IMPEDANCE SOURCE INVERTER

A THESIS SUBMITTED TO GRADUATE SCHOOL OF APPLIED SCINCES OF NEAR EAST UNIVERSITY

BY
KHALIFA ZAGHDOUD

In Partial Fulfilment of the Requirement for the degree of Master of Science in Electrical and Electronic Engineering

NICOSIA, 2019

Khalifa Zaghdoud **IMPEDANCE SOURCE INVERTER** **NEU 2019**

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Khalifa ZAGHDOUD: IMPEDANCE SOURCE INVERTER

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 Masters of Science Electrical and Electronic Engineering

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To my family

ACKNOWLEDGEMENTS

My study at the Near East University period three years learned this, this is unable to the completion of this thesis, thank you to all my professors. The guidance of Professor Ebrahim Babaei who provided me the assistance to the consistency of the steps of accomplishing this work which was preceded by his efforts during the power electronics in which I found decisive influence on the ability to follow up many of the results and studies of other researchers which helped a lot in completing this thesis.

I will not forget the patience and their supportive attitude towards my family during the period of study.

ABSTRACT

This thesis presents an impedance-source or power converter type and with it's control method. The Z-source converter presented here is for dc to ac converter, voltage source inverter. In fact; the Z-source inverter's concept can be applied to other conversion topologies such as dc-dc, ac-dc and ac-ac converters. Since it is invented, the Z-source inverter has shown great advantages over the classical voltage-source and current-source converters. The concept of shoot-through is utilized which allows the one-leg's switches to switch simultaneously in case of voltage source inverter; which was not allowed before. The shoot-though allows further improvement in the output voltage range, where it is used to increase the output level. Simulation using PSCAD are presented for single phase Z-source inverter controlled using pulse width modulation in order to show the basic operation of the converter.

***Keywords*:** Converter; impedance-source inverter; pulse width modulation; voltage source inverter; current source inverter

ÖZET

Bu tez bir empedans kaynağı veya güç çevirici tipi ve kontrol yöntemi ile sunulmaktadır. Burada sunulan Z-kaynak dönüştürücü, dc dönüştürücü, voltaj dönüştürücüdür. Aslında; Z-kaynak invertörünün konsepti, dc-dc, ac-dc ve ac-ac dönüştürücüler gibi diğer dönüşüm topolojilerine uygulanabilir. Z-kaynağı invertör, icat edildiği için klasik voltaj kaynağı ve akım kaynağı dönüştürücülerine göre büyük avantajlar göstermiştir. Tek bacaklı anahtarların, gerilim kaynağı invertörü durumunda eşzamanlı olarak geçişine izin veren ateşleme kavramı kullanılır; Daha önce izin verilmedi. Çekiş, çıkış seviyesini arttırmak için kullanıldığı çıkış voltaj aralığında daha fazla iyileştirmeye izin verir. PSCAD kullanarak simülasyon, dönüştürücünün temel çalışmasını göstermek için darbe genişlik modülasyonu kullanılarak kontrol edilen tek fazlı Z-kaynaklı invertör için sunulmuştur.

***Anahtar Kelimeler*:** Dönüştürücü; empedans-kaynak invertörü; darbe genişlik modülasyonu; voltaj kaynağı invertörü; akım kaynağı invertörü

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LIST OF ABBREVIATIONS

AC:	Alternating Current
BJT:	Bipolar Junction Transistor
CSI:	Current Source Inverter
DC:	Direct Current
EMI:	Electromagnetic Interference
GTO:	Gate Turn-Off Thyristor
HVDC:	High Voltage Direct Current
IGBT:	Insulated Gate Bipolar Transistor
IPM:	Intelligent Power Module
MOSEFET:	Metal Oxide Semiconductor Field Effect Transistor
PWM:	Pulse Width Modulation
RMS:	Root Mean Square
SVM:	Space Vector Modulation
THD:	Total Harmonic Distortion
VSI:	Voltage Source Inverter
ZSI:	Z-Source Inverter

CHAPTER 1
INTRODUCTION

Conventional converter topologies such as voltage source inverter (VSI) and current source inverter (CSI) are commonly used as power electonics circuits for power conversion purposes. The VSI producses an ac output (after filtering it) which is limited below the dc input voltage, which means that VSI is buck type converter. The buck operation nature of the VSI limit its operation to power conversion applications and ac drive circuits. An additional dc-dc unit is connnected to the dc input of the converter in order to further increase the dc input voltage,which leads to an increase in the ac output voltage. As a result; the additional dc-dc boost converter increases the system cost, control complexity and reduceses the effiency. Furthermore, any misgating for the inverter bridge switches cause short circuit and destroies the power switching devices. For that, a dead-time is set between the upper and the lower switching devices at the same leg in order to avoid short circuit occurances.

On the other hand, for CSI type of converter, the output voltage is always greater than the input voltage. In order to have an output voltage which is less than the input an additional dc-dc buck converter is installed at the input of the CSI. Which increase the cost, control complexity and reduceses the overall efficency. Besides the fact that the lower and the upper switches should be turnned-on simaltaneously, if not; an open circuit for the dc input source cause huge current flow and destroys the power switching devices.

The idea of impedance-source converter (ZSI) was originally developed due to the limitation in VSIs and CSIs. The conceptual and theoritical limitations in the conventional converters types linmited their application and complicates their control methods. While the ZSI great advantage can be seen as: it can operate as VSI inverter (buck type) or as CSI inverter (boost type) depending on the application. Where the output voltage can ideally ranges from zero to infinity.

Since the invention of the ZSI inverter, there are hundereds of research works on this interesting topology, and this thesis presents it's basic operation and control.

CHAPTER 2
LITRETURE REVIEW

2.1 Introduction

Power electronics is used in converting the electrical energy from one form to another. Meaning to convert DC to AC or DC and to convert the AC power to AC or DC power. In order to be able to do these four conversion types, one needs to consider power electronics application, control and topologies. The power conversion should be done in an efficient, clean, compact, and robust manner for convenient utilization.

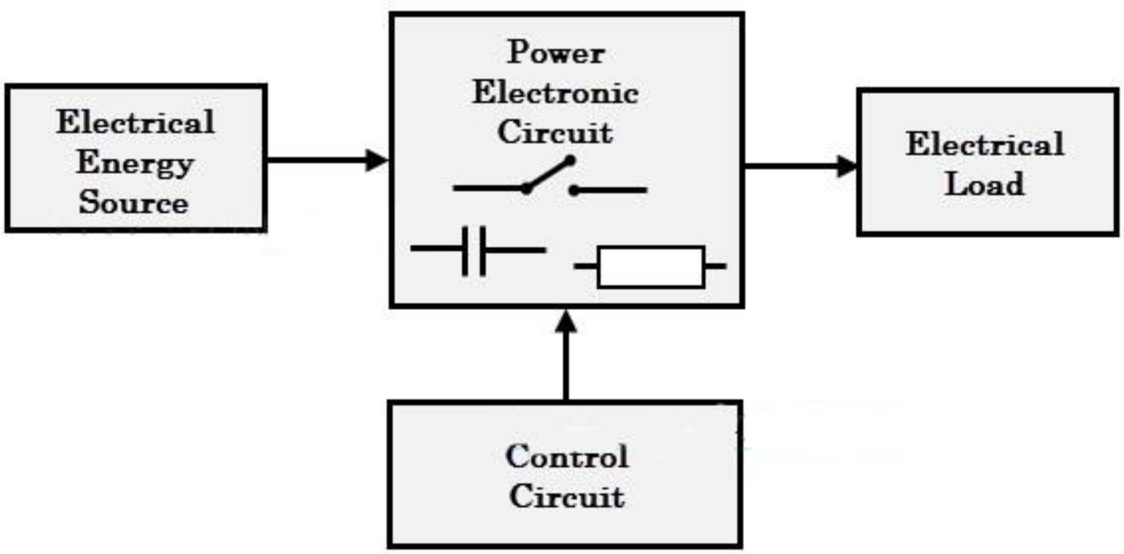

Fig 2.1: Basic configuration of power electronic converter (Rashid, 2018)

Power converters shown in Fig 2.1 differs from linear electronics (the electronics used in ICs for instance) is in their power rating. In linear electronics the power ranges in few watts, while in power electronics applications the power reaches up to megawatts values. For example, power semiconductor diode is the “power level” counter part of the “low power signal diodes”. These power devices, however, are required to carry up to several KA of current under forward bias condition and block up to several KV under reverse biased condition. Similarly, we have Bipolar Junction Transistor (BJT), Gate Turn-Off Thyristor (GTO), Metal Oxide Semiconductor Field Effect Transistor (MOSFET) and Insulated Gate Bipolar Transistor (IGBT) which are among many other power semiconductor used in the field of power electronics.

2.2 AC to DC Converters

AC to DC converters are referred to as rectifiers also, it "rectifies" the sinusoidal waveform of power into a pure DC power. Basic configuration of any AC-Dc converter is shown in Fig 2.2 The conversion maybe to an AC voltage or current in general. Due to the fact that the conversion is done from AC power supply, usually the output is not pure DC, instead, it contains high frequency harmonics in it. This requires using an electronic filter to smooth the power output. The filtering may done passively or it may be done by passive and active filtering process. The passive filtering refers to adding a passive element to the circuit like C or LC or higher order filters, while the active filtering refers to involve the control technique in reducing the ripple of the output power.

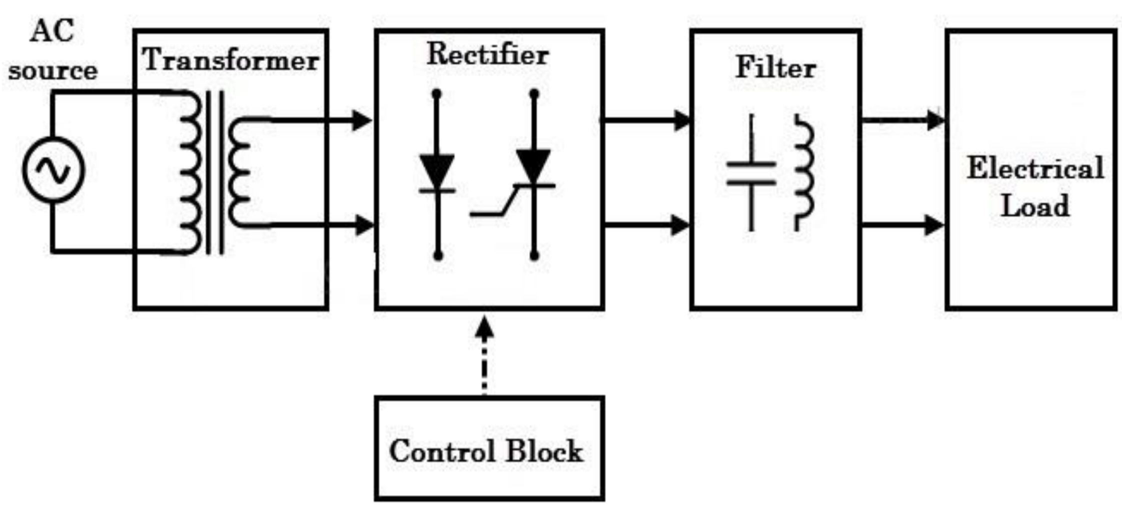

Fig 2.2: : Block diagram of an AC-DC rectifiers (Holmes & Lipo, 2003)

Rectifiers are used to provide DC power supply and in high voltage direct current (HVDC) power transmission system, where the power in converted from AC to DC then again to AC at high power rating, this is done in order to avoid the classical problem associated with using high power transformers. Basically, rectifiers are used to provide power to daily used devices like televisions, computes and laptops etc. In the following we are going to take about the basic AC to DC circuit used in literature.

2.3 Single Phase Rectifiers

2.3.1 Single Phase Half-wave rectifiers

Fig 2.3 shows a single phase half-wave rectifier using a single diode. The input is a sinusoidal voltage from the grid, connected to a single phase transformer. The output of the transformer is connected directly to a power diode and load in series. The load may be used as simple resistance. Because the diode will conduct in the positive half-cycle only, the positive part of the input sinusoidal is seen at the output and the average output voltage is given as

$$V_{dc} = \frac{V_{peak}}{\pi} \tag{2.1}$$

Where V_{peak} represents the peak value of the input voltage V_{in}. The average root mean square (RMS) output voltage is

$$V_{rms} = \frac{V_{peak}}{2} \tag{2.2}$$

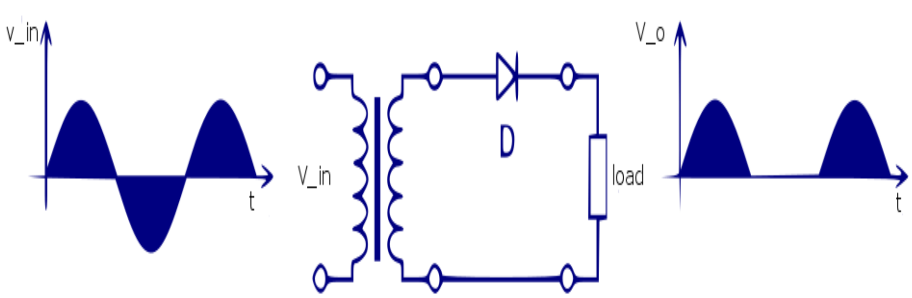

Fig 2.3: Single phase half-wave rectifier (Holmes & Lipo, 2003)

2.3.2 Single Phase Full-wave Rectifier

This type of rectifier is also called center-tapped rectifier because the transformer output is centered to the load terminal, while the other load terminal (the positive terminal) is connected to the cathodes of the two diodes as shown in Fig.2.4. The average output voltage is given as

$$V_{dc} = \frac{2V_{peak}}{\pi} \tag{2.3}$$

And the RMS output voltage is

$$V_{dc} = \frac{V_{peak}}{\sqrt{2}} \tag{2.4}$$

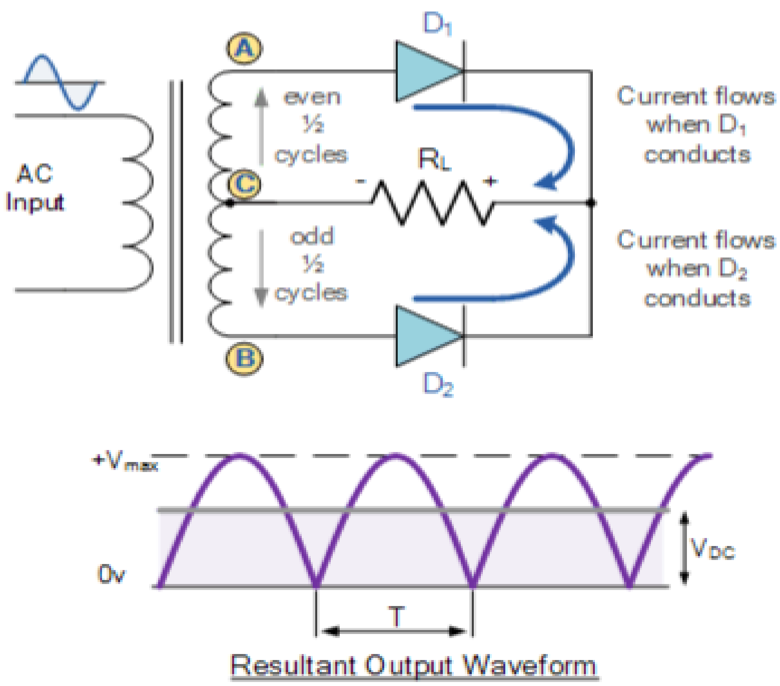

Fig 2.4: Half-Bridge full wave rectifier (Eelectronics-tutorials, 2017, October 4)

The main disadvantage of this type of full wave rectifier circuit is that a larger transformer for a given power output is required with two separate but identical secondary windings making this type of full wave rectifying circuit costly compared to the "Full Wave Bridge Rectifier" circuit equivalent.

In full-bridge full-wave rectifier there are four diodes used in the circuit. The main advantage of this bridge circuit is that it does not require a special center tapped transformer, thereby reducing its size and cost. The single secondary winding is connected to one side of the diode bridge network and the load to the other side as shown in Fig 2.5.

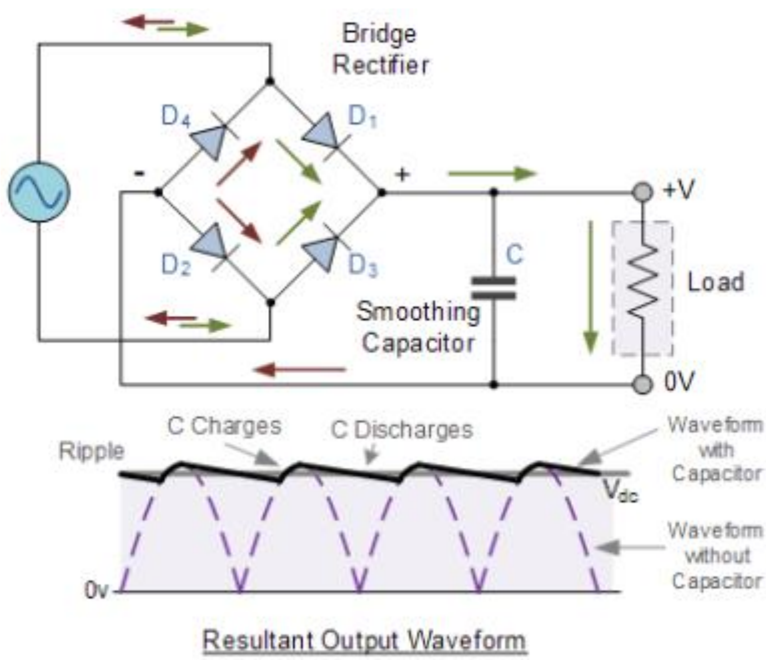

Fig 2.5: Full bridge full-wave rectifier (Eelectronics-tutorials, 2017, October 4)

The four diodes are arranged in order to have only two diodes connecting in each half cycle. Diode D_1 and D_2 are connecting in the positive half cycle, while diode D_3 and D_4 are connecting during the negative half cycle. When two diodes are connecting to let power flow in the loads, the other pair are blocked and vice versa. The average output voltage is given as in (2.3) while the RMS voltage is given as in (2.4). The usage of the capacitor is to reduce the ripple in the output voltage, and the relationship between the capacitor size and the ripple reduction is proportional.

2.4 Three Phase Rectifiers

2.4.1 Three Phase Half-wave rectifiers

This type of rectifier uses three diodes at the output of a three phase transformer shown in Fig 2.6. The transformer ratio maybe one-to-one, lower or higher depends on the application. The output of the rectifier should be connected to L-filter in order to suppress the inrush current at the starting of the power as shown in. Similar to the single phase rectifier, a capacitor is used in parallel with the load in order to reduce the ripple of the output voltage. The average output voltage is given as

$$V_{dc} = \frac{3\sqrt{3}}{2\pi} V_{peak} \tag{2.5}$$

Where $V_{peak} = \sqrt{2} V_{line-neutral}$.

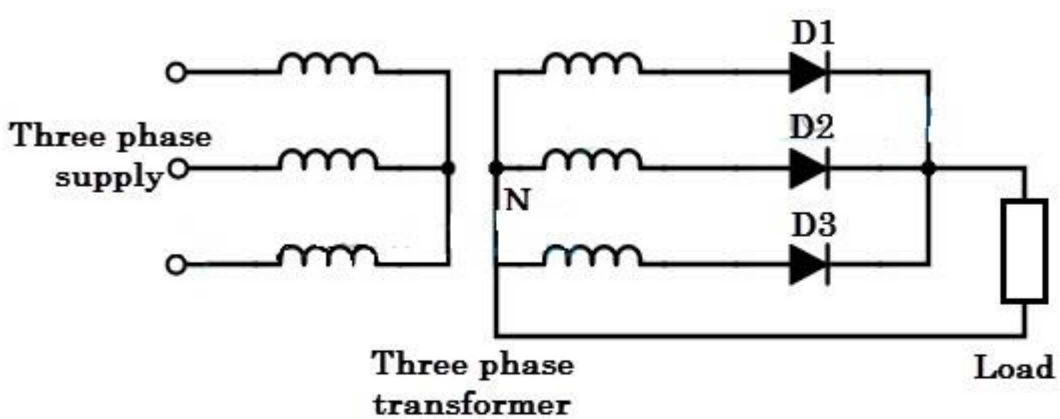

Fig 2.6: Three Phase Half-wave rectifier (Rashid, 2018)

2.4.2 Three Phase Full-wave rectifiers

Fig 2.7 shows the basic construction of a three phase full-wave diode rectifier. As in half-wave rectifiers, an input L-filter is used to suppress the starting current. While a capacitor is used at the parallel of the output voltage in order to reduce the ripple of the output voltage. The average of the output voltage is given as

$$V_{dc} = V_{dc} = \frac{3\sqrt{3}}{\pi} V_{peak} \tag{2.6}$$

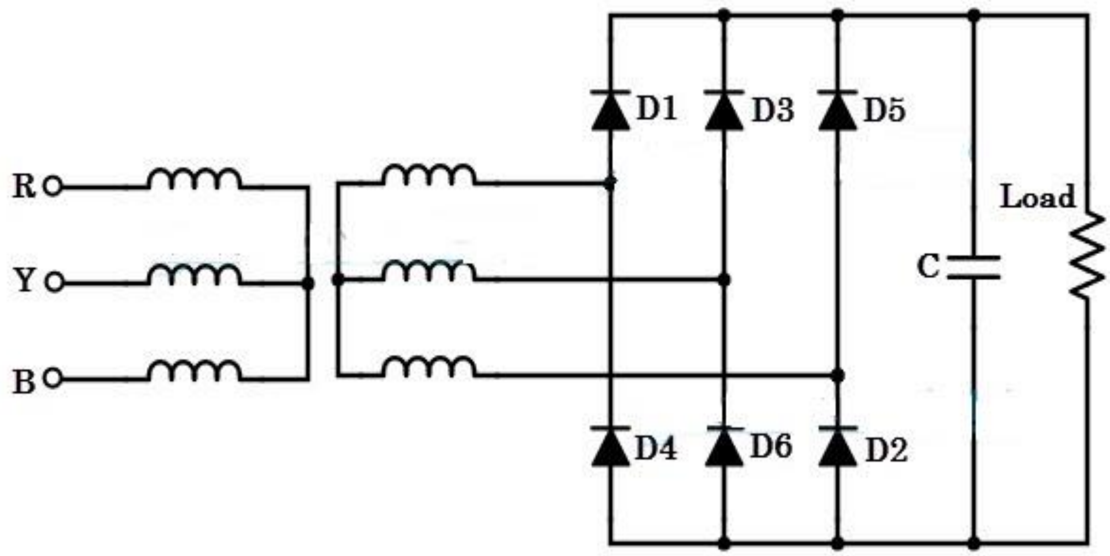

Fig 2.7: Three Phase Full-wave rectifier (Rashid, 2018)

There are controller and un-controlled types of rectifiers. It should be noted that in this section we listed only the uncontrolled type of rectifiers, where diodes are used in the rectifiers. The controller type use thyristors, which are controlled by means of changing the firing angle. For each toplogy and as the firing angle is changing the average of the output voltage is changing.

2.5 DC to DC Converters

Dc to DC converters are also called choppers, which is used to convert the DC voltage from one level to another. The conversion may be used to step-up or to step-down the output voltage, based on the output voltage the choppers are classified. Before using power electronics circuits, the conversion was doable by using by linear electronic circuit or a resistor. This will cause big amount of losses in the circuit and heat in the passive element. Fig 2.8 shows the configuration of a DC chopper where the input and the output are DC voltages. The chopper itself may represents a single power electronic switch or more complex circuit than that.

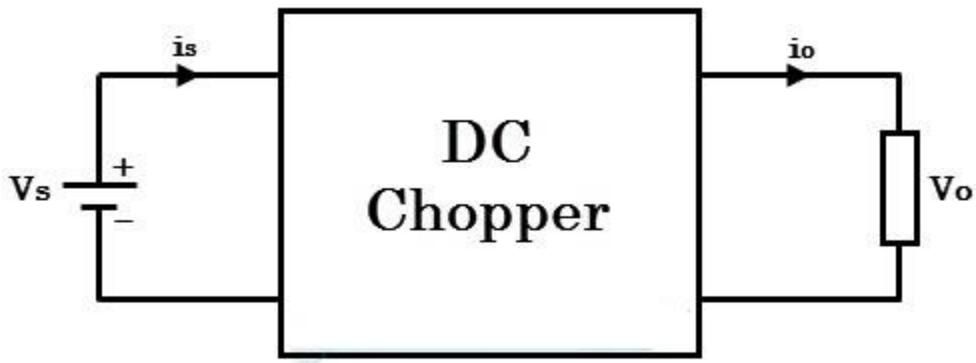

Fig 2.8: DC chopper (Wikipedia, 2018, September 2)

The DC choppers are used in most of nowadays electronic devices such as cellular phones, computers, photovoltaic applications, wind turbines and computers. All these devices are involving a DC power conversion unit where the supply may be a battery or DC source. As in most of kind of converters, the output voltage is not pure DC voltage, instead it may contain harmonics in it. Regulators are used to in order to remove the harmonics and reduce the ripple of the output voltage.

2.5.1 Step-down Chopper (Buck)

Fig 2.9 shows the configuration of a buck DC converter, where the average output voltage is less than the input DC voltage. The switch in the circuit can be any power switch such as thyristor, IGBT or Mosefet. The switch controls the power flow to the output.

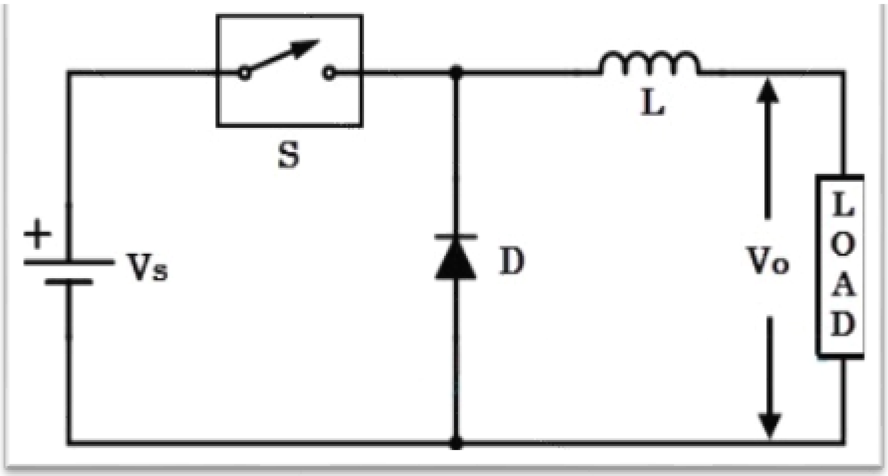

Fig 2.9: Step-down chopper(electronicshub, 2018)

The switch has a duty ratio (d) which is defined as the turning-ON time over the total switching period T. The average of the output voltage is given as

$$V_{dc-av} = dV_s \tag{2.7}$$

Where $d = T_{ON} / T$ and V_s represents the DC voltage supply. The diode (D) acts as a free-wheeling diode that allows the load current to flow through it when thyristor is turned OFF. If this diode is absent, a high induced EMF in inductance may cause damage to the switching device.

2.5.2 Step-up Chopper (Boost)

In this chopper the average of the output voltage is higher than the input DC voltage. It is also called bosst converter because it “boost” or increase the input voltage to a higher value. Fig 2.10 shows the basic structure of the boost converter.

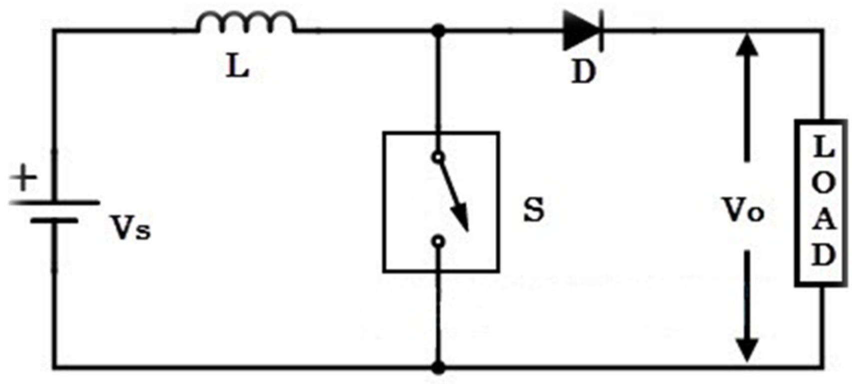

Fig 2.10: Step-up chopper (electronicshub, 2018)

The mathematical relation between the input and the output voltage is given as

$$V_{dc-av} = \frac{1}{1-d} V_s \tag{2.8}$$

When the switch is turned ON, the diode is reversed-baised and the input voltage source is not supplying the load. During that time the inductor is charge-up. While when the switch is turned-OFF the power in the source in addition to the energy stored in the inductor are both injected into the load. Hence a higher voltage is obtained at the output.

2.5.3 Buck-Boost Chopper

Fig shows the basic configuration of a Buck-Boost chopper. This circuit work as buck or as boost depends on the duty ratio value. This type of converter combines the previous two types in one model. The chopper average output voltage is given as

$$V_{dc-av} = \frac{-d}{1-d} V_s \tag{2.9}$$

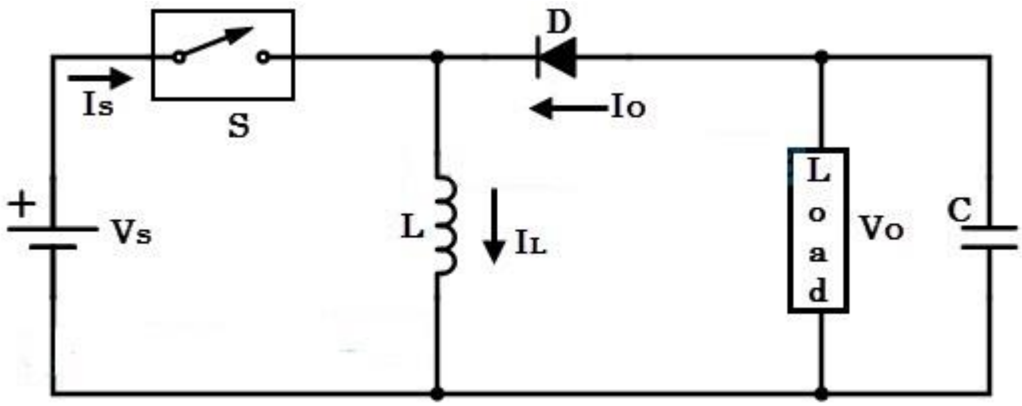

Fig 2.11: Buck-Boost Chopper (electronicshub, 2018)

From (2.10) we notice that the output voltage is always negative. Thus (ideally) the absolute value of the output voltage increases to infinity for 1>d>0.5 and therefore the converter works as boost chopper, and works as buck chopper for 0.5>d>0.

2.6 AC to AC Converters

This type of converter converts an AC power into another AC power, the output power may differ in voltage value or frequency. In the following we will list some of the most common AC to AC converters (Johann W., Fried, Rodriguez, & W. Wheeler, 2011; Klug & Klaassen, 2005; Mohan, 2011; Nguyen & Hong-Hee, 2014; Schweizer, Friedli, & Kolar, 2013).

2.6.1 AC/AC Voltage Converters

This converter type have a pair of anti-parallel thyristor, also called back-to-back converter. The thyristor are controlled by separate control unit which is feed from the output voltage as shown in Fig 2.11 At the very beginning of invention these types of converters, the TRIAC we firstly used. TRIAC is directionally conducting device and it is suitable for this application, but due to its low rating it is not used in high power applications instead it is application is limited to small power ratings applications.

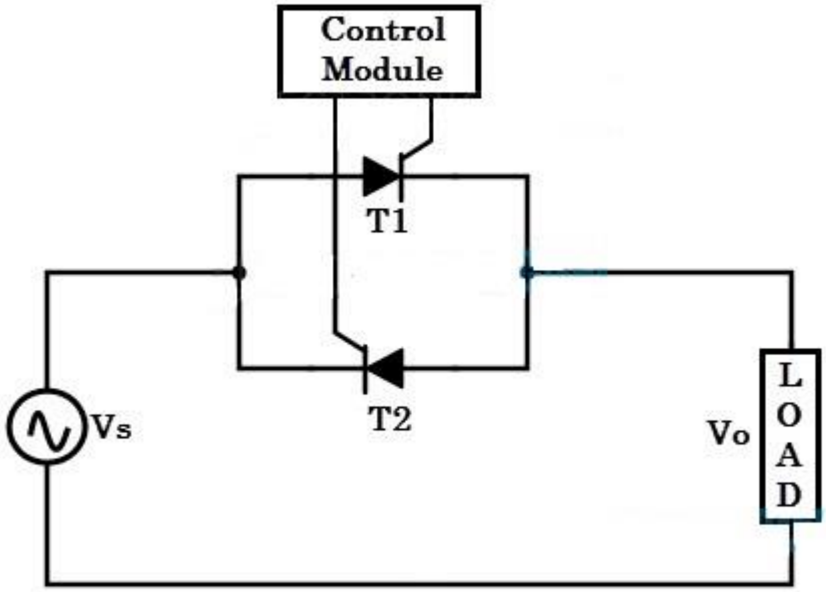

Fig 2.11: Thyristor-based AC to AC voltage converter (electronicshub, 2018)

From the above figure, T1 is working during the positive half cycle while T2 is working during the negative half cycle. This is done by apply proper triggering to the thyristors using the control unit. Eventually, the output RMS is varying by varying the firing angles of T1 and T2 and is given by

$$V_{rms} = V_{peak}\sqrt{1-\frac{\alpha}{\pi}+\frac{\sin(2\alpha)}{2\pi}} \tag{2.10}$$

2.6.2 AC/AC Frequency Converters

The main duty of this converter is to vary the frequency of the output voltage or current with respect to the input voltage or current frequency. I adjustable speed drives and induction heating application the magnitude of the output voltage is also controlled (i.e. can be varied). This type of converters can be classified as

1) Matrix converters

The usage of the matrix converters evolves in order to attain a higher output power density. The power conversion method does not require an intermediate power storage like capacitor or inductor and it is used in three phase applications (Nguyen & Hong-Hee, 2014).

2) Cyclo converter.

This type converts a constant voltage, constant frequency AC waveform to another AC waveform of a lower frequency by producing the output waveform from segments of the AC supply without an intermediate DC link (Klug & Klaassen, 2005).

2.7 DC to AC converters

DC to AC converters shown in Fig 2.13 are also called inverters and their basic job is to convert the DC power (current or voltage) into an AC power (current or voltage). The DC input is obtained from batteries or renewable energy sources while the AC output may be supplied to loads or to the grid.

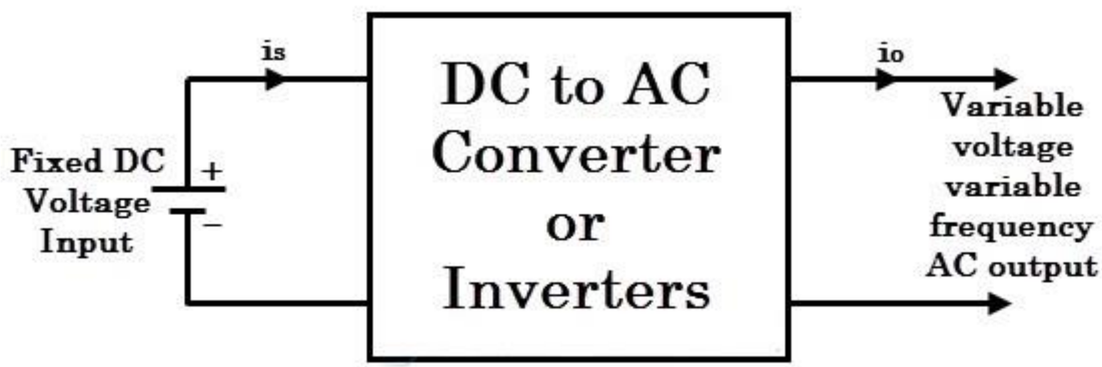

Fig2.

Fig 2.13: DC to AC power converter(Rashid & Rashid, 2005)

Power inverters are use in most every renewable energy application and in most of the industrial application. It is very interesting kind of converter and has drawn the attention of the researchers in the field of power electronics and control. Because of its importance, we are going to explain in details the inverter structures, topologies and most common control methods in the following sections.

2.7.1 Modulation of Single-Phase Voltage Source Inverters

Pulse width modulation (PWM) refers to the process where the pulse width is modulated according to the required control action governed from the feedback system. An inverter is said to be controlled using PWM implies that both voltage and frequency of the inverter output is controlled, either one of them or both. Usually, the inverter is supplied from a fixed DC voltage source and for single phase inverter case we have two legs where each leg has two switches, four switches in total. In here, each phase legs of the inverter is working as chopper and operates at high frequency the inverter output voltage is controlled by chopping action accordingly.

For voltage source inverter the analysis of one phase on leg is done by considering the fundamental and the harmonic output voltages merged by the modulation of the control signal of the inverter. This analysis is should be studied under different carrier and sampling frequencies. As a result, the pulse width to be applied to the inverter will be determined (calculated). Next, we need to consider how to apply these pulses in accordance with the other pulses, meaning, which one are applied first and the four pulses (in single phase case) are to be considered. The total interactions of the harmonics at the inverter output is produced by the harmonics of each inverter leg in addition to harmonic cancellation which occurs between the two legs of the inverter. In the following sections we are going to discuss PWM operation in details.

2.7.1.1 Single Phase Inverter

Fig shows a single phase voltage source inverter controlled by pulse width modulator. The four-switches-two-legs inverter is also called H-bridge (full bridge) because it looks like the H letter. The switches are copuled to a DC source V_{dc} in the figure, and each leg is controlled by it's own modulator. The control logic cab be explained as follow: take phase leg a for instance, the carrier is compared (substracted) to the modulation signal ($M\cos(w_0t)$) and the output is directed to switch T_1 and T_2. The result will switch the phase leg a to the upper DC rail when the reference waveform is greater than the carrier, and to the lower DC rail when the carrier waveform is greater than the reference waveform.

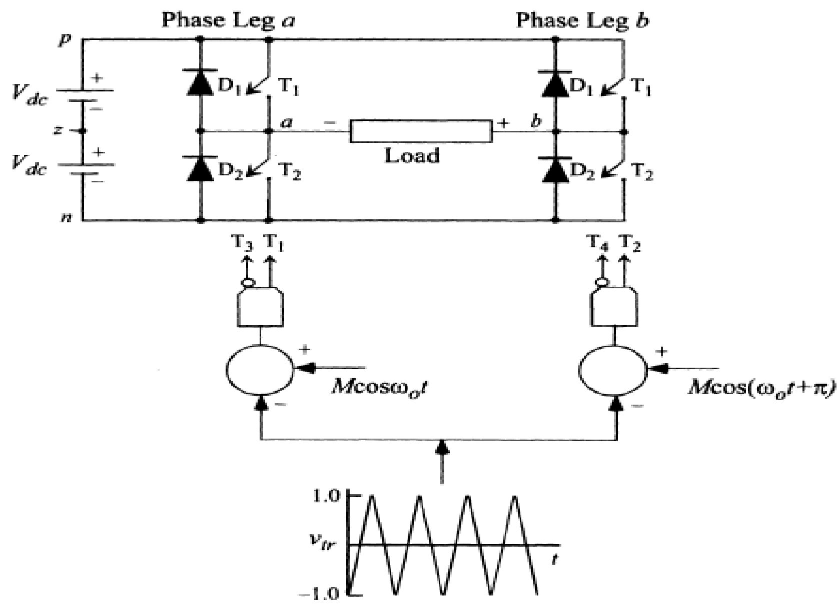

Fig 2.14: PWM control of a single-phase full-bridge voltage source inverter(Holmes & Lipo, 2003)

In here the inverter output voltage V_{ab} have the same frequency as w_0, while the fundamental harmonics are going to appear around the carrier frequency and its multiples. Additionally, the particular form of the carrier and reference waveforms depends on the PWM strategy that is implemented. According to the numver of levels which appear at the inverter output voltage, one may classify its type. So we have two levels, three levels and multilevel inverters. In the following sections we are going to discuss the three level and the two level PWM techniques.

2.7.1.2 Three-Level Modulation of a Single-Phase Inverter

Refer to Fig 2.12 where the two phase legs are modulated with 180° degree phase shift with triangular carrier. The modulated signals are defined as

$$v_{az}^{*} = V_{dc} M \cos(w_o t)$$
and (2.11)
$$v_{bz}^{*} = V_{dc} M \cos(w_o t - \pi)$$

Where M represents the modulation index and is defined as the normalized inverter output voltage magnitude with respect to the DC bus voltage

$$M = \frac{v_{ab}}{V_{dc}} \tag{2.12}$$

And it ranges between 0 and one for normal modulation operation. If M is greater than one, then it said that the inverter is working in overmodulaltion operation region. The inverter leg voltage is measured with respect to the DC bus voltage zero midpoint and the fundamental line-to-line inverter voltage is given as

$$v_{ab} = v_{az} - v_{bz} = 2V_{dc}M\cos(w_o t) \tag{2.13}$$

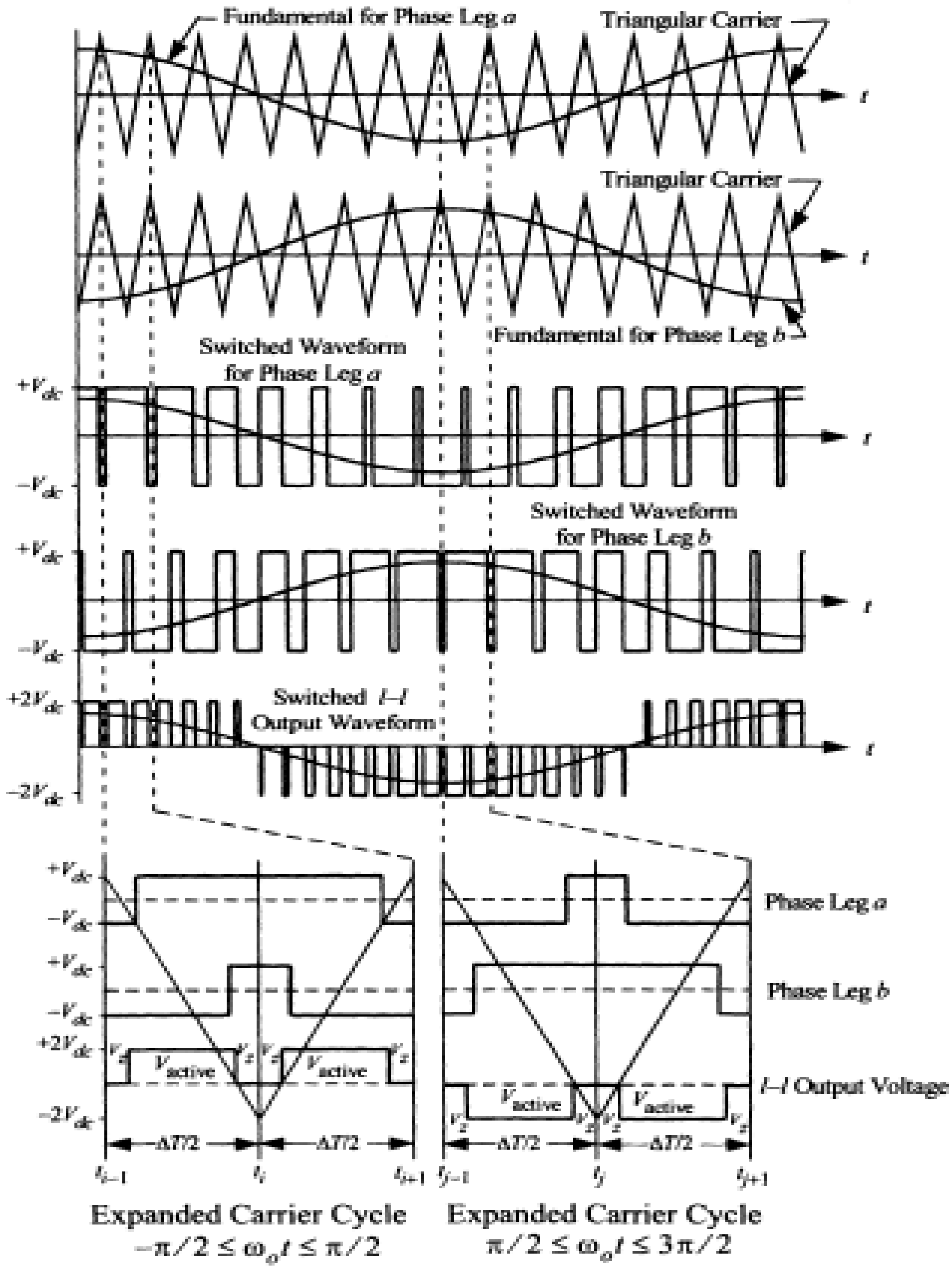

Fig 2.12: Three-level naturally sampled sine-triangle PWM process for single-phase VSI (Holmes & Lipo, 2003)

Eventually, this control topology produces a three-level naturally sampled sine-triangle PWM voltage as shown in Fig 2.14. The inverter output voltage (line-to-line voltage) contains a three levels output, namely $+\frac{V_{dc}}{2}, -\frac{V_{dc}}{2}$ and the zero level. Each leg of the inverter switches between the upper and the lower DC rails continuously over the fundamental cycle as the carrier waveform ramps above and below the reference waveform.

2.7.1.3 Two-Level Single-Phase PWM

For single phase full bridge inverter model given in Fig 2.13, the two-level modulation strategy makes the switching of one phase leg exactly negative the other, as shown in . The line-to-line inverter output voltage v_{ab} produced in this method contains $+\frac{V_{dc}}{2}$ and $-\frac{V_{dc}}{2}$, and it (the inverter voltage) switches between these two values only without the zero value. One may notice that the inverter output voltage in three level inverter output case looks closer to the sinusoidal than the one in two level output.

Since the switched output of phase leg b is the exact opposite of phase leg a, it will have identical magnitude and inverted sign harmonic components. Consequently when phase leg b is subtracted from phase leg a to create the line-to line voltage output voltage for two-level modulation, all the harmonic components of phase leg a will remain in the line-to-line solution without any cancellation.

As a consequence, the odd carrier sideband harmonic will not be cancelled in this method as in the three level PWM.

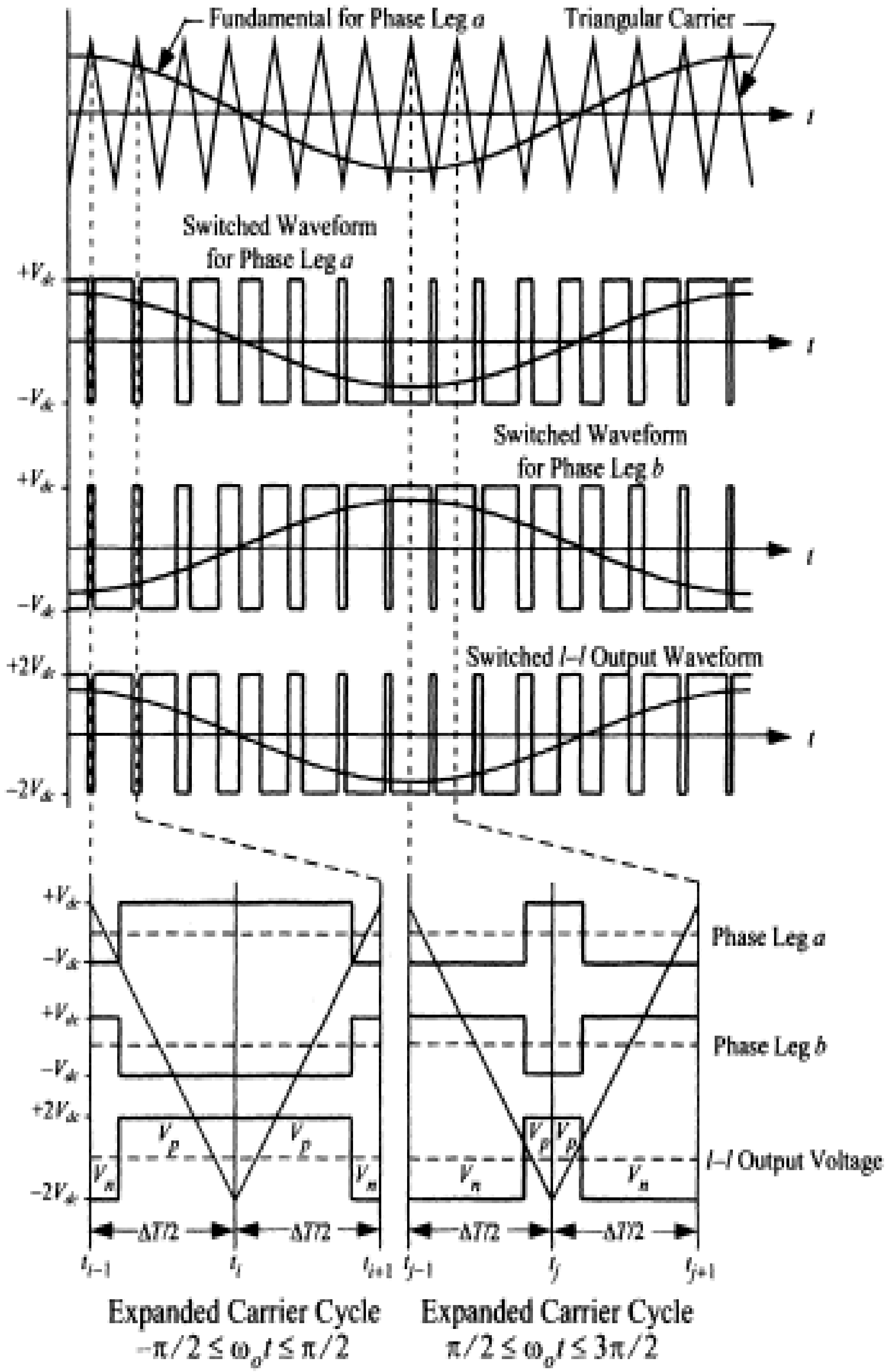

Fig 2.13: Two-level naturally sampled sine-triangle PWM process for single phase VSI (Holmes & Lipo, 2003)

2.7.2 Modulation of Three-Phase Voltage Source Inverters

In previous section we discussed the details of basic priciples of open loop control moulation techniques for single phase inverter. In this section we presents a pulse width modulation technique for three phase voltage source inverter with fixed carrier frequency.

2.7.2.1 Topology of a Three-Phase Inverter (VSI)

Fig 2.18 shows the topology of three phase voltage source inverter, which have an additional leg compared to single phase inverter. By means of control, the reference sinusoids are shifted by 120^o whereas they were shifted by 180^o in case of single phase PWM inverter.

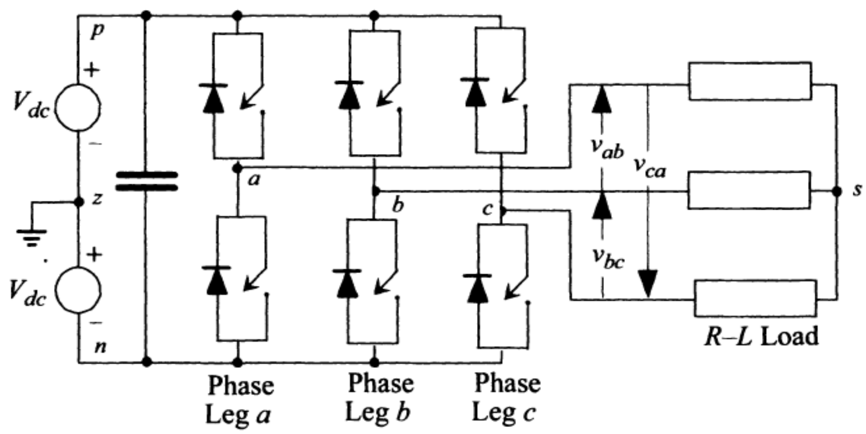

Fig 2.18: Three phase voltage source inverter(Holmes & Lipo, 2003)

The same logic will be followed as in single phase VSI for developing the control of three phase system. Yet, the implementation will be a bit complex as it will be shown in the following sections.

2.7.2.2 Three-Phase Modulation with Sinusoidal References

Fig and Fig 2.14 shos the naturally sampled pulse width modulation control method used to control a three phase voltage source inverter. The sinusoids are 120^o phase shifted in time and can be written as:

$$\begin{aligned} v_{az}^{*} &= V_0 \cos(w_0 t) = MV_{dc}\cos(w_0 t) \\ v_{bz} &= V_0 \cos(w_0 t - 2\pi/3) = MV_{dc}\cos(w_0 t - 2\pi/3) \\ v_{cz} &= V_0 \cos(w_0 t - 4\pi/3) = MV_{dc}\cos(w_0 t - 4\pi/3) \end{aligned} \tag{2.14}$$

where V_0 is the output voltage peak magnitude, M is the modulation index defined as $M = V_0 / V_{dc}$ and the reference waveforms are defined w.r.t. the DC bus center point *z*.

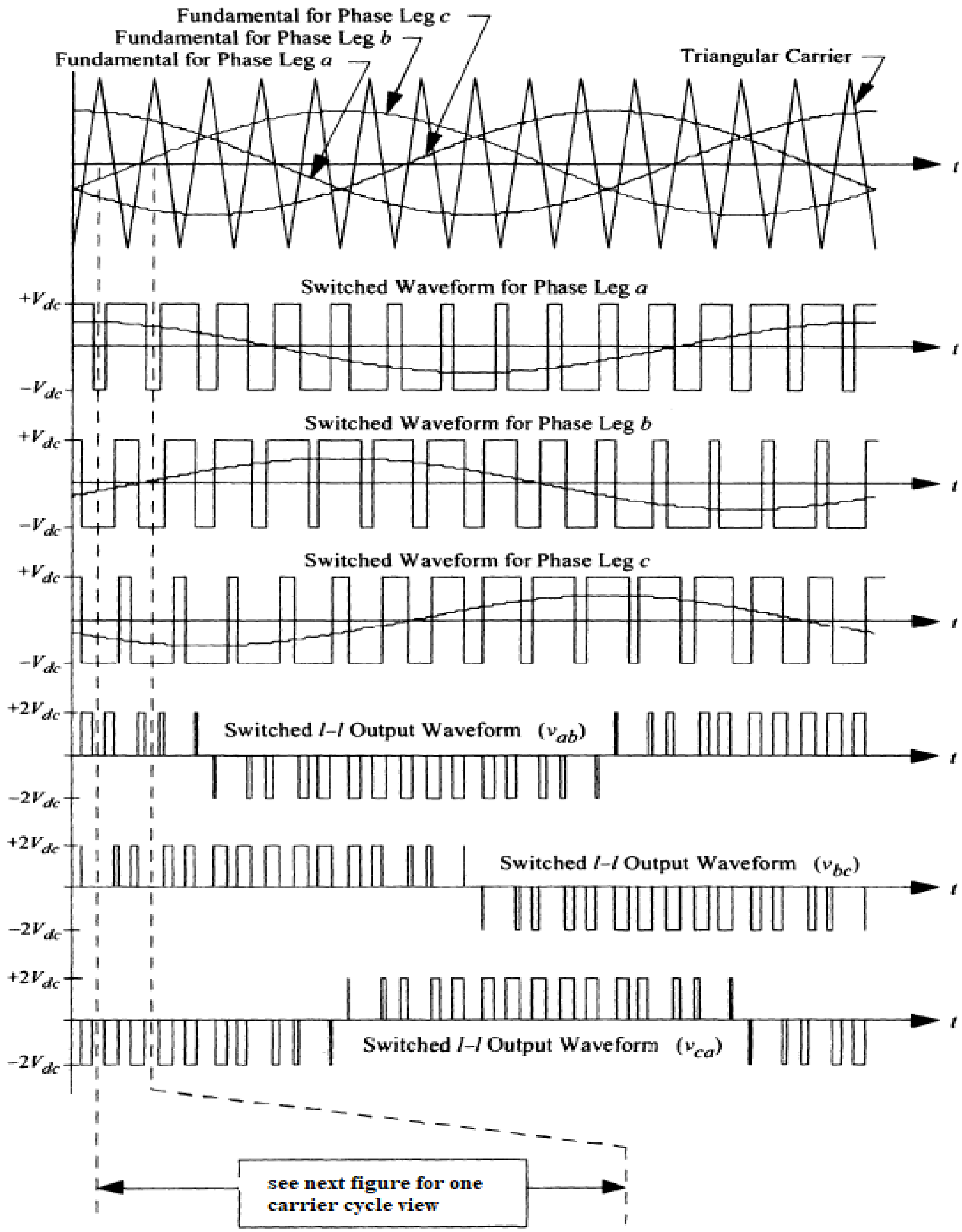

Fig 2.19: Naturally sampled sine-triangle modulation for three phase voltage source inverter (Holmes & Lipo, 2003)

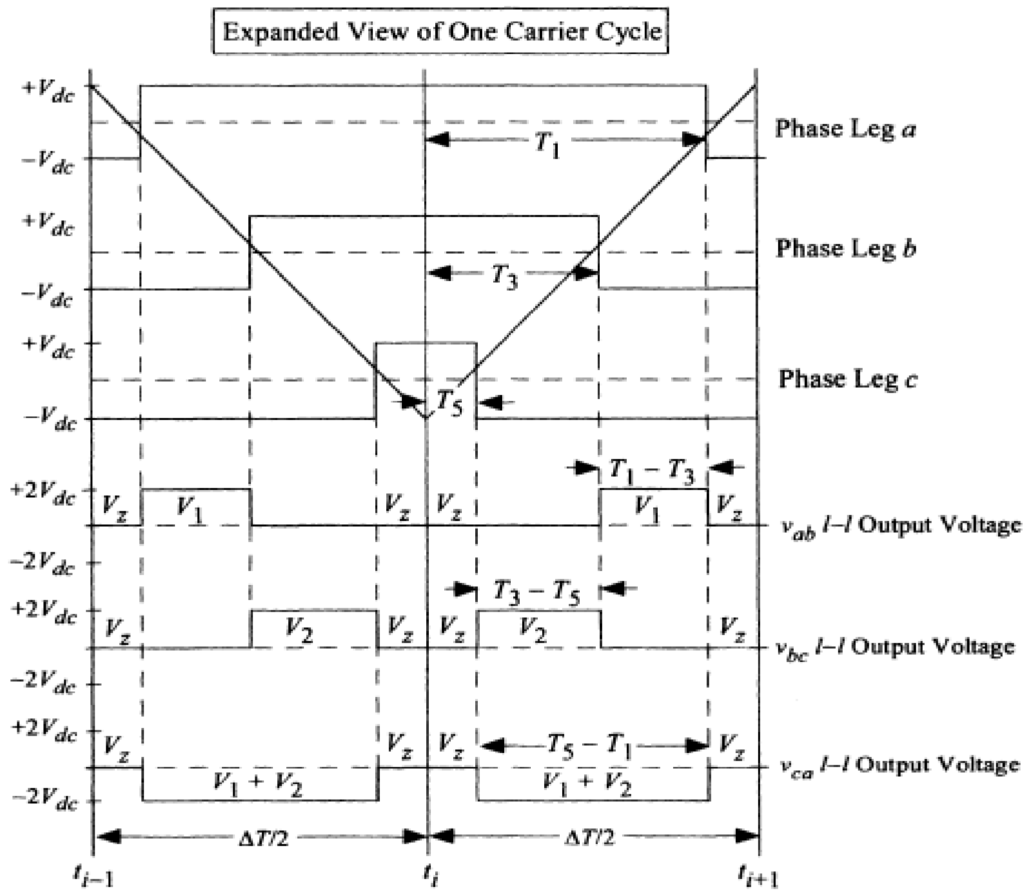

Fig 2.14: Sine-triangle modulation for three-phase voltage source inverter: expanded view of one carrier interval (Holmes & Lipo, 2003)

The phase-to-phase inverter output voltage is defined as the difference between two phase voltages as

$$\begin{aligned} v_{ab}^{*} &= v_{az}^{*} - v_{bz}^{*} = \sqrt{3} M V_{dc} \cos(w_0 t + \tfrac{\pi}{6}) \\ v_{bc}^{*} &= v_{bz}^{*} - v_{cz}^{*} = \sqrt{3} M V_{dc} \cos(w_0 t - \tfrac{\pi}{2}) \\ v_{ca}^{*} &= v_{cz}^{*} - v_{az}^{*} = \sqrt{3} M V_{dc} \cos(w_0 t + \tfrac{5\pi}{6}) \end{aligned} \quad (2.15)$$

Where the maximum value of the magnitude reference is calculated when M=1 which found to be $V^{\max} = \sqrt{3} V_{dc}$.

2.7.2.3 Space Vector Modulation

In this section, we are going to present another control method of three phase inverters. Space vectoe modulation (SVM) is an alternative method of determening the width of the pulse to be applied to the switches of the inverter. SVM has the advantage of minimizing the total harmoinc distortion (THD) of the output signal. Each stationary frame vector corresponds to a specific angular frequency position

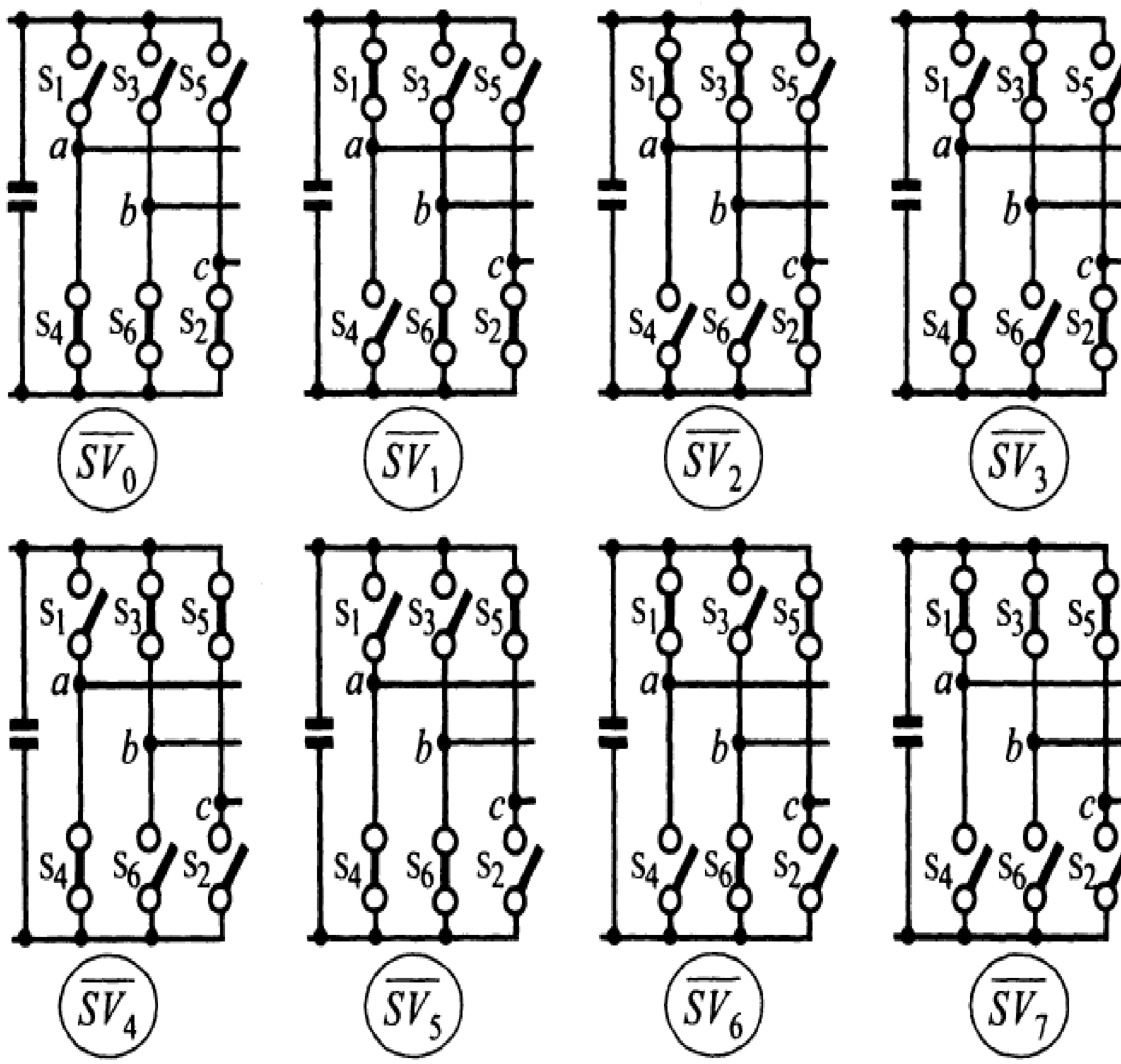

Fig 2.15: Eight possible phase leg switch combinations for a VSI (Holmes & Lipo, 2003)

In SVM, if we consider the three phase inverter with six switches then one may notoice that there are only eight possible applicabile control vector to the inverter, they are all shown in Fig 2.15. Notice that if all the upper or lower switches are ON then we have short circuit on the output resulting a zero output voltage. These two vectors are SV_0 and SV_7 where the rest (six vectors) corresponds to form the d-q frame stationary vectors as shown in Fig 2.16 and the magnitude of each of the six active vectors is given as

$$\left|\overline{SV}_k\right| = \sqrt{v_d^2 + v_q^2} = \frac{4}{3}V_{dc}, \quad k = 1...6 \tag{2.16}$$

Note that in order to make a continous current flowing in each phase leg of the inverter, the lower phase leg switches ($S_4, S_{6,} S_2$) are represented as "NOT" the upper phase leg switches ($\overline{S_1}, \overline{S_3}, \overline{S_5}$).

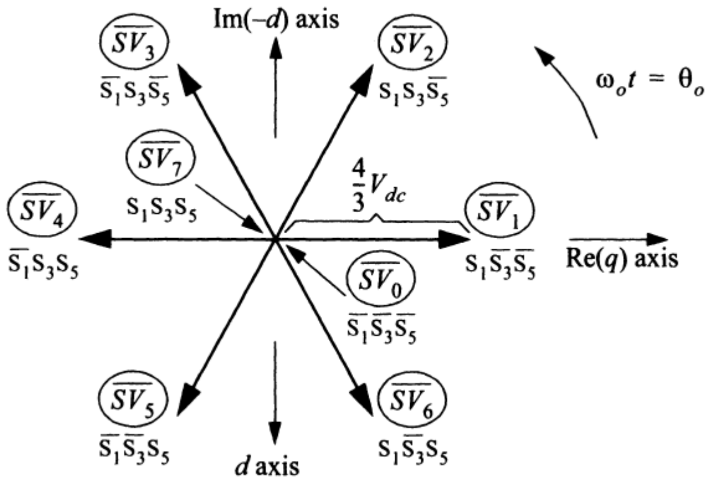

Fig 2.16: Location of eight possible stationary voltage vectors for a VSI in the d-q (Re-Im) plane, each vector has a length (Holmes & Lipo, 2003)

Generally speaking the inverter tracks a circle defined by equation (2.16). However, we have only six nonzero vectors on the d-q frame, so the applied vectors will switch in counterclockwise direction producing a ahexgon shape, more accurate tracking of the target circle on the *d-q* plane can be accomplished by more sophisticated pulse width modulation techniques.

At any time step and after identifying the stationary vectors an output voltage vector can be calculated by means of averaging of the closest two space vectors in addition to the zero vecotr over one switching period . For the sake of explanation, lets consider that the output voltage vectors falls in the first 60° of the dq-plane as shown in Fig 2.21 Generally, in order to produce we need at least two space vectors or more, refer to the output reference voltage can be averaged over

$$\overline{V_o^*} = V_o \angle \theta_o = \frac{T_{SV_1}}{\Delta T / 2} \overline{SV_1} + \frac{T_{SV_2}}{\Delta T / 2} \overline{SV_2} \tag{2.17}$$

where T_{SV_1} is the application time of the space vector $\overline{SV_1}$, and similarly T_{SV_2} is the application time of the space vector $\overline{SV_2}$.

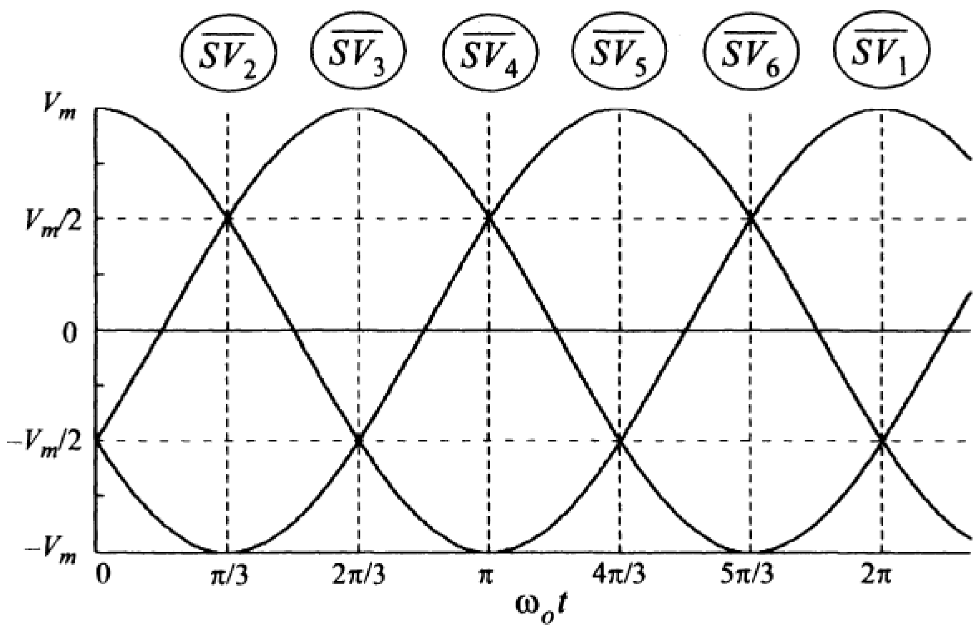

Fig 2.23: VSI phasor angular positions in fundamental cycle for space vector (Holmes & Lipo, 2003)

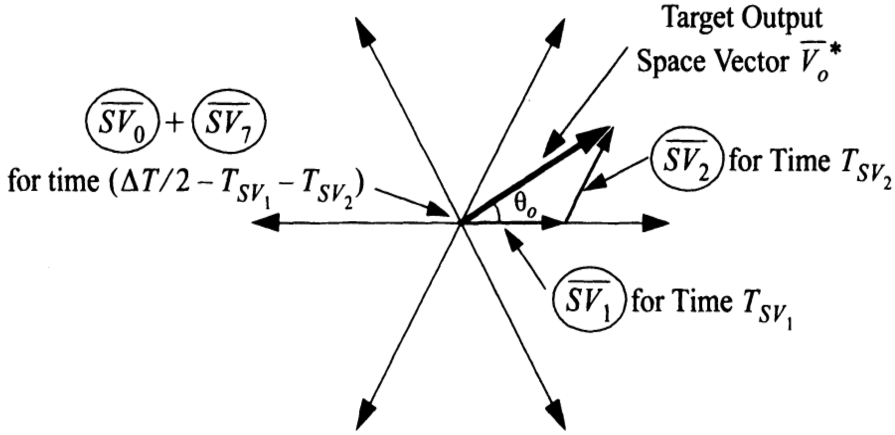

Fig 2.17: Creation of an arbitrary output target phasor by the geometrical summation of the two nearest space vectors (Holmes & Lipo, 2003)

Equation (2.17) can be written in polar format as

$$\frac{\Delta T}{2} V_o \angle \theta_o = T_{SV_1} V_m \angle 0 + T_{SV_2} V_m \angle \pi / 3 \tag{2.18}$$

Where V_m is the peak voltage value. In cartesian form (2.18) can be written as

$$V_o (\cos\theta_o + j\sin\theta_o) \frac{\Delta T}{2} = T_{SV_1} V_m + T_{SV_{20}} V_m + (\cos\frac{\pi}{3} + j\sin\frac{\pi}{3}) \tag{2.19}$$

Equation the real and imjainary componenets we have

$$T_{SV_1} = \frac{V_o \sin(\frac{\pi}{3} - \theta_o)}{V_m \sin\frac{\pi}{3}} \frac{\Delta T}{2} \quad \text{Active time for } \overline{SV_1} \tag{2.20}$$

$$T_{SV_2} = \frac{V_o \sin\theta_o}{V_m \sin\frac{\pi}{3}} \frac{\Delta T}{2} \quad \text{Active time for } \overline{SV_2} \tag{2.21}$$

From (2.20) and (2.21), one may calculate the output voltage from the desired space vectors as

$$\begin{aligned} \overline{V_o^*} &= \frac{T_{SV_1}}{\Delta T/2} \overline{SV_1} + \frac{T_{SV_2}}{\Delta T/2} \overline{SV_2} \\ &= \frac{V_o\sqrt{3}}{V_{dc}} \cos(\theta_o + \frac{\pi}{6}) \overline{SV_1} + \frac{V_o\sqrt{3}}{V_{dc}} \cos(\theta_o - \frac{\pi}{2}) \overline{SV_2} \end{aligned} \tag{2.22}$$

The maximum phase possible value of V_o

$$V_o^{\max} = V_m \sin\frac{\pi}{3} = \frac{2}{\sqrt{3}} V_{dc} \tag{2.23}$$

And the maximum possible line-to-line voltage is

$$V_{line-to-line}^{\max} = \sqrt{3} V_o = 2 V_{dc} \tag{2.24}$$

It is important to mention that the zero vector is also considered in the calculation of the average voltage equation. However, there are no specific rule which one of the zero vector to use $\overline{SV_0}$ or $\overline{SV_7}$ and where exactly to place the zero vector, in the middle, start of or at the end of the half sampling period. Table 2.1 summarize all possible active space vectors of three phase voltage source inverter.

Table 2.1: Active Space Vector Components for a VSI (Holmes & Lipo, 2003)

$\omega_o t = \theta_o$	Space Vectors	Space Vector Active Times
$0 \le \theta_o < \frac{\pi}{3}$	$\overline{SV_1}$	$T_{SV_1} = \frac{V_o}{V_{dc}}\frac{\sqrt{3}}{2}\cos\left(\theta_o + \frac{\pi}{6}\right)\frac{\Delta T}{2}$
	$\overline{SV_2}$	$T_{SV_2} = \frac{V_o}{V_{dc}}\frac{\sqrt{3}}{2}\cos\left(\theta_o - \frac{\pi}{2}\right)\frac{\Delta T}{2}$
$\frac{\pi}{3} \le \theta_o < \frac{2\pi}{3}$	$\overline{SV_2}$	$T_{SV_2} = \frac{V_o}{V_{dc}}\frac{\sqrt{3}}{2}\cos\left(\theta_o - \frac{\pi}{6}\right)\frac{\Delta T}{2}$
	$\overline{SV_3}$	$T_{SV_3} = \frac{V_o}{V_{dc}}\frac{\sqrt{3}}{2}\cos\left(\theta_o - \frac{5\pi}{6}\right)\frac{\Delta T}{2}$
$\frac{2\pi}{3} \le \theta_o < \pi$	$\overline{SV_3}$	$T_{SV_3} = \frac{V_o}{V_{dc}}\frac{\sqrt{3}}{2}\cos\left(\theta_o - \frac{\pi}{2}\right)\frac{\Delta T}{2}$
	$\overline{SV_4}$	$T_{SV_4} = \frac{V_o}{V_{dc}}\frac{\sqrt{3}}{2}\cos\left(\theta_o - \frac{7\pi}{6}\right)\frac{\Delta T}{2}$
$\pi \le \theta_o < \frac{4\pi}{3}$	$\overline{SV_4}$	$T_{SV_4} = \frac{V_o}{V_{dc}}\frac{\sqrt{3}}{2}\cos\left(\theta_o - \frac{5\pi}{6}\right)\frac{\Delta T}{2}$
	$\overline{SV_5}$	$T_{SV_5} = \frac{V_o}{V_{dc}}\frac{\sqrt{3}}{2}\cos\left(\theta_o - \frac{3\pi}{2}\right)\frac{\Delta T}{2}$
$\frac{4\pi}{3} \le \theta_o < \frac{5\pi}{3}$	$\overline{SV_5}$	$T_{SV_5} = \frac{V_o}{V_{dc}}\frac{\sqrt{3}}{2}\cos\left(\theta_o - \frac{7\pi}{6}\right)\frac{\Delta T}{2}$
	$\overline{SV_6}$	$T_{SV_6} = \frac{V_o}{V_{dc}}\frac{\sqrt{3}}{2}\cos\left(\theta_o - \frac{11\pi}{6}\right)\frac{\Delta T}{2}$
$\frac{5\pi}{3} \le \theta_o < 2\pi$	$\overline{SV_6}$	$T_{SV_6} = \frac{V_o}{V_{dc}}\frac{\sqrt{3}}{2}\cos\left(\theta_o - \frac{3\pi}{2}\right)\frac{\Delta T}{2}$
	$\overline{SV_1}$	$T_{SV_1} = \frac{V_o}{V_{dc}}\frac{\sqrt{3}}{2}\cos\left(\theta_o - \frac{\pi}{6}\right)\frac{\Delta T}{2}$

CHAPTER 3

ZSI MODEL AND SIMULATION RESULTS

3.1 Introduction

In previous sections we introduce various types of inverters common in literature. In 2003 Prfo. F. Peng from Michigan State University, USA invented a new type of converters which is called Z-type converter (Peng, 2002). After that the research on ZSI has extended to various types of power electronics application (Holland & Peng, 2005; Holland, Shen, & Peng, 2005; Miaosen & Peng, 2005; Peng, 2004; Peng, Shen, & Qian, 2004; Peng, Xiaoming, Xupeng, & Zhaoming, 2003; Shen, Jin, et al., 2004; Shen, Joseph, Wang, Peng, & Adams, 2004, 2005). In simple words the basic principle of the converter can be explained as follow: basically, in conventional converters (let us take the inverter as an example) we have either voltage source inverter (VSI) or current source inverter (CSI) . While the voltage source inverter has the following limitations (Abdelhakim, Blaabjerg, & Mattavelli, 2018a, 2018b):

1) The DC input voltage has to be greater than the ac input voltage, so it is akind of buck type inverter, and cannot boos the voltage. If higher ac output voltage is desired at the output an additional DC-DC converter is used at the input of the inverter, or an additional AC-AC converter is used at the output of the inverter. In both cases, higher cost will merge due to the additional parts.

2) In each leg, the upper and the lower switches cant be switched ON simaltaneously. If it happned, we are shorting the DC supply voltage which will destroy the switches due to high current passing through them. In order to avoid that a “dead-time” is providing between the ON of the upper switch and the switch ON of the other switch from the same leg.

3) The VSI when compared to CSI, it requires an extra filter at it's output in order to provide pure sinusoidal voltage. The increases the cost and the complexity of the control algorithm.

On the other hand, the CSI has the following limitaions (Azmi, Tajuddin, Mohamed, & Hwai, 2017; Garcia et al., 2010; Guedouani, Fiala, & Boucherit, 2013; Hombu, Ueda, & Ueda, 1987; Hombu, Ueda, Ueda, & Matsuda, 1985; Murphy & Egan, 1983; Peak & Plunkett, 1983; Potdukhe, Munshi, & Munshi, 2015; Wu, Dewan, & Slemon, 1989; Zmood & Holmes, 2001):

1) The DC input voltage should be smaller than the AC output voltage. The DC source is connnected to an inductor in order to limit the current passing from the source to the inverter. The inverter type in this called is boost type of inverter and cannot be used to work as buck inverter except if an additional power conversion stage is utilized to do so, which increases the system cost and complexity.

2) Because a current is drawn from the soucre, a path for the current should be always avilabile. In order to do so, at least one switch in each leg should be kept ON always in order to provide a way for the source current. If not, a high spark will be produced which destroies the converter.

3) While in VSI, we can use low-cost and high-performance IGBT modules and intelligent power modules (IPMs), in CSI an additional series diode is connected to the main switch to block the reverse voltage of the inverter. This limit the usage of power inverter modules, which complicates the utilization of CSIs and increases the cost.

From the above discussion, it is clear that both types of inverters have the following prolblems and limitations: 1) They are working as boost inverter as in CSIs, or buck inverter as in VSIs. Non can be used for buck-boost opertion. 2)VSI cannot be used as CSI, and vice versa. 3) Botth types are senestive to electromagnetic interferance (EMI).

ZSI has a great advantage to overcome all the previous problems by simply employing an impedance to the inverter input or to the converter input, in general. This is true for the AC-AC, AC-DC, DC-DC and DC-AC converters. In the following section we'll explain the basic concept of the ZSI.

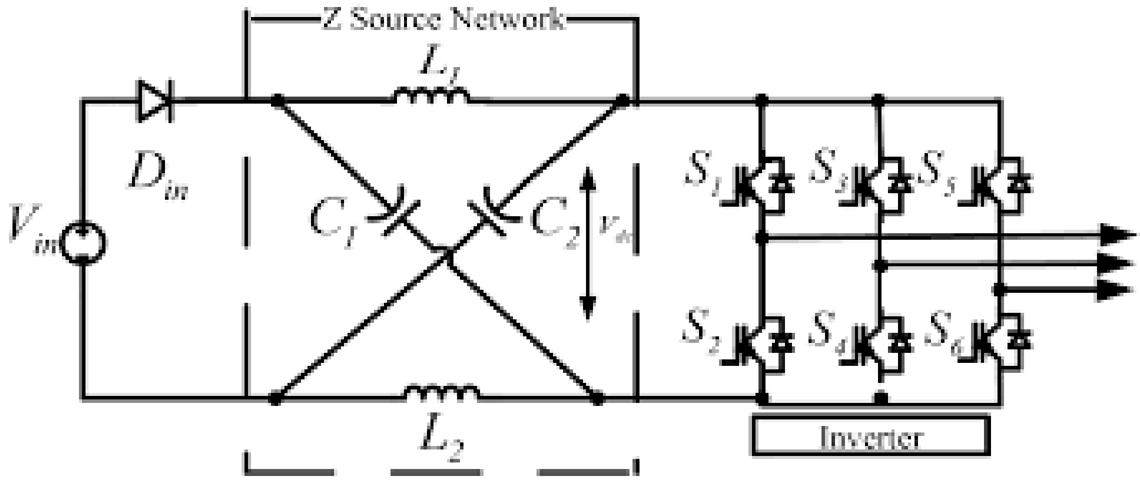

Fig 3.1: Three phase ZSI model (Peng, 2002)

3.2 ZSI Model

Fig 3.1 shows a three phase ZSI which is supplied by a single DC source. An impedance netwok is coupled to the input of the inverter, this network consists of Z-like form of two inductances and two capacitors. The output of the impedance network is connected to the positive and the negative DC bus and then to the six switches three phase inverter. Each leg consists of two bidirectional switches with antiparalled diode to ensure bi-directional power flow through the switch. The midpoint between the switches is connected to the inveter output. The inverter output supplies a three phase filter then the load, in general.

3.2.1 Equivalent Circuit and Principle of Operation

As we conclude in the previous sections, the unique feature of the ZSI inverter is the possibility of providing the power over wide range of values. This implies the functionality of the inverter as buck, boost and buck-boost type of inverter. This feature is not avilabile in either VSI or CSI. One additional feature of ZSI is the ability to short-circuit any of the two switches in the same leg. This adds an additional switching state to the three phase inverters, in addition to the conveentional eight allowded states in case of three phase VSIs. The ZSIs have one extra zero state when the load terminals are shorted through both the upper and lower devices of any one phase, any two phase legs, or all three phase legs. The additional zero state is called shoot-through state (or vector), and it is the state which adds the buck-boost feature to the ZSI.

Refer to Fig 3.1 we can express the equivalent circuit of the ZSI as shown in Fig 3.2 when the inverter is in shoot-through state. The equivalent circuit is shown from the DC-link side. Notice that the diode is series with the voltage source is turned-on during the shoot-through. While the shoot-through can be maintained by either of the following seven ways: shoot-through thru any one phase leg, mixtures of any two phase legs, and all three phase legs. In case we don’t have shoot-through the inverter works as in conventional VSIs, and it will draw some current as shown in Fig 3.3.

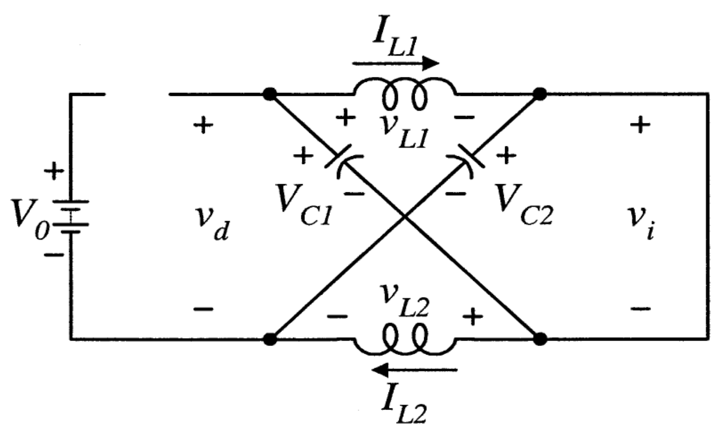

Fig 3.2: Equivalent circuit of the ZSI in shoot-through zero state (Peng, 2002)

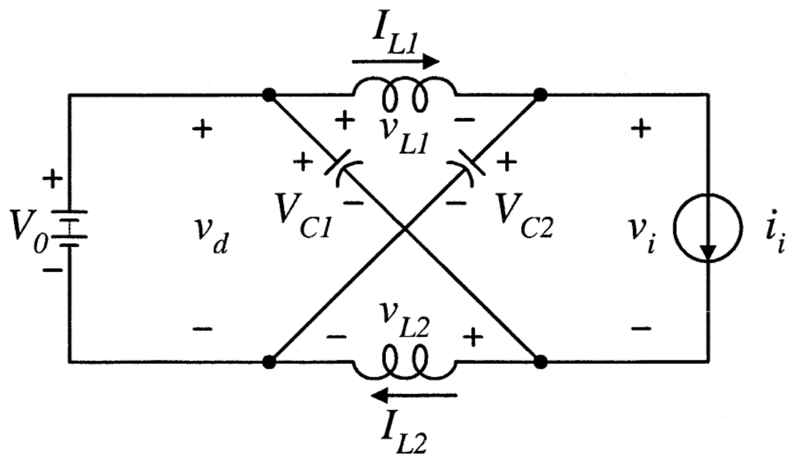

Fig 3.3: Equivalent circuit of the ZSI in any of the non-shoot-through states (Peng, 2002)

3.2.2 Output Voltage Gain

In the following analysis it is assumed that the inductance values of the two inductors is equal $L_1 = L_2$ and the same assumption for the capacitors $C_1 = C_2$, that is to have symetrical network. The symetry implies that the capacitor voltages are equal and the inductor's voltages are equal as

$$V_C = V_{C_1} = V_{C_2} \text{ and } v_L = v_{L_1} = v_{L_2} \tag{3.1}$$

The time where the shoot-through is applied is refered to as T_0, while the total time of the switching period is referd to as T . Refer to Fig 3.2 and if we asume that the inverter is in the shoot-through state then we have

$$v_L = V_C, \;\; v_d = 2V_C \text{ and } v_i = 0 \tag{3.2}$$

The DC source voltage is given as V_0 . Defining the non-shoot through time as T_1, then at that time duration we have

$$v_L = V_0 - V_C \;\; v_d = V_0 \text{ and } v_i = V_C - v_L = 2V_C - V_0 \tag{3.3}$$

In steady state, the average inductor voltage should be zero. Using (3.2) and (3.3)we have

$$\begin{aligned} \overline{v}_L &= V_L = \frac{T_0 V_C + T_1 (V_0 - V_C)}{T} = 0 \\ \Rightarrow \frac{V_C}{V_0} &= \frac{T_1}{T_1 - T_0} \end{aligned} \tag{3.4}$$

The same principle is applied to the average of the DC-link voltage across the inverter is given by

$$\overline{v}_i = V_i = \frac{T_0 .0 + T_1 (2V_C - V_0)}{T} = \frac{T_1}{T_1 - T_0} V_0 = V_C \tag{3.5}$$

With peak value of

$$\hat{v}_i = V_C - v_L = 2V_C - V_0 = \frac{T_1}{T_1 - T_0} V_0 = BV_0 \tag{3.6}$$

Where B is defined as the boost factor due to the shoot-through zero state and given as

$$B = \frac{T_1}{T_1 - T_0} = \frac{1}{1 - 2\frac{T_0}{T}} \geq 1 \tag{3.7}$$

For an inverter working under the influence of M value modulation index, the output peak phase voltage from the inverter can be expressed as

$$\hat{v}_{ac} = M \bullet \frac{\hat{v}_i}{2}, \tag{3.8}$$

And by employing (3.6) we conclude

$$\hat{v}_{ac} = M \bullet B \bullet \frac{V_0}{2} \tag{3.9}$$

From(3.9) we derive the following definition: The buck-Boost factor, which is given as

$$B_B = M \bullet B \text{ (ranges between 0 and } \infty) \tag{3.10}$$

The modulation index M in addition to the shoot-through time T_0 determine the value of the buck-boost factor. And if the value of $B_B < 1$ the inverter works as buck inverter, where the output voltage is lower than the input voltage. While the inverter works as boost inverter if $B_B > 1$, where the output voltage is higher than the input voltage.

3.3 Simulation Results

Fig 3.4 shows the model used in simulation for three phase ZSI with LC filter at the output. The load consist of simple resistance. The simulation parameters are given in The **simulations** is done under 10kHz fixed switching frequency initiated by a triangular carrier PWM nethod of control. The z-soucre inverter is working under open-loop condition where the control signals are given from the controller to the switches without taking a feedback to the controller. The shoot-through zero-state is also included in the pulse width modulator.

The phase-to-phase output voltage of the inverter is shown in Fig 3.5

Table 3.2. Simulation is done using PSCAD platform.

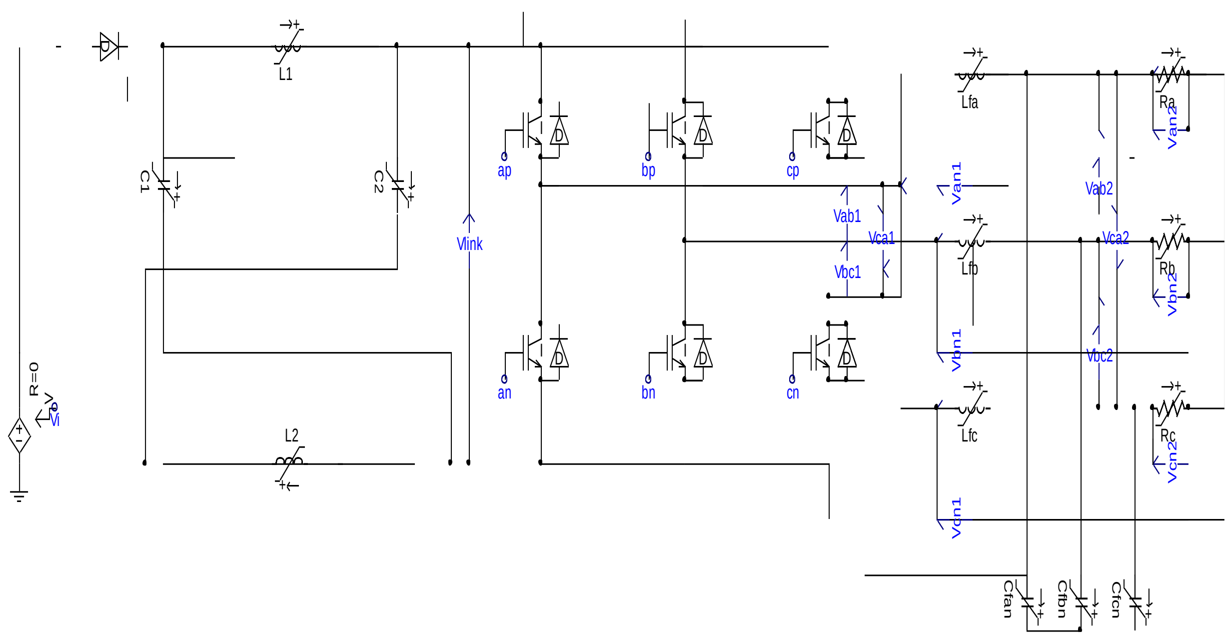

Fig 3.4: ZSI model used in the simulation

The simulations is done under 10kHz fixed switching frequency initiated by a triangular carrier PWM nethod of control. The z-soucre inverter is working under open-loop condition where the control signals are given from the controller to the switches without taking a feedback to the controller. The shoot-through zero-state is also included in the pulse width modulator.

The phase-to-phase output voltage of the inverter is shown in Fig 3.5

Table 3.2: Simulation parameters

Parameter	Symbol	Value
DC link voltage	V_i	200 V
Z-side inductors	$L_1 = L_2$	2mH
Z-side capacitances	$C_1 = C_2$	200uF
Filter-side inductance	$L_{fa} = L_{fb} = L_{fc}$	5mH
Filter-side Capacitance	$C_{fa} = C_{fb} = C_{fc}$	10uF
Load resistance	$R_a = R_b = R_c$	$25\,\Omega$
Switching frequency	f_s	10kHz
Modulation index	M	0.8

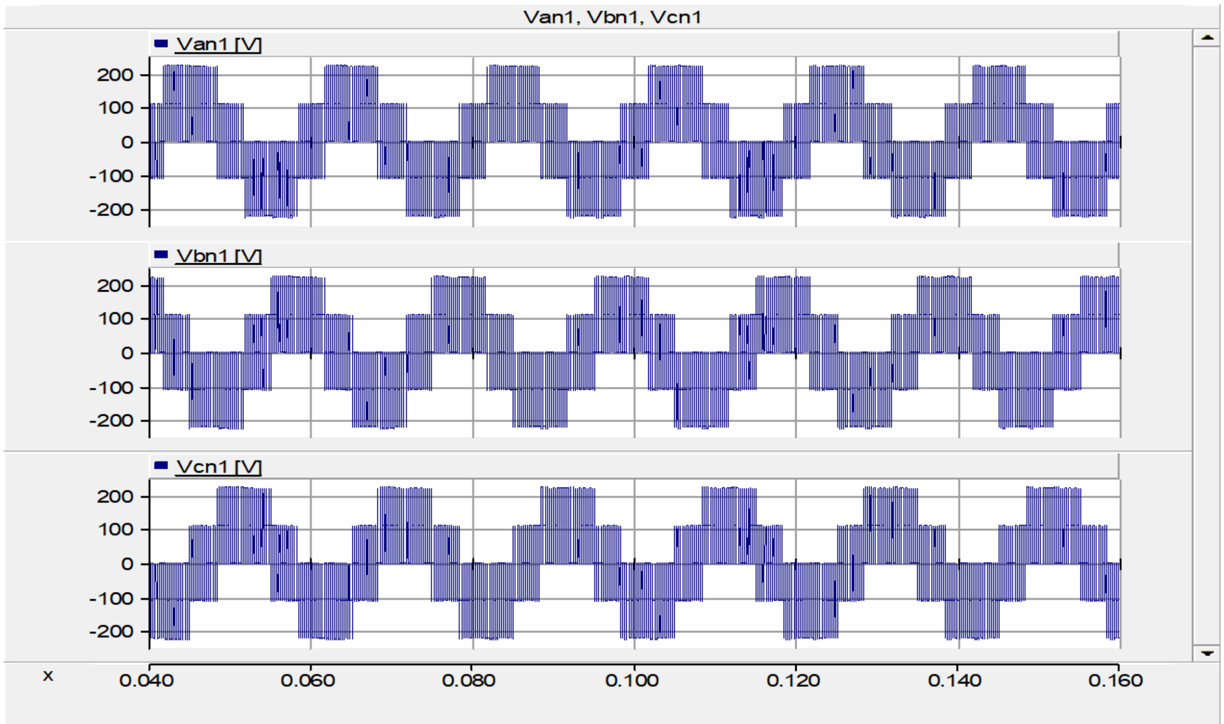

Fig 3.5: Phase to phase output voltage from the inverter

While the loads volatges are given in Fig , which is clearly sinusoidal voltage waveform.

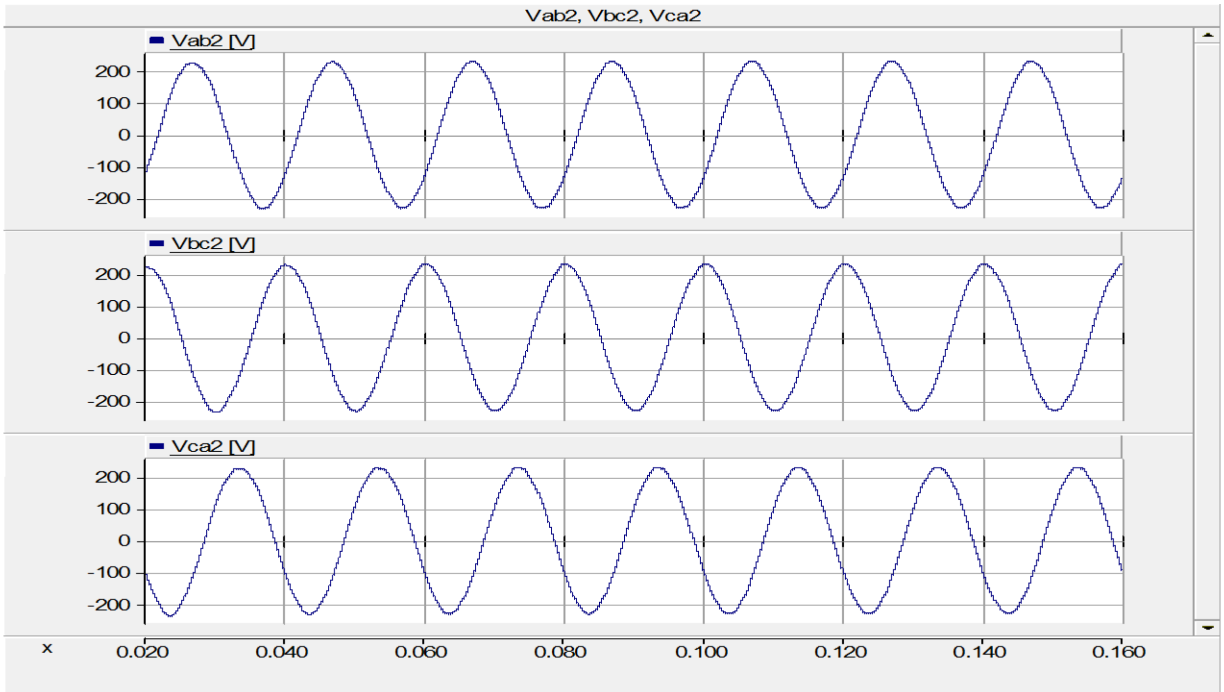

Fig 3.6: The load phase voltage of three phase resistve load

Additionally the control signal supplied to the inverter are given in Fig 3.6 by using a carrier based triangular PWM shown in Fig 3.7.

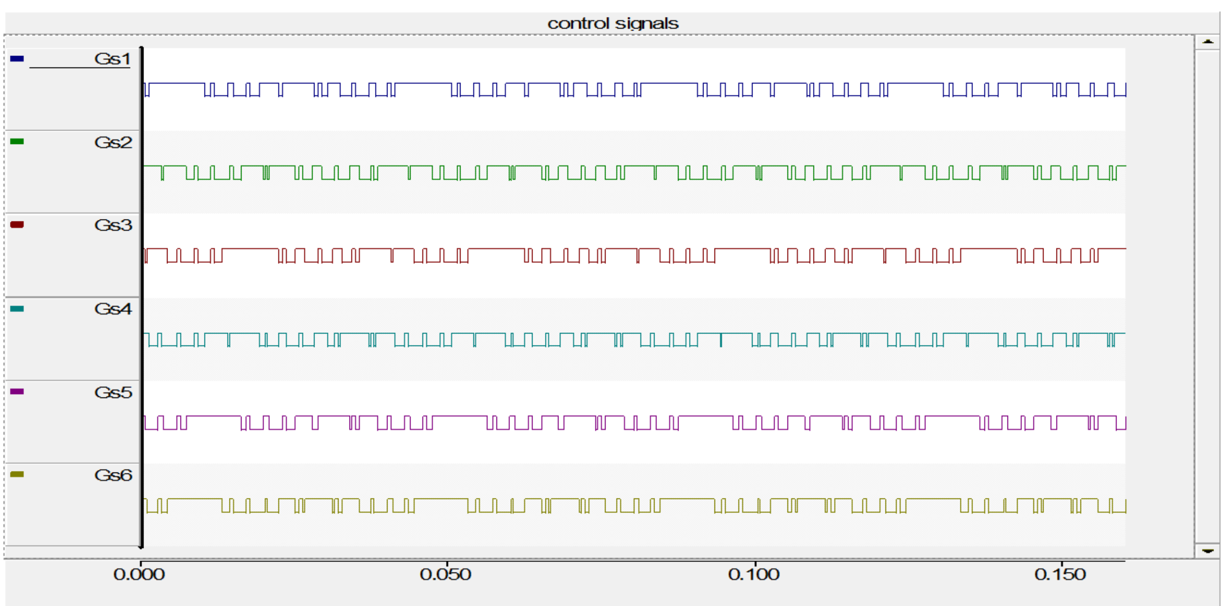

Fig 3.6: Gate control signals.

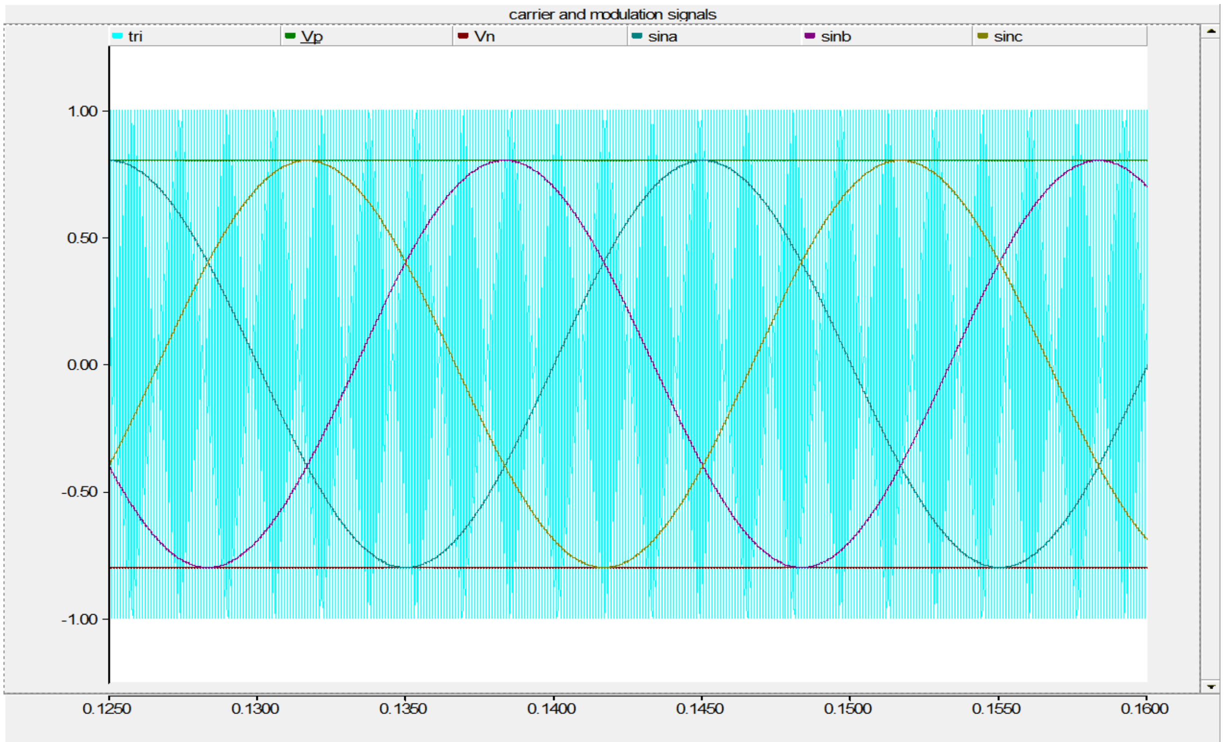

Fig 3.7: Triangular signal and modulated sinusoidal signals

CHAPTER 4
CONCLUSIONS

In this thesis the basic model of impedance source inverter is presented. Review for the configurations and the control techniques of the existining voltage source inverter is given. The main featur of the ZSI is that it is ability to work as step-up or step-down type of converter. Where the limitiations asscoiated with the conventional voltage source cpnverter is eleimanted. The main advaantages of the ZSI can be listed as: 1) wide range of output voltage vale; 2) reduce the size and the cost of the active and passive components used in conventiona VSIs;3) reduce the voltage stress on the active power switching deviceses; 4) reduce the electromagnetic compatibility 5) high effieciency and reliability.

Generally speaking, the invention of Z-source converter open a new line of research in this very intresting topology. Since then; there are a lot of research on this topology, where differet modification were applied to the converter in order to further improve the power quality and renage of th output and input voltages. Additionally, the research aim to invent a compact form of the ZSI with most simple control topologies.

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