SAFE-COMMUTATION AC-AC CONVERTER BASED ON Z-SOURCE STRUCTURE:ANALYSIS AND SIMULATION

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY

By
ABDULSALAM ASHUOR MOHAMMED ALMABROUK

In Partial Fulfilment of the Requirements for the Degree of Master of Science in Electrical and Electronic Engineering

NICOSIA, 2019

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Approval of Director of Graduate School of Applied Sciences

Prof. Dr. Nadire CAVUS

We certify this thesis is satisfactory for the award of the degree of Master of Science in Electrical and Electronic Engineering

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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Date:

ACKNOWLEDGEMENTS

I would like to express my deep and sincere gratitude to my research supervisor, Prof. Dr. Ebrahim Babaei, Near East University, Northern Cyprus, for giving me the opportunity to conduct this research by providing invaluable guidance throughout the process. His dynamism, vision, sincerity and motivation have deeply inspired me. He has taught me the methodology to carry out the research and to present the research works as clearly as possible. It was a great privilege and honor to work and study under his guidance. I am extremely grateful for what he has offered. I would also like to thank him for his friendship, empathy, and great sense of humor.

I would also like to take the time to thank my friends and family for their immense contribution, suggestions and moral support. I would also like to thank my examination committee for taking their time to review my thesis.

I am extremely grateful to my parents for their love, prayers, caring and sacrifices while educating and preparing me for my future. Also, I will like to express my thanks to my brothers and sister, for their support and valuable prayers.

To my parents…

ABSTRACT

Impedance based converters have provided the needed solutions to the drawbacks of current and voltage source converters. Advancement in these areas have yielded the development of several topologies. In this paper, a single-phase impedance-based topology called gamma ZS converter is introduced to resolve the limitation of the preceding topology; Trans ZS converter. The desired gain in the proposed gamma topology is achieved by utilizing a coupled transformer. Variations of the gain is achieved by changing the turn's ratio of the transformer within a limited range. Reduction of the turns ratio produces higher gain at the converter output; a major advantage when compared to other winding based topologies. Achieving higher output gain with limited turns ratio reduces the cost and structure of the used transformer. Also, the gamma-based converter shares common ground between the input and also exhibit buck-boost functionality.

***Keywords*:** Impedance network; Z-source converter; Trans ZS converter; Gamma Z-source converter; Voltage gain

ÖZET

Empedansa dayalı dönüştürücüler, akım ve voltaj kaynağı dönüştürücülerin kusurlarında ihtiyaç duyulan çözümleri sağlamıştır. Bu alanlardaki ilerleme, çeşitli topolojilerin gelişiminde kazanç sağlamıştır. Bu çalışmada, önceki topoloji olan Trans Zs dönüştürücünün sınırlandırılmasını gidermek için, gamma ZS adlı tek fazlı empedansa dayalı dönüştürücü tanıtılmıştır. Önerilen gama topolojisinde istenen kazanç, birleştirilmiş bir transformatör kullanılarak elde edilmektedir. Transformatörün dönüş oranının sınırlı bir aralık içinde değiştirilmesiyle, kazancın varyasyonları elde edilmektedir. Dönüş oranının azaltılması dönüştürücü üretiminde daha yüksek kazanç sağlar ve bu diğer sarım temelli topolojilere kıyasla büyük bir avantajdır. Sınırlı dönüş oranıyla daha yüksek üretim/çıktı kazancı elde etmek, kullanılmış/elden düşme transformatörün maliyetini ve yapısını düşürür. Ayrıca, gamaya dayalı dönüştürücü, girdi arasında ortak zemin paylaşır ve hızlı artırma işlevselliği sergiler.

***Anahtar Kelimeler*:** Empedans ağı; Türkçe çeviri; Trans ZS dönüştürücü; Gama Zırh dönüştürücü; Gerilim kazancı

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LIST OF ABBREVIATIONS

AC:	Alternating Current
CSI:	Current Source Inverter
CCM:	Impedance Source Inverter
DC:	Direct Current
DCM:	Impedance Source Inverter
EMI:	Electromagnetic Interference
***Γ*ZSC:**	Gamma Impedance Source Converter
PSCAD:	Power System Computer Aided Design
VSI:	Voltage Source Inverter
ZSI:	Impedance Source Inverter

CHAPTER 1

INTRODUCTION

1.1 Overview

Power electronic converters have evolved to a much better device over the last two decades; contributing immensely to the generation and transmission of electric power devoid of power quality vices such as voltage dip, short and long disturbances or interruptions, voltage swell, noise, harmonic distortion, unbalance voltages, voltage spike and fluctuations, etc. The term ***converter*** is used to describe a power electronic device or circuit which is capable of conditioning voltage or current from one level to another (step-up or step-down) or from one type to another (ac to dc or vice versa) or perform both functions. The use of power electronic converters in today's world can be seen from various sectors of human life such as communication, transport (land, sea and air), agriculture, health, industrial or factories etc.

Specific power conditioning requires the right converter to produce the desired power having the necessary voltage and current waveforms. Voltage source inverters and current source inverters use to be the most widely used and researched inverters, however, a number of drawbacks hindered their perfect applications, the major drawback of these types of inverters is step-down of buck only functionality which simply means that the output voltage of the inverter is much less than the input voltage corresponding greater losses in the system. Although there are other disadvantages, the above disadvantage alone requires the inclusion of a boost converter which increases the cost of the system and also increases the overall systems power losses.

To overcome the buck-only functionality of voltage and current source inverters, Z source or impedance based inverter was introduced. Basically the impedance source inverter provides buck-boost functionality, the relative simple topology of ZSI means that the structure can be added previous inverter topologies without any difficulties. From the simple ZSI topology introduced in 2003 which composed of symmetrical passive components; two capacitors and two inductors connected in a Z structural from between the voltage source and the main inverter circuit, several other topologies have been developed which seeks to improve the performance of the preceding topology. Impedance based converters have become the toast of researchers over the past few years because of its enormous advantages and simple topology; buck-boost functionality, higher voltage gains, reduced losses when compared to VSI or CSI topologies, different topologies for different applications.

Previous impedance based inverters were mostly used for dc to ac power conversion but recent advancement in ZS research has produced ac to ac converters with higher voltage gains when compared to existing topologies such as matrix converter, indirect and direct ac to ac converters. In the case of the matrix converter, the output voltage is limited i.e. not more than 86.33% of the input voltage, both indirect and direct converters have power line adulteration due to the presence of diode rectifiers and also the size of the capacitor (storage device) increases the cost and size of the topology hence limited application areas. The structure of matrix converters is complex due to application of bidirectional switches and also multiplex commutation circuits are required. Conventional impedance based single phase ac to ac converters have several merits such as higher voltage boost functionality during buck-boost operations, the capability to maintain or produce opposite phase angles. One major drawback of the ac to ac impedance based converter is the different grounds for both the input and the output parts of the topology. This drawbacks makes it impossible to maintain the same phase angle feature between the input voltage and the output voltage.

1.2 Thesis Problem

Voltage source inverters and current source inverters have the major disadvantage of producing output voltage which is less than the input the input voltage unless a boost converter is incorporated into the topology. The development of Z source inverter overcame the VSI and CSI limitations. Matrix converters also have the drawback of buck-only functionality and complex commutation and structures. Direct and indirect ac to ac converters also possess the disadvantage of power line adulteration due to the presence of diode rectifiers. Conventional impedance based ac to ac converters are unable to provide phase angle voltage balance for both input and output voltages due to uncommon grounds between the output and input parts of the system. All the above mentioned topologies (except Z source topology) are unable to independently provide higher output voltages which is greater than the input or source voltage.

1.3 The aim of the Thesis

The aim of my research (thesis) to simulate a single phase impedance based ac to ac converter in PSCAD environs with capabilities of solving the limitations listed above. The proposed converter will be able to provide higher voltage gains compared to the input and other topologies such as the matrix converter. Also this topology will be able to function in both buck and boost operations as desired by consumer without introducing extra converter hence reducing the size and overall cost of the system. The disadvantages of the conventional impedance based ac to ac converters which is the inability to provide phase angle voltage balance for both input and output voltages due to uncommon grounds between the output and input parts of the system will be solved by the proposed topology.

1.4 The Importance of the Thesis

World power/energy consumption is gradually shifting from fossil fuel to renewable energy source and efficient application of energy. Power electronic converters are pivotal devices in harnessing renewable energy and efficient application of renewable energy. The ability to maximise power conversion or generation will lead to reduced power cost hence improve living standards especially in developing nations. In industrial applications, providing quality power devoid of power quality drawbacks has a direct correlation to improved production, reduced maintain cost and time, reduced cost of produced goods and overall increased system efficiency.

Specifically in the case of our proposed topology, buck-boost functionality will be possible, higher boost functionality will be provided, drawbacks of conventional ac to ac impedance inverter will be eliminated.

1.5 Limitation of the Thesis

First and foremost, I would to say that all necessary procedures useful in conducting research were adhered to during the period of conducting this research. In conducting the theoretical research aspect of my thesis, topmost concern was given to plagiarism, every used material is dully referenced or properly cited. The major limitation encountered which is also shared by most of my colleges is a well-equipped laboratory which will aid us in performing practical investigation of our simulated topology.

1.6 Overview of the Thesis

The body of the thesis is segmented into the following categories:

Chapter 1: Introduction, Thesis Problem, Aim of the Thesis, The importance of the Thesis, Overview of the Thesis

Chapter 2: Literature Review of ZSI

Chapter 3: Simulation Results of Proposed topology

Chapter 4: Conclusion and Future Works

CHAPTER 2

IMPEDANCE SOURCE CONVERTER LITERATURE REVIEW

2.1 Introduction

The word converter is used in power electronics to explain devices or circuits which perform the following power conversion functions; ac - ac, ac - dc, dc - ac and dc - dc. The technical name given to the above stated power conversions are Cycloconverters, rectifiers, inverters and choppers respectively. However it should be noted that ac to ac power conversion are also referred to as choppers but with the specific name ac choppers. Impedance or Z source converters are special hybrid converter topologies where the Z source structure is coupled to any existing converter topology to improve its performance.

2.2 Conventional Converter Topologies

The most common and widely used conventional converter topologies are categorized into two groups; voltage input/source inverter/converter (VSC) and current input/source inverter/converter (CSC). These converter topologies are similar in structure but differ in the type of source or input (voltage or current) and performance parameters. The structure of a 3-phase VS converter is represented by Fig2.1 in which the circuit is composed of dc voltage source connected in parallel with a capacitor and six bidirectional and unidirectional switches from current and voltage point of view respectively.

Although VS converter has wide industrial applications, it’s still bedevilled with a number of drawbacks which causes increased cost of operation, reduced efficiency and limited application areas. Some of the disadvantages (Siwakoti, Peng, Blaabjerg, Loh, & Town, 2015) of VS converter are:

a. Buck-only operation when the converter is utilized as an inverter and boost-only converter when it’s applied as rectifier.
b. Lack shoot-through capabilities
c. Susceptible to noise generated by EMIs

d. For a perfect sinusoidal output waveforms, inductor-capacitor filter is required at the output.
e. Increased cost due to the application of boosting converter when higher voltage than the source is required.
f. Efficiency is reduced because of the boosting converter introduced into the topology. A buck-boost converter is required to perform stepup or stepdown functions.

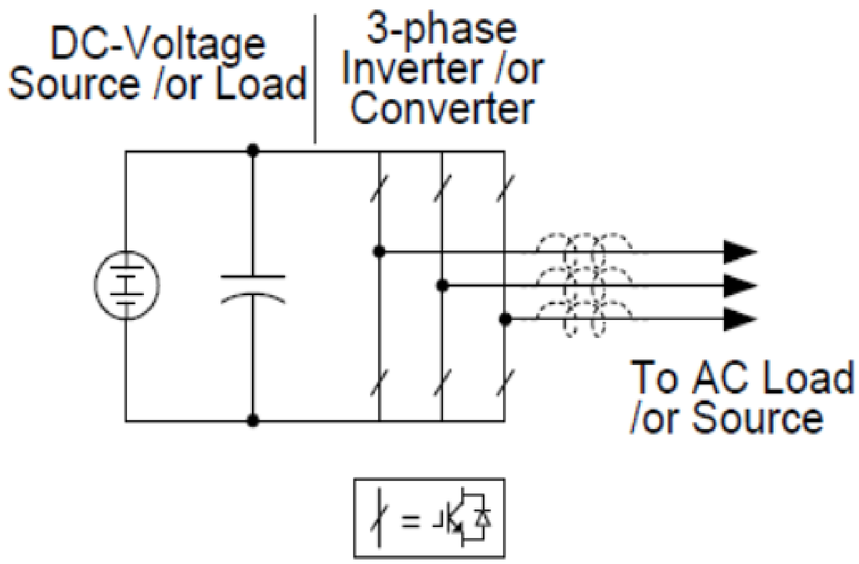


Figure 2.1: Three phase VS converter (Siwakoti et al., 2015)

The second conventional converter is known as the current source converter (CS converter). As stated above, the two conventional topologies; VS and CS are similar with the only difference being the type of source; whether voltage or current source. The structure of CS converter is shown in Fig.2.2 A series connection of input/source and a large inductor then attached to the main 3 phase inverter bridge to achieve CSC. The switches used in the CS topology is different from VS converter switches. Series connection of a diode with the type of switch to be applied in the circuit (IGBT, MOSFET, and Thyristor) is required to block reverse voltage.

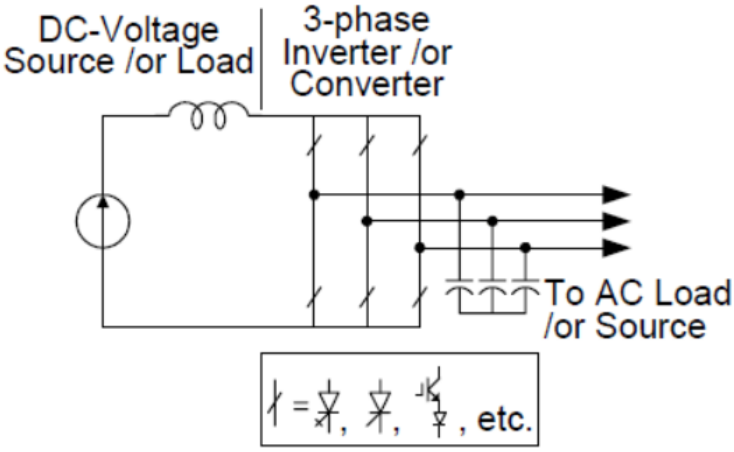


Figure 2.2: Three phase CS converter (Siwakoti et al., 2015)

The main drawbacks (Siwakoti et al., 2015) of the CS converter are:

a. When CS converter is utilized as a rectifier, the output voltage is less when compared to the input voltage.
b. When CS converter is applied as an inverter, the output voltage at maximum whiles the input/source voltage is at minimum.
c. An open circuit will lead to destruction of the switches
d. Lack of shoot-through property and susceptible to EMI noises.

When compared together, VS and CS converters have the following problems which are recurrent in both converters:

a. They are not reliable when analysing from EMI noise point of view.
b. Lack of step up-down functional.
c. Differences in converter switch topologies.

2.3 Impedance Source Converter.

Impedance or Z source based converter was introduced to resolve the limitations of VS and CS converters. This new converter topology is popularly known as ***Z source converter*** (ZS Converter) or inverter with its structure shown in Fig. 2.3. Impedance source converter circuit is composed of four passive components; two capacitors and inductors respectively. In other to derive the ZS converter topology, ZS structure is place between the inverter bridge and the input/source. Due to the numerous ZS topologies that has been developed over the years, the topology in Fig. 2.3 is now referred to as the conventional ZS converter. The circuit connection of the impedance structure is an X shaped connection of four energy storage components; C_a, C_b, L_a and L_b. One major advantage of ZS converter from the input point of view is the ability to accept ac or dc voltage to perform the following power conditioning; ac - ac, ac - dc, dc - ac and dc - dc. As shown in Fig.2.4 and Fig. 2.5, the type of switch can be the famous antiparallel amalgamation of a diode and any of the following IGBT, MOSFET, and Thyristor or the series combination of a diode and any of the following IGBT, MOSFET, and Thyristor. The proposed ZS converter in (Siwakoti et al., 2015) was applied in a fuel cell based circuit. From analysis made, the produced ac output voltage ranges from a minimum value of zero and maximum value of infinity. The distinctive characteristics of the ZS converter makes function in buck-boost mode hence able to provide variable output voltage both as rectifier circuit and inverter circuit.

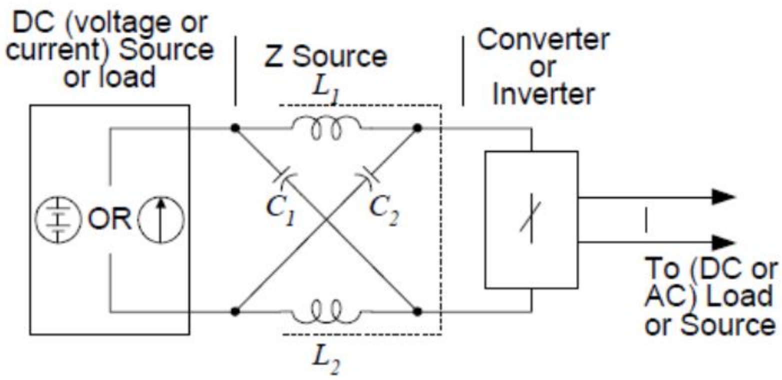


Figure 2.3: ZS converter (Siwakoti et al., 2015)

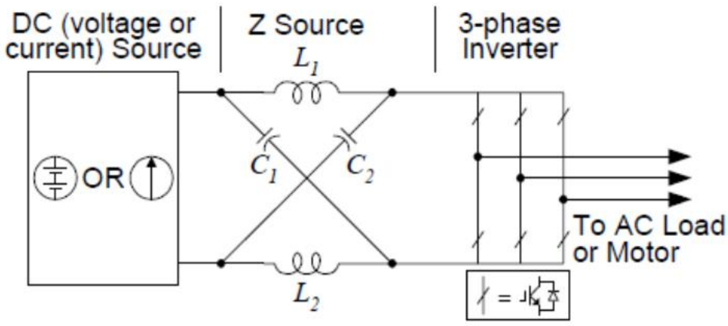


Figure 2.4: ZS converter (Siwakoti et al., 2015)

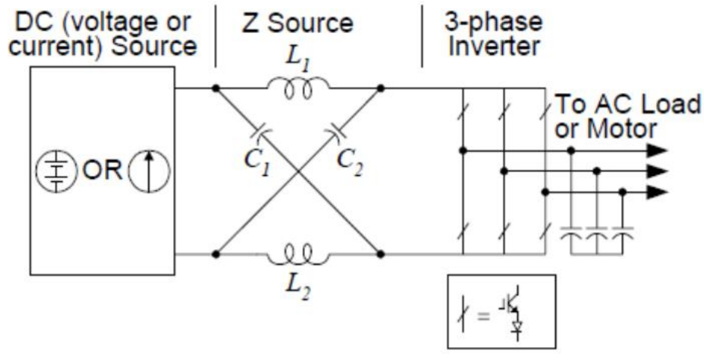


Figure 2.5: ZS converter (Siwakoti et al., 2015)

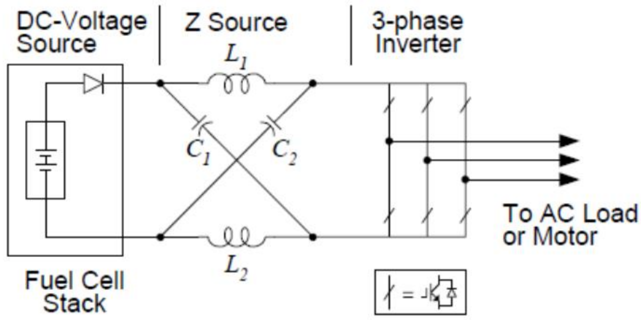


Figure 2.6: Fuel cell based ZS converter (Siwakoti et al., 2015)

Using Fig. 2.6 as the circuit to explain the operations mode of the ZS converter, the circuit is a three phase VS based ZS converter. The series connection of source input and diode is to protect the source voltage (fuel cell) since recharging of the source is not permissible. The same topology is applied in PV based ZS converters.

The control mechanism of the converter represented in Fig. 2.6 is similar to the control methods of VS converters and an additional method is added to make suitable for safe operation of the ZS converter. This added method is known as the shoot-through mode which allows short circuiting of the inverter switches without causing any harm to the converter. Basically ZS converter is analysed in two modes or sates, the first being shoot-through mode and non-shoot-through mode. The shoot-through in ZS converter is derived by switching on of all switches or any set of switch on the same phase or leg in the inverter bridge. The shoot-through mode is not possible in both VS and CS converters; this lead to the destruction of converter components. The buck-boost functionality of ZS converter is basically due to the shoot-through capabilities in the ZS converter. In analysing the two modes of operation of the ZS converter, the following figures will be utilized.

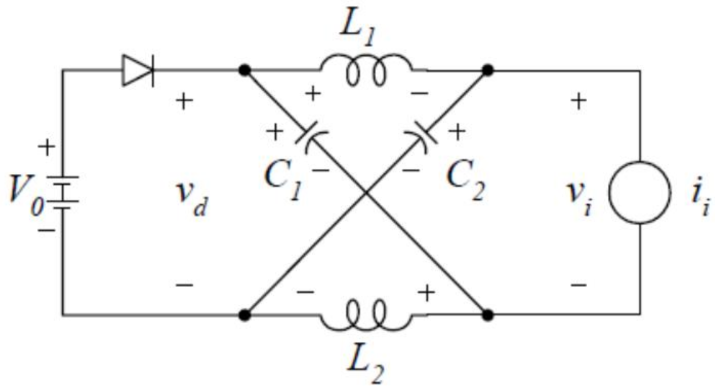


Figure 2.7: ZS converter equivalent circuit(Siwakoti et al., 2015)

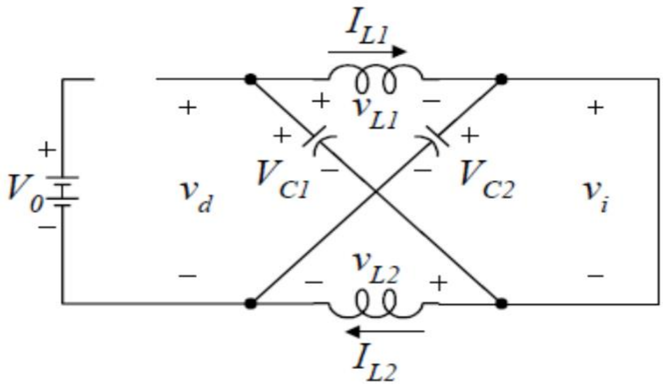


Figure 2.8: Shoot-through mode of ZS converter(Siwakoti et al., 2015)

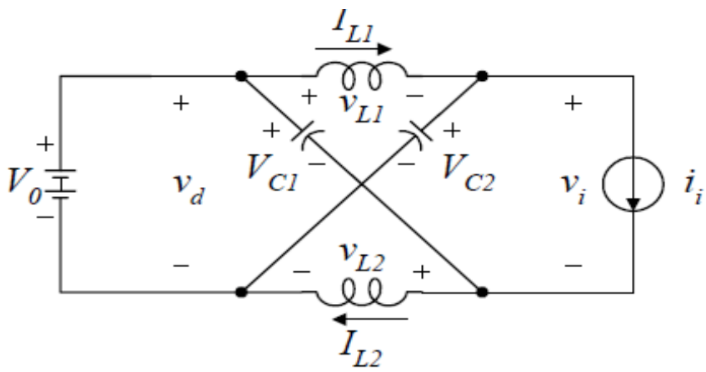


Figure 2.9: Non-shoot through mode of ZS converter(Siwakoti et al., 2015)

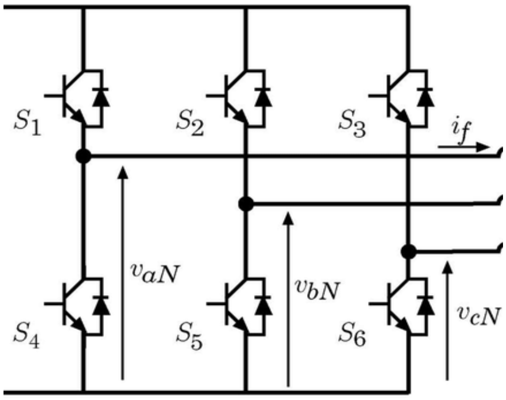


Figure 2.10: Inverter bridge(Siwakoti et al., 2015)

The equivalent circuit of ZS converter of Fig. 2.6 seen from the dc voltage point is shown in Fig. 2.7. The impedance structure voltage output which is also the input voltage of the inverter bridge is represented by v_i which also serves as the source voltage of the 3 phase converter bridge. Fig. 2.8 shows the shoot-through circuit and this is achieved by turning on all switches or any of the following switch combination of Fig. 2.10; S_1 and S_4, S_2 and S_5, S_3 and S_6. Fig. 2.10 shows the inverter bridge circuit in ZS converter with appropriate switch representation and labelling. Once shoot-through mode is achieved, the diode in Fig. 2.8 is reverse biased hence the source or input is cut-off. The non-shoot-through mode is represented by Fig. 2.9 and represents any of the six control schemes of the three phase inverter. The diode is forward biased in this mode hence the source or input is connected conducts voltage to the impedance structure. To efficiently control the ZS converter, any of the following conventional PWM techniques can applied:

a. Sinusoidal PWM
b. Unified PWM

Circuit analysis of the two modes of operation; shoot-through mode and non-shoot-through modes is done to show the mathematical equations for the two modes. The first step in analysing the circuits is to provide symmetric conditions for the passive components. Symmetric conditions simply means that the magnitude of the passive components are same ie the voltage of the capacitors are equal and the inductor voltages are also same.

$$\begin{cases} V_C = V_{C1} = V_{C2} \\ V_L = V_{L1} = V_{L2} \end{cases} \tag{2.1}$$

In the shoot-through mode (Fig. 2.8), the inductor voltage and capacitor voltage are equal, the impedance input voltage (v_d) devoid of the dc source voltage V_0 is two times the capacitor voltage and short-circuit of the inverter renders v_i to be zero.

$$\begin{cases} V_C = V_L \\ v_d = 2V_C \\ v_i = 0 \end{cases} \tag{2.2}$$

In the non-shoot-through mode (Fig. 2.9), the source voltage and the impedance input voltage are equally because the diode is forward biased hence it supplies voltage to the impedance structure. Inductor voltage is the variation of the source voltage and the voltage due to the capacitor component whiles the impedance voltage output (v_i) is the variation of the voltages across the two energy storage components; capacitor and inductor.

$$\begin{cases} V_L = V_0 - V_C \\ v_d = V_0 \end{cases} \tag{2.3}$$

$$\begin{cases} v_i = V_C - V_L \\ v_i = 2V_C - V_0 \end{cases} \tag{2.4}$$

All this occurs in the time period of T1. This time period is derived when one switching period is segmented into two parts, ie

$$T_0 + T_1 = T \tag{2.5}$$

Hence the gain ratio is derived by:

$$V_L = \frac{(T_0 V_C + T_1 [V_0 - V_C])}{T} = 0 \tag{2.6}$$

Ratio of capacitor voltage to source voltage is given by:

$$V_C / V_0 = T_1 \left[\frac{1}{T_1 - T_0} \right] \tag{2.7}$$

The impedance structure output voltage is given by:

$$\begin{cases} v_i = [T_0 + T_1(2V_C - V_0)] \frac{1}{T} \\ v_i = T_1 \left[\frac{1}{T_1 - T_0} \right] = V_C \end{cases} \tag{2.8}$$

The maximum impedance structure output voltage is given by:

$$\begin{cases} v_{i_m} = V_C - V_L \\ v_{i_m} = 2V_C - V_0 \\ v_{i_m} = T_1\left[\frac{1}{T_1 - T_0}\right]V_0 = BV_0 \end{cases} \tag{2.9}$$

The boost factor B is given by:

$$\begin{cases} B = T_1\left[\frac{1}{T_1 - T_0}\right] \\ B = \left[\frac{1}{1-2\frac{T_0}{T}}\right] \geq 1 \end{cases} \tag{2.10}$$

The maximum ac voltage output of the three phase converter is represented by (2.11), where M is the modulation index.

$$\begin{cases} v_{ac} = \frac{1}{2}v_{i_m}M \\ v_{ac} = \frac{1}{2}V_0BM \end{cases} \tag{2.11}$$

By selecting the requisite factor commonly associated to buck-boost state, the inverter output voltage can be varied from zero to infinity. ZS converter was introduced to resolve the limitations associated with the conventional VS and CS converter topologies. Several other ZS converter topologies have been introduced to overcome limitations of ZS converter; basically to improve the conventional ZS topology. Examples of improved ZS converter topologies are categorized according to the following headings (just to mention a few):

a. Quasi topology
b. Bidirectional topology
c. Switched Topology
d. Tapped topology
e. Cascaded topology
f. Transformer topology
g. Y-source impedance
h. Magnetically coupled topology

2.3.1 Quasi ZS Topology

The quasi ZS topology is the first improvement of the conventional ZS converter. Even though it’s an improvement of the latter topology, not much changes occurs in the component count only the circuit formation. Two major converter topologies exist for the quasi ZS converter when analysed from the perspective of the current flow at the input; basically they ***continuous*** current input (CCI) and ***discontinuous*** current input (DCI). The various quasi converter topologies from the current flow perspective and type of input source are shown below.

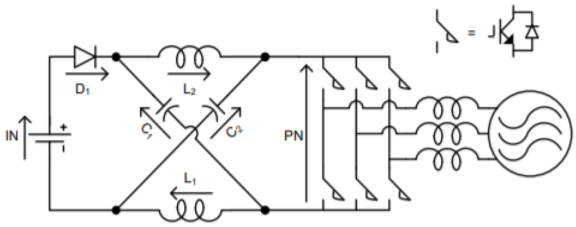


Figure 2.11: DCI VS ZS converter(F. Z. Peng, 2004)

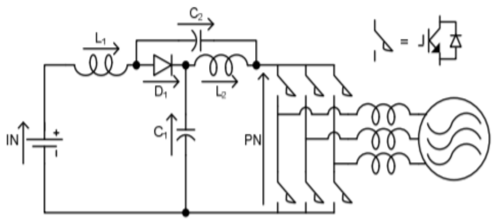


Figure 2.12: CCI VS ZS converter(F. Z. Peng, 2004)

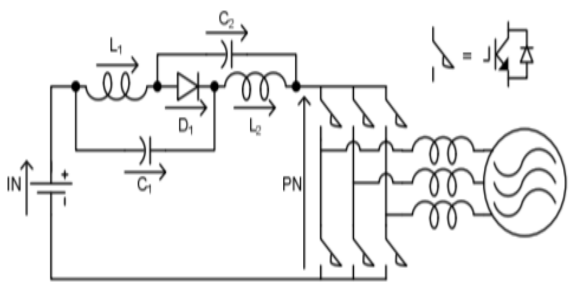


Figure 2.13: DCI VS QZS converter(F. Z. Peng, 2004)

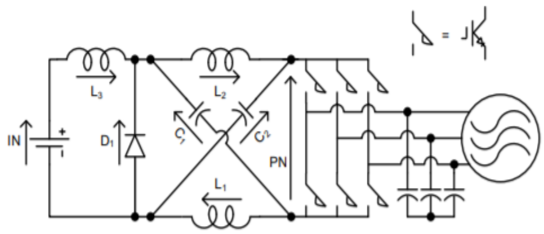


Figure 2.14: CCI CS ZS converter(F. Z. Peng, 2004)

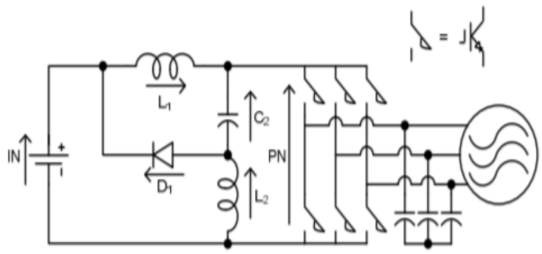


Figure 2.15: DCI VS QZS converter(F. Z. Peng, 2004)

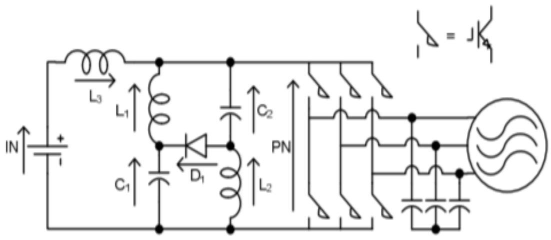


Figure 2.16: CCI CS QZS converter(F. Z. Peng, 2004)

One major advantage of the quasi ZS converter topology is the minimum magnitude of the stress on the capacitor and inductors in both continuous and discontinuous input current topologies which is caused by the voltage. Also the inverter and the source or input share the same ground; an important feature in converters. The control methods applied in the quasi ZS and conventional ZS topologies are the same, some commonly used control techniques are found in (Peng, 2003)(F. Z. Peng, 2004)("Zsource inverter for adjustable speed drives"," 2003)(Miaosen Shen, Jin Wang, Alan Joseph, Fang Z. Peng, Leon M. Tolbert, and Donald J. Adams, 2004)(F.Z. Peng, M. Shen, 2004)(M. Shen, 2005), the component count is a little less in the quasi ZS converter. Two different set of converters are presented in Fig. 2.11 to Fig. 2.16, voltage and current input converter and continuous and discontinuous current source converters. In other to achieve discontinuous state, the magnitude of the inductors when compared to other system component is very small (M. Shen, 2005), to explain this mode in broader perspective, discontinuous state is controlled as the active state of the conventional three phase VS converter but controlling the converter in discontinuous state is complex; one leg/phase has a current value larger than the total currents due to the inductors or are equal (J. Anderson, 2008). The quasi ZS converter supplied by a current input is also operated in two states or modes, shoot-through and non-shoot-through. The non-shoot-through mode which is also referred to as active mode is the same control technique which is applied to conventional VS or CS converter; the switching mechanism is done by turning on only one switch in either the upper or lower levels of the converter switching structure. To achieve shoot-through mode, all switches belonging to either the upper levels or lowers are turned-off. Analysis of the quasi ZS which is supplied by a voltage source is done and complete system or components equations are given in (J. Anderson, 2008), also complete mathematical analysis of the circuits in Fig. 2.11 to Fig.2.16 are given. Simulation together with experimental results are investigated based on Fig. 2.17 in (J. Anderson, 2008). Fig. 2.17 is a VS quasi ZS inverter and Fig. 2.18 is the back-back based quasi ZS converter.

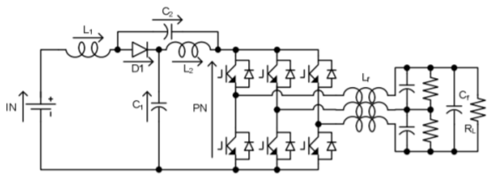


Figure 2.17: Continuous CI VS quasi ZS(M. Shen, 2005)

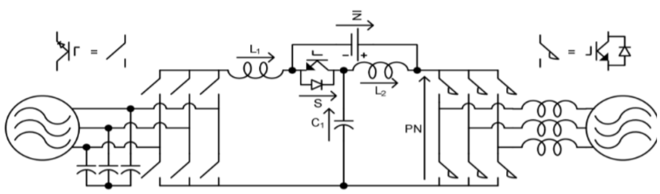


Figure 2.18: Back-back quasi ZS converter(M. Shen, 2005)

2.3.2 Quasi ZS Topologies

In (Engineering & Circuit, 2009), a quasi ZS inverter is applied in generation of power by photovoltaic methodology. The use of ZS converter in photovoltaic systems is a beneficial combination due to the advantages of high voltage gain associated with ZS converter topologies. What this means is that, efficient application of solar resources is achieved by utilizing minimum resources to provide the desired power and also cost of production is reduced because single stage power conversion is archived with ZS converter.

In (Engineering & Circuit, 2009), voltage input based quasi ZS inverter is investigated in PV power generation. The circuit structure of VS ZS and quasi VS ZS topologies are shown in Fig. 2.19 and Fig. 2.20 respectively. To achieve voltage input quasi ZS converter from the conventional VS ZS converter, the position of the impedance components are rearrange as shown in Fig. 2.20. The two inductors are connected in series sandwich by the diode, one capacitor is connected in parallel with one inductor and diode; constituting the output of the impedance network. The second capacitor shares the same ground with the source and inverter circuit.

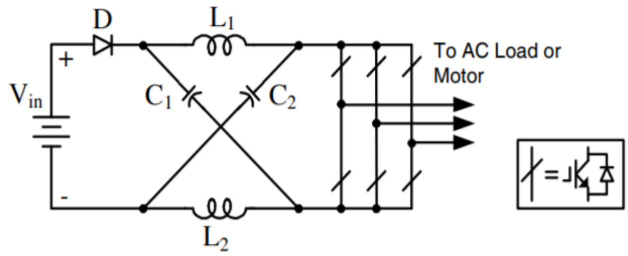


Figure 2.19: VS ZS inverter(M. Shen, 2005)

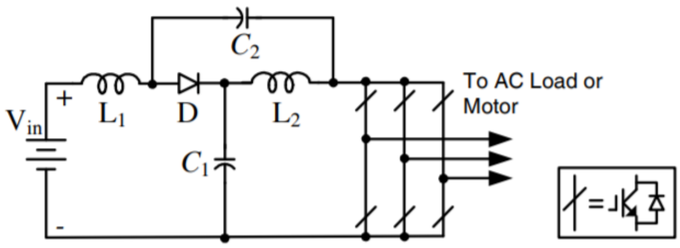


Figure 2.20: VS quasi ZS inverter(M. Shen, 2005)

The quasi ZS converter is investigated in two states; shoot-through mode which is the mode where all switches in the circuit or on a particular phase are turned-on. In this state, the energy storage components in the impedance structure are allowed to fully charge and no current flows to the load, also this mode is possible in ZS converter due to the presence of the impedance structure, this is one major limitation of the conventional CS or VS converter, the impedance network serves as a protective shield in this mode, shielding other circuit components from damage caused by short-circuit, also ZS converter are able to withstand the effects of EMIs (J. Anderson, 2008). The second is similar to the method used in controlling any VS converter and most used techniques are the PWM methods; this mode is the non-shoot through mode. Because of the inductor L_1, the quasi VS ZS converter can thought off as a CS converter. Circuits showing the two modes of operation of the quasi ZS converter is represented by Fig.2. 21 and Fig. 2.22. It should be noted that the VS quasi ZS inverter has a continuous current supply at the input and the magnitude of voltage on the second capacitor is less.

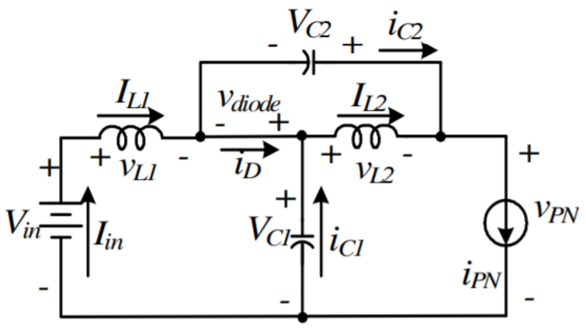


Figure 2.21: Non-shoot through phase of VS q ZS converter(M. Shen, 2005)

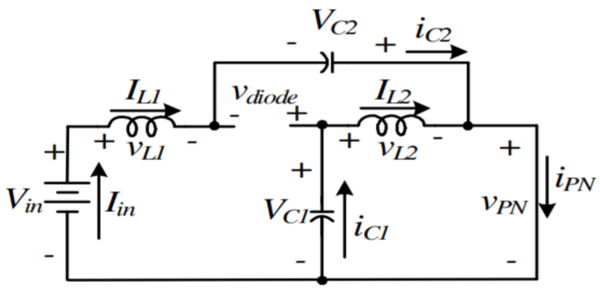


Figure 2.22: Shoot through phase of VS q ZS converter(M. Shen, 2005)

Mathematical analysis of the two modes of operation of the converter will yield the following equations. Let the following represent the component values shown in Fig. 2.21 and Fig. 2.22. V_{LA} is the first inductor voltage, V_{LB} is the second inductor voltage. V_{CA} is the first capacitors voltage and the second capacitor voltage is given by V_{CB}. The period of switching for both shoot through and non-shoot-through is given $T = T_a + T_b$ where T_a represent the shoot through mode and T_b represent the non-shoot-through mode. In the shoot through mode, the switching period is T_b and hence:

$$\begin{cases} T_A = T_0 \\ T_B = T_1 \\ V_{S1} = V_{IN} \end{cases} \tag{2.12}$$

$$\begin{cases} V_{LA} = V_{L1} \\ V_{LB} = V_{L2} \\ V_{S2} = V_{PN} \end{cases} \tag{2.13}$$

$$\begin{cases} V_{CA} = V_{C1} \\ V_{CB} = V_{C2} \end{cases} \tag{2.14}$$

$$\begin{cases} V_{LA} = V_{S1} - V_{CA} \\ V_{LB} = -V_{CB} \\ V_{S2} = V_{CA} - V_{L2} \\ V_{S2} = V_{CA} + V_{CB} \\ V_d = 0 \end{cases} \tag{2.15}$$

The non-shoot-through period is represented by Tb which yields the following equations:

$$\begin{cases} V_{LA} = V_{CB} + V_{S1} \\ V_{LB} = V_{CA} \end{cases} \tag{2.16}$$

$$\begin{cases} V_{S2} = 0 \\ V_d = V_{CA} + V_{CB} \end{cases} \tag{2.17}$$

After the transient state, the steady state period occurs and the following equations are developed for average values:

$$\begin{cases} V_{LA} = \frac{[T_a(V_{CA}+V_{S2})+T_b(V_{S2}-V_{CA})]}{T} \\ V_{LB} = \frac{[T_a V_{CA}+T_b(V_{S2}-V_{CB})]}{T} = 0 \end{cases} \tag{2.18}$$

$$\begin{cases} V_{CA} = \frac{T_b}{T_b-T_a} \\ V_{CB} = \frac{T_a}{T_a-T_b} \end{cases} \tag{2.19}$$

The maximum impedance network output voltage is given by (2.20) where B is the boost factor:

$$\begin{cases} V_{S2_{max}} = V_{CA} + V_{CB} \\ V_{S2_{max}} \frac{1}{1-2\frac{T_a}{T}} V_{s1} \\ V_{s2_{max}} = V_{S1} B \end{cases} \tag{2.20}$$

The converter can be operated such that a buck mode is derived or a boost mode is or a combination of the two modes; buck-boost mode is derived. In the buck or step-down mode the maximum voltage output of the VS quasi ZS converter is given by (2.21) where M is the modulation index.

$$V_{S3} = \frac{1}{2} V_{S1} M \tag{2.21}$$

Similarly in the step-up mode or boost mode, the maximum voltage output of the VS quasi ZS converter is given by (2.22) where M is the modulation index and B is the boost factor.

$$V_{S3} = \frac{1}{2} V_{S1} MB \tag{2.22}$$

Application of quasi ZS converter in photovoltaic systems has seen drastic increase due to its ability to withstand wide range of output voltage from the solar cells. A list of publications where various quasi based ZS converter topologies have been applied in photovoltaic systems is shown in (Z. J. Zhou, Zhang, Xu, & Shen, 2008)(Al, 2013)(Abu-Rub et al., 2013)(Farhangi, 2006)(Sun et al., 2012)(Y. Xue, B. Ge, 2012)(Y. Liu, B. Ge, H. Abu-Rub, 2014b)(Y. Zhou, Liu, & Li, 2013)(Y. Liu, B. Ge, H. Abu-Rub, 2014a). For example in (Liu, Y., Ge, B., Abu-Rub, H., 2015), quasi ZS converter is used to probe the effects of current ripple in the circuit and also analyse the effects of voltage with low frequency on the system. Analysis of the circuit in (Liu, Y., Ge, B., Abu-Rub, H., 2015) is just as that of any quasi ZS based converter. In (W. Liang, Y. Liu, B. Ge, H. Abu-Rub, R. S. Balog, n.d.), a quasi ZS converter with energy storage capabilities is used to probe the effects of harmonics due to low frequency on the converter and system as whole. The circuit of the proposed converter of (W. Liang, Y. Liu, B. Ge, H. Abu-Rub, R. S. Balog, n.d.) is represented by Fig. 22. Analysis of the circuit in the two modes of operations; shoot and non-shoot through modes are represented by Fig. 23 and Fig. 24 respectively.

The main difference between the conventional quasi ZS converter and the one proposed in (W. Liang, Y. Liu, B. Ge, H. Abu-Rub, R. S. Balog, n.d.) is that there's a capacitor between the source and the impedance block, also energy storage component is connected across the second capacitor. Due to fluctuations in energy output from the PV, a capacitor is desire to supply consistent voltage to the impedance structure.

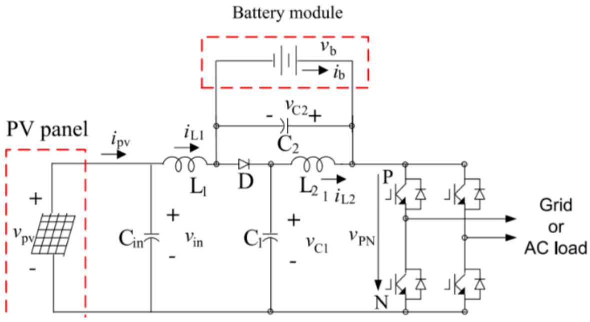


Figure 2.23: EES based quasi ZS converter(M. Shen, 2005)

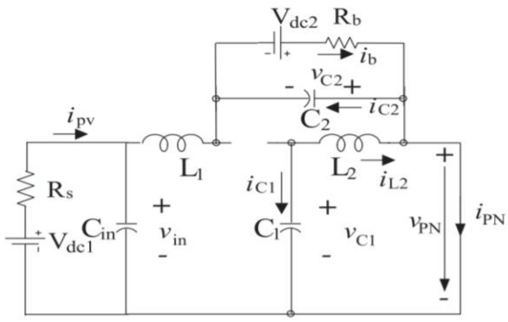


Figure 2.24: EES based quasi ZS converter in shoot through mode(M. Shen, 2005)

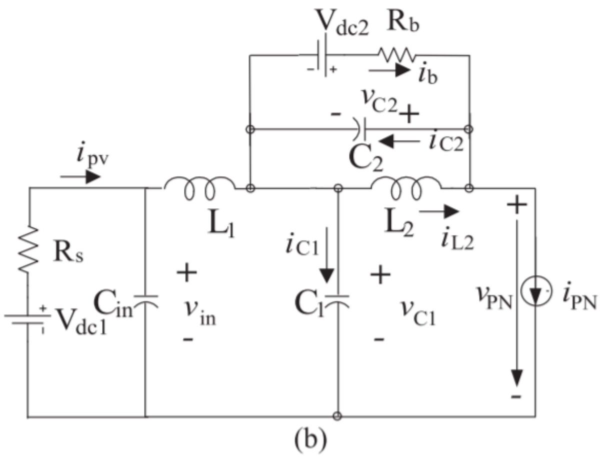


Figure 2.25: EES based quasi ZS converter in non-shoot through mode(M. Shen, 2005)

In(F. Khosravi, N. Ahmad Azli, 2014), a quasi ZS converter having less number of components is applied in a three network. The circuit of the proposed converter is shown in Fig. 2.25. Analysis of the circuit of done from cost benefit perspective to the consumer. Compared to conventional three phase system, this topology uses only four switches whiles the latter uses six switches for the same function. Some major advantages of this topology are reduction in losses due switching, reduced systems cost due to less components, minimum current harmonics. Also the control technique used (SVPWM) eliminates the need for filter circuits. Similar to other quasi ZS converters, the two modes of operation exist. Detailed system description for these modes are found in the paper although its similar to other quasi topologies with differences in the applied control technique.

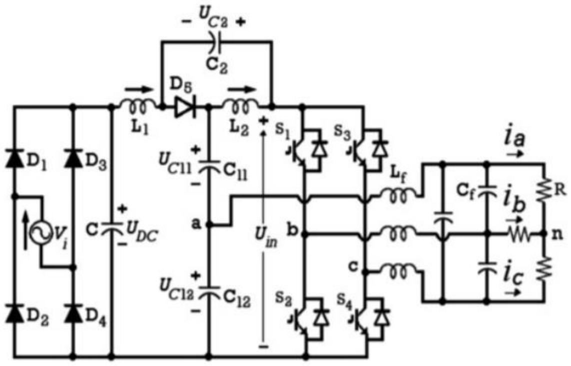


Figure 2.26: quasi ZS converter(M. Shen, 2005)

In (D. Sun, B. Ge, X. Yan, D. Bi, H. Zhang, Y. Liu, H. Abu-Rub, L. BenBrahim, 2014), a combination of energy storage and cascaded topology are combined to produce a quasi ZS converter. Several units of ESS based quasi ZS converter are connected in series to produce a cascaded topology. Fig. 2.26 shows the circuit of the proposed topology; an unusual advantage of this topology is combinations of the two topologies advantages.

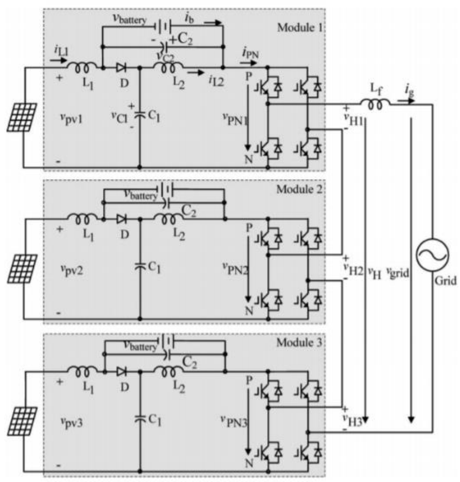


Figure 2.27: Cascaded ESS quasi ZS converter(M. Shen, 2005)

One major area in cascaded topologies which was not analysed in this topology is the symmetric and asymmetric properties; analysis of this important factor will be very useful future works. Because of the cascaded topology, higher output voltage will be derived because, the sum of the individual voltage output will determine the total system output voltage.

Another topology is the combination of neutral point clamped and the quasi topology; this is made to achieve the advantages of the two topologies, this topology is popular referred to as qZNPC. Prior to the introduction of qZNPC (F. Khosravi, N. Ahmad Azli, 2014), the conventional Z source converter and the NPC topology were combined to form one topology; this new topology still had the disadvantages of the conventional ZSC which are discontinuous current supply and component stress caused by voltage. The proposed new topology qZNPC solves the disadvantages of the latter topology, Fig. 2.27 shows the single phase qZNPC. The proposed qZNPC is a cascaded topology of two qZS which are symmetric in condition. Due to reduced voltage stress, fast switches are utilized and this leads to the application of high switching frequency which produces higher quality output waveforms and power density. Detailed analysis of various ZSC and qZS topologies have been investigated in (F. Khosravi, N. Ahmad Azli, 2014). The conventional PWM control technique can be applied in operating the proposed converter; here one reference signal and four carrier signals are applied in the PWM technique and another method is derived from the frequency, i.e. the switching frequency is made equal to the output frequency and this technique is also used in controlling the converter.

The boost factor of the proposed converter is given by (2.23) and the voltage gain is also given by (2.23) where the shoot through mode duty cycle is given by Ds(O. Husev, C. R. Clemente, E. R. Cadaval, D. Vinnikov, 2015).

$$\begin{cases} B = \frac{1}{1-2D_S} \\ G = \frac{1-D_S}{(1-2D_S)\sqrt{2}} \end{cases} \tag{2.23}$$

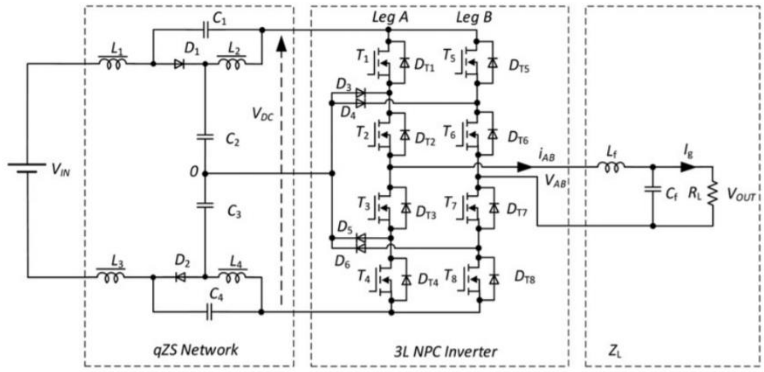


Figure 2.28: qZNPC(M. Shen, 2005)

A quasi topology and T type converter are combined to form the quasi Z source T type converter; qZSTT (V. Fernão Pires, A. Cordeiro, 2016). Similar to the qZNPC, two quasi topologies having symmetric conditions are combined with the T type inverter to form the qZSTT. This topology is analysed under two conditions; fault and normal conditions, a feature which is not common in analysis of most Z source converters. Fig. 2.28 shows the circuit of qZSTT, the switches connecting the quasi network and T type inverter are made up of bidirectional switches, this is to allow for current flow in both direction.

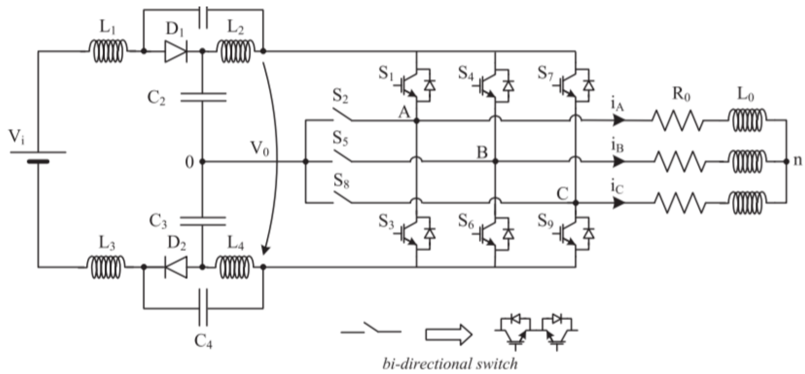


Figure 2.29: qZSTT(M. Shen, 2005)

2.3.3 Switched ZS Topologies.

The switched ZS topologies are also types of the impedance based inverters which seeks to further improve the converter's efficiency based on the voltage gain, boosting capabilities and reductions of the passive components. Fundamentally, two types of two switched topologies are available, the switched inductor and switched capacitor. Based on the two fundamental topologies, several other topologies can be derived based on the following: type of source, type of phase, and combination with other topologies.

The switched inductor (*SL*) is achieved by interchanging either one or all the inductors in the impedance network with a switched inductor. The conventional ZS converter or the quasi ZS converter can be used to achieve to the switched inductor topology by the above process. Fig. 2.29 shows switched inductor topology which is derived from the conventional ZS converter. The *SL* topology has the following advantages: higher boost abilities, greater power density, higher voltage gain utilizing better modulation index and solidness (Ellabban, O., Abu-Rub, 2016). In the case of quasi ZS converter with *SL* topology, the second inductor is interchanged with a switched inductor to derive the *SLqZSI.* The circuit diagram of the SLqZSI topology is represented by Fig.2. 30.

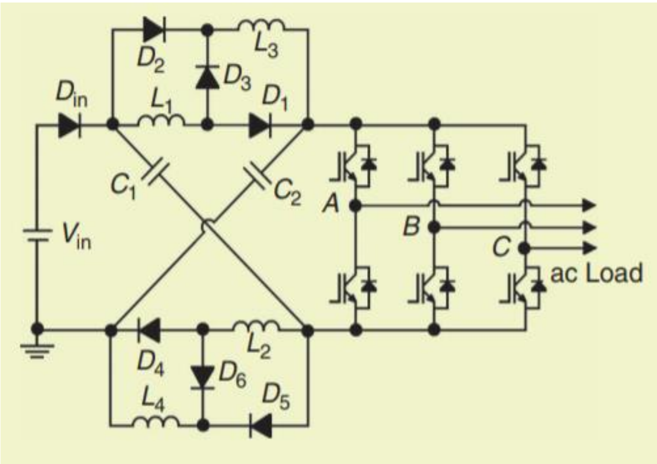


Figure 2.30: SL Topology(M. Shen, 2005)

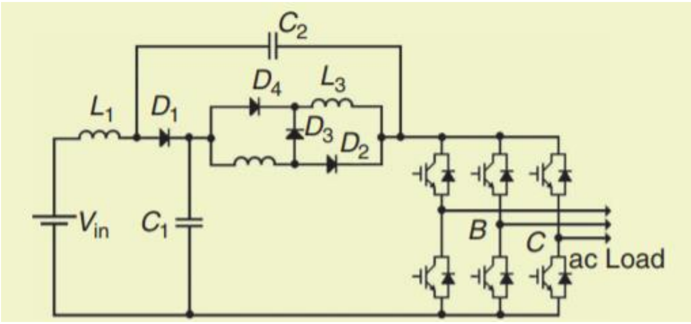


Figure 2.31: SLqZSI(M. Shen, 2005)

Another type of the switched topology is called Switched Boost Inverter (Ravindranath, A., Mishra, S., Joshi, 2013), and this also derived from the conventional ZS converter. This topology seeks to primarily reduce the number of passive components which directly reduces the size and cost of the converter; instead more active components are utilized and this gives more room for controlling the converter. Circuit of the SBI topology is shown in Fig. 2.31 which is also controlled in two modes; shoot through mode and non-shoot through mode. Fig. 2.32a and Fig. 2.32b shows the two modes of operation of the converter. The impedance network in this topology has only three components, two passive components one inductor and one capacitor and one active switch. There are diodes to prevent bidirectional current flow. The output of the circuit is connected to an LC filter.

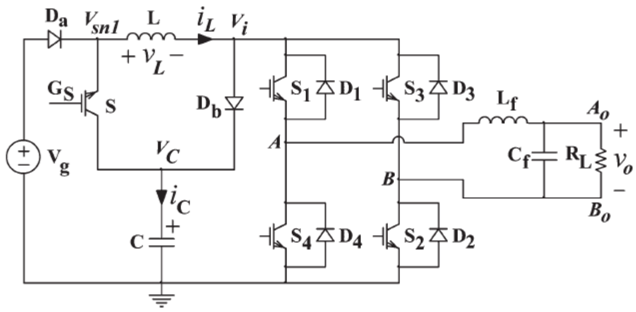


Figure 2.32: SB inverter(M. Shen, 2005)

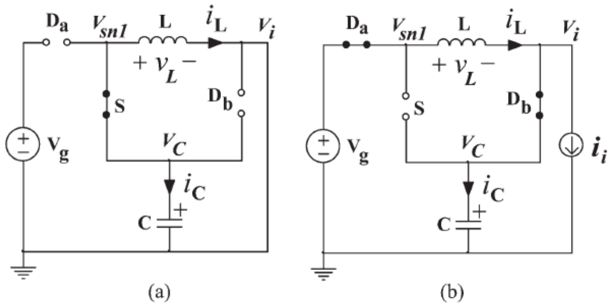


Figure 2.33: SB inverter: a) shoot through mode b) non-shoot through mode (M. Shen, 2005)

Switched capacitors are the other types of converter with the switched mechanism. Detailed analysis of the switched capacitor topology is found in (Axelrod, B., Berkovich, Y., and Ioinovici, n.d.). There are topologies which combines the switching mechanism and coupled inductor technologies to form a single inverter or converter. Basically the inductor is interchanged with a coupled inductor to form the coupled inductor topology, this is then added any existing topology tor constitute a new network. An example of such topology is the combination of a coupled inductor and switched capacitor to form a new topology known as SCLqZSI; quasi topology is also used. Fig. 2.33 shows the topology of the proposed SCLqZSI.

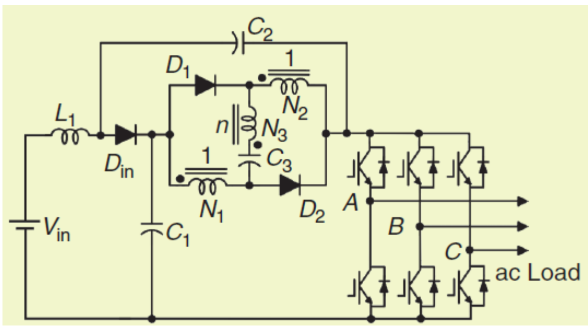


Figure 2.34: SCLqZSI(M. Shen, 2005)

In (Ismeil, Orabi, Kennel, Ellabban, & Abu-Rub, 2014), an improved version of the switched ZS converter is analysed in both simulation and experimental phases. This new topology called improved SL and improved SC topologies are derived by improving the performance of the conventional switched inductor and switched capacitor topologies. However emphasis is laid on the improved SL topology. The circuit of the proposed topology is shown in Fig. 2.34. The improved SL topology eliminates the demerits of the switched inductor topology. Some of these limitations are high voltage stress on the components and fast inflow currents (Yu Tang, Shaojun Xie, Chaohua Zhang, & Zegang Xu, 2009)(Zhang, n.d.). Improved SL topology is derived by series connection of the impedance structure and the inverter; this idea is similar to the improved conventional ZS converter. However the boost factor for both SL and improved are the same (Ismeil et al., 2014)and it's given by equation (2.25). Detailed analysis of the component stress can be found in (Ismeil et al., 2014)with experimental and pictorial results. The number of components used in both switched topologies are the same. This the improved SL topology is similar to conventional improved ZS converter, it can be stated that improved SL overcomes the limitation of wide range of topologies such ZSI, IZSI and Switched SL. One major disadvantage of the conventional ZS converter is minimum voltage gain and limited boosting capabilities; all these limitations are solved in the improved switched inductor converter. The switched inductor is also analysed in two states; shoot through and non-shoot through modes; Fig. 2.35a and Fig. 2.35b shows the circuit diagrams for these modes.

$$B = \frac{1+D}{1-3D} \tag{2.25}$$

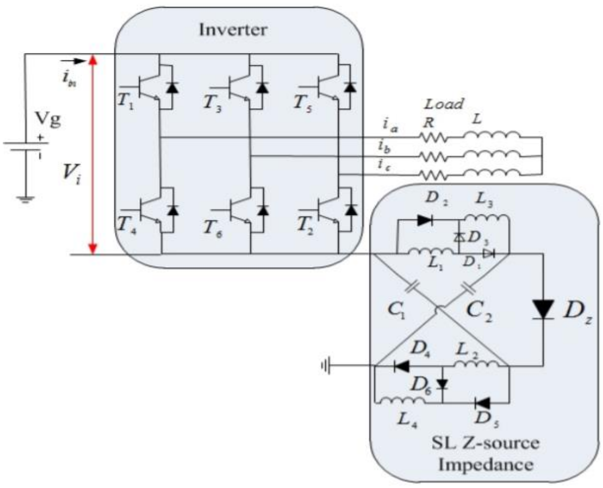


Figure 2.35: Improved SL(M. Shen, 2005)

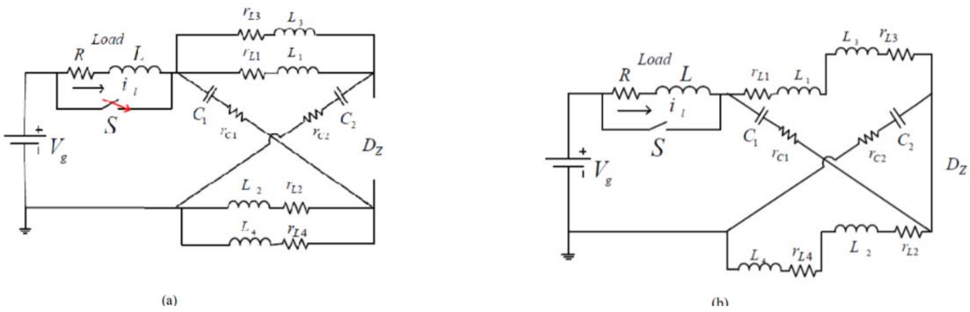


Figure 2.36: Improved SL a) shoot-through mode b) non-shoot-through mode (M. Shen, 2005)

A new switched topology is analysed in. This topology is a combination of three methodologies; switched idea, coupled idea and quasi idea, hence this topology is referred to as switched coupled inductor qZS converter. this topologies inherits the advantages of all the topologies used including that that of the conventional ZS converter which are single stage power conditioning, ability withstand effects of EMs and buck-boost functionality. The circuit of the proposed SCLqZSI is shown by Fig. 2.36 and it's derived by using a switched capacitor and a coupled inductor having 3 windings together with quasi technology. The SCLqZSI topology is able to produce higher boosting factor than the latter topologies, also because higher modulation index is used, the waveform of the output parameters are better than latter topologies due to utilization of higher switching frequency. The following publications have literatures on control, topologies and modelling of impedance source converter related to this topology; SCLqZSI (F. Z. Peng, M. Shen, 2005)(M. Shen et al., 2006)(J. Liu, J. Hu, 2007)(J.-W. Jung and A. Keyhani, 2007)(F. Z. Peng, X. Yuan, X. Fang, 2003)(Guo et al., 2013)(Fang, Qian, & Peng, 2005)(M.-K. Nguyen, Y.-G. Jung, 2010). SCLqZSI topology has better boosting capabilities than the quasi ZS converter and trans ZS converter; this is achieved with lower turns ratio of the coupled inductor and adding only one more component; capacitor. Boosting factor B is given by (2.26) where D is the duty cycle.

$$B = 3\ \frac{1}{1-4D} \tag{2.26}$$

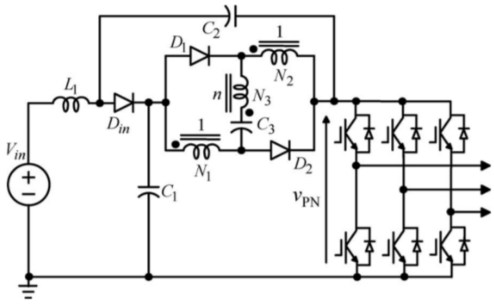


Figure 2.37: SCLqZSI(M. Shen, 2005)

In (M. K. Nguyen, T. D. Duong, Y. C. Lim, 2018) a switched capacitor topology and SBI topology are combined to form a new topology known as SCqSBI. This topology seeks to improve the qSBI topology by adding two components (diode and capacitor) to it to form SCqSBI. The aim of this topology is increase the voltage gain capabilities of the new topology and also reduce the component stress caused by voltage. Utilizing the "quasi" principles means that continuous supply of source current is possible and also reduced component stress are introduced into the converter topology, detailed analysis of qSBI when compared to qZS converter can be found in (M.-K. Nguyen, Lim, & Park, 2015). Two types of SCqSBI are shown in Fig. 2.37. The two topologies were developed from (M. K. Nguyen, Le, Park, & Lim, 2015) where two circuits of qSBI were analysed. In analysing the circuit, type 1 is used and the two modes of operation are used. The circuit diagram for the two modes of operation are shown in Fig. 2.38a and Fig. 38b. The booting factor of SCqSBI is two times more than qSBI; equation 2.27 and 2.28 represents the B value of qSBI and SCqSBI topologies.

$$B = \frac{1}{1-2D} \tag{2.27}$$

$$B = \frac{2}{1-2D} \tag{2.28}$$

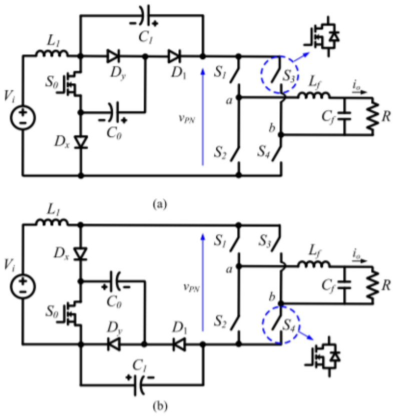


Figure 2.38: SCqSBI(M. Shen, 2005)

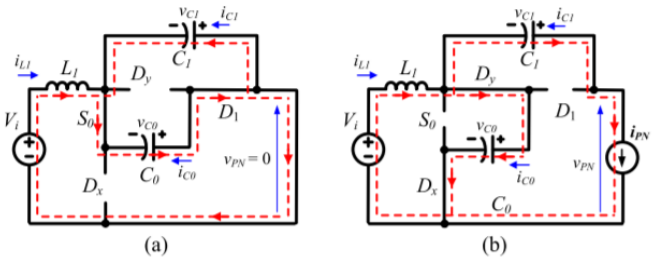


Figure 2.39: SCqSBI a) shoot through b) non-shoot-through

(M. Shen, 2005)

An enhanced topology of switched inductor is introduced in (Fathi & Madadi, 2016), this topology is derived by switching the impedance network in SL topology to obtain the Enhanced Boost SL topology. The circuit for the proposed circuit EBSL is shown in Fig. 2.39. This topology produces better output waveforms when compared to conventional topologies because higher modulation index and short period of shoot through is utilized. Voltage stress is also minimised in this topology. The mode of operation is the same as the conventional impedance networks, in the shoot through mode (Fig. 2.40a) inductors and capacitors in switching part of the circuit forms a parallel network. Two diodes are reverse biased (D_3, D_4) and two diodes are reverse biased (D_1, D_2), also diode Din is turned off because the capacitor voltages are greater than the source voltages. In the non-shoot through mode, the switching of the diodes are opposite of the shoot through mode. The forward and reverse biased diodes are D_1, D_2 and D_3, D_4, D_{in} respectively. The boost factor is given by (2.29) and the relationship between gain and output voltage is given by (2.30).

$$B = \frac{1}{2D^2 - 4D + 1} \tag{2.29}$$

$$G = \frac{2V_{ac}}{V_{in}} \tag{2.30}$$

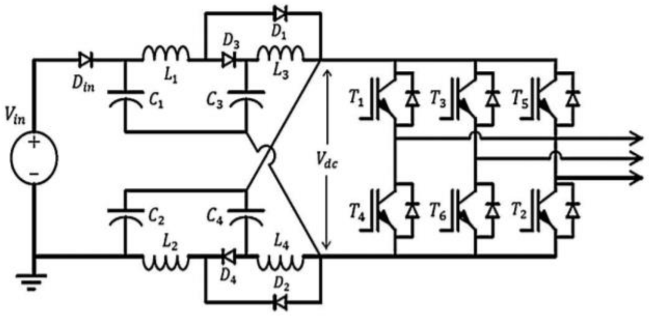


Figure 2.40: EBSL

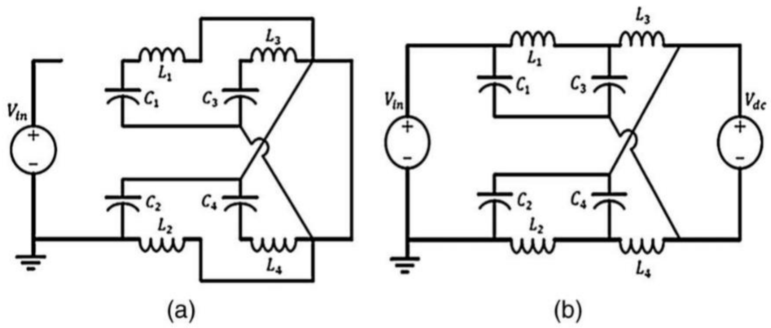


Figure 2.41: ESBSL a) shoot through b) non-shoot through(M. Shen, 2005)

A switched boost topology is presented in (Minh-Khai Nguyen, Geum-Bae Cho, 2016). The switched boost topology SB exhibits several advantages when compared to half bridge ZS converter proposed in(Guo, F., Fu, L., Lin, C.H., n.d.). Some these advantages are reduced number of passive components, common ground between the input and output, continuous supply of source current due to the series connection of the inductor and the source voltage and better output waveforms. The circuit of SB is shown in Fig. 2.41 and it’s made up of two passive components (one inductor and one capacitor) and five switches. The circuit of SB is analysed in three modes; continuous conduction mode, ideal components and finally large capacitance. These modes of operating the SB topology constitute the two modes which is very prevalent in all impedance based topologies; shoot-through and non-shoot through mode.

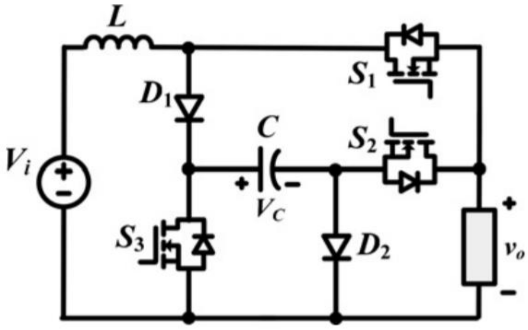


Figure 2.42: Switched boost ZS converter(M. Shen, 2005)

A novel topology of impedance Z source converter is presented in (H. Shen, Zhang, Qiu, & Zhou, 2016). This topology of converter has two unique features; higher voltage gain and same ground between the source and the load. This topology is applied in dc-dc power conversion. Also the proposed converter boast of reduced component stress due to voltage and having a simple structure. The output voltage of the proposed dc-dc converter is given by (2.31) and it circuit is represented by Fig. 2.42. This topology is uses two modes of operation; shoot through and non-shoot through. Detailed analysis can be found in (H. Shen et al., 2016).

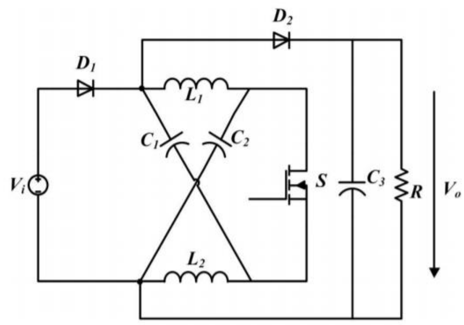


Figure 2.43: Common ground high voltage dc-dc converter(M. Shen, 2005)

2.3.4 Trans and T ZS Topologies.

The popular Trans ZS converters are composed of impedance network and the main inverter circuit; the impedance network utilizes transformers or coupled inductors to produce the required windings. It should be stated that Trans and T ZS converters are similar in topology with only a little difference. The new T source converter presented in (R. Strzelecki, M. Adamowicz, N. Strzelecka, 2009) presents different types of impedance network structure with a transformer. Two types of modifications are presented in Fig.

2.43; in the first modification, the number passive components are same as the conventional LC lattice structure with the inclusion of a transformer, in the second type (c) in modification 1, one inductor is eliminated. Only one capacitor and one or two transformers are used in the second modification in Fig. 2.43. The circuit of the proposed T source inverter and its modes of operations are shown in Fig. 2.44 and Fig. 2.45 respectively. One major advantage of T source converter is higher voltage gain utilizing minimum number of components.

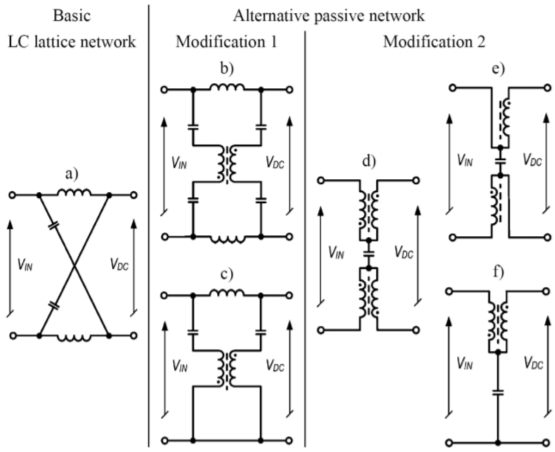


Figure 2.44: LC lattice modifications(M. Shen, 2005)

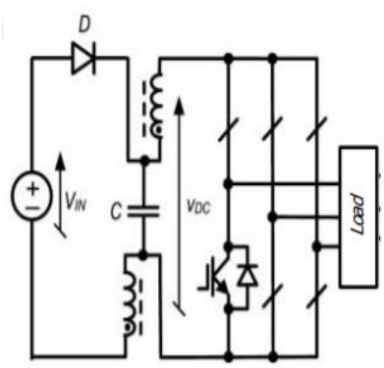


Figure 2.45: T Source inverter(M. Shen, 2005)

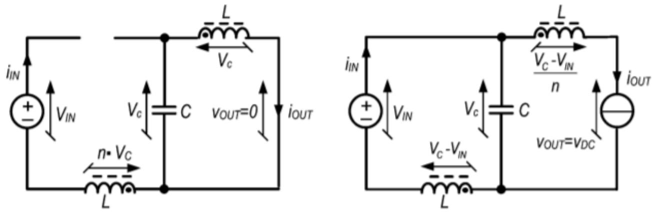


Figure 2.46: Shoot through and non-shoot through mode(M. Shen, 2005)

VS Trans qZS converter topology (Qian, Peng, & Cha, 2011) is derived from qZS coupled converter; the circuit of both topologies are presented in Fig. 2.46 and Fig. 2.47 respectively. The two conductors are connected to form a winding network. One capacitor is removed from the new topology and the diode and capacitor are rearranged to form the desired trans qZS converter. This new topology inherits the merits of qZS converter plus higher output capabilities, better output waveform with maximum modulation index. The buck-boost state is derived due to the shoot through mode; a feature which is not present in non Z source based converters. In the shoot through mode (Fig. 2.48b), the main diode connected in series with the source is reverse biased hence the source voltage is disconnected from the circuit. The voltage gain G and boost factor B of the voltage source Trans qZS converter are given by:

$$B = \frac{1}{1-(n+1)D_{sh}} \tag{2.31}$$

$$G = \frac{M}{1-(1+n)(1-\frac{\sqrt{3}}{2}M)} \tag{2.32}$$

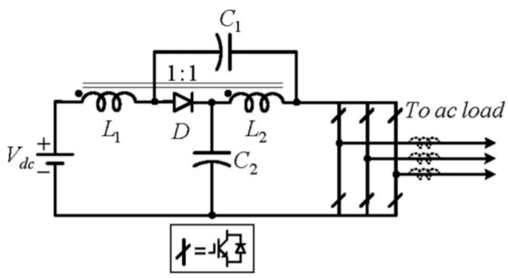


Figure 2.47: qZS coupled inverter

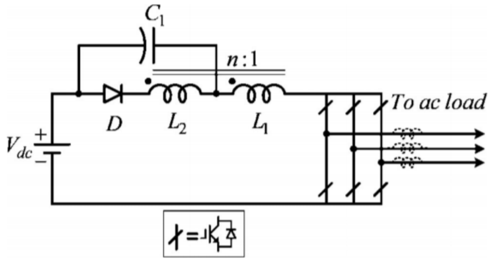


Figure 2.48: Trans qZS converter(M. Shen, 2005)

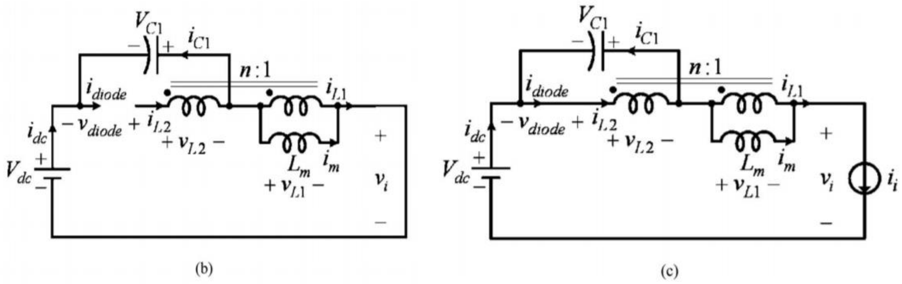


Figure 2.49: Trans qZS converter a) shoot-through mode b) non-shoot through mode (M. Shen, 2005)

The current source based Trans qZS converter is also presented in Fig. 2.49. Also this topology is derived from the CS qZS coupled converter shown in Fig. 2.50. The equivalent circuit and the modes of operation are shown in Fig. 2.51. To obtain current source, an inductor is connected in series with the source. This inductor renders the source as a continuous current supply source. Also the transformer windings is achieved by using a coupled inductor.

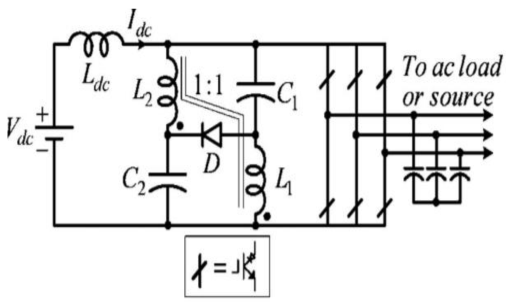


Figure 2.50: CS-qZS coupled converter(M. Shen, 2005)

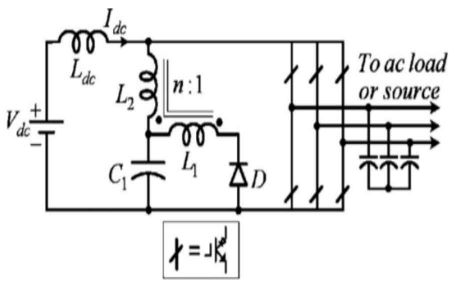


Figure 2.51: CS-Trans-qZS converter(M. Shen, 2005)

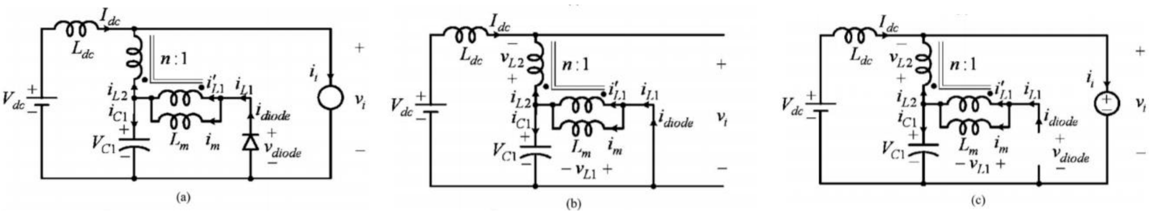


Figure 2.52: CS-Trans-qZS converter: a) equivalent circuit b) open circuit c) non-open circuit(M. Shen, 2005)

A new topology of Trans based converter is presented in (M.-K. Nguyen, Choi, Lim, & Choi, 2016). This novel topology is composed SBI topology and transformer based topology. The new topology is referred to Trans SBI. The main advantage of this topology is the application of minimum turns ratio of the transformer to produce higher voltage output. The quality of the output waveform is highly improved due to the usage of high modulation index. If the proposed Trans-SBI is compared to the tapped inductor ZSI; the number of passive components is significantly reduced but has one more active switch. This topology is highly required in photovoltaic systems and fuel cell applications. Two types of Trans-SBI are presented and analysed in (M.-K. Nguyen et al., 2016).The circuits of the two topologies are shown in Fig. 2.51a and Fig. 2.51b. The boost factor is given by:

$$B = \frac{1+Dn_S}{1-D(2+n_S)} \tag{2.33}$$

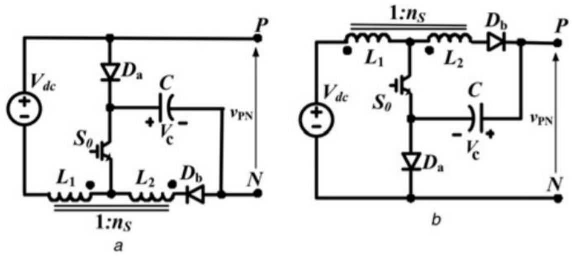


Figure 2.53: Trans-SBI: a) Type 1 b) Type 2(M. Shen, 2005)

In (L. He, S. Duan, 2013), an ac-ac power conversion converter is introduced utilizing the Trans ZS converter; this topology is a single phase ac-ac converter and boast of the following advantages when compared to conventional ZS converter and qZSI; common ground between the input and output, high voltage gain, continuous supply current at the input; a useful factor in minimising current harmonics. The Trans methodology is achieved by utilizing a coupled inductor. AC-AC power converters are utilized industry where the supply is ac and the desired load voltage is ac, this methodology is highly desired because it's a single stage power conversion, losses are heavily reduced and efficiency is increased, also connections between supply and grid is easily done with extra cost. Some ac-ac conversion methods are matrix converter(S. Vidhya and T. Venkatesan, 2018)(M. Vijayagopal, P. Zanchetta, L. De Lillo, L. Empringham, L. Tarisciotti, 2017)(H. F. Ahmed, H. Cha, A. A. Khan, J. Kim, 2017)(J. W. Kolar, F. Schafmeister, S. D. Round, 2007), PWM ac-ac converters (A. A. Khan, H. Cha, n.d.)(A. A. Khan, H. Cha, 2016)(H. F. Ahmed, H. Cha, A. A. Khan, n.d.)(D. Vincenti, H. Jin, n.d.)(L. G. G. de Vicuna, M. Castilla, J. Miret, J. Matas, 2009)(N. A. Ahmed, K. Amei, 1999), indirect ac-ac converter (P. Alemi, Y. C. Jeung, 2015)(Alexandridis, n.d.)(J. G. de Oliveira, H. Schettino, V. Gama, R. Carvalho, n.d.)(E. C. dos Santos, C. B. Jacobina, N. Rocha, n.d.)(A. C. N. Maia, C. B. Jacobina, 2017). The proposed ac-ac Trans ZS converter proposed in (L. He, S. Duan, 2013)is built with safe commutation circuit. Safe commutation circuit is desired because of the use of bidirectional switches as in the case of matrix converter. Fig. 2.52 shows the proposed topology and Fig. 2.53a and Fig. 2.53b shows the commutation circuit during deadtime operation and overlap operation. The voltage gain of the proposed converter is given by:

$$G = \frac{v_0}{v_i} \tag{2.34}$$

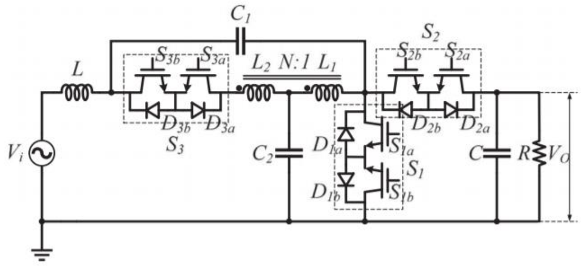


Figure 2.54: AC-AC Tran ZS converter(M. Shen, 2005)

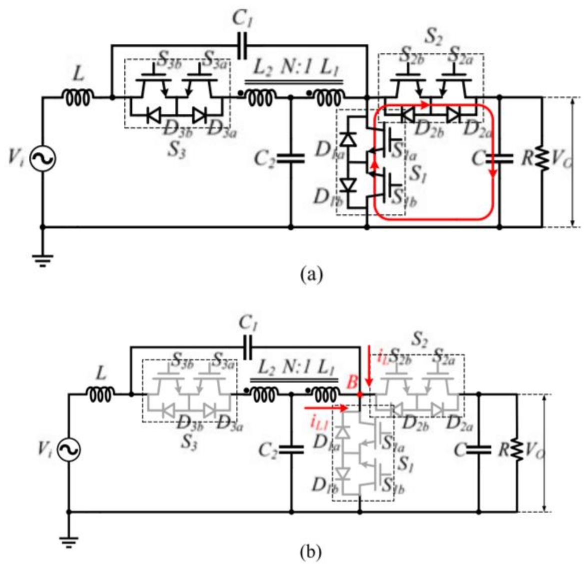


Figure 2.55: Safe Commutation circuit   a) Overlap period b) Deadtime period (M. Shen, 2005)

A combination of three topologies; NPC, Trans and gamma topologies have joined to form the proposed converter in (W. Mo, P. C. Loh, n.d.). This topology combines the advantages of the converters to produce a novel one. Some of the advantages of the new topology are; high modulation index hence better output waveforms, reduced component stress, much practical higher output voltage. A three phase gamma based NPC converter is shown in Fig. 2.54. The main circuit is represented by Fig. 2.54a and the shoot through and non-shoot through of only the upper structure is shown by Fig. 2.54b and Fig. 2.54c respectively.

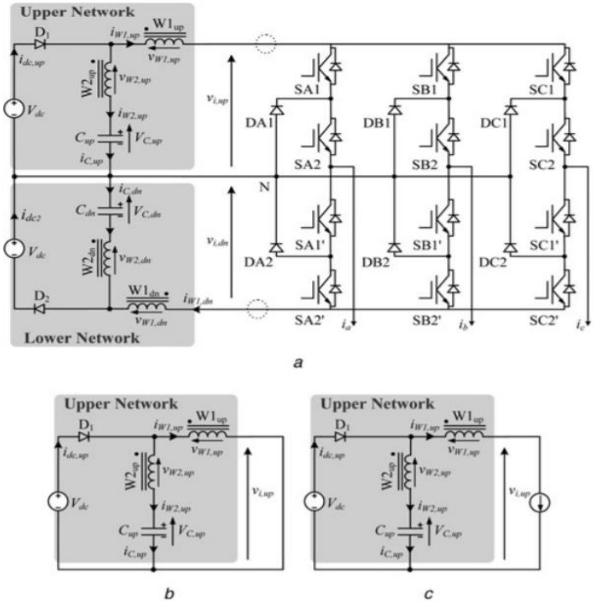


Figure 2.56: Trans gamma based ZS converter(M. Shen, 2005)

One topology which does not belong to the Trans topology but it’s worth mentioning is the tapped inductor ZS converter. The tapped inductor exhibits advantages similar to the Trans inductor topology; high boosting capabilities, reduced system voltage stress and higher voltage gain. Circuit of the tapped inductor derived from the conventional ZS converter. Each tapped inductor in the upper and lower am of the converter is composed of two windings.

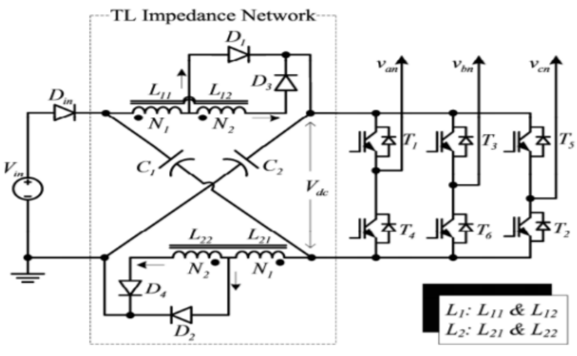


Figure 2.57: Tapped inductor ZS converter(M. Shen, 2005)

2.3.5 Gamma ZS Topologies

This section of the thesis will investigate different topologies of ZS converter with emphasis on gamma, delta, sigma, matrix and magnetically coupled ZS converters. These topologies are being investigated based on their ac-ac power conversion. Starting with the Gamma topology which is a further development of the conventional ZS converter to achieve higher voltage, better output waveform and reduced number of passive components.

A differential state gamma ZS inverter is investigated in (Reddiprasad Reddivari, n.d.). The main advantage here is that the voltage gain is maximised by utilizing minimum turns ratio. Compared to the transformer type gamma converter, the differential gamma topology does not have the following problems: compact coupling, large and heavy size, high cost of the system, maximum turns ratio, increased instantaneous currents. Gamma based coupled converters are the only type of coupled or transformer based ZS converter which are able to produce high output voltage with minimum turns ratio and minimum number of components. The gain of the gamma based converter is given by (2.35) where a, M and D are the turns ratio, modulation index and duty cycle respectively. Fig. 56 shows the flowchart for the derivation of the gamma based converter from the conventional ZS converter.

$$\begin{cases} a = \frac{w_1}{w_2} \\ G = \frac{M}{1-\left(1+\frac{1}{a-1}\right)D} \end{cases} \tag{2.35}$$

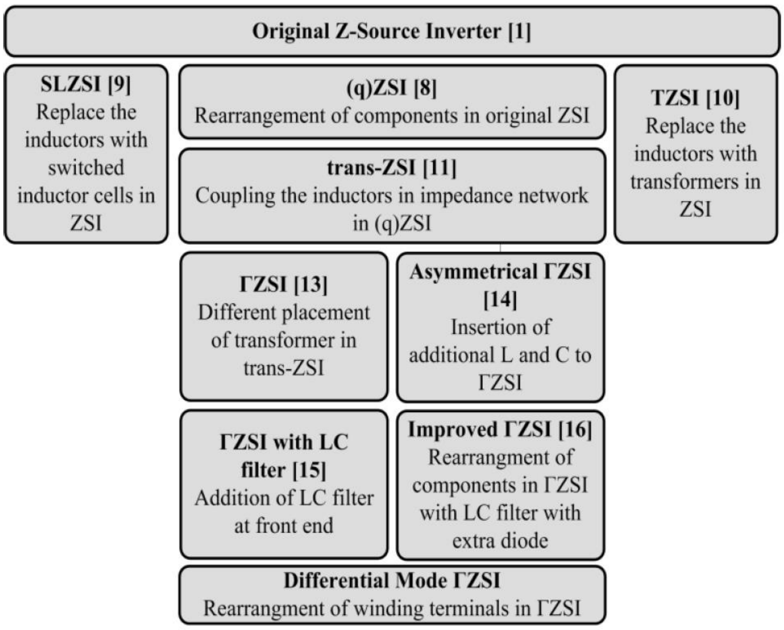


Figure 2.58: Derivation of gamma based converter

To provide continuous supply of source current and stop inrush currents at start-up, an improved version of gamma based ZS converters are introduced in (W. Mo, n.d.)(M. R. Banaei, R. Alizadeh, N. Jahanyari, 2016). However these components introduces new limitations such as increased cost, increased size and increased losses. To achieve continuous current input and minimum inrush current, a new topology with double ZS network is introduced by (Hanif, n.d.). The differential gamma converter topology under review under this section is derived from the conventional gamma topology shown in Fig. 2.57a. The circuit of the differential gamma converter is shown in Fig. 2.57b. The difference between the two topology is changing of the winding position as shown in Fig. 2.58a and Fig. 2.58b.

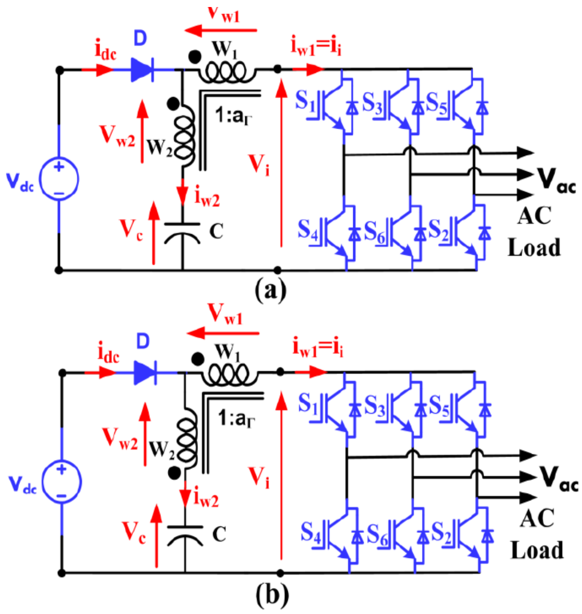


Figure 2.59: Gamma ZS converters: a) Conventional topology b) Differential Topology (Sabahi, 2017)

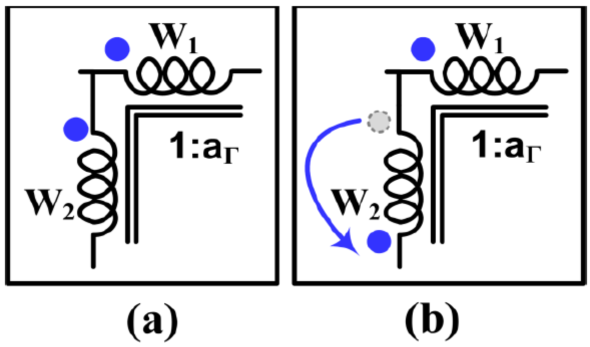


Figure 2.60: Gamma ZS windings a) conventional Topology b) Differential topology (Sabahi, 2017)

Two methods of increasing the output voltage is proposed in this paper (Sabahi, 2017). The converter which achieves this merits is a half bridge inverter based on gamma ZS converter, hence the topology is referred to as half bridge gamma inverter. Higher output voltage is achieved by either varying the turns ratio of the coupled inductor or the transformer or by varying the shoot through duty cycle; the two methods uses low levels of duty cycle or turns ratio to achieve higher output voltage ratio. The circuit diagram of the proposed converter is shown in Fig. 2.59. Whiles the four modes of operation are shown in

Fig. 2.60 where the first, second, third and fourth modes of operation are represented by Fig. 2.60a, Fig. 2.60b, Fig. 2.60c and Fig. 2.60d respectively. The shoot through mode is achieved in the 1st and 3rd modes of operation and the non-shoot through mode is achieved in 2nd and 4th modes of operation.

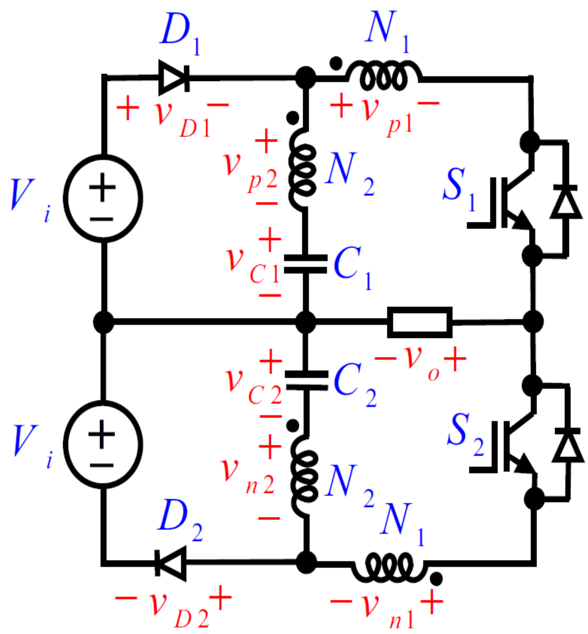
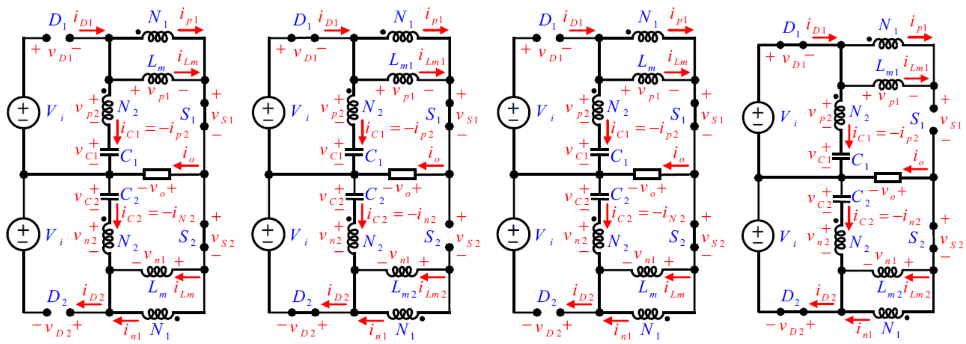


Figure 2.61: Half bridge gamma converter (Sabahi, 2017)



(a) (b) (c) (d)

Figure 2.62: Modes of operation of HB gamma converter (Sabahi, 2017)

The boost factor and the output voltage of the converter is given by (2.36) and (2.37) respectively.

$$B = \frac{-N_{12}+1}{-N_{12}+1(1-D_{ST})} \tag{2.36}$$

$$V_{0\max} = \frac{-N_{12}+1}{-N_{12}+1(1-D_{ST})} V_i \tag{2.37}$$

Asymmetrical gamma based ZS converter is introduced in (Mo, W., Loh, P.C., Blaabjerg, 2014). Also the topology produces higher output voltage with lower turns ratio. In topologies where continuous current flow is not achieved, component stress is at maximum however the stress in the asymmetrical topology is distributed evenly. Two types of asymmetrical topologies are presented in (Mo, W., Loh, P.C., Blaabjerg, 2014). In both types, two capacitors and two coupled inductors are used to achieve the required topology. To provide continuous input current, an inductor is connected in series with the voltage source. Fig. 2.61 shows the two topology of asymmetric gamma ZS converter. the shoot through mode and non-shoot through mode for type 1 and type 2 are given by Fig. 2.62 and Fig. 2.63 respectively.

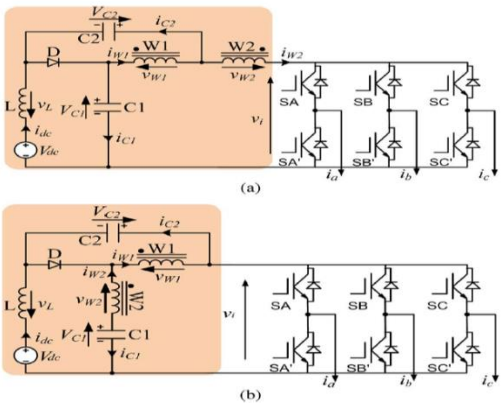


Figure 2.63: Asymmetric gamma ZS converter (Sabahi, 2017)

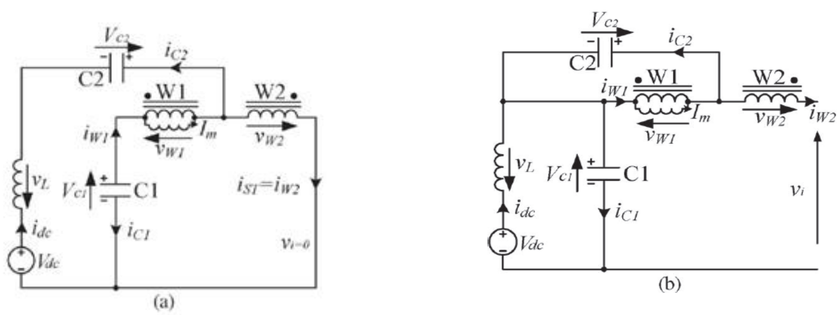


Figure 2.64: Asymmetric gamma ZS converter mode of operation (Sabahi, 2017)

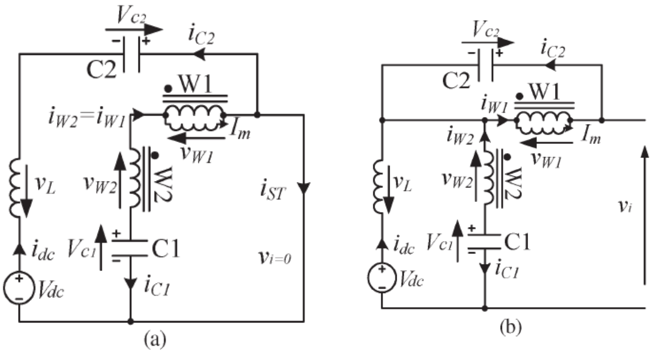


Figure 2.65: Asymmetric gamma ZS converter mode of operation (Sabahi, 2017)

An improved gamma ZS converter having a snubber circuit without loses is presented in (Sabahi, 2017), the impedance network uses a transformer instead of a coupled inductor, also a clamping diode is used to clamp voltage flow. The snubber circuit is used to overcome the problems caused by stray and leakage inductance from the magnet components. The circuit of the proposed improved gamma ZS converter using high frequency transformer is represented by Fig. 2.64. The main advantages of the proposed converter are:

a. It retains the merits of all conventional ZS topologies having same impedance structures.
b. Boost functionality
c. High voltage gain utilizing high modulation index
d. Compact structure, minimum turns ratio for higher output voltage gain
e. Quality output waveforms

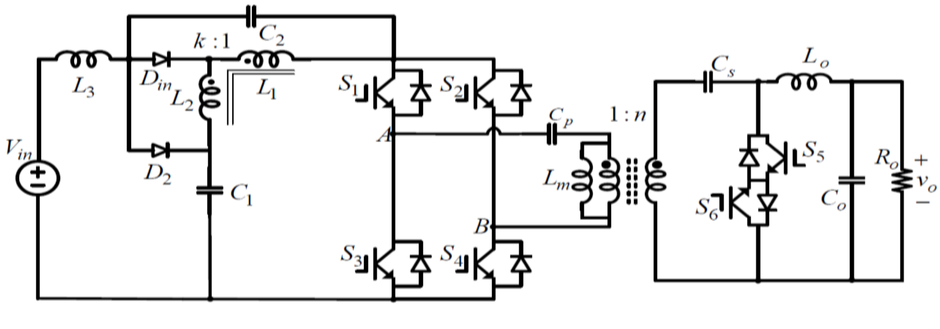


Figure 2.66: Improved gamma ZS converter (Sabahi, 2017)

The modes of operation is similar to all impedance based converters and the circuit representing these modes is represented by Fig. 2.65. The shoot through mode is given by Fig. 2.65a, and the active state, zero state 1and zero mode 2 are given Fig. 2.65b, Fig. 2.65c and Fig. 2.65d respectively.

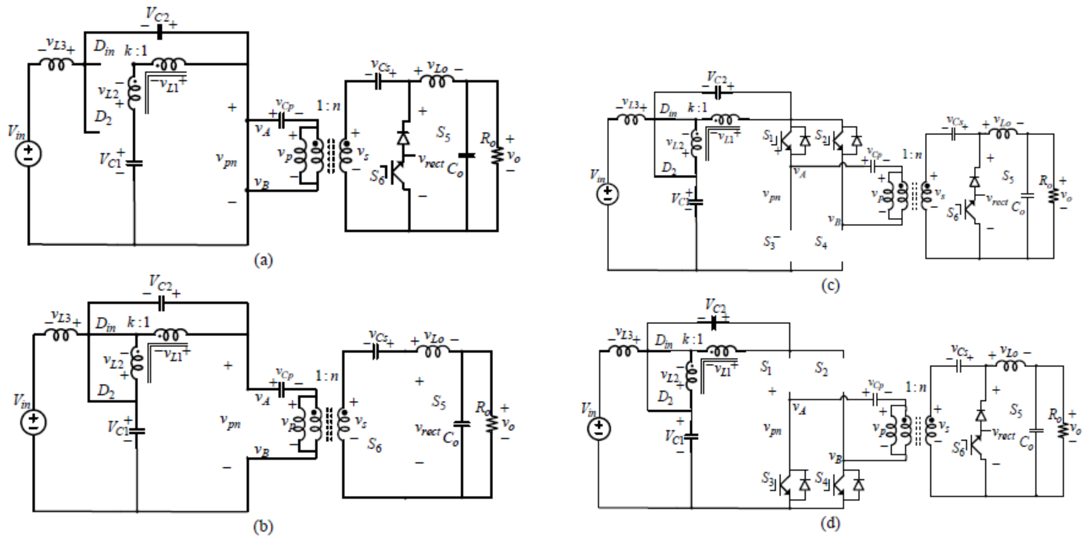


Figure 2.67: Modes of operation improved gamma ZS converters (Sabahi, 2017)

The voltage gain and the boost factor equation for the proposed converter are given below:

$$\begin{cases} G = nBM \\ B = \frac{k-1}{[k(1-2D)-1+D]} \end{cases} \tag{2.38}$$

Switched inductor and gamma ZS topologies are combined in (H. Zeinali, A. Mostaan, 2014) to form a switched inductor gamma converter which retains the advantages of the two topologies hence able to produce higher voltage gain than most gamma based topologies. The circuit diagram of the proposed converter and its modes of operation circuits (shoo through and non-shoot through) are given by Fig. 2.66 and Fig. 2.67 respectively.

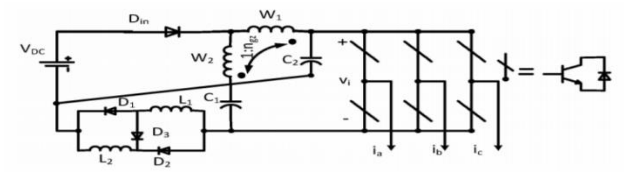


Figure 2.68: SL gamma converter(Mo, W., Loh, P.C., Blaabjerg, 2014).

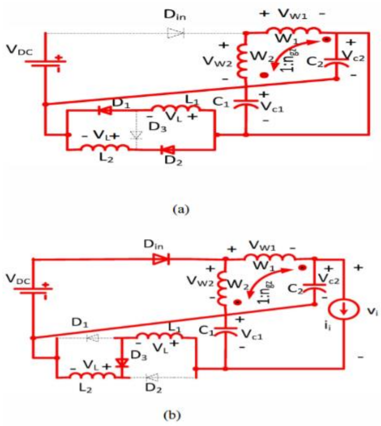


Figure 2.69: Modes of operation(Mo, W., Loh, P.C., Blaabjerg, 2014).

The boost factor is given by:

$$B = \frac{1+D}{1-\left(1+\frac{ngz}{ngz-1}\right)D-\frac{D^2 ngz}{ngz-1}} \tag{2.39}$$

The converter ac output voltage is given by:

$$V_{ac} = 0.5MBV_{Dc} \tag{2.40}$$

2.4 Conclusion

Several types impedance based topologies have been investigated in this section starting with the conventional ZS converter which resolves the problems of the voltage and current source inverters. The conventional ZS converter has the following advantages: buck-boost ability, shoot through capabilities, high boosting and voltage gain functionalities, EMIs capabilities. Quasi ZS topologies were introduced to overcome limitations of the conventional ZS converter, quasi ZS has the following advantages; reduced voltage stress, increased gain, continuous and discontinuous current flow as desired. The switched and coupled inductors were introduced as an improvement of the quasi and conventional topologies, switched boost topology was introduced to increase the boosting factor whiles reducing the number of passive components, trans Zs topologies and the gamma topologies were introduced to overcome the limitation of the trans or t topologies. The gamma based topologies increases the voltage gain whiles reducing the component stress, better output waveforms, and reduced turns ratio.

CHAPTER 3

SELECTED TOPOLOGY AND SIMULATION RESULTS

3.1 Introduction

Power electronic converters have become vital components in the efficient delivery and utilization of generated power; whether from fossil fuels or renewable energy source but the latter is gaining more importance due to its numerous advantages. Some applications of converters can be found in the following sectors of society; education, communication, health, military, transport and aviation, just to mention few. In less than 10 years from now, most European countries will cease to use fossil fuels, renewable energy will become the main source of energy hence power electronic converters will be an integral component of energy delivery.

Power electronic converters perform the following power conditioning under the following headings: inversion, rectification, chopping both for ac and dc where the ac chopping is known as cycloconversion. In our research, the focus of the use of power electronic converters will be to provide ac output voltage from an ac input voltage hence the converter can be classified as a Cycloconverters. This topology belongs the family impedance based converters which were introduced to resolve the limitation of the conventional voltage and current source converter popularly known as VSI and CSI respectively.

3.2 Gamma (Γ) Z Source Converter

The selected converter topology under investigation is known as the gamma (Γ) Z source converter applied as ac-ac converter hence having the name ac-ac gamma converter. The use of this topology is for a single phase converter. Gamma converter were introduced in [1] as improvement of the Trans Z source converters because higher output voltage is achieved in the Trans ZS converter by increasing the turns ratio of the transformer winding; but in practical applications it's impossible to achieve certain higher levels of voltage at the output. The gamma and Trans Z source converters are similar from component count point of view with the difference being the structural placement of the transformer or coupled inductor windings. In the gamma Z source topology, higher output voltage is delivered by reducing the turns ratio of the winding which is a major advantage when compared to the Trans topologies. Z source. Two topologies of gamma ZS converter were presented by (Siwakoti et al., 2015) Fig. 3.1a and Fig. 3.1b shows the circuit of the two topologies. In Fig. 3.1a, a diode is place in series with the voltage source to protect the source from reverse current flow and the second circuit (Fig. 3.1b) is a voltage source based gamma converter.

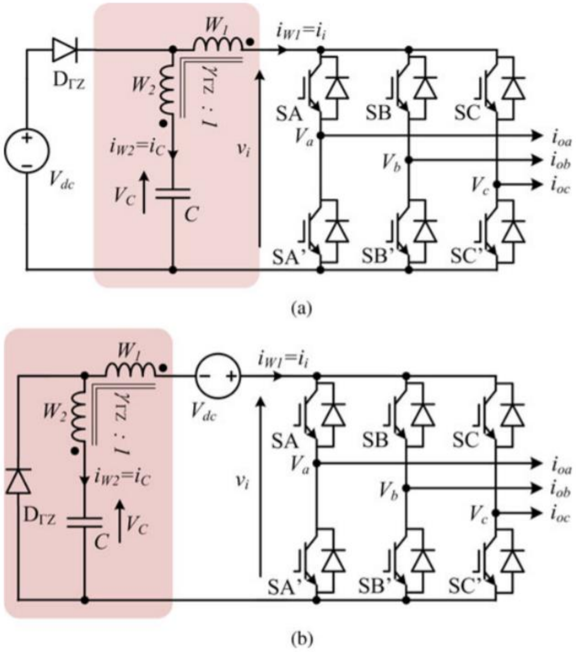


Figure 3.1: Conventional gamma source converter(Siwakoti et al., 2015)

The topology of gamma source being investigated in our research derived from the topology of the conventional topology shown in Fig. 3.1a, because our topology is being applied an ac-ac converter, structural changes are made to the circuit, bidirectional switches are used. Fig. 3.2 show the circuit of the ac-ac gamma converter under investigation in this thesis. The circuit is composed of the source, four switches connected in bidirectional mode, the transformer windings and an output LC filter. The advantages of this topology are buck-boost functionality, common ground for the input and output, variable output phase, higher output voltage with reduced turns ratio, simple structure, reduced components numbers, higher efficiency and minimum cost of the converter.

Because of ac-ac power conversion of this topology, a safe commutation circuit is included in the topology to protect the topology from voltage spikes and current spikes.

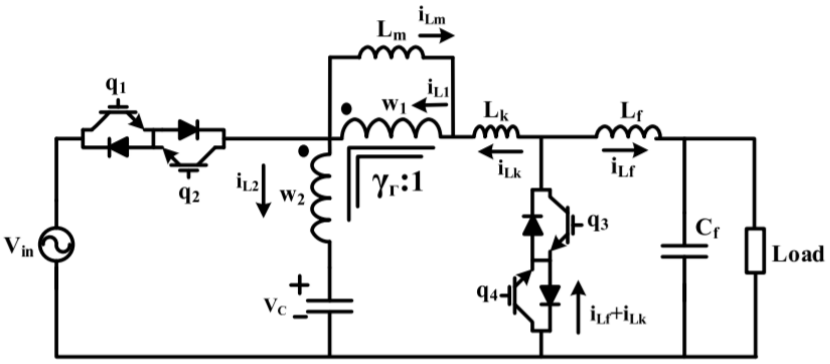


Figure 3.2: AC-AC gamma Z source converter(Siwakoti et al., 2015)

Let the turns ratio of the gamma converter be γ_Γ hence:

$$\gamma_\Gamma = \frac{w_1}{w_2} \tag{3.1}$$

The boost factor B of the proposed ac-ac gamma converter is given by:

$$B = \frac{1-D}{1-D\left(1+\frac{1}{\gamma_\Gamma - 1}\right)} \tag{3.2}$$

Higher boost factor is achieved in the region of (3.3) when compared to traditional ac-ac ZS converter. When the boost factor is chosen to be greater 0 (zero), the duty cycle of the shoot through mode will have the new limits given by (3.4); higher boost facto will be gained when the turns ratio chosen is small.

$$1 < \gamma_\Gamma < 2 \tag{3.3}$$

$$0 < D < \frac{\gamma_\Gamma - 1}{\gamma_\Gamma} \tag{3.4}$$

Analysis of the proposed ac-ac converter is done with the following prepositions:

1. The converter components re ideal hence lossless.
2. The conduction mode of the conductor is CCM (continues conduction mode)

Just as with all impedance based converters, this topology has two modes of operation; shoot through mode and non-shoot through mode. The first mode of operation (shoot through) occurs in the period DTs and the second mode of operation (non-shoot through) occurs in the period of (Ts – DTs). The winding is achieved by using a coupled inductor having the following parts:

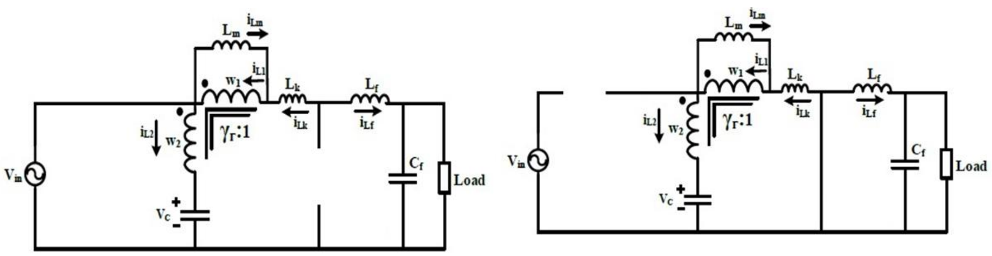
a. Magnetizing inductor represented by Lm
b. Coupling coefficient k
c. Turns ratio γ_Γ

The following equations are derived for the parts mentioned above:

$$\gamma_\Gamma = \frac{V_{w1}}{V_{w2}} \tag{3.5}$$

$$k = L_m \frac{1}{L_m + L_k} \tag{3.6}$$

The shoot through and non-shoot through mode circuits are given by Fig. 3.3a and Fig. 3.3b respectively.



a. Non-shoot through b. Shoot through

Figure 3.3: AC-AC gamma Z source converter operation(Siwakoti et al., 2015)

Non-shoot through

$$L_m \frac{d}{dt} i_{Lm}(t) = -\gamma_\Gamma v_C(t) + \gamma_\Gamma v_i(t) \tag{3.7}$$

$$L_f \frac{d}{dt} i_{Lf}(t) = \frac{\gamma_\Gamma}{k} v_C(t) - v_o(t) + \left(1 - \frac{\gamma_\Gamma}{k}\right) v_i(t) \tag{3.8}$$

$$C \frac{d}{dt} v_C(t) = \gamma_\Gamma i_{Lm}(t) - \gamma_\Gamma i_{Lf}(t) \tag{3.9}$$

$$C_f \frac{d}{dt} v_o(t) = i_{Lf}(t) - \frac{v_o(t)}{R} \tag{3.10}$$

Shoot-through

$$L_m \frac{d}{dt} i_{Lm}(t) = \frac{k.\gamma_\Gamma}{\gamma_\Gamma - k} v_C(t) \tag{3.11}$$

$$L_f \frac{d}{dt} i_{Lf}(t) = -v_o(t) \tag{3.12}$$

$$C \frac{d}{dt} v_C(t) = \frac{\gamma_\Gamma}{1-\gamma_\Gamma} i_{Lm}(t) \tag{3.13}$$

$$C_f \frac{d}{dt} v_o(t) = i_{Lf}(t) - \frac{v_o(t)}{R} \tag{3.14}$$

The voltage gain of the converter is given by:

$$G = \frac{v_0}{v_i} = \frac{1-D}{\left(1+\frac{k}{\gamma_\Gamma - k}\right)1-D} \tag{3.15}$$

From (3.15) the boost factor B is given by:

$$B = \frac{v_C}{v_i} = \frac{1-D}{\left(1+\frac{k}{\gamma_\Gamma - k}\right)1-D} \tag{3.16}$$

3.3 Commutation Method

The switches utilized in the configuration of the gamma based converter circuit in Fig. 3.2 is composed of bidirectional switches which are derived from an arrangement of switches called common emitter topology. A safe or proper commutation is needed to protect the switches and other components from excessive voltage during turn on and turn off. Voltage spikes are caused by an abrupt difference in the current of the inductor whiles current spikes are caused by a sudden difference in the voltage found in the capacitor which is also known as capacitor voltage [2-3]. Commutation circuits are provided in power electronic converters because of the difference in characteristics of switches, one term which is mostly used is deadtime which basically means that, switches will not respond to commands of turn on and turn off at the same time, the difference in time for the switches to achieve the same commands is known as deadtime. To protect switches from the effects of deadtime, complementary switching is done as shown in Fig. 3.4a and Fig. 3.4b.

Detailed explanation of this commutation switching can be found in [4], Fig. 3.5 shows the implementation of the safe commutation method, detailed explanation of the method is found in [4].

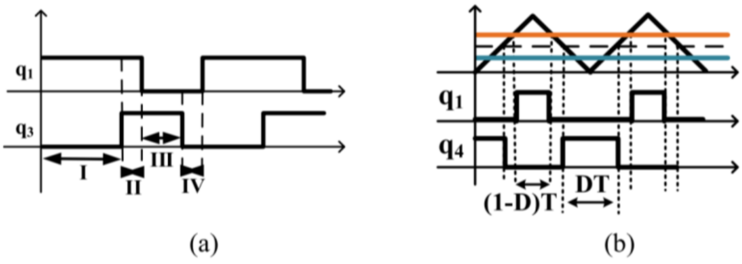


Figure 3.4: Switches modulation(Siwakoti et al., 2015)

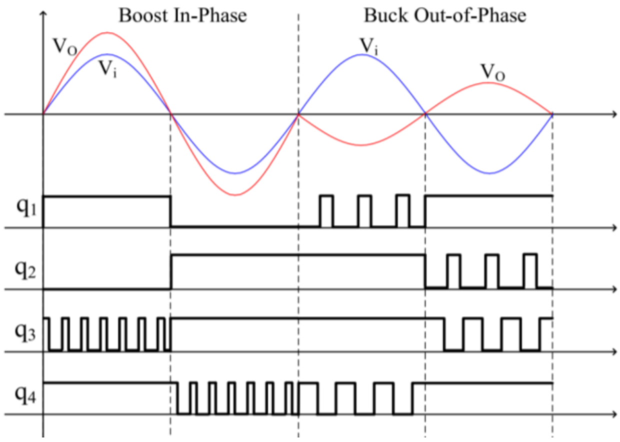


Figure 3.5: Safe commutation method(Siwakoti et al., 2015)

3.4 Comparison Between Gamma Z-source and T Z-Source

The boost factor of the Trans- Z-source converter is given as

$$B = \frac{1-D}{1-(1+n)D} \tag{3.17}$$

While the boost factor of the proposed controller method is

$$B = \frac{v_C}{v_i} = \frac{1-D}{1-D\left(1+\frac{1}{\gamma_\Gamma - 1}\right)} \tag{3.18}$$

The current flowing in both T and gamma type Z-Source converter is shown in Fig. 3.6. For turn ratio of 1.1 and less, the converter current in both Trans Z-Source and gamma type Z-source converter is the same. While for turn ratio greater than 1.1, the Gamma Z-Source converter has higher current value than T-Z-Source converter.

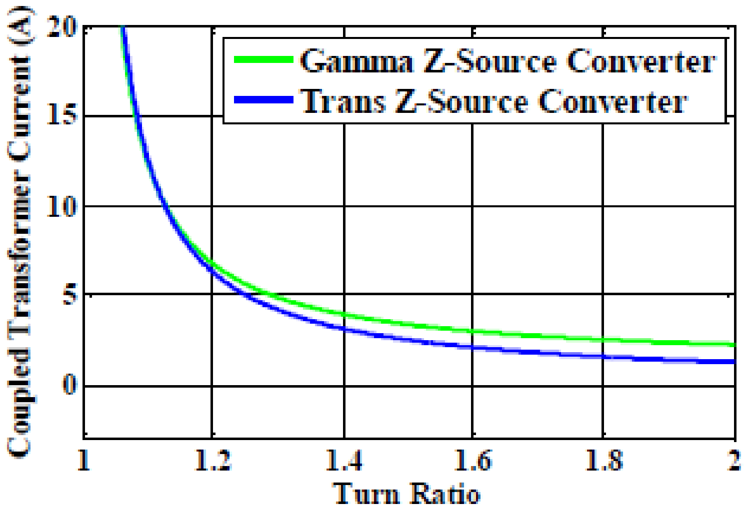


Figure 3.6 Current passing through Gamma and T Z-Source Converter.

For example, when the turn ratio is 1.8, the Trans Z-Source converter has current value of 2.5A, whereas the Gamma Z-Source converter has 3A current value.

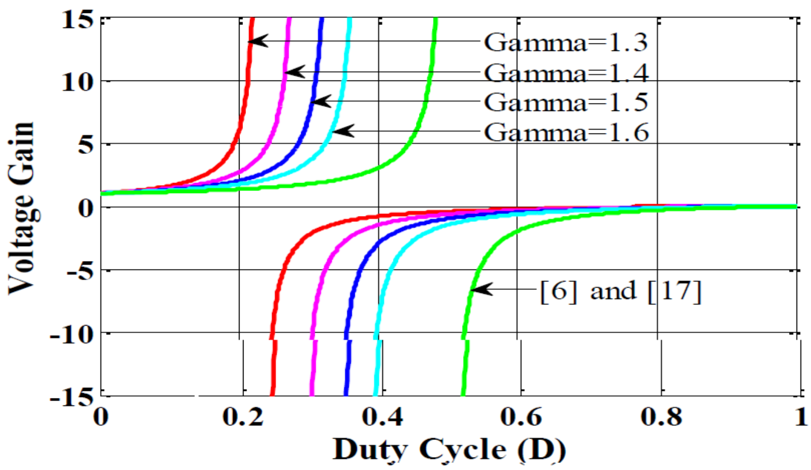


Figure 3.7 Output voltage gain versus duty cycle of Gamma Z-Source Converter.

Fig. 3.7 shows the voltage gain variation for Gamma Z-source converter for different values of duty ratio which varies from 0 to 1. The results are obtained for different values of gamma. When gamma is 1.3 the converter works as positive booster from duty value of 0 till D reaches value of 0.22 approximately. Whereas it works as negative booster after 0.22 with maximum value of negative booster at 0.22. Notice that as gamma increases, the value of duty ratio required to change from negative to positive booster increases.

3.5 Simulation Results

Simulation for the single phase ac-ac gamma ZS converter is carried in PSCAD environs, the results are done for two case scenarios; buck based topology and boost topology. Basically the same topology is used to provide an output voltage which is way greater than the input voltage hence the boost topology. Also the same topology is used to provide an output voltage which is much less than the source voltage hence buck topology or phenomenon. What this means is that the same to topology is applied to achieve buck-boost functionality. Table 3.1 shows the values of the parameters used in the simulation and Fig. 3.6 show the circuit used in modelling the PSCAD based circuit for simulation.

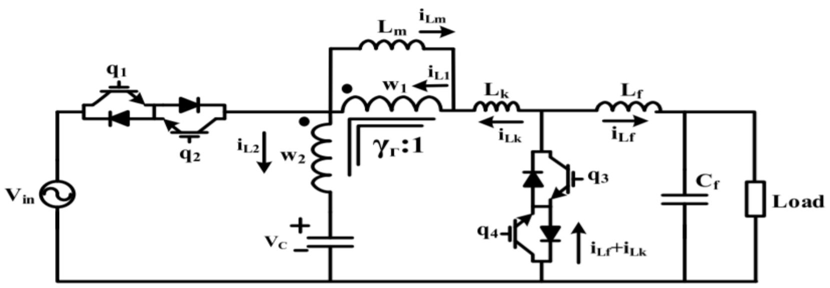


Figure 3.8: AC-AC gamma Z source converter(Siwakoti et al., 2015)

Table 3.1: Component Values

Parameter (Component)	Value
Input voltage	17.68V
Capacitor C	25 µF
Capacitor C	19.0 µF
Capacitor C_f	4µF
Inductor L_m	0.6µH
Inductor L_f	50mH
Load (RL)	60Ω, 100mH
Switching frequency	30000Hz
Duty cycle	0.36 boost 0.7 buck
Turns ratio, coupling coefficient	94/96, 0.999

3.5.1 Boost Simulation

The results of the simulation done for the proposed gamma based converter used in single phase application is shown below in graphical presentation. The simulation results shown below is done ***boost*** phenomenon. The simulation results for the following parameters are shown; current and voltage values for switches, passive components, transformer values and both input and output values.

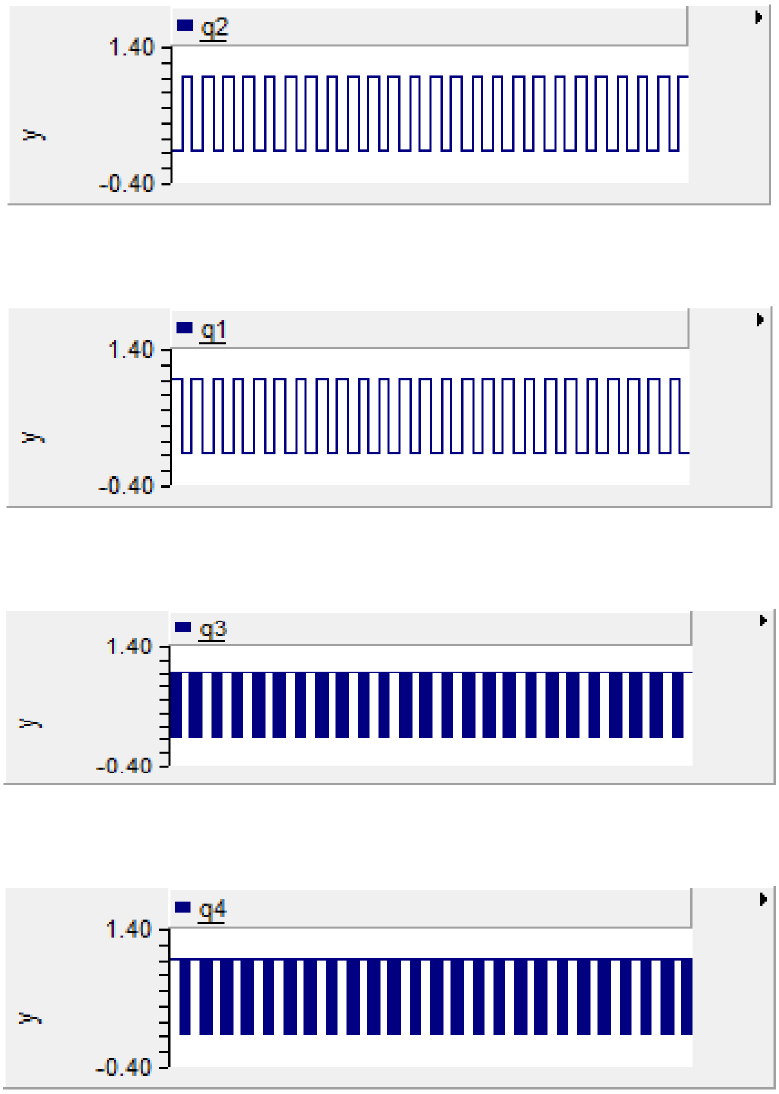


Figure 3.9: Switches commands

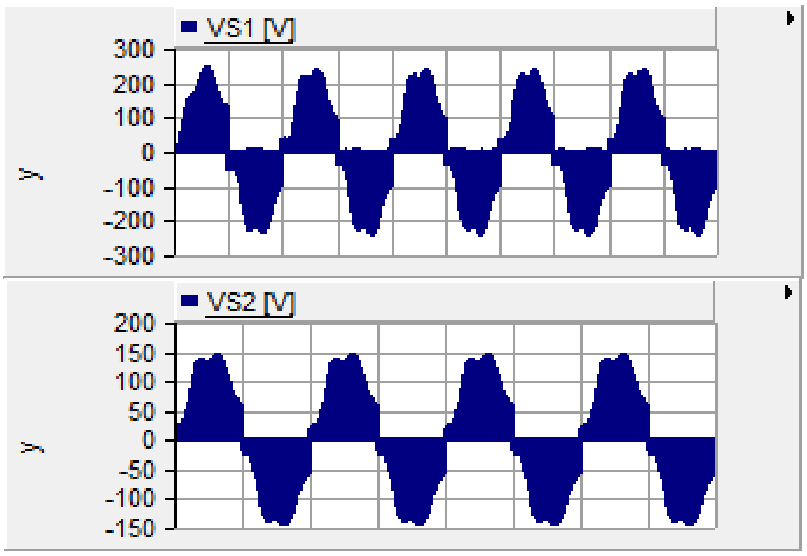
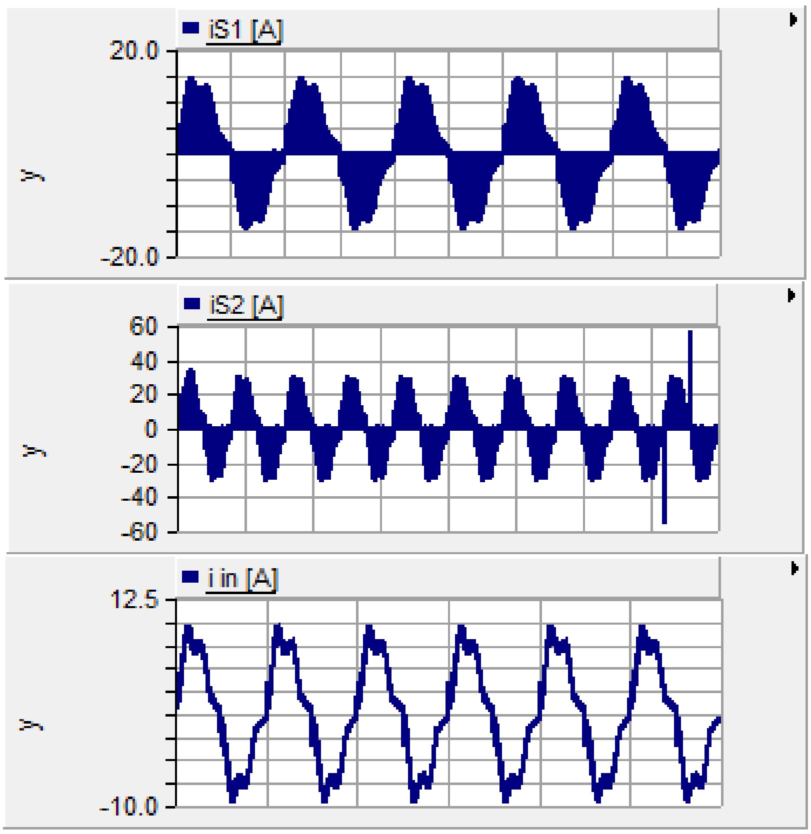


Figure 3.10: Voltage across the switches



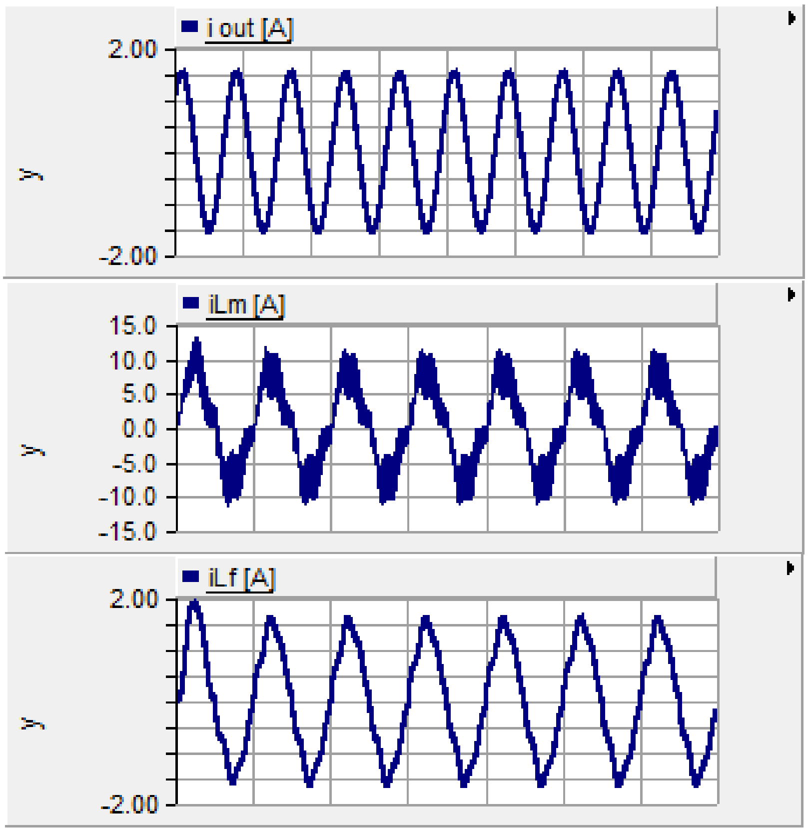


Figure 3.11: Current results

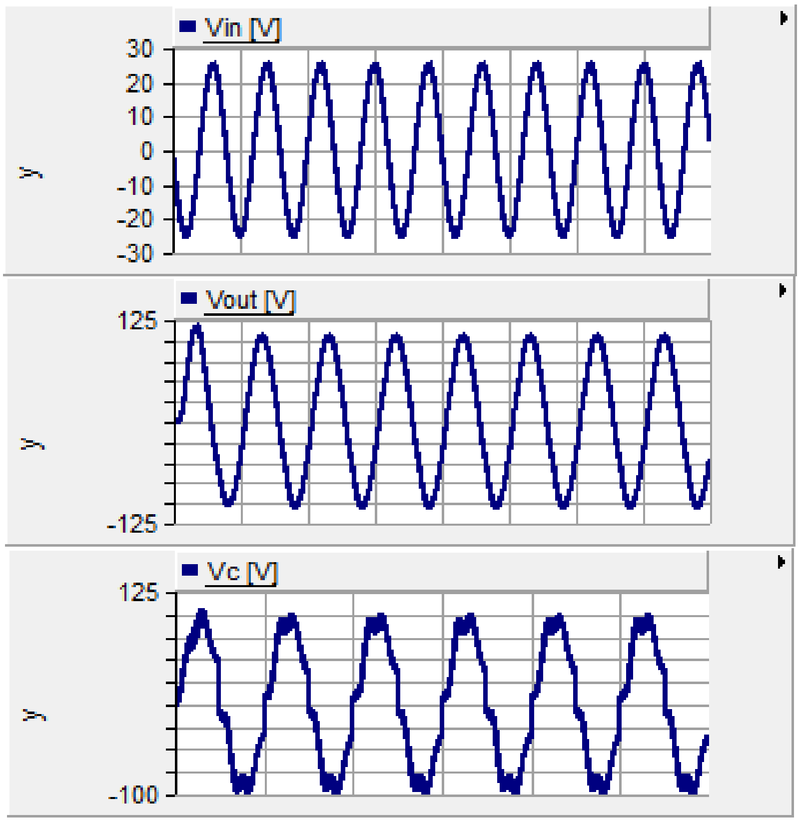


Figure 3.8: Voltage results

The simulation results generated above from Fig. 3.7 to Fig. 3.10 shows the results for ac-ac gamma converter used in the boost mode. The parameters and values used for the simulation is found in Table 3.1, in other to generate switch commands for the bidirectional switches, the commands of Fig. 3.7 are generated. Fig. 3.8 show the voltage values for the bidirectional switches, VS1 represents the voltage of the first bidirectional switch and VS2 represents the voltage of the second bidirectional switch. VSI and VS2 can be considered as the blocking voltages of the bidirectional switches. Fig. 3.9 show the various current values generated. IS1 and IS2 represents the current values of first and second bidirectional switches respectively. The input and output current values are also shown, the inductors L_m and L_f values are also given by the results. Since the topology is operated in the boost mode, the voltage output results shows that its value is more than the source voltage. The capacitor voltage value is also given by the graph named V_C; Fig. 3.10 represents the graph of all voltage values across the components, input and output results.

3.5.2 Buck Simulation

The results of the simulation done for the proposed gamma based converter used in single phase application is shown below in graphical presentation. The simulation results shown below is done ***buck*** phenomenon. The simulation results for the following parameters are shown; current and voltage values for switches, passive components, transformer values and both input and output values.

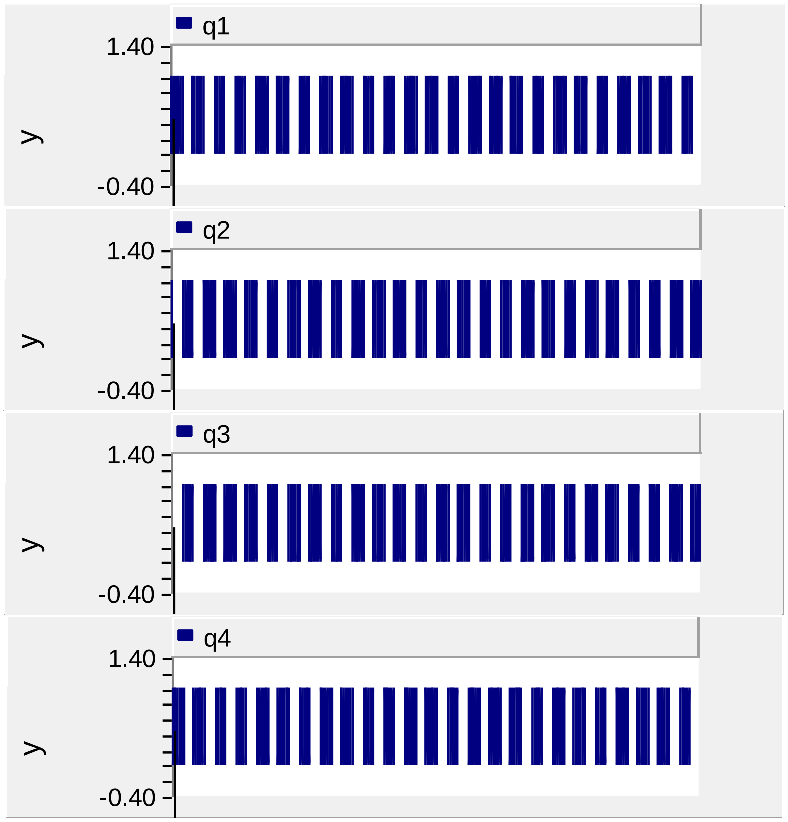


Figure 3.9: Switches commands

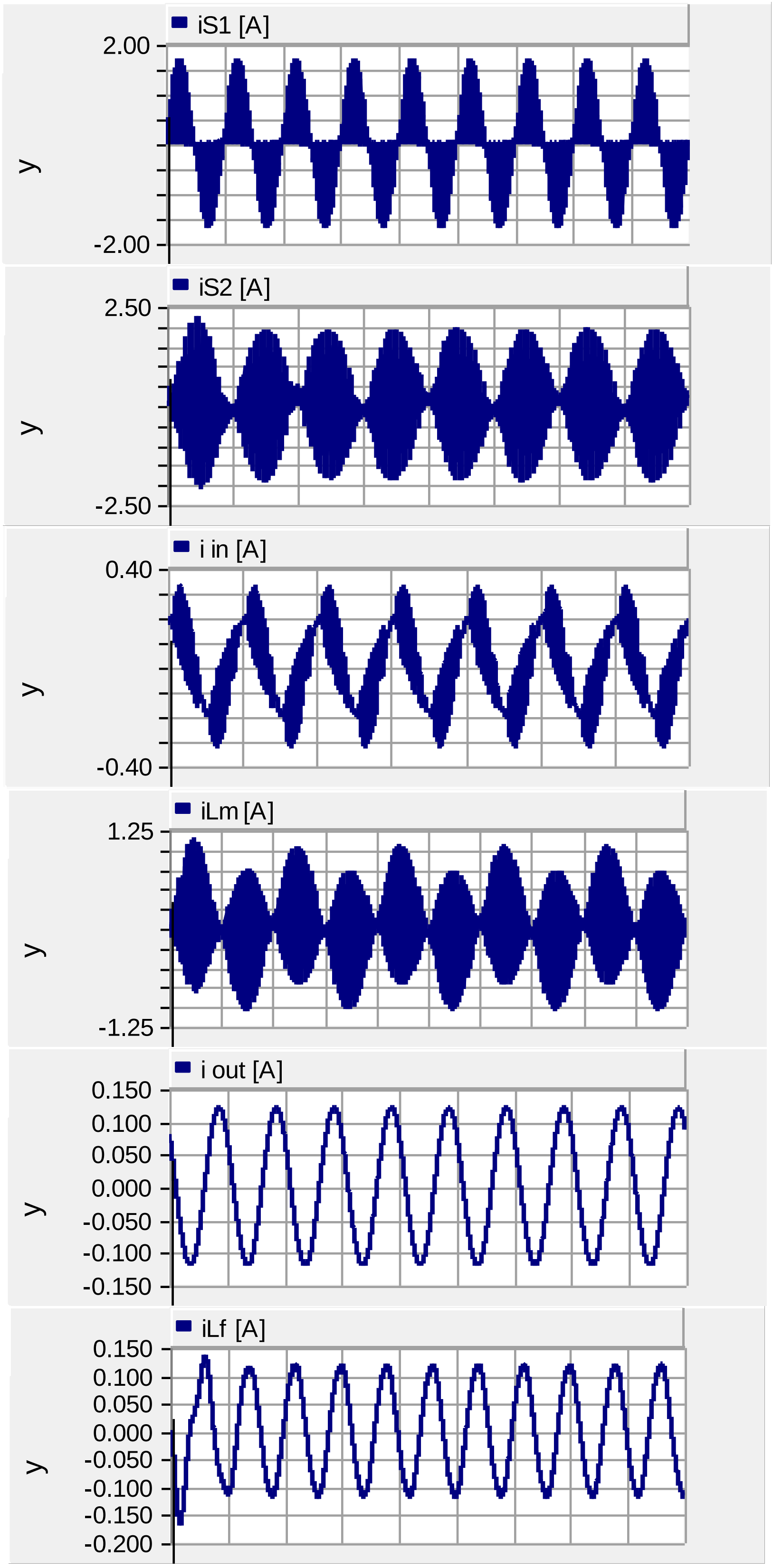


Figure 3.10: Current results

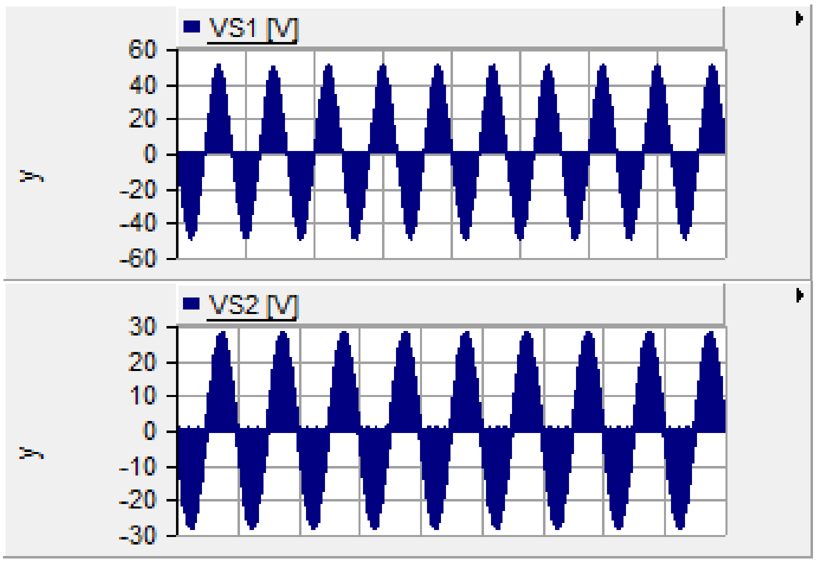


Figure 3.11: Voltage across the switches

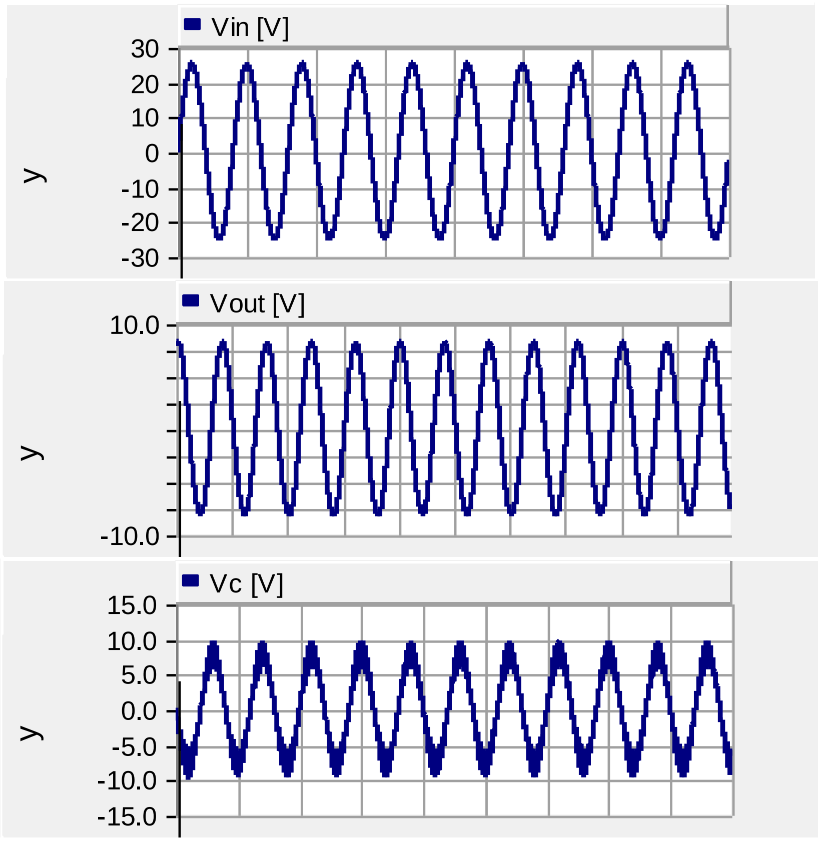


Figure 3.12: Voltage results

The simulation results generated above from Fig. 3.11 to Fig. 3.14 shows the results for ac-ac gamma converter used in the buck mode. The parameters and values used for the simulation is found in Table 3.1, in other to generate switch commands for the bidirectional switches, the commands of Fig. 3.11 are generated. Fig. 3.14 show the voltage values for the bidirectional switches when the converter is operated in ***buck mode***, VS1 represents the voltage of the first bidirectional switch and VS2 represents the voltage of the second bidirectional switch. VSI and VS2 can be considered as the blocking voltages of the bidirectional switches. Fig. 3.11 shows the various current values generated. IS1 and IS2 represents the current values of first and second bidirectional switches respectively. The input and output current values (i_{in} and i_{out}) are also shown, the inductors L_m and L_f values (current values) are also given by the results. Since the topology is operated in the buck mode, the voltage output results shows that its value is less than the value of the source voltage. The capacitor voltage value is also given by the graph named V_C; Fig. 3.14 represents the graph of all voltage values across the components, input and output results.

3.6 Conclusion

The goal of this section is to provide simulation results for the selected structure of converter under investigation. The selected converter is a single phase impedance based gamma converter operated as a cycloconverter i.e. delivering an ac voltage from an ac voltage source. The circuit of the proposed converter is analysed mathematical to provide the correct equations governing the circuit. Simulation is carried in two modes using the component values for buck and boost based converter; the results for the two simulations is shown above. Mathematical and simulation are verified which shows that the two results are the same.

CHAPTER 4

CONCLUSION

4.1 Conclusion

Power electronic converters have evolved to a much better device over the last two decades; from voltage and current source converters to multilevel or multi-step converter and impedance based converter; contributing immensely to the generation and transmission of electric power devoid of power quality vices such as voltage dip, short and long disturbances or interruptions, voltage swell, noise, harmonic distortion, unbalance voltages, voltage spike and fluctuations, etc.

As explained in chapter one of this thesis, the term or word ***converter*** is used to describe a power electronic device or circuit which is capable of conditioning voltage or current from one level to another (step-up or step-down) or from one type to another (ac to dc or vice versa) or perform both functions. The use of power electronic converters in today's world can be seen from various sectors of human life such as communication, transport (land, sea and air), agriculture, health, industrial or factories etc.

Voltage and current source converters can be described as the pioneer converter which have received much utilization in academia and industry but their disadvantages lead to the introduction of impedance based converter popularly known as ZS converter. The impedance based converter has resolved a lot of the disadvantages of VS and CS converters; some major limitations which have been solved are buck-boost functionality, single stage conditioning of power especially in the case of ac-ac conversion, high boosting abilities without introduction of a second converter and most importantly reduced of converter system where buck-boost capabilities are required. Although the impedance based converters solved the limitations of the conventional converters, they also introduced initial limitations which reduced the efficiency. The conventional ZS converter's limitations were resolved with the introduction of the quasi ZS topologies which were very useful in photovoltaic system applications because of its ability to accept wide range of voltage fluctuations; a common phenomenon associated with photovoltaic systems. Other topologies which were later introduced are the high boosting topologies popularly known as the switched boost topology; this topology had the main advantage of higher boosting abilities with reduced number of passive components. Other switched topologies are the switched inductor, switched capacitor or the combination of the capacitor and inductor into one switched topology.

The above mentioned topologies had impedance network which did not contain any windings, hence the Trans, T and gamma based impedance converters having windings were introduced. Higher gain or boosting was achieved in the impedance-winding based converter by increasing the turns ratio of the windings, however the gamma based topologies achieved higher boosting by utilizing a reduced number of turns ratio which an opposite method to the Trans T topology.

The goal of our thesis is to investigate the simulation of gamma based converter applied in single phase ac-ac power conditioning. The advantage of gamma based converter in ac-ac power condition when compared to other topologies such as matrix converter, direct ac-ac, and indirect ac-ac converters is the gamma based topology provides higher output voltage than the matrix topology, the gamma topology has reduced number of circuit component, single stage power conditioning is achieved with the gamma topology, the power system is not polluted by the gamma based converter. Common grounds between the input and the output of the gamma topology provides balanced voltage at the source and output. Simulation our proposed converter in PSCAD is done in chapter three of this thesis and results generated to confirm our mathematical equation. The results are produced for two case scenarios; buck methodology and boost methodology. The same circuit parameters and components are utilized for both cases and results produced. The results produced confirms the stated mathematical equations where higher boosting capabilities are achieved with reduced number of turns ratio of the transformer or coupled inductor. For example, in the boost topology, the input voltage is approximately 18V which produces a very high output voltage of approximately 125volts. Analysis of the simulation shows that application of the gamma based converter for power conversion is an ideal choice. Buck functionality, boost functionality and buck-boost functionality can be achieved with one topology without any major changes to the circuit. Since successful power conversion is achieved with the proposed topology, it will be a useful device in achieving efficient utilisation of renewable energy sources hence help in reducing global warming. Using renewable energy will increase the availability of power to especially third or developing countries, boost socio-economic activities hence improve on standard of living.

4.2 Recommendation

Future or further investigation of the gamma based topology can be done by combining previous topologies such as quasi, cascaded, switched etc. to the gamma based topology analyse the effect of the new topology. For instance I will like to research into the cascaded topology and analyse the converter from symmetrical and asymmetrical points of view.

REFERENCES

A. A. Khan, H. Cha, and H. F. A. (n.d.). "An improved single-phase direct PWM inverting buck-boost AC-AC converter," IEEE ,. *Trans. Ind. Electron.*, *63*(9), 5384–5393.

A. A. Khan, H. Cha, and H. F. A. (2016). ,"High-efficiency single-phase AC-AC converters without commutation problem,." *IEEE Trans. Power Electron*, *31*(8), 5655–5665.

A. C. N. Maia, C. B. Jacobina, and G. A. A. C. (2017). "A new three-phase AC-DC-AC multilevel converter based on cascaded three-leg converters,." *IEEE Trans. Ind. Appl*, *53*(3), 2210–2221.

Abu-Rub, H., Iqbal, A., Ahmed, S. M., Peng, F. Z., Li, Y., & Baoming, G. (2013). Quasi-Z-source inverter-based photovoltaic generation system with maximum power tracking control using ANFIS. *IEEE Transactions on Sustainable Energy*, *4*(1), 11–20. https://doi.org/10.1109/TSTE.2012.2196059

Al, B. G. et. (2013). "An energy stored quasi-Z-source inverter for application to photovoltaic power system,." *IEEE Trans. Ind. Electron.*, *60*, 4468–4481,.

Alexandridis, G. C. K. and A. T. (n.d.). "Full-scale modeling, control, and analysis of grid-connected wind turbine induction generators with back-to-back AC/DC/AC converters,. *IEEE J. Emerg. Sel. Topics Power Electron.*, *2*(4), 739–748.

Axelrod, B., Berkovich, Y., and Ioinovici, A. (n.d.). 'Switched capacitor/switched inductor structures for getting transformerless hybrid DC–DC PWM converters.' *IEEE Trans. Circuits Syst.*, 687–696.

D. Sun, B. Ge, X. Yan, D. Bi, H. Zhang, Y. Liu, H. Abu-Rub, L. BenBrahim, F. P. (2014). "Modelling, impedance design, and efficiency analysis of quasi-Z source module in cascade multilevel photovoltaic power system,." *IEEE Trans. Ind. Electron.*, *61*, 6108–6117.

D. Vincenti, H. Jin, and P. Z. (n.d.). "Design and implementation of a 25-kVA three-phase PWM AC line conditioner,." *IEEE Trans. Power Electron.*, *9*(4), 384–389.

E. C. dos Santos, C. B. Jacobina, N. Rocha, and E. R. C. da S. (n.d.). , “Sixphase machine drive system with reversible parallel AC-DC-AC converters,.” *IEEE Trans. Ind. Electron., 58*(5), 2049–2053.

Ellabban, O., Abu-Rub, H. (2016). Z-Source inverter: topology improvements review. *IEEE Ind*, . 6–24.

Engineering, E., & Circuit, Q. I. (2009). Quasi-Z-Source Inverter for Photovoltaic Power Generation Systems. *2009 Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition*, 918–924. https://doi.org/10.1109/APEC.2009.4802772

F. Khosravi, N. Ahmad Azli, and A. K. (2014). “Design of a reduced component count single-phase to three-phase quasi-z-source converter,. *” IET Power Electron.,* 489–495.

F. Z. Peng, M. Shen, and Z. Q. (2005). “Maximum boost control of the Zsource inverter,.” *IEEE Trans. Power Electron*, *20*.

F. Z. Peng, X. Yuan, X. Fang, and Z. Q. (2003). “Z-source inverter for adjustable speed drives,.” *IEEE Power Electron*, *1*(2), 33–35.

F. Z. Peng. (2004). Z-Source Inverter for Motor Drives., 249–254.

F.Z. Peng, M. Shen, and Z. Q. (2004). Maximum boost control of the Z-source inverter. *Proc. IEEE PESC’04*, 255–260.

Fang, X. P., Qian, Z. M., & Peng, F. Z. (2005). Single-phase Z-source PWM AC-AC converters. *IEEE Power Electronics Letters*, *3*(4), 121–124. https://doi.org/10.1109/LPEL.2005.860453

Farhangi, B. F. and S. (2006). “Comparison of Z-source and boost-buck inverter topologies as a single phase transformer-less photovoltaic grid connected power conditioner,.” *Proc. 37th IEEE PESC*, 1–6.

Fathi, H., & Madadi, H. (2016). Enhanced-Boost Z-Source Inverters with Switched Z-Impedance. *IEEE Transactions on Industrial Electronics*, *63*(2), 691–703. https://doi.org/10.1109/TIE.2015.2477346

Guo, F., Fu, L., Lin, C.H., et al. (n.d.). ‘Development of an 85-kW bidirectional quasi-Z-source inverter with DC-link feed-forward compensation for electric vehicle applications’,. *IEEE Trans. Power Electron.,* 5477–5488.

Guo, F., Fu, L., Lin, C. H., Li, C., Choi, W., & Wang, J. (2013). Development of an 85-kW bidirectional quasi-Z-source inverter with DC-link feed-forward compensation for electric vehicle applications. *IEEE Transactions on Power Electronics*, *28*(12), 5477–5488. https://doi.org/10.1109/TPEL.2012.2237523

H. F. Ahmed, H. Cha, A. A. Khan, J. Kim, and J. C. (2017). “A single-phase buck-boost matrix converter with only six switches and without commutation problem,.” *IEEE Trans. Power Electron.*, *32*(2), 1232–1244,.

H. F. Ahmed, H. Cha, A. A. Khan, and H. G. K. (n.d.). “A novel buck-boost AC-AC converter with both inverting and non-inverting operations and without commutation problem,.” *IEEE Trans. Power Electron.*, *31*(6), 4241–4251.

H. Zeinali, A. Mostaan, and A. B. (2014). “Switched inductor gamma source inverter,.” In *5th Power Electronics, Drive Systems and Technologies Conf. (PEDSTC)* (p. 187–192.).

Hanif, Z. A. M. (n.d.). , “Operational Analysis of Improved Γ-Z-Source Inverter with Clamping Diode and its Comparative Evaluation,”,. *In IEEE Transactions on Industrial Electronics*, *99*, 1–1.

Ismeil, M., Orabi, M., Kennel, R., Ellabban, O., & Abu-Rub, H. (2014). Experimental studies on a three phase improved switched Z-source inverter. *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, 1248–1254. https://doi.org/10.1109/APEC.2014.6803466

J.-W. Jung and A. Keyhani. (2007). “Control of a fuel cell based Z-source converter. *IEEE Trans. Energy Convers*, *22*(2), 467–476.

J. Anderson, F. Z. P. (2008). Four quasi-Z-source inverters. *Proc. IEEE PESC*, 2743–2749, Ju.

J. G. de Oliveira, H. Schettino, V. Gama, R. Carvalho, and H. B. (n.d.). , “Study on a doubly-fed flywheel machine-based driveline with an AC/DC/AC converter,.” *IET Elect. Syst. Transp., 2*(2), 51–57.

J. Liu, J. Hu, and L. X. (2007). “Dynamic modelling and analysis of Z source converter-derivation of ac small signal model and design-oriented analysis,” , vol. 22, no. 5, pp. Sep. *IEEE Trans. Power Electron.*, *22*(5), 1786–1796,.

J. W. Kolar, F. Schafmeister, S. D. Round, and H. E. (2007). “Novel three-phase AC-AC sparse matrix converters,.” *IEEE Trans. Power Electron., 22*(5), 1649–1661,.

L. G. G. de Vicuna, M. Castilla, J. Miret, J. Matas, and J. M. G. (2009). “Sliding-mode control for a single-phase AC/AC quantum resonant converter,.” *IEEE Trans. Ind. Electron.*, *56*(9), 3496–3504.

L. He, S. Duan, and F. P. (2013). “Safe-commutation strategy for the novel family of quasi-Z-source AC/AC converter,” . *IEEE Ind. Informat*, *9*(3), 1538–1547.

Liu, Y., Ge, B., Abu-Rub, H., et al. (2015). ‘Comprehensive modelling of single phase quasi-Z-source photovoltaic inverter to investigate low-frequency voltage and current ripple’,. *IEEE Trans. Ind. Electron.*, 4194–4202.

M.-K. Nguyen, Y.-G. Jung, and Y.-C. L. (2010). “Single-phase ac-ac converter based on quasi-Z-source topology,.” *IEEE Trans. Power Electron*, *25,* 2200–2210.

M. K. Nguyen, T. D. Duong, Y. C. Lim, Y. G. K. (2018). “Switched-Capacitor Quasi-Switched Boost Inverters”,. *IEEE Trans. Of Ind. Electronics, 65,* 5105–5113.

M. R. Banaei, R. Alizadeh, N. Jahanyari, and E. S. N. (2016). “An ac Zsource converter based on gamma structure with safe-commutation strategy,”.,. *IEEE Trans. Power Electron*, *31*(2), 1255–1262.

M. Shen, F. Z. P. (2005). Operation modes and characteristics of the Z-source inverter with small inductance. *Proc. IEEE IAS’*, 1253–1260.

M. Vijayagopal, P. Zanchetta, L. De Lillo, L. Empringham, L. Tarisciotti, and P. W. (2017). “Control of a direct matrix converter with modulated model predictive control," . *IEEE Trans. Ind. Appl*, *53*(3), 2342– 2349,.

Miaosen Shen, Jin Wang, Alan Joseph, Fang Z. Peng, Leon M. Tolbert, and Donald J. Adams, "Maximum constant. (2004). boost control of the Z-source inverter. *Proc. IEEE IAS*, 142.

Minh-Khai Nguyen, Geum-Bae Cho, Y.-C. L. (2016). "Switched-boost network-based single-phase boost DC–AC converter", 2016, Vol. 9, Iss. 14, pp.. *IET Power Electron, 9*, 2723–2730.

Mo, W., Loh, P.C., Blaabjerg, F. (2014). 'Asymmetrical Γ-source inverters.' In *IEEE Trans. Ind. Electron.* (p. 637–647.).

N. A. Ahmed, K. Amei, and M. S. (1999). "A new configuration of singlephase symmetrical PWM AC chopper voltage controller,." *IEEE Trans. Ind. Electron.*, *46*(5), 942–952.

Nguyen, M.-K., Choi, J.-H., Lim, Y.-C., & Choi, Y.-O. (2016). Trans-switched boost inverters. *IET Power Electronics*, *9*(5), 1065–1073. https://doi.org/10.1049/iet-pel.2015.0202

Nguyen, M.-K., Lim, Y.-C., & Park, S.-J. (2015). A Comparison Between Single-Phase Quasi- <inline-formula> <tex-math notation="LaTeX">Z</tex-math></inline-formula>-Source and Quasi-Switched Boost Inverters. *IEEE Transactions on Industrial Electronics*, *62*(10), 6336–6344. https://doi.org/10.1109/TIE.2015.2424201

Nguyen, M. K., Le, T. V., Park, S. J., & Lim, Y. C. (2015). A class of quasi-switched boost inverters. *IEEE Transactions on Industrial Electronics*, *62*(3), 1526–1536. https://doi.org/10.1109/TIE.2014.2341564

O. Husev, C. R. Clemente, E. R. Cadaval, D. Vinnikov, and S. S. (2015). "Single phase three-level neutral-pointclamped quasi-Z-source inverter,." *IET Power Electron.*, *8*(1), 1–10.

P. Alemi, Y. C. Jeung, and D. C. L. (2015). "DC-link capacitance minimization in T-type three-level AC/DC/AC PWM converters,." *IEEE Trans. Ind. Electron., 62*(3), 1382–1391.

Peng, F. Z. (2003). Z-Source Inverter. *IEEE Transactions on Industry Applications*, *39*(2), 504–510.

Qian, W., Peng, F. Z., J& Cha, H. (2011). Trans-Z-Source Inverters. *IEEE Transactions on Power Electronics*, *26*(12), 3453–3463. https://doi.org/10.1109/TPEL.2011.2122309

R. Strzelecki, M. Adamowicz, N. Strzelecka, and W. B. (2009). "New type T-source inverter,." *In Proc. Compat. Power Electron*, 191–195.

Ravindranath, A., Mishra, S., Joshi, A. . '. (2013). Analysis and PWM control of switched boost inverter'. *IEEE Trans. Ind. Electron.*, 5593–5602.

Reddiprasad Reddivari, D. J. (n.d.). "Differential mode gamma source inverter with reduced switching stresses",. In *IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*.

S. Vidhya and T. Venkatesan. (2018). "Quasi-Z-source indirect matrix converter fed induction motor drive for flow control of dye in paper mill,." *IEEE Trans. Power Electron.*, *33*(2), 1476–1486.

Sabahi, E. S. A. ; E. B. ; V. R. ; M. (2017). "A new topology for half-bridge Z-source inverter based on gamma structure." In *10th International Conference on Electrical and Electronics Engineering (ELECO)*, (pp. 330–334).

Shen, H., Zhang, B., Qiu, D., & Zhou, L. (2016). A Common Grounded Z-Source DC-DC Converter With High Voltage Gain. *IEEE Transactions on Industrial Electronics*, *63*(5), 2925–2935. https://doi.org/10.1109/TIE.2016.2516505

Shen, M., Wang, J., Joseph, A., Peng, F. Z., Tolbert, L. M., & Adams, D. J. (2006). Constant boost control of the Z-source inverter to minimize current ripple and voltage stress. *IEEE Transactions on Industry Applications*, *42*(3), 770–778. https://doi.org/10.1109/TIA.2006.872927

Siwakoti, Y. P., Peng, F. Z., Blaabjerg, F., Loh, P. C., & Town, G. E. (2015). Impedance-

Source Networks for Electric Power Conversion Part I: A Topological Review. *IEEE Transactions on Power Electronics*, *30*(2), 699–716. https://doi.org/10.1109/TPEL.2014.2313746

Sun, D., Ge, B., Peng, F. Z., Haitham, A. R., Bi, D., & Liu, Y. (2012). A new grid-connected PV system based on cascaded H-bridge quasi-Z source inverter. *IEEE International Symposium on Industrial Electronics*, 951–956. https://doi.org/10.1109/ISIE.2012.6237218

V. Fernão Pires, A. Cordeiro, D. F. and J. F. M. (2016). “Quasi-ZSource Inverter With a T-Type Converter in Normal and Failure Mode,.” *IEEE Transactions on Power Electronics*, 7462–7470.

W. Liang, Y. Liu, B. Ge, H. Abu-Rub, R. S. Balog, and Y. X. (n.d.). “Doubleline-frequency ripple model, analysis & impedance design for energy stored single-phase quasi-Z source photovoltaic system,”. *IEEE Trans. Ind. Electron*, *65*(04).

W. Mo, P. C. Loh, F. B. and P. W. (n.d.). “Trans-Z-source and Γ - Z-source neutral-point-clamped inverters,.” *IET Power Electronics*, *8*(3), 371–377.

W. Mo, P. C. L. and F. B. (n.d.). , “Asymmetrical $Gamma$-Source Inverters,.” *In IEEE Transactions on Industrial Electronics*, *61*(2), 637–647,.

Y. Liu, B. Ge, H. Abu-Rub, and F. P. (2014a). “An effective control method for quasi-Z-source cascade multilevel inverter-based grid-tie single-phase photovoltaic power system,.” *IEEE Trans. Ind. Informat.*, *10*.

Y. Liu, B. Ge, H. Abu-Rub, and F. P. (2014b). “Phase-shifted pulse-width amplitude modulation for quasi-Z-source cascade multilevel inverter based photovoltaic power system,.” In *IET Power Electron.* (pp. 1444–1456).

Y. Xue, B. Ge, and F. P. (2012). “Reliability, efficiency, cost comparisons of MW-scale photovoltaic inverters,.” *In Proc. IEEE ECCE*, 1627–1634.

Yu Tang, Shaojun Xie, Chaohua Zhang, & Zegang Xu. (2009). Improved Z-Source Inverter With Reduced Z-Source Capacitor Voltage Stress and Soft-Start Capability.

IEEE Transactions on Power Electronics, *24*(2), 409–415. https://doi.org/10.1109/tpel.2008.2006173

Zhang, S. X. Y. T. C. (n.d.). "Research on third harmonic injection control strategy of improved Z-Source Inverter" pp. In *Energy Conversion Congress and Exposition, 2009. ECCE 2009. IEEE* , (p. 3853 – 3858.).

Zhou, Y., Liu, L., & Li, H. (2013). A high-performance photovoltaic module-integrated converter (mic) based on cascaded quasi-z-source inverters (qzsi) using egan fets. *IEEE Transactions on Power Electronics*, *28*(6), 2727–2738. https://doi.org/10.1109/TPEL.2012.2219556

Zhou, Z. J., Zhang, X., Xu, P., & Shen, W. X. (2008). Single-phase uninterruptible power supply based on Z-source inverter. *IEEE Transactions on Industrial Electronics*, *55*(8), 2997–3004. https://doi.org/10.1109/TIE.2008.924202

Zsource inverter for adjustable speed drives". (2003). *IEEE Power Electronics Letters*, *1*(2), 33–35.