THREE PHASE AC TO AC Z-SOURCE CONVERTER

A Dissertation submitted in partial fulfillment of the requirements for the award of degree

Of

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In

Power Systems

Submitted by

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DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled, **"Three Phase AC to AC Z-Source Converter"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in **Power Systems** submitted to Electrical and Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Dr. Santosh Sonar, Assistant Professor, EIED. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

Punit 15/7/15

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It is certified that the above statement made by the candidate is true to the best of my knowledge and belief.

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DEDICATED TO MY PARENTS

TEACHERS AND FRIENDS

ABSTRACT

With the increasing research in power converters, there is a thrust on finding the solution to obtain a more efficient buck-boost converter which can transfer AC to AC directly with the minimal component requirement. For this the concept of impedance source converter is used. A Z-source network has an advantage over traditional converters like voltage source (V-source), current source (I-source) and push-pull converters that it can operate in shoot-through state which helps to boost the output voltage.

The simulation work for three phase AC to AC Z-source converter has been carried out and the results are verified mathematically. The converter has some limitations like maximum obtainable boost factor is 1.15. This limitation is eliminated in improved topology having twelve bidirectional switches. Though the number of switches required in improved topology is doubled, the maximum obtainable boost factor is very high (in our case boost factor obtained is 1.8). In the thesis work a thorough analysis and comparison of the two converters are presented. Both converters voltage sag and swell capabilities are verified by simulation and mathematical results. State space averaging technique for mathematical modelling of both the converters. The closed loop analysis of the two converters is tried and simulation results are presented in support of that.

Further, frequency control is also possible in both the converters which is not presented in this thesis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

SCR	Silicon Controlled Rectifier
GTO	Gate Turn Off Thyristor
IGBT	Insulated Gate Bipolar Transistor
VSI	Voltage Source Inverter
CSI	Current Source Inverter
ZSI	Impedance Source Inverter
BJT	Bipolar Junction Transistor
ZSC	Impedance Source Converter
IM	Induction Motor
UPS	Uninterruptible Power Supply
NPC	Neutral Point Clamped
SVM	Space Vector Modulation
D	Duty Cycle
THD	Total Harmonic Distortion
PID	Proportional Integral Derivative
PWM	Pulse Width Modulation

CHAPTER-1

INTRODUCTION

1.1 OVERVIEW

In 1900, with the launch of mercury arc rectifier, power electronics has taken birth. With the innovation of silicon transistor in 1948 at Bell Telephone Laboratories the electronics revolution has taken place. The next product also was launched by Bell Laboratories in 1956 which was a PNPN triggering transistor, which is also renounced as thyristor or silicon controlled rectifier (SCR). Then General Electric in 1958 developed the commercial thyristor. There are various types of switches like Gate Turn off Thyristor (GTO), Insulated Gate Bipolar Transistor (IGBT), power metal oxide semiconductor field effect transistor.[1] and many more which were developed thereafter and they find there use in power electronic inverters and converters. The devices which can converts dc power into ac power is known as inverter. The device that converts any other form like ac to ac, dc to dc and ac to dc are known as converters. Our work is mainly focused on ac to ac conversion. There are two types of traditional inverters which will be discussed in this chapter.

1.2 TYPES OF TRADITIONAL INVERTERS

- Voltage Source Inverter (VSI)
- Current Source Inverter (CSI)
- Push Pull Inverter

1.2.1 VOLTAGE SOURCE INVERTER

The dc source in VSI has a very small impedance. Forced commutation is required if VSI uses thyristors. Load commutation is also possible in case the load is underdamped. If VSI uses transistors like Bipolar Junction Transistors (BJTs), IGBTs, PMOSFETs [2] then it can be turned off by self-commutation method. Inverters are also classified as:

1. Bridge inverters
2. Series inverters
3. Parallel inverters

The VSI is widely used. V-source inverter is a buck inverter for dc-ac conversion and V-source converter is a boost rectifier for ac-dc conversion. There is need of feedback diodes in its circuitry. These are used to provide bidirectional current flow and unidirectional voltage blocking.

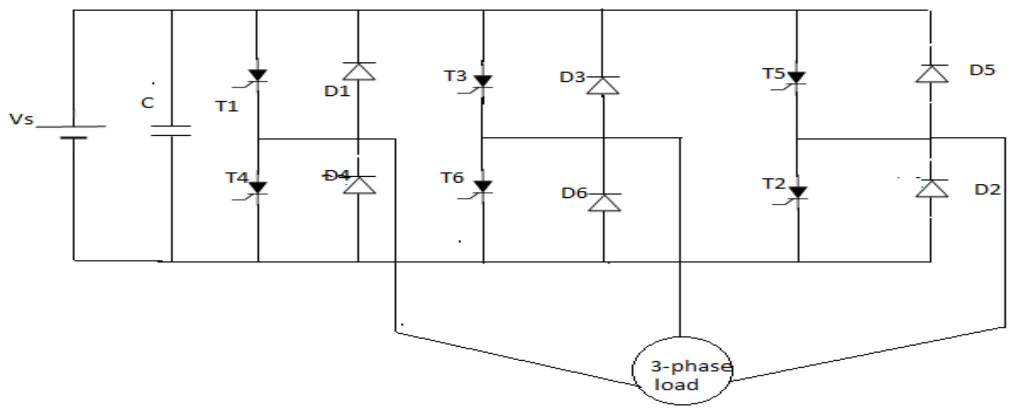

Figure 1.1: Three phase full bridge Voltage Source Inverter

3-phase inverter uses six switches for its performance and the upper and lower devices of each leg cannot be gated on at the same instant, else a shoot-through would occur and damage the devices. Dead time has to be provided in VSI to avoid this situation. [3]

1.2.2 CURRENT SOURCE INVERTER

A CSI converts input dc current to ac output current. A CSI doesn't require feedback diodes. As the switches used in CSI have to face reverse voltage, devices such as GTO, power transistors and power MOSFETs cannot be used.

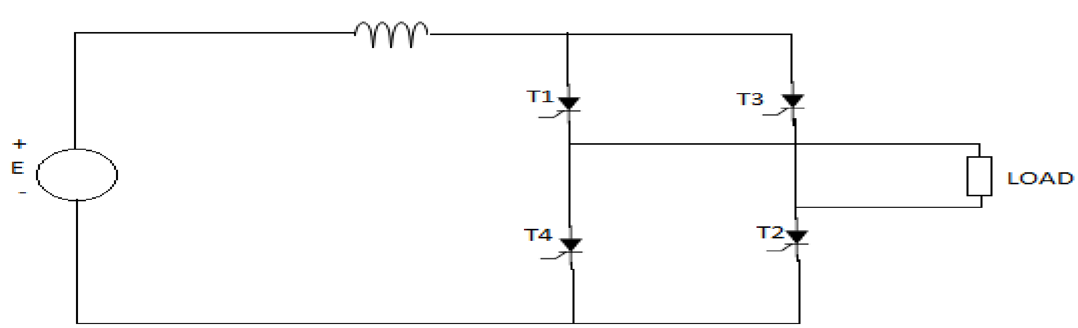

Figure 1.2: A single phase Current Source Inverter

I-source inverter is a boost inverter for dc to ac conversion and I-source converter is a buck rectifier for ac-dc conversion. Overlap time for safe current commutation is provided in CSI. A diode in series with thyristor is used for providing unidirectional current flow and bidirectional voltage blocking.

To overcome the problems associated with these two traditional converters a new concept of impedance (Z-source) has been developed. This Z-source concept can be used in any type of conversion i.e. ac to ac, dc to dc, ac to dc and dc to ac.

1.2.3 PUSH PULL INVERTER

A transformer with center tapped primary winding is required in push-pull inverter circuit. The main advantage of a push-pull inverter is that no more than one switch in series conducts at any instant of time. This can be important if a low-voltage source is supplying DC input to converter, where voltage drop across one switch in series would result in significant reduction in energy efficiency. It is difficult to avoid dc saturation of transformer in this inverter.

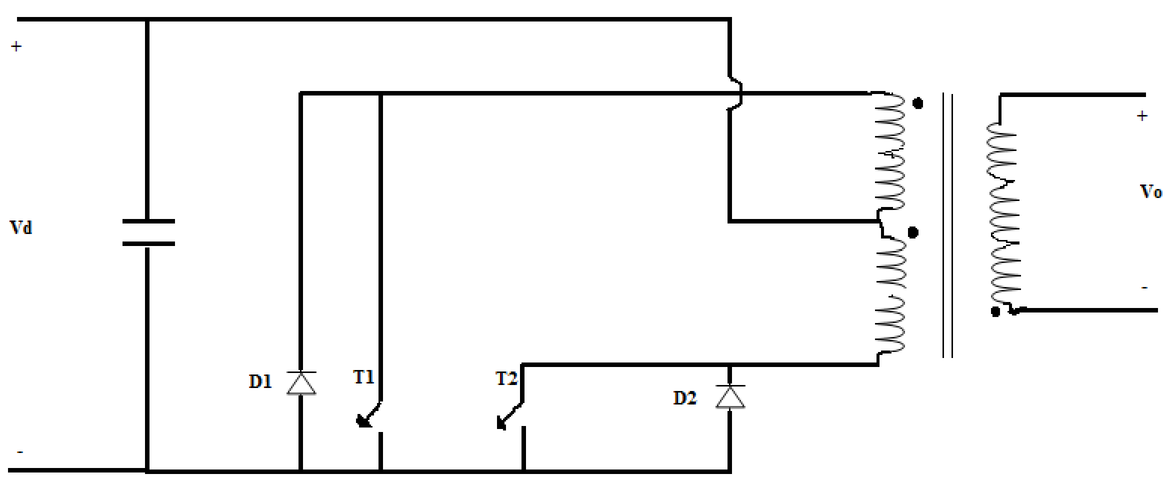

Figure 1.3: Single Phase Push Pull Inverter

In a pulse width modulated (PWM) push-pull inverter for producing sinusoidal voltage the transformer must be designed for fundamental output frequency. The number of turns designed should be greater than that in case of switched mode power supplies. This will result in high transformer leakage inductance, which is proportional to square of number of turns, provided all other dimensions are kept constant. This makes it difficult for a sine wave modulated PWM push pull inverter to operate at switching frequencies higher than 1 kHz.

1.3 Z-SOURCE INVERTER

It utilizes a unique impedance network that integrates the converter main circuit to source or load, it contains the features which were not present in traditional VSI or CSI. It uses two inductors and two capacitors in X shape to provide Z-source. Ac output voltage from ZSI can vary from zero to infinity. It is basically a buck-boost inverter which overcomes the problems associated with traditional converters.

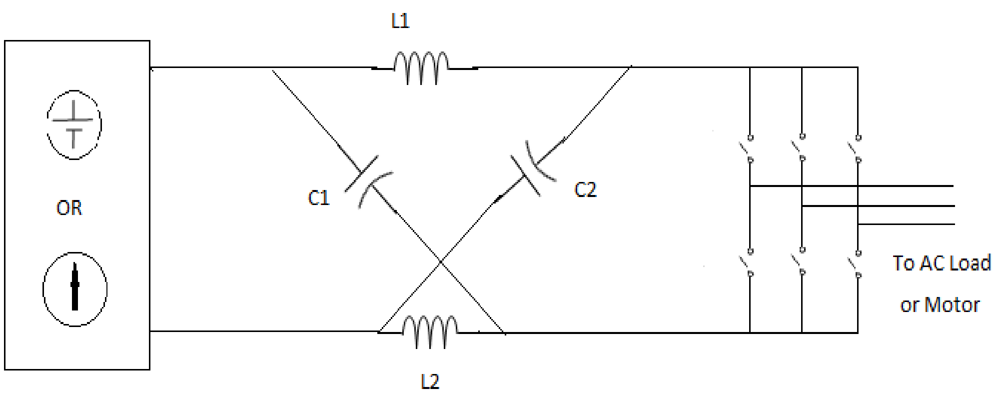

Figure 1.4: Three phase Z-source Inverter

ZSI has nine switching states as compared to VSI that has eight switching states. VSI has six active vectors along with two zero states, ZSI has one more zero state which is a shoot-through zero state which helps to boost the output voltage. [3]

1.4 COMPARISON OF VSI, CSI AND ZSI

Table 1.1: Comparison of Z-source inverter with traditional inverters

VSI	CSI	ZSI
1. It operates as buck inverter for dc-ac operation. 2. It operates as boost rectifier for ac-dc operation. 3. Vulnerable to EMI noise. 4. It has one capacitor. 5. They are not interchangeable i.e. VSI can't be used instead of CSI. 6. Less efficient.	1. It operates as boost inverter for dc-ac operation. 2. It operates as buck rectifier for dc-ac operation. 3. Vulnerable to EMI noise. 4. It has one inductor. 5. They are not interchangeable i.e. CSI can't be used instead of VSI. 6. Less efficient.	1. It can operate as both buck or boost inverter for any mode of operation. 2. It can operate as both buck or boost inverter for any mode of operation. 3. Less EMI noise. 4. It has two capacitors and two inductors. 5. It is possible with the help of ZSI. 6. More efficient.

1.5 LITERATURE SURVEY

Paper [3] has presented a solar cell triggered Z source inverter and proved that it results in less total harmonic distribution (THD) compared to traditional inverters. To enhance the efficiency of solar system, output power is maximized by aligning solar panels with sun and also the Z-source inverter.

In paper [4] the author provided a control system based on ZSI for conversion of wind power. With the varying wind speed it was challenging to maintain the steady output voltage with the help of ZSI. The closed loop controller automatically manages the wind generator voltage and also controls shoot-through and non-shoot through state duty cycles.

A detailed comparison of ZSI and traditional inverters is propound in [5] and by simulation proved that the shoot-through state in ZSI is responsible for the boost of voltage at the output.

A three phase ac to ac Z source converter for direct ac to ac conversion compared to traditional ac-ac converters is explained in [6]. This converter can protect the equipment from voltage sag or swell as it can buck or boost the voltage and it is a single stage conversion process with minimal number of components.

The author propound a new configuration of single phase pulse width modulated (PWM) ac-ac converters with minimal no of switches in [7] as they use only two switches. These converters found applications for ac-ac line conditioning to overcome voltage sag, surge or load fluctuations.

In paper [8] the author introduced a ZSI system and control for motor drives which minimizes the motor ratings to deliver a required power and also it can decrease in-rush and harmonic current.

A new structure for Z-source converters has been proposed in [9] that helped in reducing the size and system cost. Z source capacitor voltage or inductor current has been reduced by new topology.

The paper [11] suggested a Z-source converter and its control methodology for enacting dc-ac, ac-dc, ac-ac or dc-dc power conversion. ZSI for fuel cell application is presented and a comparison with traditional converters is also cited.

A family of PWM ac-ac converters is introduced in [12] with only two switches that includes buck, boost, cuk or buck-boost converters. They become solid-state transformers by duty ratio control and they found applications in ac-ac line conditioning.

A ZSI based control strategy to regulate power from fuell cell and used it in hybrid electric vehicles has been presented in [13] as it reduces the cost by not using dc-dc converter for battery control which were used traditionally.

A new Z-source toplogy which is renounced as a single phase quasi Z-source ac-ac converter has been introduced in [14] which has a high efficiency, lower THD and high input power factor as compared to traditional Z-source converter. It found application as a voltage regulator for ac-ac line conditioning.

The Z-source inverter with traditional inverters i.e. VSI and CSI has been compared in [15]. By his comparison he found that the Z-source concept can be applied to whole scenario of power conversion and ZSI has a limitation that it has a low boost ratio.

In paper [16] the author presented a three phase ac to ac Z-source converter which can maximize the boost ratio. This converter has three injected capacitors and more bidirectional switches as compared to the Z-source converter (ZSC) in [6].

The output of single phase wind generator is converted into a three phase power with the help of a ZSI based closed loop controller in [17]. The voltage is boosted with the help of shoot-through zero state of ZSI.

A three level ac-dc-ac ZSC that can buck-boost the output voltage has been introduced in [18]. A neutral point clamped (NPC) inverter is cascaded with Z-source network to a front-end diode rectifier. It was modulated using full dc-link (FDCL) or patial dc-link (PDCL).

The modelling of three phase Z-source boost rectifier has been explained in [19] which was operated as first stage of a two stage power factor correction (PFC) power supply and their control transfer functions are designed in both steady state and dynamic state.

An algorithm to control the capacitor voltage is implemented in [20] which improves the transient response for dc boost of ZSI. For boosting the dc voltage a modified space vector pulse width modulation scheme is applied.

A comparison of ZSI fed three phase induction motor (IM) drive with CSI and VSI fed IM drive has been delivered in [21]. The motor parameters such as stator current, rotor current, rotor speed and electromagnetic torque are examined.

Many configurations for direct ac-ac converters has been presented in [22] which authorize the use of commercial switch modules. These converter found their applications as a voltage restorer that could be imparted on either source or load side.

The design module for a doubly fed induction generator (DFIG) employing back-to-back PWM voltage source converters in rotor circuit with grid connected system is intoduced in [23]. An outlying AC load can also be supplied by using this scheme.

A quasi Z-source converter has been employed in [24] that can buck or boost the output voltage and be in-phase and out-of-phase with the input voltage. It has a reduced size as compared to traditional ZSC and there is continuous input current.

A simple boost control methodology has been introduced in [25] that have unconventional realtion with modulation index and shoot-through duty ratio employing high modulation index for producing output voltage that demands high voltage gain which results in a reduced voltage stress on devices of ZSI.

Single phase Z-source converter is introduced in [26] employing four switches that incorporates voltage fed and current fed too. A new commutation approach is presented that overcomes the commutation problems associated with traditional converters.

The paper [27] propound a single phase ZSI based voltage regulator that counterbalance wide range of voltage variations utilizing a simple PWM z source ac-ac converter with closed loop control.

A ZSI based uniterruptible power supply (UPS) configuration is presented in [28] that utilize a LC network to couple main circuit of inverter to battery bank that can maintain the desired ac output voltage during voltage drop at battery bank with higher efficiency.

Introdcution of a control strategy for a neutral point clamped (NPC) inverter based on space vector modulation (SVM) is made in [29] which reduces harmonics to a greater extent without utilizing any extra commutation circuitry .

Single phase ac-ac converter employing four switches and a three phase ac-ac converter utilizing six switches are simulated in [30] and also safe commutation is attained without a snubber circuit.

1.6 OBJECTIVE

- To increase the voltage gain of three phase ac to ac Z-source converter.
- Comparison of two different configurations of three phase ac to ac ZSC.
- To design a closed loop controller for constant output voltage.

1.7 ORGANIZATION OF THESIS WORK

Chapter 1 displays the introduction of power electronic converters, literature survey on different topologies, scope, objectives and organization of research.

Chapter 2 deals with the three phase ac to ac ZSC topologies.

Chapter 3 deals with the closed loop control of three phase ac to ac ZSC.

Chapter 4 gives the detailed analysis and simulation results.

Chapter 5 deduces the thesis work by providing the positive and negative features of the work and scope of future work.

References section enlists antecedent papers published by researchers in reorganization of Z-source networks surveyed by the author.

1.8 KEY CONTRIBUTION TO THESIS

1. Designing a basic simulation model of three phase ac to ac Z-Source Converter.
2. Performance analysis of different parameters by simulation and mathematical justification.
3. Improved topology analysis and comparison with traditional one.
4. Duty cycle control by closed loop controller to obtain constant output voltage.

1.9 MATERIALS AND METHODS

- The three phase ac to ac Z-Source converter presented in [6] is base of the thesis, we designed a simulation model for the converter, based on simulation analysis we were able to find out that the converter has a limitation that it can only obtain maximum boost factor 1.15. Mathematical analysis of the converter has been done by using state space averaging technique and this limitation of maximum obtainable boost factor is justified. In order to enhance the boost factor we surveyed [7]-[16] and find out that this can be achieved by the converter presented in [16].
- The converter presented in [16] is an improved 3 phase ac to ac Z source converter that can obtain maximum boost ratio up to 2 theoretically. By simulation analysis of the converter we were able to achieve maximum boost factor 1.8 which is much better than the previous converter. Mathematical analysis of the converter is done again by using state space averaging technique and justified the simulation results. The simulation analysis and mathematical justification of both the converters has been compared.
- The simulation has been carried out by using the Simulink tool in MATLAB. The parameters has been set by daily analysis and simulation. The ideal switch block is used for bidirectional switches and the pulses to that is provided with the help of a triangular

wave and a comparator. To achieve proper sinusoidal voltage the filter is used i.e. a combination of 3 inductor and 3 capacitors. To check the total harmonic distortion (THD) the Fast Fourier Transform (FFT) analysis is done as in [10].

- From [17] we find the closed loop control process and its application to wind energy control, so we tried to design closed loop controller for both the converters. Duty cycle is being controlled with this closed loop system which utilizes a proportional-integral-derivative (PID) controller which is tuned manually. Constant output voltage is achieved with the closed loop control.

CHAPTER-2

THREE PHASE AC TO AC Z-SOURCE CONVERTER

2.1 THREE PHASE AC TO AC CONVERTER CONFIGURATION

The three phase ac to ac Z-source converter is a single step ac to ac conversion process unlike traditional converters which employs a diode end rectifier and uses Z-source as a dc link. It employs three inductors and three capacitors in impedance network. It can buck or boost the voltage to a desirable value with minimal number of components. It can protect the equipment from voltage sag or surge.

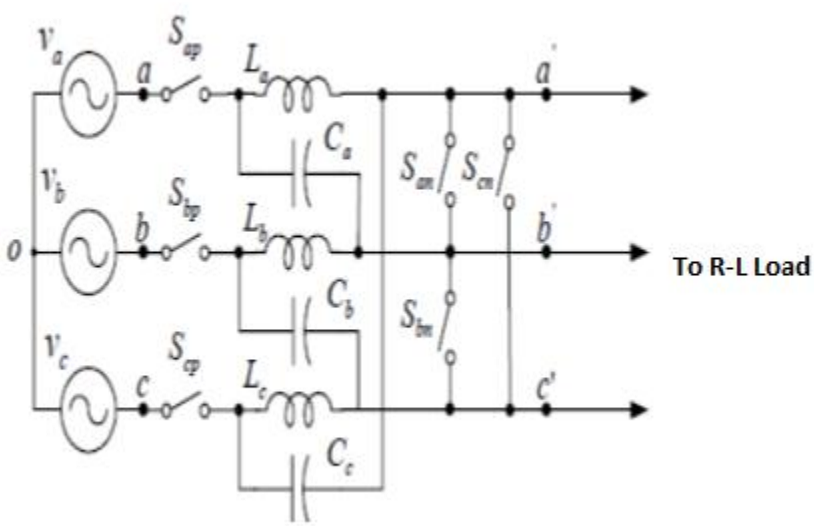

Figure 2.1: Three Phase AC to AC Z-source Converter

The Z-source converter can operate in shoot-through and non-shoot-through state. The switches employed in the circuit are all bidirectional. S_{ap}, S_{bp}, S_{cp} and switches S_{an}, S_{bn}, S_{cn} are complemented and gated according to the pulses shown in figure 2.2

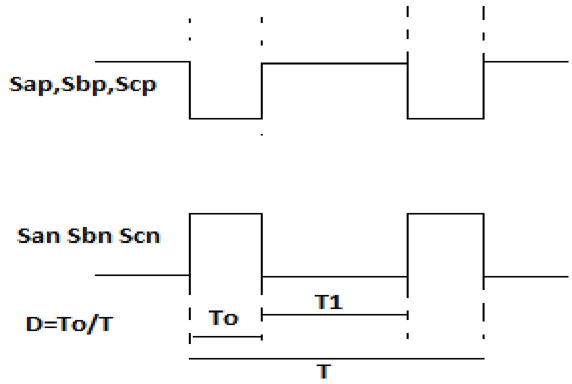

Figure 2.2: Gating Signals Sequence

D, is the duty cycle.

The output can be changed by duty ratio control.

The two operating states are shown below:

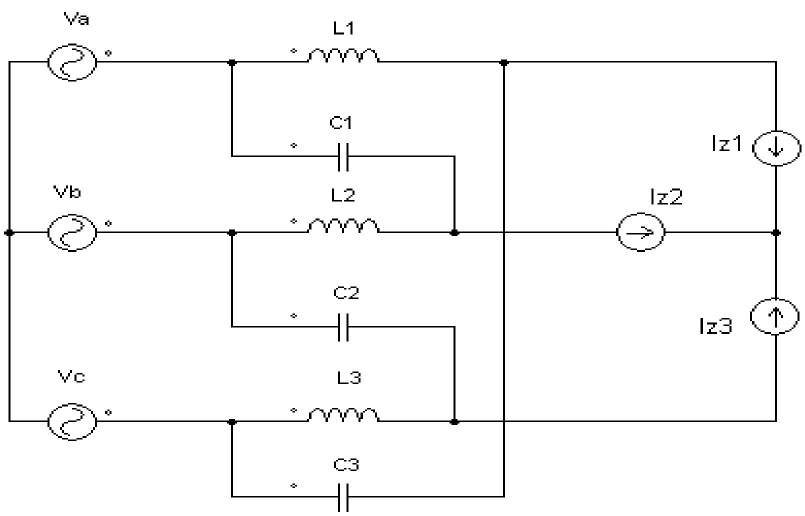

Figure 2.3: Non-Shoot-Through State

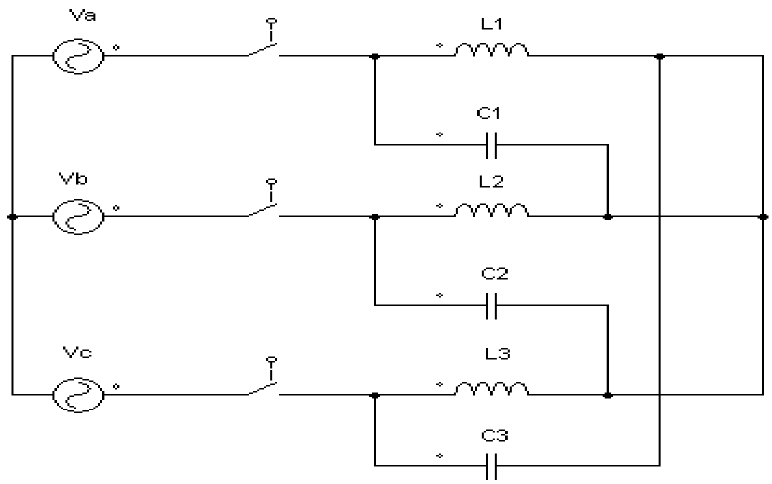

Figure 2.4: Shoot-Through State

The Input line Voltages to the converter-

$$\begin{pmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{pmatrix} = \begin{pmatrix} V_i.e^{i0} \\ V_i.e^{-i.\frac{2\pi}{3}} \\ V_i.e^{i.\frac{2\pi}{3}} \end{pmatrix} \qquad \text{Equation 2.1}$$

Corresponding Output line Voltages are-

$$\begin{pmatrix} V_{a'b'} \\ V_{b'c'} \\ V_{c'a'} \end{pmatrix} = \begin{pmatrix} V_o.e^{i0} \\ V_o.e^{-i.\frac{2\pi}{3}} \\ V_o.e^{i.\frac{2\pi}{3}} \end{pmatrix} \qquad \text{Equation 2.2}$$

Voltage across Inductors-

$$\begin{pmatrix} V_{L1} \\ V_{L2} \\ V_{L3} \end{pmatrix} = \begin{pmatrix} V_L.e^{i0} \\ V_L.e^{-i.\frac{2\pi}{3}} \\ V_L.e^{i.\frac{2\pi}{3}} \end{pmatrix} \qquad \text{Equation 2.3}$$

Voltage across Capacitors-

$$\begin{pmatrix} V_{C1} \\ V_{C2} \\ V_{C3} \end{pmatrix} = \begin{pmatrix} V_C.e^{i0} \\ V_C.e^{-i.\frac{2\pi}{3}} \\ V_C.e^{i.\frac{2\pi}{3}} \end{pmatrix}$$ Equation 2.4

There exists two states shoot-through and non-shoot through state as shown in Figure 2.3 and Figure 2.4 respectively. During non-shoot through period (1-D)T the switches S_{ap}, S_{bp}, and S_{cp} are kept on while the switches S_{an}, S_{bn}, S_{cn} are off. In shoot-through period DT the switches S_{ap}, S_{bp}, and S_{cp} are kept off while the switches S_{an}, S_{bn}, S_{cn} are on.

Therefore, $V_{L1}=V_{C3}-V_{ca}$ Equation 2.5

$V_{L1}=V_{C1}$ Equation 2.6

Averaging the voltage across inductor L_1 over one ac line period in steady state .We have

$$V_c.[\frac{3D-1}{2}+i\,.\frac{\sqrt{3}}{2}.(1-D)=V_i(1-D)(-\frac{1}{2}+i\,.\frac{\sqrt{3}}{2})$$ Equation 2.7

$$\frac{V_C}{V_i}=\frac{(1-D)}{\sqrt{3D^2-3D+1}}$$ Equation 2.8

Assuming filter and Z-source network inductances are very small and can be neglected. If the line frequency voltage drop across the inductor are neglected then the output line to line voltage can be approximated to V_C.

$$\text{Gain } G=\frac{V_o}{V_i}=\frac{(1-D)}{\sqrt{3D^2-3D+1}}$$ Equation 2.9

The gain vs duty cycle curves shows the range of duty cycle to buck or boost the output voltage and the maximum boost is 1.15 at 0.33 duty cycle.

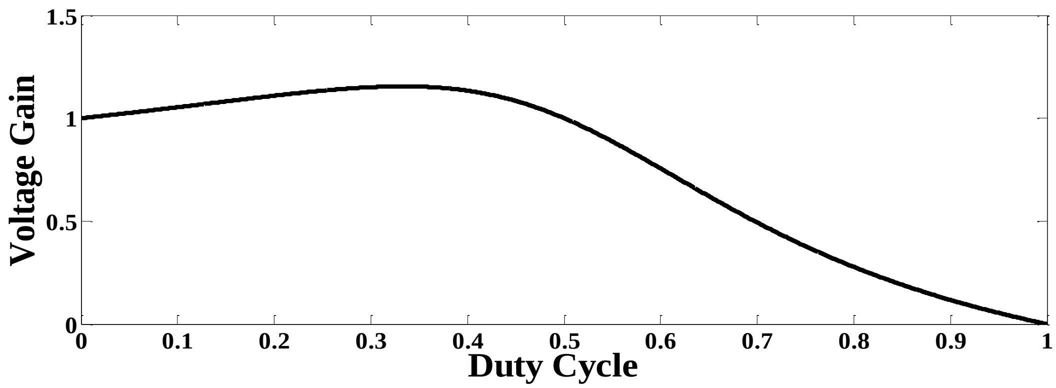

Figure 2.5: Gain Vs Duty Cycle Curve

The simulation results and analysis of this converter will be discussed in the following chapter i.e. Chapter 3.

2.2 IMPROVED THREE PHASE AC TO AC Z-SOURCE CONVERTER

This topology is bit different from the earlier converter discussed in this chapter in context of construction and voltage gain. This converter incorporates a Z-network like earlier converter, bi-directional switches and injected capacitors. Energy storing is the role played by these injected capacitors. In shoot-through state these capacitors are injected to the Z-network as additional energy to charge for Z-source inductors. So the maximum boost ratio of this converter is increased as compared to the earlier converter.

There are twelve bidirectional switches used in this configuration, and one bidirectional switch combined with a diode bridge. The output voltage can be controlled by controlling the duty cycle.

The sequence of gating signals for this converter is presented in Figure 2.6

The converter topology of the proposed converter is shown in Figure 2.7

It also operates in two states i.e. Shoot-through and Non-Shoot-Through State.

The two operating states of this converter are shown in Figure 2.8 and 2.9 respectively.

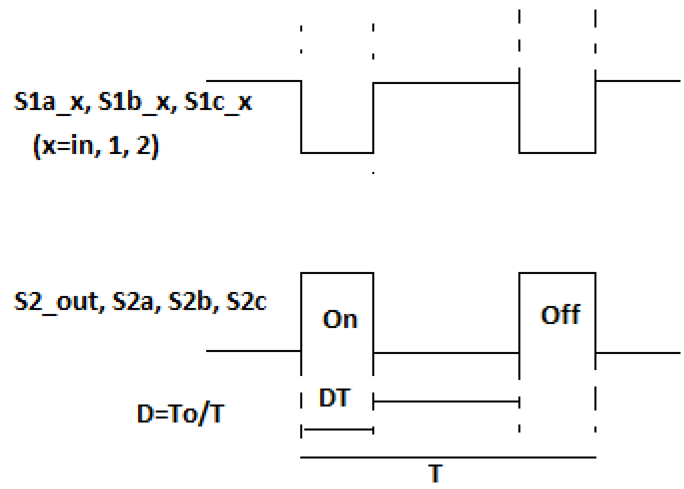

Figure 2.6: Gating Sequence

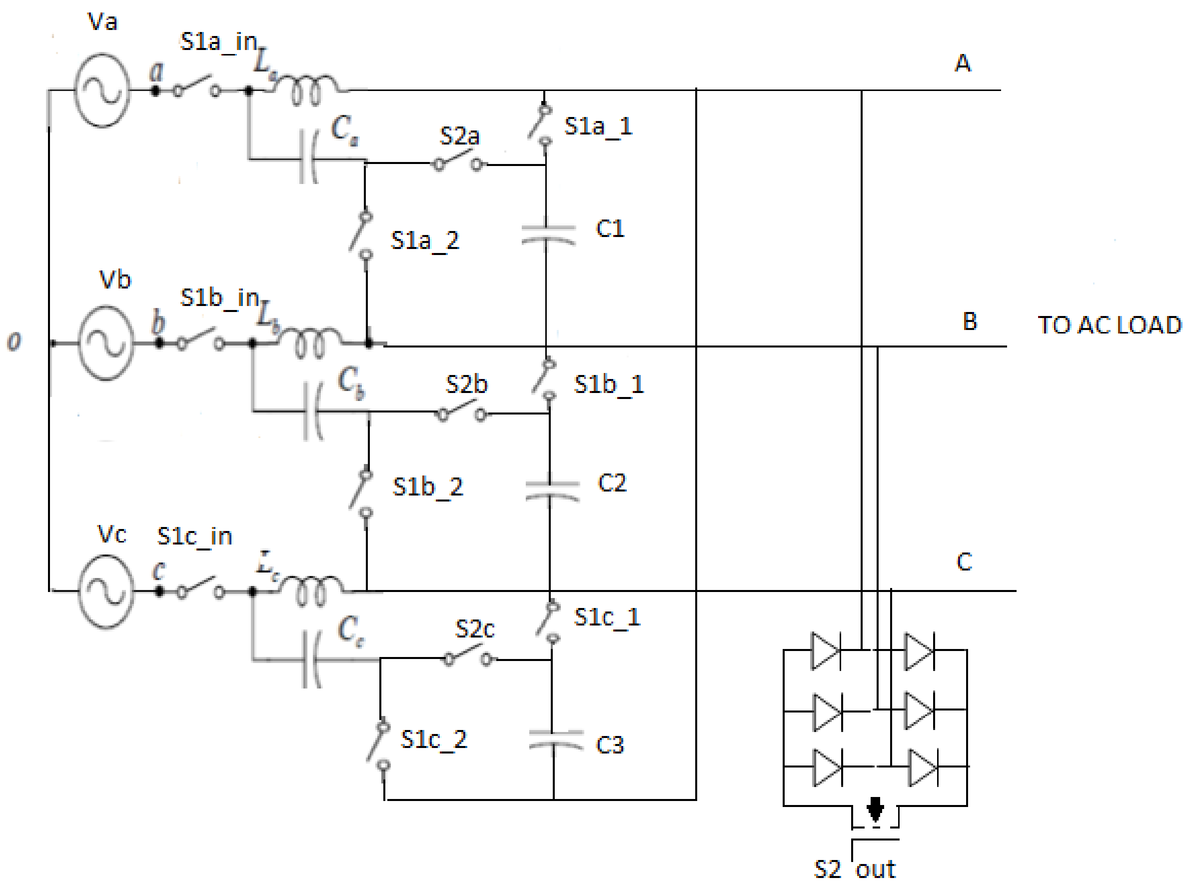

Figure 2.7: Improved topology of Three Phase AC to AC ZSC

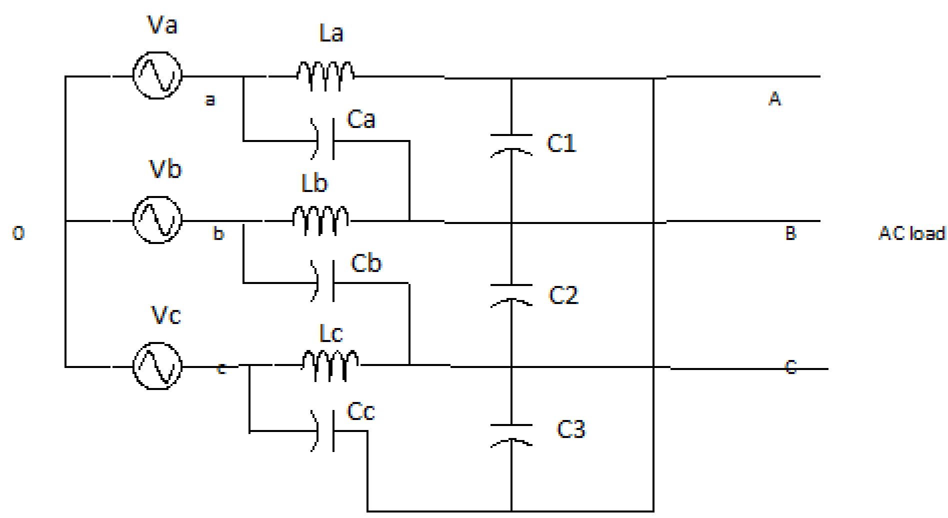

Figure 2.8: Non-Shoot-Through State

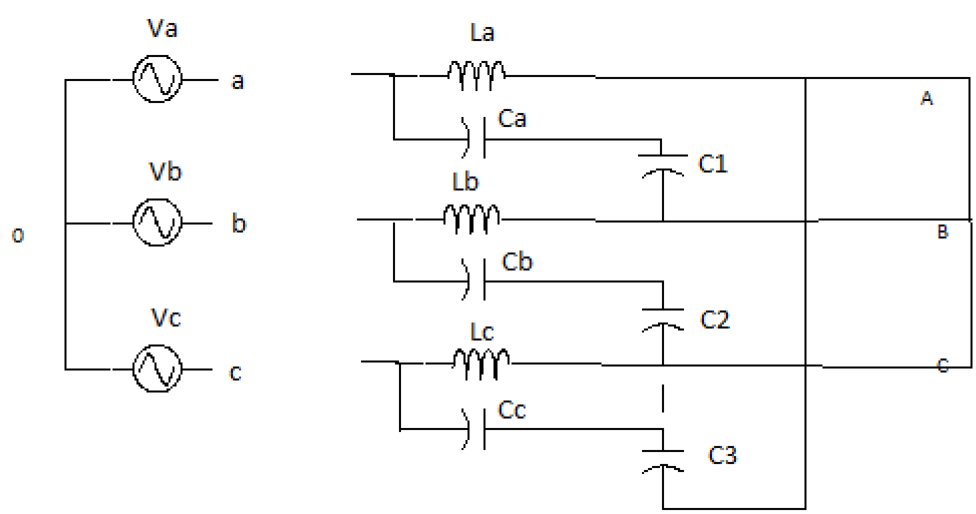

Figure 2.9: Shoot-Through State

The Z-network among three phases is symmetrical as inductors, capacitors of Z-network and injected capacitors have same inductances and capacitances.

Applying the technique above for mathematical modelling, we were able to find out the voltage gain of this converter.

$$\frac{V_o}{V_i} = \frac{1-D}{\sqrt{12D^4 - 30D^3 + 25D^2 - 8D + 1}} \qquad \text{Equation 2.10}$$

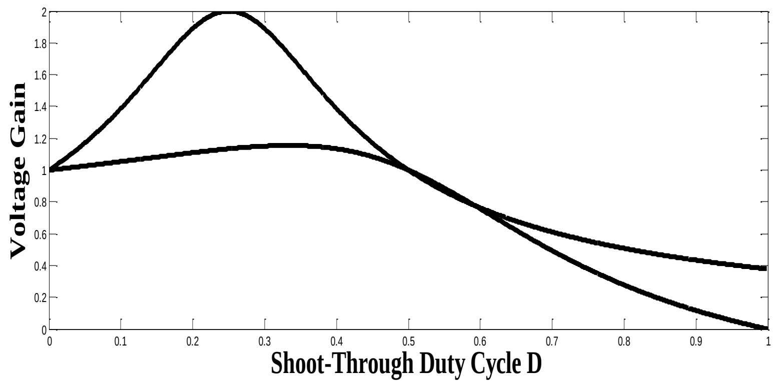

Figure 2.10: Gain Vs Duty Cycle Comparison of Both Converters

Now we will finally compare these two converters theoretically and will proceed to analysis and simulation results of both converters in Chapter 4.

Table 2.1: Comparison of two three phase AC to AC ZSCs

CONVERTER 1	CONVERTER 2
1. It can be used as a Buck-Boost converter.	It can be used a Buck-Boost converter.
2. It has a maximum boost ratio of 1.15	It can boost the voltage up to 2 times.
3. It uses 6 bidirectional switches.	It uses 13 bidirectional switches.
4. It uses 3 capacitors for impedance network.	It uses 3 capacitors for impedance network and also 3 injected capacitors to increase boost ratio.
5. It can be used in shoot through state.	It can be used in shoot through state.
6. It has voltage gain $\frac{1-D}{\sqrt{3D^2 - 3D + 1}}$	It has voltage gain $\frac{1-D}{\sqrt{12D^4 - 30D^3 + 25D^2 - 8D + 1}}$

Table 2.2: Operating States Comparison

Converter type	Shoot-Through State	Non Shoot-Through State
Converter 1	$\begin{pmatrix} V_{C1} \\ V_{C2} \\ V_{C3} \end{pmatrix} = \begin{pmatrix} V_{L1} \\ V_{L2} \\ V_{L3} \end{pmatrix}$	$\begin{pmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{pmatrix} = \begin{pmatrix} V_{C1} \\ V_{C2} \\ V_{C3} \end{pmatrix} - \begin{pmatrix} V_{L2} \\ V_{L3} \\ V_{L1} \end{pmatrix}$
Converter 2	$\begin{pmatrix} V_{C1} \\ V_{C2} \\ V_{C3} \end{pmatrix} + \begin{pmatrix} V_{Ca} \\ V_{Cb} \\ V_{Cc} \end{pmatrix} = \begin{pmatrix} V_{L1} \\ V_{L2} \\ V_{L3} \end{pmatrix}$	$\begin{pmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{pmatrix} = \begin{pmatrix} V_{C1} \\ V_{C2} \\ V_{C3} \end{pmatrix} - \begin{pmatrix} V_{L2} \\ V_{L3} \\ V_{L1} \end{pmatrix}$

The summation of harmonics in a system is known as total harmonic distortion (THD). To understand the concept of THD imagine an AC source with an electrical load.

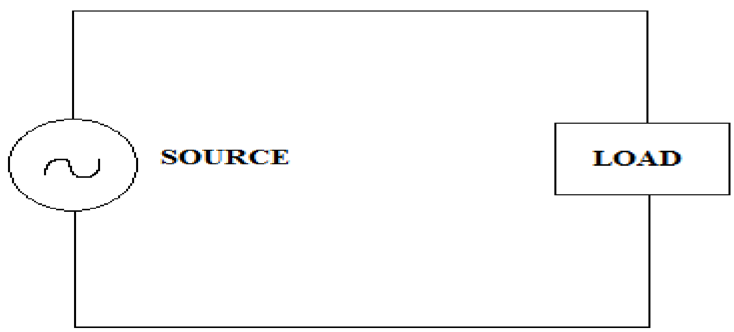

Figure 2.11: Power System with AC Source and Electrical Load

The type of load effects the power quality of the system. Linear loads draw current in a sinusoidal manner, so they don't distort the waveform. Non-linear loads draw current that is not perfectly sinusoidal, voltage waveform distortions are also present with them. Ideal sine wave doesn't have any harmonics.

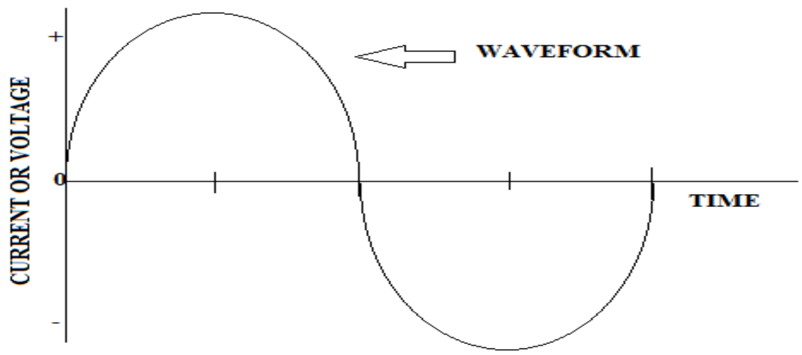

Figure 2.12: Ideal Sine Wave

Distorted waveform can drastically alter the shape of sinusoid.

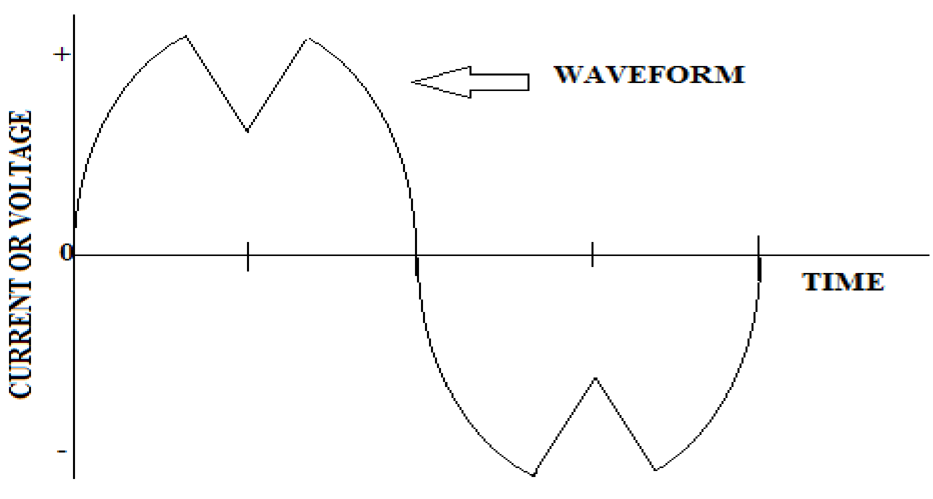

Figure 2.13: Distorted Waveform

Total harmonic distortion is the summation of all harmonic components of current or voltage waveform compared against fundamental component of current or voltage wave.

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots V_n^2}}{V_1} * 100\% \qquad \text{Equation 2.11}$$

The limits on voltage harmonics are thus set at 5% for THD and 3% for any single harmonic. Low values of THD ensures proper operation and a longer life span of equipment.

CHAPTER-3

CLOSED LOOP CONTROL OF 3-PHASE AC-AC ZSC

3.1 REPRESNTATION OF SINGLE PHASE CIRCUIT

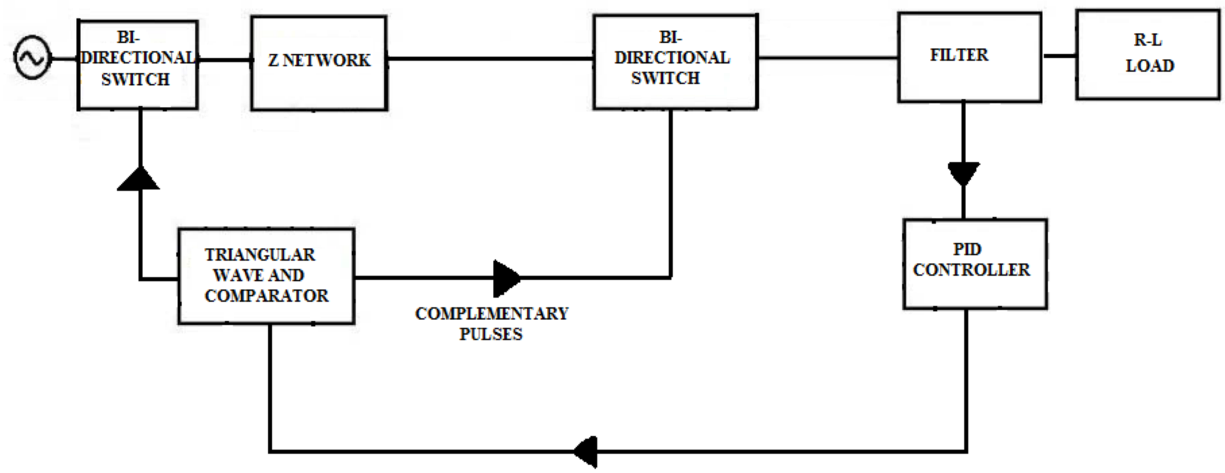

Figure 3.1: Block diagram representation of Single Phase Circuit

The closed loop control is necessary to achieve constant output voltage during voltage sag or swell and for that purpose a PID controller is installed as represented in block diagram above.

3.2 PROPORTIONAL-INTEGRAL-DERIVATIVE (PID) CONTROLLER

A PID Controller is a closed loop feedback mechanism used frequently in industrial control systems. Error value is calculated by this controller as a difference between measured variable and desired set point. Three constant parameters are involved which are denoted as P, I and D.

$K_P =$ Proportional Gain

$K_i =$ Integral Gain

$K_D =$ Derivative Gain

A parallel PID representation is shown below:

$$C = K_P + \frac{K_i}{s} + \frac{K_D s}{T_f s + 1}$$ Equation 3.1

Where T_f is first order derivative filter time constant.

Table 3.1: Effects of increasing a parameter solely

Parameter	Rise Time	Overshoot	Settling Time	Steady-State Error	Stability
K_P	Decrease	Increase	Small Change	Decrease	Degrade
K_i	Decrease	Increase	Increase	Eliminate	Degrade
K_D	Minor Change	Decrease	Decrease	No effect in theory	Improve if K_D small

The PID Controller will be used for designing a closed loop control for three phase ac to ac ZSC. So that any variation in input voltage will be controlled i.e. we can get constant ac output voltage. The behavior of the gains can be understood by the table presented above and can be used for simulating the closed loop.

The closed loop control simulation results are presented in the following chapter.

3.2.1 RISE TIME

Rise time is defined as "the time required for the response to rise from x% to y% of its final value", with 0%-100% rise time common for underdamped second order systems, 5%-95% for critically damped and 10%-90% for overdamped systems.

3.2.2 OVERSHOOT

In control theory, overshoot refers to an output exceeding its final, steady-state value. For a step input, the percentage overshoot (PO) is the maximum value minus the step value divided by the step value.

3.2.3 SETTLING TIME

Tay, Mareels and Moore (1997) defined settling time as "the time required for the response curve to reach and stay within a range of certain percentage (usually 5% or 2%) of the final value.

3.2.4 STEADY-STATE ERROR

Steady-state error is defined as the difference between the input and output of a system in the limit as time goes to infinity (i.e. when the response has reached the steady state). The steady-state error will depend on the type of input (step, ramp, etc) as well as the type of the system.

CHAPTER-4

RESULTS AND DISCUSSIONS

4.1 ANALYSIS OF 3-PHASE ZSC WITHOUT FILTER

Table 4.1: Open Loop readings of 3-phase ZSC without filter by varying duty cycle

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Inductor µH	Capacitor µF	Output voltage (V)	THD %age
300	20	0.25	500	10	314.5,318.2, 318.3	190.91
300	20	0.33	500	10	363.5,365.5, 365.8	171.07
300	20	0.5	500	10	428.8,429, 428.8	107.69
300	20	0.66	500	10	395.2,398, 397.7	104.61

Table 4.2: Open Loop readings of 3-phase ZSC without filter by varying Inductance

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Inductor	Capacitor µF	Output voltage (V)	THD %age
300	20	0.5	500µH	10	428.8,429, 428.8	107.69
300	20	0.5	50µH	10	451.2,450.4, 451.1	118.52
300	20	0.5	5mH	10	423.8,423.9, 423.8	105.50
300	20	0.5	1mH	10	428,428.1, 428	106.89

Table 4.3: Open Loop readings of 3-phase ZSC without filter by varying Capacitance

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Inductor µH	Capacitor	Output voltage (V)	THD %age
300	20	0.5	500µH	10µF	428.8,429, 428.8	107.69
300	20	0.5	500µH	100µF	436.1,436.9, 437	113.10
300	20	0.5	500µH	1mF	509.1,508.5, 509	125.94
300	20	0.5	500µH	10mF	281.9,331.3, 250.4	160.75

Table 4.4: Open Loop readings of 3-phase ZSC without filter by varying Switching Frequency

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Inductor µH	Capacitor mF	Output voltage (V)	THD %age
300	20	0.5	50	2	522.6,526.6, 522.8	145.88
300	18.5	0.5	50	2	523.9,527.2, 523.6	148.37
300	15	0.5	50	2	527.9,528.8, 526.7	150.80
300	25	0.5	50	2	520.3,524.9, 522.7	139.64

After the detailed analysis of 3-phase ZSC without filter, we found out that to stabilize the waveform i.e. to make it sinusoidal, we need to use filter and analyze the behavior using it. The detailed analysis of 3-phase ZSC with filter is also presented in this Chapter.

4.2 ANALYSIS OF 3-PHASE ZSC WITH FILTER

Table 4.5: Open Loop readings of 3-phase ZSC with filter by varying Filter Inductance

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Inductor	Capacitor μF	Output voltage (V)	THD %age
300	20	0.5	1 μH	1	618.5,626.9, 625.3	98.67
300	20	0.5	100 μH	1	654.5,653.1, 650.9	97.45
300	20	0.5	1mH	1	654.7,653.3, 651.1	97.53
300	20	0.5	100mH	1	654.8,653.4, 651.1	97.78

Table 4.6: Open Loop readings of 3-phase ZSC with filter by varying Filter Capacitance

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Inductor mH	Capacitor	Output voltage (V)	THD %age
300	20	0.5	100	1 μF	618.5,626.9, 625.3	97.78
300	20	0.5	100	100 μF	654.5,653.1, 650.9	103.46
300	20	0.5	100	1mF	654.7,653.3, 651.1	104.84

After the analysis of 3 phase ZSC by varying filter inductance and capacitance, we realized that we are able to get the desired sinusoidal output, so we need to analyze the buck boost behavior of the converter by varying its duty cycle which is provided in the next table.

From this simulation analysis we have also obtained some waveforms which are also represented in this Chapter along with the detailed analysis of improved topology of 3 phase ZSC.

Table 4.7: Open Loop readings of 3-phase ZSC with filter by varying Duty cycle

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Inductor mH	Capacitor µF	Output voltage (V)	THD %age
300	20	0.3	55	50	150.1	13.54
300	20	0.38	55	50	212.9	4.90
300	20	0.5	55	50	284.3	0.62
300	20	0.6	55	50	255.4	6.98

Table 4.8: Open Loop readings of 3-phase ZSC with different filter parameters by varying Duty cycle

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Inductor mH	Capacitor µF	Output voltage (V)	THD %age
300	20	0.35	35	100	313.2	5.14
300	20	0.38	35	100	343.8	2.81

Table 4.9: Comparison for buck boost mode using different filter parameters

Input Voltage (V)	Duty Cycle	Filter Parameters	Output Voltage (V)	THD %age
300	0.38	55mH & 50µF	212.9V	4.90
300	0.38	35mH & 100µF	343.8V	2.81

4.3 SIMULATION RESULTS OF THREE PHASE AC TO AC ZSC

The three phase input voltage of root mean square value 300V is shown in Figure 4.1. The peak voltage curve is indicated in the following figure.

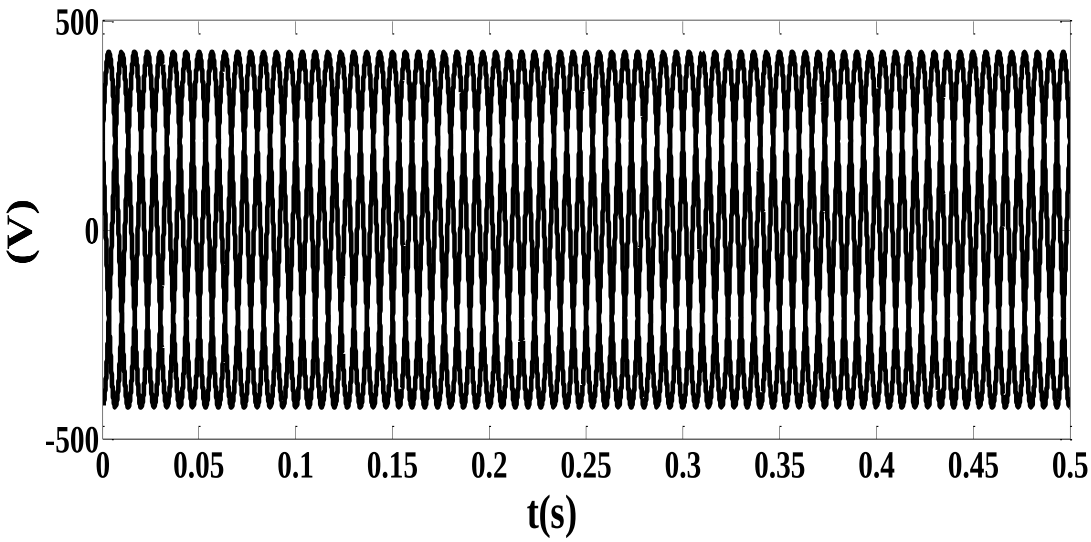

Figure 4.1: Three phase Balanced Input voltage

Figure 4.2 represents the output voltage without using filter with impedance network parameters as 500µH and 10µF with switching ratio 20 kHz and duty cycle at 0.38.

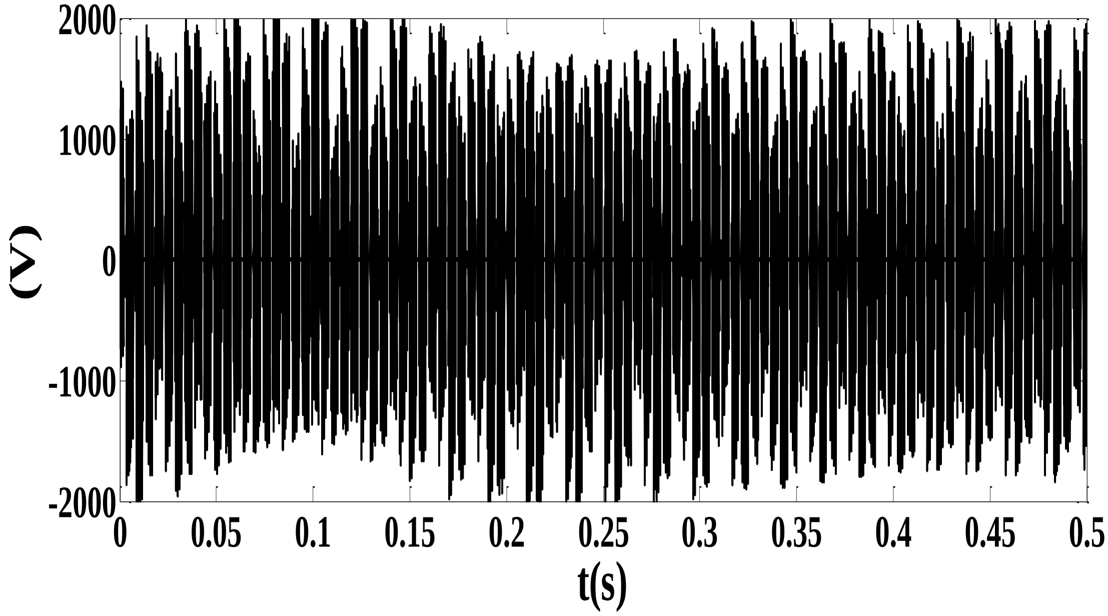

Figure 4.2: Output Voltage waveform without Filter

Figure 4.3 indicates the FFT analysis of the output voltage without filter and we can clearly see that the THD is 193.90% which is undesirable. So there is a need to add filter to the circuit.

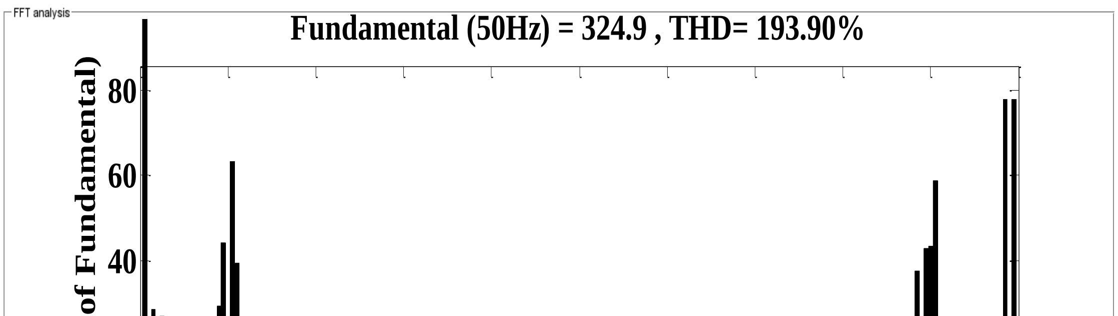

Figure 4.3: Total Harmonic Distortion (THD) Analysis of Output voltage without filter

After adding an LC filter of 55mH & 50μF we can get the desired sinusoidal output voltage in buck mode which is shown in Figure 4.4.

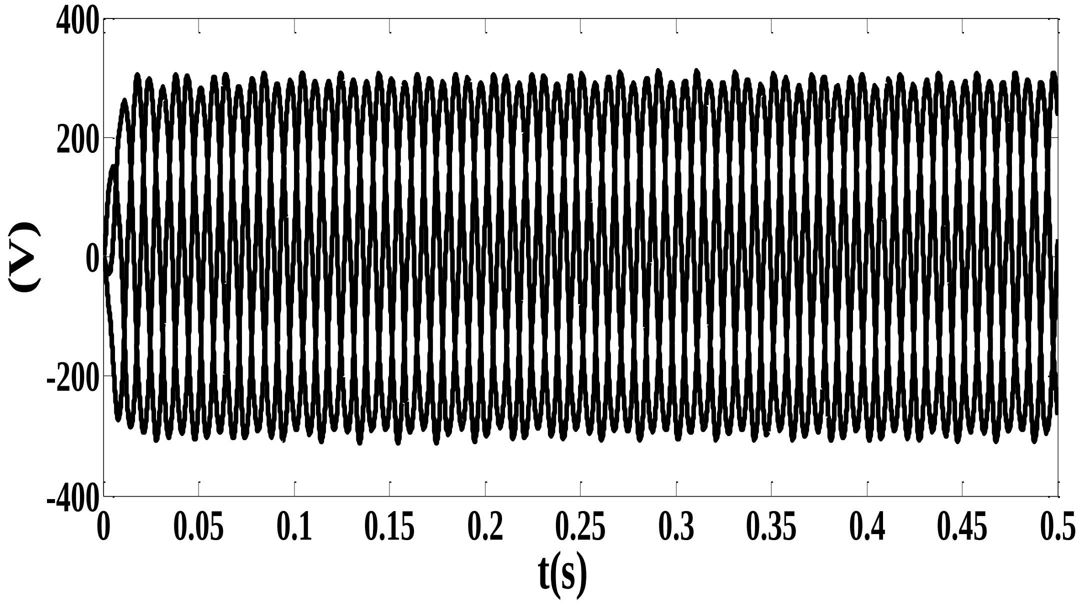

Figure 4.4: Output Voltage with filter in Buck Mode

We can clearly see from Figure 4.5 that the THD content has been reduced after addition of filter and it is less than 5% which can be considered favorable.

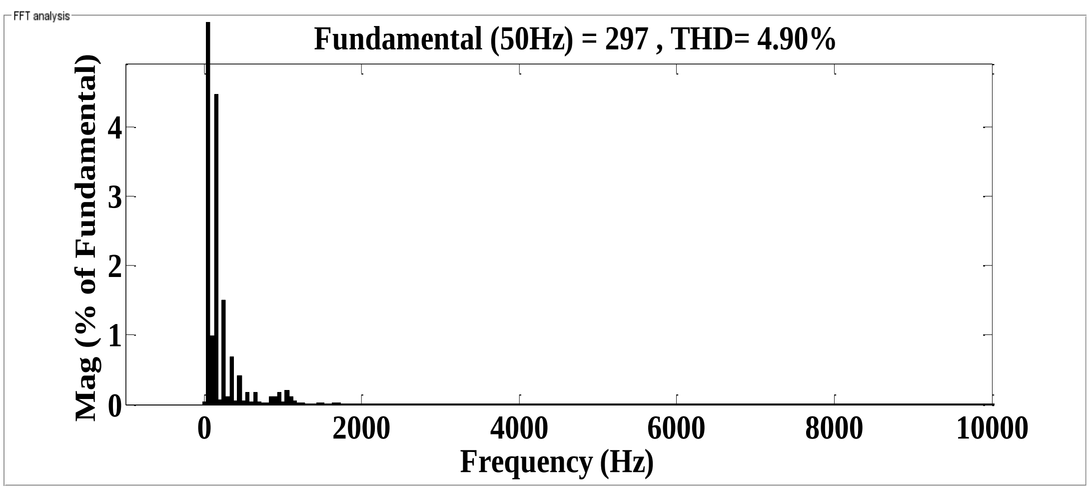

Figure 4.5: THD Analysis of Output Voltage with filter in Buck Mode

The voltage can be made higher by changing the filter parameters from 55mH & 50μF to 35mH & 100μF which is provided in Figure 4.6. The output voltage in this case 343.8 V phase to phase rms which is 15% greater than the input voltage which was 300V rms phase to phase.

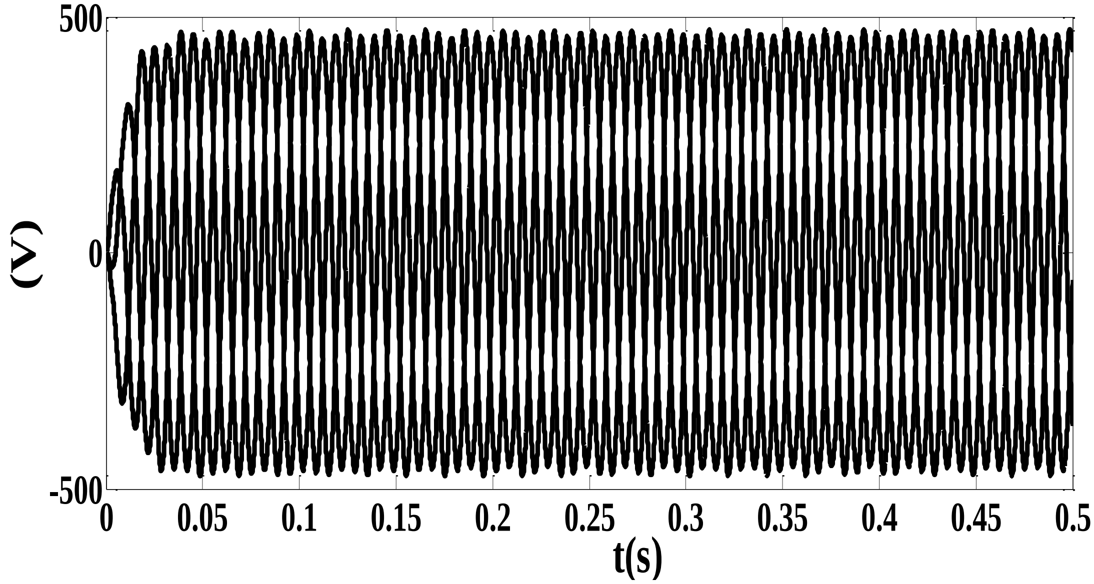

Figure 4.6: Output Voltage with filter in Boost Mode

From FFT analysis presented in Figure 4.7 we can clearly see that the THD is less than 5% which is considerable. So far by the analysis of three phase ac to ac impedance source converter has been done and we have identified a limitation that it has a boost factor of 1.15. So now we implement the improved converter topology to achieve boost factor greater than 1.15.

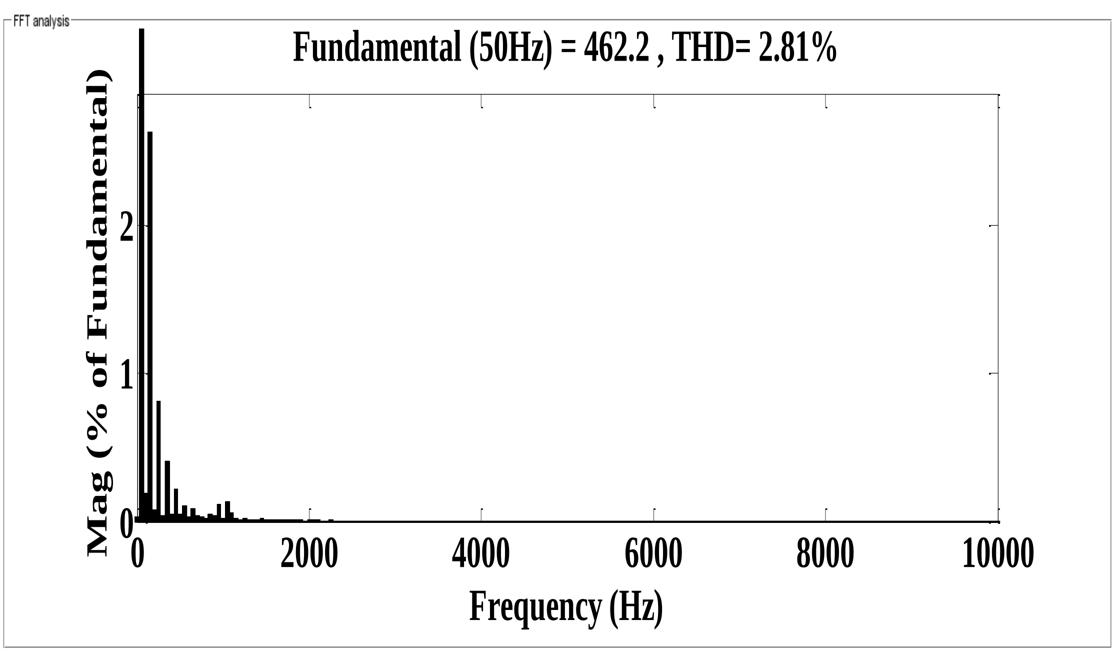

Figure 4.7: THD Analysis of Output Voltage with filter in Boost Mode

4.4 ANALYSIS OF IMPROVED THREE PHASE AC TO AC ZSC WITHOUT FILTER

So far we have analyzed the three phase ac to ac converter by changing different parameters and simulation results were also provided. Now we will analyze the improved topology of three phase ac to ac ZSC. Table 4.10 to Table 4.14 shows the analysis by changing duty cycle, Z-network inductance, impedance network capacitance, injected capacitance and switching frequency respectively.

In this chapter we will analyze the behavior of this improved topology with and without filter and get simulation results for the same.

The injected capacitors have an added advantage in this topology that it can boost voltage to a greater extent during shoot-through state.

Total harmonic distortion (THD) analysis has also been done and shown in tabular data and will also be represented later in the chapter under simulation results section.

Table 4.10: Open Loop readings of Improved 3-phase ZSC without filter by varying duty cycle

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Inductor mH	Capacitor µF	Injected Capacitor µF	Output voltage (V)	THD %age
300	20	0.18	1	10	100	17.56,21.52, 19.34	231.77
300	20	0.24	1	10	100	848.9,522.7, 489.4	175.31
300	20	0.33	1	10	100	74.73,71.06, 80.75	144.42
300	20	0.42	1	10	100	108.3,126.1, 128.9	130.20

Table 4.11: Open Loop readings of Improved 3-phase ZSC without filter by varying Inductance

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Inductor	Capacitor µF	Injected Capacitor µF	Output voltage (V)	THD %age
300	20	0.24	1mH	10	100	848.9,522.7, 489.4	175.31
300	20	0.24	100µH	10	100	496.2,339.1, 277.4	199.35
300	20	0.24	1 µH	10	100	228.2,237.8, 176.3	281
300	20	0.24	20mH	10	100	132.4,128.9, 93.01	170.89

Table 4.12: Open Loop readings of Improved 3-phase ZSC without filter by varying Capacitance

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Inductor mH	Capacitor	Injected Capacitor µF	Output voltage (V)	THD %age
300	20	0.24	1	10µF	100	848.9,522.7, 489.4	175.31
300	20	0.24	1	1mF	100	299.6,308.8, 319.8	174.06
300	20	0.24	1	10mF	100	197,168.5, 164.1	171.20
300	20	0.24	1	500µF	100	350.7,491.2, 728.8	178.29

Table 4.13: Open Loop readings of Improved 3-phase ZSC without filter by varying Injected Capacitance

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Inductor mH	Capacitor µF	Injected Capacitor	Output voltage (V)	THD %age
300	20	0.24	1	10	100 µF	848.9,522.7, 489.4	175.31
300	20	0.24	1	10	1 µF	204.4,203.9, 226	231.28
300	20	0.24	1	10	1mF	49.35,42.89, 50.37	210.26
300	20	0.24	1	10	800 µF	59.6,66.39, 64.84	189.83

Table 4.14: Open Loop readings of Improved 3-phase ZSC without filter by varying Switching Frequency

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Inductor mH	Capacitor µF	Injected Capacitor µF	Output voltage (V)	THD %age
300	20	0.24	1	10	100	848.9,522.7, 489.4	175.31
300	18	0.24	1	10	100	39.97,46.69, 9.158	179.97
300	22	0.24	1	10	100	23.19,25.67, 4.357	190.32
300	23	0.24	1	10	100	37.5,44.36, 11.46	188.08

4.5 ANALYSIS OF IMPROVED THREE PHASE AC TO AC ZSC WITH FILTER

The analysis of improved converter topology by varying different parameters and with the addition of LC filter in circuit has been presented in Table 4.14 to Table 4.19. With the addition of filter in the configuration we are able to achieve desirable results as THD is getting below 5%.

Table 4.15: Open Loop readings of Improved 3-phase ZSC with filter by varying Filter Inductance

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Filter Inductor mH	Filter Capacitor µF	Output voltage (V)	THD %age
300	20	0.24	20	700	450.1	2.3
300	20	0.24	15	700	754.4	0.62
300	20	0.24	10	700	1747	1.08
300	20	0.24	30	700	240.2	2.84

Table 4.16: Open Loop readings of Improved 3-phase ZSC with filter by varying Filter Capacitance

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Filter Inductor mH	Filter Capacitor	Output voltage (V)	THD %age
300	20	0.24	13	700µF	1026	0.56
300	20	0.24	13	850µF	597.4	1.10
300	20	0.38	13	1mF	412.3	2.53
300	20	0.5	13	500µF	2138	1.39

By varying LC filter parameters we analyzed that the output voltage is being sinusoidal. We now have to analyze the behavior of circuit with LC filter at different duty cycle.

Table 4.17: Open Loop readings of Improved 3-phase ZSC with filter by varying Duty Cycle

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Filter Inductor mH	Filter Capacitor μF	Output voltage (V)	THD %age
300	20	0.24	20	700	450.1	2.3
300	20	0.3	20	700	161.9	0.86
300	20	0.38	20	700	134.7	0.71
300	20	0.5	20	700	336.7	0.76

After analysis of improved converter topology with filter at different duty cycle, there is now need to analyze it with different filter parameters and varying duty cycle.

Table 4.18: Open Loop readings of Improved 3-phase ZSC with different filter by varying Duty Cycle

Input Voltage (V)	Switching Frequency (kHz)	Duty Cycle	Filter Inductor mH	Filter Capacitor μF	Output voltage (V)	THD %age
300	20	0.24	13	880	550.9	0.91
300	20	0.3	13	880	373.1	0.41
300	20	0.38	13	880	181	0.8
300	20	0.5	13	880	642.5	0.57

Table 4.19: Buck Boost Mode Analysis of Improved 3-phase ZSC by Different Parameters

Input Voltage (V)	Duty Cycle	Filter Parameters	Output Voltage (V)	THD %age
300	0.24	13mH & 880μF	550.9	0.91
300	0.38	13mH & 880μF	181	0.8

4.6 SIMULATION RESULTS OF IMPROVED THREE PHASE AC TO AC ZSC

Figure 4.8 shows the balanced three phase input voltage which is an rms phase to phase voltage of 300V and the peak voltage is provided in the Figure.

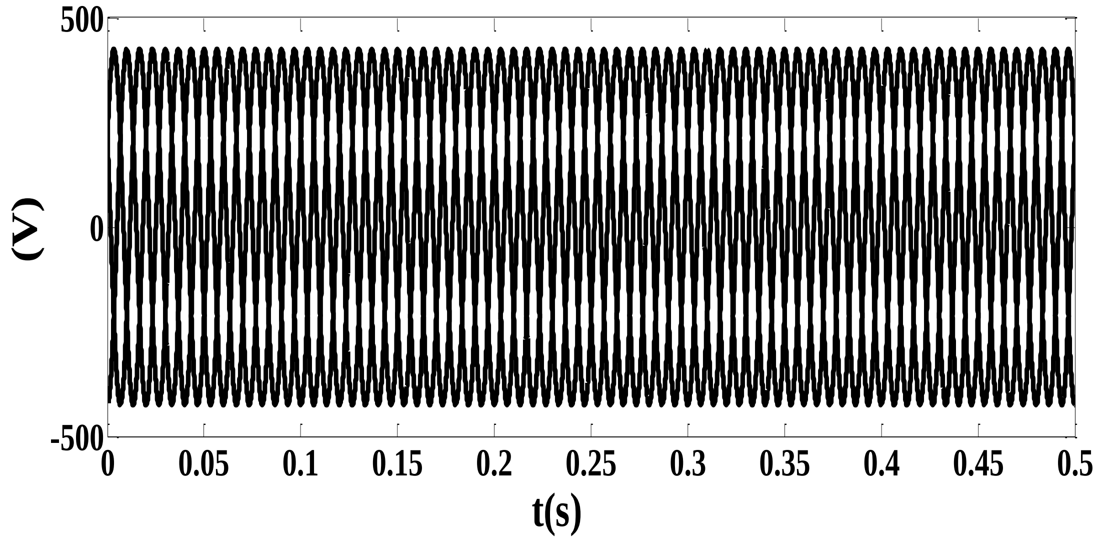

Figure 4.8: Three Phase Balanced Input Voltage

The output voltage without filter is represented in Figure 4.9 and the Z-network parameters were 1mH, 10µF and the injected capacitance of 100µF.

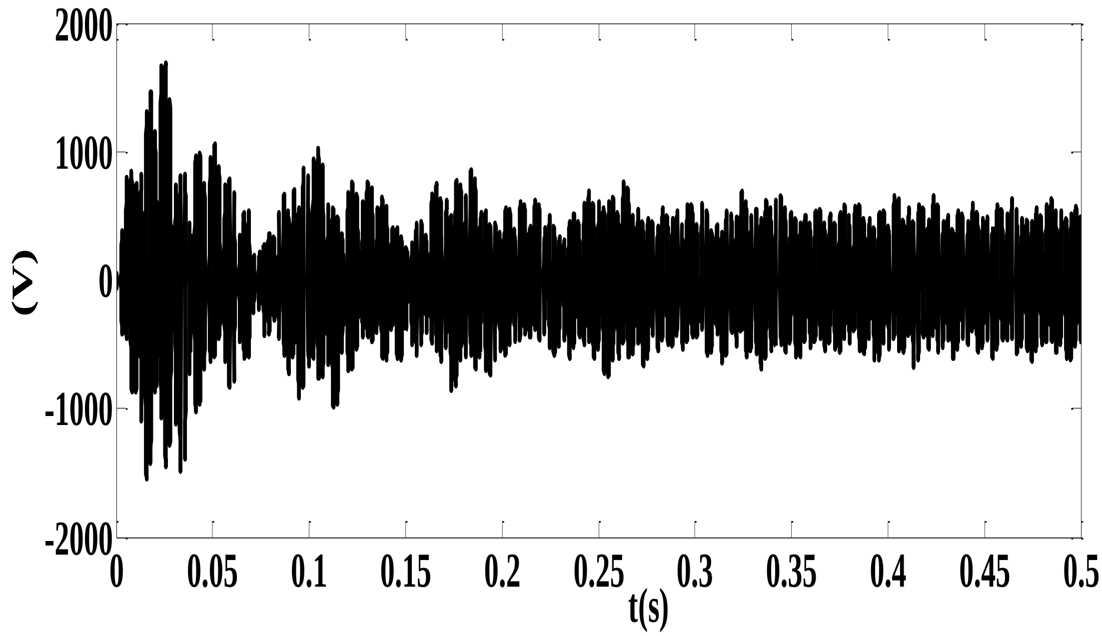

Figure 4.9: Output Voltage without filter

From the FFT analysis presented in Figure 4.10, we can see that the THD is 175.94% which is greater than acceptable 5%. We can clearly feel the requirement of LC filter to achieve a sinusoidal output voltage with THD less than 5%.

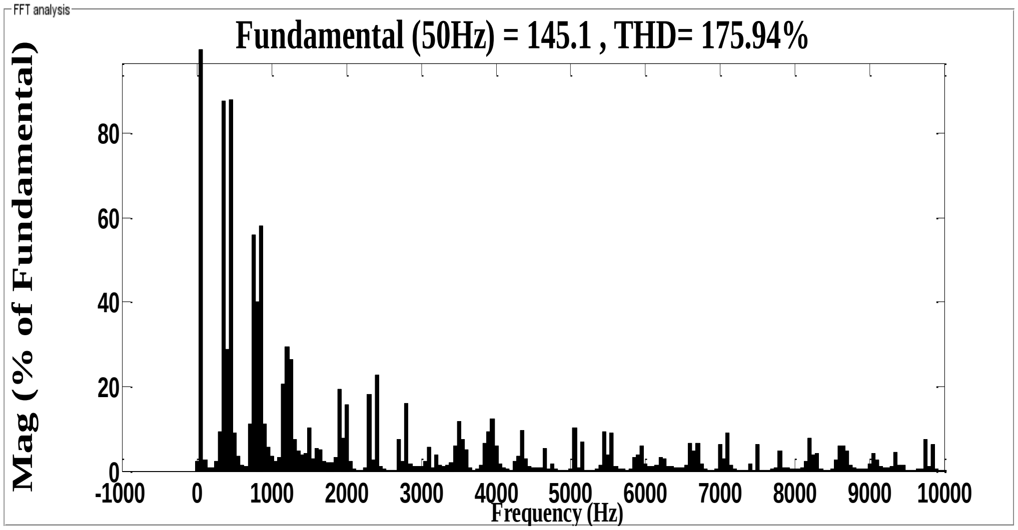

Figure 4.10: THD Analysis of Output Voltage without filter

The output voltage at 0.24 duty cycle with filter parameters 13mH & 880μF is shown in Figure 4.11. The output voltage is 550.9 V phase to phase rms which is nearly more than 80% of the input voltage. I.e. we have achieved a boost factor of more than 1.8 which is desired from this improved converter topology.

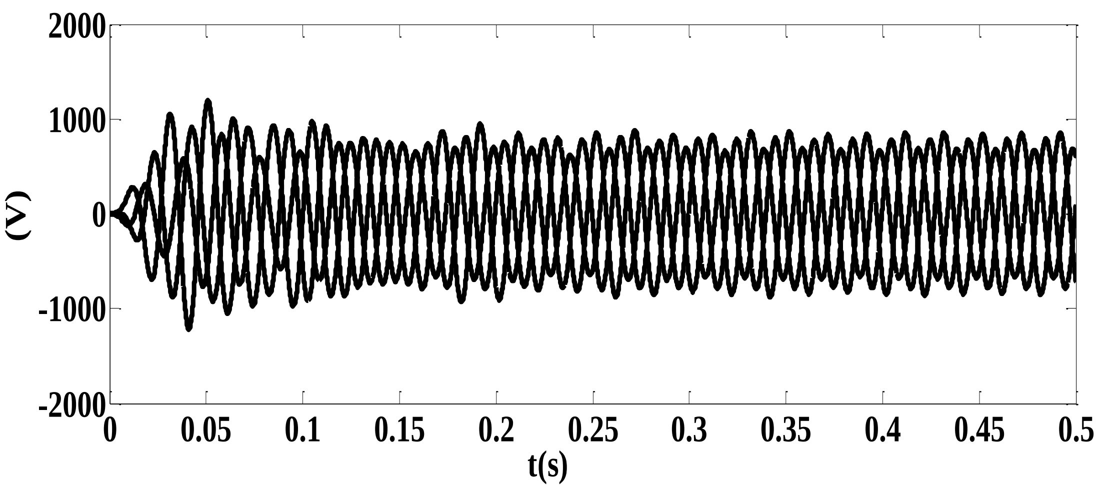

Figure 4.11: Output Voltage with filter in Boost Mode

Figure 4.12 shows the FFT analysis of the output voltage with filter at 0.24 duty cycle and it is clearly seen that we have got THD very less than 5%.

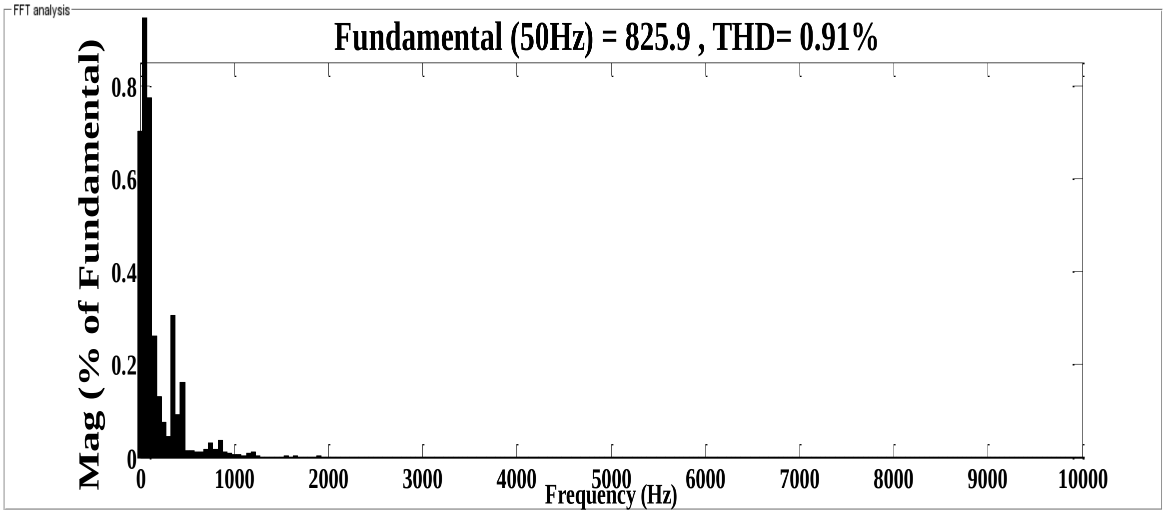

Figure 4.12: THD Analysis of Output Voltage with filter in Boost Mode

With the filter parameters remaining same, duty cycle is varied and at 0.38 duty cycle we got the output voltage as 181V which is very less than the input voltage as indicated in Figure 4.13. So we can say that the converter is now operating in buck mode.

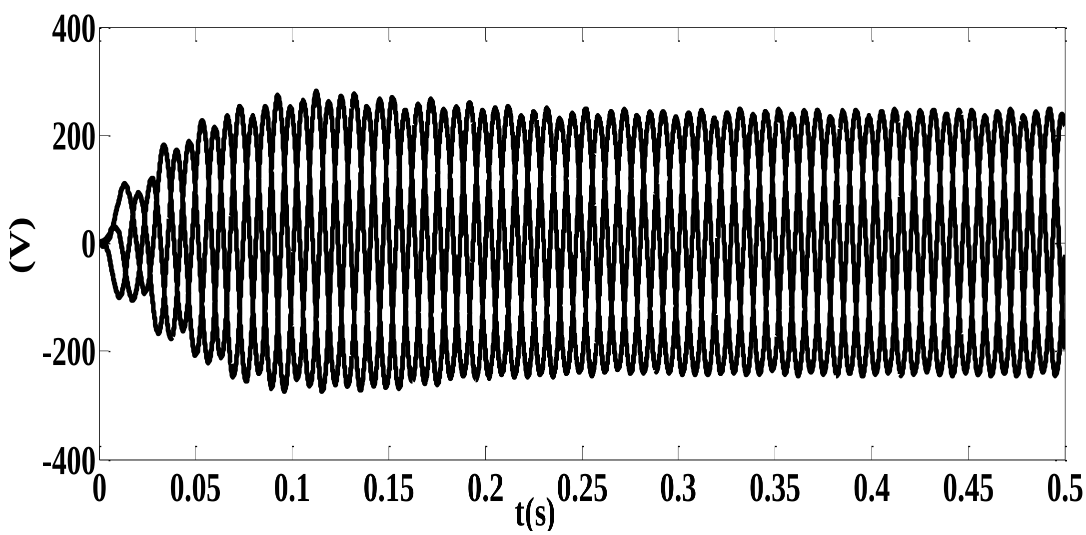

Figure 4.13: Output Voltage with filter in Buck Mode

The FFT analysis of Figure 4.13 clearly states that the THD is very less than 5%. From the simulation analysis we found out that the converter can be operated in buck and boost mode.

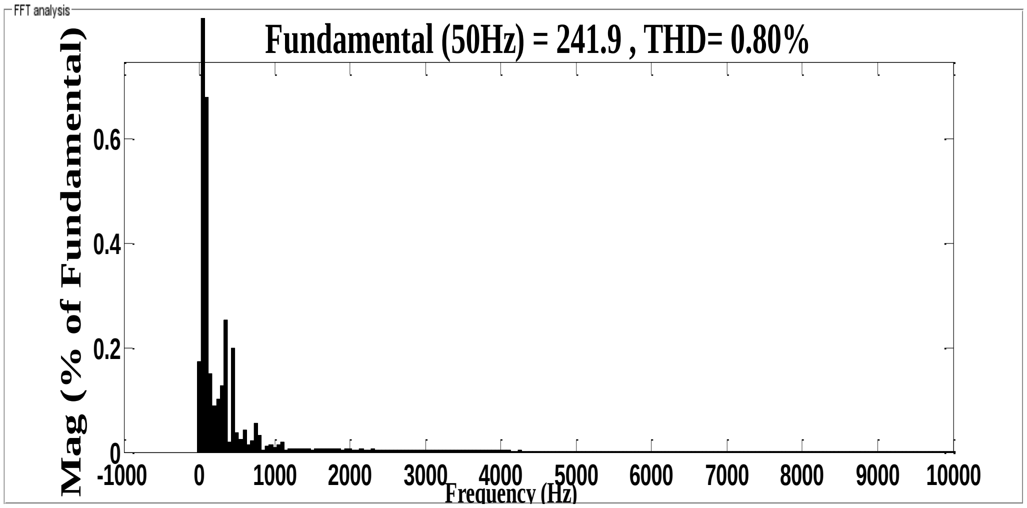

Figure 4.14: THD Analysis of Output Voltage with filter in Buck Mode

4.7 SIMULATION RESULTS OF CLOSED LOOP CONTROL OF 3-PHASE AC-AC ZSC

The closed loop simulation analysis is being shown in Figure 4.15 to 4.17. The three phase balanced input voltage with 10% voltage increase in the interval 1 to 1.5 is presented in Figure 4.15.

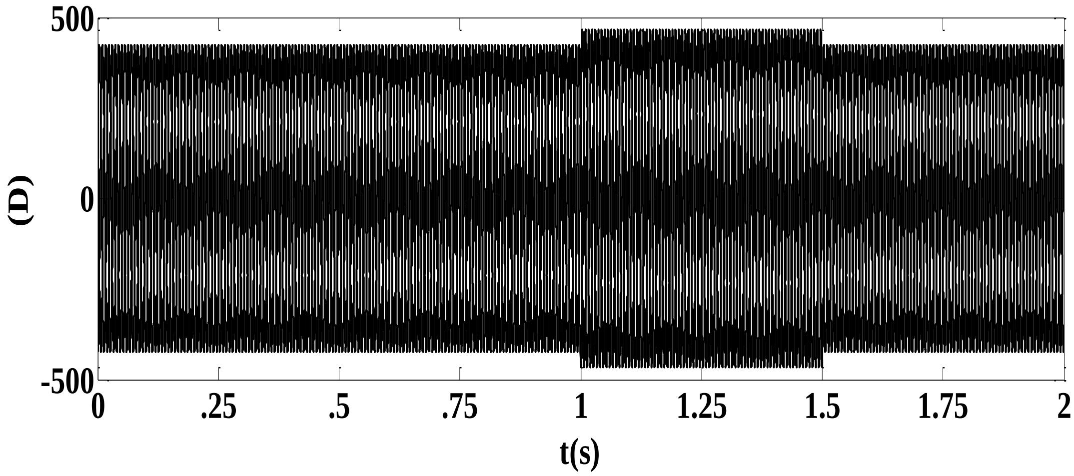

Figure 4.15: Input Voltage with 10% variation

The Z-network parameters are taken as 500µH and 10µF with 20 kHz switching frequency. The duty ratio is controlled with the help of PID controller whose output is shown in Figure 4.16.

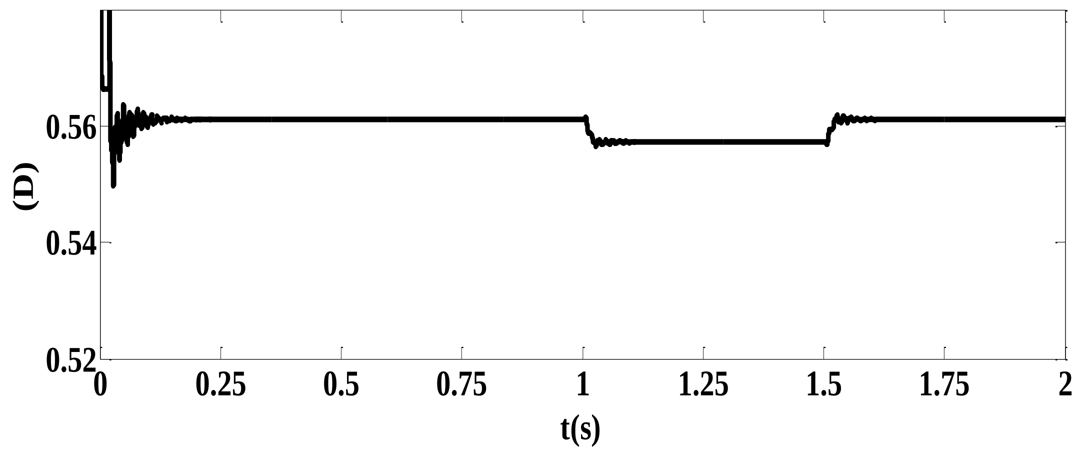

Figure 4.16: PID Output

The output voltage is assumed to be constant after the implementing closed loop control. In our case there is some voltage regulation during input voltage change at 1 to 1.5. Figure 4.17 shows the output voltage of the controller. The PID parameters are K_P = -0.035, K_i = .00001 and K_D = 0.001. The LC filter parameters used are 1.1mF and 400µF.

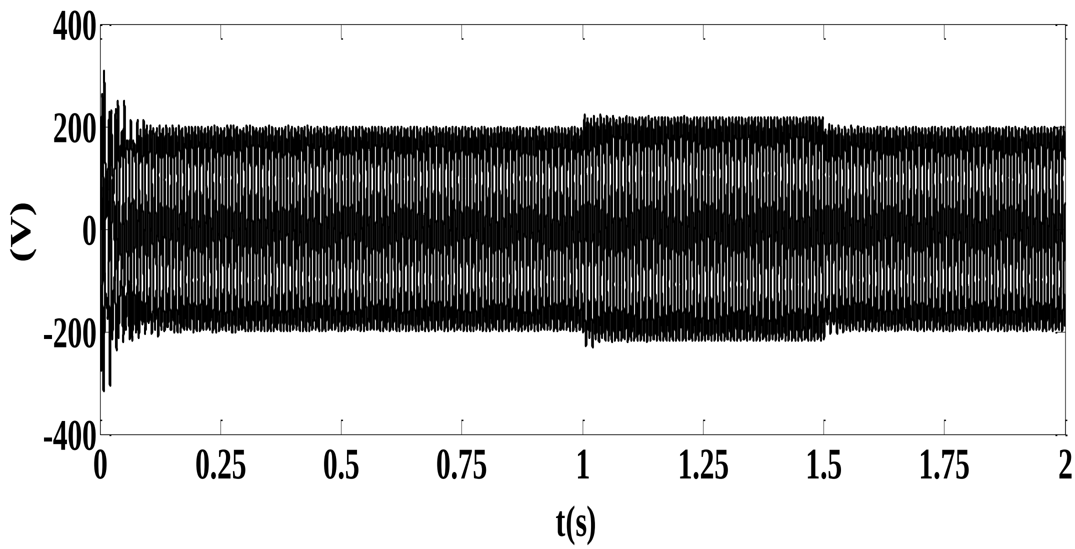

Figure 4.17: Output Voltage in Closed Loop

4.8 DEDUCTION

1. From the above analysis and simulation results we found out that the filter have impact on magnitude of voltage.
2. From the above results, we can easily identify that the latter converter can boost the voltage greater than the former.
3. The closed loop control provides constant output voltage.
4. The output voltage of THD less than 5% is achieved.

CHAPTER-5

CONCLUSIONS AND FUTURE SCOPE

5.1 CONCLUSIONS

This thesis shows the voltage control of a 3-phase ac to ac Z-Source converter. Two different topologies has been compared for the purpose. Following conclusions can be drawn from the work:

1) Three phase ac to ac Z-source converter can be used as a buck-boost converter.
2) Two different topologies of three phase ac to ac converters has been compared and the improved topology overcomes the limitation of former one i.e. it can boost the voltage more than 15% which was limitation of former three phase ac to ac converter topology.
3) Both the converters can protect the equipment from voltage swell and sag but the improved topology has enhanced capabilities.
4) The closed loop controller takes care input voltage variation and load variation.
5) The filter used in the converter has impact on voltage magnitude as analyzed by simulation.
6) The PID output is compared with a triangular wave, any change in PID output changes the pulse width which in turn changes the output voltage.

5.2 FUTURE SCOPE

There are some shortcomings associated with this research work. So there is a scope for improvement.

1) Frequency control can also be achieved for this converter using different topologies or cycloconverter.
2) This converter can also be used in fuel cell systems, motor drive applications, speed control of wind power and many other such applications.

LIST OF PUBLICATIONS

- P. Kumar and S.Sonar "A Three-Phase AC-AC Buck-Boost Converter using Impedance Network," *International Journal Of Electronincs, Electrical and Computational System*, vol. 4, no. March, pp. 348–355, 2015. **(Published)**
- P. Kumar and S.Sonar "A Three-Phase AC-AC Buck-Boost Converter using Impedance Network," *International Conference on Emerging Trends of Engineering, Science, Management and Applications*, March 2015. **(Presented)**

REFERENCES

[1] Muhammad H. Rashid,"Power Electronics Circuits, Devices and Appliocations,"Pearson, 2013.

[2] P.S. Bhimbra,"Power Electronics,"Khanna publishers, 2009.

[3] S. Sudakar and S. Annadurai, “Z – Source Inverter Using Renewable Energy System,” *International Journal of Scientific Engineering and Research*, vol. 2, no. 3, pp. 91–96, 2014.

[4] S. Sonar and T. Maity, “Z-source inverter based control of wind power,” *2011 Int. Conf. Energy, Autom. Signal*, pp. 1–6, Dec. 2011.

[5] P. J. Aswar and P. H. Zope, “Study And Analysis Of Single Phase ZSI,” *Int. J. Res. Advent Technol.*, vol. 1, no. 5, pp. 281–289, 2013.

[6] F. Zhang, X. P. Fang, F. Z. Peng, and Z. Qian, “A New Three-Phase AC-AC Z-source Converter,” *Twenty-First Annu. IEEE Appl. Power Electron. Conf. Expo. 2006. APEC ’06.*, pp. 123–126, 2006.

[7] X. P. Fang, Z. M. Qian, and F. Z. Peng, “Single-Phase Z-Source PWM AC-AC Converters,” *IEEE Power Electron. Lett.*, vol. 3, no. 4, pp. 121–124, Dec. 2005.

[8] F. Z. Peng, “Z-source inverter for motor drives,” *2004 IEEE 35th Annu. Power Electron. Spec. Conf. (IEEE Cat. No.04CH37551)*, pp. 249–254, 2004.

[9] Y. Tang, S. Xie, and C. Zhang, “New structure and topological derivation of Z-source converters,” *2009 4th IEEE Conf. Ind. Electron. Appl.*, pp. 788–793, May 2009.

[10] P. Kumar, “A Three-Phase AC-AC Buck-Boost Converter using Impedance Network,” *International Journal of Electronics, Electrical and Computational System*, vol. 4, no. March, pp. 348–355, 2015.

[11] F. Z. Peng, “Z-Source Inverter,” *IEEE Trans. Ind. Electron.*, vol. 39, no. 2, pp. 504–510, 2003.

[12] F. Z. Peng, L. Chen, and F. Zhang, "Simple Topologies of PWM AC – AC Converters," *IEEE Power Electronics Letters*, vol. 1, no. 1, pp. 10–13, 2003.

[13] K. Holland and F. Z. Peng, "Z-source inverter control for traction drive of fuel cell - battery hybrid vehicles," *Fourtieth IAS Annu. Meet. Conf. Rec. 2005 Ind. Appl. Conf. 2005.*, vol. 3, pp. 1651–1656, 2005.

[14] M. Nguyen and Y. Jung, "Single-Phase AC – AC Converter Based on Quasi Z-source topolgy," *IEEE Transactions on Power Electronics*, vol. 25, no. 8, pp. 2200–2210, 2010.

[15] A. Florescu, O. Stocklosa, M. Teodorescu, C. Radoi, D. A. Stoichescu, and S. Rosu, "THE ADVANTAGES, LIMITATIONS AND DISADVANTAGES OF Z-SOURCE INVERTER COMPARED TO VOLTAGE / CURRENT," no. 1, pp. 483–486.

[16] M. Nguyen, Y. Jung, Y. Lim, J. Oum, and G. Cho, "Three-phase AC-AC Z-source converter (TPZC) with maximum boost voltage ratio," *2009 IEEE 6th Int. Power Electron. Motion Control Conf.*, vol. 3, pp. 1004–1008, May 2009.

[17] S. Sonar and T. Maity, "A Single Phase to Three Phase Buck-Boost Converter cum Voltage Regulator suitable for Wind Power," *Energy and Power*, vol. 2, no. 3, pp. 33–38, May 2012.

[18] P. C. Loh, F. Gao, P.-C. Tan, and F. Blaabjerg, "Three-Level AC–DC–AC Z-Source Converter Using Reduced Passive Component Count," *IEEE Trans. Power Electron.*, vol. 24, no. 7, pp. 1671–1681, Jul. 2009.

[19] G. L. Calzo, a. Lidozzi, L. Solero, and F. Crescimbini, "Three-phase Z-source power supply design," *IET Power Electron.*, vol. 5, no. 8, p. 1270, 2012.

[20] Q. Tran, T. Chun, J. Ahn, and H. Lee, "Algorithms for Controlling Both the DC Boost and AC Output Voltage of Z-Source Inverter," *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2745–2750, Oct. 2007.

[21] D. Kumar and Z. Husain, “A Comparative Study of Z-Source Inverter Fed Three-Phase IM Drive with CSI and VSI fed IM,” *International Journal of Power Electronics and Drive System*, vol. 3, no. 3, pp. 259–270, 2013.

[22] T. B. Soeiro, C. A. Petry, J. C. S. Fagundes and I. Barbi, “Direct AC – AC Converters Using Commercial Power Modules Applied to Voltage Restorers,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 278–288, 2011.

[23] G. M. Asher, “Doubly fed induction generator uising back-to-back PWM converters and its application to variable- speed wind-energy generation,” 1996.

[24] M. Nguyen, Y. Lim, and Y. Kim, “A Modified Single-Phase Quasi-Z-Source AC – AC Converter,” *IEEE Trans. Power Electron.*, vol. 27, no. 1, pp. 201–210, 2012.

[25] B. Y. Husodo, S. Ayob, and M. Anwari, “Simulation of Modified Simple Boost Control for Z -Source Inverter,” *International Journal of Automation and Power Engineering*, vol. 2, no. 4, pp. 57–64, 2013.

[26] Y. Tang, C. Zhang, and S. Xie, “Single-Phase Four Switches Z-Source AC-AC Converter,” *APEC 07 - Twenty-Second Annu. IEEE Appl. Power Electron. Conf. Expo.*, pp. 621–625, Feb. 2007.

[27] S. Sonar, T. Maity, and M. Minu, “Single phase transformerless wide range ac boost voltage regulator based on z-source network,” *Int. J. Electr. Power Energy Syst.*, vol. 47, pp. 193–197, May 2013.

[28] W. X. Shen, “Single-Phase Uninterruptible Power Supply Based on Z-Source Inverter,” *IEEE Trans. Ind. Electron.*, vol. 55, no. 8, pp. 2997–3004, Aug. 2008.

[29] F. B. Effah, P. Wheeler, J. Clare, and A. Watson, “Space-Vector-Modulated Three-Level Inverters With a Single Z-Source Network,” *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 2806–2815, 2013.

[30] Y. Tang, S. Xie, and C. Zhang, "Z-Source AC – AC Converters Solving commutation problem," *IEEE Trans. Power Electron.*, vol. 22, no. 6, pp. 2146–2154, 2007.

APPENDIX-A

PARAMETERS FOR OPEN LOOP SYSTEM

DUTY CYCLE	**SWITCHING FREQUENCY**	**Z-NETWORK INDUCTANCE L**	**Z-NETWORK CAPACITANCE C**	**FITER (L)**	**FILTER C**
0.38	20 kHz	500 μH	10 μF	55mH	50 μF
0.38	20 kHz	500 μH	10 μF	35mH	100 μF

CURRICULUM-VITAE

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Career Objective:

To impart quality education with emphasis on Electrical Engineering and to rectify related problems in minds of concerned one's, which they can apply in their professional life.

Technical Qualification:

- Pursuing M.E. in Power Systems (2013-15) with current CGPA 8.46 from Thapar University, Patiala, Punjab.
- B.Tech in Electrical Engineering (2008-12) with 71.9% from Ch. Devilal Memorial Govt. Engineering College, Sirsa, Haryana.

Academic Experience

- 7 months experience as Lecturer in DITMR College, Faridabad (NCR).

Key Responsibilities Handled

- Conducting lectures and preparing the material for undergraduate students.
- Collaborate with colleagues to address teaching issues.
- Preparing teaching material and utilizing it for the progress of students.
- Utilizing the skills and qualities by assigning work to the students.
- Managing the class of students in absence of the college professor as well as motivating students for having desired effects.

Internships

1. NTPC

- Duration : Six Weeks(05/07/2010 to 14/08/2010)

Trainee Profile

1. Work on LT and HT motors
2. LT and HT switchgears
3. Switchyard

2. Sofcon India Pvt. Ltd.

- Duration : 3 months

Trainee Profile

1. Work on different type of PLCs.
2. Programming of PLCs
3. Work on Variable frequency Drives
4. SCADA

Thesis Topic

- Three phase AC to AC Z-source Converter.

Academic project

- AUTOMATIC STAR DELTA STARTER
- VARIABLE FREQUENCY DRIVE

Area of Specialization

- Power Electronics and Drives

Publications

- Punit Kumar, Santosh Sonar, A Three-Phase AC-AC Buck-Boost Converter using Impedance Network, International Journal of Electronics, Electrical and Computational System IJEECS ISSN 2348-117X Volume 4, Special Issue March 2015.

Academic Credentials

- XIIth passed with 72% from C.B.S.E. Delhi in 2008.
- Xth passed with 74% from C.B.S.E. Delhi in 2006

Computer Skill

- MS office
- Internet

Key skills

- MATLAB
- Simulink

Achievement

- GATE 2013 qualified.

Personal Information:

Father's Name	:	Mr. Vijay Kumar
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Marital Status	:	Unmarried
Nationality	:	Indian
Language Known	:	English & Hindi

Declaration

I hereby declare that the above information given by me is true to the best of my knowledge and belief.