

“STUDY OF SOFT SWITCHING CONVERTER FOR BRUSHLESS DC MOTOR DRIVE”

A Thesis Report Submitted In Partial Fulfillment of The

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CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled, “**Study of Soft Switching Converter for Brushless DC Motor Drive**” in partial fulfillment of the requirements for the award of degree of **Master of Engineering (Power System and Electric Drives)** in the **Department of Electrical And Instrumentation Engineering**, at **Thapar University, Patiala**, is an authentic record of my own work carried out under the supervision of **Mr. Souvik Ganguli (Asstt. Professor)** and refers other researcher’s work which are duly listed in the reference section.

The matter embodied in this thesis has not been submitted for the award of any other degree to any other university.

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ABSTRACT

Permanent magnet (PM) brushless DC motors (BLDCM) are generated by virtually inverting the stator and rotor of PM DC motors. The 'DC' term does not refer to a DC motor. These motors are actually fed by rectangular AC waveform. The advantage of these motors is the removal of brushes, leading to eliminate many problems associated with brushes. Another advantage is the ability to produce a larger torque because of the rectangular interaction between current and flux and an increase in electric loading with higher power density. Within the last decade, the research and development on BLDCM drives have been focused on the motor topology design and optimization as well as the motor control strategies. Nevertheless, most of these converter topologies employ the hard-switching technique which causes high switching losses and severe electromagnetic interference. Recently, a number of soft-switching techniques, providing zero-voltage switching (ZVS) or zero-current switching (ZCS) condition, have been successfully developed. Surprisingly, the development of ZVS soft-switching converters for BLDCM drives has been very little. Until recently, a few studies on soft-switching converters for BLDCM drives have been carried out. In this thesis, soft switching technique using IGBT's is applied for Brushless DC Motor. Its principle of operation and simulation results will be given. It possesses some definite advantages over hard switching including improves the motor torque, speed of motor high switching frequency, high power density and high efficiency. The simulation model is developed using the most commonly used MATLAB/SIMULINK environment. The reason for choice of MATLAB/SIMULINK as a development tool is because it is the most important and widely used simulation software and is an integral part of taught program in most of the universities in electrical/electronic/computer engineering courses.

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LIST OF SYMBOLS

V	Voltage
N	Number of Winding Turns per Phase
l	Length of the Rotor
R	Internal Radius of the Rotor
B	Magnet Flux Density
ω	Angular Velocity
i	Phase Current,
L	Inductance
θ	Rotor Position
R	Resistance
T	Torque

LIST OF ABBREVIATIONS

DC	Direct Current
PMBLDC	Permanent Magnet Brushless DC Motor
BLDC	Brushless DC Motor
PMSM	Permanent Magnet Synchronous Motor
AC	Alternating Current
EMI	Electromagnetic Interference
PWM	Pulse Width Modulation
RPM	Revolutions per Minute
E.M.F	Electromotive Force
MOSFET	Metal Oxide Silicon Field Effect Transistor
IGBT	Insulated Gate Bipolar Transistor
PMAC	Permanent Magnet Alternating current
CNC	Computer Numeric Controlled
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
ZVS-PWM	Zero-Voltage-Switching Pulse-Width Modulation
DSPM	Pole Doubly Salient Permanent-Magnet
PI	Proportional–Integral
SDF-DSPM	Stator-Doubly-Fed Doubly-Salient Permanent-Magnet
PWM-ZVSMRC	Pulse Width-Modulated Zero-Voltage Switching Multi-Resonant Converter
ZCT	Zero-Current Transition
PFC	Power-Factor-Correction
ZVT	Zero-Voltage-Transition
2Q	Two- Quadrant

4Q	Four- Quadrant
VSI	Voltage Source Inverter
DSP	Digital Signal Processor
SCR	Silicon Controlled Rectifier
BJT	Bipolar Junction Transistors
ZVMR	Zero-Voltage Multi-Resonant
RDCL	Resonant Dc Link
QRDCL	Quasi-Resonant Dc Link
SRDCL	Series Resonant Dc Link
PRDCL	Parallel Resonant Dc Link
ARCP	Auxiliary Resonant Commutated Pole
ARS	Auxiliary Resonant Snubber

CHAPTER 1

INTRODUCTION

1.1 GENERAL

A motion system based on the Direct Current (DC) motor provides a good, simple and efficient solution to satisfy the requirements of a variable speed drive. Although dc motors possess good control characteristics and ruggedness, their performance and applications in wider areas is inhibited due to sparking and commutation problems. Induction motor do not possess the above mentioned problems, they have their own limitations such as low power factor and non-linear speed torque characteristics. With the advancement of technology and development of modern control techniques, the Permanent Magnet Brushless DC (PMBLDC) motor is able to overcome the limitations mentioned above and satisfy the requirements of a variable speed drive.

1.2 PERMANENT MAGNET MACHINES

The permanent magnet machines have the feature of high torque to size ratio. They possess very good dynamic characteristics due to low inertia in the permanent magnet rotor. Permanent magnet machines can be classified into dc commutator motor, permanent magnet synchronous motor (PMSM) and permanent magnet brushless dc (PMBLDC) motor. The permanent magnet dc commutator motor is similar in construction to the conventional dc motor except that the field winding is replaced by permanent magnets.

The PMSM and PMBLDC motors have similar construction with polyphase stator windings and permanent magnet rotors, the difference being the method of control and the distribution of windings. The PMSM motor has sinusoidally distributed stator windings and the controller tracks sinusoidal reference currents. The PMBLDC motor is fed with rectangular voltages and the windings are distributed so as to produce trapezoidal back e.m.f.

1.3 HISTORY OF BRUSHLESS D.C

The earliest evidence of a Brushless D.C. motor was in 1962 when T.G. Wilson and P.H. Trickey made a "DC Machine with Solid State Commutation". It was subsequently developed as a high torque, high response drive for specialty applications such as tape and disk drives for computers, robotics and positioning systems, and in aircraft where brush wear was intolerable due to low humidity. Unfortunately, the technology to make such a motor practical for industrial use over 5 hp simply did not exist until a number of years later. With the advent of powerful and permanent magnet materials and high power, high voltage transistors in the early to mid 80,s the ability to make such a motor practical became a reality The first large Brushless DC motors (50 hp or more were designed by Robert E. Lordo at POWERTEC Industrial Corporation in the late 1980s. Today, almost all of the major motor manufacturers make Brushless DC motors in at least some horsepower sizes and POWERTEC makes Brushless DC from 1/2 to 300 hp as a complete product line (had has announced 500 Hp available in October, 1992). Brushless DC has had a substantial impact in some industry market areas, primarily Plastics and Fibers and most recently a mining company has put several of these drives at 300 hp ratings operating coal conveyors in underground mines. The drives work on the same principle as all DC motors but the motor is built "inside out" with the fields (which are permanent magnets) on the shaft of the motor and the "armature" on the outside. The fields turn and the "armature" stays stationary. To duplicate the action of the commutator (which no longer needs to exist since the winding is now stationary), a magnetic encoder is mounted to the shaft of the motor to sense the magnetic position of the fields on the shaft. The controller "sees" the magnetic position information and determines through simple logic which motor lead should have current going to a winding and which motor lead should return the current from the winding.

The controller has power devices which connect the voltage on a capacitor bank to the correct motor lead at the correct time when the shaft encoder demands it. In this way the motor and controller act in the same way as a brush DC motor but without the brushes. The controller is built in a very similar way to the controller used in an AC variable

frequency drive or in an AC Vector drive because all three types use a PWM type of variable voltage control to their respective motors

1.4 PMBLDC MOTOR

Brushless dc motors use an electronic control to sequentially energize the stator poles. The motor consists of permanent magnet rotor and the distributed stator windings are wound such that electromotive force is trapezoidal. Permanent magnet motors are usually small because of permanent magnet rotor. Brushless dc motors provide less maintenance, longer life, lower EMI and quieter operation than wound rotor DC motor due to elimination of brushes. They have better speed torque characteristics and low inertia, which improves their dynamic performance when compared to a dc motor [33].

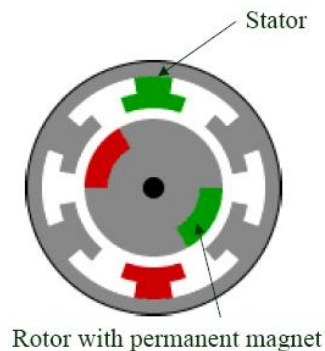


Figure 1.1. Cross sectional view of a BLDC motor

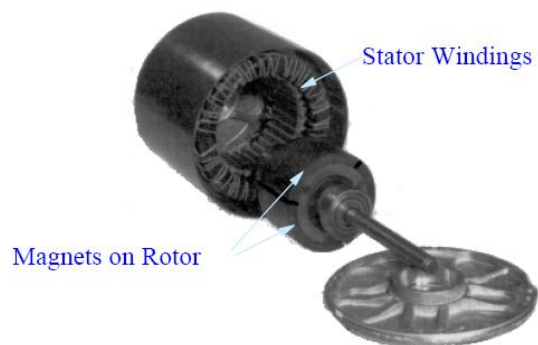


Figure 1.2. Structure of BLDC motor

1.5 ELECTRIC MOTOR DRIVES

The systems that controlled electric motors in the past suffered from very poor performance and were inefficient and expensive. In recent decades, the demand for greater performance and precision in electric motors, combined with the development of better solid state electronics and cheap microprocessors has led to the creation of modern adjustable-speed drives. An adjustable speed drive is a system that includes an electric motor as well as the system that drives and controls it [1a]. Any adjustable-speed drive can be viewed as five separate parts: the power supply, the power electronic converter, the electric motor, the controller, and the mechanical load.

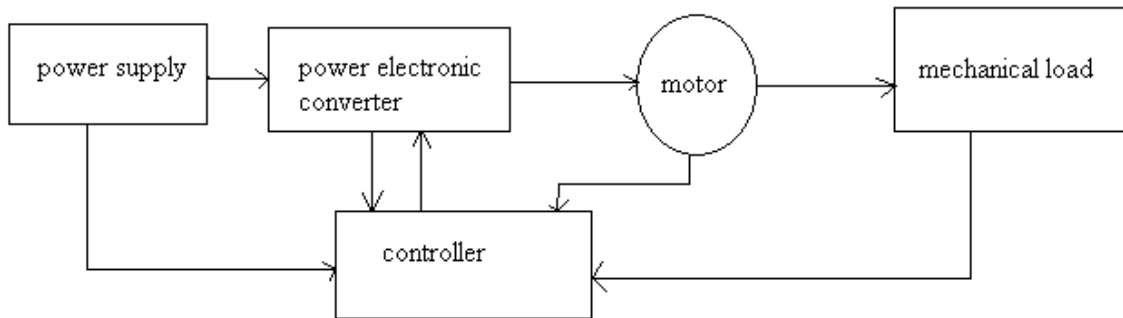


Figure 1.3 Typical Adjustable Speed Drive

The power supply is the source of electric energy for the system. The power supply can provide electric energy in the form of AC or DC at any voltage level. The power electronic converter provides the interface between the power supply and the motor. Because of this interface, nearly any type of power supply can be used with nearly any type of electric motor. The controller is the circuit responsible for controlling the motor output. This is accomplished by manipulating the operation of the power electronic converter to adjust the frequency, voltage, or current sent to the motor. The controller can be relatively simple, or as complex as a microprocessor. The electric motor is usually,

But not necessarily, a DC motor or an AC induction motor[33]. The mechanical load is the mechanical system that requires the energy from the motor drive. The mechanical load can be the blades of a fan, the compressor of an air conditioner, the rollers in a conveyor belt, or nearly anything that can be driven by the cyclical motion of a rotating shaft.

1.5.1 PMBLDC Motor Drives

With the advancement in technology and development of modern control techniques using solid state devices and micro electronics have contributed to new energy efficient electric drives which use PMBLDC motor which is able to overcome the limitations such as low power factor and non linear speed torque characteristics and satisfy the requirements of a variable speed drive. The permanent magnet machines have the features of high torque to size ratio and possess very good dynamic characteristics due to low inertia in the permanent magnet rotor and better power factor and better output power per unit mass & volume without sacrificing the reliability [33][2a]. Because of these reasons PMBLDC motors are extensively used in wide range of applications including information technology equipment such as computers, printers & scanners, household appliances, aerospace, electric vehicles, robotics etc.

1.6 RECENT ADVANCES IN BRUSHLESS DC MOTOR

Permanent magnet brushless DC motor (PMBLDC) motors are increasingly being used in a wide spectrum of applications such as domestic equipments, automobiles, information technology equipment, industries, public life appliances, transportation, aerospace, defense equipment, power tools, toys, vision and sound equipment and medical and health care equipment ranging from microwatts to megawatts. It has become possible because of their superior performance in terms of high efficiency, fast response, light weight, precise and accurate control, high reliability, maintenance free operation, brushless construction, high power density and reduced size.

Recent developments in PMSM motor technology in terms of availability of high performance rare earth PM materials, varying motor constructions such as axial field, radial field, package type, rectangular fed, sine fed motors, improved sensor technology, fast semiconductors modules, low cost high performance microelectronics devices, new control philosophy such as robust, adaptive, fuzzy, neural AI based controllers, have been a boon to their widespread use in the large speed ranges from few revolutions to thousand revolutions per minute (rpm). They have been proven most suitable for position control in machine tools, robotics.

1.7 TYPES OF BRUSHLESS MOTORS

There are two types of brushless DC motors called the in-runner and out-runner. The in-runner motor has permanent magnets located on the inside of the stationary electromagnets. An out-runner motor has the permanent magnets located on the outside.

1.7.1 In-runner Motors

In-runner motors are good when high speeds are needed. They are more efficient than outrunner motors the faster they spin. However, due to the gearbox, it makes the motor more susceptible to parts failing.

The characteristics of in-runner motors are:

- High R.P.M
- Low torque
- Requires gearbox
- Noise

1.7.2 Out-runner Motors

Out-runner motors spin slower but output more torque. They are easier to use since a gearbox is not required and run very quiet.

The characteristics of out-runner motors are:

- Low RPM
- High torque
- Quiet

CHAPTER 2

PERMANENT MAGNET BRUSHLESS DC MOTOR

2.1 INTRODUCTION

PMBLDC motors are one of the motor type's fast gaining popularity. They find applications in industries such as appliance, automotive, aerospace, consumer, medical and instrumentation. PMBLDC motors do not use brushes for commutation, instead they are electronically commutated. The stator of the PMBLDC motors consists of stacked steel laminations axially cut along the inner periphery. Though the stator resembles that of an induction motor, the windings are distributed in a different manner. The rotor is made up of permanent magnets and consists of alternate north and south poles. Ferrite magnets are traditionally used to make permanent magnets [3a]. Rare earth alloy magnets are gaining popularity due to their high magnetic density per volume. An alloy of neodymium, ferrite and boron has been used of late to make permanent magnets.

2.2 ADVANTAGES IN GOING FOR BLDC MOTOR

Among low power servo applications, classical DC motors are very popular because they are reasonably cheap and easy to control. The main disadvantage is the mechanical collector, which has only a limited life period. Also, brush sparking can destroy the rotor coil, generate EMC problems. For a Brushless DC motor, an electronic inverter avoiding mechanical collector does the commutation of the coils. Therefore, BLDC motor is more reliable and as the price of power electronic devices is still decreasing, the brushless dc motor replaces more and more the conventional dc motor. So permanent magnet brushless dc motors and drives are being used increasingly in a wide range of applications. This has been made possible with the advantages of high performance permanent magnets with high coercivity and residual magnetism, which make it possible for the PM to have superior power density, torque to inertia ratio and efficiency, when

compared to an induction or conventional dc machine [33]. Brushless DC motors can be subdivided into two major parts, the rotor and the stator.

2.3 STRUCTURE AND OPERATION

As their names suggest, the rotor is the rotational part of the motor while the stator is the stationary part. Structurally the stator assembly surrounds the rotor. Embedded into the side of the rotor are permanent magnets; external is the fan propeller blade. The motor coil is part of the stator assembly, and is placed inside the rotor. Brushless DC motors utilize Hall-effect sensors to provide positional and rotational information, which informs the LOGICAL INVERTER how to drive the motor coil. Brushless DC motors usually come in fixed voltage types, such as 5V, 6V, 12V, 24V, 48Vetc, with one of the most common ones in use being the 12V type. When the rated voltage is applied to the motor it will rotate with maximum speed, but by changing this applied voltage the motor speed can be controlled. Naturally, the voltage is higher and then speed is higher and vice versa.

The brushless DC motor is essentially configured as a permanent magnet rotating past a set of current carrying conductors. In this respect, it is equivalent to an inverted DC commutator motor, in that the magnet rotates while the conductors remain stationary. In both cases, the current must reverse polarity every time a magnet pole passes by, in order that the torque is unidirectional. In the DC commutator motor, the commutator and brushes perform the polarity reversal.

In the brushless DC motor, the polarity reversal is performed by power MOSFETS, which must be switched in synchronism with the rotor position. The stator is normally 3-phase star connected. Each commutation sequence has one of the windings energized to positive power (current entering into the winding) and the second winding energized to negative power (current exits the winding) and third winding non-energized. Torque is produced by the interaction of the magnetic field produced by the stator windings and the permanent magnets.

2.3.1 Hall Sensors

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall effect sensors embedded into the stator. Most BLDC motors have three Hall sensors embedded into the stator on the non-driving end of the motor. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.

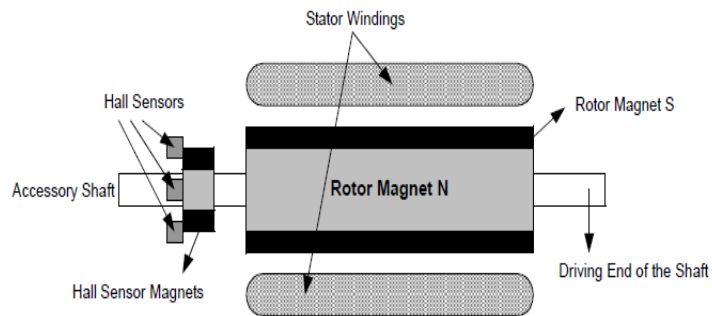


Figure 2.1 Transverse section of BLDC

Above Figure 2.1 shows a transverse section of a BLDC motor with a rotor that has alternate N and S permanent magnets. Hall sensors are embedded into the stationary part of the motor. Embedding the Hall sensors into the stator is a complex process because any misalignment in these Hall sensors, with respect to the rotor magnets, will generate an error in determination of the rotor position. To simplify the process of mounting the Hall sensors onto the stator, some motors may have the Hall sensor magnets on the rotor, in addition to the main rotor magnets. These are a scaled down replica version of the rotor. Therefore, whenever the rotor rotates, the Hall sensor magnets give the same effect as the main magnets. The Hall sensors are normally mounted on a PC board and fixed to the enclosure cap on the non-driving end. This enables users to adjust the complete assembly of Hall sensors, to align with the rotor magnets; in order to achieve the best The

Hall sensors may be at 60° or 120° phase shift to each other. Based on this, the motor manufacturer defines the commutation sequence, which should be followed when controlling the motor performance. Based on the physical position of the Hall sensors, there are two versions of output.

2.4 FEATURES

The PMSM motors have many advantages over the dc commutator motor. They have better torque-speed characteristics due to the elimination of brush friction at higher speeds, which improves the useful torque output in the PMSM motor and has long operating life with less maintenance. The permanent magnet rotors have low inertia, which improves the dynamic response of the motor [34]. The brushless motor provides noiseless operation with improved speed range. In addition, the ratio of torque developed to the size of the motor is higher, making it useful in applications where space and weight are critical factors. The use of permanent magnet rotor eliminates the rotor copper losses and provides considerable improvement in thermal characteristics

2.5 BLDC MOTOR PRINCIPLE

BLDC motors are basically inside-out DC motors. In a DC motor the stator is a permanent magnet. The rotor has the windings, which are excited with a current. The current in the rotor is reversed to create a rotating or moving electric field by means of a split commutator and brushes. On the other hand, in a BLDC motor the windings are on the stator and the rotor is a permanent magnet. Hence the term inside-out DC motor.

Many motor types can be considered brushless; including stepper and AC-induction motors, but the term “brushless” is given to a group of motors that act similarly to DC brush type motors without the limitations of a physical commutator. To build a brushless motor, the current-carrying coils must be taken off the rotating mechanism. In their place, the permanent magnet will be allowed to rotate within the case. The current still needs to be switched based on rotary position; figure 2.1(a) shows a reversing switch is activated by a cam.

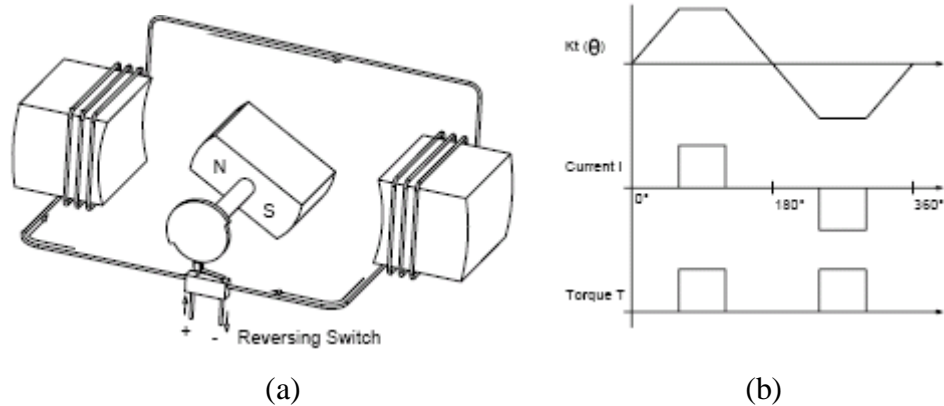


Figure 2.2 (a) Basic operation of BLDC motor

(b) Waveform of current and torque of basic BLDC motor

This orientation follows the same basic principle of rotary motors; the torque produced by the rotor varies trapezoidal with respect to the angle of the field. As the angle θ increases, the torque drops to an unusable level. Because of this, the reversible switch could have three states: positive current flow, negative current flow, and open circuit [35]. In this configuration, the torque based on rotary position will vary as the current is switched as shown in figure 2.2(b)

2.6 TRAPEZOIDAL BACK E.M.F

In general, Permanent Magnet Alternating current (PMAC) motors are categorized into two types. The first type of motor is referred to as PM synchronous motor (PMSM). These produce sinusoidal back e.m.f and should be supplied with sinusoidal current / voltage. The second type of PMAC has trapezoidal back e.m.f and is referred to as the Brushless DC (BLDC) motor. The BLDC motor requires that quasi-rectangular shaped currents are to be fed to the machine.

When a brushless dc motor rotates, each winding generates a voltage known as electromotive force or back e.m.f, which opposes the main voltage supplied to the windings. The polarity of the back emf is opposite to the energized voltage. The stator has three phase windings, and each winding is displaced by 120° . The windings are

distributed so as to produce trapezoidal back emf. The principle of the PMSBLDC motor is to energize the phase pairs that produce constant torque. The three phase currents are controlled to take a quasi-square waveform in order to synchronize with the trapezoidal back e.m.f to produce the constant torque [36]. Fig.2.3 shows the trapezoidal back e.m.f and quasi-square wave currents of the three phases.

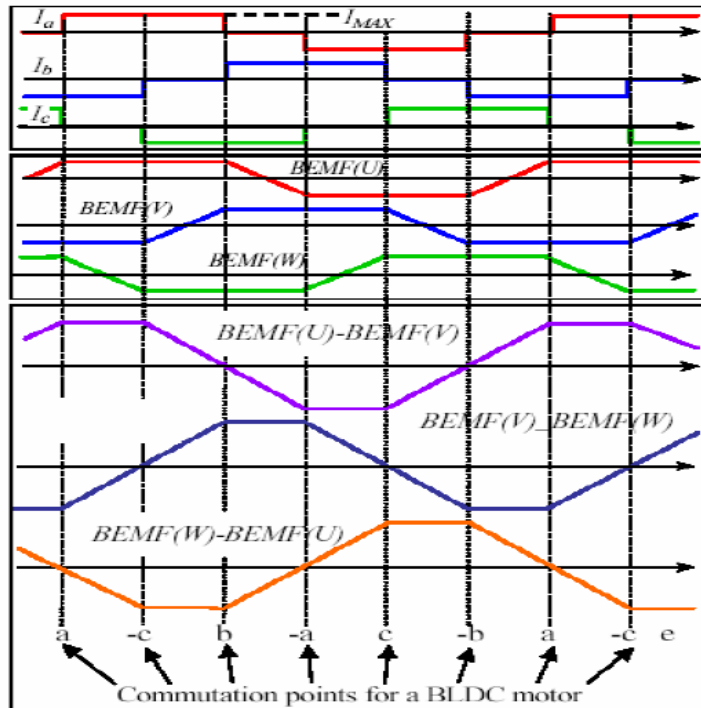


Figure 2.3 Back e.m.f and phase currents of PMSBLDC motor

2.7 TORQUE GENERATION

In this model, the Torque T is the product of the theoretical motor constant K_t times the supplied current I . In a single pole system such as this, usable torque is only produced for 1/3 of the rotation. To produce useful torque throughout the rotation of the stator, additional coils, or “phases” are added to the fixed stator.

The developed torque by each phase is the product of the motor constant K_t and the current I .

The sum of torques is $T_A + T_B + T_C$

Assumption made is all the phases are perfect symmetry,

$$K_{t(motor)} = K_{t(A)} = K_{t(B)} = K_{t(C)}$$

$$I_{motor} = I_A = I_B = I_C$$

At any given angle θ , the applied torque as measured on the rotor shaft is

$$T_{motor} = 2 * K_{t(motor)} * I_{motor}$$

The key to effective torque and speed control of a BLDC motor is based on relatively simple torque and back e.m.f equations, which are similar to those of the DC motor.

The back e.m.f magnitude can be written as:

$$E = 2NlrB\omega$$

And the torque term as:

$$T = \left(\frac{1}{2}i^2 \frac{dL}{d\theta}\right) - \left(\frac{1}{2}B^2 \frac{dR}{d\theta}\right) + \left(\frac{4N}{\pi} Br l \pi i\right)$$

Where;

N is the number of winding turns per phase,

l is the length of the rotor, r is the internal radius of the rotor,

B is the rotor magnet flux density,

ω is the motors angular velocity,

i is the phase current,

L is the phase inductance,

θ is the rotor position,

R is the phase resistance.

The first two terms in the torque expression are parasitic reluctance torque components.

The third term produces mutual torque, which is the torque production mechanism used in the case of BLDC motors. To sum up, the back e.m.f is directly proportional to the motor speed and the torque production is almost directly proportional to the phase current. These factors lead to the following BLDC motor speed control scheme:

The BLDC motor is characterized by a two phase ON operation to control the inverter. In this control scheme, torque production follows the principle that current should flow in only two of the three phases at a time and that there should be no torque production in the region of back e.m.f zero crossings. The following figure describes the electrical waveforms in the BLDC motor in the two phases ON operation.

This control structure has several advantages:

- Only one current at a time needs to be controlled.
- Only one current sensor is necessary.
- The positioning of the current sensor allows the use of low cost sensors as a shunt.

We have seen that the principle of the BLDC motor is, at all times, to energize the phase pair which can produce the highest torque. To optimize this effect the back e.m.f shape is trapezoidal. The combination of a DC current with a trapezoidal back e.m.f makes it theoretically possible to produce a constant torque. In practice, the current cannot be established instantaneously in a motor phase; as a consequence the torque ripple is present at each 60 degree phase commutation.

2.8 THREE PHASE INVERTER

The BLDC motor control consists of generating DC currents in the motor phases. This control is subdivided into two independent operations: first, stator and rotor flux synchronization, then control of the current value. Both operations are realized through the three phase inverter depicted in the following scheme. The flux synchronization is derived from the position information coming from sensors. From the position, the controller defines the appropriate pair of transistors (S1 to S4) which must be driven. The regulation of the current to a fixed 60 degrees reference can be realized in either of the two different modes.

2.8.1 The Pulse Width Modulation (PWM) Mode

The supply voltage is chopped at a fixed frequency with a duty cycle depending on the current error [35]. Therefore both the current and the rate of change of current can be

controlled. The two phase supply duration is limited by the two phase commutation angles. The main advantage of the PWM strategy is that the chopping frequency is a fixed parameter; hence, acoustic and electromagnetic noises are relatively easy to filter. There are also two ways of handling the drive current switching: hard chopping and soft chopping. In the hard chopping technique both phase transistors are driven by the same pulsed signal: the two transistors are switched-on and switched-off at the same time. The power electronics board is then easier to design and is also cheaper as it handles only three pulsed signals. A disadvantage of the hard chopping operation is that it increases the current ripple by a large factor in comparison with the soft chopping approach. The soft chopping approach allows not only a control of the current and of the rate of change of the current but a minimization of the current ripple as well. In this soft chopping mode the low side transistor is left ON during the phase supply and the high side transistor switches according to the pulsed signal.

2.8.2 The Hysteresis Mode

In the hysteresis-type current regulator, the power transistors are switched off and on according to whether the current is greater or less than a reference current. The error is used directly to control the states of the power transistors. The hysteresis controller is used to limit the phase current within a preset hysteresis band. As the supply voltage is fixed, the result is that the switching frequency varies as the current error varies. The current chopping operation is thus not a fixed chopping frequency PWM technique. This method is more commonly implemented in drives where motor speed and load do not vary too much, so that the variation in switching frequency is small [35]. Here again, both hard and soft chopping schemes are possible. Since the width of the tolerance band is a design parameter, this mode allows current control to be as precise as desired, but acoustic and electromagnetic noise are difficult to filter because of the varying switching frequency.

2.9 TYPICAL BLDC MOTOR APPLICATIONS

BLDC motors find applications in every segment of the market. Automotive, appliance, industrial controls, automation, aviation and so on, have applications for BLDC motors.

Out of these, we can categorize the type of BLDC motor control into three major types:

- Constant load
- Varying loads
- Positioning applications

2.9.1 Applications with Constant Loads

These are the types of applications where a variable speed is more important than keeping the accuracy of the speed at a set speed. In addition, the acceleration and deceleration rates are not dynamically changing. In these types of applications, the load is directly coupled to the motor shaft. For example, fans, pumps and blowers come under these types of applications. These applications demand low-cost controllers, mostly operating in open-loop.

2.9.2 Applications with Varying Loads

These are the types of applications where the load on the motor varies over a speed range. These applications may demand high-speed control accuracy and good dynamic responses. In home appliances, washers, dryers and compressors are good examples. In automotive, fuel pump control, electronic steering control, engine control and electric vehicle control are good examples of these. In aerospace, there are a number of applications, like centrifuges, pumps, robotic arm controls, gyroscope controls and so on. These applications may use speed feedback devices and may run in semi-closed loop or in total closed loop. These applications use advanced control algorithms, thus complicating the controller. Also, this increases the price of the complete system.

2.9.3 Positioning Applications

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

CHAPTER-3

LITRATURE REVIEW

3.1 INTRODUCTION

Brushless Direct Current (BLDC) motors are one of the motor types rapidly gaining popularity. BLDC motors are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and Instrumentation. As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors like, better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation, higher speed ranges. Within the last decade, the research and development on BLDCM drives have been focused on the motor topology design and optimization as well as the motor control strategies. Nevertheless, most of these converter topologies employ the hard-switching technique which causes high switching losses and severe electromagnetic interference (EMI). Recently, a number of soft-switching techniques, providing zero-voltage switching (ZVS) or zero-current switching (ZCS) condition, have been successfully developed. In this chapter different reviews on Brushless DC Motor, soft switching techniques such as zero voltages switching (ZVS), zero-current switching (ZCS), a zero-voltage-switching pulse-width modulated (ZVS-PWM) are discussed.

3.2 EARLIER WORKS: AN OVERVIEW

T.J.E. Miller [1] introduced the permanent magnet materials and characteristics, B-H loop and demagnetization characteristics, applications of permanent magnets in motors. He discussed the square wave permanent brushless motor, sine wave permanent magnet brushless motor and their torque, e.m.f equations and torque/speed characteristics.

12 A Kusko and S.M. Peeran [2] presented definitions of a brushless dc motor are inadequate to distinguish it from other types of brushless motors in the industry. A formal definition of a brushless dc motor is described. The definition includes the components of the motor and the types of circuits to energize the stator windings.

M.A.Jabbar, M.A.Rahman [3] discussed the design considerations for permanent-magnet motors intended for brushless operation. Two rotor configurations are described - the imprecated rotor and the segmented rotor. The segmented rotor is designed especially for high speed operation. A brushless DC drive system is also described and the performance of a neodymium-iron-boron excited p.m. motor with an imprecated rotor in a BLDC drive is presented.

C.C. Chan, J.Z. Jiang, G.H. Chen, X.Y. Wang, K.T. Chau [4] proposed a novel high power density permanent magnet motor drive for electric vehicles. The motor is a poly phase multi-pole square wave PM motor, which can be classified as a kind of PM brushless dc motor. Therefore, as the proposed motor drive possesses distinct advantages of high power density, high efficiency and superior dynamic performance, it is very suitable for EV applications.

Jinyun Gan, K. T. Chau, C. C. Chan and J. Z. Jiang [5] proposed a new five-phase, surface-inset, permanent-magnet (PM), brushless dc motor drive. The motor drive has advantages of both the PM brushless dc motor drive and the dc series motor drive. The motor configuration and principle of operation are so unusual that the magnetic field distribution and steady-state performance are analyzed by the finite-element method (FEM). This proposed motor drive is promising for modern electric vehicle applications.

Ming Cheng, K. T. Chau, C. C. Chan and Qiang Sun [6] proposed a new 8/6-pole doubly salient permanent-magnet (DSPM) motor drive, which offers the advantages of higher power density, higher efficiency, and wider speed range. The corresponding control and operation of the motor drive are presented. A variable proportional–integral (PI)

controller combined with bang-bang control for the DSPM motor drive is developed. The two-phase operation mode of the 8/6-pole DSPM motor offers the possibility of eliminating the torque ripple of the motor drive.

K. T. Chau, Y. B. Li, J. Z. Jiang, and Chunhua Liu [7] presented a new outer-rotor stator-doubly-fed doubly-salient permanent-magnet (SDF-DSPM) machine, which can be used as the integrated starter-generator for modern automobiles and mild hybrid electric vehicles. This newly designed SDF-DSPM machine is analyzed by using both the magnetic circuit model and finite element method, and assessed by performance simulation.

K. T. Chau, Dong Zhang, J. Z. Jiang, Chunhua Liu, and Yuejin Zhang [8] discussed a novel in-wheel motor, which artfully integrates a magnetic gear into a permanent-magnet brushless (PMBL) DC motor so that they can share a common PM rotor, hence offering both high efficiency and high power density. A 2-kW 600/ 4400-rpm magnetic-gear outer-rotor PMBL DC motor is designed and analyzed, which is particularly suitable for battery-powered electric motorcycles.

Dragan Maksimovic and Slobodan Cuk [9] determined that an additional independent control needed to eliminate the undesirable variable switching frequency of quasi-resonant converters can be obtained if the output rectifier is replaced by an active switch. The concept is applicable to all classes of quasi-resonant converters. It is demonstrated that in addition to operation at constant switching frequency, selected classes of constant-frequency quasi-resonant (CF-QR) topologies feature extended range of accessible conversion ratios and load currents.

Guichao Hua, Ching-Shan Leu, and Fred C. Lee [10] determined that soft-switching techniques applied to the PWM converters, with the exception of few isolated cases, are subjected to either high switch voltage stresses or high switch current stresses, or both. A new class of zero-voltage-transition PWM converters is proposed where both the

transistor and the rectifier operate with zero-voltage switching, and are subjected to minimum voltage and current stresses. Bread boarded converters are constructed to verify the novelty of the proposed new family of converters.

K.T. Chau [11] presented a new pulse width-modulated zero-voltage switching multi-resonant converter (PWM-ZVSMRC) operating at constant switching frequency. It had been controlled the switching frequency. This converter possessed the advantages of PWM converter and frequency-modulated (FM) ZVS-MRC. In contrast to its quasi resonant counterpart, namely the PWM-ZVS-QRC, it provides significant reduction in voltage stress and dramatic improvement in load range.

Hengchun Mao, Fred C. Y. Lee, Xunwei Zhou, Heping Dai, Mohummet Cosan, and Dushan Boroyevich, [12] introduced that existing zero-current transition (ZCT) converters do not solve main switch turn-on problems and require auxiliary switches to be turned off with high current and, therefore, are not suitable for high-power applications. The Novel ZCT schemes enable all main switches and auxiliary switches to be turned on and off under zero-current conditions. The proposed technology is well suited for dc–dc and three phase converters with insulated gate bipolar transistors (IGBT's), MOS-controlled thyristors (MCT's), and gate-turnoff switches (GTO's).

K.T. Chau, T.W. Ching, C.C. Chan, and David T.W. Chan [13] presented a novel zero-voltage-transition (ZVT) two-quadrant (2Q) converter for dc motor drives. It possessed the definite advantage that both main transistors and rectifiers can operate with zero-voltage switching in both motoring and regenerating modes, while both of these switches are only subjected to unity voltage and current stresses, namely the same as its PWM counterparts. This converter is particularly useful for dc traction systems in which both motoring and regenerative braking are desired to have high efficiency.

T. W. Ching, K.T. Chau, and C.C. Chan [14] presented a novel two-quadrant (2Q) zero-current transition (ZCT) converter with the capabilities of 2Q power flow, and ZCT switching profile for DC motor drives. It possessed the advantages that both the main and auxiliary switches can operate with zero-current switching (ZCS), reduced switching losses and stresses, minimum voltage and current stresses as well as minimum circulating energy during both the motoring and regenerating modes. This converter is particularly useful for DC traction systems in which both motoring and regenerative braking are desired to have high efficiency.

Jih-Sheng Lai, Senior [15] proposed the resonant snubber based soft switching inverters for electric propulsion drives. The newly developed soft-switching inverter employs an auxiliary switch and a resonant inductor per phase to produce a zero voltage across the main switch so that the main switch can turn on at the zero-voltage condition.

Jih-Sheng Lai and Junhong Zhang [16] designed soft-switching inverters to eliminate the switching loss, but the traditional techniques are only effective for certain operating points. The negative current cycle effect on zero-voltage switching type inverters and proposes a simple timing control technique for adaptively of operating in a wide range of source voltage and load current conditions.

Yong Li, Fred C. Lee and Dushan Boroyevich [17] proposed a new soft-transition control strategy for a three-phase zero-current-transition (ZCT) inverter circuit. The proposed strategy is realized by planning the switching patterns and timings of these four switches based on the load current information. The proposed strategy is also suitable for three-phase power-factor-correction (PFC) rectifier applications. The operation principles, including a detailed analysis based on the state-plane technique, and a design rule are described.

Zhi Yang Pan and Fang Lin Luo [18] introduced a novel soft-switching inverter which generates notches of the dc bus voltage becomes to zero during chopping switches commutation to guarantee all switches working in zero voltage state. It had the applications because of its low inertia, fast response, high power density, high reliability and maintenance-free.

T.W. Ching and K.U. Chan [19] presented a new zero-voltage-transition (ZVT) soft-switching converter for brushless DC motor drives. The ZVT converter possessed the definite advantages that both main transistors and diodes can operate with zero-voltage switching (ZVS), unity device voltage and current stresses. It is a very desirable feature for high frequency switching power conversion where power MOSFETs are used. This converter is especially advantageous for brushless DC motor drives, such as electric scooter applications.

T. W. Ching [20] presented a review on the development of soft-switching power converters for electric vehicle (EV) propulsion and recent research trends will also be discussed, with emphasis on soft-switching converters for dc motor drives, soft-switching inverters for ac motor drives and soft-switching converters for switched reluctance motor (SRM) drives.

Richard Redl, Gabor T. Reizik and Brian P. Erisman [21] presented a new family of ICs for driving insulated-gate transistors is introduced. Three member of the family are designed for soft-switching converters and converters with synchronous rectifiers; two members are designed for converters with zero-voltage-switching or zero-current switching active snubbers. Due to their low stand-by current and a unique first pulse wake-up feature, all ICs are suitable for operation in self biased power supplies. The ICs also have a dual-function pin for high-speed cycle-by-cycle current limiting or for selecting a low current stand-by state.

Yen-Shin Lai, Fu-San Shyu and Yong-Kai Lin [22] presented a novel PWM technique for BLDM drives with bootstrap driver circuit. As compared with existing PWM techniques for BLDM drives the presented technique doesn't cause any reversal DC-link current and thereby reducing the DC-link voltage fluctuation of the drives. Experimental results derived from an FPGA-based BLDM drives will be presented to fully support the analysis and claim.

Ji Hua, Li Zhiyong [23] presented a simulation method of modularization design for brushless DC motors (BLDCM). Based on the mathematical model of BLDCM, some isolated functional blocks, including BLDCM body block, speed PI controller block, current hysteresis controller block, current reference block, inverter block and commutation logic block, have been modeled in Matlab/Simulink.

R. Krishnan and P. Vijayraghavan [24] presented a new converter topology for permanent magnet brushless dc (PMBDC) motors. It has the advantages of minimum number of power switching devices, equal voltage rating for all the switching devices and variable dc link voltage for application to the motor. The operational characteristics of this converter-driven PMBDC drive are derived for four-quadrant performance. The feasibility of the proposed converter topology for the four quadrant PMBDC motor drive system is validated by extensive dynamic simulation of the motor drive system.

P. Mutschler, G. Bachmann [25] studied both the reducing of switching losses and the dv/dt limitation is examined. While in the range of very high power the Resonant Pole topology seems to be interesting, in range of medium power, PWM operated Resonant DC-Voltage Link Inverters seem to be favourable, because apart from the passive components, only two additional switches are necessary to perform soft switching for all employed switches and also focus on two Notching DC Link Inverters with PWM capability. The two topologies have been compared in simulation and an experimental

setup for one of them is under construction which will be used to examine the voltage and current stresses of the active and passive components

David W. Berning and Allen R. Hefner [26] presented techniques for validating the performance of insulated gate bipolar transistor (IGBT) circuit simulator models for soft-switching circuit conditions. The circuits used for the validation include a soft-switched boost converter similar to that used in power-factor correction, and a new half-bridge testbed that is specially designed to examine the details of IGBT soft-switching waveforms. The new testbed is designed to emulate the soft-switching circuit conditions of actual applications circuits, while allowing the easy change of IGBT operating conditions. The testbed also eliminates the problems of commutating diode noise and IGBT temperature rise found in actual application circuits.

HE Hucheng, DU Jingyi and CAO Xiaosheng and LIU Weiguo [27] presented a novel zero voltage transition (ZVT) three-phase soft-switching voltage source inverter (VSI) for BLDCM drive systems. The ZVT-VSI consists of three switches, six diodes, three capacitors and an inductor. Soft switching operation of all switching devices in inverter is realized by adding auxiliary resonant unit to DC link of conventional one. Auxiliary switches are also operated under zero current switching (ZCS) or zero voltage switching (ZVS). The inverter is suitable for PWM operation. .

Seyyed.M. Madani and M. M. Shahbazi [28] presented a new low cost, highly efficient, reliable and compact motor drive topology. The drives consist of a three-phase permanent magnet brushless DC (BLDC) motor, a soft switching dc-dc converter and a three-phase inverter containing six silicon controlled rectifiers (SCRs). A micro controller or a digital signal processor (DSP) will be used to control the overall system. The proposed system is fault tolerant due to its current regulated nature, where it can even withstand a solid short-circuit at its output terminals. The drive is low cost with respect to the commercially used IGBT-based systems. Since all the switches used in the output three phase inverter are

current commutated, and the dc-dc converter uses soft-switching techniques, this drive has much lower switching losses than the conventional PWM drive.

HE Hucheng, LIU Weiguo, DOU Manfeng, and MA Ruiqing [29] presented a novel zero voltage transition parallel resonant DC link voltage source inverter (ZVT-PRDCL-VSI) for BLDCM drive systems. The inverter possess advantages of low switching power loss, low inductor power loss, small device voltage stress, simple control scheme and no unbalancing problem of neutral-point voltage. The operation principle and control scheme of the inverter are analyzed.

Chang-hee Won, Joong-Ho Song, and Ick Choy [30] presented a comprehensive study result on reducing commutation torque ripples generated in brushless dc motor drives with only a single dc-link current sensor provided in the inverter dc-link. In brushless dc motor drives equipped with only a single current sensor, it seems that commutation torque ripple suppression which is practically effective in low speed as well as high speed regions has not been reported. A proposed commutation compensation technique combined with deadbeat dc-link current controller is based on a strategy that the current slopes of the incoming and the outgoing phases during the commutation interval can be equalized by a proper duty-ratio control.

Yen-Shin Lai Young-Kai Lin [31] presented a unified approach to back-EMF detection of brushless DC motor drives without using any current and Hall sensors. Theoretical analysis of back-EMF derived from BLDCM drives without using any current and Hall sensors fully confirm the theoretical analysis detection is presented, and followed by the relationship between PWM techniques and back-EMF detection. It will be shown that the back-EMF detection depends upon the PWM techniques and the method is required to be slightly modified as the PWM technique is changed Experimental results.

Jih-Sheng Lai[32] presented *a* soft-switching inverters and proposes two alternative options for electric propulsion drives. The newly developed soft-switching inverter employs an auxiliary switch and a resonant inductor per phase to produce a zero voltage across the main switch so that the main switch can turn on at the zero-voltage condition. Both the auxiliary switch and the resonant inductor are operating at a fractional duty, and thus are small in size as compared to the main inverter circuit components

3.3 CONCLUSION

From the various earlier works that on BLDC Motors, various types soft switching techniques, control strategies and different types of converter designs are used. Their applications, performances and their experimental results are also discussed as earlier work review. Now, a soft switching of BLDC motor using IGBT is tried. For which the analysis and simulation results are done in the last chapter. Soft switching using IGBT gives low switching losses, higher efficiency, reduce torque ripples and improves speed as compared to hard switching

3.4 OBJECTIVE

The objective of this work is to develop a soft-switching converter for BLDC motor drive and study some of its performance parameters. Relative comparison is also being made with the hard switching converters used for BLDC motor drives. MATLAB Simulink is used to develop the drive model. The proposed model proved innovative and satisfactory in terms of the simulation results obtained.

3.5 ORGANIZATION OF THE THESIS

The thesis comprises of five chapters with introduction as the first chapter. The PMBLDC drive and its operation are explained in second chapter. Literature review done in third chapter. Chapter four deals with soft switching techniques. Chapter five comprises of the simulations done using MATLAB Simulink. The simulation results for the soft switching of BLDC motor drive are discussed in this chapter. Chapter six discusses the conclusion and future scope of the work.

CHAPTER-4

SOFT SWITCHING

4.1 INTRODUCTION

Traditional hard-switching inverters presented several problems during switching. During turn-on, the device current rises from zero to the load current with additional diode reverse recovery and stray capacitor charging and discharging currents on top of the load current. Typically, a current spike will occur, and the peak device power consumption is extremely high. During turn-off, the device voltage rises. Due to the leakage inductance in the loop, a voltage overshoot caused by $L di/dt$ will occur, and the device voltage will exceed the dc bus voltage. This voltage overshoot can be reduced by a good circuit layout and high frequency dc bus capacitors. The turn-off loss varies among different types of devices depending upon the turn-off delay and current fall time. The power MOSFET consumes least turn-off loss [32]. The insulated gate bipolar transistor (IGBT) turn-off loss also varies among different manufacturing processes and its associated minority carrier lifetime killing. Some ultrafast IGBTs may have low turn-off loss close to that of power MOSFETs. The bipolar junction transistors (BJTs), in general, have a long turn-off delay time and consequently, high switching losses. Another switching problem is the voltage rise and fall rate, di/dt . During turn-on, the voltage falls to zero when the opposite switch turns on. During turn-off, the voltage rises to the dc bus voltage with an overshoot.

After observing so many problems with the hard-switching inverter, the use of soft-switching inverter is a logical choice to serve the following purposes:

- 1) Eliminate switching losses
 - Improve efficiency
 - Better utilize devices
 - Reduce heat sink size and cooling requirement
- 2) Reduce switching dv/dt

- Eliminate switching associated EMI
 - Avoid capacitance coupling currents between windings
 - Avoid induced currents through bearings
- 3) Allow high frequency switching
- Avoid acoustic noise
 - Respond faster
 - Reduce torque and current ripple

4.2 COMPARISON BETWEEN SOFT AND HARD SWITCHING

Semiconductors utilized in Static Power Converters operate in the switching mode to maximize efficiency. Switching frequencies vary from 50 Hz in a SCR based AC-DC Phase Angle Controller to over 1.0 MHz in a MOSFET based power supply. The switching or dynamic behavior of Power Semiconductor devices thus attracts attention specially for the faster ones for a number of reasons: optimum drive, power dissipation, EMI/RFI issues and switching-aid-networks.

With SCR's 'forced commutation' and 'natural (line) commutation' usually described the type of switching. Both refer to the turn-off mechanism of the SCR, the turn-on dynamics being inconsequential for most purposes. A protective inductive snubber to limit the turn-on di/dt is usually utilized. For the SCR's the turn-off data helps to dimension the 'commutation components' or to set the 'margin angle'. Conduction losses account for the most significant part of total losses.

Present day fast converters operate at much higher switching frequencies chiefly to reduce weight and size of the filter components. As a consequence, switching losses now tend to predominate, causing the junction temperatures to rise. Special techniques are employed to obtain clean turn-on and turn-off of the devices. This, along with optimal control strategies and improved evacuation of the heat generated, permit utilization of the devices with a minimum of duration.

Conventional PWM power converters when operated in a switched mode operation, the Power Switches have to cut off the load current within the turn-on and turn-off times

under the hard switching conditions. Hard switching refers to the stressful switching behavior of the power electronic devices. The switching trajectory of a hard-switched and soft switched power device is shown below in Fig. 1. During the turn-on and turn-off processes, the power device has to withstand high voltage and current simultaneously, resulting in high switching losses and stress. Dissipative passive snubbers are usually added to the power circuits so that the dv/dt and di/dt of the power devices could be reduced, and the switching loss and stress be diverted to the passive snubber circuits. However, the switching loss is proportional to the switching frequency, thus limiting the maximum switching frequency of the power converters. Typical converter switching frequency was 20 kHz to 50 kHz. The stray inductive and capacitive components in the power circuits and power devices still cause considerable transient effects, which in turn give rise to electromagnetic interference problems. The transient ringing effects are major causes of EMI.

Soft-switched converters that combine the advantages of conventional PWM converters and resonant converters have been developed. These soft-switched converters have switching waveforms similar to those of conventional PWM converters except that the rising and falling edges of the waveforms are 'smoothed' with no transient spikes is shown below Fig. 3. Unlike the resonant converters, soft-switched converters usually utilize the resonance in a controlled manner. Resonance is allowed to occur just before and during the turn-on and turn-off processes so as to create ZVS and ZCS conditions. Other than that, they behave just like conventional PWM converters. With simple modifications, many customized control integrated control circuits designed for conventional converters can be employed for soft-switched converters. Because the switching loss and stress have been reduced, soft-switched converter can be operated at the very high frequency (typically 500 kHz to a few Mega-Hertz). Soft-switching converters also provide an effective solution to suppress EMI and have been applied to DC-DC, AC-DC and DC-AC converters.

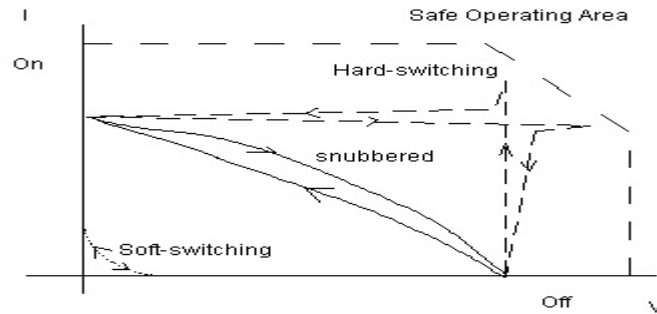


Figure 4.1 Typical switching trajectories of power switches

	Hard-switching	Soft-switching
Switching loss	Severe	Almost zero
Overall efficiency	Norm	Possibly Higher
Heat-sinking requirement	Norm	Possibly lower
Hardware count	Norm	More
Overall power density	Norm	Possibly higher
EMI problem	Severe	Low
<i>dv/dt</i> problem	Severe	Low
Modulation scheme	Versatile	Limited
Maturity	Mature	Developing
Cost	Norm	Higher

Table- 4.1 Comparison between hard and soft switching

4.3 LOSSES IN POWER SEMICONDUCTORS

A converter consists of a few controlled and a few uncontrolled devices (diodes). While the first device is driven to turn-on or off, the uncontrolled device operates mainly as a slave to the former. Power loss in the converter is the aggregate of these losses. Occasionally the diode and the controlled device are housed in the same module. The losses corresponding to each contribute to the temperature rise of the integrated module.

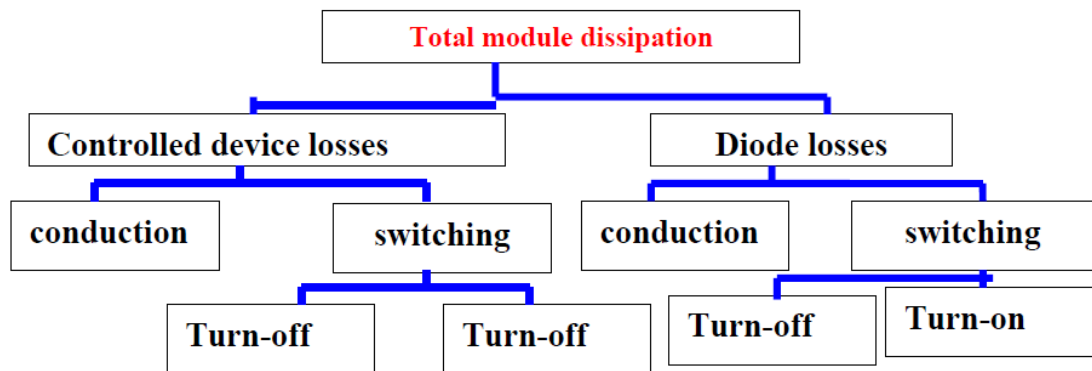


Figure 4.2 Total Module Dissipation

4.3 CLASSIFICATION OF SOFT SWITCHING INVERTERS

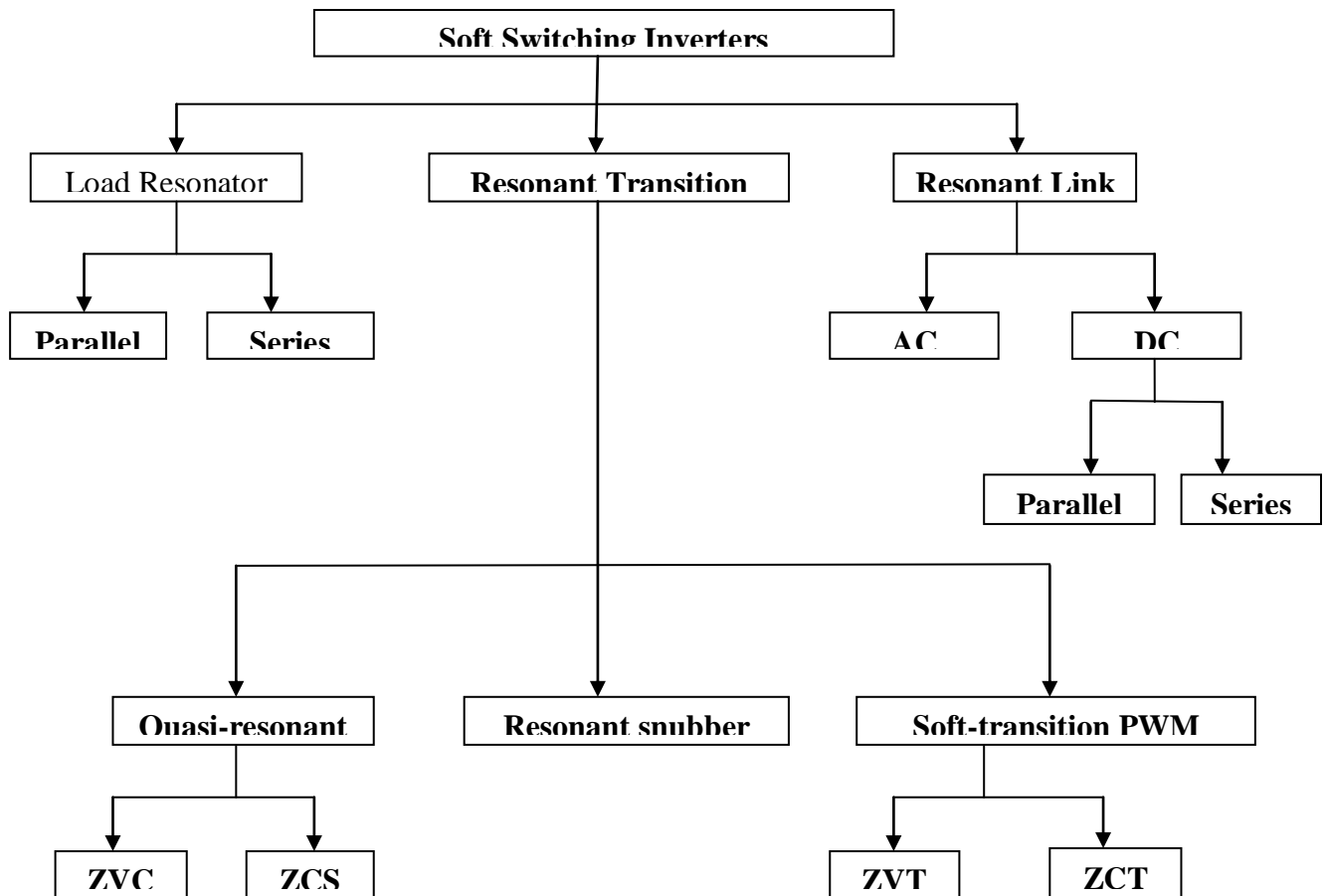


Figure 4.3 Block Diagram of soft switching inverters

The evolution of power converter topologies normally follows that of power devices, aiming to achieve high power density, high efficiency, high controllability and high reliability. Power converters may be ac-dc, ac-ac at the same frequency, ac-ac at different frequencies, dc-dc or dc-ac. loosely, dc-dc converters are known as dc choppers while dc-ac converters are known as inverters, which are respectively used for dc and ac motors. Initially, dc choppers were introduced in the early 1960s using force-commutated thyristors that were constrained to operate at low switching frequency. Due to the advent of fast-switching power devices, they can now be operated at tens or hundreds of kilohertz[19].

Two-quadrant (2Q) dc choppers are desirable because they convert battery dc voltage to variable dc voltage during the motoring mode and revert the power flow during regenerative braking. Furthermore, four-quadrant (4Q) dc choppers are employed for reversible and regenerative speed control of dc motors. 2Q and 4Q dc choppers are shown in Figure 4.4.

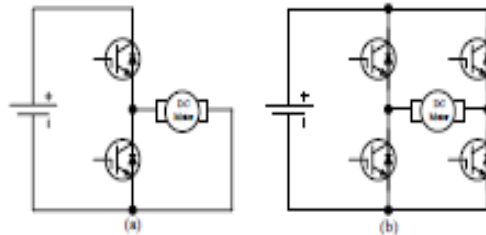


Figure 4.4 Dc choppers- (a) 2Q; (b) 4Q.

Inverters are generally classified into voltage-fed and current-fed types. Because of the need of a large series inductance to emulate a current source, current-fed inverters are seldom used. In fact, voltage-fed inverters are almost exclusively used because they are very simple and can have power flow in either direction. A typical three-phase full-bridge voltage-fed inverter is shown in Figure 4.5.

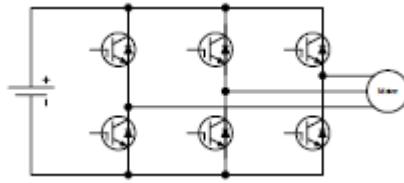


Figure 4.5 Three-Phase full-bridge voltage-fed inverter.

The output waveform of an inverter may be rectangular, six-step or pulse width modulation (PWM), depending on the switching strategy for different applications. For example, a rectangular output waveform is produced for a permanent magnet (PM) brushless dc motor, while a six-step or PWM output waveform is for an induction motor. It should be noted that the six-step output is becoming obsolete because its amplitude cannot be directly controlled and rich in harmonics. On the other hand, the PWM waveform is harmonically optimal and its fundamental magnitude and frequency can be smoothly varied for speed control. Starting from the last decade, numerous PWM switching schemes have been developed for voltage-fed inverters, focusing on the harmonic suppression, better utilization of dc voltage, tolerance of dc voltage fluctuation as well as suitability for real-time and microcontroller-based implementation. These schemes can be classified as voltage-controlled and current-controlled PWM. The state-of-the-art voltage-controlled PWM schemes are natural or sinusoidal PWM, regular or uniform PWM, harmonic elimination or optimal PWM, delta PWM, carrier-less or random PWM, and equal-area PWM. On the other hand, the use of current control for voltage-fed inverters is particularly attractive for high-performance motor drives because the motor torque and flux are directly related to the controlled current. The state-of-the-art current-controlled PWM schemes are hysteresis-band or band-band PWM, instantaneous current control with voltage PWM, and space vector PWM.

4.4 REQUIREMENTS OF SOFT-SWITCHING CONVERTERS

Soft-switching converters are recently receiving wide attention in the literature. Instead of using hard or stressed switching, power converters can adopt soft or relaxed switching.

The key of soft-switching is to employ a resonant circuit to shape the current or voltage waveform such that the power device switches at zero-current or zero-voltage condition.

In general, the use of soft-switching converters possesses the following advantages:

- Due to zero-current or zero-voltage switching condition, the device switching loss is practically zero, thus giving high efficiency.
- Because of low heat sinking requirement and snubber less operation, the converter size and weight are reduced, thus giving high power density.
- The device reliability is improved because of minimum switching stress during soft switching.
- The EMI problem is less severe and the machine insulation is less stressed because of lower dv/dt resonant voltage pulses.
- The acoustic noise is very small because of high frequency operation.

On the other hand, their key drawbacks are the additional cost of the resonant circuit and the increased complexity. Although soft-switching dc-dc converters have been widely accepted by switched-mode power supplies, the corresponding development is much slower. As the pursuit of power converters having high efficiency and high power density for BLDC Motor is highly desirable, the development of soft-switching power converters for motor drives is in progress.

4.5 SOFT-SWITCHING DC-DC CONVERTERS

There have been many soft-switching dc-dc converters developed for switched-mode power supplies, these converters cannot be directly applied to dc motors. Apart from suffering excessive voltage and current stresses, they cannot handle backward power flow during regenerative braking. In recent years, some soft-switching dc-dc converters have been specially developed, which offers the capability of bidirectional power flow for both motoring and regenerative braking.

4.5.1 Zero-voltage multi-resonant converters

A two-quadrant (2Q) zero-voltage multi-resonant (ZVMR) converter has been applied for dc motors drives. The 2Q-ZV-MR converter is created by adding a resonant inductor and two resonant capacitors to a conventional 2Q-PWM dc drive, as shown in Figure 4.6.

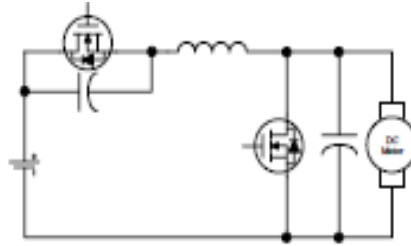


Figure 4.6 Q-ZV-MR Converters

Major advantages of the 2Q-ZV-MR converter are as follows:

- Constant frequency operation.
- Utilization of all built-in diodes of the power switches and absorption of major parasitic.
- Zero-voltage-switching (ZVS) for all power switches.
- Bidirectional power flow for both motoring and regenerative braking.
- Full ranges of both voltage conversion ratio and load.
- Short-circuit operation capability.

However, the circulating energy and the conduction losses associated with the MR cell are significantly increased, hence the power rating of the power metal-oxide semiconductor field-effect transistor (MOSFET) are higher as compared with their PWM counterpart.

4.5.2 Zero-voltage-transition converters

A 2Q zero-voltage-transition (ZVT) soft-switched dc-dc converter has been developed for dc motor drives. The 2Q-ZVT converter is created by adding a resonant inductor, a resonant capacitor and two auxiliary switches to a conventional 2Q-PWM dc drive, as shown in Figure 4.7. It should be noted that the ZVT technology is highly desirable for power MOSFET based power conversion. It is due to the fact that the power MOSFET device generally suffers from severe capacitive voltage turn-on losses.

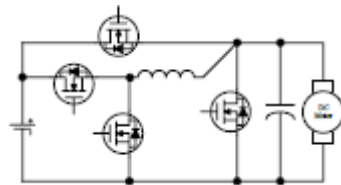


Figure 4.7 Q-ZVT converter fed dc motor drive.

Major advantages of the 2Q-ZVT dc motor drive are as follows:

- Zero-voltage-switching (ZVS) for all main switches and rectifiers.
- Bidirectional power flow for both motoring and regenerative braking.
- Unity device voltage and current stresses during both the motoring and regenerating modes of operation.
- Same resonant tank for both forward and backward power flows.
- Stray capacitances are utilized as part of the resonant components.
- Utilization of all built-in diodes of the power switches, thus minimizing the overall hardware count and cost.

4.5.3 Zero-current-transition converter

A 2Q zero-current-transition (ZCT) soft-switched dc-dc converter has been developed for dc motor drives. The 2Q-ZCT converter is created by adding a resonant inductor, a resonant capacitor and two auxiliary switches to a conventional 2Q-PWM dc drive, as shown in Figure 4.8 This 2Q-ZCT converter is particularly useful for those high-power

dc motor applications, employing the insulated-gate bipolar transistor (IGBT) as power devices, which generally suffer from diode reverse recovery during turn-on and severe inductive turn-off switching losses.

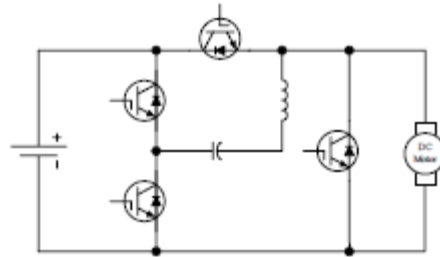


Figure 4.8 Q-ZCT converter fed dc motor drive.

Major advantages of the 2Q-ZCT dc motor drive are as follows:

- Zero-current-switching (ZCS) for all switches and rectifiers.
- Bidirectional power flow for both motoring and regenerative braking
- Same resonant tank for both forward and backward power flows.

4.5.4 Four-quadrant zero-transition converters

4Q dc choppers are employed for reversible and regenerative speed control of dc motors. Instead of using mechanical contractors to achieve reversible operation, the 4Q dc chopper is employed so that motoring and regenerative braking in both forward and reversible operations are controlled electronically. Following the spirit of development on the 2Q-ZVT and 2Q-ZCT converters; 4Q-ZVT and 4Q-ZCT converters fed dc motor drives are recently developed, as shown in Figures 4.9 and 4.10 respectively. Major advantages of 4Q converters are similar to their 2Q counterparts.

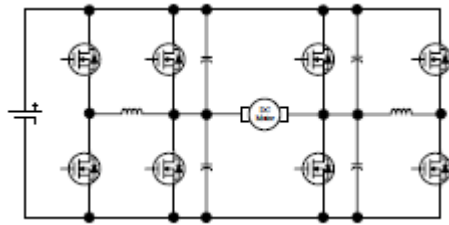


Figure 4.9 Q-ZVT converter

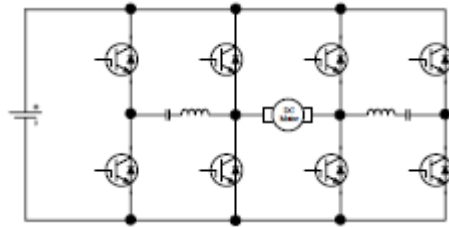


Figure 4.10 Q-ZCT converter

4.6 SOFT-SWITCHING DC-AC INVERTERS

The development of soft-switching inverters for ac motors (including induction motors, PM brushless motors and PM hybrid motors) has become a research direction in power electronics. Figure 8 shows a milestone of soft-switching inverters, namely the three phase voltage-fed resonant dc link (RDCL) inverter developed in 1989.

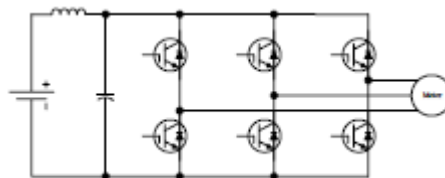


Figure 4.11 Three-Phase Voltage-fed RDCL Inverter.

Subsequently, many improved soft-switching topologies have been proposed, such as the quasi-resonant dc link (QRDCL), series resonant dc link (SRDCL), parallel resonant dc link (PRDCL), synchronized resonant dc link, resonant transition, auxiliary resonant commutated pole (ARCP), and auxiliary resonant snubber (ARS) inverters. A number of development goals of soft-switching inverters have been identified. Recently, the delta-

configured ARS version has satisfied most of these goals, and has been demonstrated to achieve an output power of 100 kW.

4.6.1 Resonant dc link inverter

Figure 4.12 shows a basic resonant dc link (RDCL) inverter. In this circuit, the inverter input voltage is pulsating by adding a parallel resonant network between the dc voltage source and the inverter bridge, therefore the link voltage has zero crossings which create the desirable

ZVS conditions for inverter switches. The peak resonating voltage is twice the dc source voltage under no load condition and more than three times the dc source voltage under the transition from motoring mode to regeneration mode.

By adding an auxiliary switch and a stored-voltage clamp capacitor in the conventional RDCL, as shown in Figure 4.12, a better voltage clamping level of 1.3-1.5 times the dc source voltage can be achieved, but the additional components result in increased cost and reliability penalty.

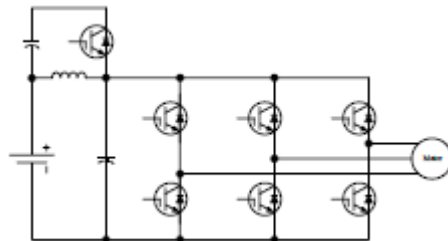


Figure 4.12 Active Clamped RDCL Inverter.

Major advantages of RDCL are as follows:

- Minimum number of power devices.
- Elimination of snubber.
- ZVS for main switches.
- Low dv/dt at motor terminals.
- High resonant as well as switching frequencies.
- Low sensitivity to parasitic impedance and device recovery effects.

There are several improved versions based on the basic RDCL inverter. However, some technical problems remain unsolved, such as:

- High voltage stress of 1.3-1.5 times the dc source voltage (even with clamping).
- Pre-charging problem of the voltage clamp capacitor.
- Rich in sub-harmonics due to discrete modulation.
- High switching losses for the auxiliary switches and diodes.

4.6.2 Auxiliary resonant commutated pole inverter

The auxiliary resonant commutated pole inverter (ARCP) or quasi-resonant inverter shifts the resonant inductor away from the main power flow and connected to the split capacitors for bidirectional commutation, as shown in Figure 4.13. A bidirectional switch is series connected to the resonant inductor to control the direction of resonant energy transfer. These auxiliary switches are operated with ZCS and required to withstand only half of the dc source voltage.

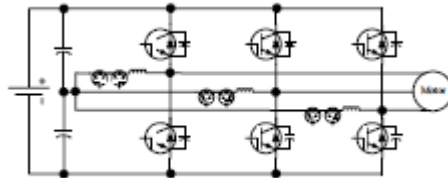


Figure 4.13 ARCP Inverter.

Since the auxiliary switches are not associated with any load energy transfer, their power ratings are much smaller than the main power devices.

Main features of ARCP inverters are as follows:

- Conventional PWM or space vector modulation (SVM) can be applied for controlling the ARCP.
- Unity voltage/current stresses on main switches
- Equivalent spectral performance to hard-switching converter.

- Auxiliary switches are required to withstand half of the dc source voltage only.
- ZVS for main switches while ZCS for auxiliary switches.

However, some technical problems remain unsolved, such as:

- System performance varies with load current.
- Additional bulky energy storage capacitors are required.
- Several split capacitors are required.
- Long resonant period since only half dc source voltage is applied for resonance.

4.6.3 Auxiliary resonant snubber inverter

An improvement of ARCP inverter, the resonant circuit of ARS inverter is placed between phase outputs, instead of using a centre tapped dc link for commutation. The principle of ARS inverter is to utilize the resonant capacitor across the device to achieve zero turn-off loss and the resonant inductor along with the auxiliary switches to achieve zero-voltage turn on. The auxiliary branch is connected between two phase legs. Circuit operation if ARS inverter is similar to ARCP inverter except its commutation relies on the interaction between at least two phase-legs. By using auxiliary switches and resonant inductors along with resonant snubber capacitors to achieve the soft-switching condition, two three-phase topologies of the ARS inverter are shown in Figure 4.14 and Figure 4.15.

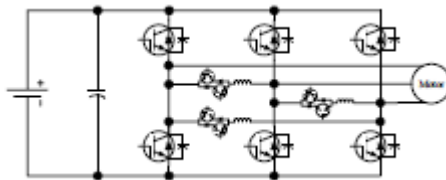


Figure 4.14 Delta-connected ARS inverter.

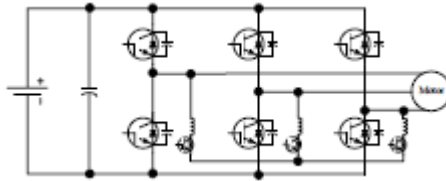


Figure 4.15 Star-connected ARS inverter.

Major features of ARS inverter are summarized as follows:

- Minimum auxiliary components when compared with ARCP inverter and low cost.
- Simple resonant inductor current control.
- ZVS for main switches and ZCS for auxiliary switches.
- Parasitic inductance and stray capacitance are utilized motor as part of the resonant components.
- Comparatively less over-voltage or over-current penalty in main switches.
- Modification of conventional PWM control strategies is required.

CHAPTER-5

RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

The objective of this project is to simulate the soft switching of PMBLDC motor. In order to achieve this, a good idea about the simulation of PMBLDC motor using MATLAB. The simulation is done using MATLAB 7.5. The model is developed using MATLAB/SIMULINK incorporating m-file S functions which is an user-defined functions block.

5.2 SOFTWARE USED

5.2.1 MATLAB 7.5

MATLAB (Matrix Laboratory) was invented in late 1970s by Cleve Moler. It is a high-level language and its interactive environment helps us to perform computationally intensive tasks faster than with traditional programming languages such as C, C++, and FORTRAN. Another important feature of MATLAB is that it helps in modeling, simulating, and analyzing dynamic systems using SIMULINK, so it is widely used in applications that describe real-world phenomena. It supports linear and nonlinear systems, modeled in continuous time or sampled time. Simulink encourages us to try things out. We can easily build models from scratch, or take an existing model and add to it. We have instant access to all the analysis tools in MATLAB, so we can take the results and analyze and visualize them. The goal of simulink is to give us a sense of the fun of modeling and simulation, through an environment that encourages us to pose a question, model it, and see what happens. The simulations done in this present project are discussed in further sections.

5.3 DESIGNING OF SOFT SWITCHING CIRCUITS

While Designing Soft switching circuits we need to keep in mind the following points:

- 1 All switches work under soft-switching condition, so their power losses are small.
- 2 For the purpose of the phase current control, it is necessary to modulate the phase voltage. This is especially important at low speed, when the motor back-e.m.f is low.
- 3 The voltage gain of the converter should be maximum possible in order to extend the constant power operation mode and increase the maximum speed.
- 4 Large fall time of phase current results in negative torque and this time can be reduced if demagnetising voltage is as high as possible.
- 5 It is necessary, at the same time, to control current in one phase and force demagnetising of some other phase of the motor. This is crucial for reduction of the torque ripple.
- 6 Converter has to be single rail in order to reduce the voltage stress across the semiconductor switches.
- 7 The power converter must not require bipolar windings or rely upon the motor construction.
- 8 A low number of semiconductor switches is desirable

Phase current in IGBT based power converter is controlled by selecting from three possible states:

- i) Both switches in a phase leg are on, and phase is energized from power supply (220v) here (magnetizing stage).
- ii) Both switches in a phase leg are off. Phase current commutates to the diodes and decays rapidly (demagnetizing stage).
- iii) Only one of the switches is off. The voltage across winding is near zero and phase current decays slowly (freewheeling).

Experimental investigation is based on a three-phase BDLC with stator and rotor pole widths equal to 36 degree. The air- gap and the rotor length are 0.3 mm and 50.2 mm, respectively, and the per-phase winding resistance is 4.

5.4 SWITCHING STATES OF IGBT'S

(A) Magnetizing stage (Phase1)

(A1) Q1- and Q+ are on (IGBT 3, 1),

(A2) Q1 + and Q- are on (IGBT (3, 2)

It should be noted at this point that these two states lead to two possible directions of the phase current. This means that the current in the winding is bipolar, rather than unipolar.

a) Magnetization Stage

The BLDC under consideration is of short pitched design, where torque is produced entirely due to the variation of the self-inductance with rotor position, it is obvious that the same torque can be generated with both uni-polar and bipolar currents. In both A1 and A2 switching states, full DC bus voltage is available across the winding for magnetization stage.

b) Demagnetizing Stage

IGBT Q- is on (A1 magnetizing) or Q+ is on (A2 magnetizing). The switches in off-going phase leg are off. Phase current commutates to diodes and decays rapidly. During demagnetization stored a Novel Power Inverter for BDLC Drives 459 energy in the off-going phase is returned to the power supply and on-coming phase.

c) Freewheeling

The winding can be short-circuited by either turning off switches (Q+, Q-) or (Q+, Q-). Phase current decays slowly. During low speed operation phase current has to be limited or controlled in order to reduce torque ripple. This can be done by alternating between states A and B or between states A and C. It is preferable to use states A and C because this results in lower switching frequency for the same current ripple.

5.5 Model without Soft-Switching:

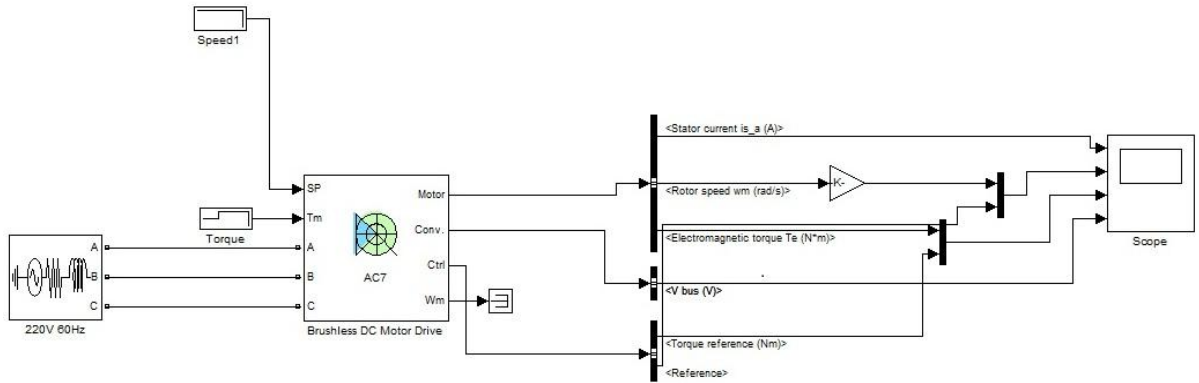


Figure 5.1 BLDC without soft switching

5.6 Model with Soft-Switching:

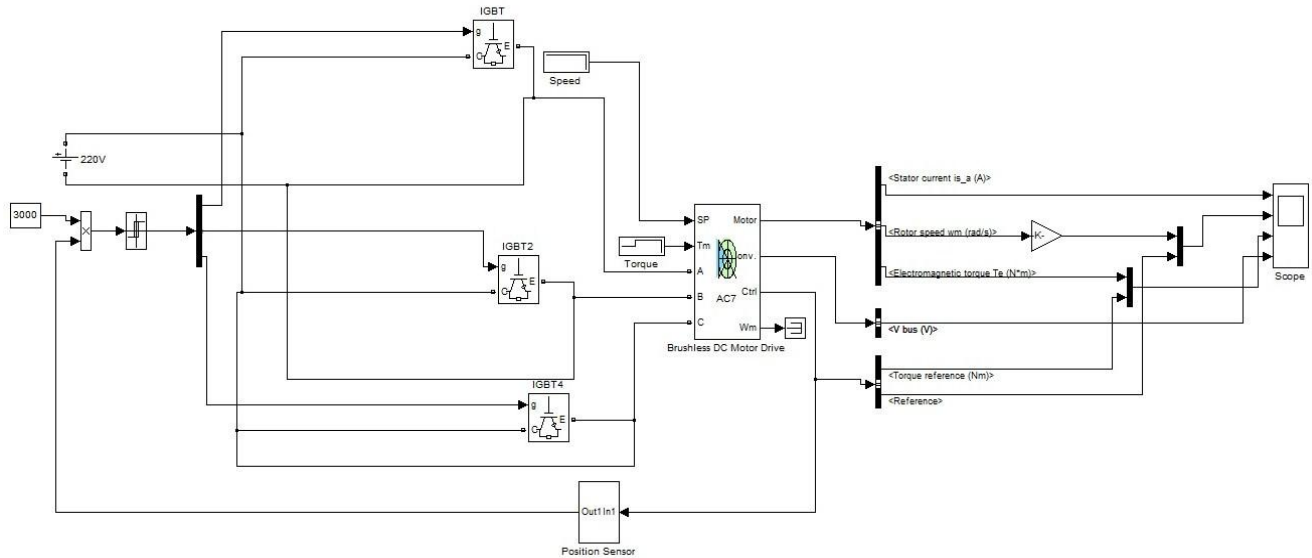


Figure 5.2 BLDC with soft switching

5.7 Circuit operation for BLDC Motor

Current is passed through one of the stator windings. Torque is generated by the tendency of the rotor to align with the excited stator pole. , if the poles a1 and a2 are energised then

the rotor will align itself with these poles. Once this has occurred it is possible for the stator poles to be de-energised before the stator poles of b1 and b2 are energised. The rotor is now positioned at the stator poles b. This sequence continues through c before arriving back at the start. This sequence can also be reversed to achieve motion in the opposite direction. This sequence can be found to be unstable while in operation.

The direction of the torque generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flowing through the phase winding. Continuous torque can be produced by intelligently synchronizing each phase's excitation with the rotor position. The amount of current flowing through the BDLC winding is controlled by switching on and off power electronic devices, IGBTs here, which can connect each BDLC phase to the DC bus.

5.7.1 Circuit operation using IGBT's

The Soft switching circuit uses 3 IGBT's .The IGBTs act as switches to provide a series of DC pulses to the brushless dc motor. Since Brushless DC Motor frequency controls are for 3-phase motors, there are 3 IGBTs, one for each phase. IGBT connects each motor terminal to the positive side of the DC supply 220 V. In that way, each terminal to terminal or line to line voltage can be either positive or negative. By controlling the switching sequence of the IGBTs, the control provides a simulated 3-phase sine voltage with frequency and voltage control. The waveform is composed of DC pulses and doesn't look too much like a sine wave, but the effective value is a reasonably good simulation of a sine wave. Torque ripple of motor is reduced significantly. For a given voltage of supply, torque and speed of the motor are doubled. For a given speed of the motor, the voltage stress of switching device is reduced half, the insulation class requirement can be also reduced. BDLC (AC7) required 220 V to operate. The Soft switching circuit plays role for drive system for BDLC. From the constant block we are providing 3000 and soft switching circuit is designed to operate and switch if V_f goes above 220 v, which it is doing and exciting two phases of BDLC at a time (it can be A,B or B,C or A,C) depending upon the input signal. The speed precisely follows the acceleration ramp.

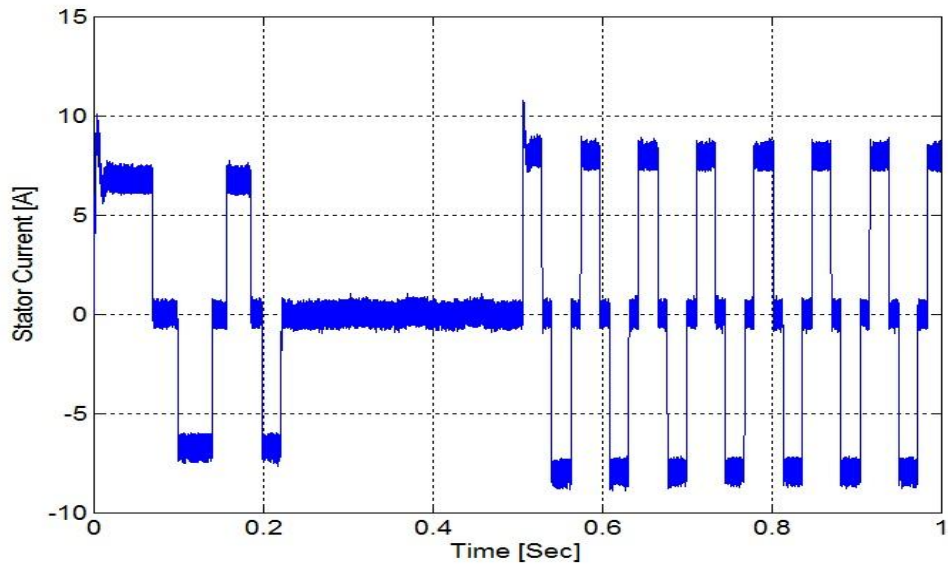


Figure 5.3 Stator Current without Soft Switching

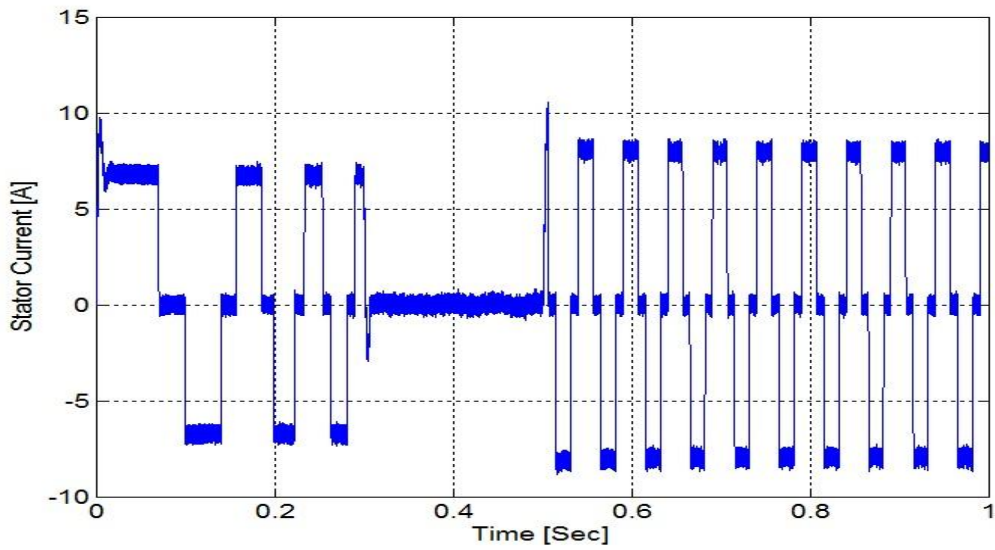


Figure 5.4 Stator Current with Soft Switching

We compared the outputs of stator current of both the without soft switching model and IGBT soft switching model. Maximum current in both the model's output is 10A. As

clear from output , the stator current starts decreasing in interval (0,0.02) and start fluctuating and becomes constant after 0.2 and remain constant until 0.5.And then got proper and gives sine wave after 0.5 onwards in without soft switching model. The stator current with soft switching model is more sinusoidal than without soft switching model. its remain constant in interval (0.3 to 0.5).the stator current with soft switching more stable and it gives better torque.

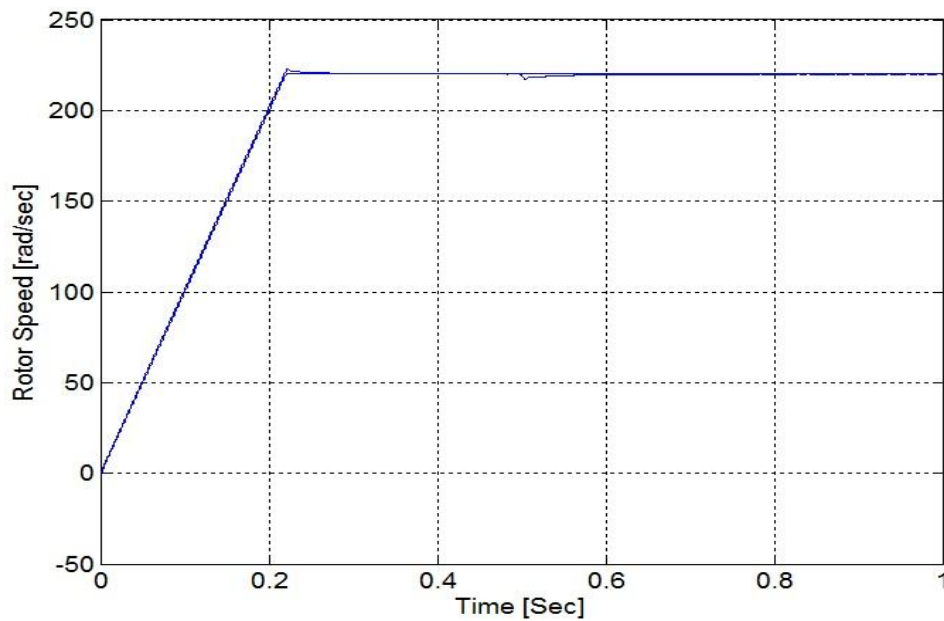


Figure 5.5 Rotor Speed without Soft Switching

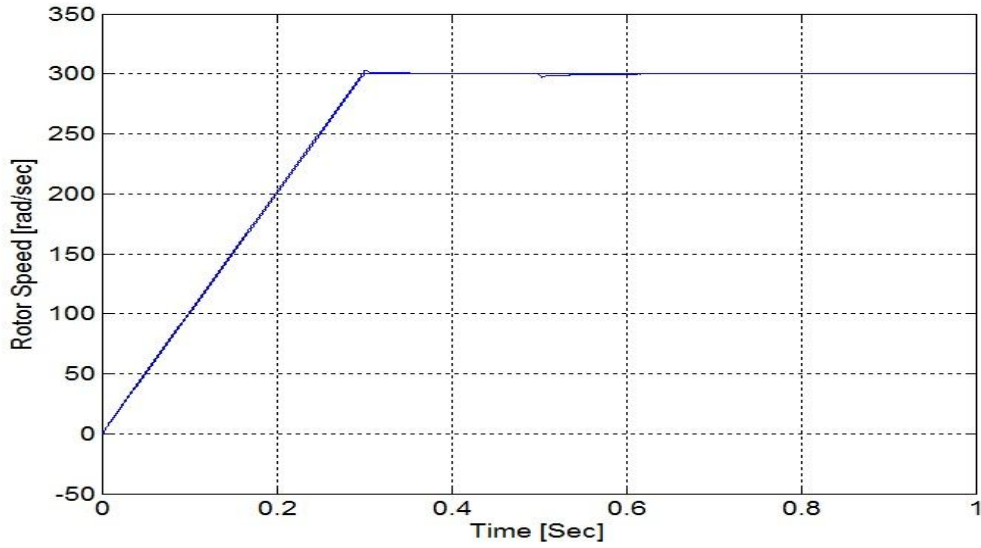


Figure 5.6 Rotor Speed with soft switching

We compared the outputs of rotor speed of without soft switching model and IGBT soft switching model. Maximum speed of without soft switching model is 225 (rad/sec) and maximum speed of with soft switching model is 300 (rad/sec). As clear from outputs rotor speed improves with soft switching using IGBT's. Rotor speed starts increasing from zero, after some time it become constant.

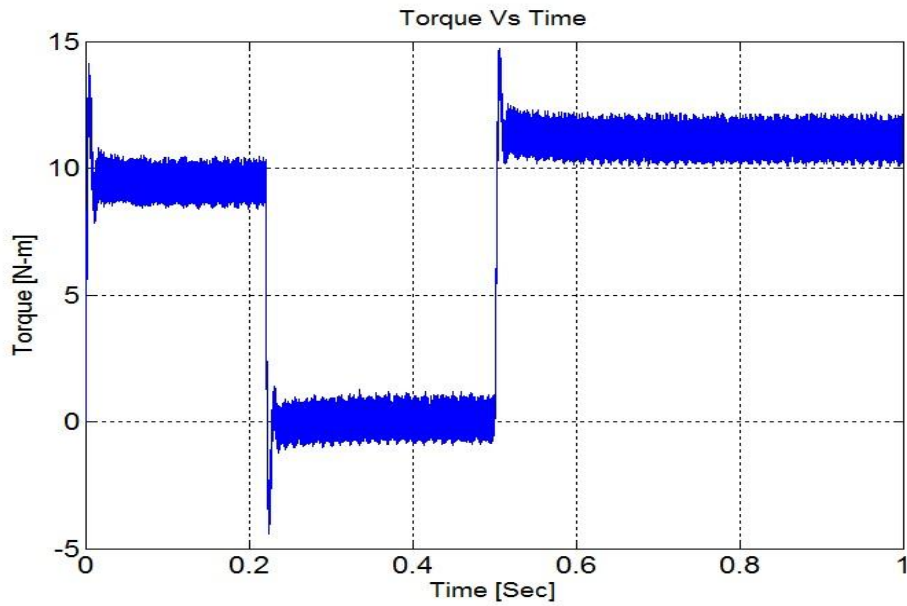


Figure 5.7 Torque without Soft Switching

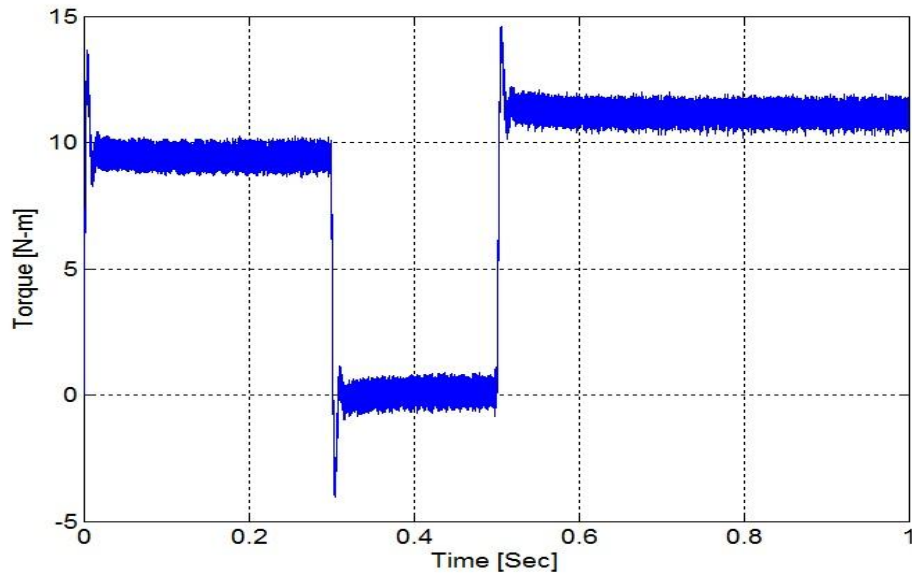


Figure 5.8 Torque with Soft Switching

We compared the torque outputs of without soft switching model and IGBT soft switching model. Maximum torque in both models is 14 N-m. As clear from output, torque start decreasing in interval (0, 0.01) and after that it becomes constant up to 0.22 and further decreases and becomes negative. After that it again starts increasing and becomes constant in interval from 0.23 to 0.5. From 0.5 it again starts increasing to maximum value and after it again decreasing and become constant in without soft switching. Torque in soft switching model decreasing in interval (0, 0.01) and after that it become constant up to 0.3 and further decreases and become negative. After that it again starts increasing and becomes constant in interval from 0.3 to 0.5. From 0.5 it again starts increasing to maximum value and after it again decreasing and become constant. From the outputs we observed that torque improves with soft switching technique.

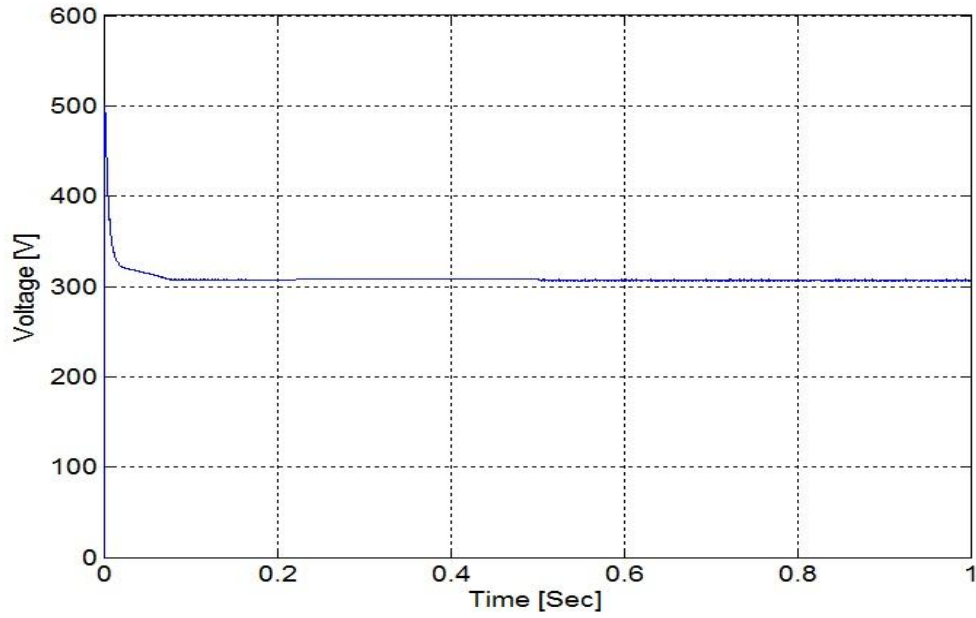


Figure 5.9 Voltage without Soft Switching

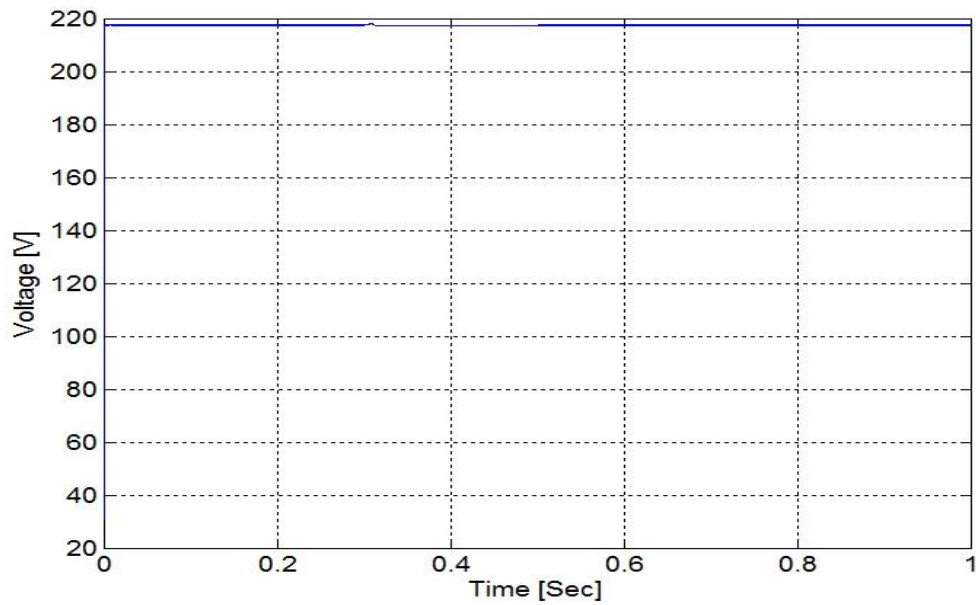


Figure 5.10 Voltage with Soft Switching

We compared the voltage outputs of without soft switching model and IGBT soft switching model. Voltage in without soft switching decreases first and after that it

becomes constant. In soft switching voltage remain constant over the whole period. There is no effect on bus voltage when motor starts with soft switching.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION AND FUTURE SCOPE OF WORK

A sincere effort is made to develop a novel soft-switching converter for a BLDC motor drive using MATLAB Simulink. The waveforms for stator current, rotor speed, torque and voltage were studied in comparison with the existing hard-switching converters for the BLDC motor drive. Simulation results obtained justify these facts. A hardware circuitry now needs to be developed which can be taken up as a future scope of work.

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