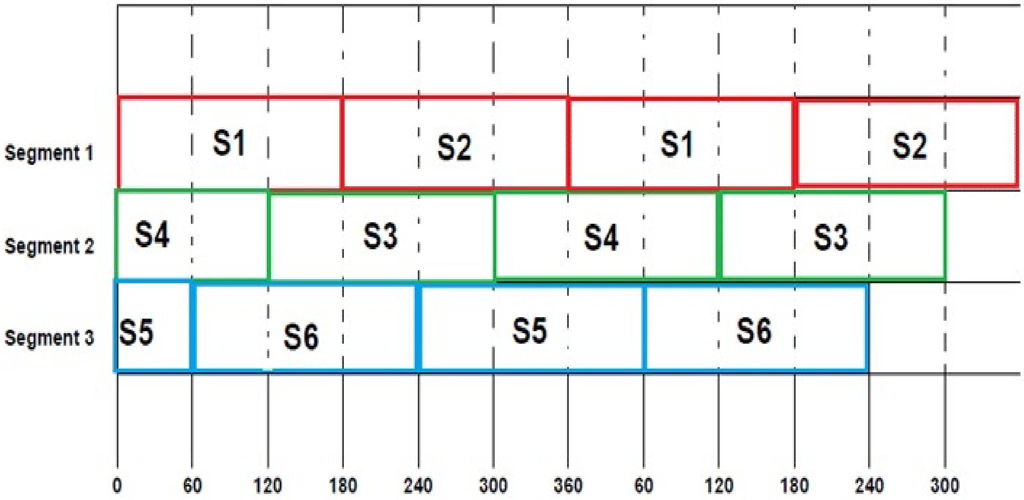

Fig 1.3. switching sequence in 180-degree commutation of BLDC motor

Recent research trends leads to 150 degree commutation technique as well. In this technique, each device links to positive supply for 150-degree duration and then off for 30 degree duration and again connects to negative supply for 150 degree duration and off for 30 degree duration for a complete time period. This has better efficiency than 120-degree commutation technique and less efficient than 180-degree commutation technique. More complicated than 120-degree commutation and less complicated than 180-degree commutation. It has lesser torque ripple than 120-degree commutation and has more toque ripple than 180-degree commutation.[18][19].

In short, it is moderate in all parameters when compared to both 120 and 180-degree commutation techniques.

1.5 Sensor-based control

Position sensors which are mechanical components, such as a shaft encoder, or a hall sensor, or resolver are used in sensor-based control approaches to give rotor position information. These all fundamentally do the same thing, which is to give a signal, which is an indicator of when to commutate the motor.

1.5.1 Resolver

The resolver is a sensor that uses induced current to output an analog voltage with respect to the rotor position. This outputs a sine and cosine wave. These signals together tell the angular position of the rotor to a high degree of accuracy. This signal needs to be processed by an MCU to determine where and when to commutate.

1.5.2 Encoder

The encoder is either an optical or electromechanical device that is attached to the motor shaft. The encoder outputs a pattern in binary zeros and ones with respect to the rotor position. Some encoders outputs 256 or more pulses when the motor makes one mechanical revolution. A microcontroller can count these pulses to determine where the motor is and when to commutate the motor.

1.5.3 Hall sensors

The Hall effect sensors are devices that use the Hall effect to determine the rotor's magnetic field and output either, a 1 or a 0 as shown in Fig.1.4. Three Hall effect sensors are used to determine which of the six commutation states the motor driver needs to be in. There are many factors which need to be considered while using hall sensors [20]. For a three-phase BLDC motor, each stage of the commutation sequence is accomplished by energizing one of the windings positively, the second negatively, and the third open.

To compare these three sensored controlled devices, resolvers give a high resolution on where the rotor is, allowing for very accurate position sensing applications. Encoders can also allow a high resolution than Hall effect sensors can, but lower resolution than resolvers, Hall sensors gives a low resolution on where the rotor is, but are more simple and lower cost to implement. It is important to note that resolvers or encoders require precise coupling to the motor shaft while sensors need to be placed inside the physical construction of the motor. Hall effect Hall sensors, also known as Hall position sensors, are widely used and popular. Each of the three phase windings has one Hall Sensor. They send out three overlapping pulses that comprise a 60-degree range.

Here, hall sensors have been used to send the information sensed to the control unit.

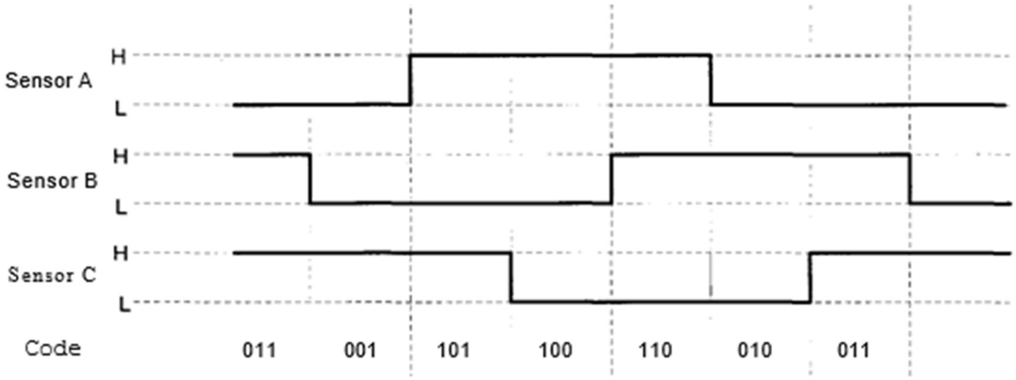

Fig.1.4. Binary code of hall sensor outputs

1.6 Sensor-less approach using back EMF

1.6.1 Need for sensor-less approach

Sensored method is common method but is less reliable because of presence of sensors for detection of position of rotor. Sometimes, it is not possible to place hall sensors at exact positions [21][22]. So, sensor-less method is more durable, reduces cost of sensors and makes system robust. There are many applications for which machine may work in harsh environment like electric vehicles [23]. Sometimes, load would be high for which motor operates at high current. This produces high temperature and can result in false detection of position by sensors or even failure of sensors. The following are some of the reasons to go for sensor-less approach for some applications:

- Additional connections between the control unit and position sensors are not possible.
- Wiring and sensors are expensive.

There are certain methods to stabilize the system during failure of hall sensors depending on type of fault by interpolation using some algorithms and estimating the signals which are somewhat complicated [24]. So, sensor-less method of commutation of BLDC motor is needed in some cases, which does not require hall sensors at all. This control scheme uses no position sensors, so it must estimate the rotor position in relation to the stator by using parameters such as winding resistance, or back EMF to determine where or when to commutate the motor. Some such applications are in refrigerators, air conditioners and micro-computers [25][26][27]. These methods require ADCs, DSPs and combines multiple techniques which are complex to implement [28].

1.6.2 Back EMF & it's detection

Back EMF is a voltage induced on a wire, when a continuously varying magnetic field is applied. Faraday's Law states that the induced voltage in a wire is directly proportional to the number of turns of a coil of wire, changing magnetic field, and the area of the coil. When motor rotates, the magnetic field seen on the stator is changing, and a voltage is generated on the face of the motor according to Faraday's Law. This EMF generates a magnetic field which opposes the change in original magnetic flux driving the motor's spin. This voltage is known as a "back" EMF since it resists the motor's natural action. The magnitude of the EMF is directly proportional to the speed of the rotor for a particular motor with a constant magnetic flux and number of windings.

This voltage can be in two shapes, either a sinusoidal or a trapezoid wave form, depending on how the motor is designed. The Back EMF voltage actually corresponds to a specific angle of the rotor, means the back EMF can be used to determine the rotor's effective position. The Back-EMF has a trapezoidal form and its amplitude is proportional to the actual speed of a motor. The amplitude, as well as the sign and phase sequence, vary during the speed reversal.

Back EMF constant is a parameter specified by BLDC motor manufacturers that can be used to estimate back EMF for a particular speed. Subtracting the back EMF value from the source yields the voltage across a coil. The voltage difference between the back EMF and the supply voltage causes the motor to draw the rated current and provide the rated torque, when a motor is operating at rated speed. Driving the machine faster than the rated speed raises back EMF, which reduces the voltage difference across the windings, lowering current and torque. rotating the motor even faster would bring back EMF (and motor losses) to exactly equal to the supply voltage, resulting in zero current and torque. Back EMF is sometimes considered a disadvantage because it reduces the motor's torque. But, in BLDC motor, this parameter can be used for commutation. So, this is an advantage.

Back EMF is being measured, observed and using it for detecting commutation sequence in this approach. The back EMF can be measured using a variety of methods. The easiest method is using a comparator to compare half of the DC bus voltage with the back EMF. The main disadvantage of this basic comparator method is that the three windings may not be similar, which results in a positive or negative phase displacement from true zero crossing point. The motor will most likely continue to run, but it may draw too much current. The alternative could be to use parallel resistor networks with the motor windings to create a virtual neutral point. The virtual neutral point is then compared to the back EMF.

Another way is to detect back EMF and deciding the commutation, in conjunction with trapezoidal control is during the commutation state, where one phase is being tri-stated or high impedance. Using Analog-to-digital converters (ADC) is another option. Many MCUs for BLDC motor control contain high-speed ADCs that are ideal for this application. The back EMF is attenuated using this manner, allowing it to be supplied straight to the MCU. The ADC samples the signal and compares it to a digital value that corresponds to the zero point. The coil’s sequence of energization points to the next step when the two values match. This method has several advantages, such as the ability to remove switching components of high-frequency from the back EMF signal using digital filters.

Sensor-less BLDC control of motor has one big disadvantage: when the motor is motionless, no back EMF is created, leaving the MCU without information regarding the stator and rotor positions. This problem can be solved by starting the motor in an open loop arrangement by sequentially energizing the coils. Although the motor is not likely to run efficiently, it will begin to rotate. The speed will eventually be sufficient for control system, to generate sufficient back EMF to convert to regular (and efficient) closed-loop operation. Sensor-less BLDC motors may not be a good choice in applications that demand very low speeds since back EMF is related to rotational speed. In this case, BLDC motors with Hall-effect sensors may be a better fit. The growing popularity of sensor-less BLDC motors has prompted semiconductor companies to create circuits specifically suited for controlling and driving such devices. The motor's control system normally consists of an MCU and an IGBT – or MOSFET – driver. For sensor-less BLDC motor control, a variety of MCUs are available, ranging from simple 8-bit devices, which are cheap, to higher-performance 32-bit and 16-bit devices with the bare minimum of peripherals needed for driving the motor. Three-phase ADCs, comparators and PWMs are included in these peripherals for overcurrent protection.

Sensor-less BLDC motors are more simple and perhaps more durable than Hall-effect sensors, especially when certain application needs motor to operate in unclean and humid environments. The removal of the position sensor and its connections between the control unit and the motor are advantages of the sensor-less approach. The motors use back EMF monitoring to detect the relative locations of the stator and rotor in order to apply the proper coil energizing sequence. One disadvantage of working in open loop is that back EMF won't be generated when the motor is stationary, therefore startup is hampered. As a result, the motor may take some time to settle and run smoothly. Another problem is that the back EMF is low and difficult to measure at low speeds, which can lead to wasteful operation. In these applications, sensor-equipped BLDC motors should be considered.

In this work, zero-crossing approach is used for sensor-less detection, using 120-degree commutation which is simple to implement and it is found to be efficient as well. The zero crossing locations of Back-EMF induced in the windings of motor are detected using the sensor-less rotor position technique. While one of the three phase windings is not energized, the phase Back-EMF's Zero Crossing locations are detected. Collected data is used to commutate the powered phase pair and manage the phase voltage.

1.7 Commutation techniques of BLDC motor

In this work, there are mainly two types of commutation techniques have been discussed in detail. They are:

- Sensored commutation technique
- Sensor-less commutation technique

Both of these techniques are combined with 120-degree commutation in the work that has been carried out.

As, it is known that detection of commutation sequence using back EMF is not possible when motor is stationary or rotating with less speed, sensored approach has been used for less duration and then shifted the model to sensor-less commutation technique proposed.

The proposed Control technique includes:

— Sensor-less Zero Crossing commutation of Back EMF control
— Closed loop operation without using current loop
— Variable speed and torque application
— Motoring mode of operation

1.8 Summary

This chapter has given brief summary of need for using BLDC motor, applications, commutation techniques, recent trends of BLDC motor. This also focused on sensors used in sensored approach and different techniques for sensor-less approach.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Now-a-days, from small toy to industrial drives, every application has electric machine. This made the researchers to design motors to be energy efficient. Conventional drives like DC motors contain mechanical components for commutation (brush and commutator system), which needs frequent failures and requires maintenance and are less efficient. AC motors such as Induction motors doesn't requires mechanical components but flux control method through which this motor has been controlled is complex. But, their characteristics are suitable for many applications.

The discovery of BLDC motor solved the above problems. It became extensively useful for almost every application from residential applications to industrial applications, microcomputers and electric vehicles because of their characteristics similar to brushed DC motor. These doesn't require any mechanical part for commutation, since these are commutated electronically. For this, sensing of position is necessary. Most of the applications uses hall sensors for this but some harsh working environments may make sensor fail or false detection. So, a sensor-less method has been explained in this thesis work.

Jape et al. [1], compared all the electric motors used till date, for E-vehicle applications. They gave a brief about DC brushed motor, Brushless DC motor, Induction motor, synchronous motor, switched reluctance motor for electric vehicle applications comparing torque-speed characteristics and parameters like power-to-weight ratio, cost.

2.1.1 Sensored approach

One of the popular and conventional method over a decade or more is commutation of BLDC motor using sensors. This method's efficiency has been improved by using efficient controllers for torque, speed and combining them with other techniques like fuzzy logic, pwm. Hall sesors role and it's impacts on system during fault or due to misalignment and their selection is seen from [2-6].

Publications [2]-[3], explained efficient PID controllers and it's controlling strategies for BLDC motor for electric vehicle applications. [2] aims at reducing overshoot and settling time which would make the system respond faster. [3] utilizes simple PID controller combined with fuzzy logic. This aims at improving steady state performance during conditions like dynamic load, set point is variable.

M. A. Hassanin et al. [4] explains how to select size of BLDC motor and other major components according to electric vehicle specifications. It has given a brief explanation about BLDC motor and it's dynamics in E-vehicle applications and given a detailed method to select size of motor.

C. W. Lu [5], proposed a highly efficient toque controller for BLDC motor. In this, parameters like drive efficiency, dynamic performance of motor, acoustic noise and utilization of inverter has been compared with conventional controller and found this to have efficient performance.

M. Štulrajter et al. [6] aims to illustrate the drawbacks of trapezoidal commutation control using sensor-less approach at high speeds, as well as to present a strategy that extending the traditional technique to high-speed areas.

2.1.2 Sensor-less approach

Because of necessity of detecting rotor position without using hall sensors due to their malfunctioning in some working environments, sensor-less detection became necessity in such applications. Among many sensor-less approaches, one popular approach is by using back EMFs and this has been explained for many application from [7-8] and [25-28].

Kalyani et al. [7-8], explains the sensor-less approach for BLDC motor control through phase voltages. By deducing the back EMFs from phase voltages and estimation switching duration and pattern has been explained.

Mousmi et al. [9-11], explains the detection of faults in hall sensors, which makes system unstable when undetected and that it can be overcome by giving intelligence to hall sensors. This publication also explains starting BLDC with faulty hall sensors considering the fact it's difficult to repair hall sensors as they are present in between the stator coils. Limitations and effect on performance with such sensors has been explained and presented and how intelligence to hall sensors solves this problem in emergencies.

T. Rudnicki et al. [12] presented detailed operation of pmsm motor by analyzing it mathematically. Foc technique has been used and it's processing units have been explained.

Kim et al. [13] discussed how to optimize shape of rotor (magnets) and how to select magnetization which directly impacts back EMF of motor. This has been done by carrying out FEM analysis on different magnet shapes with magnetization directions different from each.

The publications [14-17], explained the working of BLDC using 120 degree commuatation and how to make this technique effective by means of efficient controllers and combining them with PI, using pwm control techniques. The main factors which are considered for analysis are speed, torque and it's ripples. These publications explained how to improve speed performance, torque control using hysteresis current controller, which controls torque by controlling current and how to reduce ripples in torque.

Ozgenel MC. [18-19], presented a detailed analysis, design and implementation of 150 degree commutation technique for BLDC motor and compared with conventional method. The increase in power and increase in load capability by using this commutation technique has been shown.

The publication [20], explains how the selection of hall effect sensors impact over all efficiency. Some parameters, which should be kept in mind while choosing hall sensors like stability, repeatability, sensitivity, time response have been explained and given insights on choosing hall sensor based on these.

J. S. Park et al. [21-22], given methods to compensate the incorrect alignment of hall sensors which reduces one particular switching pattern duration and increases the other, which impacts overall performance of drive. Performance of drive has been observed with correct alignment compared to incorrect alignment.

A. Goswami et al. [23] addressed the challenges of controller in E-Rickshaw application. A controller has been designed to withstand faults and efficient heat sink as heat generates in E-Rickshaw application is more.

M. Ebadpour et al. [24] addressed how to improve the dynamic performance of BLDC motor drive by addressing hall sensors faults fast, and make the system stable.

The publications [25-28], explained the sensor-less commutation techniques using back EMFs and sensor-less approach trends in various applications like microcomputers, high speed applications e.t.c.,

2.2 Summary

This chapter explains the summary of trends and techniques that are observed for commutation of BLDC motor in various applications. This explained the working, design and efficient controlling of speed, torque using PID controllers and hysteresis current controllers combined with techniques like fuzzy logic, pwm e.t.c., in various applications. Different commutation techniques and their mathematical analysis and implementation has been discussed.

This chapter also explained the trends and different motors and their selection in electric vehicles. Hall sensor selection and it's importance in BLDC motor commutation and efficiency has been explained. Faults in hall sensors, it's types, detection of faults, mis-alignments and compensating techniques have also been discussed.

Sensor-less commutation, it's methods, for different type of applications has been explained. Selection of shape and magnetization of rotor magnets and it's impact on back EMF is also discussed.

CHAPTER 3

SENSORED CONTROL OF BLDC MOTOR

3.1 120-degree commutation of BLDC Motor

A three-phase bridge inverter made of six switches which controls the commutation pattern of a BLDC motor for 120° commutation. The high-side is turned on in one phase, the low-side switch is turned on in other phase, and both the high- and low-side switches are turned off in the third phase. Each switch is connected to the positive supply for 120 degrees. In the total time duration of 360 degrees, each switch is connected to positive supply for 120 degrees and then off for 60 degrees duration and get connected to negative supply for 120 degrees duration and off for another 60 degrees duration.

With 120° square-wave commutation, fig.6.illustrates the Phase voltage with respect to the neutral point of a motor and the phase-to-phase voltage. At any one time, this commutation approach conducts electric currents into two elements (i.e., windings). As a result, the phase voltage with respect to the neutral of a motor is always VDD/2.

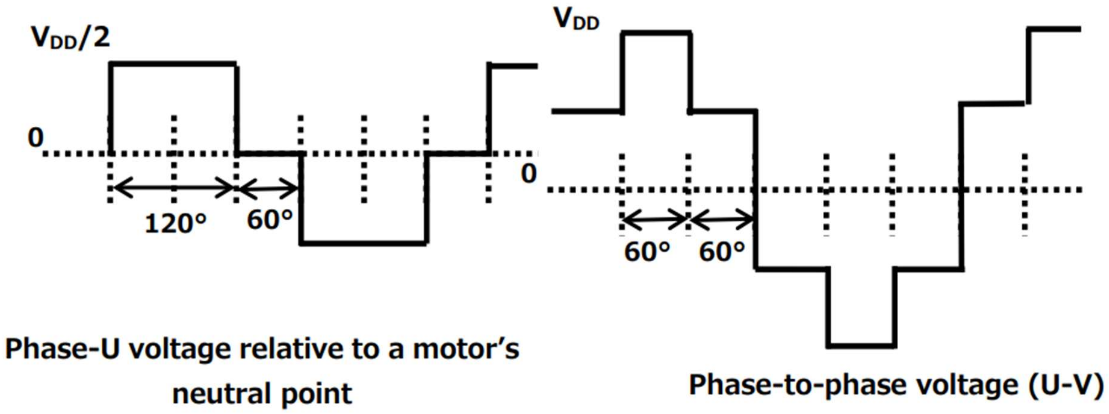

Fig.3.1. Theoretical waveforms of voltage in three phase inverter with 120 degree commutation

An inverter circuit and its current path are shown in Fig.7. There are intervals in each electrical cycle when each phase does not conduct electricity with 120° commutation. Voltage arises at the phase terminals at these times. In the case of Phase U, for example, Phase V and Phase W conduct current when Phase U is not conducting. The Phase-U terminal voltage seems to be equal to VDD/2, i.e. the voltage at the neutral point of the Phase-V and Phase-W windings, even though Phase U is not conducting current. The back-EMF created in each phase by motor rotation is added to the Phase-U terminal voltage in reality.

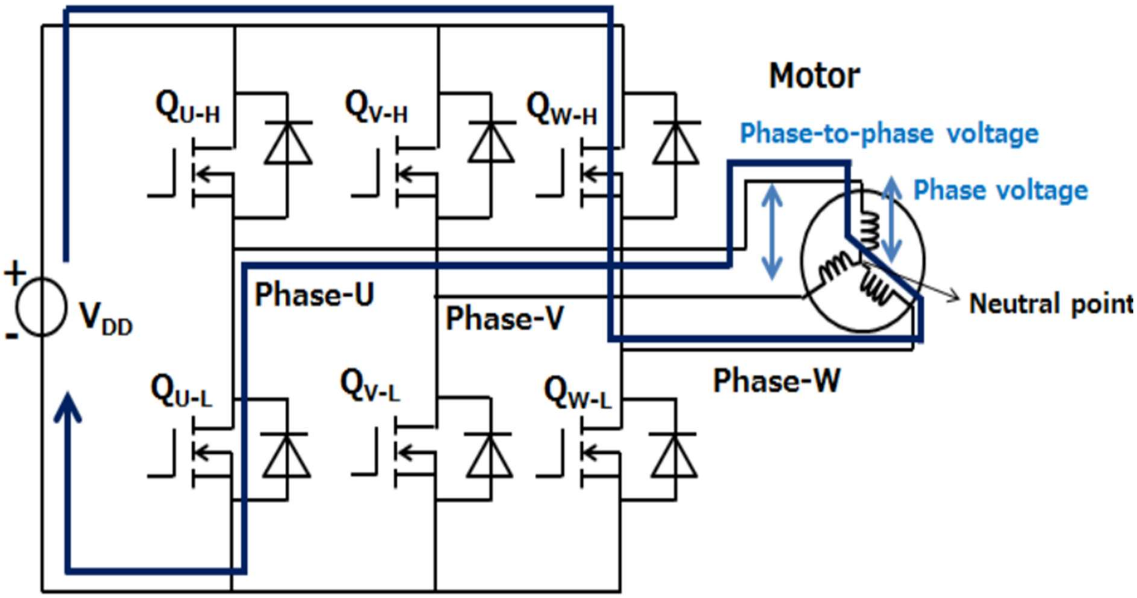

Fig.3.2. Three-phase inverter working with 120-degree commutation

3.2 Modelling of BLDC Motor

A star connected, three-phase BLDC motor with rotor made up of permanent magnets, driven by a three-phase inverter is taken. Assumptions made for the mathematical modelling of this motor are as follows: [16]

i. To avoid saturation, motor is operated at current less than rated current and maintained uniform air gap. (neglected saturation effects)

ii. Motor is isotropic.

iii. Uniform air gap is maintained throughout.

iv. Saliency (due to the usage of permanent magnets in rotor) and damper windings effects are neglected.

v. Small losses like stray and iron losses have been neglected.

vi. Due to harmonic fields of stator, the induced current in rotor is neglected.

vii. Motor's phases are balanced and rotor has permanent magnets with trapezoidal back emf shape.

viii. Compared to self-inductance, mutual inductance between the windings is negligible.

Phase voltages are given as follows:

$$V_{an} = L_{an}\frac{di_{an}}{dt} + R_{an}i_{an} + e_{an} \quad \text{--(3.1)}$$

$$V_{bn} = L_{bn}\frac{di_{bn}}{dt} + R_{bn}i_{bn} + e_{bn} \quad \text{--(3.2)}$$

$$V_{cn} = L_{cn}\frac{di_{cn}}{dt} + R_{cn}i_{cn} + e_{cn} \quad \text{--(3.3)}$$

Where,

V_{an}, V_{bn} and V_{cn}, are the voltages of respective phases with respect to neutral.

i_{an}, i_{bn} and i_{cn} are the respective currents of phases.

R_{an}, R_{bn} and R_{cn} are the stator resistances of respective phases.

L_{an}, L_{bn} and L_{cn} are the inductances of respective phases.

e_{an}, e_{bn} and e_{cn} are the back EMFs of respective phases.

Or

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R+\rho L & 0 & 0 \\ 0 & R+\rho L & 0 \\ 0 & 0 & R+\rho L \end{bmatrix} \begin{bmatrix} i_{an} \\ i_{bn} \\ i_{cn} \end{bmatrix} + \begin{bmatrix} e_{an} \\ e_{bn} \\ e_{cn} \end{bmatrix} \quad \text{-- (3.4)}$$

Where,

$L_{an} = L_{bn} = L_{cn} = \mathrm{L} = L_{Sn} - L_{Mn}$

L_{Sn} is self-inductance of armature of stator in henry,

L_{Mn} is mutual-inductance in henry,

Whereas,

$R_{an} = R_{bn} = R_{cn} = R$ are resistances of armature in ohm.

v_{an}, v_{bn} and v_{cn} are terminal phase voltages of motor in volts.

i_{an}, i_{bn} and i_{cn} are respective phase currents of motor in amperes.

e_{an} , e_{bn} and e_{cn} are the back EMFs of motor in volts

The expression of back EMFs are represented as :

$$e_{an}(\mathrm{t}) = K_E * \emptyset(\theta) * \omega(\mathrm{t}) \qquad \text{-- (3.5)}$$

$$e_{bn}(\mathrm{t}) = K_E * \emptyset(\theta - \frac{2\pi}{3}) * \omega(\mathrm{t}) \qquad \text{-- (3.6)}$$

$$e_{cn}(\mathrm{t}) = K_E * \emptyset(\theta + \frac{2\pi}{3}) * \omega(\mathrm{t}) \qquad \text{-- (3.7)}$$

The produced torques are given by:

$$\tau_{\mathrm{E}}(\mathrm{t}) = (e_{an}i_{an} + e_{an}i_{bn} + e_{cn}i_{cn})/\,\omega \qquad \text{-- (3.8)}$$

$$\tau_{an}(\mathrm{t}) = K_T * \emptyset(\theta) * i_{an}(\mathrm{t}) \qquad \text{-- (3.9)}$$

$$\tau_{bn}(\mathrm{t}) = K_T * \emptyset(\theta - \frac{2\pi}{3}) * i_{bn}(\mathrm{t}) \qquad \text{-- (3.10)}$$

$$\tau_{cn}(\mathrm{t}) = K_T * \emptyset(\theta + \frac{2\pi}{3}) * i_{cn}(\mathrm{t}) \qquad \text{-- (3.11)}$$

Where K_T is the torque constant.

$$\tau_E(t) = \tau_{an}(t) + \tau_{bn}(t) + \tau_{cn}(t) \qquad \text{-- (3.12)}$$

$$\tau_{\mathrm{E}}(\mathrm{t}) - \tau_{\mathrm{L}}(\mathrm{t}) = \mathrm{J}\frac{\mathrm{d}\omega(\mathrm{t})}{\mathrm{dt}} + \mathrm{B} * \omega(\mathrm{t}) \qquad \text{-- (3.13)}$$

Where,

τ_E is electromagnetic torque in N-m.

ω is angular speed of motor in radians per second.

τ_L is load torque in N-m.

J is rotor's inertia in [kgm^2],

B is damping constant.

3.3 Hall sensor

A hall sensor's output voltage is varied in accordance to the strength of the magnetic field applied. A BLDC motor comprises of three Hall sensors that are electrically 120 degrees apart in the typical design. A BLDC with the conventional Hall arrangement (sensors electrically 120 degrees apart). can yield six acceptable binary state combinations: 110,101,011,001,010, and 100, for example. The sensor delivers the rotor's angular location in degrees multiples of 60, which the controller takes to determine the rotor's presence in the 60-degree sector. The obtained all hall sensors combination, based on the position of rotor, decides the next switching pattern to energize the coils desired for 120-degree commutation of the BLDC motor.

The Hall sequence or the rotor position are used by the controller to operate the motor. It energizes the phases of the stator winding, ensuring that the rotor maintains a torque angle of 90 degrees with a 30 degrees divergence limit between the rotor d-axis and the stator magnetic field.

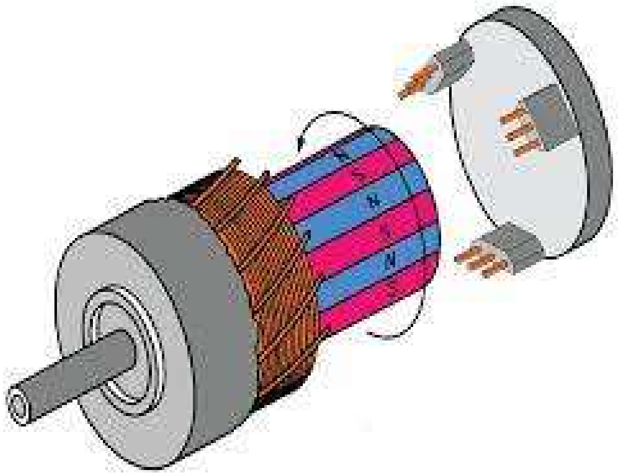

Fig.3.3. Hall effect sensor

Hall decoder, which decides switching pattern to be ON and sends pulses to trigger switches, is given in table 3.1.

TABLE 3.1 SWITCHING SEQUENCE WITH HALL SIGNALS

S No.	**Hall sensors**			**Switches**					
	H3	***H2***	***H1***	***AL***	***AH***	***BL***	***BH***	***CL***	***CH***
1	1	0	1	0	1	1	0	0	0
2	0	0	1	0	1	0	0	1	0
3	0	1	1	0	0	0	1	1	0
4	0	1	0	1	0	0	1	0	0
5	1	1	0	1	0	0	0	0	1
6	1	0	0	0	0	1	0	0	1

If an application is using hall sensors, it is important to consider many factors which effects the output of hall sensors and selection of these sensors should be done based on these factors for any application. They are:

3.3.1 Sensitivity

A Hall-effect sensor get activated by a magnetic field. The sensitivity level is determined by the sensor's proximity to the magnet, the magnet's strength and the air gap. The magnetic field strength (in Gauss) needed to modify the state of a bipolar Hall effect sensor should be specified in product datasheets (operate and release). A high sensitivity sensor, usually less than 60 Gauss, enables the use of less expensive magnetic materials or smaller magnets, which is becoming increasingly relevant as rare earth magnet costs are rising up gradually. High sensitivity also allows for a larger air gap, allowing the sensor to be located far away from the magnet while maintaining high reliability and design flexibility.

Alternatively, for the same air gap, the sensor that is more sensitive, results in improved reliability and repeatability. It means that a high-sensitivity Hall-effect sensor or a sensor with a lower magnetic switch point produces higher efficient motor performance.

3.3.2 Repeatability

The latching time of a Hall-effect sensor is referred to as repeatability. It is highly related along with high sensitivity since it allows for higher repeatability in the sensor. When the sensor output is activated, current is directed through the coil windings in the motor's stationary component (stator). This current generates a magnetic field that interacts with generated permanent magnet's field on the shaft, spinning it.

A highly repeatable sensor changes state as the magnet rotates by it at the same angular point each time the magnet passes by. A complete rotation of the motor shaft, for example, is 360 degrees. When shaft is rotated at five degrees when the motor is started. In the next rotation also, a high repeatability sensor activates at five degrees mostly.

A sensor is said to have high repeatability when it gives a steady reaction time that keeps all angular readings very near to same value. The timing among current that flows through the coil and shaft's position must be as precise as possible to generate the maximum torque on the shaft. If the response of sensor to magnetic field changes is delayed, the sensor's bandwidth will be reduced and leads to accuracy errors. Any of the error in Hall-effect sensor's switching point reduces the motor's torque, leading to decrease in motor's efficiency.

3.3.3 Stability

Stability, like repeatability, refers to the changes in angular position in relation to temperature or voltage. if the sensor's output changes it's state at five degrees at 25 °C, t he Gauss level necessary to turn on a component(sensor) at 125°C should be as similar as possible to that required to switch on a part at 25°C.

This is an important parameter because exact location detection requires temperature stability as well as high sensitivity. For BLDC motor efficiency, Magnetic stability is also important which improves jitter performance, and reduces speed fluctuation.

3.3.4 Time of response

The time it takes for the sensor's output to change it's state is known as response time. If a sensor has a 30 Gauss operating point and a 30 Gauss magnetic field is introduced to it, the response time is obtained by determining where the 30 Gauss field is applied to the point where the output changes state. Commuting a BLDC is more efficient when the response time to a change in the magnetic field is faster. Due to sluggish reaction or delay, a sensor may switch at a different magnetic field level than what is necessary, resulting in accuracy issues.

To achieve maximum efficiency, motors must transition at a precise point. Miscommutation causes torque constant (Kt) to be lower and increases torque ripple, which can increase noise and have an influence on system performance and efficiency. It's also worth noting that sensor makers have used a technology called chopper stabilization to achieve great sensitivity and stability across temperature. Using single or dual Hall effect sensing elements, this results in a high repeatability and stability over the operational temperature range. However, due to many drawbacks, such as increased electrical noise and poor response time, this technique may reduce motor efficiency.

Hall sensor is a very small element in a system, using BLDC motor but it highly impacts BLDC motor’s performance which impacts system efficiency.

3.4 PI controller

A PI controller is used to regulate speed controller in this project. The output signal to the PI controller is speed error, which is the difference between the reference speed and the actual speed of the motor. For each set of speeds, the Kp and Ki values are determined through trial and error. The output from the PI controller i.e., speed error signal is given to the source, which is controlled DC voltage source. Based on the signal of the speed error, voltage amplitude is changed which in terms either increases or decreases the speed as both the quantities are directly proportional to each other.

3.5 Working of sensored model

Initially, the rotor's position is detected by the hall sensors and the generated three signals are sent to hall decoder. Hall decoder decodes the binary outputs and generates next switching state based on the previous hall output pattern and sends pulses which triggers switches in three-phase inverter. Inverter energizes corresponding windings based on commutation technique that is desired (120 or 180) and rotor starts rotating nd hall sensors continues to sense and this pattern goes on. Based on reference speed and actual speed i.e., the difference between them, an error signal gets generated and this controls input supply to the inverter and correspondingly, speed will be adjusted based on the amplitude of DC supply.

3.6 Simulation

BLDC Motor using sensored mode of commutation is modelled and simulated in MATLAB. A 1kW, 48V BLDC motor with the rated speed of 3000 rpm is taken. Rest of the parameters specified in Table 3.2 are used in simulation. The motor is operated under various operating conditions such as:

i. Rated speed and rated torque operation.

ii. Rated speed with step variation of torque.

TABLE 3. 2 MODEL PROPERTIES

Machine Parameters		
Number of pole pairs, p	4	
Resistance of stator per phase, R_s	2.8750	Ω
Self-inductance of stator per phase, L_s	8.5	mH
Mutual inductance of stator, M_s	0.00001	H
Rotor inertia J_m	0.0008	Kgm^2
Flux linkage Ψ_m	0.175	Wb
Rated Speed	3000	RPM
Rated Power	1	kW
Electromagnetic torque τ	3.18	N-m

3.7 Matlab simulation model

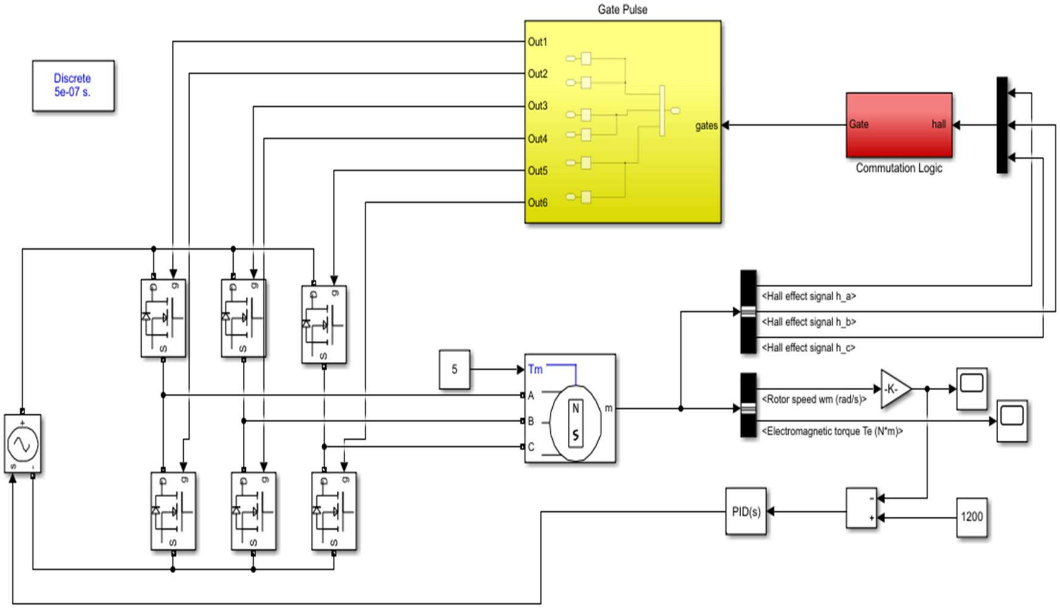

Fig.3.4. Matlab simulink model of the sensored control

Results:

(i) Rated speed and rated torque operation

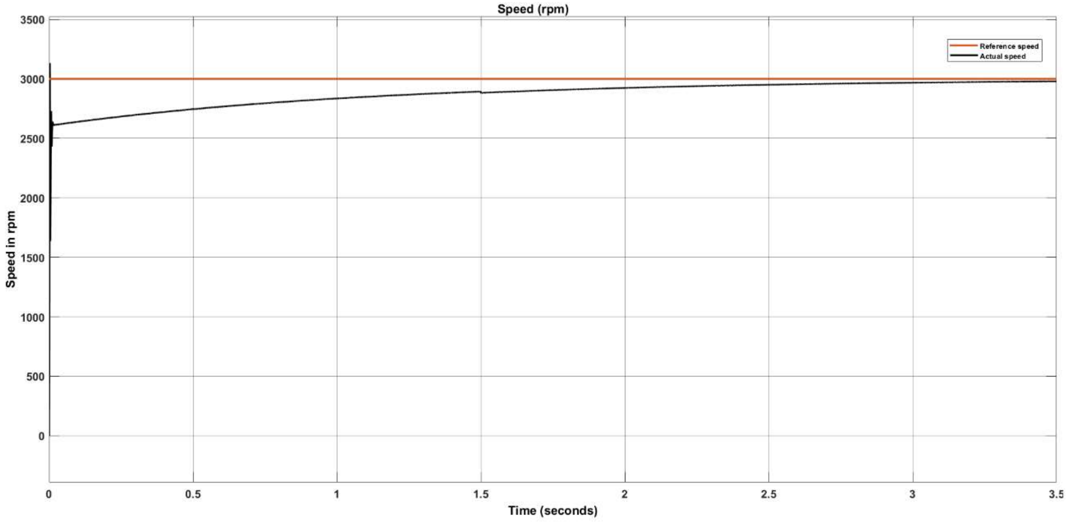

Fig.3.5. Rotor speed in rpm for complete simulation time

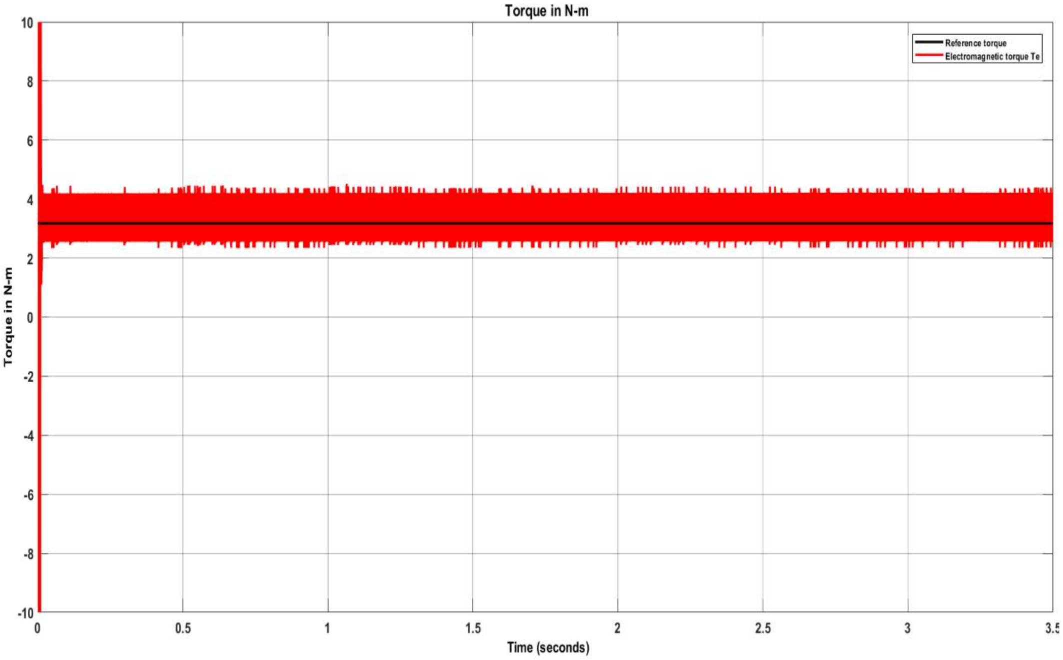

Fig.3.6. Torque in N-m

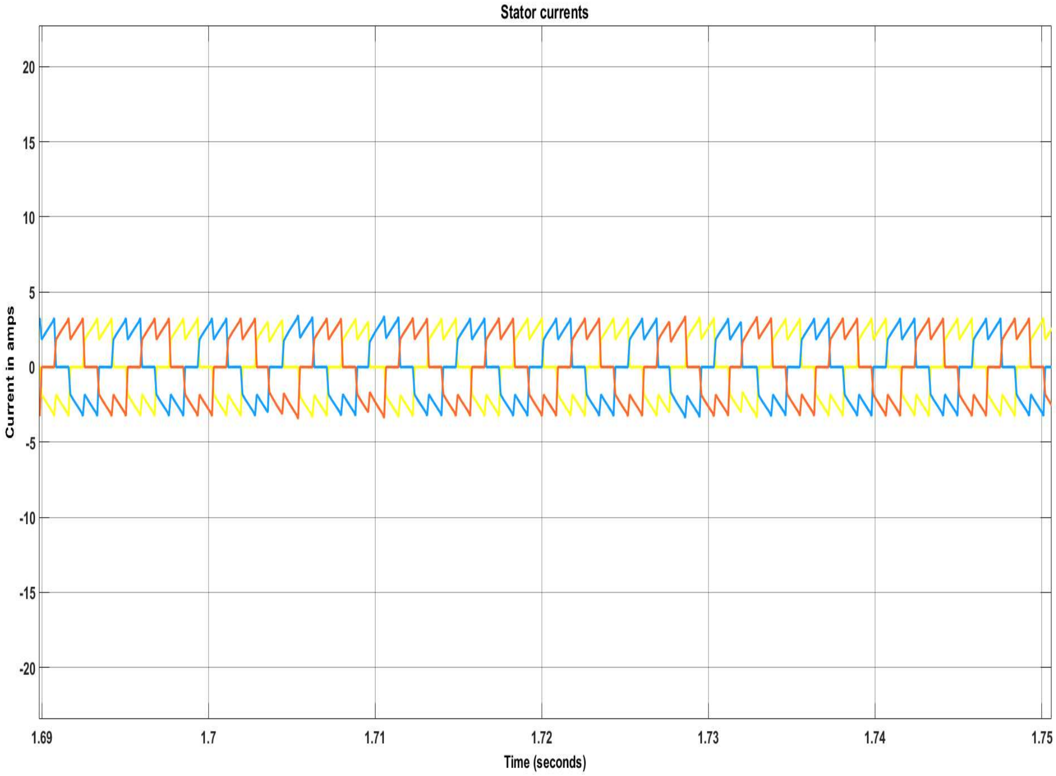

Fig.3.7. Stator currents in amps

(ii) Rated speed with step variation of torque

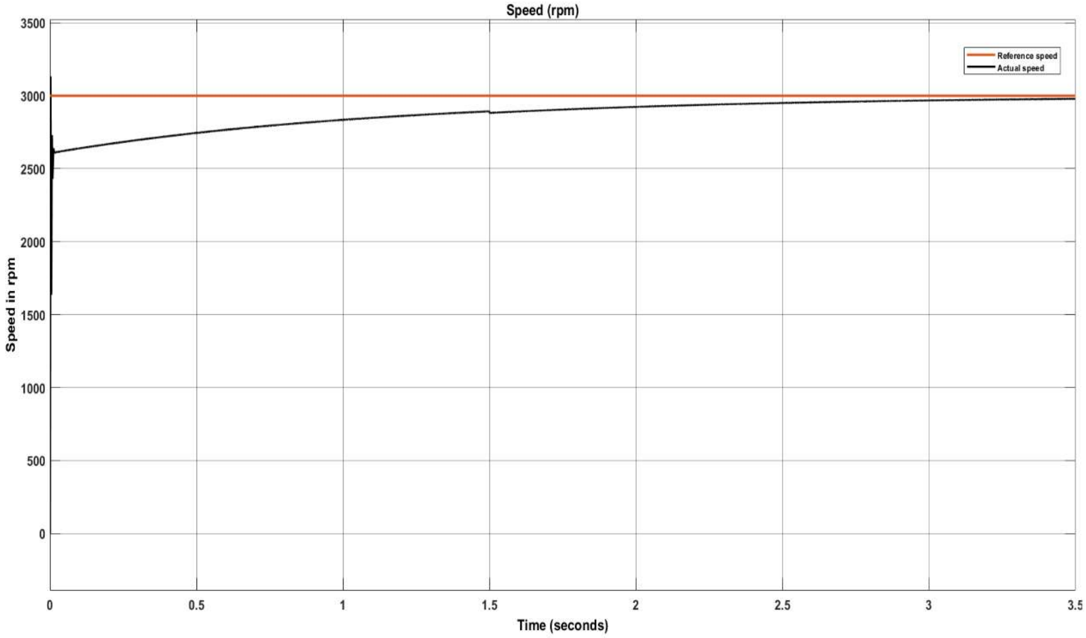

Fig.3.8. Rotor speed in rpm for complete simulation time

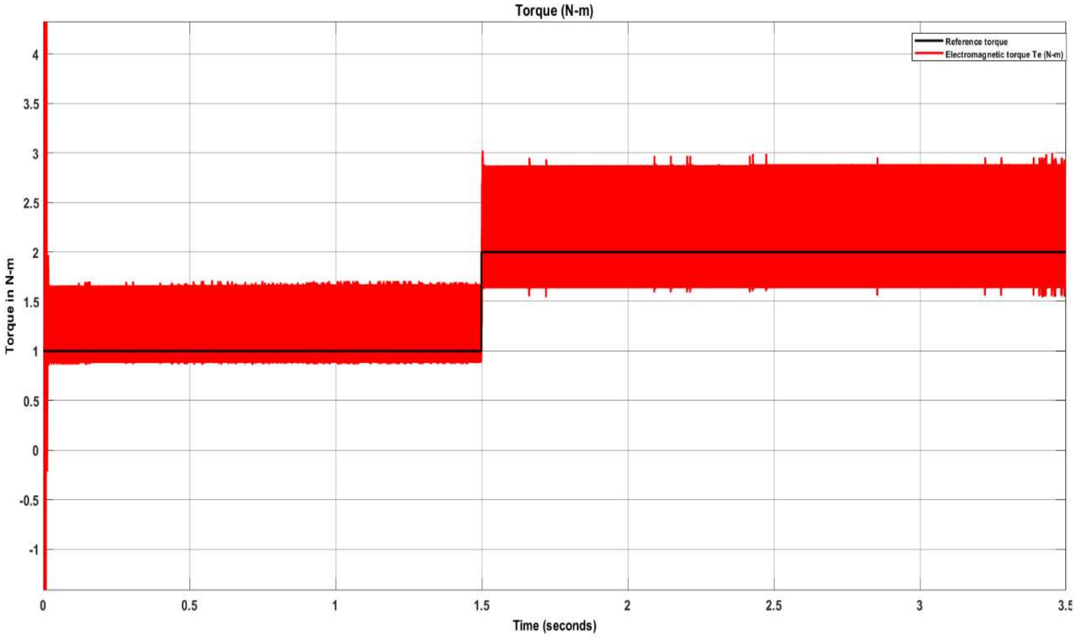

Fig.3.9. Rotor torque in N-m

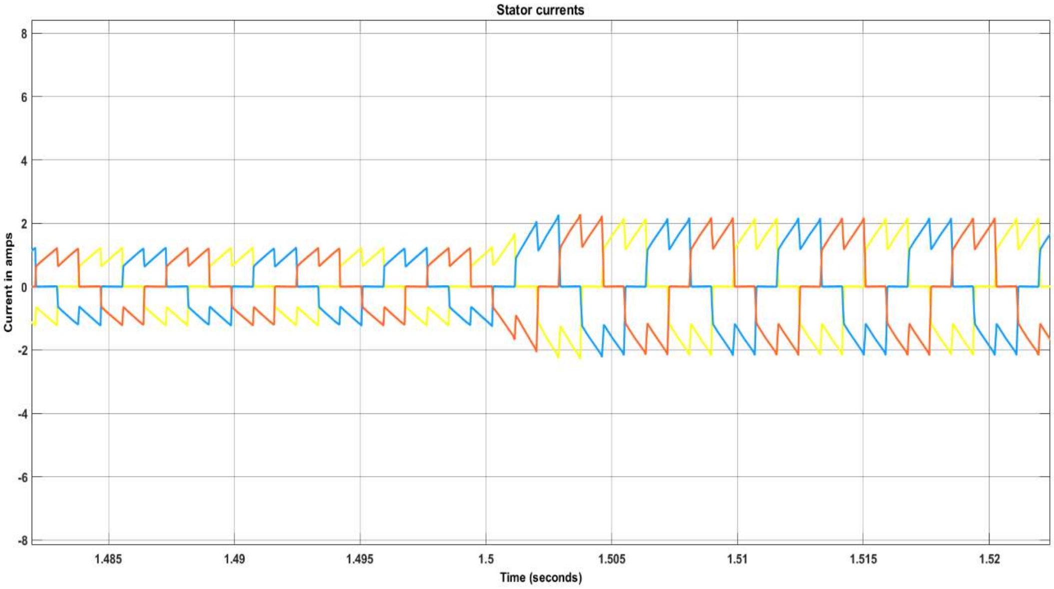

Fig.3.10. Stator currents in amps

3.8 Summary

This chapter has given a brief about working and mathematical analysis of 120-degree commutation of BLDC Motor with sensored mode. In this chapter, 120-degree commutation with hall sensors is verified by simulating the model. Simulated results are matching with theoretical results. This chapter also explained about the parameters to be considered for choosing hall sensor for particular application and how these factors impact motor efficiency.

CHAPTER 4

SENSOR-LESS CONTROL OF BLDC MOTOR

4.1 Background

In zero-crossing approach, back emfs generated are used to decide switching pattern. By analyzing the changes in all three back emfs of the motor as well as the switching pattern at which particular transition occurs, hall sensor outputs are deduced. This can be done using decoder of hall sensors. Decoder is generally used in sensored drives of BLDC motors with 120-degree commutation in electric vehicle. Motor should be in running condition for observing the changes in back emf, to get switching pulses for switches. So, initially the model with hall sensors is used for a very short duration and then switched back to sensor-less mode. Line voltages of the inverter are used to generate back emfs, in which changes need to be observed. In this work, 120-degree commutation is used. The sensored and sensor-less commutation modes of operation are explained. Results are presented using Matlab software. Results of sensor-less mode operation are exactly matching with that of sensored model.

There are particular cases in which this model can be used in an effective way. One such case is, as a backup to the models with hall sensors, in applications like electric vehicles. In such systems, failing of one or more hall sensors affect complete working. Proposed method is simple and reliable in such cases.

Another case could be when the system is utilizing a sensor-less backup along with sensored mode where the transition from the sensored mode to the sensor-less mode affects dynamic performance of the motor. There are also cases where BLDC motor is used for application where the load torque is quite high resulting in high current. This high current increases the temperature of motor which may affect the functionality and reliability of hall sensors. In such cases also, this model could be an effective option.

4.2 Block Diagram of proposed work

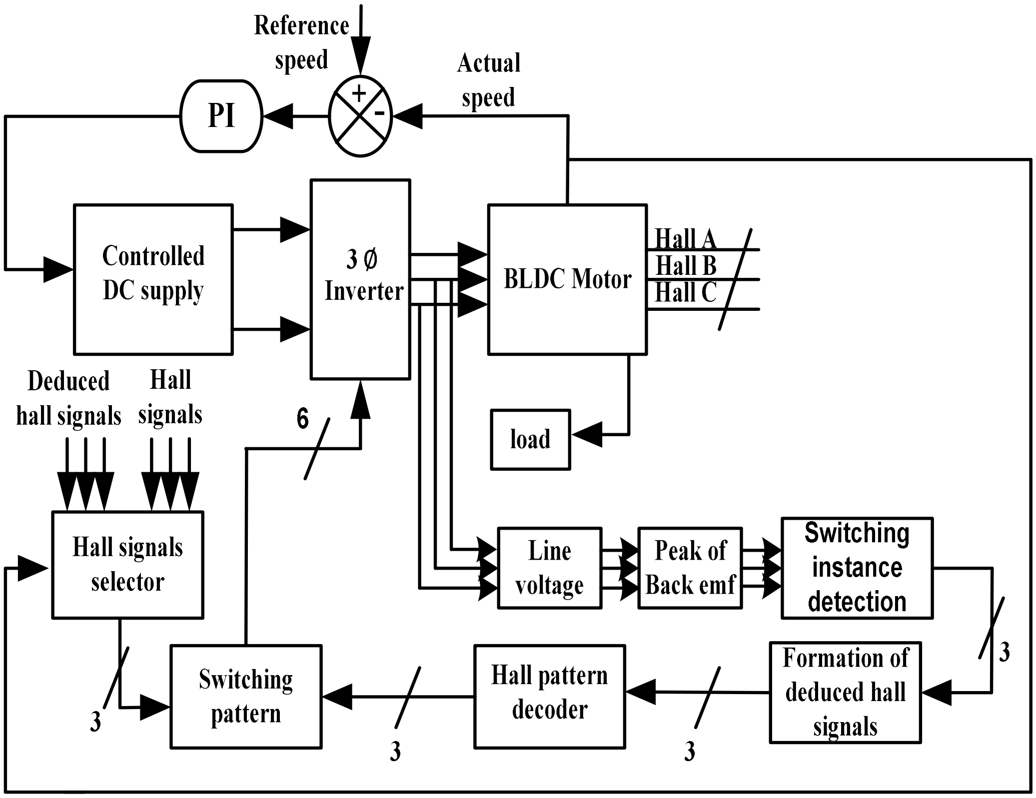

Fig.4.1. System block diagram

Fig4.1 shows the system block diagram of the proposed method. The system consists of a three-phase inverter using MOSFETs as switches for driving a BLDC motor.

A PI controller is used to make the motor operate at the desired speed and speed error signal is given to control the DC voltage to inverter. Initially, the motor is operated using hall sensors and then shifted to proposed sensor-less model and this has been done using hall sensor selector. Hall sensor selector takes speed as input. When the threshold speed is reached, hall sensor selector shifts from sensored to sensor-less method.

Based on the position of the rotor, outputs have been received from hall sensors and based on the sequence of hall sensors output, next switching pattern is given to MOSFETs in the form of pulses. This activates corresponding phases in motor and motor keeps running. This is consistent with sensored mode operation of BLDC motor. In sensor-less mode, hall signals have been deduced, which need to be sent to decoder circuit to generate next switching pattern. Using the measured phase voltages, Line voltages are obtained. Then back emfs are derived from line voltages. The zero crossing of the back emf waveforms are identified and are used to obtain the triggering points and the duration of switching. Then corresponding hall signals are deduced by observing the switching pattern using hall sensor decoder.

4.3 Design and implementation of proposed technique

A BLDC motor can be modelled in the same way as that of a three-phase synchronous machine. Certain dynamic characteristics differs since the rotor consists of a permanent magnet. Generally, flux linkage from rotor to stator depends on magnet used. As a result, saturation of the magnetic flux linkage is common in these motors. It is not necessary for the source to be sinusoidal. As long as the peak voltage does not exceed the motor's maximum voltage limit, a square wave or other wave shape can be used. A star connected, three-phase BLDC motor with rotor made up of permanent magnets, driven by a three-phase inverter is taken. Assumptions made for the mathematical modelling of this motor are as follows: [7]

i. To avoid saturation, motor is operated at current less than rated current and maintained uniform air gap. (neglected saturation)

ii. Motor is isotropic.

iii. Uniform air gap is maintained throughout.

iv. Saliency (due to the usage of permanent magnets in rotor) and damper windings effects are neglected.

v. Small losses like stray and iron losses have been neglected.

vi. Due to harmonic fields of stator, the induced current in rotor is neglected.

vii. Motor’s phases are balanced and rotor has permanent magnets with trapezoidal back emf shape.

viii. Compared to self-inductance, mutual inductance between the windings is negligible. Phase voltages are given as follows:

$$V_{an} = L_{an}\frac{di_{an}}{dt} + R_{an}i_{an}+e_{an} \quad \text{--(4.1)}$$

$$V_{bn} = L_{bn}\frac{di_{bn}}{dt} + R_{bn}i_{bn} + e_{bn} \quad \text{--(4.2)}$$

$$V_{cn} = L_{cn}\frac{di_{cn}}{dt} + R_{cn}i_{cn} + e_{cn} \quad \text{--(4.3)}$$

Where,

$V_{an,}$ V_{bn} and $V_{cn,}$are the voltages of respective phases with respect to neutral.

$i_a,$ i_b and i_c are the respective currents of phases.

R_{an},R_{bn} and R_{cn} are the stator resistances of respective phases.

L_{an}, L_{bn} and L_{cn} are the inductances of respective phases.

$e_{an,}$ e_{bn} and e_{cn} are the back emfs of respective phases.

Using (3.1), (3.2) and (3.3), line voltages obtained from phase voltages are as follows:

$$V_{ab} = V_{an} - V_{bn} = L\frac{d(i_a - i_b)}{dt} + R(i_a - i_b) + e_{an} - e_{bn} \quad \text{--(4.4)}$$

$$V_{bc} = V_{bn} - V_{cn} = L\frac{d(i_b - i_c)}{dt} + R(i_b - i_c) + e_{bn} - e_{cn} \quad \text{--(4.5)}$$

$$V_{ca} = V_{cn} - V_{an} = L\frac{d(i_c - i_a)}{dt} + R(i_c - i_a) + e_{cn} - e_{an} \quad \text{--(4.6)}$$

Where,

V_{ab}, V_{bc}, V_{ca} are line voltages.

Without neutral point also, these voltages can be estimated, by measuring voltage with respect to negative dc bus voltage. The difference between any two line voltages is given by,

$$V_{abbc} = V_{ab} - V_{bc}$$

$$= L\frac{d(i_a - 2i_b + i_c)}{dt} + R(i_a - 2i_b + i_c) + e_{an} - 2e_{bn} + e_{cn} \quad \text{--(4.7)}$$

Consider the interval in which phase B is open, phases C and A are conducting which is indicated by the region shaded in Fig.4.2. Phase C, in this interval is connected to negative voltage and phase A is connected to positive voltage with phase B open. Hence, $i_b = 0$ and $i_a = -i_c$, making back emf of phases A and phase C as opposite as well as equal. In this interval, difference of line voltages is given by,

$$V_{abbc} = V_{ab} - V_{bc} = e_{an} - 2e_{bn} + e_{cn} = -2e_{bn} \quad \text{--(4.8)}$$

Similarly, e_{an} as well as e_{cn} can be obtained.

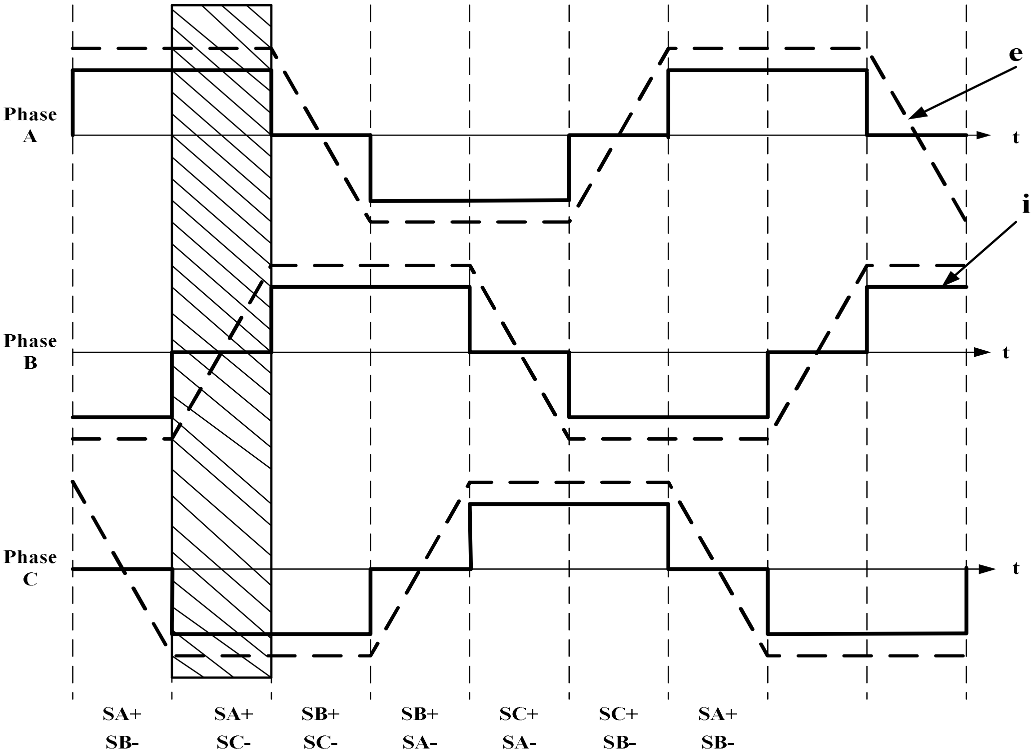

Fig.4.2. Switching instance detection with back emf transitions

Obtained back emfs are adjusted. One emf is either raising or falling while other two back emfs are constant at any instant of time. From the back emfs variation in all three phases and by checking the zero crossing of them in raising and falling directions, interval of each switching pattern can be decided.

Hence, hall signals can be estimated and are given to decoder and the decoder's signals are used to trigger the corresponding switches to be ON. The hall signal decoder for generating switching pattern is shown in the table I, which decides the switches to be ON for particular section according to the previous switching pattern and new hall signal state. The generated new hall signal states will be sent to decoder further and this decides switching sequence and sends pulses to trigger the switches of the inverter. Based on the switching sequence, windings of stator of BLDC motor gets energized and based on rotor position, new deduced hall signals gets generated.

Rotor speed is calculated as given below:

$$\omega_m = \frac{e_a i_a + e_b i_b + e_c i_c}{\tau_e} \qquad \text{--(4.9)}$$

Where,

$$\tau_e = K_t[f(\theta_e)i_a + f(\theta_e - \frac{2\pi}{3})i_b + f(\theta_e + \frac{2\pi}{3})i_c \qquad \text{--(4.10)}$$

Here,

ω_m is rotor speed in radians per second,

τ_e is electromagnetic torque in N-m,

K_t is torque constant in N-m/A,

$f(\theta_e)$ is function for trapezoidal back emf given by,

$$f(\theta_e) =$$

$$\begin{array}{ll} 1 & 0 \le \theta_e < \frac{2\pi}{3} \\ 1 - \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right) & \frac{2\pi}{3} \le \theta_e < \pi \\ -1 & \pi \le \theta_e < \frac{5\pi}{3} \\ -1 + \frac{6}{\pi}\left(\theta_e - \frac{5\pi}{3}\right) & \frac{5\pi}{3} \le \theta_e < 2\pi \qquad \text{--(4.11)} \end{array}$$

Speed in rpm in terms of hall transitions can be given by,

$$N_m = \frac{60}{(\frac{p}{2})6\Delta t} \qquad \text{--(4.12)}$$

Where,

p is number of pole pairs,

Δt is hall transition time

4.4 Flowchart of proposed model

Fig.3. shows flowchart of the proposed model. At starting, as back emfs are zero, hall sensors signals are utilized for generation of switching pattern thereafter, deduced hall sensor model is used for generation of switching pattern as shown in the flow chart. Transition of the model from sensored to sensor-less utilizing speed as input through hall selector, inputs which are being measured and utilized for sensor-less approach can be understood from this flowchart.

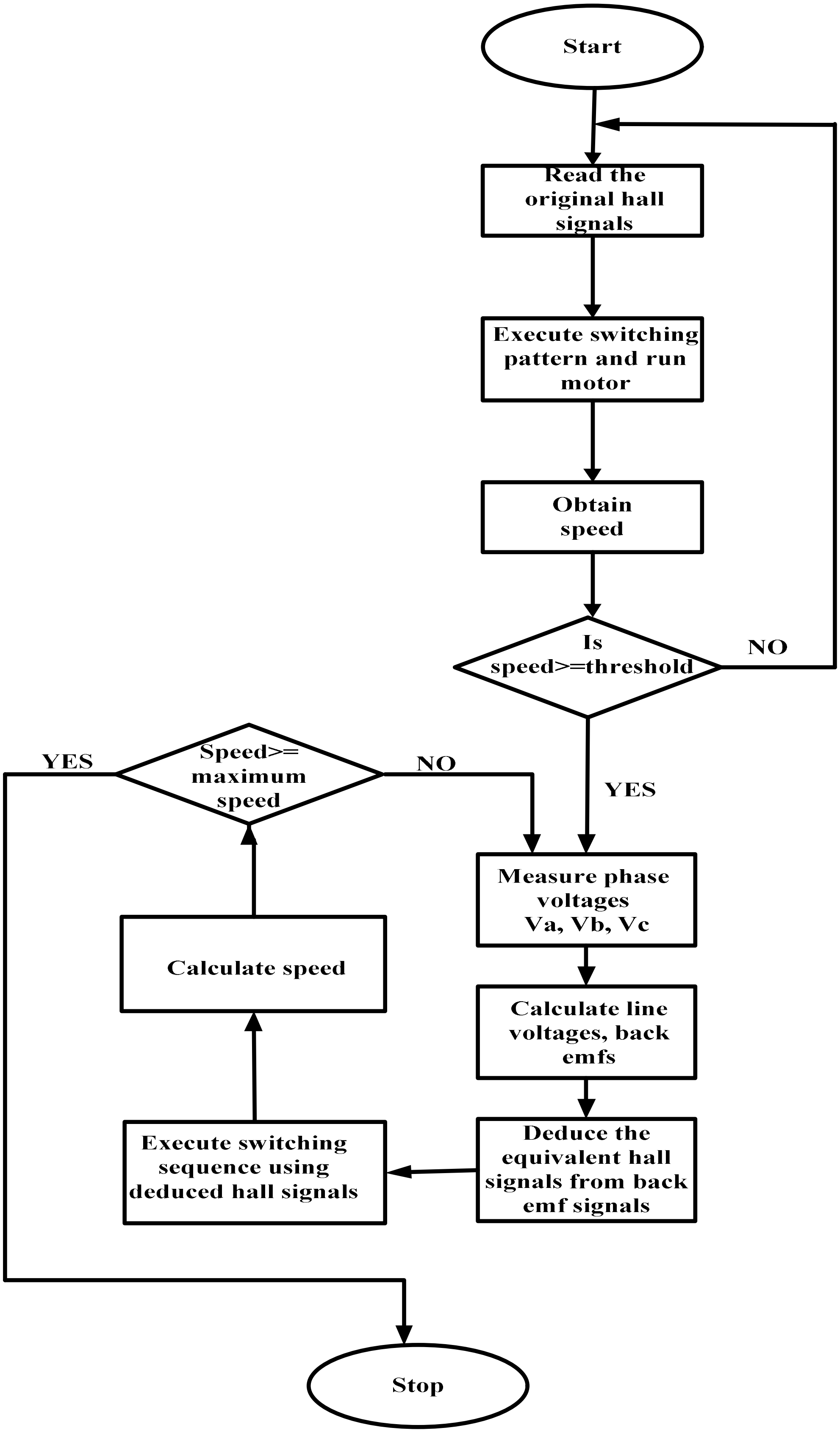

Fig.4.3. Flow chart of the proposed model

4.5 Summary

This chapter has explained about the work that is carried out on sensor-less commutation of BLDC motor through back EMFs, which have been obtained from line voltages of stator windings. This also explained the need for using sensored approach in the proposed work at the time of starting.

CHAPTER 5

SIMULATION AND RESULTS

5.1 Simulation

BLDC Motor using sensor-less mode of commutation is modelled and simulated in MATLAB. A 1kW, 48V BLDC motor with the rated speed of 3000 rpm is taken. Rest of the parameters specified in Table 5.1 are used in simulation. The motor is operated under various operating conditions such as:

i. Rated speed and constant torque operation.

ii. Linearly increasing speed with step variation of torque.

TABLE 5.1 MODEL PROPERTIES

Machine Parameters		
Number of pole pairs, p	4	
Resistance of stator per phase, R_s	2.8750	Ω
Self-inductance of stator per phase, L_s	8.5	mH
Mutual inductance of stator, M_s	0.00001	H
Rotor inertia J_m	0.0008	Kgm^2
Flux linkage Ψ_m	0.175	Wb
Rated Speed	3000	RPM
Rated Power	1	kW
Electromagnetic torque τ	3.18	N-m

5.1.1 Matlab simulation model

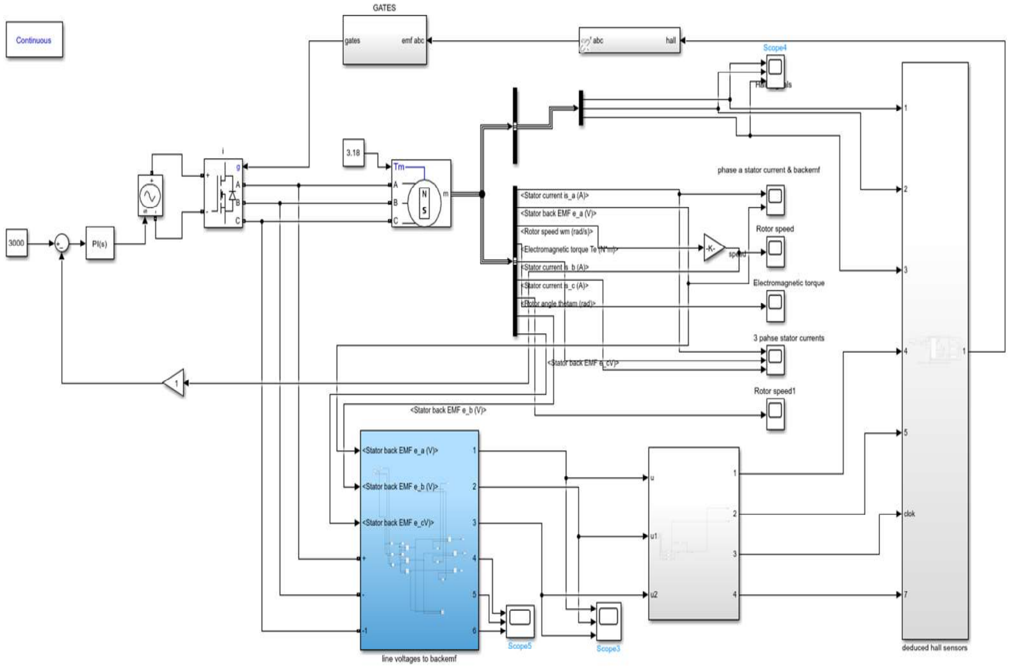

Fig.5.1. Matlab simulink model of the proposed drive system

5.2 Results

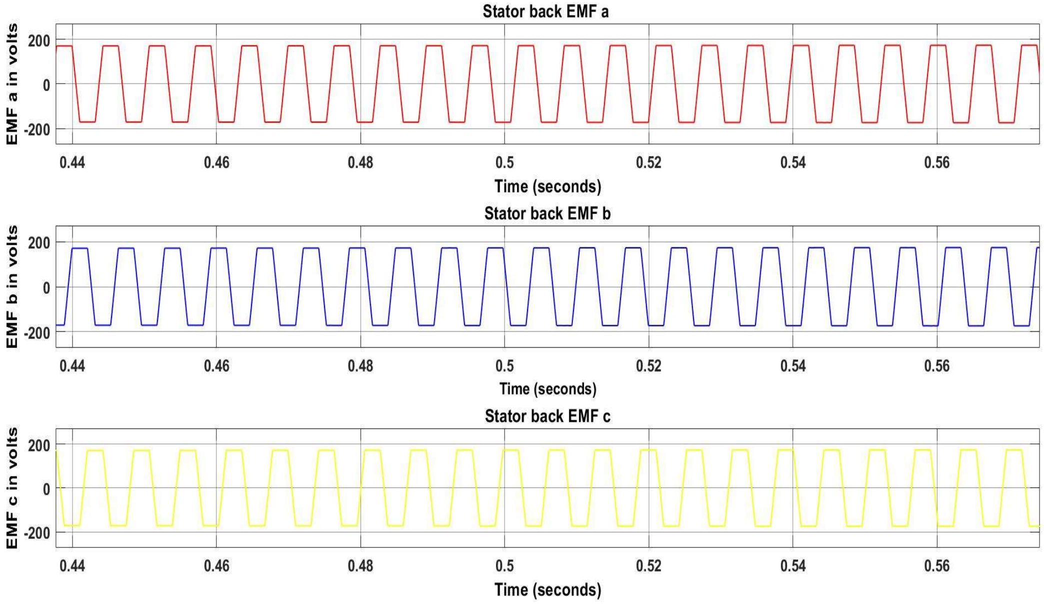

Fig.5.2. Generated Back emfs of motor

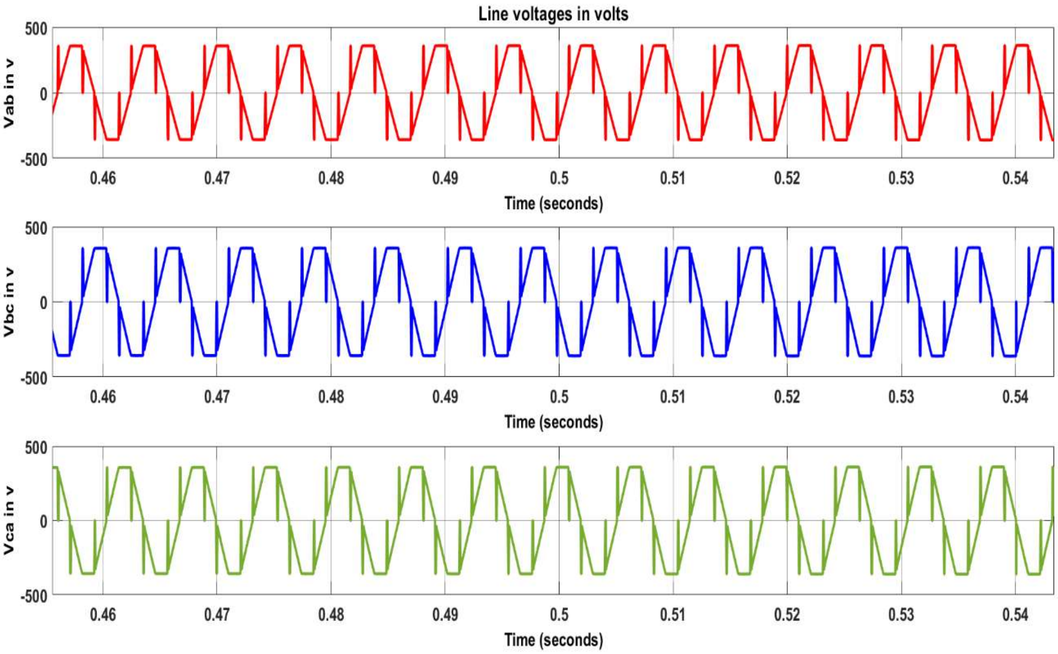

Fig.5.3. Line voltages obtained from inverter output

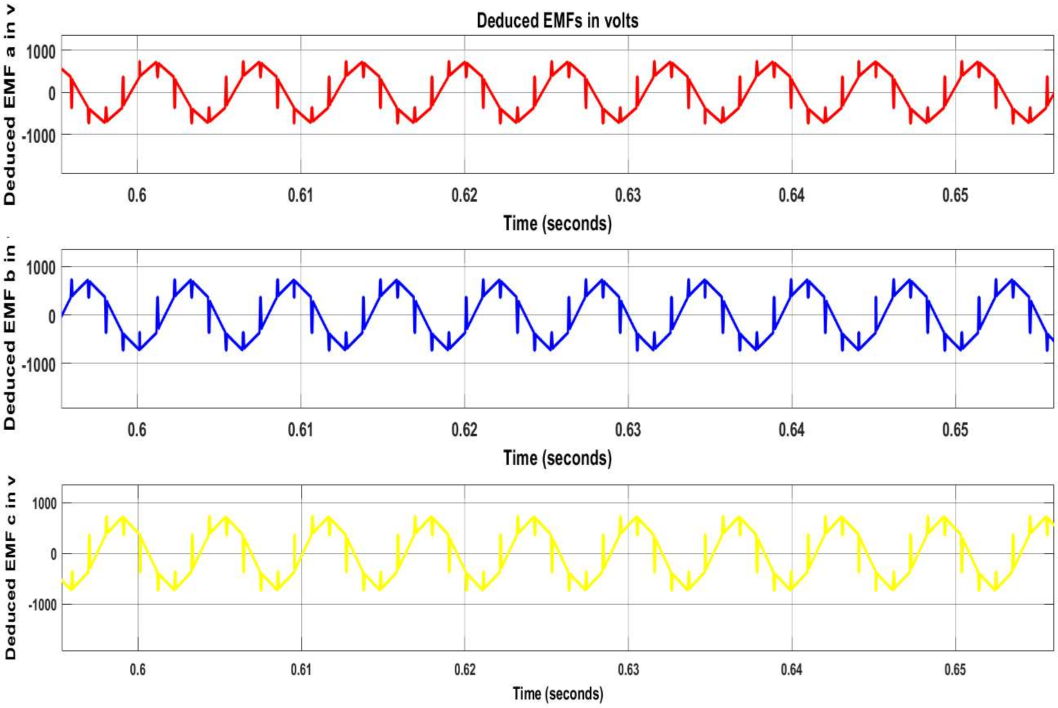

Fig.5.4. Deduced EMFs from line voltages

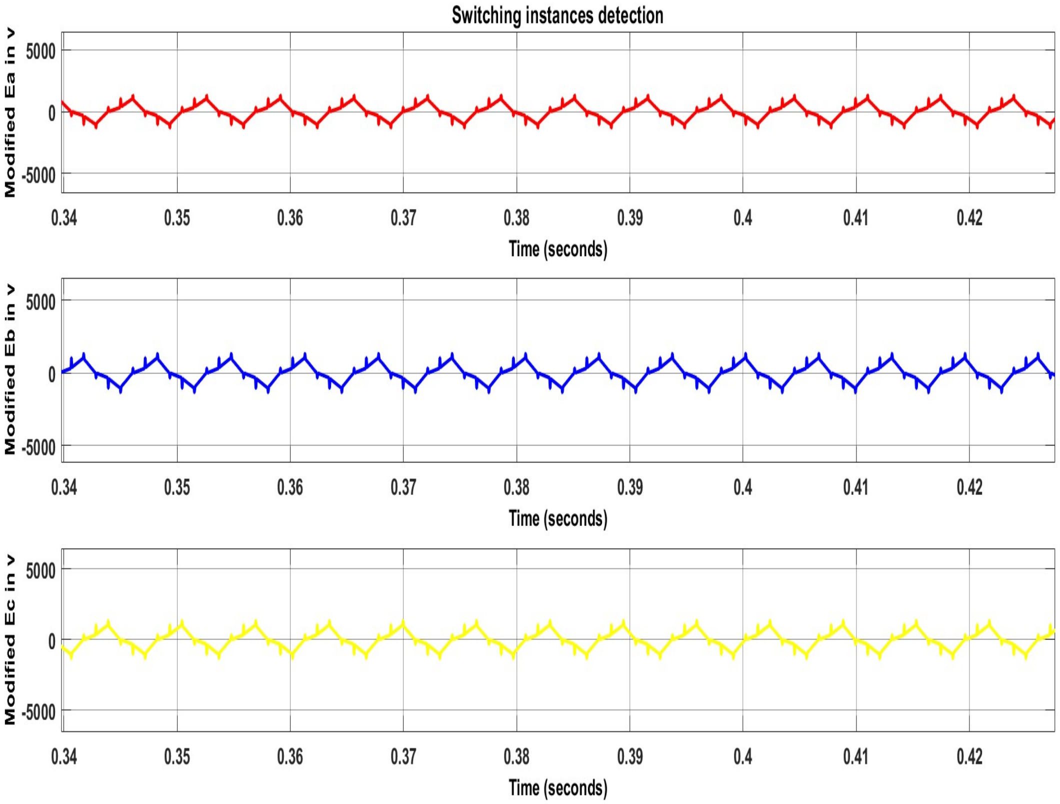

Fig.5.5 Modification of deduced Back EMFs to detect switching pattern

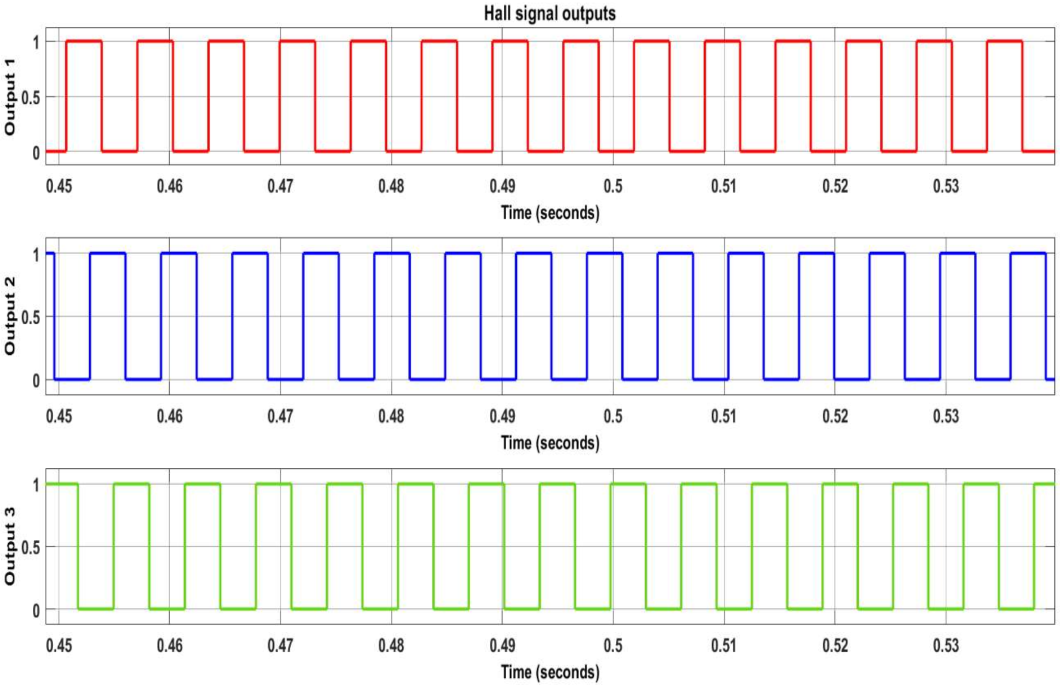

Fig.5.6. Deduced hall sensor equivalent signals

5.2.1 Rated speed and constant torque operation

The motor is Initially operated at rated speed of 3000 rpm and constant torque of 1 N-m. Till 0.5 seconds, hall signals have been used. After 0.5 seconds, proposed method has been implemented. In this case, initial speed of operation for constant speed and torque case is 2700 rpm when reference speed is 3000rpm.

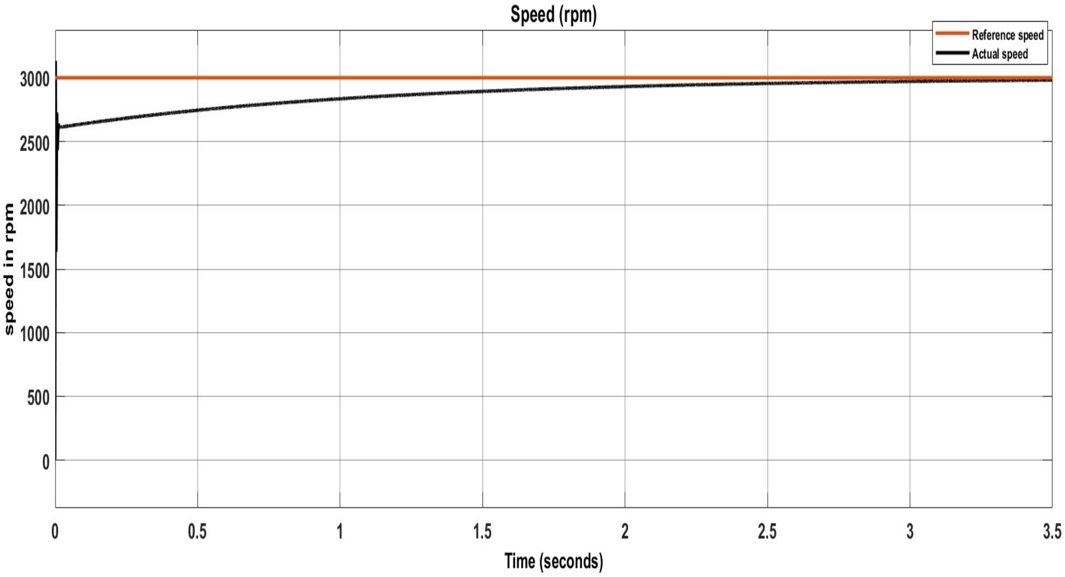

Fig.5.7. Rotor speed in rpm for complete simulation time

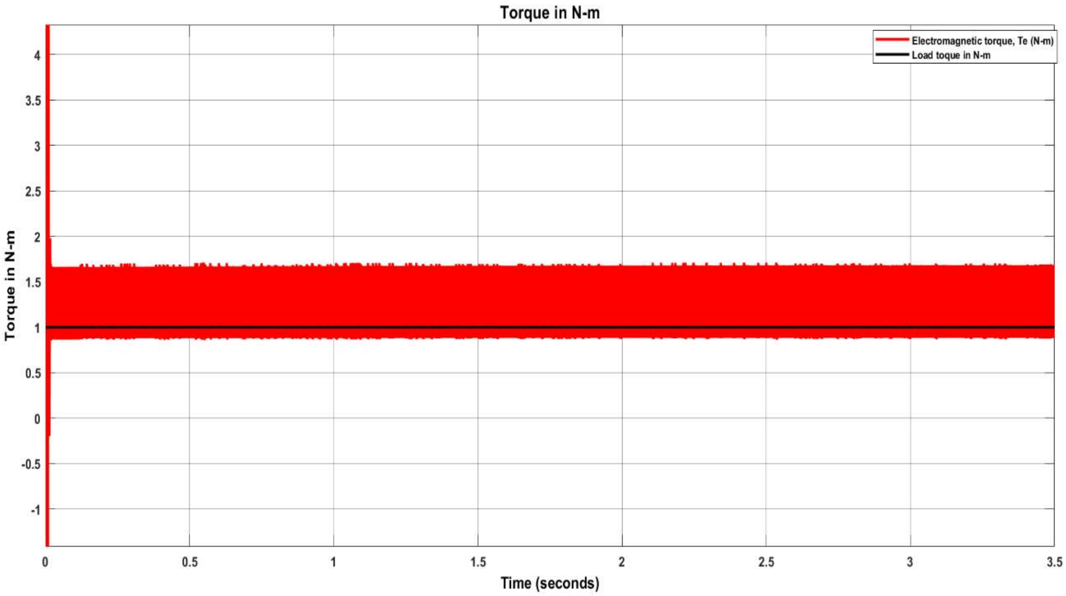

Fig.5.8. Rotor torque in N-m

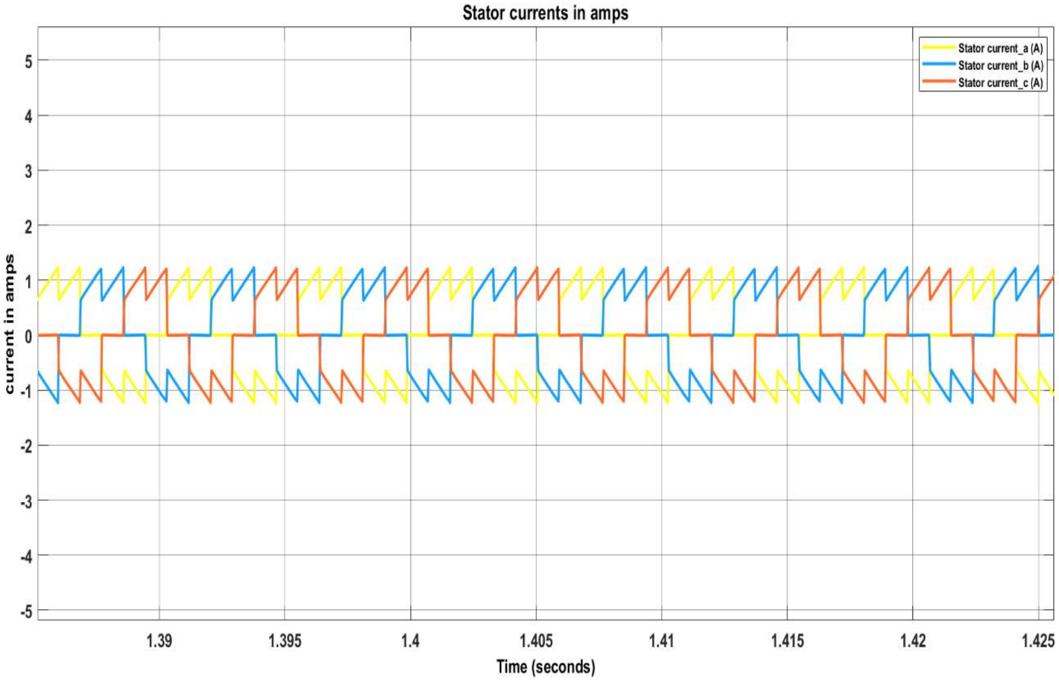

Fig.5.9. Stator currents in amps

5.2.2 Linearly increasing speed with step variation of torque

In the second case, motor is operated for linearly varying speed from 2500- 3000 rpm and step change in torque from 1 N-m to rated torque of 3.18 N-m as shown in fig.7. At 0.5 seconds, reference speed is 2570 rpm and the motor's speed is 2350 rpm. So, for this case, this is initial speed of operation when shifted to the proposed method.

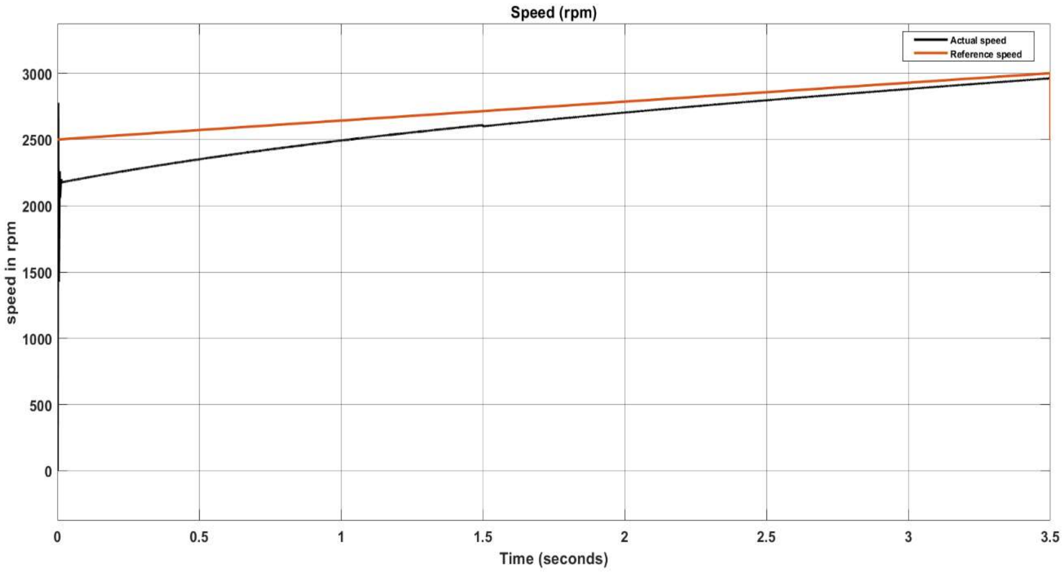

Fig.5.10. Rotor speed in rpm for full simulation time

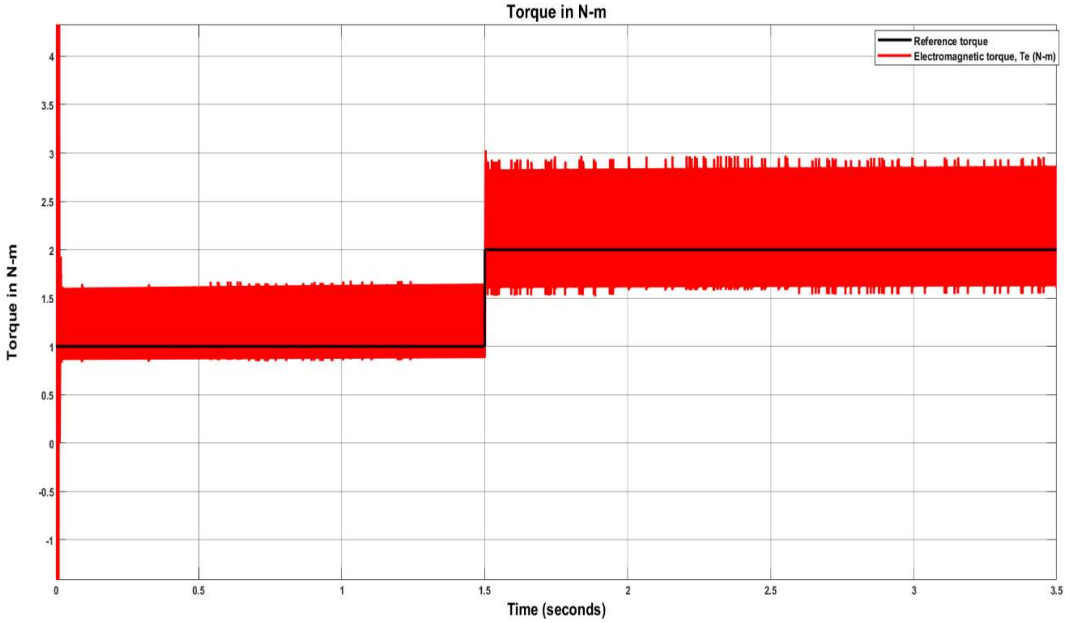

Fig.5.11. Rotor torque in N-m

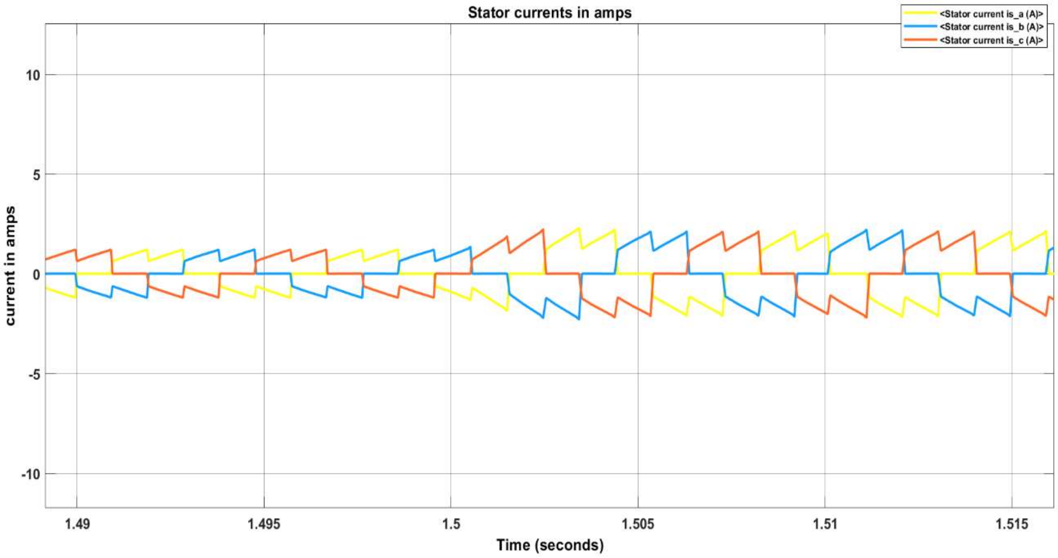

Fig.5.12. Stator currents in amps

5.3 Analysis and discussions

The dynamic response of the proposed method are presented in Fig.5.1-5.12. The line voltages, back emf of motor, modified emfs to detect zero crossing in the waveforms, stator currents, motor speed, torque waveforms are presented for analysis. Observations that can be made from the above results are given below:

i. Reference speed given to the motor is rated speed and it is observed from Fig. 5.7. that motor is able to run at desired speed and results are exactly same as that of with hall sensors, means deduced signals are working accurately.

ii. Constant torque of 1 N-m is given as load torque as shown in Fig.5.8. It is observed that motor is able to track the speed and torque, throughout the simulation range.

iii. It is observed that all three modified emfs are displaced at 120° because of trapezoidal commutation of motor.

iv. The deduced hall sensor signals are in sink with back emf variations which shows that the deduced hall signals are working accurately.

It is seen that the proposed method is able to handle sudden load change along with varying reference speed.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE OF WORK

6.1 Conclusion

BLDC motor has been used in various applications because of it's high efficiency, low maintenance and many advantages. Since these motors are electronically commutated, sensing of position is necessary. Most of the applications uses hall sensors for this but some harsh working environments may make sensor fail or false detection. So, a sensor-less method has been proposed. This thesis work presents simulation and analysis of the sensored method which uses hall sensors as well as sensor-less BLDC motor control methods by using equivalent hall signals deduced using line voltages in a detailed manner.

At the time of starting or when the speed of motor is low, back EMF that is generated is low as back EMF is proportional to speed of motor, for which detection of switching pattern is not possible and hence the Motor has been started using original hall sensor values and later on shifted to the proposed method. The transition from starting method to the proposed method is also presented in the work. Further, the motor drive is tested on linearly varying speed up to rated speed and step load torque varying up to full rated load torque using the proposed method.

- Switching from the sensored mode to sensor-less mode using this method is verified to be smooth.
- The working of proposed method is verified by comparing the line voltages, stator currents, back emf waveforms.
- Method is tested for rated speed with constant torque and the motor is able to catch up the load.
- Method is tested for a sudden step load increase with linearly varying speed and the drive is able to sustain the operation smoothly.
- As the transition is happening electronically, switching from sensored to sensor-less approach is faster. Hence, dynamic response of the motor is good.

6.2 Future scope

From the above observations made and from the obtained results shown in above, it is found that the simulated model is best suitable for the below mentioned applications:

i. This method is using hall sensors for very small duration making it sensor-less, sensored and sensor-less modes both can be combined as required by the type of application for which BLDC motor being used.

ii. It can be used as a backup method for sensored applications. This is simple and easy to implement.

iii. It can be used as fast fault tolerant method in case of hall sensors failure.

iv. Shifting of mode from sensored to sensor-less is very smooth with no disturbances which improves overall dynamic performance in the applications for which this method is used.

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LIST OF COMMUNICATED PAPERS

1. Kamma Ranjani and Mini Sreejeth, “Simulation and Analysis of Proposed Technique for BLDC Motor Drive Running on Deduced Hall Sensor Equivalents” IEEE-Sponsored Third International Virtual Conference on Power Engineering Computing and Control (PECCON), May, 2022.[accepted]