SPEED CONTROL AND COMPENSATION OF TORQUE RIPPLE IN BLDC MOTOR USING SPIDER BASED SLIDING MODE CONTROLLER

A PROJECT REPORT

submitted by

AKHIL ALEX
(Reg. No. TKM20EEII02)

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with specialisation in

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Department of Electrical and Electronics Engineering
TKM College of Engineering
Kollam - 691005
KERALA

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DECLARATION

I undersigned hereby declare that the project report entitled "**Speed Control And Compensation Of Torque Ripple In Bldc Motor Using Spider Based Sliding Mode Controller**", submitted for partial fulfillment of the requirements for the award of degree of Master of Technology in Electrical and Electronics Engineering with specialisation in Industrial Instrumentation and Control, of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of *Prof. Sumayya Jaleel*, Assistant Professor, Department of Electrical and Electronics Engineering. This submission represents my ideas in my own words and where ideas or words of others have been included. I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

Kollam
July 01, 2022

AKHIL ALEX

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

TKM COLLEGE OF ENGINEERING

KOLLAM - 691005

CERTIFICATE

This is to certify that the report entitled " **Speed Control And Compensation Of Torque Ripple in Bldc Motor Using Spider Based Sliding Mode Controller** " submitted by **AKHIL ALEX** , **(Reg. No. TKM20EEII02)** of fourth semester to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electrical and Electronics Engineering with specialisation in Industrial Instrumentation and Control, is a bonafide record of the project work done by him under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

Prof. Sumayya Jaleel Project supervisor Assistant Professor Department of EEE TKM College of Engineering	**Prof. Sumayya Jaleel** Project Coordinator Assistant Professor Department of EEE TKM College of Engineering
Prof. Shanavas T N PG Coordinator Associate Professor Department of EEE TKM College of Engineering	**Dr. Sabeena Beevi K** Head of the Department Associate Professor Department of EEE TKM College of Engineering

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Abstract

Brushless DC (BLDC) motors are used in a wide variety of industrial & domestic applications like CNC machines, industrial robots, and so forth. Since there are no brushes in BLDC motor, the commutation is carried out electronically. Position sensors are used to determine the rotor's position. Every 60 electrical degrees, the motor requires information regarding the position of rotor. As a consequence, 3 hall effect sensors are being used. When the back electromotive force waveform is trapezoidal, the produced torque in a BLDC is constant under ideal circumstances. The output torque, however, exhibits torque ripple. This torque ripple can approach 50% of the average torque in sensorless motor drives, resulting in noise, vibrations, and serious failures. On the other hand, smooth torque is essential for better performance in household and commercial applications. In order to achieve instantaneous torque with no ripple, it is crucial to reduce this torque in BLDC motors. This research therefore suggests a tiny capacitor dc link-based torque ripple reduction technique. In order to quickly settle the system and prevent torque ripples, the capacitor is managed by a spider-based controller that was developed using the spider's cobweb-building activity. The Spider-based controller is designed to generate the capacitor control signal. A first-order sliding mode controller built on the proportional reaching law is also used to control the speed performance. The impact of using a spider based small DC link capacitor switching on the decrease of torque ripple is studied. The merits of the proposed control technique in terms of settling time and torque ripple are then examined by comparing it with SMC only and Spider based PID.

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Abbreviations

ABC	Artificial Bee Colony
AIOFL	Adaptive Input Output Feedback Linearization
ANN	Artificial Neural Network
BLDC	Brushless Direct Current motor
DTC	Direct Torque Control
FLC	Fuzzy Logic Controller
GA	Genetic Algorithm
PID	Proportional Integral Derivative
PSO	Particle Swarm Optimization
PWM	Pulse Width Modulation
SMC	Sliding Mode Control
TIC	Taylor Instrumental Company
VSC	Variable Structure Control

Notations

V_m	Amplitude of input voltage, V
f	Frequency, Hz
V_a, V_b, V_c	Phase Voltages, V
I_a, I_b, I_c	Phase currents, A
R	Resistance of each phase in BLDC, Ω
L	Inductance of each phase in BLDC , mH
M	Mutual Inductance, mH
E_a, E_b, E_c	Back-EMF of phase a,b,c, V
T_a, T_b, T_c	Torque produced by each phase, Nm
Ω_m	Angular speed of rotor, rad/s
Θ_m	Mechanical angle of rotor, rad
K_e	Back-EMF constant, $\frac{v}{rad.s^-1}$
K_t	Torque Constant, $\frac{Nm}{A}$

Chapter 1

INTRODUCTION

1.1 Overview

The Brushless DC (BLDC) motor is quickly earning acceptance due to its use in a variety of industries, including instrumentation, industrial automation equipment, automotive, aerospace, consumer goods, and consumer electronics. The benefits of BLDC motors over induction and brushed DC motors are numerous [1]. Some of these include: improved speed-to-torque characteristics; high dynamic responsiveness; high efficiency; longer life; low noise; and higher speed ranges. The BLDC motors are electronically commutated rather than using brushes, as the name suggests. Position sensors are used in this type of commutation to determine the rotor position in relation to the stator winding. Every 60 electrical degrees, a 3-phase BLDC motor needs information regarding the position of rotor. Consequently, 3 Hall sensors are employed. The counter-EMF waveform has a significant impact on the BLDC motor's torque. In Bldc motors, when the back electromotive force (BEMF) waveform of a brushless DC motor(BLDC) is of the trapezoidal type, the resultant torque is constant under ideal circumstances. However, because to the actual layout of the motor and its specifications, there is practically torque ripple in the output torque. Due to this, torque ripple is created which varies with speed and reaches a maximum of 50% of the typical torque. Consequently, they cause vibrations, noise, and significant faults in sensorless motor drives. To use a BLDC motor for household applications, the torque must be reduced. Typically, there are three types of torque in BLDC: 1) cogging torque 2) reluctance torque and 3) mutual torque. Due to the coreless stator design of BLDC motors, harmonics caused by back-EMF and flux coupling are also absent.Thus, there is no greater impact caused by cogging & reluctance components. The mutual torque, however, only results in an actual ripple. The ripples are significantly lessened when the back-EMF and phase current waveform of specific phases are well-coordinated.

A diode rectifier, a bulkier dc link capacitor, and an inverter with rotor position feedback make up a typical BLDC motor drive.In this work, a dc link capacitor is used to achieve the torque ripple compensation. The pulse delivered to the small capacitor is managed by a control switch. A spider-based SMC controller is used to provide the gate pulses needed for the capacitor switch and to regulate the speed of the BLDC motor.

1.2 Objective

A BLDC motor is a permanent magnet synchronous motor that controls the armature currents using position detectors and an inverter. The bldc motor is frequently referred to as an inside-out dc motor since its armature is in the stator and the magnets are on the rotor and its operating characteristics match those of a dc motor. The commutation is done electronically rather than a mechanically like that in traditional dc motor, making it practically maintenance-free. Position sensors are used in this type of commutation to determine the rotor position with relation to the stator winding. At every 60 electrical degrees, a three-phase BLDC motor needs information regarding the rotor position. Three Hall Effect sensors are therefore employed. However, to get a smooth response in torque and speed with a low ripple content, the motor must be controlled.
The specific objectives are as follows:

- Modelling the BLDC motor.
- Developing Sliding Mode Controller.
- Torque ripple compensation by capacitor switching
- Simulation and Evaluation of results.
- Finally, the performance of Spider-SMC controller is compared with the Spider-PID controller

1.3 Organisation of the report

This report is organised as follows, Chapter 2 presents a deep literature review. Chapter 3 describes about the working and modelling of BLDC motor. Chapter 4 provides the torque analysis and torque ripple reduction strategy.Chapter 5 gives an idea about the proposed model, including brief idea on each controllers used. Chapter 6 provides the modelling of controllers that have been used in this work. Simulation Results are presented in Chapter 7. Chapter 8 includes the conclusion suggestions concerning the work and future scope.

Chapter 2

LITERATURE REVIEW

2.1 Overview

In BLDC, the produced torque is constant under ideal circumstances when the back electromotive force waveform is of the trapezoidal type. However, actually, the shape of the trapezoidal back EMF is influenced by the inductance effect of winding and forces the torque to fluctuate. This fluctuations are referred to as Torque ripple. This torque ripple varies with speed and touches 50% of the typical torque, and they generate noise, vibrations, and severe issues with motor drives. Nevertheless, smooth torque is crucial to get improved performance for usage in industry applications and at home applications. Many methods are presented to reduce torque ripple to achieve the motor's smooth responsiveness.

2.2 Existing Control Techniques

In order to lower component costs, limit enclosure space, and improve reliability, a Brushless direct current motor without dc link capacitor is suggested in [2]. The drive circuit is powered directly from a rectified mains supply under the absence of small dc link capacitor. The lack of the dc link capacitor greatly lowers the cost of the entire motor drive, but at the penalty of torque ripples, which are unavoidable and are anticipated to occur at zero mains supply crossings. The compensation strategies for torque ripple can be broadly divided into two prominent categories. The first widely used method is to physically alter the motor to lessen the torque ripple. This includes modifying the stator and rotor's magnetic designs and the windings [3], in-order to account for the pulsing torque. The other common practise is to adjust the controller. A control approach based on the Adaptive Input Output Feedback Linearization (AIOFL) method is given, in which reference voltages are generated to the three-phase voltage source inverter, in order to obtain a better response with less ripple in the motor's torque [4]. In BLDC motors, the Direct Torque Control (DTC) technique is employed to achieve precise torque control, however it has significant torque ripple and constant switching frequency [5]. The most often used controllers for regulating the speed and torque of BLDC motors are the standard PI and PID controllers. These controllers are simple to create and have a straightforward structure. They do not, however, offer a better response when the load is changing and the dynamic response is poor. In[6], a Fuzzy logic Controller (FLC) was employed to improve the dynamic response of the motor. The primary advantage of FLC is that it improves dynamic reaction while not requiring a mathematical model of the system. However, FLC encounters several challenges when choosing a rule base and membership functions. A conventional PID and FLC combination is utilised as a controller to get a good response from the motor [7]. An Artificial Neural Network (ANN) controller was also used to control BLDC motor speed[8]. It is a strong controller with a lot of data handling capacity. However, it is unable to provide an accurate result because of its offline data training. Recently PID controller tuning methods like Artificial Bee Colony (ABC), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and others [9] were also used in order get better performance.

2.3 Concluding remarks

Motivated by the above discussion and in order to overcome the issues, speed regulation and torque ripple compensation based on spider based SMC is developed.

Chapter 3

BRUSHLESS DC MOTOR

3.1 Overview

An electric motor transforms the electrical energy into mechanical energy. Motors vary depending on their power source and the way by which they produce rotation.

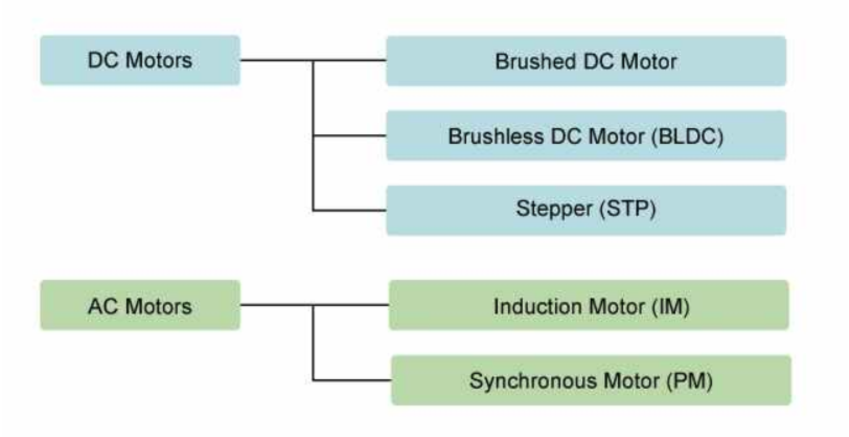


Figure 3.1: Classification of motors

Brushed DC motors are frequently utilised because of their straightforward construction and simple control. They are frequently employed in automobiles. These motors are appropriate for a variety of tasks due to their inexpensive cost. However, one disadvantage is that due to their constant contact, frequent and periodic maintenance is necesssary. A stepper motor is also a DC motor that rotates in a particular angle for each pulse. These motors are frequently employed to execute positioning corrections. Rotation is synchronous with supply current frequency in synchronous motors. The revolving trays in microwave ovens are frequently driven by these motors. In induction motor, thhe rotation speed varies with frequency and are frequently utilised in mixers, fans etc. Of these, brushless DC motors (BLDC) are particularly popular because of their high efficiency and exceptional controllability. This chapter will provide a detailed understanding on the BLDC motor,its construction, operation, advantages, limitations, applications and finally the mathematical modelling.

3.2 BLDC motor

In a conventional dc motor, a commutator-brush combination aids in producing unidirectional torque. Brushless DC motors don't need brushes, as its name suggests. Here, unidirectional torque is produced via an integrated inverter/switching circuit. Because of this, these motors are also called as "electronically commutated motors".

Figure 3.2: Inner rotor BLDC motor

Like all motors, these motors also have a stator and a rotor. The rotor is mounted with permanent magnets, while the stator consists of wounded poles. The inverter/control circuit, also

Figure 3.3: Outer rotor BLDC motor

known as the controller, is frequently included into the stator assembly.

There are two types of BLDC motors based on their construction/design: (i) inner rotor design (ii) outer rotor design.

1) Inrunner(inner rotor design): Here the rotor is placed at the core (center) and the stator winding surrounds it, as shown in Figure 3.2.

2) Outrunner(Outer rotor design): Here stator windings are placed inside while the rotor with permanent magnets, surrounds the stator, as shown in Figure 3.3.

A BLDC motor is essentially a modified PMSM motor with a trapezoidal back-emf rather than a sinusoidal one as in the case of the PMSM. The arrangement of the stator windings and the design of the rotor magnets influence the shape of back emf. Figure 3.6 shows the trapezoidal and sinusoidal back emf. The sinusoidal motor requires a high resolution position sensor because, for best operation, the rotor location must be determined at every instant. More complicated hardware and software are also needed. The trapezoidal motor is more efficient and less expensive. Bldc motors come in a wide variety of forms, but the three phase motor is the most popular because of its effectiveness and minimal torque ripple. The amount of power electronic components required to precisely control the stator currents is reduced with this type of motor, which is another benefit.

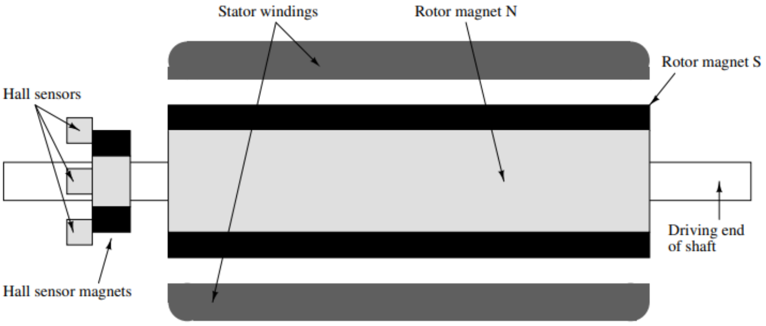


Figure 3.4: BLDC motor transverse section

Figure 3.4 shows a transverse section of a bldc motor. The stator winding needs to be switched on in a specific order for the BLDC motor to move. The position of the rotor, which is determined by the Hall sensor integrated in the stator, must be known in order to determine which winding will receive electricity first in accordance with the order of electrification. The Hall sensor will emit either a high level signal or a low level signal when the rotor magnetic pole passes close by, indicating whether the north magnetic pole or the south magnetic pole is passing by the sensor. The precise order of commutation can be determined using the combination of the three Hall sensor signals.
Due to their advantages like:

- Better speed versus torque characteristics.
- Decreased electric noise generation and a wider speed range.
- Reduced maintenance
- High operating pace both when it is loaded and when it is empty.
- Smaller in size and lighter.
- High efficiency, brushless DC motors do not have excitation loss when compared to AC motors, and do not experience brush friction loss or sparks when compared to brushed DC motors.

These motors are used in wide variety of applications. However it has some limitations:

- A brushless DC motor costs more than a brushed DC motor, and the electronic controller adds to the setup cost as well. This is because traditional motors use a low-cost mechanical commutation system including brushes.
- There are minimal vibrations during low-speed rotation when a brushless DC motor is used. however, at high speed these vibrations are diminished.
- Due to the brushless DC motor's natural, inherent vibration frequency, this frequency might occasionally equal or approach the vibration frequency of the body or plastic parts, leading to the occurrence of resonance phenomena. Although it is normal to see resonance phenomena in many brushless DC motor based devices, this resonance can be decreased through tuning.
- Brushed DC motors are simple to use and have straightforward wiring. After connecting the positive terminal to the positive wire and the negative terminal to the negative wire, the motor will begin to rotate. Due to the use of electronic control and its connection to all of the electromagnets, wiring and operation of brushless DC motors are more complicated.

Some particular applications of BLDC motors include:

- DVD/CD players and hard drives for computers
- Electric and hybrid vehicles
- Various CNC machines, Robots
- Laundry equipments
- Blowers, fans etc

3.3 Construction of BLDC motor

BLDC motors has a stator and a rotor,as shown in Figure 3.5. Different physical configurations of BLDC motors are possible. These motors can be single phase, two phase, or three phase depending on the windings in the stator[10]. The most popular type of motor is a three-phase

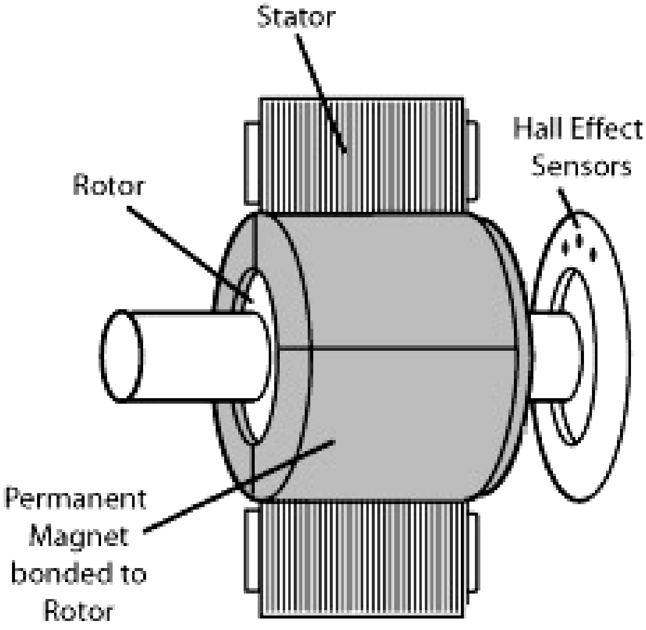


Figure 3.5: Construction of BLDC motor

BLDC with a permanent magnet rotor. It primarily consists of a stator, rotor, and hall sensor.

1. Stator: Steel laminations are piled to form the BLDC motor's rotor, which carries the windings. These windings are inserted into slots that have been axially carved along the stator's inner perimeter.Stator windings, slots are shown in Figure 3.7 . Either a star or a delta arrangement of these windings is possible. But the majority of BLDC motors have a three-phase stator with a star connection.

Numerous interconnected coils are used to build each winding, with one or more coils being inserted into each slot. Each of these windings is dispersed around the stator's periphery to provide an even number of poles. Motors rated at 100 V or greater are utilised for automation systems and industrial applications. The majority of BLDC motors typically have three stator windings coupled in a "Y" or "star" pattern (without a neutral point). The windings can be wound in either trapezoidal or sinusoidal fashion and produce back emf of trapezoidal or sinusoidal shape respectively as in Figure 3.6.

2. Rotor: The rotor of a BLDC motor contains a permanent magnet as in Figure 3.7. Depending on the needs of the application, the rotor's pole count may vary. The material's flux density needs to be high for the motor to produce its greatest amount of torque. To generate

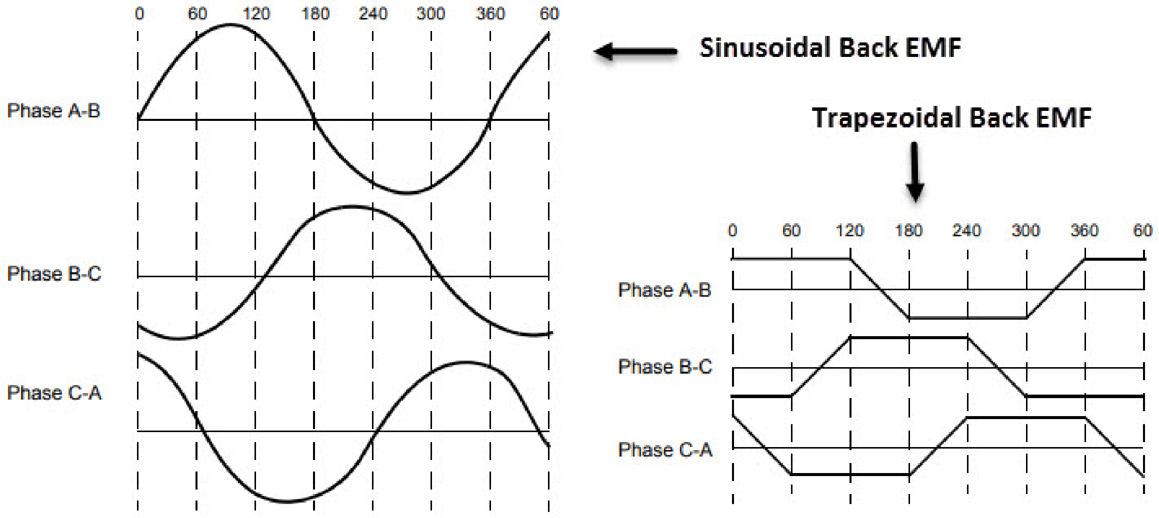


Figure 3.6: Trapezoidal & sinusoidal Back-emf

the necessary magnetic field density, the rotor must be made of an appropriate magnetic material. Magnets made of rare earth alloys are frequently utilised in innovative designs. Samarium Cobalt (SmCo), Neodymium (Nd), and Ferrite, and Boron (NdFeB) are few alloys .
A BLDC motor can be built either with the rotor outside the core and the windings inside, or with the windings outside the core. The motor operates at low current and dissipates less heat in the first configuration because the rotor magnets function as an insulator. It frequently appears in fans. However, the motor dissipates more heat, increasing its torque in the other configuration and hard disc drives make use of it.

3. Position Sensors/ Hall sensors: In a BLDC motor, the commutation is managed electronically because there are no brushes. The windings of the stator must be activated sequentially in order to turn the motor, and the location of the rotor's North and South poles must be known in order to precisely activate a specific set of stator windings.The position of the rotor is often detected and converted into an electrical signal using a position sensor, which is typically a hall sensor (which operates on the concept of the Hall Effect). Since the commutation of BLDC motors is electronically regulated, turning the motor requires sequential energization of the stator windings. Recognizing the location of the rotor is important before activating a specific stator winding. Therefore, the rotor position is sensed by the Hall Effect sensor built inside the stator. The majority of BLDC motors sense the position of the rotor using three integrated Hall Sensors in the stator. The information from the Hall sensor allows the rotor position and stator armature excitation to be synchronised. Every time the rotor poles come within close proxim-

Figure 3.7: Stator & Rotor

ity to a sensor, Low and High signals are generated. Based on the combined responses of these three sensors, it is possible to determine the precise commutation sequence to the stator winding.

3.4 Operation of BLDC motor

The term "electronic commutated motor" is also used to describe BLDC motors. The rotor is devoid of brushes, and electronic commutation is carried out at some rotor positions. The magnetic steel sheets used to construct the stator magnetic circuit are typically magnetic. In addition to being coiled as a single coil on the magnetic pole, the stator phase windings can also be put into the slots. The permanent magnets' magnetization and location on the rotor are selected in a way that produces a trapezoidal-shaped back-EMF. This makes it possible to employ a rotational field with little torque ripple by using a 3-phase voltage system. In contrast to brushless DC motors, which reverse the polarity of the current using semiconductor switches that must be switched in time with the rotor movement, DC commutator motors use commutators and brushes to execute the polarity reversal. The absence of the commutator has another benefit besides increased reliability. Additionally, the DC motor's maximum speed is restricted by the

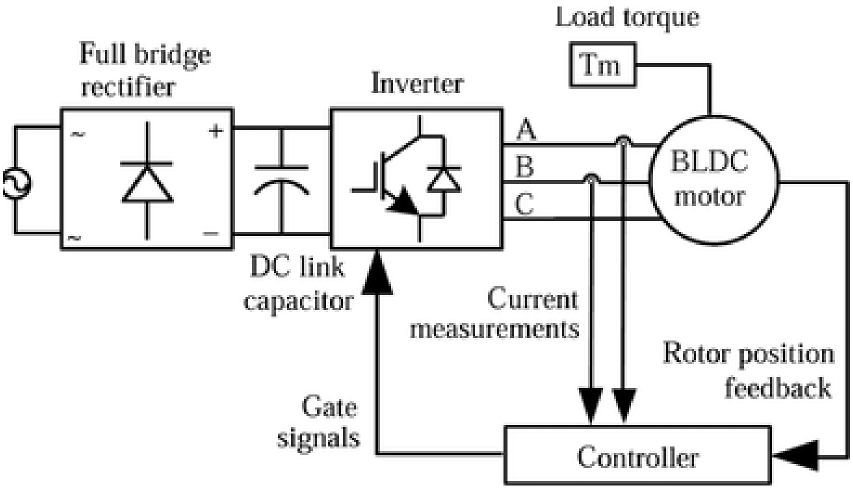
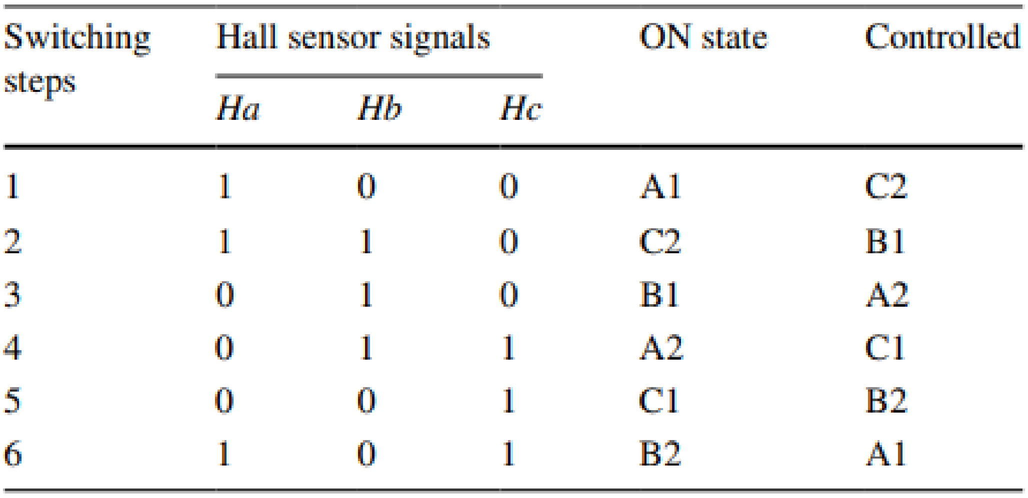


Figure 3.8: BLDC drive with small capacitor



Switching steps	Hall sensor signals			ON state	Controlled
	Ha	*Hb*	*Hc*		
1	1	0	0	A1	C2
2	1	1	0	C2	B1
3	0	1	0	B1	A2
4	0	1	1	A2	C1
5	0	0	1	C1	B2
6	1	0	1	B2	A1

Figure 3.9: Inverter Switching Sequence

commutator. As a result, the BLDC motor can be used in applications, that require high speed. The stator field windings of the BLDC motor receive the pulsing DC. Three pole pairs—X, Y, and Z—are taken into consideration. The poles X1 and X2 magnetise as south and north, respectively, when a DC pulse is passed through pair X. The pulsated DC then travels through Y and then through Z once the current applied to pole pair X is shut off. The magnet will therefore continue to rotate constantly in a clockwise manner. The three pairs of stator coils are electrically commutated to create the rotating field, and this is done with the help of a inverter, which is employed on motor's driver side to act as a 3-phase supply.

Based on the knowledge of the rotor position, only two phases are ever powered on in BLDC motor driver with trapezoidal back emf . The third phase's associated switches are left in the off

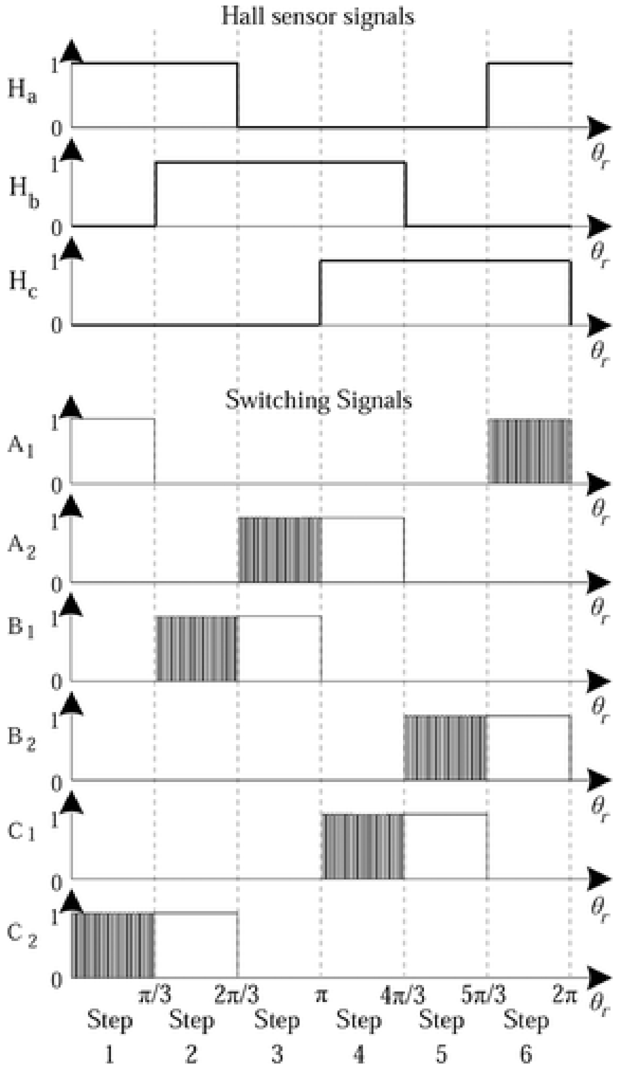


Figure 3.10: Hall sensor outputs

state. As a result, there are never more than two switches on the inverter that are in use. PWM or hysteretic control signals generated by a microprocessor are frequently used to regulate these two switches. Such a switching mechanism is improper for motor drives without a DC link capacitor since there is no continuation path for the phase current during the off state of the two controlled switches.

The switching algorithm used in the proposed BLDC motor drive[11],[13] is based on controlling a single switch and maintaining the other switch in the on state during the switching interval. While the controlled switch is in the off state, the switch that is still on offers a free-flowing path for the inductive current. With the use of rotor position data gathered by Hall effect sensors, the switching states are shown in Figure 3.9. Switching signals and the outputs of Hall effect sensors, represented by the letters Ha, Hb, and Hc, along with rotor position θr, in radians is shown in Figure 3.10. A1, A2, B1, B2, C1, and C2 are switches for the inverter's phase legs A, B, and C, respectively, where subscripts 1 and 2 stand for the upper and lower switches for each phase leg.

Consider the operation of the brushless DC motor drive during step 2 of the switching sequence[11],[13] as shown in Figure 3.9, when switch B1 is controlled and switch C2 is left in the ON position. The buck converter shown in Fig. 3.11 operates similarly to how the BLDC motor drive operates during step 2. R and 'L' represent resistance and inductance of the winding of stator respectively, e is the line value of the back emf, S is the controlling switch, D is the freewheeling diode.

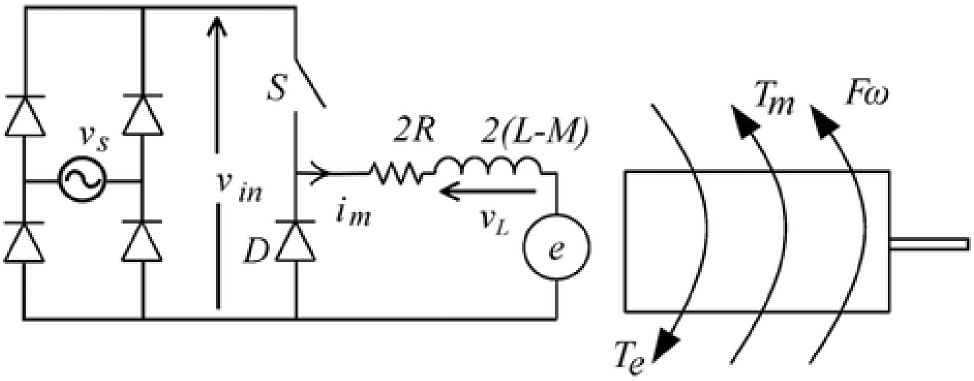


Figure 3.11: Model of brushless DC motor[12]

By applying Kirchhoff's voltage law is applied to the motor[12] driving circuit during the ON state and the OFF state of the switch "S" in Figure 3.11 we get:

$$v_{\text{in}}(t) - 2i_m(t)R - (2L - 2M)\frac{\mathrm{d}i_m(t)}{\mathrm{d}t} = e(t) \tag{3.1}$$

$$-2i_m(t)R - (2L - 2M)\frac{\mathrm{d}i_m(t)}{\mathrm{d}t} = e(t) \tag{3.2}$$

Input voltage is given by:

$$V_{\text{in}}(t) = V_m|\sin(2\pi f t)| \tag{3.3}$$

where,

V_m is the amplitude of input voltage

f is the frequency

3.5 Modelling of BLDC

The above mentioned advantages, applications marked the importance of modelling the BLDC motor.The assumptions for the same includes:

- Saturation of magnetic circuits is disregarded.
- The mutual and self inductance of each phase is constant and equal.
- Eddy current and hysteresis losses are eliminated.
- Every semiconductor switch is ideal.

The following equations represent the modelling of BLDC motor's armature winding and the values used for the modelling is provided in Table 3.1.[20]

$$\mathrm{V_a = RI_a + (L - M)dI_a/dt + E_a} \tag{3.4}$$

$$\mathrm{V_b = RI_b + (L - M)dI_b/dt + E_b} \tag{3.5}$$

$$\mathrm{V_c = RI_c + (L - M)dI_c/dt + E_c} \tag{3.6}$$

The instantaneous back EMF in BLDC is expressed as:

$$\mathrm{E_a = K_e\omega_m F\left(\theta_c\right)} \tag{3.7}$$

$$\mathrm{E_b = K_e\omega_m F\left(\theta_e - 2\pi/3\right)} \tag{3.8}$$

$$\mathrm{E_c = K_e\omega_m F\left(\theta_e + 2\pi/3\right)} \tag{3.9}$$

Each phase's electric torque is equal to the product of the supply current I, the motor constant Kt, and is given by:

$$\mathrm{T_a = K_t i_a F\left(\theta_e\right)} \tag{3.10}$$

$$\mathrm{T_b = k_t i_b F\left(\theta_e - 2\pi/3\right)} \tag{3.11}$$

$$\mathrm{T_c = k_t i_c F\left(\theta_e + 2\pi/3\right)} \tag{3.12}$$

Thus the resultant electromagnetic torque T_E can be expressed as follows:

$$\mathrm{T_E = T_a + T_b + T_c} \tag{3.13}$$

The simple motion system equation with inertia J, friction coefficient B, and load torque T_l:

$$\mathrm{T_E - T_{\mathit{l}} = Jd^2\theta_m/dt^2} + \beta d\mathrm{\theta_m/dt} \tag{3.14}$$

Table 3.1: Specifications of BLDC motor

Parameters	**Notations**	**Value**
Resistance	R	3Ω
Inductance	L-M	15mH
Rotor Inertia	J	$0.0024Kgm^2$
Friction coefficient	B	0.001Nms
Poles	P	4
Back- emf	E	Trapezoidal
Torque constant	Kt	$0.8NmA^-1$
Rated power	P	250W

The relation between electrical rotor speed and position is given by:

$$\theta_{\mathrm{e}} = (\mathrm{P}/2)\theta_{\mathrm{m}} \tag{3.15}$$

$$\omega_{\mathrm{m}} = \mathrm{d}\theta_{\mathrm{m}}/\mathrm{dt} \tag{3.16}$$

V_a, V_b, V_c : Phase voltages

I_a, I_b, I_c :Phase currents

R : Resistance of each phase of BLDC

L : Inductance of each phase of BLDC

M : Mutual inductance

E_a, E_b, E_c : Back- EMF of phase a, b,c

T_a, T_b, T_c : Electric torque produced by each phase

T_E : Electric torque produced by BLDC

K_e : Back-EMF constant

K_t : Torque constant

ω_m :Angular speed of rotor

Θ_m : Mechanical angle of rotor

3.6 Concluding Remarks

This chapter has provided a brief idea on BLDC motors, their construction, and working. The next chapter presents the torque analysis of BLDC motor.

Chapter 4

TORQUE ANALYSIS

4.1 Overview

In BLDC, when back-emf is of trapezoidal type, the developed torque is constant in ideal conditions. But practically this is not possible as there will be some ripple in torque output.

4.2 Torque Analysis

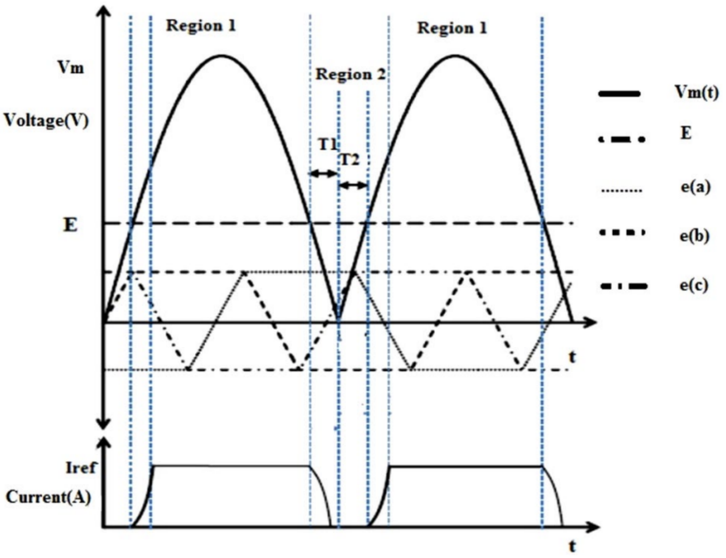


Figure 4.1: Torque Analysis

A BLDC motor with a perfect trapezoidal back emf is assumed to simplify the analysis. The magnitude of e(t) during the constant 120 degree period of the trapezoidal back emf waveform is defined as E. During this time, two of the motor phases are energised.

According to the magnitude of the phase current, rectified voltage is split into two zones, as shown in Figure 4.1. In the first region, the phase current is same as I_{ref} as back emf is less than rectified voltage, however, when rectified voltage is less than back emf, there is a drop in phase current and it becomes unpredictable. This may lead to uncontrollable torque at region 2.

4.3 Torque Ripple Compensation

Due to unpredictable phase current, the BLDC motor drive without a DC link capacitor causes torque ripples and discontinuities in area 2. For applications that demand a continuous output torque, these are not preferred. Additionally, variations in torque cause the motor drive to vibrate and produce noise. These vibrations may put unwanted strain on the bearings, mountings thus questioning about the dependability of BLDC drive. Additionally, compared to a motor drive with a rigid DC link, a motor drive with the absence of DC link capacitor produces less torque on average. To address this issue, a torque ripple compensation mechanism based on an actively regulated small capacitor is suggested.

The anti-parallel freewheeling diode connected to S_{DC} charges C_{DC} in region 1 of Figure 4.1. The gate signal applied to S_{DC} can control the discharge since the capacitor has no natural path for discharge. The capacitor must be able to maintain Im(t) at reference current, in region 2 by using the energy stored in C_{DC} so as to minimise the torque ripple. The controller is designed in such a way that it controls the switch S_{DC} based on E and Vin(t). The line-to-line back emf(E) can be calculated from the motor speed, which in turn can be found using the information obtained from the position of rotor. The size of C$_{DC}$ is lower than a DC link capacitor used in a typical BLDC motor drive since it only powers the motor in 2^{nd} region(E>Vin(t)).

To account for the ripples in the torque, a low cost capacitor and a switch can be employed. Also, to keep Im(t) at reference current, the value of C_{DC} is chosen in such a way that it can maintain the DC link voltage in area 2 when E >Vin(t) and this value is given by:

$$C_{DC}\frac{dV_{in}(t)}{dt} = I_{avg} \tag{4.1}$$

where Iavg stands for the average current used to keep Im(t) at reference current(Iref) through the DC link. The differential term in (4.1) shows, how quickly the voltage across C_{DC} changes in region 2, when back emf(E) >Vin (t). It is challenging to arrive at an analytical solution for Iavg because of the discrete character of the current pulled from the DC link and the time-varying duty cycle of the switch caused by Vin(t). The buck converter basis simulation model, however, can find Iavg. The minimum value of C_{DC} which is required to provide Iavg is:

$$C_{DC} = \frac{2TI_{\mathrm{avg}}}{V_m - E} \tag{4.2}$$

Now, to generate the switching pulses a spider concept based controller is utilised.

4.4 Concluding Remarks

The compensation of torque ripple can be attained through the charging and discharging of the dc link capacitor. However, since the capacitor lacks a natural discharge path, it requires an external trigger to achieve the same. Thus a switch is used in this work to control the capacitor. The switching(gate) pulses for the switch is generated with the help of a spider based controller, which is explained in the next chapter.

Chapter 5

METHODOLOGY

5.1 Overview

In this proposed model,the compensation for torque ripple and speed control is developed for a Brushless DC motor at very low cost. This make use of a spider based Sliding Mode Controller and a small dc link capacitor instead of a larger capacitor for minimization of torque ripple and speed regulation.

5.2 Proposed System

An inexpensive torque ripple minimization method is presented for a BLDC motor as in Figure 5.1. Here, a small dc link capacitor is used for minimizing torque ripple. The capacitor is switched with the help of a switch whose switching sequence is controlled by a spider web-building concept based controller. Additionally, the speed loop of the BLDC motor is controlled using the concept of reaching law with the help of Sliding Mode Controller.

5.3 Sliding Mode Controller

Variable Structure Control (VSC), sometimes known as "astatic" control, was suggested by a scholar by the name of Emelyanov [14]. With the use of a control input, a discontinuous hyperplane, also known as a switching hyperplane, switching surface, or sliding surface, is artificially inserted into the system in VSC. A novel type of VSC is then obtained when the system states

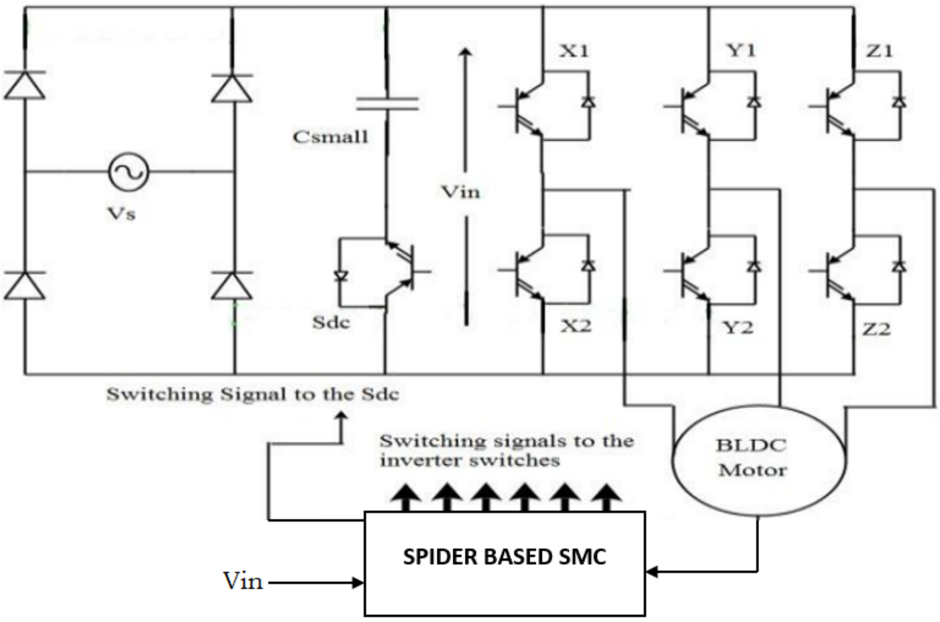


Figure 5.1: Block Diagram

are directed toward the hyperplane and then forced to slide along it or within its constrained area. This new type VSC is called as Sliding Mode Control.

Sliding Mode Controller has been used in numerous system types, including linear and nonlinear systems, continuous and discrete-time systems, small- and large-scale, and infinite dimensional systems[15]. It is a reliable method for managing the systems, including the control obtained for underwater vehicles, drones, robotic arms, and mobile drives and spaceships, among many others. The control law in SMC is dynamic, which implies that it is always changing in accordance with some established rules. These rules are known as "Switching Functions" .The controller should push the system in such a way that the state-trajectories arrive at the pre-defined sliding surface in a finite amount of time, and then maintain the system there or in close proximity to it.The key benefits of SMC include: order reduction; parametric invariance, or robustnes.

It has been an important field of research to create controllers based on SMC. Additionally, numerous related techniques have occasionally been put forth. The foundation for all of them, however, is the same; the first step is to design the sliding surface in the state-space in order to obtain the reduced order sliding motion. The system's control law must be determined in the second stage in order for the system to move toward the sliding surface described in the first step and remain there or very near it after that.[16] There are two phases involved in SMC as shown in Figure 5.2:

a) Reaching Phase

b) Sliding Phase

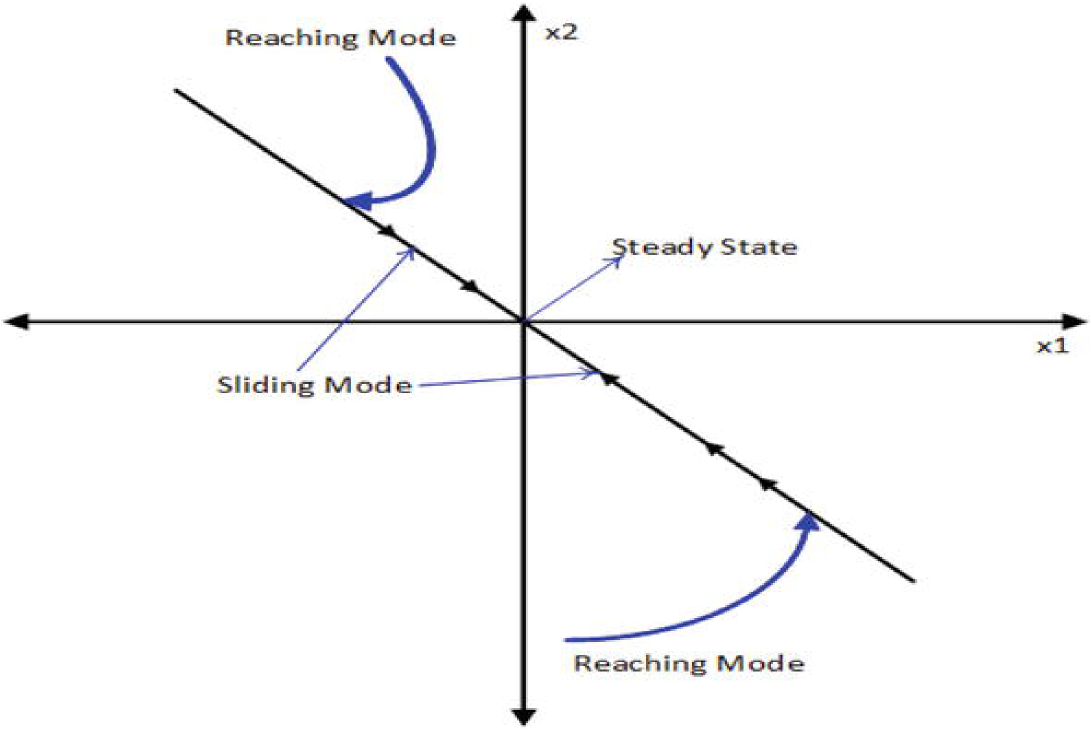


Figure 5.2: Phases in Sliding Mode Control

In the first section, the trajectory progresses in a finite amount of time toward the sliding surface from any point on the phase plane. The system is susceptible to parameter alterations and disturbance rejection during this portion of the phase trajectory, which is also referred to as the non-sliding phase or reaching phase. The second phase is the sliding phase, during which the trajectory of the state travels to the origin along the sliding surface without ever leaving it. During the reaching phase, the system's dynamics are directed toward the surface in a limited amount of time. The reachability condition is the criterion that ensures the reachability of the system.[17]

Mathematically, the reaching condition can be written as:

$\dot{S} < 0$ when S > 0

$\dot{S} > 0$ when S < 0

Although the reaching and stability are guaranteed by the reaching condition, it is unclear how the sliding surface is achieved. The details of how the system reaches the sliding surface are crucial because they affect the transient behavior of the system. For this we use different reaching law approaches.

5.4 Proportional Integral Derivative Controller

The first version of the PID controller was created Elmer Sperry in 1911. However, the first pneumatic controller with a fully tunable proportional controller wasn't released until 1933 by the Taylor Instrumental Company (TIC). A few years later, control experts discovered that the steady state error seen in proportional controllers could be eliminated by resetting the point to some hypothetical value, provided the error wasn't zero. The proportional-Integral controller was created as a result of this resetting, which "integrated" the error. The first PID pneumatic controller with a derivative action was then created by TIC in 1940, which minimised overshooting problems. Engineers were finally able to identify and set the proper PID controller parameters in 1942, due to the implementation of Ziegler and Nichols tuning criteria. As the name suggests, a PID controller combines proportional control with additional integral and derivative modifications that improve the device's ability to automatically account for system changes. The main objective of PID controller is to force feedback to match a setpoint.

The fundamental idea underlying a PID controller is that each of the terms—proportional, integral, and derivative—must be independently set.

1) P element: This is the "present" error, proportional to the error at time t.

2) I element: corresponding to the accumulation of the "past" mistake as measured by the integral of the error up to the time t.

3) The "future" error , which is proportional to the derivative of the error at moment t.

5.5 Spider based Controller

A proposal for a solution to difficult scientific issues that draws inspiration from the inhabitants and biological evolution of living things is known as a biologically inspired controlling. To create switching pulses for the switch S_{DC}, one such approach that resembles a spider building a web can be used. Initially, a silky thread is produced from the spider's mouth as part of the web-building process. The spider produce silk and shot it into the air so that it would stick in a specific spot. The location where it sticks depends on factors like the silk's tensile strength and the spider's distance.

The uncontrollable torque resulted due to the drop in phase current in region 2, need to be compensated. For this the capacitor discharging and charging is necessary, which can be achieved using a switch. The controller that works based on the web buliding activity of a spider generates switching pulses for the switch S_{DC}. Back emf & rectified voltage should be compared in this case.

5.6 Concluding Remarks

This chapter discussed about the control approach that was used in this work to attain the objectives. A brief idea about the proposed method, the controllers being used are presented in this chapter. Next chapter shows the modelling of the controllers.

Chapter 6

MODELLING OF CONTROLLERS

6.1 Overview

This chapter deals with the modelling of controllers that have been used in the proposed model. The main controllers that are used in the work includes a sliding mode controller which is used to control the speed and a spider based controller for the compensation of torque. Additionally, a proportional integral derivative controller is also used for the purpose of comparison.

6.2 Sliding Mode Controller

Two primary tasks are involved in sliding mode design: a. Choosing a secure sliding surface [18] in the state space where the state trajectory will eventually land. b. Creating a suitable control law that will push the state trajectory to travel to this sliding surface in a finite amount of time. There are two types of sliding surfaces: linear and nonlinear. A linear sliding surface is normally selected for easiness.Determining the sliding surface S(t) is hence the initial stage in SMC . After choosing the sliding surface, care must be taken to create the control law that moves the controlled variable to its reference value and fulfils the aforementioned equation. The continuous part, ueq, and the discontinuous part, usw, make up the two additive elements of the SMC control law, u.

$$u = ueq + usw \tag{6.1}$$

$$\mathrm{S} = \left(\frac{\mathrm{d}}{\mathrm{dt}} + \alpha\right)^{\mathrm{n}-1} \mathrm{e} \tag{6.2}$$

The above equation(6.2) can be used to find the sliding surface S where,

n - system order

e - error signal

α - positive constant

For speed control,

$$\mathrm{S} = \mathrm{e} = \omega\mathrm{ref} - \omega \tag{6.3}$$

ω_{ref} is the Reference speed.

Now a control law (u) has to be found which satisfies the reaching condition.

$$S\dot{S} < 0 \tag{6.4}$$

The reaching law approach[19] which is used to attain the reaching condition(6.4) is normally represented as follows:

$$\dot{\mathrm{S}} = -\varepsilon \mathrm{sgn}(S) - KS \tag{6.5}$$

Where,

K, ε - positive constants

S - Sliding surface

sgn is the signum function defined as

$$\mathrm{sgn}(S) = \begin{cases} 1 & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ -1 & \text{if } S < 0 \end{cases} \tag{6.6}$$

From above equations we get,

$$T = J(\varepsilon \mathrm{sgn}(S) + KS + \dot{\omega}\mathrm{ref}) + T_l + B(\omega\mathrm{ref} - e) \tag{6.7}$$

So,here SMC algorithm is employed

6.3 Proportional Integral Derivative Controller

Figure 6.1 shows a Proportional Integral Derivative controller.

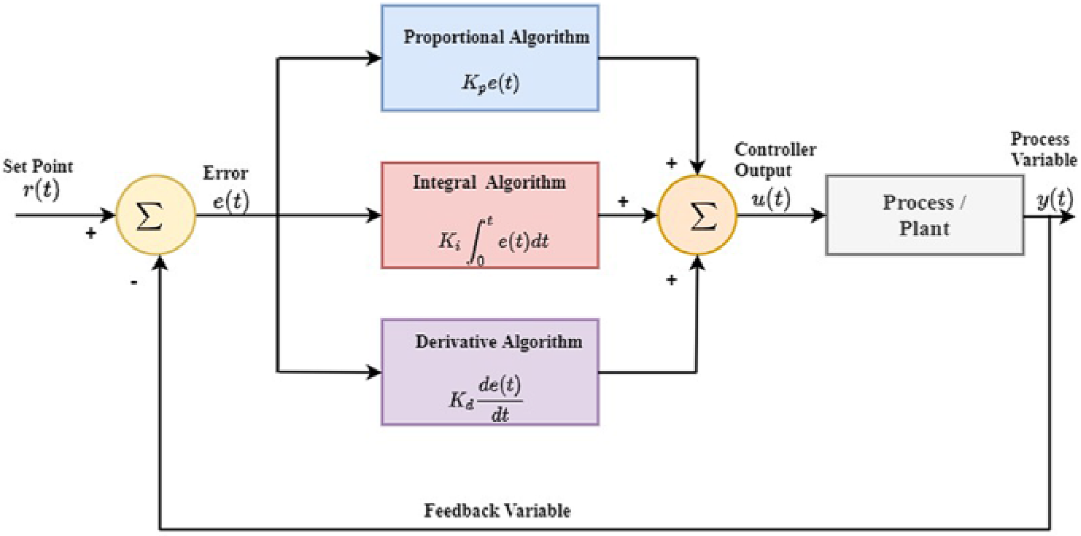


Figure 6.1: Proportional Integral Derivative Controller

$$T = K_P(\omega_{ref} - \omega) + K_I \int_o^t (\omega_{ref} - \omega)dt + K_D \frac{d}{dt}(\omega_{ref} - \omega) \tag{6.8}$$

where,

T is the torque

ω_{ref} is the reference speed

ω is the speed at any instant

K_P is the proportional gain

K_I is the integral gain and K_D is the derivative gain.

6.4 Spider based Controller

A spider-based controller [20] generates switching pulses for the switch S_{DC}. Back emf & rectified voltage should be compared in this case. As a result, depending on the rectified voltage and back emf, the small capacitor utilised may charge or discharge. Discharging of the capacitor is necessary in region 2,to keep the phase current at Iref and to produce ripple-free torque. Discharging can be started by applying a switching pulse to the switch S_{DC} and this happens only when the capacitor is sufficiently charged during region 1. Initially, a silky thread is produced from the spider's mouth as part of the web-building process. The controller receives input signals similar to that, such as input voltage and back emf. The spider produce silk and shot it into the air so that it would stick in a specific spot. The location where it sticks depends on factors like the silk's tensile strength and the spider's distance.

- The spider starts out with the voltage waveform (thread), reads the voltage value at each instant (looking for a site to fix silk).
- It then proceeds to the waveform's zero crossing, which is the appropriate location for fixing silk.
- It then transfers to a different spot(duty ratio of the switch SD) and attach silk.
- Finally, by consuming the prior thread, it returns to the original position. This action implies that the switch S_{DC} is being turned on and off.

6.5 Concluding Remarks

This chapter discussed about the modelling of different controllers that have been used in the work. Next chapter shows the simulation results.

Chapter 7

RESULTS AND DISCUSSION

7.1 Overview

MATLAB/Simulink is used to validate the performance of the Spider based Sliding mode controller. The performance of the proposed controller was validated and the comparison with Spider based PID was done to evaluate its effectiveness.The merits of the proposed control technique in terms of settling time and torque ripple are then examined by comparing it with SMC only and Spider based PID.

7.2 Model Validation

The open loop response of the BLDC motor is discussed below.The torque output and Speed of the open loop model is shown in Figure 7.1 and Figure 7.2

The open loop response shows higher ripple content in torque and speed of the machine which will have effect on stability of the system . Also variable speed application is not possible in open loop control.It may cause noise, vibrations and serious faults to motor. So in order to get better control response spider based sliding mode controller is introduced.

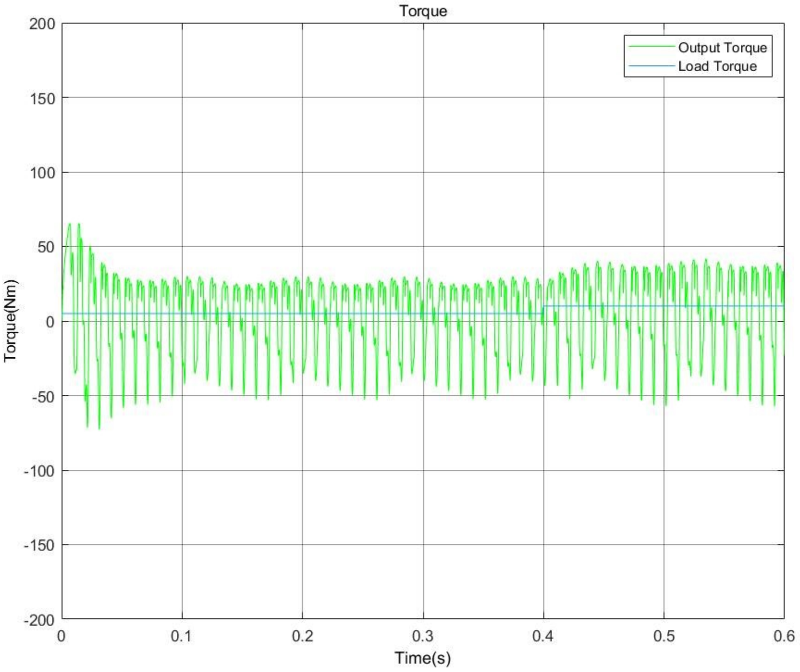


Figure 7.1: Torque Output of open loop model

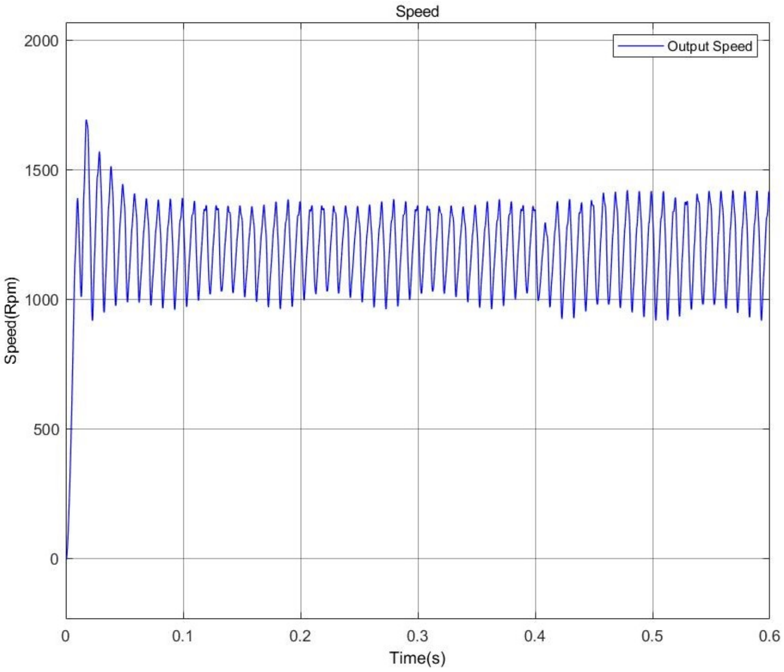


Figure 7.2: Speed of open loop model

7.3 Sliding Mode Controller

Figure 7.3, shows the analysis of torque under the absence of capacitor switching i.e., with SMC alone. Here the peak value and overshoot is very high

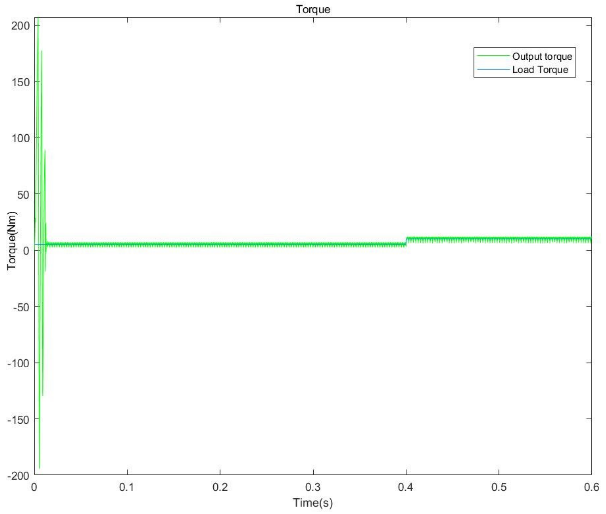


Figure 7.3: Torque Analysis with SMC only (without capacitor switching)

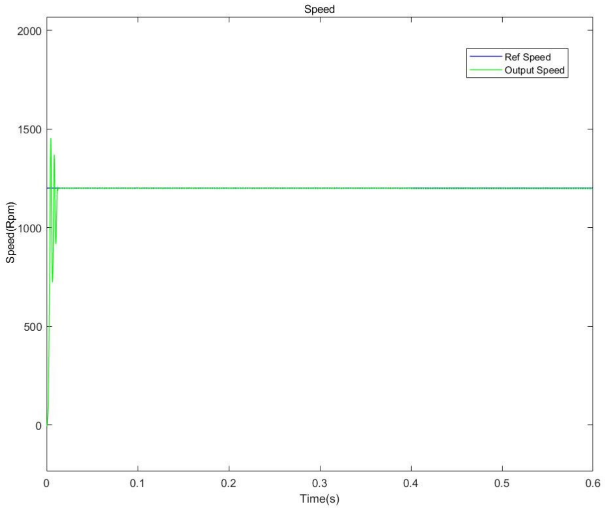


Figure 7.4: Speed Analysis with SMC only (without capacitor switching)

Figure 7.4 shows the simulation results of speed control using SMC, here the settling time is also high.

7.4 Spider based PID Controller

Figure 7.5, shows the analysis of torque under Spider based PID. Here the settling time is high but ripples are low when compared to the SMC only technique.

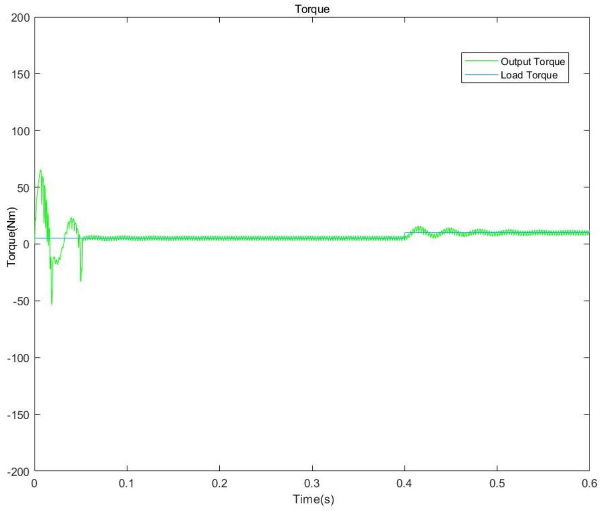


Figure 7.5: Torque Analysis with Spider based PID

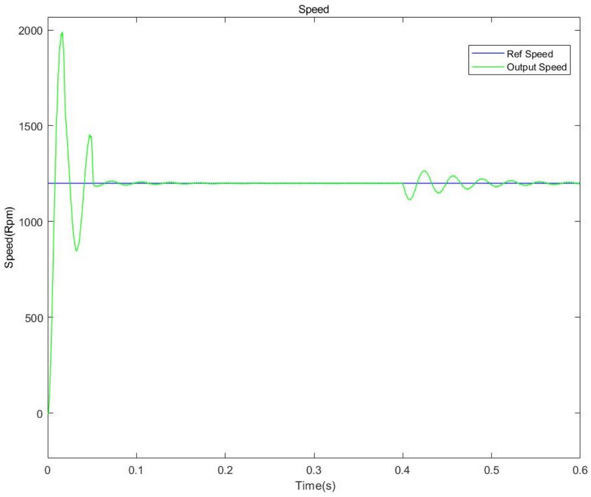


Figure 7.6: Speed Analysis with Spider based PID

Figure 7.6 shows the simulation results of speed control using Spider based PID controller. Here the speed settles slowly.

7.5 Spider based SMC Controller

Figure 7.7, shows the analysis of torque under Spider based SMC Controller. Here it is clear that the peak value and ripples are reduced effectively

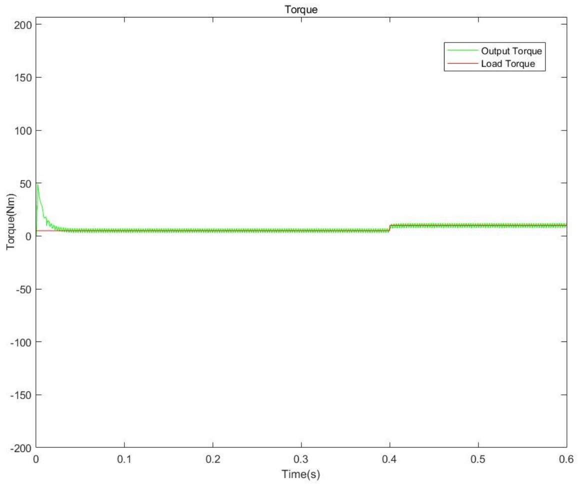


Figure 7.7: Torque Analysis with Spider based SMC

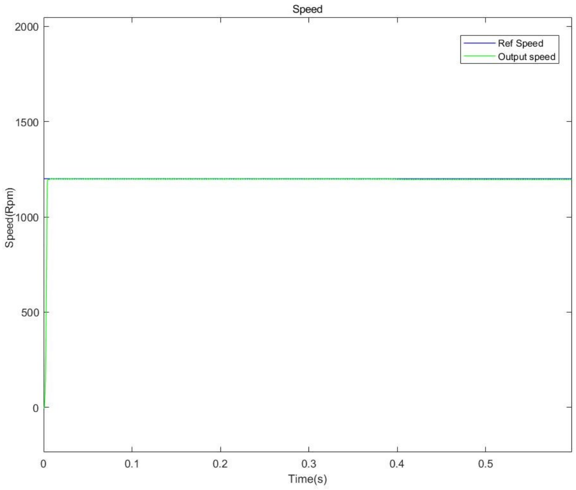


Figure 7.8: Speed Analysis with Spider based SMC

Figure 7.8 shows the simulation results of speed control using Spider based SMC. Here the speed settles faster and the ripples are reduced effectively.

7.6 Comparison Between SMC, Spider-PID & Spider SMC

Table 7.1: Torque Ripple Analysis

	Peak Value	Settling Time	Torque Ripple
SMC Only	201	0.04	24%
Spider PID	64	0.055	42%
Spider SMC	48	0.03	10%

The merits of the proposed control technique in terms of settling time and torque ripple are examined in Table 7.1 by comparing it with SMC only and Spider based PID.

7.7 Concluding remarks

This chapter verified the effectivenes of proposed control approach in torque ripple compensation and regulation of speed. The control technique used a Sliding mode control for speed regulation and Spider based controller for troque ripple compensation.

Chapter 8

CONCLUSION AND FUTURE SCOPE

The aim of the work was to develop a Spider based SMC controller for the torque ripple compensation and regulation of speed. A small dc link capacitor is used for compensation of torque. This was achieved by generating switching pulse for the switch that connects the capacitor. The generation of switching pulse utilized a controller that works based on the concept of the web building activity of a spider. The generated pulse will help the capacitor to discharge, helping to maintain $I_m(t)$ at I_{ref}. A first order sliding mode controller was also used to control the speed of the motor.

The simulation results showed the effectiveness of the proposed Spider SMC in terms of settling time, peak value and torque ripple. Furthermore, comparison of the proposed Spider based SMC with Spider based PID proved that the proposed control approach of BLDC for torque ripple compensation and regulation of speed is efficient. The future work considers the tuning of PID with modern optimization techiniques like Ant Colony Optmization(ACO) so as to obtain better results when incorporated with the Spider concept based controller.

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[1] Akhil Alex, Sumayya Jaleel, "Speed Control and Compensation of Torque Ripple in BLDC Motor Using Spider Based Sliding Mode Controller", *International Congress on Control Systems* , 2022 - Accepted.