SVPWM Controlled BLDC Motor Drive Using Modified Zeta Converter for Power Factor Correction

Submitted by:
Muhammad Hamid Raza-2012-Ms-ee-106

Supervised by: Dr. Syed Abdul Rahman Kashif

Department of Electrical Engineering
University of Engineering and Technology Lahore

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Internal Examiner

External Examiner

Chairman
Department of Electrical Engineering

Dean
Faculty of Electrical Engineering

Department of Electrical Engineering
University of Engineering and Technology Lahore

Declaration

I, Muhammad Hamid Raza, declare that the work presented in this thesis is my own.

Signed:_________________

Date:__________________

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First of all I would like to thank Allah Almighty for everything. I would like to thank my supervisor Dr. Syed Abdul Rahman Kashif. It is because of his assistance and counselling that I am able to complete such difficult task. His encouragement and inspiration facilitated me to resolve difficulties associated with the task. I would also like to thank my honorable review committee. Their precious feedback abetted me to clarify and express my pathway in research.

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Dedicated to my Family and Friends, who has always been my inspiration. . .

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
BLDC	Brushless DC
CCM	Continuous Conduction Mode
DBR	Diode Bridge Rectifier
DC	Direct Current
DCM	Discontinuous Conduction Mode
DICM	Discontinuous Inductor Conduction Mode
EMF	Electromotive Force
ESR	Equivalent Series Resistance
IGBT	Insulated-Gate Bipolar-Transistor
m	Modulation Index
MOSFET	Metal Oxide Field Effect Transistor
PFC	Power Factor Correction
PI	Proportional Integral
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse Width Modulation
RPM	Revolution Per Minute
SPWM	Sinusoidal Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation
THD	Total Harmonic Distortion
VSI	Voltage Source Inverter

Preface

The main goal of this research is Power Factor Correction of SVPWM Controlled BLDC Motor drive by reducing the total harmonic Distortion THD using Modified Zeta Converter. The main culprit for low power factor in swathing patterns of converter and inverters used in BLDC Motor Drive Circuit. Thus in this thesis we research to improve anteceding control techniques for improved power quality and better performance.

In this thesis first chapter is introduction. It includes elementary overview of the study, problem statement and goal of research. The second chapter is designated as Literature Survey encompassing detailed analysis of Brushless Motor, Space Vector Pulse Width Modulation, Modified Zeta Converter and an outline of research persistent in domain of BLDC Motor Drive. In chapter three we elucidate our recommended design with the help of tools to comprehend our research. The fourth chapter detailed evaluation of simulation and results achieved. Chapter five covers conclusion and an overview of anticipated future work.

Abstract

This Thesis portray in words the Space Vector Pulse Width Modulation controlled BLDC Motor Drive circuit along with Power Factor Correction by using Modified Zeta Converter. The drive is designed to obtain reduced Total Harmonic Distortion for Power Factor Correction. The basic design of BLDC Motor Drive contains AC voltage source as input source for a Diode Bridge Rectifier. The output DC voltage is filtered out for reducing ripples. The smooth DC output voltage is supplied to Modified Zeta Converter. The output voltage of modified Zeta converter is controlled by using Pulse width modulation. The Modified Zeta Converter is utilized in discontinuous inductor conduction mode for better power factor. This controlled DC voltage is supplied to Voltage Source Inverter as input. Voltage Source Inverter is designed to convert input DC into suitable AC voltage source. The output voltage of Voltage Source Inverter depends upon switching patterns applied to power transistors generated by Space Vector Pulse Width Modulation. The output of Voltage Source Inverter is supplied to BLDC Motor for controlling the speed. The proposal is then simulated and assessed for improved power factor, low total harmonic distortion and better speed control via MATLAB/Simulink environment in Simpowersystem Simscape toolbox.

Keywords— Voltage Source Inverter; Space Vector Pulse Width Modulation; BLDC Motor; Modified Zeta Converter; Discontinuous inductor Current Mode.

Chapter 1

1.Introduction

1.1.Overview:

The recent development in the field of Brushless DC (BLDC) Motor Drive provided a better and easy speed control. For any new type of motor it is very hard to find applications if it does not provide special features and better performance than already existing substitutes. Due to new areas of applications highly efficient motors with advanced features and greater reliability are needed. Motors has industrial as well as domestic applications including aerospace, defense, marine, automobiles, computer disk drives, robotics, aircraft toys, pumping systems and in medical healthcare which demands motors with high torque to density ratio, high speed, low power consumption and high speed. BLDC Motor is highly efficient with easy control that’s why it is suitable for low power applications. It has turn out to be an outstanding replacement to brushed DC Motor.

In this thesis a BLDC Motor Drive is designed for better speed control and high power efficiency. A Modified Zeta Converter is used to transform pulsating DC into a controllable DC voltage by using PWM pulses. This provides an improved power quality design. SVPWM pulses are utilized for voltage source inverter switching to convert DC into AC voltage. This offers an improved power factor design with low total harmonic distortion and a broad and easy speed control.

1.2.Brief History of BLDC Motor Drive:

Ernst Werner von Siemens invented DC Motor in 1856. Due to this great invention the system international unit of conductance is named after him. Harry Ward Leonard provided first effective DC Motor speed control in 19th century with the use of a rheostat in field winding. In 1960 with the invention of thyristor by Electronic Regulator Company, the Ward Leonard system was discarded.

Historically there was no way out of driving a DC Motor without using “brushes”. Graphite made brushes are utilized for power conduction to the rotor. These brushes provides commutation in which polarity of rotor is reversed after every half cycle. So in this way a commutator has become a control mechanism for voltage polarity. This DC

Motor has a lot of drawbacks. Brushes needed a periodic replacement due to wear out. The making and breaking of brushes and split rings creates sparks and induces electromagnetic interference which makes it dangerous to use in explosive environment. In a DC brushed motor the only way to control the speed and torque is voltage which makes the control difficult. A brushed DC Motor suffer from a large amount of friction losses. The imperfections of DC Motor are solved by BLDC Motor. BLDC motor was invented by P.H. Trickey and T.G. Wilson. They replaced the physical commutator with thyristors based electronic commutators. The named their invention as “a DC machine with solid state commutation.”

Permanent magnet materials and high voltage transistors come to be easily accessible in 1980s which enhanced the mechanical power of BLDC Motor comparable to brushed DC Motor. Robert E. Lordo revealed a BLDC Motor with 10 times greater power than ever before.

1.3.Electric Machine Drive:

Environmental conditions and operational characteristics of an electric motor depends upon the type of application being used. To achieve the desirable efficiency, speed, and torque a suitable motor drive circuit is needed. Generated torque of a motor depends upon the output voltage and frequency of variable frequency drive. The output frequency depends upon the switching frequency of control unit. A voltage source inverter will produced higher voltage if switches are ON for a longer period and higher frequency will be generated if switches are ON for short periods i.e. for short switching intervals. Three phase voltage is generated by switching upper and lower switches of voltage source inverter in a sequence. Basic components of a drive are input DC-DC converter for converting pulsating DC into variable DC, DC link capacitor voltage providing constant voltage and output inverter which finally converts fixed DC into sinusoidal AC. A very suitable method for speed control is to change the applied frequency of the supplied voltage. Speed can also be changed by changing number of poles, but it will results in speed variations in fixed steps and it has costly winding designs. The developed torque of a motor depends upon the voltage to frequency (V/Hz) ratio. Rated torque can be changed by changing this ratio. With different output frequencies a drive can provide multiple torque curves. The electric motor speed can be controlled by varying the switching frequency of output inverter. High frequency switching will obviously generate high frequency the phase supply which in turn can generate greater speed. The switching of power electronic devices used is decided by the control unit. Typically a microprocessor or digital signal processor (DSP) based control unit is designed for this purpose. Previously thyristor based drives have been utilized. Thyristor have three terminals anode, cathode and gate. Gate terminal is used to turn it ON by a gate pulse and a polarity reversal to turn it OFF. A thyristor conducts in ON state and blocks the voltage in OFF state. A special control block was needed for this purpose. Thyristor were replaced by bipolar transistors in mid-1970s. In early 1990s insulated-gate bipolar-transistor (IGBT) were invented which lead the machine design to better perfections with greater speed and reduced amount of loses. The output of a drive is not exactly sinusoidal. There are constant magnitude voltage pulses generated by alternatively switching positive and negative switches. The switching frequency of power device is also known as carrier frequency. Typical switching frequencies are in the range of 3 kHz to 4 kHz. To obtain a high resolution output and smooth waveform higher switching frequency is needed but this increases switching losses or heat loses and in turn decreases the efficiency. Recent developments increased the complexity but they are reliable, easily controllable and smaller in size. They provide better performance and also they don't generate harmonics in the power system. They are available with improved power factor design. It had also added the feature of "plug and play". They have reduced the size of power electronic drive circuits.

1.4.BLDC Motor:

The BLDC Motor is an inverted version of DC motor with wound stator, normally salient pole and permanent magnet rotor inside. As the rotor is a permanent magnet there is no need of brushes for commutation. As a result there is no drawback of sparking as it happens in commutators. It is an AC motor but still referred as DC motor because of electronic commutation involved. The commutation is performed by applying DC voltage source to stator coils in a sequential pattern. The current in each coil of the motor is alternating which categorize this into AC motors. The back EMF of the motor is trapezoidal. It is a very efficient motor as many current researches claimed its 96 percent efficiency in 100 W load. It is also considered in world fastest motors as a BLDC Motor with a speed of 400k RPM has been reported.

Normally a BLDC Motor has three phase wound rotor which allow to use a six power electronic switch inverter. These six switches are turned ON and OFF by some PWM technique for obtaining alternating waveform. The operation of BLDC Motor can be made sensorless by taking feedback of motor’s back-EMF. It can be operated in sensored applications by using Hall Effect position sensor or optical encoders. This motor is normally used in disk drive servo, fuel/oil pumps, throttle control and anti-lock braking systems. BLDC Motor has cleaner and less noisy operation. It is lighter, cheap, lower inertia and normally fixed speed motor but it has complex electronic speed control.

1.5.SVPWM control:

Historically PWM technique was developed in mid 1960s by Kirnnich, Bowes, Heinrick [1]. In 1964 SPWM was developed by Schonung and Stemmler [2]. The SVPWM was developed in mid 1980s [3]. SVPWM is a very proficient technique in control due to increased DC bus efficiency and reduced computation time and harmonics. It has very effective roll in voltage and frequency control applications due to broad linear modulation span. It has low power consumption due to reduced switching losses [4].

In PWM control the switching time is dependent on duty ratio of generated pulses. Modulated signal is produced by relating reference signal with carrier signal. This modulated signal controls the duty ratio of pulses. Whereas in SVPWM technique the voltages are represented by space vector in different sectors. Each voltage vector is resultant of adjacent voltage vectors in that respective sector. There are five major steps in SVPWM control configuration. This strategy starts with the calculation of phase angle and reference voltage magnitude based on supply voltage. Then next step is to find out modulation index. In third step it is required to catch on sector number from sector angle. Fourth step is about calculating T_1, T_2 and T_0. In final step modulation time of switching states is calculated [5].

In SVPWM eight switching pattern are utilized for approximated reference voltage vector to find sector [6]. In motor drive applications SVPWM is used to control switching of inverter for DC to AC conversion. This reduces the THD of output voltage of inverter and input current applied to the motor [4]. Its DC bus voltage usage efficiency is 90.6 % which is 15.5 times greater than SPWM [7]. Over modulation based SVPWM was suggested by Holtz in 1991 which further increased the DC bus efficiency [8, 9]

1.6. Problem Background and Statement:

BLDC Motor drive consists of rectifier, converter and inverter. The rectification process induces power quality problems. The power factor drops down to 0.8 due to increased Total Harmonic Distortion (THD) which increases the losses. To prevent these losses power factor correction design of inverter has been proposed [10-16].

The most commonly used power factor correction based configuration is AC-DC Boost converter [10-11]. It supplies a fixed DC link voltage across VSI input and PWM switching pulses control the input currents which controls the motor speed. This configuration has increased amount of switching losses due to very higher f_{sw} (10 KHz to 20 KHz) as demanded by the setup. A four switch controlled by PWM, based configuration reduced the cost factor because of less switches being used. But again it increased the switching losses as its operation also demands a high switching frequency [12]. A BLDC Motor drive based on active rectifier has also proposed [13]. The VSI was supplied by active rectifier. This is a high cost configuration due complex control mechanism and large number of sensors needed in the design. That’s why it is considered less favorable for low cost applications. A variable DC link voltage based configuration has been proposed as power factor correction for speed control drives [15]. A front end Cuk converter have been presented as a same concept [16]. The converter was design to operate in continuous conduction mode (CCM). This required three voltage sensors for controlling DC link voltage which makes it suitable to use in high power applications.

A power factor Pre-regulator design was presented in form of a Zeta converter [17-19]. It was very suitable for low power application due to its efficient and dynamic response. A controlled DC- link voltage using Zeta converter based Brushless Motor drive design for power factor correction has been proposed in [20]. It utilizes continuous conduction mode (CCM) which requires two control loops. This is not a cost effective solution due to increased number of sensors. So it is considered less suitable in high power applications. A generalized canonical switching cell based DC-DC converter proposed in [21]. A Modified Zeta converter based low cost BLDC Motor drive is proposed in [22].

The summary of problem statement is as follows:

1. The rectification process in BLDC motor drive induces THD results in low power quality and low PF.
2. PFC based converters can be utilized for power factor improvement but the solution are costly because of large number of sensors and high switching losses involved.
3. PWM based converters have been utilized for power factor improvement more efficiently.
4. Modified Zeta converter is an ideal solution for power factor improvement and SVPWM based switching of VSI can a best solution for speed control of BLDC motor.

5. There have been a lot of researches proposed in the field of Total Harmonic Reduction but the problem of low PF is yet to be solved.

1.7. Goal of Research:

The research has following coveted goals:

1. To simulate SVPWM Controlled BLDC Motor drive with Modified Zeta Converter for PFC in MATLAB/Simulink and compare the results with existing techniques.
2. To design a BLDC Motor Drive for improved speed control and reduced Total Harmonic Distortion.
3. To validate the proposed design in MATLAB/Simulink environment.

The intention is to enhance the performance of BLDC Motor Drive and improve PF.

1.8. Scope of Research:

This thesis emphases on Power Factor Correction by reducing THD of BLDC Motor Drive. The scope of this research composition is the performance assessment of BLDC Motor Drive as defined by the existing highest degree of development in the field and the proposed solutions. SVPWM based control is used in designing BLDC Motor Drive for improved power quality. MATLAB/Simulink is utilized to simulate the proposed solution.

1.9. Organization of Thesis:

This thesis is systematized in five vital chapters. Chapter 1 includes Introduction about the proposed idea, problem statement, goal of the thesis and scope of the research work. Chapter 2 focuses briefly on literature review. It includes understanding of BLDC Motor, Modified Zeta Converter and SVPWM. The methodology proposed as a solution to the problem stated is presented in chapter 3. Chapter 4 comprises the details of MATLAB/Simulink replication of the proposed solution. Chapter 5 compacts the results of research. In Chapter 6 conclusion and the future work of the research are discussed.

Chapter 2

2. Literature Review

2.1.Introduction:

To improve power quality many PFC based converters have been proposed [10-16]. Out of them AC-DC Boost converter is very common [10-11]. It has constant DC link voltage. It uses PWM switching pulses to control the input currents. This requires high switching frequency. A four switch configuration proposed to be a cost effective solution but it also has high switching losses [12]. An active rectifier has been proposed to be a good solution for power factor improvement but it is costly and complex [13]. A variable DC link voltage and front end Cuk converter are also suggested solution for PFC [15, 16].

Zeta converter is proposed to be good for PFC in low rated applications [17- 19]. A CCM based Zeta converter with controlled DC link voltage and PFC based BLDC Motor drive have been proposed [20]. Generalized canonical switching cell based DC-DC converter have been proposed in [21]. There is still a need to find better, cost effective and simple solution for power quality improvement in BLDC motor drive applications.

2.2.BLDC Motor:

BLDC Motor is a very versatile motor. It has large number of industrial applications due to its unique features. They have applications mostly in low horsepower appliances. It is highly efficient, reliable and noiseless motor with a very compact mechanical design. Previously it was mostly being used in fixed speed applications but recent researches have added broad-range variable speed feature in BLDC Motor. These researches made this motor a cost effective solution for low power applications.

BLDC Motor have very high power density due to light and compact design with high torque to inertia ratio. It has a permanent magnet rotor which minimizes the losses due to less mechanical friction and zero I^2R losses. It is a very high speed motor because of electronic commutation as there is no speed limitation by the use of mechanical commutators.

BLDC Motor have obsoleted the use of conventional single phase induction motors for domestic appliances like Fans, pumps, Compressors in refrigerators and air conditioners.

BLDC Motor have advantage of increased dynamic response, low power consumption. It is more cost effective, batter efficient with easily adjustable variable speed control over single phase split phase induction motors, shaded pole and universal motors.

BLDC Motors are somewhat different from conventional Brushed DC Motor. In conventional DC Motors brushes are used to connect to split rings to provide DC supply to armature winding. As armature winding rotates and reversal of polarity of DC supply can cause serious problems, split rings are used to save them from this problem. These split rings which are known as commutators are used to make sure that the direction of current and direction of rotation does not vary.

Wherever in BLDC Motors armature coil is stationary and instead of rotating armature, rotor is a permanent magnet. In this type of arrangement it is complicated to control the current flow in stationary armature coil. BLDC Motors uses electronic commutation instead of conventional commutator. Electronic commutation is done by electronic controller. These electronic controllers are actually semiconductor circuits which controls the current flowing into the armature coils. BLDC Motors are more expensive as compared to a conventional DC Motors due to complex speed control comparatively.

2.2.1. Applications

BLDC Motor have a widespread applications in domestic appliances as well as industrial automation and control. These applications can be categorized in many different ways. BLDC Motors are suitable in constant speed application where a fixed load is directly connected with the shaft of the motor. This requires open loop control which normally used in low cost applications.

BLDC Motors are also suitable for variable loads. There are many application in automotive and aerospace which not only require variable speed but also the applied load varies according to demand. These type of applications are mostly semi closed or closed control loop which makes the system complicated and high priced.

BLDC Motors are also used in positioning applications where mechanical power is to be transmitted by the use of belts and gears. These are variable speed and variable load applications. This type of application requires acceleration, deceleration, constant speed and certain positioning. These application requires closed loop control for position, torque and speed control of BLDC Motor using sensors. This increases the price of application

2.2.2. Background

A BLDC Motor drive is a controlled permanent magnet synchronous motor (PMSM) with trapezoidal back emf, fed by a voltage source inverter. In BLDC Motor field flux is provided by rotor while armature is stationary. Stationary armature has so many advantages. It makes heat flow easier and more convenient cooling arrangement of armature coil.

BLDC Motor is an AC motor with permanent magnet rotor having torque current characteristics similar with conventional DC Motor. Instead of commutation by brushes, electronic commutation is used which have zero sparking. Because of absence of brushes there is no mechanical wear and tear of carbon brushes and commutator which results in minimized maintenance. This makes BLDC Motor a more rugged as compared to conventional DC Motor.

BLDC Motor is a modified permanent magnet synchronous motor with a trapezoidal back emf instead of sinusoidal. The back emf region should be as short as possible but not shrink enough which makes the phase tough to commutate. A perfect 120^{o} apart back emf results in smooth torque.

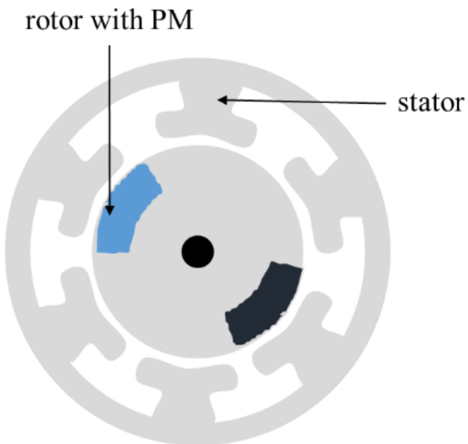

Figure 2.1 cross sectional outlook of BLDC Motor

2.2.3. Principle of Operation

BLDC Motor uses three phase voltage source inverter for supplying power. BLDC Motor is recognized as an electronic motor due to electronic commutation involved. For the purpose of electronic commutation power semiconductor devices are turned on/off by a 60^{o} apart triggering pulses. This minimizes sparking and wear out of BLDC Motor for reducing maintenance cost.

The basic elements in a BLDC Motor drive includes BLDC Motor, sensors, control block and voltage source inverter as shown in figure 2.2. Sensors sends machine parameters to control block which control the gate pulses of voltage source inverter. Then the voltage source inverter injects current pulses into the windings of BLDC Motor.

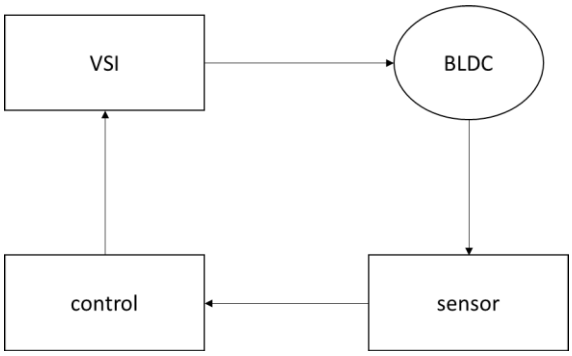

Figure 2.2 BLDC Motor drive configuration

A BLDC Motor is shown in figure 2.1 with a permanent magnet rotor moving at a fixed angular speed ω in anticlockwise direction. In this cross sectional view center of the South Pole is represented by d-axis representing $\theta=0^o$. At that instant ac has a constant back emf of E_{ac} as a result of magnetic effect of stator winding. To overcome this back emf a voltage V_{ac} is supplied across ac winding. Due to this supplied voltage i_a current flows into phase a and i_c current flows in phase c of BLDC Motor. Both of these currents are equal in magnitude. i_{ac} is resultant vector obtained by vector addition of i_a and i_c . Due to this alternating current i_{ac} a flux Φ_{ac} is produced along the direction of current in South magnetic pole. Φ_m is produced in the direction of North Pole. A torque T_e is produced by the interaction of these two fluxes.

$$T_e=\lambda*i_{ac} \qquad (2.1)$$

$$T_e= N\ \Phi_m\ i_{ac}\ \mathrm{Sin}\alpha\ K \qquad (2.2)$$

Φ_m is representing flux produced in rotor, α is phase difference between Φ_m and i_{ac} while K is the unit vector representing direction of torque produced. So the torque produced is directly proportional to magnitude of i_{ac} and α. The BLDC Motor Stator connected in star is shown in figure 2.3.

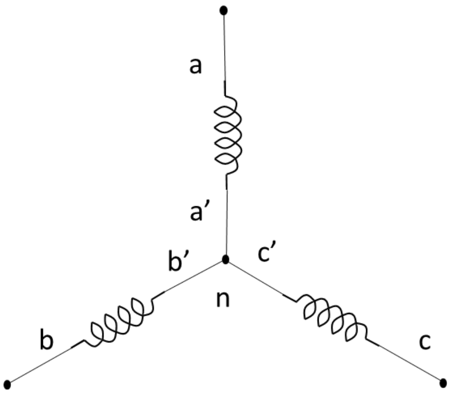

Figure 2.3 Star connected stator of BLDC Motor

As the rotor keep up rotating into anticlockwise direction, θ increases and α becomes less than 120°. As α goes down torque increases and becomes maximum at α=90° but at 60° the torque becomes equal to torque at θ=0° and E_{ac} is not constant at this interval. If this continues then eventually θ will become 120° and α=0° which reduces produce torque to zero. This will result in rotor lock as North Pole of rotor is facing South Pole of stator in zero torque condition and Motor will fail to run.

At θ<60° E_{ac} have a constant back emf while at θ>60° E_{bc} expresses constant back emf so at θ=60° bb' is electronically commutated to cc. A current i_b and i_c flows into bb' and cc' giving i_{bc} as a resultant. i_{bc} will create a flux Φ_{bc} which will be 120° apart from Φ_m. Torque is produced by the interaction of Φ_{bc} and Φ_m in anticlockwise direction. This firing sequence continues followed by the production of Φ_{ab}, Φ_{bc}, Φ_{ba}, Φ_{ca}, Φ_{cb}, and again Φ_{ab} which will create torque in anticlockwise direction and rotor attains a fixed angular velocity ω.

$T_e = N\ \Phi_m\ i_{xy}\ \text{Sin}\alpha\ K$ (2.3)

While x,y are the phases where respectively positive and negative supply terminals are connected

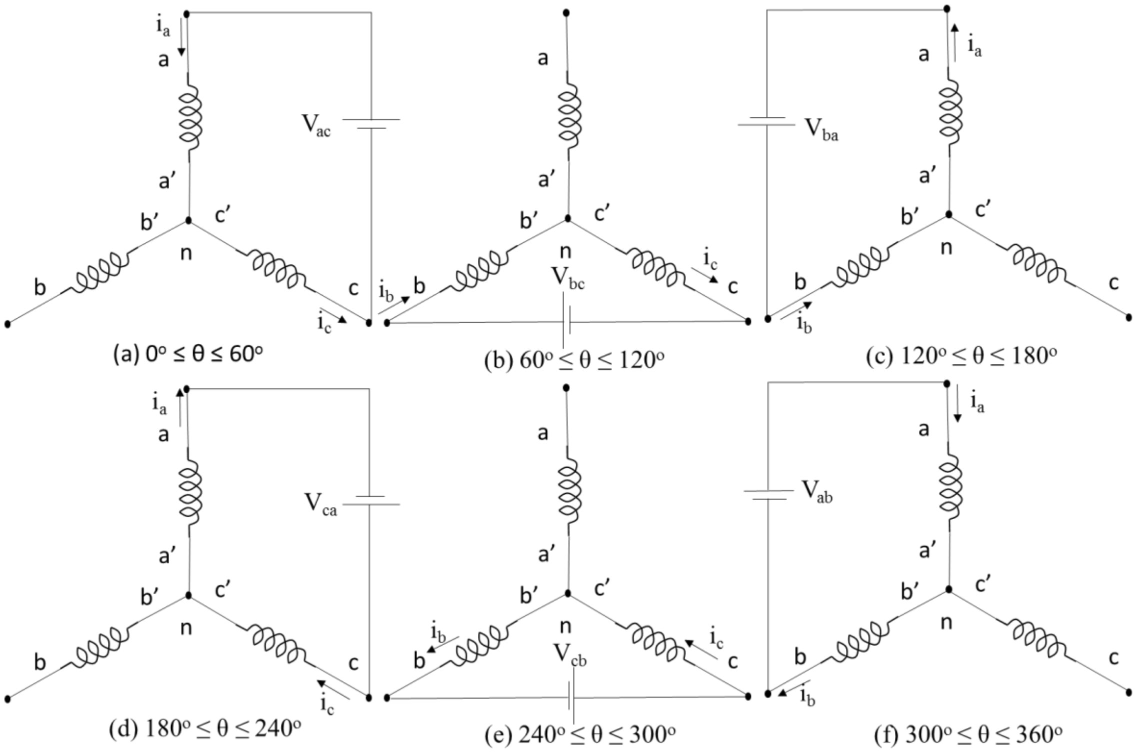

Figure 2.4 Energization sequence of three phase stator of BLDC motor

Due to the torque produced rotor rotates in anticlockwise direction. The back emf of BLDC Motor is not sinusoidal. It has trapezoidal waveform as shown figure 2.5.

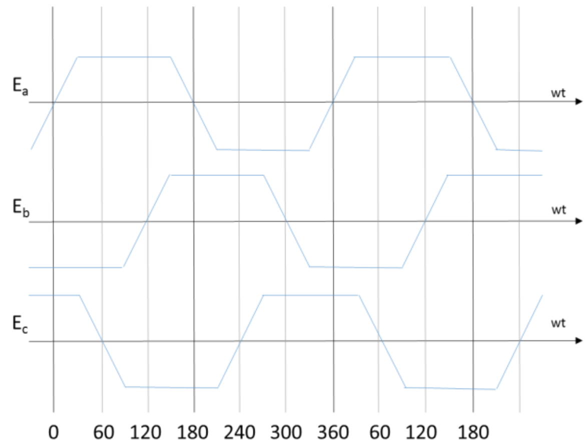

Figure 2.5 back emf waveform of BLDC Motor

2.2.3. BLDC Motor operation with Voltage Source Inverter

BLDC Motor operation depends on electronic commutation by VSI. For the purpose of electronic commutation the switching pulses of electronic switches used in three phase Semiconductor Bridge is controlled. This requires a closed loop control system. The three phase Semiconductor Bridge is called VSI which is fed by V_{dc} and fed three phase current to BLDC Motor as shown in figure 2.6.

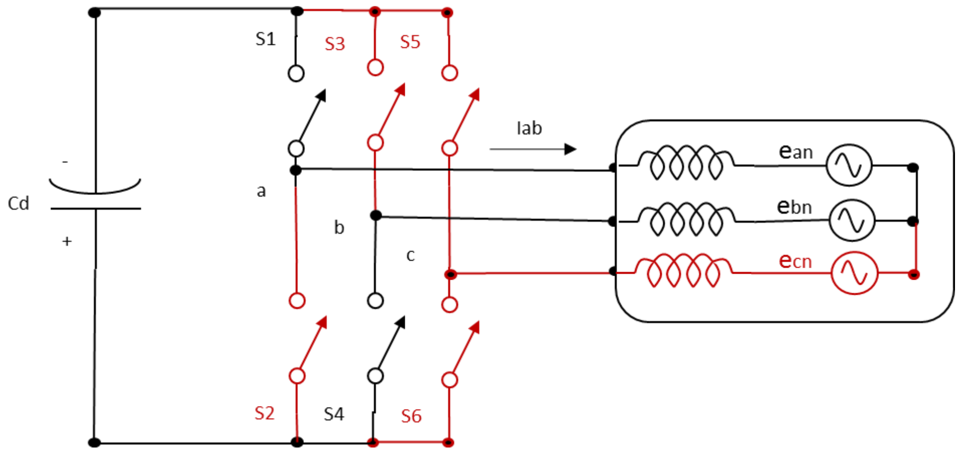

Figure 2.6 BLDC Motor with VSI

The conduction period of every switch is 120°. This results in symmetrical waveforms. Only two out of six switches are ON others are OFF at a time. For this purpose one switch is ON from upper portion and one from lower portion of all three legs of Voltage Source Inverter. For example if during an interval S_2 and S_3 are in conduction state then positive current i_d will keep flowing through phase a and negative current i_d from phase b of BLDC Motor. After 60° to keep the same direction of current into phase a S_3 is turned OFF and S_5 is turned ON. This commutates negative phase current i_d from phase b to phase c. After 60° degrees more S_2 also turned off by completing 120° of its conduction period. This pattern continues for keeping electronic commutation into progress as shown in figure 2.4. For

BLDC Motor two phase are energized at a time if it is star connected. To run BLDC Motor in anticlockwise direction the energization sequence must be ac, bc, ba, ca, cb, ab and for clockwise rotation the firing sequence must be reversed as ab, cb, ba, bc, ac. The phase angle difference between V and I waveforms which can be depicted in the figure below

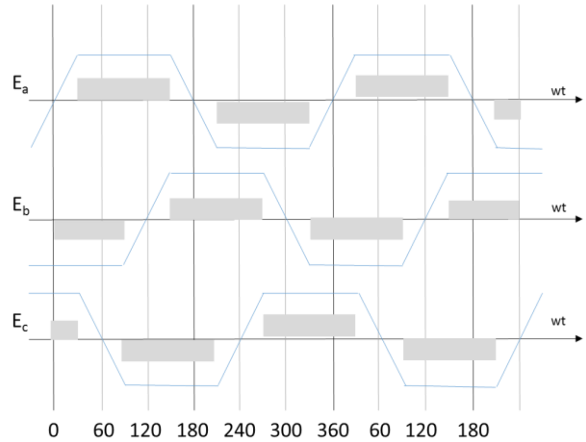

Figure 2.7 back emf and current waveform of BLDC Motor

2.3.Modified Zeta Converter:

Modified zeta converter is recently gaining great attention of the researchers due to its unique features. Its potentials are still needed to be discovered. It is capable of replacing famous sapic and cuk converters but this needs to work out on most efficient design of the modified zeta converter. It's a fourth order DC-DC converter. The input voltage is nonlinear while being applied across the input. It has a capability of step up as well as step down a voltage. In other words it has a buck-boost-buck type converter. It produces a positive output voltage from an unregulated input voltage. So it also acts like a voltage regulator. It utilized two inductors and a capacitor as dynamic storage elements for converter operation [23].

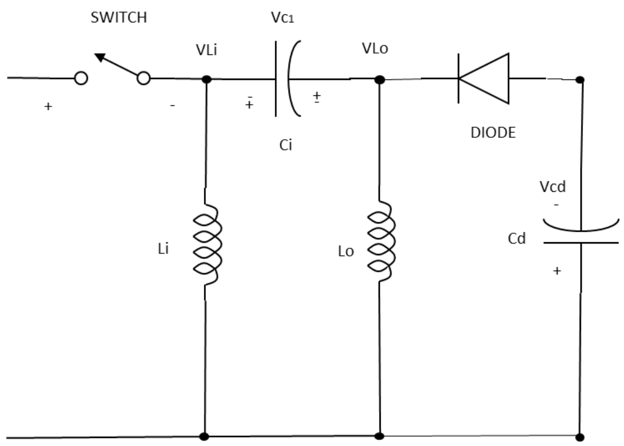

Figure 2.8 Basic circuit of modified zeta converter

The basic circuit of modified zeta converter is shown in figure. The semiconductor switch being used is considered as ideal, with zero switching loses for theoretical studies purpose. Also the ripples in the input line frequency are considered zero for an ideal operation. The operation can be divided into many modes depending upon instructor current. Here in this research the modes of modified zeta converter is divided based on its discontinuous inductor current mode.

The modified zeta converter is need to be designed to operate ideally. For this purpose the values of inductors and capacitors should be chosen properly. The inductors utilized in the design are LC filter's inductor, input inductors, output inductors (L_f, L_i, L_o) and the capacitors needed to be chosen in the design are used as intermediate, DC-link and LC filter's capacitors (C_i, C_d and C_f). The modified zeta converter elements are so chosen that the converter should operate in DICM. This only happens when the current in L_O drops to zero in every cycle. This can be attained by choosing appropriate values for L_i, and L_o. The duty cycle of the modified zeta converter is given by equation [28].

$$D(t) = \frac{V_{dc}}{V_{in}(t) + V_{dc}} \tag{2.4}$$

Where V_{dc} is the DC link voltage across the output of modified zeta converter while V_{in} is rms value of the input supply voltage.

$$D(t) \times (V_{in}(t) + V_{dc}) = V_{dc}$$

$$D(t) \times V_{in}(t) + D(t) \times V_{dc} = V_{dc}$$

$$D(t) \times V_{in}(t) = V_{dc} - D(t) \times V_{dc}$$

$$D(t) \times V_{in}(t) = V_{dc} \times (1 - D(t))$$

$$\frac{D(t)}{1 - D(t)} = \frac{V_{dc}}{V_{in}(t)}$$

$$V_{dc} = \frac{D(t)}{1 - D(t)} V_{in}(t) \tag{2.5}$$

It can also be given as

$$\frac{D(t)}{1 - D(t)} = \frac{I_{in}(t)}{I_{out}} = \frac{V_{dc}}{V_{in}(t)} \tag{2.6}$$

This implies that for obtaining a specified value of V_{dc} from the modified zeta converter the required value of V_{in} depends upon duty cycle. If duty cycle is maximum then minimum V_{in} will be required and for utilizing maximum value of V_{in} the duty cycle value must be chosen minimum. In case of a sinusoidal voltage supply V_{in} can be expressed as in equation.

$$V_{in}(t) = V_m \sin(2\pi ft) \tag{2.7}$$

Where V_m represents the peak input voltage to the modified zeta converter and f represents the supply frequency. A modulus function can be taken for obtaining instantaneous value of input voltage across the input of modified zeta converter as given in the equation.

$$|V_{in}| = |V_m \sin(2\pi ft)| \tag{2.8}$$

The instantaneous value of V_{in} is the input of modified zeta converter. This voltage contains ripples in it due to rectification involved in the process. To get a specified DC link voltage the duty cycle must be varying instantaneously according to the instantaneous value of V_{in}. The instantaneous value of D_{in} is given in the equation

$$D_{in}(t) = \frac{V_{dc}}{V_{in}(t) + V_{dc}} = \frac{V_{dc}}{|V_m \sin(2\pi ft)| + V_{dc}} \tag{2.9}$$

A constant DC link voltage is obtained across DC link capacitor. So the instantaneous value of output power across modified zeta converter is linearly dependent on the value of V_{dc} obtained. The equivalent input resistance across the input side of modified zeta converter is represented by R_{in} and is given as in equation.

$$R_{in} = \left(\frac{\{V_{in}(t)\}^2}{P_i} \right) = \left(\frac{V_s^2}{P_i} \right) \tag{2.10}$$

Where the V_s is the sinusoidal input voltage and P_i is the instantaneous output power of modified zeta converter. Here the losses are ignored and the system is considered as an ideal one. It shows that the input resistance is dependent upon the input voltage supply, DC link voltage and instantaneous power. So R_{in} will vary according to specified value of V_{dc}.

The value of L_i is given as [25].

$$L_i = \left(\frac{V_{in}(t) D(t)}{\eta I_{in}(t) f_s} \right) \tag{2.11}$$

$$L_i = \left(\frac{R_{in} D(t)}{\eta f_s} \right)$$

$$\because R_{in} = \left(\frac{\{V_{in}(t)\}^2}{P_i} \right) = \left(\frac{V_s^{\,2}}{P_i} \right)$$

$$L_i = \left(\frac{V_s^2}{P_i} \right) \left(\frac{D(t)}{\eta f_s} \right)$$

$$\because D(t) = \frac{V_{dc}}{V_{in}(t) + V_{dc}}$$

$$L_i = \left(\frac{V_s^2}{\eta P_i f_s} \right) \left(\frac{V_{dc}}{V_{in}(t) + V_{dc}} \right) \tag{2.12}$$

Where f_s is switching frequency and I_{in} is current across the input side of modified zeta converter. The value of output inductor can be given as [25]

$$L_c = \frac{V_{dc}(t)(1 - D(t))}{2 i_{L_o}(t) f_s} \tag{2.13}$$

From equation (6)

$$\because \frac{1 - D(t)}{i_{L_o}} = \frac{D(t)}{I_{in}}$$

$$L_c = \frac{V_{dc}(t) D(t)}{2 I_{in}(t) f_s}$$

$$\because \frac{1}{I_{in}} = \frac{R_{in}}{V_{in}(t)}$$

$$L_c = \frac{R_{in} V_{dc}(t) D(t)}{2 V_{in}(t) f_s}$$

From equation (4) and (10)

$$L_c = \left(\frac{V_s^{\,2}}{P_i} \right) \left(\frac{V_{dc}(t)}{2 V_{in}(t) f_s} \right) \left(\frac{V_{dc}}{V_{in}(t) + V_{dc}} \right) \tag{2.15}$$

The intermediate capacitor's value can be evaluated from [25]

$$C_i = \frac{V_{dc} D(t)}{\kappa V_{C_i}(t) R_L f_s} \tag{2.16}$$

Using equation (4)

$$C_i = \frac{V_{dc}}{\kappa V_{C_i}(t) R_L f_s} \left(\frac{V_{dc}}{V_{in}(t) + V_{dc}} \right)$$

Using equation (10)

$$C_i = \frac{P_i}{\kappa V_{C_i}(t) V_{dc} f_s}\left(\frac{V_{dc}}{V_{in}(t)+V_{dc}}\right)$$

$$\because V_{C_i}(t) = V_{in}(t) + V_{dc}$$

$$C_i = \frac{P_i}{\kappa\left(V_{in}(t)+V_{dc}\right) f_s}\left(\frac{1}{V_{in}(t)+V_{dc}}\right) \tag{2.17}$$

$$C_i = \frac{P_i}{\kappa\left(V_{in}(t)+V_{dc}\right)^2 f_s} \tag{2.18}$$

Where κ is the percentage value of permitted ripple voltages. The capacitance of DC link capacitor is given by equation 19 [25]

$$C_i = \frac{I_{dc}}{2\omega\Delta V_{dc}} \tag{2.19}$$

$$C_i = \frac{\frac{P_i}{V_{dc}}}{2\omega\delta V_{dc}}$$

$$C_i = \frac{P_i}{2\omega\delta V_{dc}^2} \tag{2.20}$$

Where δ represents voltage ripples

The modified zeta converter designed in this portion of research is to be operated in DICM. The dynamic modelling of this converter can be designed by taking into account parameters involved. The PWM pulses fed to the switch of converter is basic factor involved in the modelling. The input variable in the model are output current, input voltage and duty cycle while output variables are input current and output voltage. The mathematical model is given by equation 2.21. The transfer function of given mathematical model is given in equation 2.22. Figure 2.9 shows the small signal model of proposed converter modified form of conventional zeta converter with pulse width modulation controlled. The transfer function of equation 2.22 can be rearranged according to model shown in figure 2.9 and results in the transfer function given in equation 2.23. The equation 2.24 to 2.27 shows the small signal parameters. Using these small signal parameters the variables of transfer function are calculated in equation 2.28 to 2.32.

$$\begin{bmatrix} \hat{v}_{dc}(s) \\ \hat{i}_{in}(s) \end{bmatrix} = \begin{bmatrix} G_{u11}(s) & G_{u12}(s) \\ G_{u21}(s) & G_{u22}(s) \end{bmatrix}\begin{bmatrix} \hat{v}_{in}(s) \\ \hat{i}_{dc}(s) \end{bmatrix} + \begin{bmatrix} G_{d1}(s) \\ G_{d1}(s) \end{bmatrix}\hat{d}_i(s) \tag{2.21}$$

$$G_{u11}(s) = \left.\frac{\hat{v}_{dc}(s)}{\hat{i}_{in}(s)}\right|_{\hat{i}_{dc}=0,\hat{d}_i=0} \quad (2.22)$$

$$G(s) = \frac{M(b_2 s^2 + 1)}{(a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + 1)} \quad (2.23)$$

$$M = \frac{V_{dc(\max)}}{V_{in)}} \quad (2.24)$$

$$g_i = \frac{M^2}{R_L} \quad (2.25)$$

$$g_f = \frac{2M}{R_L} \quad (2.26)$$

$$g_o = \frac{1}{R} \quad (2.27)$$

$$a_1 = g_i L_i + \frac{g_o L_o}{2} + \frac{(C_1 + C_d)}{2g_o} \quad (2.28)$$

$$a_2 = C_1 L_1 (1 + \frac{(g_i + g_f)}{g_o} + L_o) + \frac{(C_d L_o + C_1 L_o)}{2} + L_i \times (C_d + L_o g_o{}^2)(\frac{g_i}{2g_o}) \quad (2.29)$$

$$a_3 = \frac{C_1 L_i L_o (g_i + g_f + g_o)}{2} + C_d (\frac{C_1 (L_i + L_o)}{2g_o} + \frac{g_i L_i L_o}{2}) \quad (2.30)$$

$$a_4 = \frac{C_1 C_d L_i L_o (g_i + g_f + g_o)}{2g_o} \quad (2.31)$$

$$b_2 = C_1 L_i (1 + \frac{g_i}{g_f}) \quad (2.32)$$

Using the parameters available in equation 2.28 to 2.32 in equation 2.23 the transfer function can be calculated according to the equation 2.33. While equation 2.24 shows the transfer function of PI controller used in PWM control.

$$G_c(s) = \frac{G(s)}{1 + G(s)H(s)} \quad (2.32)$$

$$H(s) = K_p + \frac{K_i}{s} \quad (2.24)$$

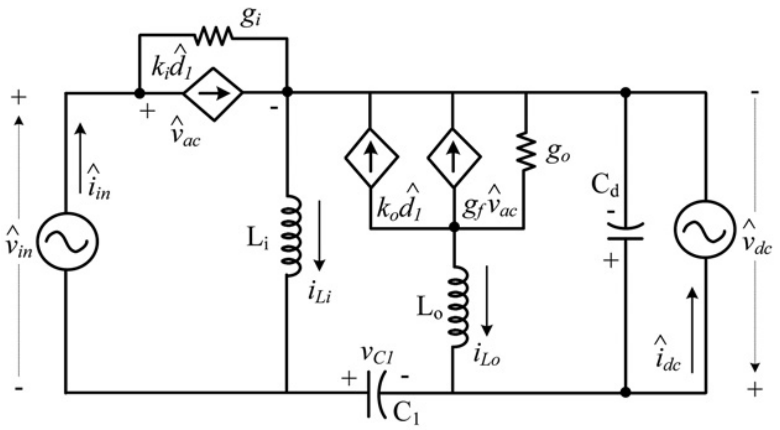

Figure 2.9 Small signal model of PWM based Modified Zeta Converter

2.4.Pulse Width Modulation:

In electric motor drive circuits a VSI is utilized to converter DC voltage to controllable AC source for speed control. To get the desired output voltage from voltage source inverter different switching schemes have been proposed. A very popular switching scheme is Pulse Width Modulation in which pulse width is used to voltage control. The Pulses have equal magnitude and dissimilar widths. Pulse Width Modulation have various modulation topologies with fundamental and high switching frequency. Due to high switching frequency lower harmonics are reduced, as a result Total Harmonics are reduced. It has many advantages including low current harmonics, uniform switching, balanced output voltage and easy Implementation. PWM has many symmetric and asymmetric configurations as shown in figure 2.8.

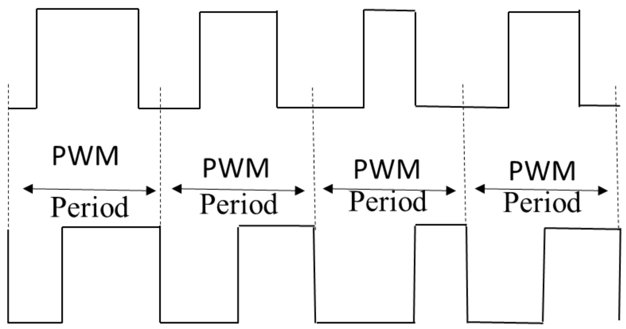

Figure 2.9 Symmetric and Asymmetric PWM switching patterns

The generation of PWM pulses are done by comparing sawtooth voltage with sinusoidal. When control voltage is greater than triangular voltage PWM output is $V_{DC}/2$ otherwise zero as shown in figure 2.10.

$$m = \left(\frac{V_{peak}}{V_{dc}/2} \right) \tag{2.25}$$

Where m is the modulation index

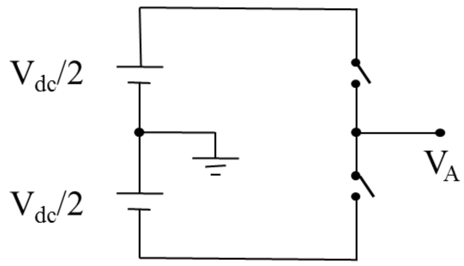

Figure 2.10 PWM generalized configuration

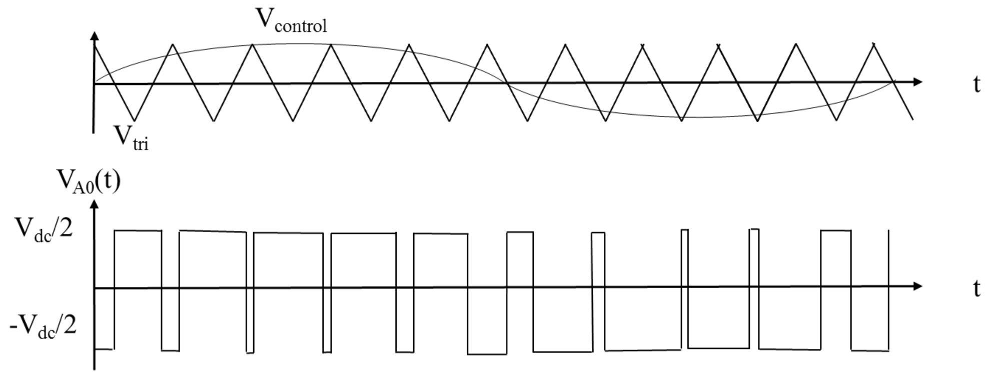

Figure 2.11 PWM pulses generation

2.4.1. Space Vector Pulse Width Modulation:

Out of various PWM topologies SVPWM has great significance. It generates gate drive pulses with unique switching time and can easily be improvised to be used in multilevel converters. SVPWM has 15% more utilization ration as compared to sinusoidal Pulse Width Modulation, giving preference for being used in high power applications. It is very suitable for speed control of electric motors. SVPWM is used to control the voltage and frequency of three phase voltage source inverters. This provides better employment of DC link voltage, efficiency and performance.

V_a ,V_b and V_c is the three phase output of voltage source inverter controlled by switching patterns of switches S_1-S_6.

$$V_a = V_{DC} \cos \theta t \tag{2.26}$$

$$V_b = V_{DC} \cos \left(\theta + \frac{2\pi}{3} \right) t \tag{2.27}$$

$$V_c = V_{DC} \cos \left(\theta + \frac{4\pi}{3} \right) t \tag{2.28}$$

S_1 ,S_3 ,S_5 and S_4 S_6 S_2 are toggle switches so if an upper switch in a leg of inverter is OFF, respective lower will be ON and vice versa. Space Vector Pulse Width Modulation generates special switching sequence for upper switches to produce required voltage with reduced harmonics.

For a three phase two level inverter there are eight possible combinations for three upper power transistors. Table represents the voltage vectors, switching combinations, line voltages and phase voltages. For three lower power transistors the switching combinations would be opposite.

Table 2.1 switching vectors,Line voltage and phase voltages of Voltage Vectors in SVPWM

Voltage Vectors	Switching Vectors			Line to Neutral Voltage			Line to Line Voltage		
	a	b	c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{an}
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/3$	V_{dc}	0	$-V_{dc}$
V_2	0	1	0	$V_{dc}/3$	$V_{dc}/3$	$-2V_{dc}/3$	0	V_{dc}	$-V_{dc}$
V_3	1	1	0	$-V_{dc}/3$	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}$	V_{dc}	0
V_4	0	0	1	$-2V_{dc}/3$	$V_{dc}/3$	$V_{dc}/3$	$-V_{dc}$	0	V_{dc}
V_5	1	0	1	$-V_{dc}/3$	$-V_{dc}/3$	$2V_{dc}/3$	0	$-V_{dc}$	V_{dc}
V_6	0	1	1	$V_{dc}/3$	$-2V_{dc}/3$	$V_{dc}/3$	V_{dc}	$-V_{dc}$	0
V_7	1	1	1	0	0	0	0	0	0

These vectors are presented in polar and rectangular form in following table 2.2

Table 2.2 Voltage Vectors in Polar and Rectangular form

Voltage Vectors	**Polar Form**	**Rectangular Form**
V_0	0	0
V_1	$\frac{2}{3}V_{DC}\,e^{j0}$	$\frac{2}{3}V_{DC}$
V_2	$\frac{2}{3}V_{DC}\,e^{j\pi/3}$	$\frac{1}{3}V_{DC} + j\frac{\sqrt{3}}{3}V_{DC}$
V_3	$\frac{2}{3}V_{DC}\,e^{j2\pi/3}$	$-\frac{1}{3}V_{DC} + j\frac{\sqrt{3}}{3}V_{DC}$
V_4	$\frac{2}{3}V_{DC}\,e^{j\pi}$	$-\frac{2}{3}V_{DC}$
V_5	$\frac{2}{3}V_{DC}\,e^{j4\pi/3}$	$-\frac{1}{3}V_{DC} - j\frac{\sqrt{3}}{3}V_{DC}$
V_6	$\frac{2}{3}V_{DC}\,e^{j5\pi/3}$	$\frac{1}{3}V_{DC} - j\frac{\sqrt{3}}{3}V_{DC}$
V_7	0	0

The eight switching vectors are clearly representing switching patterns for the inverter in figure below. It has two zero vectors which lies on the origin and six nonzero vectors.

These nonzero vectors can be joined to form a hexagon with angle of 60^o between two vectors. All of these vectors are collectively called basic space vectors.

The six basic space vector when arranged makes a hexagon. The zero vectors are placed at the origin. The hexagon is divided into six sectors by the base vectors as shown in figure 2.10. Sector 1 is space between V_1 and V_2 and sector 2 is between V_2 and V_3 and so on. In SVPWM the pulses are generated according to the position of reference vector into that space divided into six sectors. The reference vector is shown in figure 2.10 and given as

$$V_{\mathrm{Re}\,f} = \frac{2}{3}(V_a + e^{i2\pi/3}V_b + e^{-i2\pi/3}V_c) \tag{2.29}$$

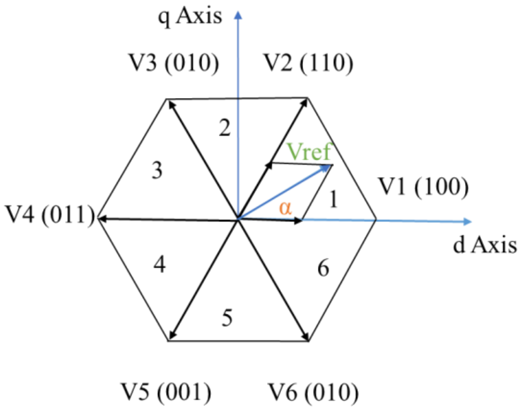

Figure 2.12 basic switching Sectors and Vectors of SWPWM

The six switches of VSI are switched according to these switching patterns decided by SVPWM. The generalized switching pattern of the eight vectors for upper three switches are shown in figure 2.11. It can be seen that between any two consecutive vectors only one switch is toggled. The output of VSI is generated according to the switching pattern.

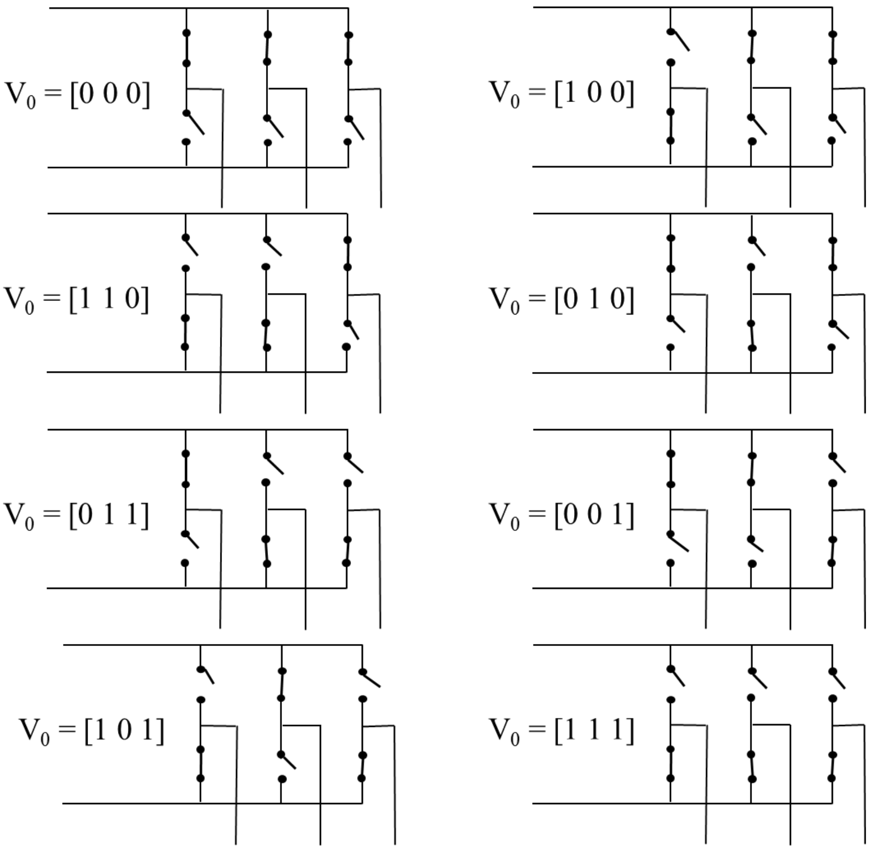

Figure 2.13 The VSI Voltage Vectors

Space Vector Pulse Width Modulation can be visualized by movement of a reference vector in dq plan where d is a horizontal axis and q is vertical axis. abc to dq transformation or clark transformation is given as

$$T_{abc-dq} = \sqrt{3/2}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3/2} & -\sqrt{3/2} \end{bmatrix} \tag{2.30}$$

dq plan is two dimensional orthogonal projection of abc three dimensional coordinate system as shown in figure 2.12.

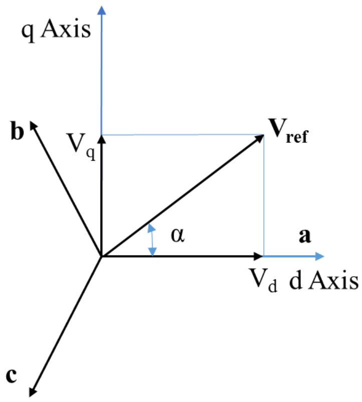

Figure 2.14 Representation of reference vector in dq Plan

$$V_{\mathrm{Ref}} = V_d + jV_q = \tfrac{2}{3}(V_a + aV_a + a^2V_a)$$

$$\therefore a = e^{i2\pi/3}$$

$$|V_{\mathrm{Ref}}| = \sqrt{V_d^2 + V_q^2}$$

$$\alpha = \tan^{-1}\left(\frac{V_q}{V_d}\right)$$

$$V_{\mathrm{Ref}} = \tfrac{2}{3}(V_a + e^{i2\pi/3}V_b + e^{-i2\pi/3}V_c)$$

Putting the values of V_a ,V_b and V_c

$$V_{\mathrm{Ref}} = \frac{2}{3}\left(V_a + \cos\left(\frac{2\pi}{3}\right)V_b + \cos\left(\frac{2\pi}{3}\right)V_c\right) + j\frac{2}{3}\left(\sin\left(\frac{2\pi}{3}\right)V_b - \sin\left(\frac{2\pi}{3}\right)V_c\right)$$

$$V_d = \frac{2}{3}\left(V_a + \cos\left(\frac{2\pi}{3}\right)V_b + \cos\left(\frac{2\pi}{3}\right)V_c\right)$$

$$V_q = j\frac{2}{3}\left(\sin\left(\frac{2\pi}{3}\right)V_b - \sin\left(\frac{2\pi}{3}\right)V_c\right)$$

Represented as

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = \frac{2}{3}\begin{pmatrix} 1 & \cos\left(\frac{2\pi}{3}\right) & \cos\left(\frac{2\pi}{3}\right) \\ 0 & \sin\left(\frac{2\pi}{3}\right) & -\sin\left(\frac{2\pi}{3}\right) \end{pmatrix}\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \frac{2}{3}\begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{pmatrix}\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix}$$

$$V_d = \frac{2}{3}\left(V_a - \frac{1}{2}V_b - \frac{1}{2}V_c\right) \qquad (2.31)$$

$$V_q = \frac{2}{3}\left(\frac{\sqrt{3}}{2}V_b - \frac{\sqrt{3}}{2}V_c\right) \qquad (2.32)$$

In sector 1 reference vector can be found from V_1 V_2 V_0 and can be represented in time duration form

$$V_{\mathrm{Ref}}.T_c = V_1.\frac{T_1}{T_c} + V_2.\frac{T_2}{T_c} + V_0.\frac{T_0}{T_c}$$

$$V_{\mathrm{Ref}} = V_1.T_1 + V_2.T_2 + V_0.T_0$$

$$T_c = T_1 + T_2 + T_0$$

$$T_c.V_{\mathrm{Ref}}.\begin{pmatrix} \cos(\theta) \\ \sin(\theta) \end{pmatrix} = T_1.\frac{2}{3}.V_{DC}.\begin{pmatrix} 1 \\ 0 \end{pmatrix} + T_2.\frac{2}{3}.V_{DC}.\begin{pmatrix} \cos\left(\frac{\pi}{3}\right) \\ \sin\left(\frac{\pi}{3}\right) \end{pmatrix}$$

real part

$$T_c.V_{\text{Re}f}.\cos(\theta) = T_1.\frac{2}{3}.V_{DC} + T_2.\frac{1}{3}.V_{DC}$$

$$T_c.V_{\text{Re}f}.\sin(\theta) = T_2.\frac{1}{\sqrt{3}}.V_{DC}$$

T_1 and T_2 will be modified as

$$T_1 = T_c.\frac{\sqrt{3}.V_{\text{Re}f}}{V_{DC}}.\sin\left(\frac{\pi}{3}-\theta\right) = T_c.m.\sin\left(\frac{\pi}{3}-\theta\right)$$

$$T_2 = T_c.\frac{\sqrt{3}.V_{\text{Re}f}}{V_{DC}}.\sin(\theta) = T_c.m.\sin(\theta) \quad 0<\theta<\frac{\pi}{3}$$

Where m is modulation index

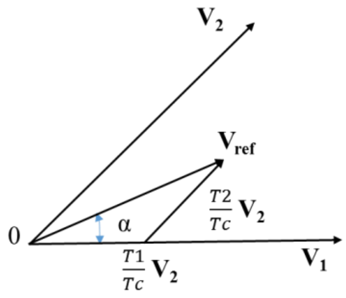

Figure 2.15 Time duration of switches in Sector 1

For other sectors the calculations of duty time is generalized as follows

$$T_1 = T_c.m.\sin\left(\frac{\pi}{3}-\theta+\frac{n-1}{3}.\pi\right)$$

$$T_1 = T_c.m.\left[\sin\left(\frac{n}{3}\pi\right)\cos(\theta)-\cos\left(\frac{n}{3}\pi\right)\sin(\theta)\right] \tag{2.33}$$

$$T_2 = T_c.m.\sin\left(\theta-\frac{n-1}{3}.\pi\right)$$

$$T_2 = T_c.m.\left[-\cos(\theta)\sin\left(\frac{n-1}{3}\pi\right)+\sin(\theta)\cos\left(\frac{n-1}{3}\pi\right)\right] \tag{2.34}$$

$$T_0 = T_c - T_1 - T_2 \tag{2.35}$$

Where n is sector number

By this calculation the switching time durations will be tabulated in table 2.3

Table 2.3 Time duration of Sectors in SVPWM

sector	Time durations		
	T_1	T_2	T_0
1	$T_c.m.\sin\left(\frac{\pi}{3}-\theta\right)$	$T_c.m.\sin(\theta)$	$T_c - T_1 - T_2$
2	$T_c.m.\sin\left(\frac{2\pi}{3}-\theta\right)$	$T_c.m.\sin\left(\theta-\frac{\pi}{3}\right)$	$T_c - T_1 - T_2$
3	$T_c.m.\sin(\pi-\theta)$	$T_c.m.\sin\left(\theta-\frac{2\pi}{3}\right)$	$T_c - T_1 - T_2$
4	$T_c.m.\sin\left(\frac{4\pi}{3}-\theta\right)$	$T_c.m.\sin(\theta-\pi)$	$T_c - T_1 - T_2$
5	$T_c.m.\sin\left(\frac{5\pi}{3}-\theta\right)$	$T_c.m.\sin\left(\theta-\frac{4\pi}{3}\right)$	$T_c - T_1 - T_2$
6	$T_c.m.\sin(2\pi-\theta)$	$T_c.m.\sin\left(\theta-\frac{5\pi}{3}\right)$	$T_c - T_1 - T_2$

In a sector there are seven switching states. A duty cycle starts with a zero vector and also ends with a zero vector. For sector 1 switching pattern is followed as 000-100-110-111-110-100-000 and total time interval is given as

$$T_c = \frac{T_0}{4} + \frac{T_1}{2} + \frac{T_2}{2} + \frac{T_0}{2} + \frac{T_2}{2} + \frac{T_1}{2} + \frac{T_0}{4} \tag{2.36}$$

The figure below shows the switching waveforms for all sectors. The waveforms are edge aligned having lower harmonics as compared to center aligned. The switching waveforms represents the location of reference vector. In Sector 1 switch S_1 ON at $\frac{T_o}{4}$ to $T_c - \frac{T_o}{4}$, switch S_2 is ON between $\frac{T_o}{4} + \frac{T_1}{2}$ and $T_c - \left(\frac{T_o}{4} + \frac{T_1}{2}\right)$, S_3 is ON in between $\frac{T_o}{4} + \frac{T_1}{2} + \frac{T_2}{2}$ and $T_c - \left(\frac{T_o}{4} + \frac{T_1}{2} + \frac{T_2}{2}\right)$, OFF for remaining time interval

Table 2.4 switching time calculation

Sector	Upper Switches	Lower Switches
1	S1= T1 +T2 +T0/2	S4= T0/2
	S3= T2 +T0/2	S6
	S5= T0/2	S2= T1 +T2 +T0/2
2	S1= T1 +T0/2	S4= T2 +T0/2
	S3= T1 +T2 +T0/2	S6= T0/2
	S5= T0/2	S2= T1 +T2 +T0/2
3	S1= T0/2	S4= T1 +T2 +T0/2
	S3= T1 +T2 +T0/2	S6= T0/2
	S5 =T2 +T0/2	S2= T1 +T0/2
4	S1= T0/2	S4= T1 +T2 +T0/2
	S3= T1 +T0/2	S6= T2 +T0/2
	S5= T1 +T2 +T0/2	S2= T0/2
5	S1= T2 +T0/2	S4= T1 +T0/2
	S3= T0/2	S6= T1 +T2 +T0/2
	S5= T1 +T2 +T0/2	S2= T0/2
6	S1= T1 +T2 +T0/2	S4= T0/2
	S3= T0/2	S6= T1 +T2 +T0/2
	S5= T1 +T0/2	S2= T2 +T0/2

A switch toggles twice in a SVPWM interval except at start and end. The switching pattern is fixed for all six sectors with two similar zero vectors.The voltage waveforms of all the six sectors are shown in figure 2.14

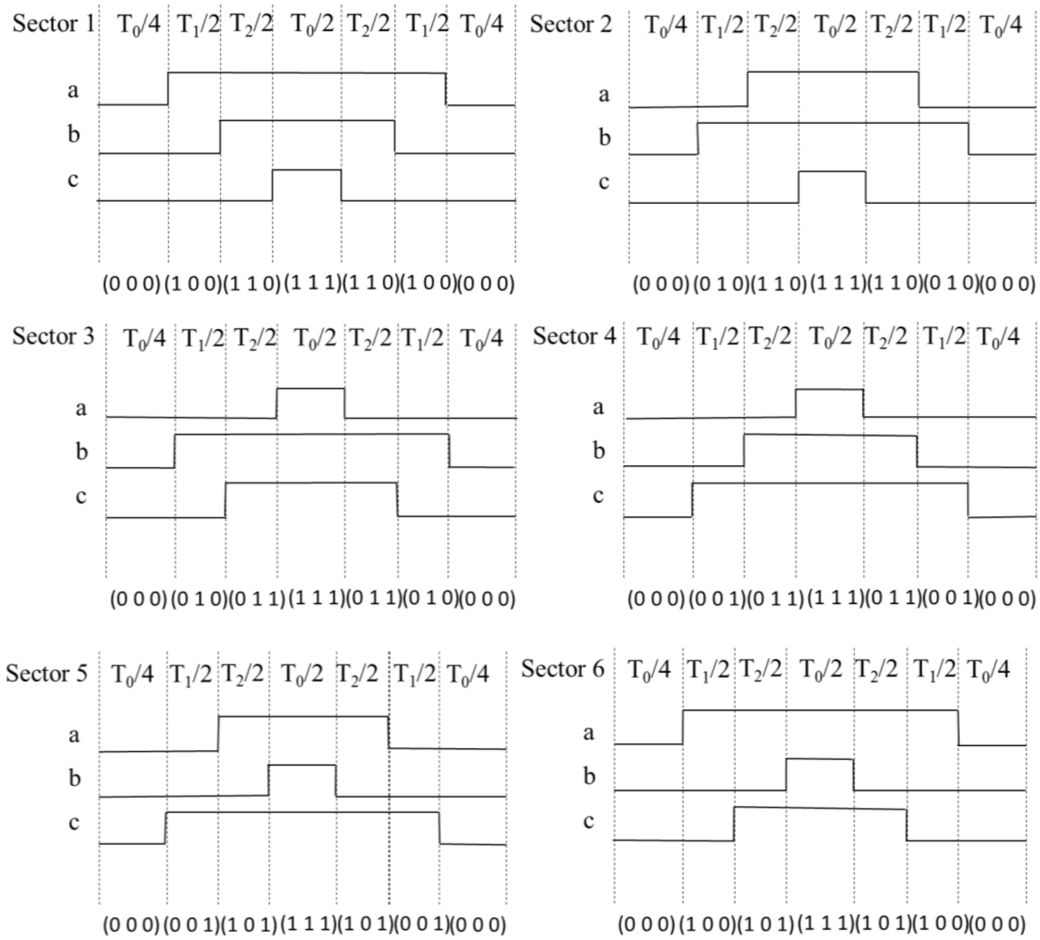

Figure 2.16 Waveform Patterns in SVPWM

Chapter 3

3.Proposed Architecture

3.1.Introduction:

There are many domestic and industrial applications which requires variable speed. Motor drive circuits are meant to control the speed of motor by adjusting suitable parameters involved. BLDC Motor is best suitable for low power applications. This motor requires versatile drive circuit for run as well as speed control. The major processes involved in BLDC Motor drive circuit rectification, fixed DC to controllable DC conversion and DC to AC inversion. As rectification is done by diode bridge rectifier, it produces a pulsating DC output. In order to get constant DC voltage these ripples are needed to be filtered out. A LC filter can be utilized to reduce these ripples but these ripples can't be completely removed due to design limitations. So there are still some ripples after passing through the filter. This eventually creates power quality problems by reducing power factor. This results in loses associated with low power factor and also effects on performance of motor being supplied by drive circuit. To solve this problem PFC based converter are meant to be involved in derived design. Modified Zeta converter when controlled by PWM switching can be used as a constant DC link voltage source. This application needs a DICM operation of Modified Zeta converter which makes this a PF pre-regulator

This paper focuses on total harmonic reduction by SVPWM controlled BLDC motor drive. As it is already discussed BLDC motor is actually an AC motor with the phase wound stator and a permanent magnet rotor. There is no physical commutator available in BLDC motor so an electronic commutation is needed. SVPWM is used switching of VSI to convert constant DC link voltage to variable and controllable AC supply. This generates 120 degree phase shifted AC currents which are injured injected into three phases of BLDC motor to generate alternating flux for motor operation. The inverters are designed to control the constant DC link voltage into AC voltage adjustable in voltage or frequency parameters. It varies the flux produced in the stator as the result the torque induced varies and eventually speed varies accordingly.

3.2. Operation of Modified Zeta Converter:

BLDC Motor drive encounters serious power quality problems. In order to reduce losses due to low power factor suitable PFC converters are designed. These converters are normally categorized into two major classes based on conduction mechanism either discontinuous conduction mode (DCM) or continuous conduction mode (CCM). Both techniques are considered good based on environment of use. CCM has low switching losses as it requires a lower switching frequency but it has a complex control consisting of two control loops and three sensors [14, 15]. DCM is suitable for LF applications as it requires only one control loop and a single voltage sensor for DC link voltage control [14, 15]. DCM offers increased losses due to high f_{sw}.

In DICM the current flow is not continuous into output inductor in a cycle. The modified Zeta converter operates on DICM to improve power factor in BLDC Motor drive. The complete DICM operation of modified Zeta converter can be divided into four major modes explained below

3.2.1. Mode A

This mode starts with the turn ON of switch S_w. As the switch turns ON charge starts building up across intermediate capacitor C_i, input inductor L_i and output inductor L_o as shown in figure 3.1. So the voltage across intermediate capacitor stars rising and current through input and output inductor starts increasing according to waveforms shown in figure 3.5. Mode A is divided in two parts. In first part voltage is increasing across intermediate capacitor due to negative charging of the capacitor. During this mode diode D is reverse biased and load is applied to the C_{dc} directly. DC link capacitor voltage discharges through load in this mode. In second part of mode A the intermediate starts charging up in positive direction as shown in figure 3.5. The intermediate capacitor voltage (C_i), output inductor current (i_{Li}) and output inductor current (i_{Lo}) keep rising. The time duration of this mode depends upon duty ratio and usually 15-25% of switching period.

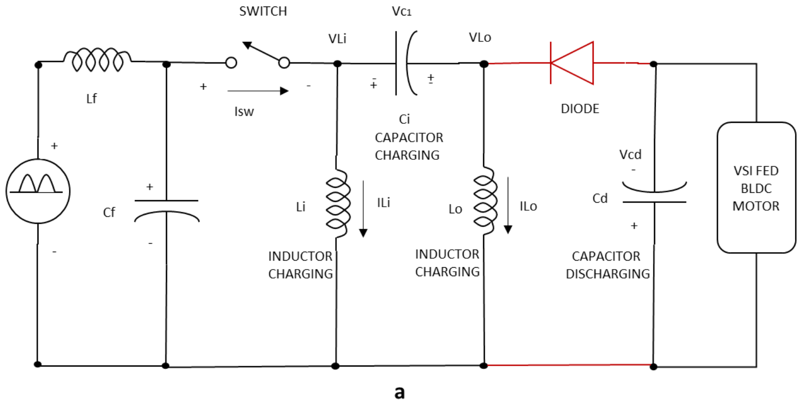

Figure 3.1 Mode A of Modified Zeta Converter

3.2.2. Mode B

This mode begins with the switch turned OFF of S_w. In this mode C_i discharges according to figure 3.2. As intermediate voltage reduces, output inductor current decreases and input inductor current keep on increasing. Diode is forward biased and starts conducting. DC link capacitor charges though this diode as a result voltage across DC link capacitor starts increasing according to waveform shown in figure 3.5. Figure 3.2 shows that the input inductor current (i_{Li}) and output inductor current (i_{Lo}) if added up, results in diode current (i_D). This mode ends when DC link capacitor charges up to voltage equal in intermediate capacitor voltage (V_{Ci}).

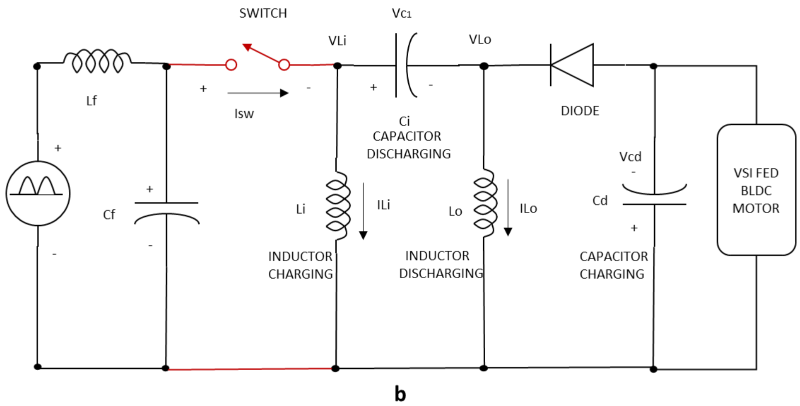

Figure 3.2 Mode B of Modified Zeta Converter

3.2.3. Mode C

This mode starts when intermediate capacitor further discharges through input and output inductor and V_{Ci} decline from V_{DC} as shown in voltage waveform figure 3.5. in this mode DC link voltage rises up as DC link capacitor charges as diode is forward biased and output inductor discharges through it. The voltage across DC link capacitor rises up and current through output inductor decreases and current through input inductor keep increasing. As the modified Zeta converter is meant to function in DICM the current through output inductor lowers to zero at ending of mode C. The output inductor is meant to be completely discharged which requires output inductance used to be lower in value than input inductance. The total time duration needed for mode B and C is 20-30% of one switching time period. Mode C is presented in figure 3.3.

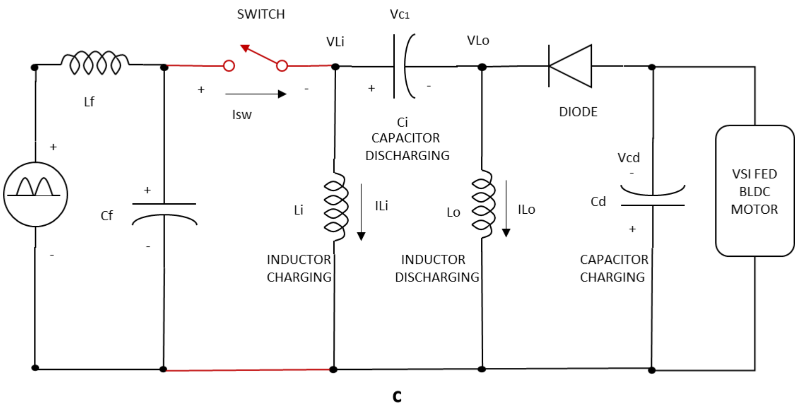

Figure 3.3 Mode C of Modified Zeta Converter

3.2.4. Mode D

This mode starts with the polarity reversal of output inductor current after reaching zero value as shown in figure 3.5. This mode is also divided into two parts. In first part of the mode input inductor current increases as the intermediate capacitor keep on discharging. During that interval diode is reverse biased and output inductor current is equal in magnitude to input inductor current. The magnitude of V_{dc} reduces as the C_{dc} discharges directly through load.

The second part of the mode starts by the time that intermediate capacitor voltage becomes 0. After this the intermediate capacitor charges up with reverse polarity as shown in figure 3.5. The input inductor voltage drops down and also the input inductor current in order to charge C_i as shown in figure 3.4. Mode D is normally longest of all other modes. It is normally 50-70% of complete cycle. The cycle repeats itself when switch S_w again turns ON.

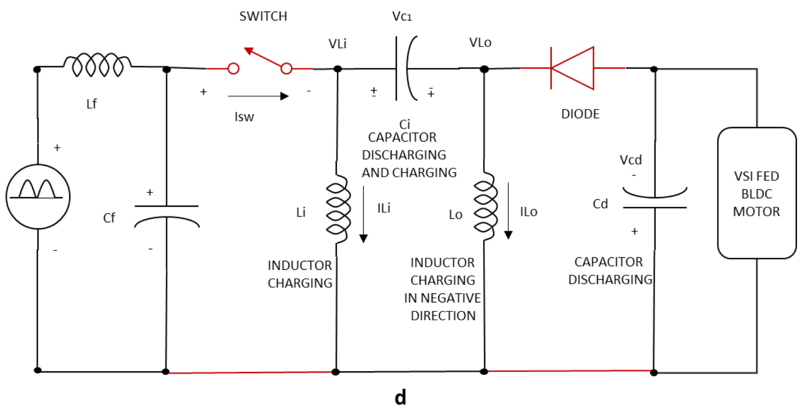

Figure 3.4 Mode D of Modified Zeta Converter

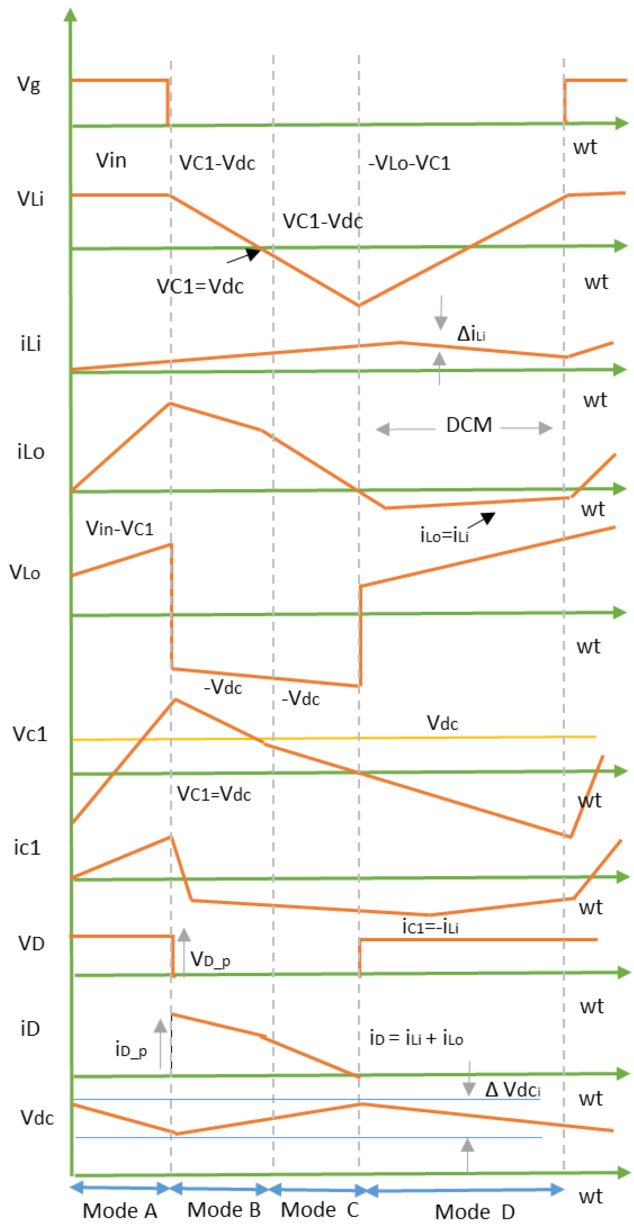

Figure 3.5 Voltage waveforms of Modified Zeta Converter

3.3.Design of modified zeta converter

The proper design of modified zeta converter is very important as it needs to operate in DICM for PFC. The basic parameters which need appropriate value selection are L_f, L_i, L_o, C_i, C_d and C_f. The value of input inductor can be obtained from equation 2.12. The switching frequency f_s is taken as 20 KHz and V_{dc} is taken as 200 Volts. For this V_{dc} the minimum value of V_s is 85V. The inductor value is chosen for maximum inductor current and given as follows according to equation 2.12

$$L_i = \left(\frac{1}{\eta f_s}\right)\left(\frac{V_{s\min}^2}{P_{i\max}}\right)\left(\frac{V_{dc\max}}{\sqrt{2}V_{s\min}+V_{dc}}\right)$$

$$L_i = \left(\frac{1}{0.2\times 20000}\right)\left(\frac{85^2}{350}\right)\left(\frac{200}{85\sqrt{2}+200}\right)$$

$$L_i = 3.22\times 10^{-3} H$$

There is 20% allowed permissible amount of ripple current in the input inductor. So the value 3.3 mH can be chosen as input inductor. The value of output inductor can be calculated from equation 2.15. For the design purpose the value of V_{dc} and V_s is considered minimum which is 50V and 85V respectively.

$$L_{oc} = \left(\frac{V_{s\min}{}^2}{P_{i\min}}\right)\left(\frac{V_{dc\min}(t)}{2\sqrt{2}V_{s\min} f_s}\right)\left(\frac{V_{dc\min}}{\sqrt{2}V_s+V_{dc\min}}\right)$$

$$L_{oc} = \left(\frac{85}{70}\right)\left(\frac{50}{2\times 85\times 20000\times\sqrt{2}}\right)\left(\frac{50}{85\sqrt{2}+50}\right)$$

$$L_{oc} = 315.3\times 10^{-6} H$$

The value of L_o is needed to be less than critical value L_{oc} so a $70\mu H$ value is chosen. The intermediate capacitor value can be evaluated by equation 2.18. For design purposes the value is calculated at maximum ripple voltage. Which is obtained while using $V_{dc\max}$ and $V_{s\max}$. So according to equation 2.18

$$C_i = \frac{P_{i\max}}{\kappa\left(\sqrt{2}V_{s\max}+V_{dc\max}\right)^2 f_s}$$

$$C_i = \frac{3530}{0.1\left(270\sqrt{2}+200\right)^2 20000} = 0.516\times 10^{-6} F$$

An approximate value of 0.66 μH is needed as C_i while κ is selected to be 10%. The DC link capacitor value can be calculated using equation 2.20. For design purpose minimum vale of V_{dc} is chosen, given as follows

$$C_{dc} = \frac{P_{i\min}}{2\omega\delta V_{dc\min}^2}$$

$$C_{dc} = \frac{70}{2 \times 314 \times 0.04 \times 40^2} = 1741.6 \times 10^{-6} F$$

The value of C_{dc} is should be greater than the value calculated here. A capacitor of 2200 μF is chosen as DC link capacitor. The value is chosen to make the ripples to be lower than 4 percent and to operate in high switching, high current applications. LC filter is designed for smoothing out the DBR’s output voltages. DBR adds ripples in the power supply which needs to be reduced for improving power quality. For maximum ripple reductions it needs a very appropriate parameter selection of the filter. The value of capacitor is given as [24]

$$C_f < C_{\max} = \frac{I_{peak}}{\omega_L V_{peak}} \tan(\theta)$$

$$C_f < C_{\max} = \frac{\left(350\sqrt{2}/220\right) I_{peak}}{314 \times 220\sqrt{2}} \tan\left(1^o\right)$$

$$C_{\max} = 401.98 \cdot nF$$

The capacitance value of C_f is chosen to be lower than $C_{\max}$ due to operation requirements. Hence a capacitor of 330 nF is chosen for this design. Here I_{peak}, V_{peak} and θ represents input parameters of power supply i.e. peak current, peak voltage, phase angle difference between current and voltage. The value of inductor can be given as [24]

$$L_f = L_{req} + L_s$$

$$L_f = \frac{1}{4\pi^2 f_c^2 C_f}$$

L_s Represents source impedance which can be taken as 4 percent of base impedance for evaluating L_{req}.

$$L_f = L_{req} + 0.04\left(\frac{1}{\omega_L}\right)\left(\frac{V_s^2}{P_o}\right)$$

$$L_{req} = L_f - 0.04\left(\frac{1}{\omega_L}\right)\left(\frac{V_s^2}{P_o}\right)$$

$$L_{req} = \frac{1}{4\pi^2 f_c^2 C_f} - 0.04\left(\frac{1}{\omega_L}\right)\left(\frac{V_s^2}{P_o}\right)$$

$$L_{req} = \frac{1}{4\pi^2 \left(20000/10\right)^2 \times 330\times10^{-9}} - 0.04\left(\frac{1}{314}\right)\left(\frac{220^2}{350}\right) = 1.57mH$$

The cut off frequency of LC filter is given as [24]

$$f_L < f_c < f_{sw}$$

3.4.: Proposed Architecture

The proposed architecture for SVPWM controlled BLDC Motor drive is shown in figure 3.6. A single phase voltage source is used as a voltage source. An uncontrolled semiconductor diode bridge rectifier is used to convert sinusoidal AC into pulsating DC. This pulsating DC voltage source involves ripples due to full wave rectification operation. LC filter are utilized for minimizing the ripple factor in order to achieve a constant DC supply. This filtered DC supply applied across the input of Modified Zeta converter. The Modified Zeta converter is composed of a MOSFET switch controlled by PWM pulses, an L_i, an L_o, an C_i and a C_{dc}. When the MOSFET switch is turned ON input inductor, intermediate capacitor and output inductor starts charging. During this interval the diode is in non-conduction mode as it is reverse biased according to configuration. The load is applied by the C_{dc} attached.

As the switch is turned OFF and the DC link capacitor discharges to lower voltage the diode goes forward biased and starts conducting. Now the converter charges the DC link capacitor equal to the voltage across intermediate capacitor and input inductor. During this interval the input inductor output inductor and intermediate capacitor discharges through diode to charge DC link capacitor up to certain constant voltage level.

A voltage sensor is utilized to sense the actual V_{dc}. This actual voltage is then related with the reference signal to produce error signal according to difference between these two values. This error signal is then applied to PI (proportional Integral) controller which generates a control signal based on the error signal and controller gain values. This control signal is then fed to PWM pulse generator which produce pulses. The width of the pulses depends on the magnitude of control signal. This pulses are then provided to the switch of Modified Zeta converter. The Switch ON time depends upon the width of pulse supplied to Gate terminal of switch. The switch ON time decides the voltage level that intermediate capacitor is to be charged. It eventually controls the output voltage of converter as the DC link capacitor is charged by the intermediate capacitor. In this way a single voltage loop is used to control the V_{dc} of Modified Zeta converter.

The DC link voltage is supplied to Voltage Source Inverter (VSI). VSI is a three leg semiconductor switches based bridge. Six IGBT based switches have been used in VSI design configuration. S_1, S_3 ,S_5 makes upper legs and S_2 ,S_4 ,S_6 configures lower legs portion respectively as shown in diagram. Switches are numbered based on switching sequence. In this switching sequence S_2 is switched ON after S_2 and S_3 is triggered ON after S_2. There is a gap of 60^o between any switching. S_1 and S_2 makes the first leg and there common junction point gives one phase of three phase output supply. Next two legs provides the other two phases. Two switches of a leg are toggle switches, if upper switch is ON respective lower switch must be OFF vice versa. When the upper switch is ON and lower switch is OFF positive half cycle of respective phase is supplied to the load reverse is needed for negative half cycle. The next respective upper and respective lower switch are triggered in same manner with a gap of 120^o phase shift. In this manner a three phase output voltage supply is attained with $\frac{2\pi}{3}$ phase shift between any two phases.

The three phase output supply generated from VSI is provided to three phase stator winding of BLDC motor to generate required flux. A speed encoder is utilized to sense the actual speed of BLDC motor. This actual speed is measured up with the reference speed and the error signal is generated. This error signal is amplified according to the proportional and integral gain of PI controller. Here the PI controller is used as speed regulator which generates control signal fed to SVPWM generator. The pulses generated by SVPWM are fed to six switches to control switch ON and OFF time. In this way generated three phase voltage of VSI is controlled by SVPWM which eventually controls the speed of BLDC motor.

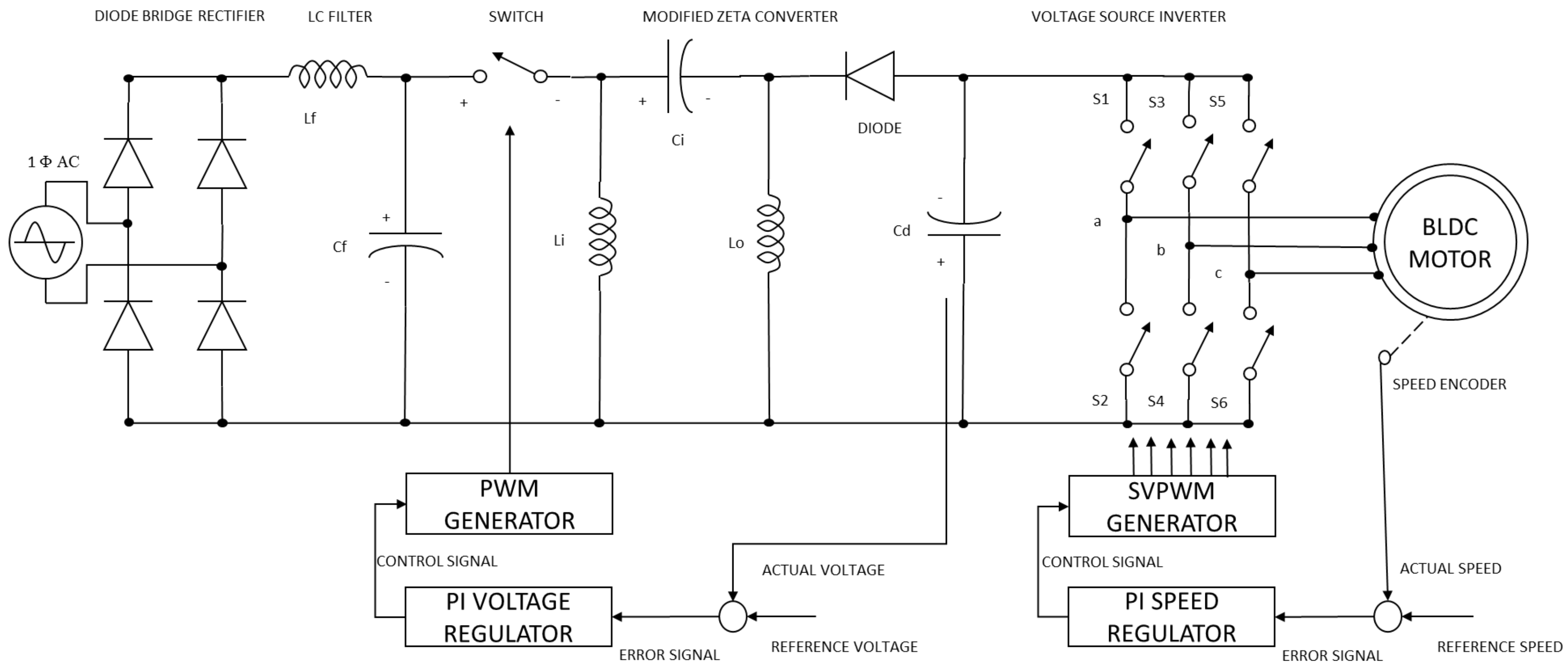

Figure 3.6 proposed architecture of SVPWM controlled BLDC Motor drive

Chapter 4

4. Simulation and Results

This chapter deals with simulation of SVPWM controlled modified Zeta converter fed BLDC motor drive. MATLAB/Simulink environment is chosen for simulation purpose as it is considered authentic and favorable for such tasks. The simulation is done in Simulink toolbox Simpowersystems. The power quality improvements by modified Zeta converter and wide range of speed control due to SVPWM control is assessed

4.1.Simulation Scenario:

The proposed idea of BLDC motor drive is simulated in MATLAB/Simulink. The screenshot of the simulation model is shown in figure 4.1. A 220V 50 Hz supply is used as an AC voltage source. Four diodes are used to design a full bridge rectifier for rectification of input AC source. It provides a pulsating output voltage with ripples. An LC filter is designed to get a smoother output DC. An inductor with inductance value of 1.6 nH and a capacitor of capacitance value 330nF are used as L_f and C_f.

The output of LC filter is supplied to Modified Zeta converter. L_i L_o and C_i are charged through MOSFET acting as switch. Modified Zeta converter is designed to operate in DICM which demands a discontinuous current through L_o even for worst switching cycle. For this purpose the value of L_o is chosen to be a much lower inductance as compare to L_i. It is taken as 70mH while the suitable value of input inductance is 3.3mH even at minimum voltage supply and maximum ripple current. An intermediate capacitor C_i of capacitance value 0.66μF is used as it is desired to have low ohmic and equivalent series resistance (ESR) for high frequency switching and surge currents. DC link capacitor is charged through a diode. A 2200μF capacitor is used as DC link capacitor C_{dc} as a higher capacitance is required for reduced ripples on high current and switching frequency values.

A voltage follower control is designed controlling the output of modified zeta converter. The V is compared with the step signal acting as a reference voltage value which fed error signal to PI controller. PI controller fed a control signal to PWM generator with 5000Hz switching frequency, to generate pulses accordingly. These out of PWM generator which is pulses is fed to MOSFET switch of modified zeta converter.

The DC link output voltage is supplied to VSI as an input. Six MOSFET switches are used are used to design VSI. The MOSFET switches are triggered by SVPWM to get three phase alternating output voltage. The output of VSI is fed to BLDC Motor as supply to three phase armature winding. The output parameters extracted from BLDC motor are stator current of phase a (I_{s-a}), rotor speed in radian per second further converted to revolution per minute (RPM) and electromagnetic torque (T_e) in Nm. The output parameters are connected to scope for waveform display.

The speed output parameter of BLDC motor is compared with the step input taken as reference speed value to get error signal which is fed to PI controller. The PI controller produces speed control signal which is fed to SVPWM generator as magnitude of reference vector. The output of SVPWM generator is de-mux and supplied to respective switches.

A sub-block of PF calculator is used to calculate the power factor of input supply by taking the cosine of the phase difference in input current and voltage. Similarly the PF of output supply of VSI is calculated then both are compared in output scope. RMS function blocks of Simulink have been introduced for taking the root mean square values of power factor across input and output. The real time values of power factor during the whole simulation time will be displayed across the scopes. A function block of THD is utilized across the input source current to calculate the distortion in the supply current. Here the supply frequency is taken as 60^o. The voltages and currents of the simulated model is connected to scope through GOTO tags. A power gui block is inserted with setting the sample time to 0.5μs to complete the simulation model.

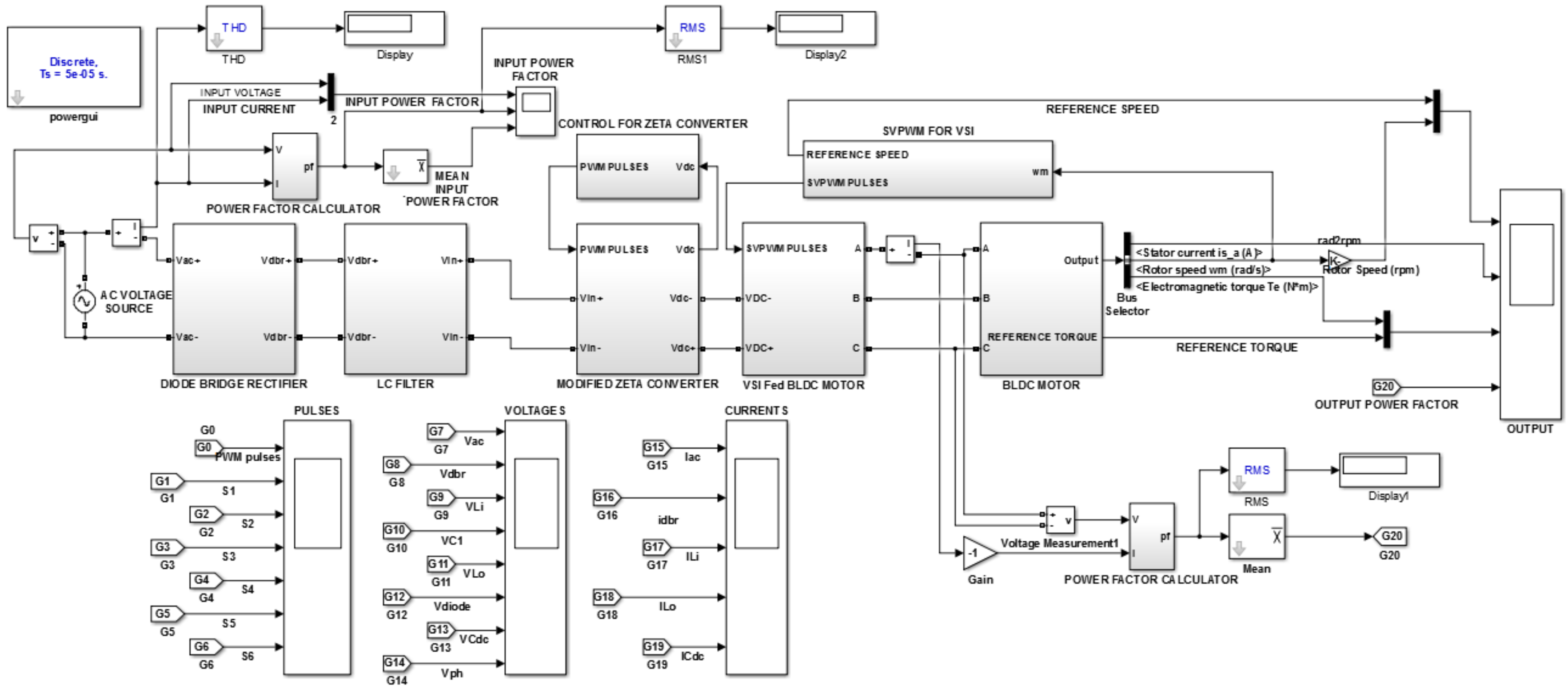

Figure. 4.1 MATLAB/Simulink model of proposed idea

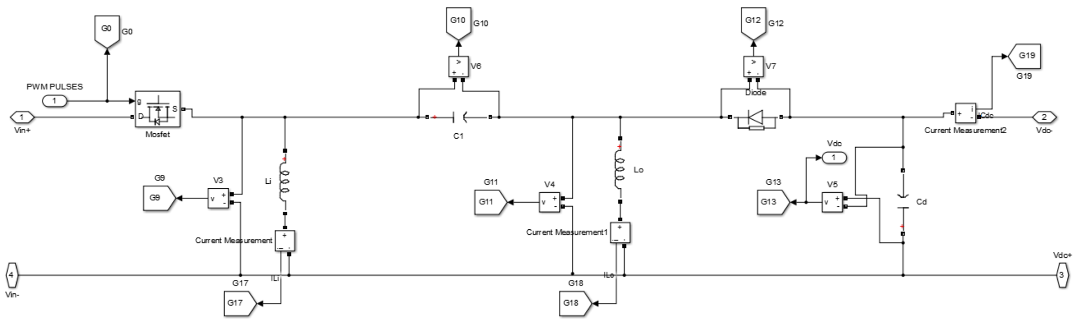

Figure. 4.2 MATLAB/Simulink model of Modified Zeta Converter

Figure 4.2 shows the simulation sub-block of BLDC motor drive which shows the modelling of modified zeta converter.

4.2.Assumptions and Simulation Parameters:

The following assumption are made for the simulation of proposed concept

1. The components used in the simulation model are considered as ideal so that there are no losses and output power is equal to the power supplied.
2. The inductors used in the design L_i and Lo are considered ideal to have R_{Li}=R_{Lo}=0. It is considered that there is no saturation problem.
3. The inductors used in the model are considered ideal so as to have ESR=0 for both Ci and Co
4. The switching period is considered negligible as compare to time constant of charging and discharging.
5. The MOSFET switches used are considered ideal with no switching losses.

4.3.Results:

The results of the simulation model are shown in the figure 4.3-4.6. Figure 4.3 shows the power quality problems created by the drive circuit itself. The figure shows the input voltage and input current. These two quantities have been compared in terms of phase angels to evaluate the phase difference which eventually tells the power factor of the supply. The power factor of the supply goes down to 0.2 as a result of the rectification process. The low power factor causes increased power losses which makes the design failing to be a favorable design. This reduced power factor disturbs the sinusoidal nature of the supply current. This disturbs the smooth operation of the power electronic devices which causes increased power losses. To make the proposed idea work for power quality improvement the power factor and THD reduction are necessary.

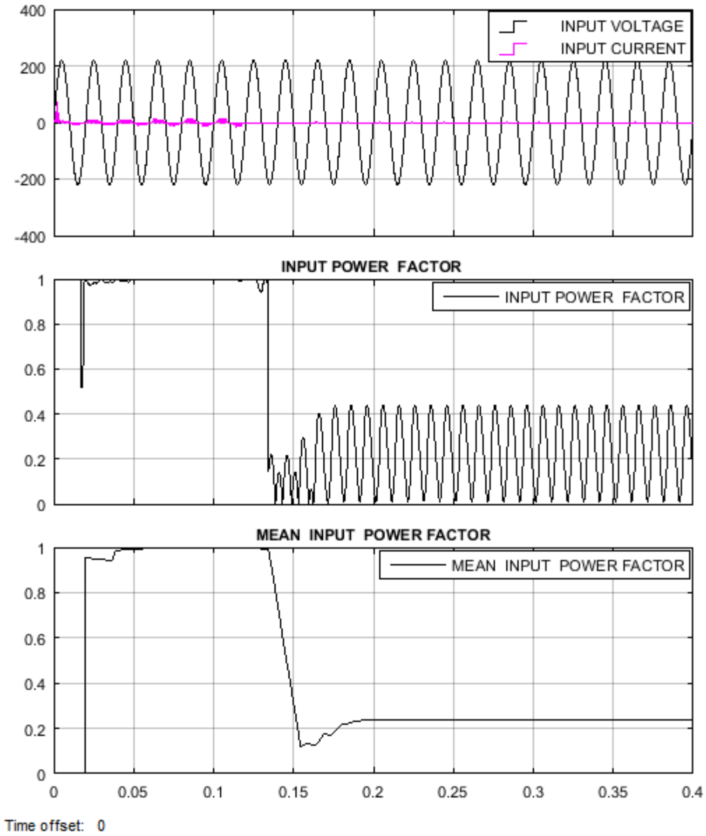

Figure. 4.3 Input parameters of BLDC motor drive

4.3.1. PFC based modified zeta converter:

Figure 4.3 shows the input parameters of BLDC motor drive it shows that the mean value of input PF is dropped around 0.2 which is very much low. The modified zeta converter improves the power factor by using PWM switching. Figure 4.4 shows the PWM pulses which are fed to the MOSFET acting as a switch, shown in figure 4.2. The pulses are generated from PWM generator block of Simulink. The are generated based on duty cycle. The duty cycle is decided by the PI controller as per error signal generated by the reference and DC link voltage.

The controller functions in order to reduce the error signal by closed loop single voltage sensor based control. The PWM signal is so generated in order to rise the voltage up to the reference voltage applied. In the simulation the reference voltage is set at 200V. The voltage waveforms of proposed idea are shown in figure 4.5. The figure shows that the DC link voltage keep rising up till it reaches its desired value. Once the reference value is achieved a fixed and fluctuation free voltage is obtained. This constant ripple free voltage is the key to PFC based BLDC motor drive. It provides a constant DC link voltage as shown in voltage waveform of figure 4.5. This DC link voltage when fed to VSI, it generates an output AC supply with increased PF.

All the voltages in the modified zeta converter are shown in figure 4.5. The AC supply voltage with a perfect sinusoidal waveform is shown here. The voltage across diode bridge rectifier shows the ripples created which are the cause of low power quality. The voltages across input, output inductor and diode are explored.

Figure 4.6 shows the current flows in the proposed BLDC motor drive. The current waveforms depicts the supply current, rectifier current, inductors and capacitor's current. The current through the output inductor as shown in the figure is not continuous. It drops to zero before the cycle finishes. It is very necessary for operating in DICM for proposed PFC based modified zeta converter.

4.3.2. Speed control through SVPWM:

The output parameters of BLDC motor drive are shown in figure 4.7. The three phase output from VSI is attained when controlled by SVPWM. The stator current of phase a is shown here which shows the sinusoidal nature of output power supply. The output phase voltage waveform of VSI is shown in figure 4.5 which is again sinusoidal in nature. The speed of BLDC motor in rpm is shown in figure 4.7. The speed is following the reference speed provided. The electromagnetic torque of BLDC motor is also shown here. The output power factor is also visible in this figure which proves the power factor improvement by the proposed scheme.

4.3.3. Comparison with Buck Boost converter based BLDC motor drive

Figure 4.8 describes the buck boost converter based BLDC motor drive. The buck–boost converter is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is equivalent to a flyback converter using a single inductor instead of a transformer as shown in figure 4.9.

Two different topologies are called buck–boost converter. Both of them can produce a range of output voltages, from an output voltage much larger (in absolute magnitude) than the input voltage, down to almost zero.

Figure 4.10 shows the output parameters of the buck boost converter based BLDC motor drive and figure 4.11 output voltage parameters. The design of buck boost converter based BLDC motor drive is more complex and lower in power factor correction as compared to modified Zeta converter based BLDC motor drive.

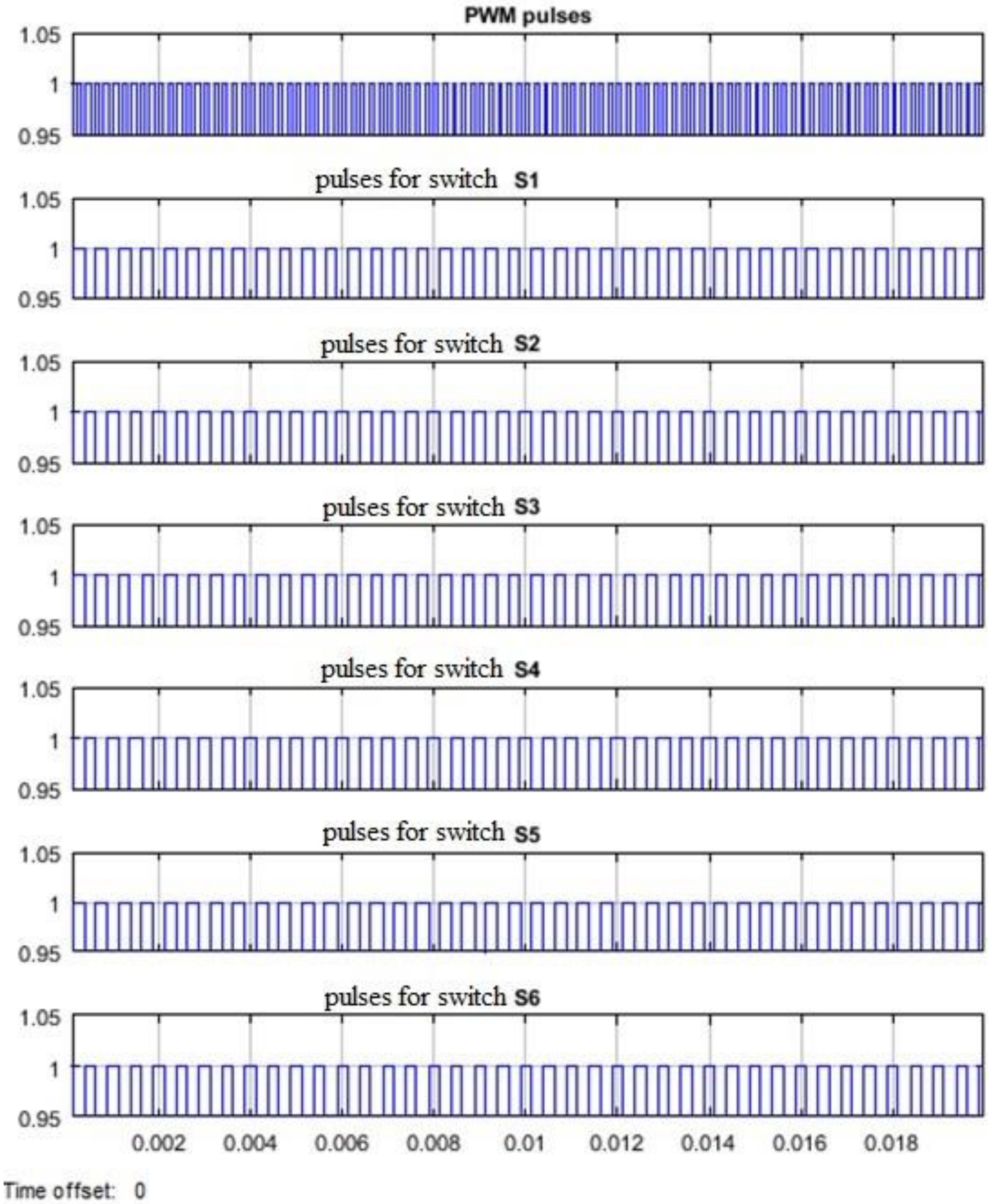

Figure. 4.4 switching pulses of BLDC motor drive switches

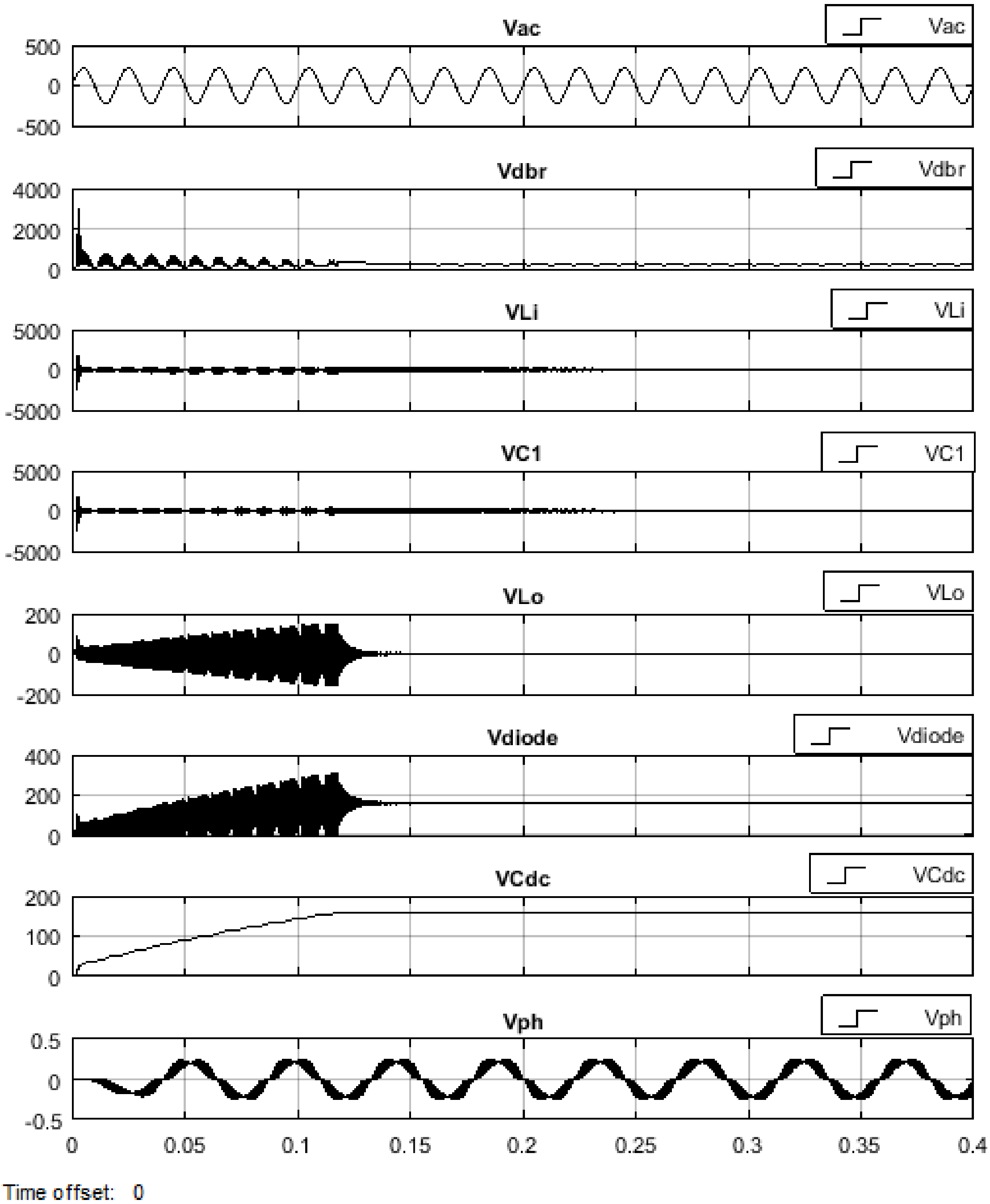

Figure. 4.5 voltage waveforms of BLDC motor drive

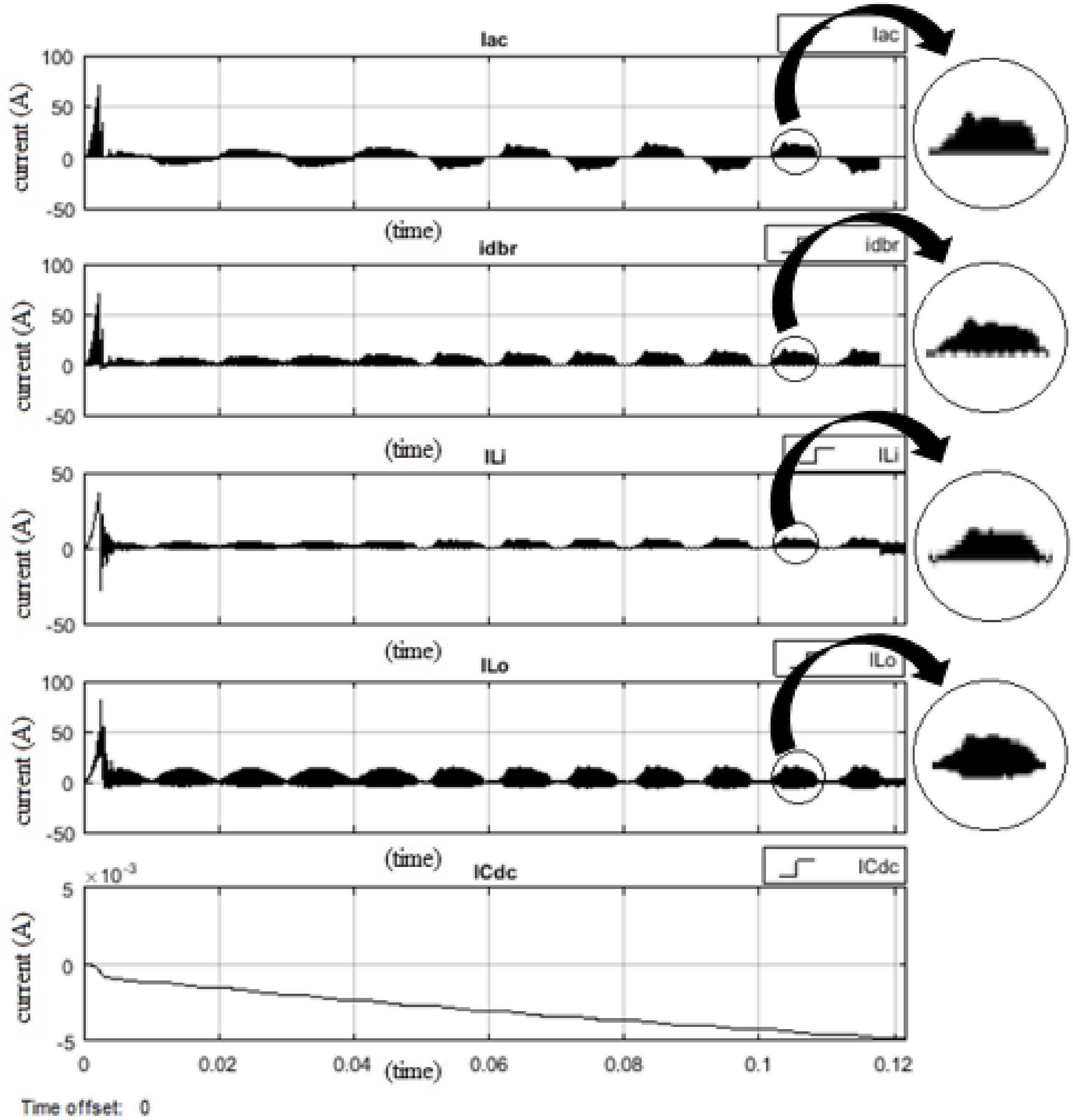

Figure. 4.6 current waveforms of BLDC motor drive

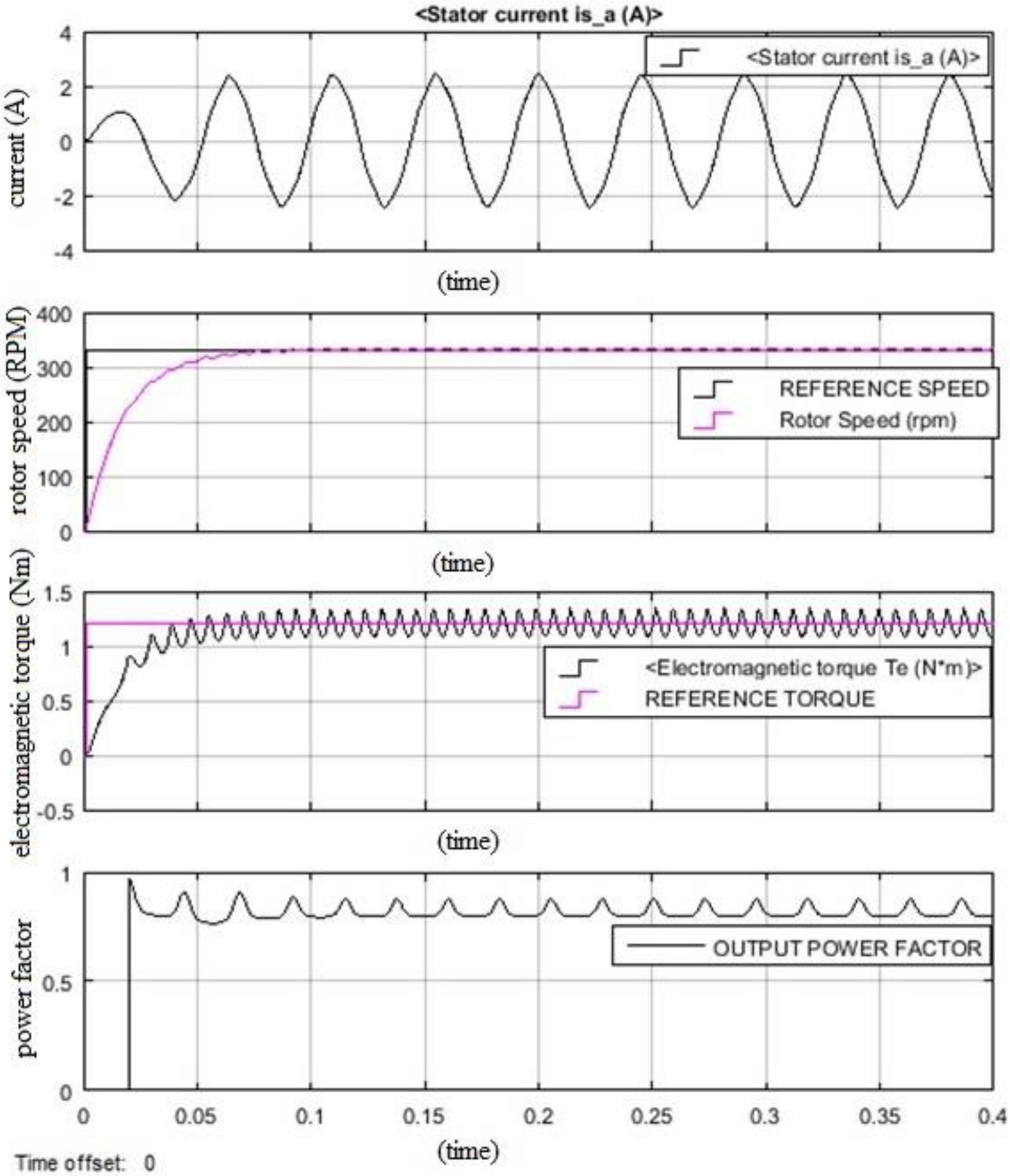

Figure. 4.7 output parameters of BLDC motor drive

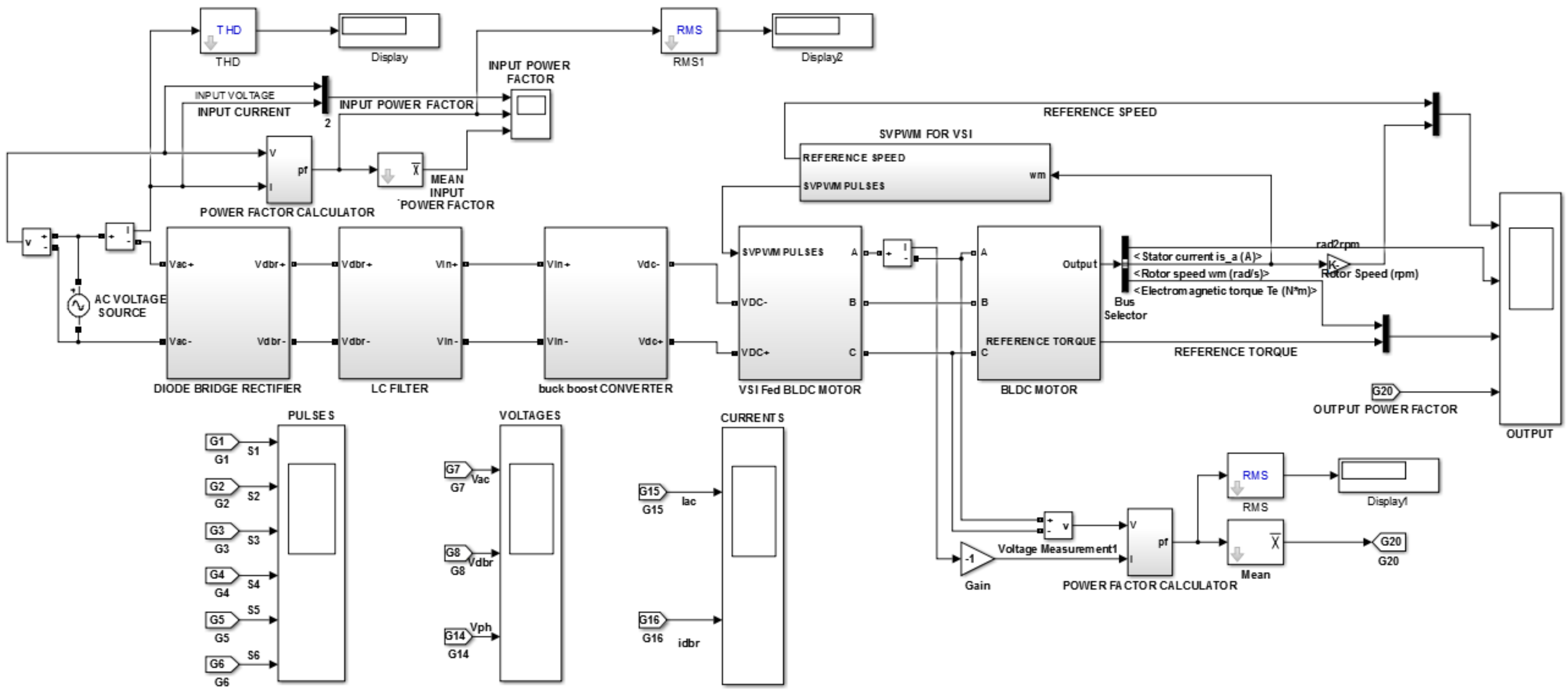

Figure. 4.8 Simulation of Buck Boost converter based of BLDC motor drive

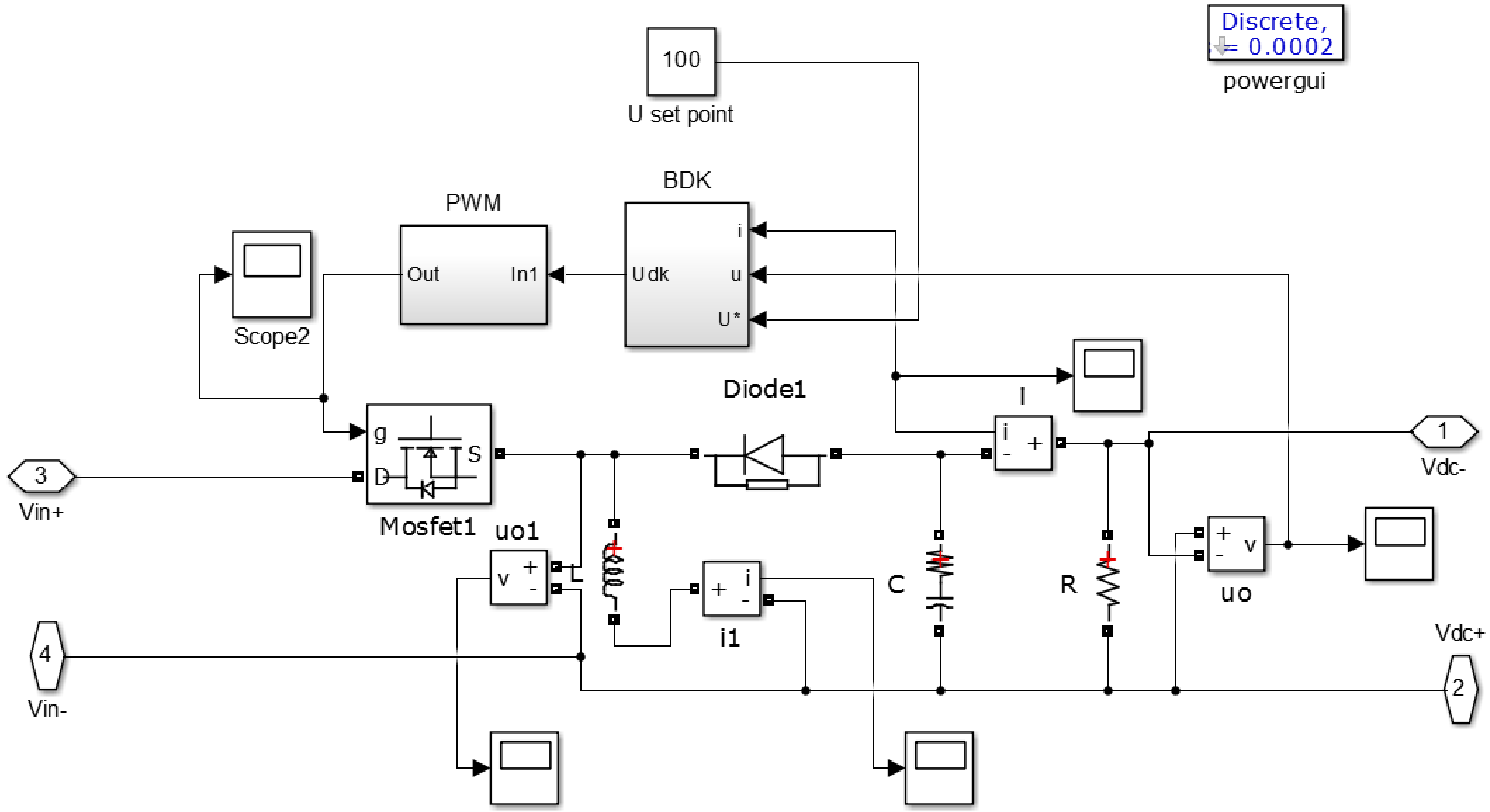

Figure. 4.9 Buck Boost converter

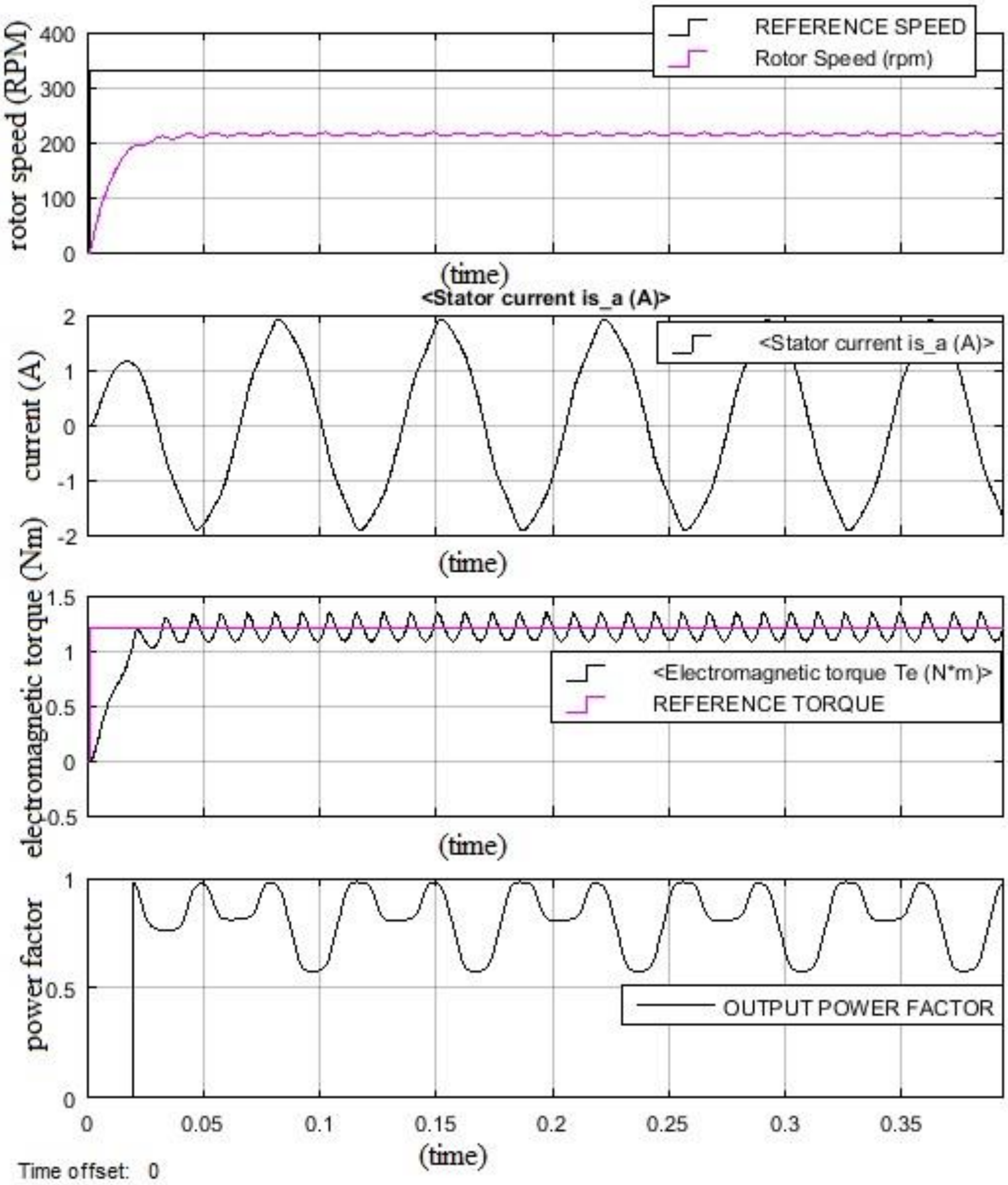

Figure. 4.10 output parameters of Buck Boost converter based BLDC motor drive

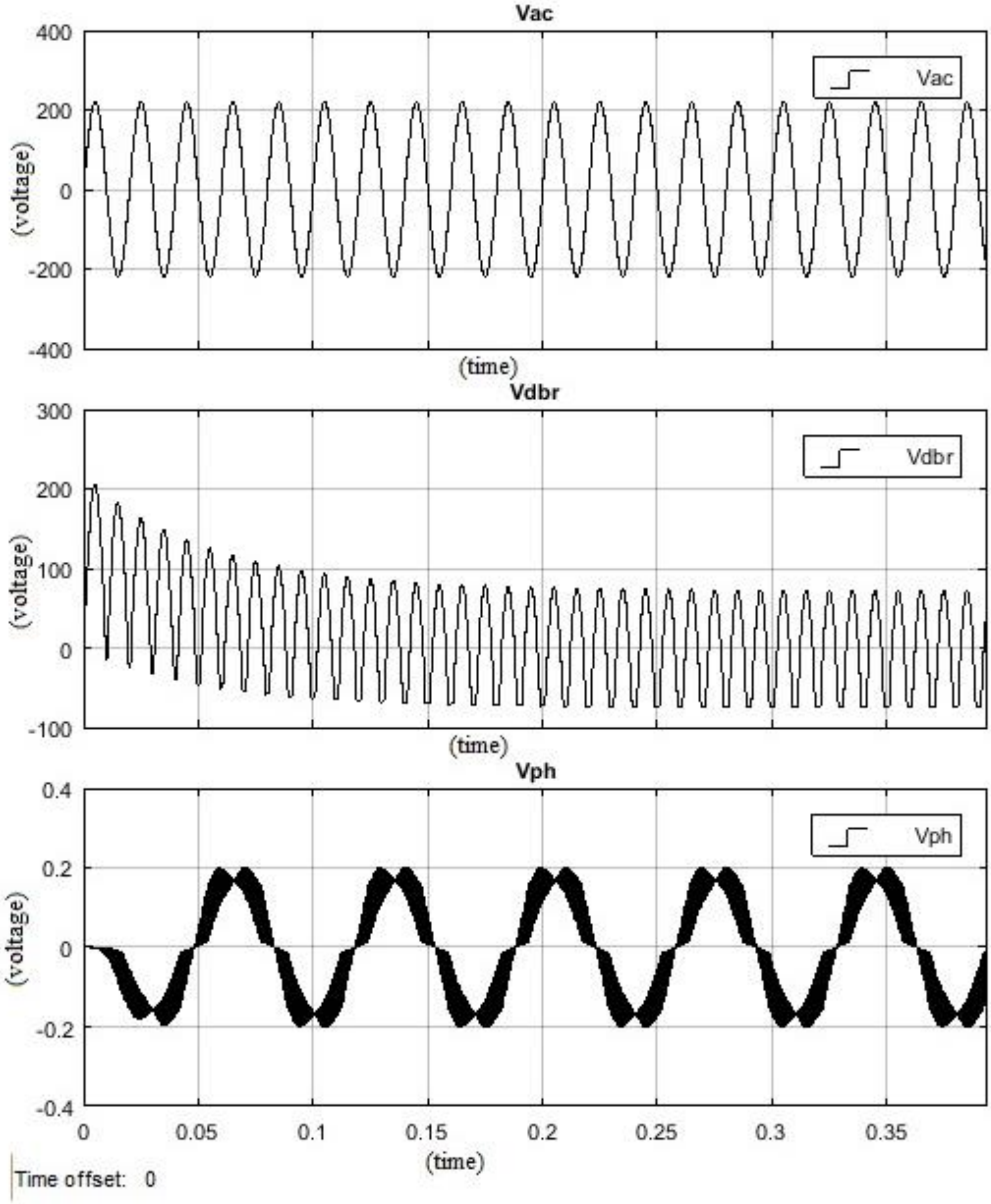

Figure. 4.11 output Voltages of Buck Boost converter based BLDC motor drive

Chapter 5

5. Conclusion and Future Work

5.1.Conclusion

In this research work a SVPWM controlled and PFC based BLDC motor drive is proposed and improved power quality solution for low power applications. The design is considered as a cost effective and wide range speed control. Modified zeta converter is used to reduce the power quality problems created by rectification process. It is modified to operate in DICM to get a constant DC link voltage. This configuration improves the power factor. A simple DC link voltage follower control is utilized for modified zeta converter. The DC link voltage fed to VSI for generating AC output which is fed to run BLDC motor. A SVPWM controlled electronic commutation is used for BLDC motor drive. This reduce mechanical losses and sparking due to absence of brushes. It also reduces electrical losses and distortions. The performance of proposed drive configurations is assessed and evaluated using MATLAB/Simulink environment. The proposed design is considered appropriate for low power and low cost applications.

5.2.Future Work:

Modified zeta converter has a great deal of importance. In future modified zeta converter would be used to regulate the DC power output of wind power generation system and SVPWM controlled VSI can be used for getting three phase AC supply out of it. Another area of this research work is to use this drive configuration for induction motor for reducing its total harmonic distortion and improving power quality.

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