PERFORMANCE COMPARISON OF MULTIPULSE CONVERTER AND Z- SOURCE INVERTER DUOS FEEDING DTC INDUCTION MOTOR DRIVE

Thesis

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

MASTER OF ENGINEERING
IN
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CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled **"Performance Comparison of Multipulse Converter and Z-Source Inverter Duos Feeding DTC Induction Motor Drive"** in partial fulfillment of the requirement for the award degree of Master of Engineering in *Power Systems* submitted in Electrical and Instrumentation Engineering department, Thapar University, Patiala is an authentic record of my own work carried out under the guidance of Mr. Parag Nijhawan, Assistant Professor, EIED, Thapar University.

The work presented in this thesis has not been submitted for the award of any other degree of this or any other university.

Date: 15 July, 2014

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This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge and belief.

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ABSTRACT

Non-linear loads like Direct Torque Control (DTC) induction motor drive are a major source of harmonics in the power system. To overcome the problem of harmonics, multipulse converters are widely used. This thesis highlights the performance comparison of different multipulse converters which have been simulated in MATLAB/SIMULINK. Performance comparison of the 6-pulse, 12-pulse and 18-pulse converters feeding R-load has been performed. The phase shift in the converters is achieved by using zig-zag phase shifting transformers. The Total Harmonic Distortion (THD) in input current and input voltage along with ripple content in the output voltage and output current have been measured and their corresponding waveforms have been observed. Also, performance comparison of 6-pulse, 12-pulse and 18-pulse converter with maximum constant boost control technique based Z-source inverter, in order to form duos feeding DTC induction motor drive have been performed. The results obtained with a multipulse converter and Z-source inverter duos have been compared with those obtained with the multipulse converter and traditional inverter duos. It has been observed that duo consisting of Z-source inverter provides better results in terms of THD in input voltage and input current. Z-source inverter improves the reliability of the system. It also reduces noise and electromagnetic interference. Simulation of 14-pulse converter which is a non-integer multiple of six, and its integral multiples has been carried out. It has been found that as the pulse number of a converter increases, THD in input voltage and input current along with ripple content in the output voltage and output current is decreased.

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LIST OF ABBREVIATIONS

ASD	Adjustable Speed Drive
BESS	Battery Energy Storage System
CEMF	Counter Electromotive Force
DTC	Direct Torque Control
DVR	Dynamic Voltage Restorer
FACTS	Flexible Alternating Current Transmission System
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical And Electronic Engineers
LVHC	Low Voltage High Current
PCC	Point of Common Coupling
PWM	Pulse Width Modulation
RMS	Root Mean Square
SMPS	Switch Mode Power Supply
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
THD	Total Harmonic Distortion
UPS	Uninterruptible Power Supply
VCIMD	Vector Controlled Induction Motor Drive
VSI	Voltage Source Inverter

CHAPTER-1

OVERVIEW

1.1 INTRODUCTION

Electricity was discovered about 400 years ago. There has been a continuous development in generation, distribution and use of electricity. During the industrial revolution, stress was given on novel and advanced methods of electricity generation and its usage. Earlier, the electrical machines and devices required significant amount of power for their operation but showed good performance. Priority was given to performance rather than the cost of the machine. However, the industrial age put emphasis on the products to be cost effective as well. With time, the demand for electricity increased in the industrial sector as well as in the residential sector. This increase in demand was met by extensive power generation and distribution grids. Electrical utilities do not operate independently but function in a large network of utilities tied together. The use of non-linear devices became dominant during 1950's. These devices also contributed to power quality problems. All these factors contributed to the need of systems requiring clean and reliable power. Power quality affects the cost and reliability of any electrical system. Consequences of poor power quality may include malfunction, accelerated wear and tear, overheating and false tripping of circuit breakers.

1.2 MULTIPULSE CONVERTERS

With the advancement in technology, more focus was put on the use of power electronic devices so as to provide most efficient energy conversion. The major objective of using power electronic devices is that they are lower in cost, lesser size, lesser weight and have reduced power loss. They also have high energy efficiency due to which removal of heat produced because of dissipated energy is reduced. However, technology of power electronics has some disadvantages. One major problem is the generation of harmonics. A rectifier is a power electronic circuit that should provide dc output voltage with lesser harmonic component. Multipulse converters provide a simple and effective technique for harmonic elimination. The phase shifting transformers have an important part in the working of multipulse converters. Multipulse converters are useful in waste water industries where lower harmonic distortion is required. They are also required in applications where a high percentage of motor drive loads is present as compared with the total facility load.

1.3 LITERATURE SURVEY

The major issue these days in our power system is to provide good quality of power. Power quality concerns with end users, utilities, engineers and manufacturers. The presence of non-linear devices and the complexities involved with industrial processes are the major factors for the increased interest in power quality [1-4]. Our system is subjected to various power quality events which include short duration variations, long duration variations, transients, voltage imbalance and waveform distortion [5]. It is very important to provide good quality of power [6-7].

Non-linear devices like rectifiers, drives etc have increased the problem of harmonics. They affect the supply voltage and supply current. These days, multipulse converters are preferred for harmonic mitigation as they have many advantages [8-9]. They are usually formed by a number of converters connected together either in series or in parallel connection. These converters should be at appropriate phase shift from each other. The phase shift can be provided by using star/delta transformers, star/polygon transformers etc. However, each one of the transformers has their own advantages. Various parameters have to be considered before selecting the type of transformer for a particular application. Some of these parameters are size, weight, mechanical characteristics, electrical indicators etc [10]. Zig-zag phase shifting transformers can also be used for providing the required phase shift [11]. Multipulse converters are based on the principle of harmonic cancellation such that the harmonics produced by one converter are cancelled by the harmonics produced by the other converter [12].

The Total Harmonic Distortion (THD) produced by a 6-pulse thyristor rectifier in the supply current exceeded the Institute of Electrical and Electronic Engineers (IEEE) limit of 5% [13]. Adjustable speed drives fed by 6-pulse converters have applications in pulp and paper industry [14]. Double-polygon transformer or a delta/delta-star transformer has been used to achieve the phase shift in between the converters for a 12-pulse converter. Also, pulse multiplication technique has been used to obtain a 24-pulse converter [15]. It has been found that an active interphase reactor in a 12-pulse converter provided clean power utility interface [16].

M. Karthika and V.V.V. Inti [17] presented the use of multipulse converters for improving the power quality. Non-linear nature of switching devices produces harmonics thereby polluting the power quality at the Point of Common Coupling (PCC). Phase shift between the converters was achieved by using an autotransformer. Simulation for 6-pulse, 12-pulse, 18-pulse and 24-pulse converter feeding Vector Controlled Induction Motor Drive

(VCIMD) has been performed in MATLAB/SIMULINK. THD of input current, distortion factor, displacement factor, power factor and dc link voltage was measured for light load and full load. It was observed that as the pulse number of a converter was increased, power quality indexes at ac mains in terms of supply current THD, supply voltage THD, power factor and distortion factor were improved.

Bhim Singh and Sanjay Gairola [18] presented a study of 6-pulse, 12-pulse and 18-pulse converter. Phase shift in 12-pulse converter was achieved by a delta/double star transformer and star/double star transformer. For an 18-pulse converter, phase shift was achieved by a delta/double fork transformer. Simulation was performed in MATLAB/SIMULINK. Input voltage and current waveforms were observed. THD of input current, THD of input voltage, distortion factor, displacement factor, power factor, dc voltage, ripple factor and load current were measured. The results depicted that the lowest levels of THD were observed in proposed 18-pulse full wave ac-dc converter. The 18-pulse converter possessed a high level of performance. It provided clean power characteristics and it could be used for high current applications.

Rakesh Maurya *et. al.* [19] suggested different topologies of Low Voltage High Current (LVHC) multipulse ac-dc converter which may cause reduction in harmonics in ac mains and ripples in dc output. The performance of these converters was investigated and compared in view of power quality aspects and suitability to LVHC applications. Simulation results for 12-pulse converters of various topologies were analysed. 24-pulse converter with primary series connected zig-zag and secondary star connected was also simulated which satisfied the requirements of maintaining good quality of power at the utility as well as at the consumer end.

Guy Olivier *et. al.* [20] presented a family of converters which were based on a distinctive series connection of the primary windings. The semiconductors were directly connected in parallel without employing the use of inter-phase transformers or any other current sharing means at the secondary side. Due to the series connection of the primary windings, current sharing became possible while the use of zig-zag connection provided the desired pulse number. Such converters are cheap due to the absence of interphase transformers. Such family of converters are particularly preferred for electrolysis and traction applications.

Maryclaire Peterson and B.N. Singh [21-22] proposed a model of 6-pulse, 12-pulse, 18-pulse, 24-pulse, 36-pulse and 48-pulse diode/thyristor converters with RL-load. A comparative study has been done for uncontrolled and controlled rectifiers. Data related to the THD at the supply side, ripple in the output voltage and power efficiency was observed. It was concluded that an increased value of triggering angle for thyristor converters resulted in an increased THD in the input current and increased ripples in the output voltage. For the regulation of output voltage, controlled multipulse converters could be used but they require a control system for the triggering of the thyristor. In addition to the power quality issue, cost and complexity have become the guidelines for the selection between the higher and lower pulse converters and between the controlled and uncontrolled converters. They have also presented an 18-pulse thyristor converter in which triggering angle of the thyristors was controlled selectively. This restructuring of the converters improved the efficiency of the rectifiers. Appropriate disabling of a single rectifier or a pair of rectifiers improved the power factor and life span of the disabled rectifier. The disabled rectifiers could also be used to feed other loads.

R. Kalpana *et. al.* [23] suggested different configurations of auto-connected transformer based 9-phase converter. This 9-phase ac-dc converter has been used to feed Switch Mode Power Supply (SMPS) so as to improve the power quality indices at the PCC. The proposed converter subdued upto 17th harmonic. It also led to the improvement of power factor at varying loads. The hexagon auto-connected transformer resulted in reduced rating of mechanics, lesser weight, lesser volume and reduced cost of SMPS.

Bhim Singh *et. al.* [24-26] analysed a polygon connected autotransformer for 12-pulse and 18-pulse converter. These converters fed Vector Controlled Induction Motor Drives (VCIMD). Such converters are suitable for applications which consist of large load variations. They have also proposed a 24-pulse ac-dc converter feeding Voltage Source Inverter (VSI) which in turn was connected to a squirrel-cage induction motor drive. A T-connected autotransformer was designed with reduced windings. The converter subdued the harmonics less than 23rd harmonic. Laboratory prototype of the proposed T-connected autotransformer based 24-pulse converter was developed. The THD and the crest factor of the supply current were improved. Also, its volume, weight and cost were less when compared with the 12-pulse ac-dc converter. Also, they have developed a 30-pulse ac-dc converter. Polygon-connected autotransformer could be used to achieve the desired phase shift. The designing of the autotransformer was done in such a manner so that it became suitable for retrofit applications. The lowest order harmonic present in the supply current corresponded to 29th harmonic. For varying operating range of loads, THD of supply current was found to be less than 5%. Also the power factor was maintained nearly to unity. The proposed converter led to reduced weight, volume, size and cost of the converter system. Also, the rating of the magnetic was reduced.

Bhim Singh and Sanjay Gairola [27-29] designed a transformer for 36-pulse ac-dc converter. The transformer has been connected in delta/fork and it could be used in the applications wherever isolation is needed when the supply voltage is stepped down. The 36-pulse converter was formed by two 18-pulse converters connected in parallel. The converter system provided clean power and possessed high level of performance. Also, the THD level of the input current was found to be less than 5% for varying loads. A polygon connected autotransformer was also designed and modeled for a 40-pulse converter. The proposed converter consisted of two 10-pulse diode rectifiers connected in parallel which produced 20-pulses of dc per cycle. Pulse multiplication technique was used to achieve a 40-pulse converter system. Designing and modeling of a delta/polygon transformer has been done which is used for a 44-pulse converter. 44-pulse converter is obtained by two 22-pulse converters connected in parallel. Simulation was carried out for varying loads and it was found that the THD level of the input current was less than 2.646% and the ripple content of the output voltage was less than 0.15%.

Rohollah Abdollahi [30] proposed a pulse doubling technique to obtain a 72-pulse converter from a 36-pulse converter. 36-pulse converter was obtained by parallel connection of two 18-pulse converters. Delta/hexagon transformer was required to achieve the desired phase shift between the converters. Tapped interphase reactor was used to double the number of pulses of the output voltage so that 72 pulses can be obtained per cycle. The THD level of the proposed converter was found to be less than 3% for variable loads.

Multipulse converters can also be implemented in to develop robust controls for High Voltage Direct Current (HVDC) systems and Flexible Alternating Current Transmission System (FACTS) [31]. Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM) have been modeled using multipulse voltage source converters. In this, 24-pulse and 48-pulse converter topologies have been utilized [32]. An 18-pulse STATCOM has been developed. It consisted of lesser number of devices and reduced magnetic [33]. A combination of multipulse-multilevel inverter topology has been proposed for implementation in a STATCOM. They are used to maintain a constant level of the ac bus voltage [34].

A Z-source converter consists of an impedance network. It can be used to overcome the problems faced by traditional voltage source inverters and current source inverters [35]. A Z-source inverter can be controlled by different control methods which are simple boost control, maximum boost control and constant boost control [36-37]. A comparative analysis has been performed for different control methods of Z-source inverter feeding induction furnace load [38]. Z-source inverter can be used for various applications like in fuel cell vehicles, Uninterruptible Power Supply (UPS) and in photovoltaic systems [39-41]. A Z-source inverter based Dynamic Voltage Restorer (DVR) has also been proposed which is used for the restoration of voltage sag and voltage swell. The proposed technique is simple and efficient [42].

1.4 SCOPE OF WORK

From the literature review, it is observed that the work on the mitigation of harmonics is very much diversified. However, there is a scope to investigate the effectiveness of different multipulse converters. Also, a combination of converters to isolate the ac source from the ac load can be investigated.

1.5 OBJECTIVE OF THESIS

The major objectives of the thesis are summarized as follows:

- A comparative analysis of 6- pulse, 12-pulse and 18-pulse converter feeding R-load has to be achieved so as to improve the power quality by mitigating the effect of harmonics.
- A comparative analysis of 6-pulse, 12-pulse and 18-pulse converter with maximum constant boost control based Z-source inverter so as to make a duo, feeding a Direct Torque Control (DTC) induction motor drive should be performed. Further, in each of the multipulse converter mentioned above, a comparative study has been carried out between the performance of the traditional inverter and the Z-source inverter in terms of THD in supply voltage and supply current.
- 14-pulse converter which is a non-integer multiple of 6 has to be simulated by connecting each of the phase by single phase supply. Using the similar concept, simulation of 28-pulse converter and 42-pulse converter which are integral multiples of 14 should be carried out. The performance of these converters should be analysed in terms of THD level at the input side and ripple content at the output side.

1.6 ORGANIZATION OF THESIS

This thesis has been compiled in eight chapters whose details are given below:

- Chapter 1 includes the introduction and the previous work which has been carried out till date. It also includes the scope of work, objective of thesis and organization of thesis.

- Chapter 2 explains about power quality and its problems. It also discusses about the various solutions of power quality.
- Chapter 3 explains about the multipulse converters.
- Chapter 4 explains about Z-source converters
- Chapter 5 presents the MATLAB/SIMULINK based models of 6-pulse, 12-pulse and 18-pulse converters feeding R-load. It provides the parameters of test system and discusses the simulation results.
- Chapter 6 presents the MATLAB/SIMULINK based models of multipulse converter and Z-source inverter duo. It provides the parameters of test system and discusses the simulation results.
- Chapter 7 presents the MATLAB/SIMULINK based models of 14-pulse, 28-pulse and 42-pulse converters feeding RL-load. It provides the parameters of test system and discusses the simulation results.
- Chapter 8 presents the conclusions of the work presented in thesis and future scope of this work.

CHAPTER-2

POWER QUALITY

2.1 INTRODUCTION

The issue of power quality has become very critical because of the loads which are sensitive to power quality disturbances. Sometimes, the loads themselves become the major reason for the deterioration in power quality. Electronic devices like computers, process controls and communication equipments are sensitive to the disturbances in the power system. The effect of power quality disturbance on equipment can be considered in terms of susceptibility and vulnerability. The temporary malfunction of a device due to disturbances in the system refers to susceptibility. This phenomenon can be observed in computing devices where if transients exceed a threshold, error occurs. An equipment is said to be vulnerable if the electric transient exceeds its insulation withstand level. This phenomenon can be observed in a rectifier which fails if it is subjected to transient voltages exceeding a certain level [7].

IEEE Standard IEEE1100 defines power quality as "the concept of powering and grounding sensitive electronic equipment in a manner that is suitable to the operation of that equipment" [2].

2.2 PERSPECTIVES OF POWER QUALITY [7]

Perspectives of power quality are as follows:

- The first perspective concerns with the customer's side of the meter. In this, focus is put on the power disturbances that effect the equipments adversely.
- The second perspective also concerns with the customer's side of the meter. In this, manufacturer of the equipment should be aware of the level of the power disturbances and their frequencies of occurrences so as to determine the tolerance limit of the equipment.
- The third perspective is from the utility. They are interested in power disturbances on both sides of the meter. They are concerned with how the power disturbances that have originated on the utility side will affect the customer equipments. They also take into consideration, the affect of user generated disturbances on the equipments of other customers or utility.

2.3 IMPORTANCE OF POWER QUALITY [7]

Recently, a lot of focus has been put on improving the power quality. The issue of power quality concerns the utility as well as the consumers. Power quality is gaining importance due to the following reasons:

- The dependency of our society on electrical supply has increased. Even a small power outage causes the industrial consumers to bear heavy economic losses. A longer interruption affects all operations of the society.
- New equipments are having higher sensitivity towards power quality problems.
- With the advent of power electronic devices like variable speed drives, new disturbances have been introduced into the supply system.

2.4 SYMPTOMS OF POWER QUALITY PROBLEMS [7]

Sophisticated electronic test equipments are required for the detection of power quality problems. Some of the symptoms of power quality problems are as follows:

- Misoperation of a piece of equipment at the same time of day.
- Tripping of circuit breakers without getting overloaded.
- Failure of equipment during a thunderstorm.
- Stopping of automated systems for no automated reason.
- Failure of electronic systems to operate on a frequent basis.
- Electronic systems operate at one location but fail to operate at another location.

2.5 POWER QUALITY ISSUES [1]

Electromagnetic phenomena can lead to power quality problems. Typical spectral content, duration and magnitude for each category of the electromagnetic phenomena are shown in Table-2.1.Power quality issues can be classified as follows:

Table-2.1: Categories and Characteristics of Electromagnetic Phenomena in Power Systems as Defined by IEEE-1159 [1]

S.No.	Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.	Transients			
	1.1 Impulsive			
	• Nanosecond	5 ns rise	< 50 ns	
	• Microsecond	1 μs rise	50 ns-1 ms	
	• Millisecond	0.1 ms rise	> 1 ms	

	1.2 Oscillatory			
	• Low frequency	< 5 kHz	0.3-50 ms	0-4 pu
	• Medium frequency	5-500 kHz	20 µs	0-8 pu
	• High frequency	0.5-5 MHz	5 µs	0-4 pu
2.	Short-duration variation			
	2.1 Instantaneous			
	• Interruption		0.5-30 cycles	< 0.1 pu
	• Sag		0.5-30 cycles	0.1-0.9 pu
	• Swell		0.5-30 cycles	1.1-1.8 Pu
	2.2 Momentary			
	• Interruption		0.5 cycle-3 s	< 0.1 pu
	• Sag		30 cycles-3 s	0.1-0.9 pu
	• Swell		30 cycles-3 s	1.1 -1.4 pu
	2.3 Temporary			
	• Interruption		3 s-1 min	< 0.1 pu
	• Sag		3 s-1 min	0.1-0.9 pu
	• Swell		3 s-1 min	1.1-1.2 pu
3.	Long-duration variation			
	3.1 Sustained interruption		> 1 min	0.0 pu
	3.2 Undervoltage		> 1 min	0.8-0.9 pu
	3.3 Overvoltage		> 1 min	1.1-1.2 pu
4.	Voltage imbalance		Steady state	0.5-2 %
5.	Waveform distortion			
	5.1 DC offset		Steady state	0-0.1 %
	5.2 Harmonics	0-100th	Steady state	0-20 %
	5.3 Interharmonics	0-6 kHz	Steady state	0-2 %
	5.4 Notching		Steady state	
	5.5 Noise	Broadband	Steady state	0-1 %
6.	Voltage fluctuation	< 25 Hz	Intermittent	0.1-7%
7.	Power frequency variations		<10 s	

2.5.1 Short-Duration Variation

Short-duration variation occurs for less than 1 minute. They are dependent on the location of occurrence of fault and the system conditions. These variations can lead to sags or voltage drops, swells or voltage rises and interruptions or complete loss of voltage, which are described as follows:

- **Sag**

It is also known as a voltage dip. This is the one of the most common power quality problem. It is depicted in Figure-2.1. It is defined as a decrease of normal voltage level between 10-90 percent of the nominal Root Mean Square (rms) voltage at the power frequency. It lasts for duration between 0.5 cycles to 1 minute. The magnitude of voltage sag depends on various factors like the type of fault, the location of the fault and the fault impedance. The time period for which voltage sag occurs basically depends on how fast the fault is cleared by the protective device. Starting of large induction motors, connection of heavy loads and faults in consumer's installations may lead to voltage sag. It may lead to malfunctioning of information technology equipments, loss of efficiency in electric rotating machines and tripping of contactors and electromechanical relays.

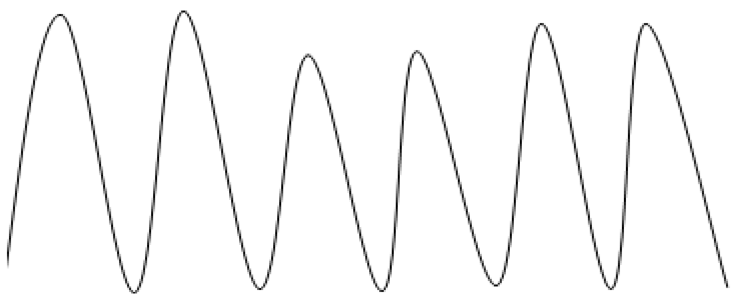

Figure-2.1: Sag

- **Swell**

It is defined as an increase of normal voltage level between 110-180 percent of the nominal rms voltage at the power frequency. It lasts for duration between 0.5 cycles to 1 minute. It is depicted in Figure-2.2. It may be caused by starting and stopping of heavy loads, badly regulated transformers etc. It may lead to data loss, flickering of lighting and screens, malfunctioning of sensitive equipments.

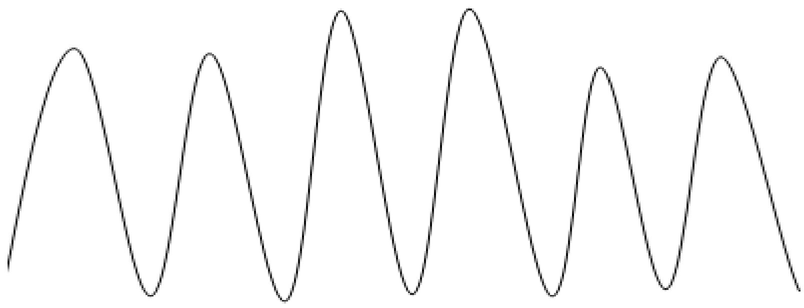

Figure-2.2: Swell

➢ **Interruption**

An interruption is said to have occurred if the line voltage or current reduces to 10 percent of the nominal. It does not exceed for more than 60 s in length. It is shown in Figure-2.3. Interruptions may be caused due to faults in the power system, failure of the equipments, control malfunctions etc.

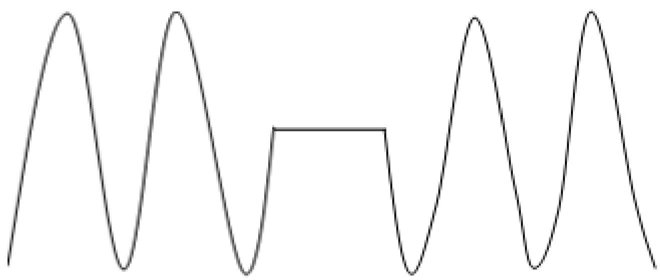

Figure-2.3: Interruption

2.5.2 Long- Duration Variation

They are basically rms variations at power frequencies. They exist for duration greater than 1 minute. It is further categorised into overvoltages, undervoltages and sustained interruptions. Its various categories are described as follows:

➢ **Overvoltage**

It can be defined as an increase in the rms ac voltage greater than 110 percent at power frequency. It lasts for duration greater than 1 minute. Various types of overvoltages are described below:

- Overvoltages which are produced due to ferroresonance, overcompensation, insulation fault, tap changer transformer etc.
- Overvoltages produced by lightning.

• Overvoltages produced due to switching operations like opening and closing of protective devices.

➢ **Undervoltage**

It can be defined as a decrease in the rms ac voltage to less than 90 percent at power frequency. It lasts for duration greater than 1 minute. Load switching or switching off a capacitor bank may lead to undervoltage.

➢ **Sustained Interruption**

The long-duration voltage variation is considered to be a sustained interruption if the supply voltage has been zero for duration greater than 1 minute. Voltage interruption that lasts for more than minute are usually permanent and they require human intervention for the restoration of the system.

2.5.3 Transients

Transients are also known as surge. Transients are characterized by high magnitudes of current and voltage or even both. It may be defined as that part of the change in a variable that disappears during transition from one steady state operating condition to another. Basically, they describe any unusual events that may occur in a power system.

Sources of transients are as follows:

• Lightning Strikes

• Switching activities: Such activities may be caused due to the following reasons:

➢ Loose connections in the distribution system may lead to the problem of arcing

➢ Neighbouring facilities

➢ Switching of capacitor banks

➢ Errors caused by humans

➢ Tap changing of transformers

➢ Bad weather conditions

➢ Operations related to reclosing

Transients are further divided into two categories which are as follows:

• **Impulsive Transient**

It can be defined as a sudden, unidirectional, non-power frequency change in the steady state condition of voltage, current or both. They can cause the excitation of the natural frequency of the system. Lightning, switching of inductive loads and electrostatic discharge are some of the common causes of impulsive transients. It is depicted in Figure-2.4.

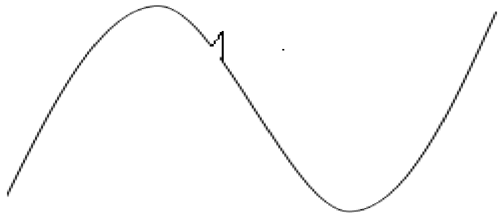

Figure-2.4: Impulsive Transient

- **Oscillatory Transient**

Oscillatory transient is described as a sudden, non–power frequency change in the steady-state condition of voltage, current, or both that has both positive and negative polarity values (bidirectional). They may occur due to capacitor bank energization, transformer ferroresonance and switching events like line or cable energization. It is depicted in Figure-2.5.

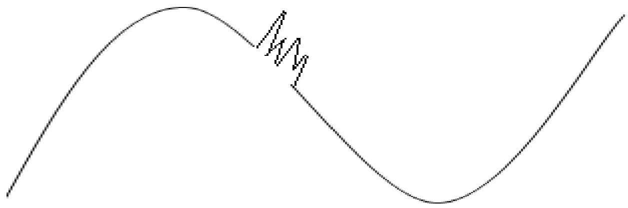

Figure-2.5: Oscillatory Transient

2.5.4 Voltage Imbalance

Voltage imbalance is said to have occurred when the voltages in a three phase system have unequal magnitude. Also, the phase difference between them may or may not be identical. Its main causes are as follows:

- It may occur if transposition of overhead transmission lines is not performed.
- It may occur in a three phase system if the single phase loading becomes unbalanced.
- It may occur if in a three phase capacitor bank, fuse is blown in one of the phase.

2.5.5 Waveform Distortion

It is defined as a steady-state deviation from an ideal sine wave of power frequency. There are five types of waveform distortion which are as follows:

- **Harmonics**

A harmonic can be defined as sinusoidal voltages or currents having frequencies that are whole multiple of the frequency at which the power system is designed to operate. This frequency is the fundamental frequency. It can be 50 Hz 0r 60 Hz. Figure-2.6 depicts harmonics. Protection from harmonics includes the use of multipulse converters, Pulse Width Modulation (PWM) rectifiers and application of passive or active harmonic filters [31]. Harmonics are commonly caused by arc furnaces, variable frequency drives, UPS, rectifiers, SMPS, electronic fluorescent lighting ballasts Adjustable Speed Drives (ASD), welding machines, and data processing equipment.

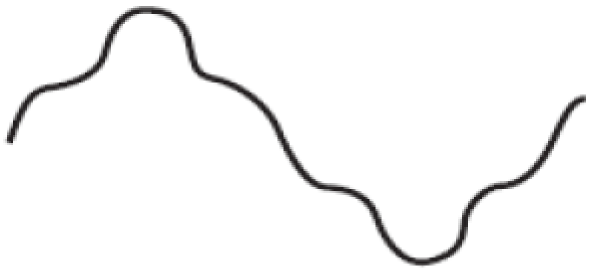

Figure-2.6: Harmonics

Harmonic distortion levels are measured by obtaining the whole harmonic spectrum. This harmonic spectrum consists of magnitudes and phase angles of each of the harmonic component. THD is a measure of harmonic distortion. It measures the whole harmonic spectrum which consists of magnitude and phase angle of each of the harmonic component present in the signal. It is represented as follows:

$$V_{THD} = \frac{\sqrt{\int_{n=2}^{\infty} V_n^{2}}}{V_1} \tag{2.1}$$

where, V_1 = rms magnitude corresponding to the fundamental component

V_n = rms magnitude corresponding to the n^{th} component.

n = 2, 3, 4,…….., ∞

➢ Consequences of harmonics

Some of the consequences of harmonics are as follows:

❖ Neutral may get overloaded

- ❖ Skin effect
- ❖ Overheating of equipments, cables and wires
- ❖ Probability of happening of resonance increases
- ❖ Zero-crossing noise
- ❖ Stress over the power factor correction capacitors increases
- ❖ Electromagnetic interference with communication systems
- ❖ Reduction in efficiency of electric machines

• **Notching**

Notching is a periodic voltage disturbance caused by the normal operation of power electronic devices when current is commutated from one phase to another. It is shown in Figure-2.7. It is mainly caused by converters that generate dc current continuously. It introduces harmonic and non-harmonic frequencies which are usually in radio frequency range. This causes negative operational effects which includes introduction of signal interference in logic and communication circuits, overloading of electromagnetic interference filters. Notching can be prevented by isolating the sensitive equipment from the source that causes the power quality problem.

Figure-2.7: Notching

• **Noise**

Noise is defined as an unwanted electrical signal with broadband spectral content lower than 200 kHz. In this, high frequency signals are superimposed on the waveform of the frequency of the power system. It may lead to data loss, disturbances in sensitive electronic equipments and errors during data processing. Its main causes are as follows:

- ➢ Arc furnaces
- ➢ Radiation due to welding machines
- ➢ Corona
- ➢ Electromagnetic interferences

➢ Power electronic equipments

➢ Improper grounding

➢ Control circuits

The effect of noise can be mitigated by using line conditioners, filters, dedicated lines or transformers. Figure-2.8 shows noise.

Figure-2.8: Noise

- **DC Offset**

It can be defined as the presence of dc voltage or current in an ac power system. It is mainly caused by the operation of electronic switching devices and geomagmetic disturbances. Various effects of dc offset in an alternating network are as follows:

➢ It may lead to electrolytic erosion of grounding electrodes.

➢ In addition to odd harmonics, even harmonics may also be generated.

➢ It may reduce the lifetime of transformers, electromagnetic devices and rotating machines.

- **Interharmonics**

Interharmonics are those frequencies that are not integer multiples of the frequency of the supply system (50 Hz or 60 Hz). Table-2.1 depicts spectral components of waveforms.

Table-2.2: Spectral Components of Waveforms (of Frequency f)

Harmonic	$f = nf_1$ where, n is an integer greater than zero
DC component	$f = nf_1$ for $n = 0$
Interharmonnic	$f \neq nf_1$ where, n is an integer greater than zero
Subharmonic	$f > 0$ Hz and $f < f_1$
f_1 = Voltage fundamental frequency (basic harmonic)	

2.5.6 Spikes

Spikes are a sudden, short surge in voltage. The voltage peak may rise up to 6000 volts. Spikes can be caused by lightning, power outages, tripping of circuit breakers, short circuits etc. Spikes can lead to breakdown of isolation in transformers, spurious operation of semiconductor devices, loss of data and burned circuit boards.

2.5.7 Flicker

It is also known as a voltage fluctuation. It may be defined as repetitive or random changes in the voltage envelope which may occur because of sudden variations in the real and reactive power drawn by a load. These are characterized by the type of load and the power system capacity. An example of voltage fluctuation is shown in Figure-2.9. Due to the fluctuating nature of connected loads, voltage waveform shows variations in magnitude. Here, the voltage changes have been modulated in a sinusoidal form. The changes in voltage can also be rectangular or irregular in shape. The current drawn by the fluctuating load determines the profile of the voltage changes. Flicker frequency is referred to as the frequency of the voltage envelope. Hence, magnitude of fluctuation and frequency of fluctuation serve as the two important parameters to voltage fluctuations. It may lead to lamp flickering, spurious tripping of relays, stalling of induction motors that operate at maximum torque. Some of the loads that may produce voltage fluctuations are as follows:

- Installations that consist of frequent motor starts like fans, air conditioner units etc.
- Arc furnaces
- Motor drives that consist of cyclic operations like mine hoists, rolling mills etc.
- Arc welders
- Devices that consists of excessive changes in motor speed like wood chippers, car shredders etc.

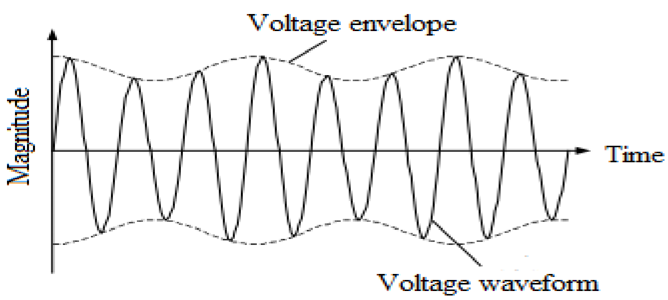

Figure-2.9: Voltage Fluctuations

2.6 SOLUTIONS TO POWER QUALITY PROBLEMS

Improvement in power quality can be performed from the customer side as well as from the utility side. The methods adopted to improve power quality are as follows:

- **Load Conditioning**

In load conditioning, it is ensured that the device is less sensitive to power quality problems. This allows operation even during significant voltage distortion.

- **Line Conditioning**

In line conditioning, systems are used to suppress or counteract the disturbances that occur in the power system. This can be achieved by using passive filters which can be connected at the sensitive load terminals. The series active power filters can be used which function as a controllable voltage source. The shunt active power filters work as a controllable current source.

CHAPTER-3

MULTIPULSE CONVERTERS

3.1 INTRODUCTION

Multipulse converters can be defined as diode/thyristor converters that provide more than 6 pulses of dc per cycle. Usually, it consists of a combination of a number of 6-pulse rectifiers connected either in parallel or in series. Each of the rectifier is fed by phase shifted secondary windings' voltages of the phase shifting transformer so as to shape the primary current near to sinusoidal. One rectifier is present at each of the secondary windings. As the number of rectifiers are increased, the number of steps in the primary current waveform are also increased. Thereby, producing a sinusoidal shaped supply current which then flows into the transformer winding. The multipulse converters that consist of diodes as switching elements are referred to as uncontrolled converters whereas the multipulse converters that consists of thyristors as switching elements are referred to as controlled converters .For harmonic mitigation, the use of uncontrolled converters is very popular. This is due to the fact that they do not require any control system for the diodes. However, output voltage cannot be controlled. In case of controlled converters, a control circuit is required for switching of the thyristors. Due to the modular control concept, the overall design and circuit realization becomes easier. Multipulse converter provides a simple and effective technique for harmonic elimination. They are based on the principle of harmonic cancellation. It involves multiple converters so that harmonics generated by one converter are cancelled by harmonics produced by the other converters [10].

3.2 ADVANTAGES OF MULTIPULSE CONVERTER [9]

Advantages of a multipulse converter are as follows:

- Multipulse converters allow a reduction in the size of the filtering element.
- Multipulse converter is a suitable configuration so as to obtain high power rating.
- It has a good dynamic response.
- The multipulse converters are simple, robust, rugged and more efficient.
- Reduction of ac input line current harmonics.
- Reduction of dc output voltage ripple.

3.3 CONFIGURATION OF A MULTIPULSE CONVERTER

The major components of a multipulse converter are as follows:

3.3.1 Zig-zag Phase Shifting Transformer [11]

Zig-zag phase shifting transformer is used to achieve the desired phase shift in between the converter voltages. It consists of three single-phase, three-winding transformers. Primary winding is connected in zig-zag manner. Each of the core leg consists of two coils i.e. the inner coil and the outer coil. Both the coils consists of same winding turns but their direction of rotation is opposite in nature. Figure-3.1 and Figure-3.2 depicts zig-zag coupling for positive phase shift and negative phase shift, respectively.

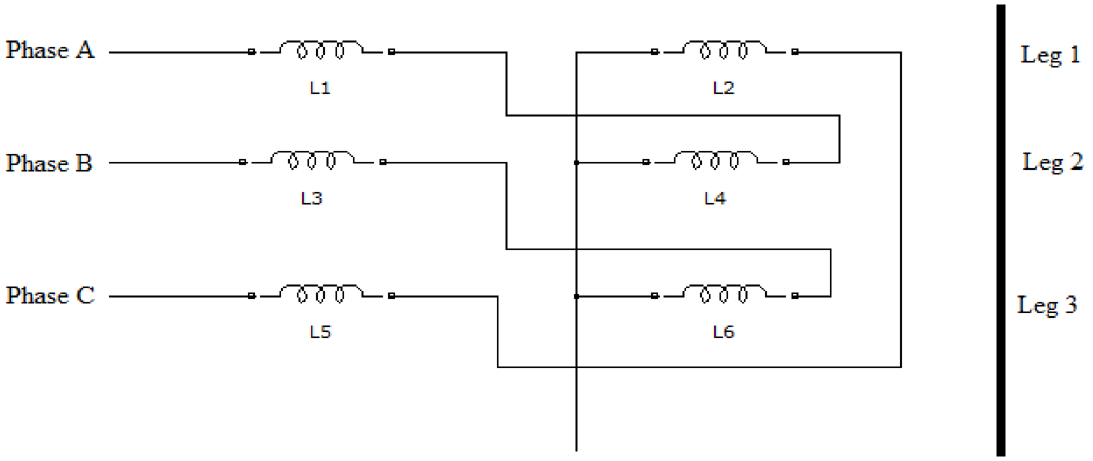

Figure-3.1: Zig-Zag Coupling for Positive Phase Shift

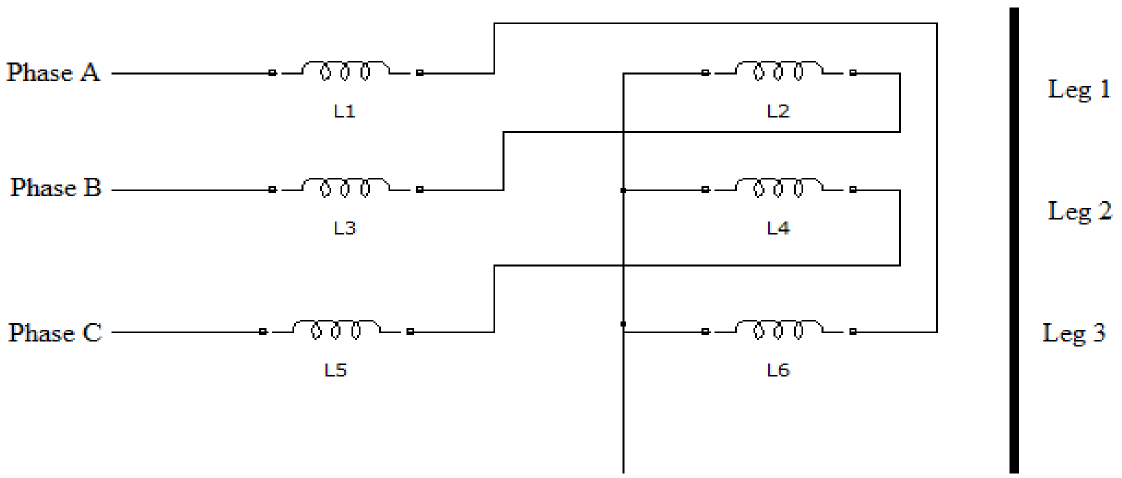

Figure-3.2: Zig-Zag Coupling for Negative Phase Shift

The secondary winding of the zig-zag phase shifting transformer is configurable. It can be configured in any of the following ways:

- Star: In case of star connected secondary winding, the secondary phase voltages will lead or lag the primary voltages by a phase angle.
- Star with accessible neutral
- Grounded star
- Delta (D11): If the secondary winding is connected in delta (D11) then an additional phase shift of +30° is provided to the phase angle.
- Delta (D1): If the secondary winding is connected in delta (D1) then an additional phase shift of -30° is provided to the phase angle.

3.3.2 Three phase rectifier

Three-phase rectifiers are commonly used in industries to produce a dc voltage and dc current for large loads. Figure-3.3 and Figure-3.4 shows the diagram and corresponding waveforms of a three phase rectifier, respectively. The three phase voltage source considered is balanced in nature.

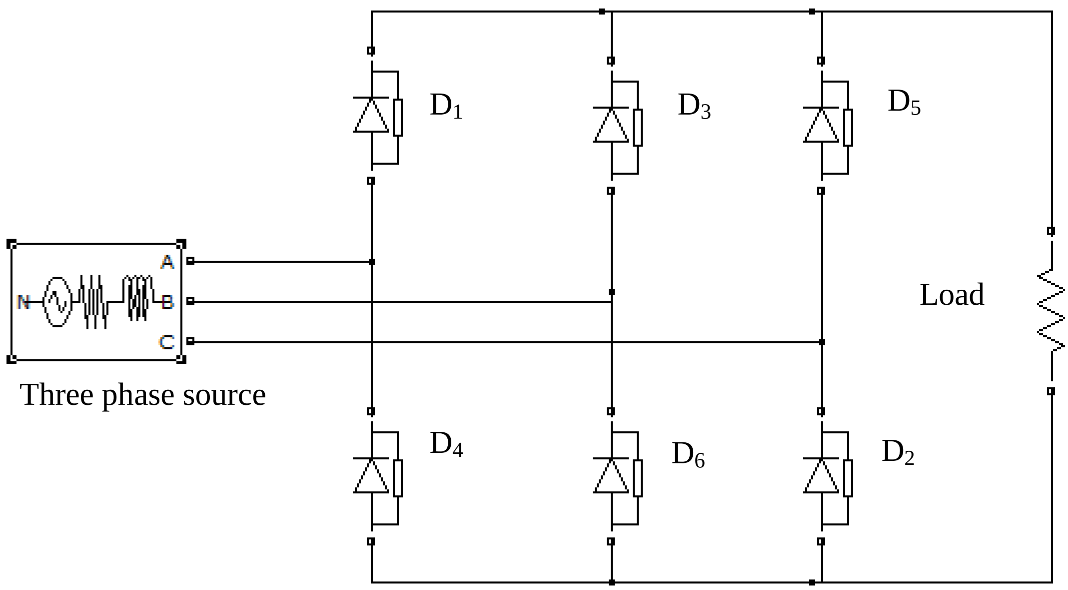

Figure-3.3: Circuit Diagram of a Three Phase Rectifier

Working of a three phase rectifier is described as follows:

- Only one diode in the top half of the bridge i.e. D_1, D_3, or D_5 will conduct at a time.
- Only one diode in the bottom half of the bridge i.e. D_2, D_4, or D_6 will conduct at a time.

• No two diodes in the same leg would conduct simultaneously else a short circuit can occur. Diode pairs (D_1, D_4), (D_3, D_6) and (D_5, D_2) cannot conduct simultaneously.

• The output voltage across the load is one of the line to line voltages of the source. For example, when D_1 and D_2 would conduct then the corresponding output voltage is V_{ac}.

• The diodes that would conduct are determined by which line to line voltage is the maximum at that instant.

• There are six combinations of line to line voltages. Each combination exists for an interval of 60°.

• As six transitions occur in line to line voltages for each period of the source voltage, the circuit is also referred to as a 6-pulse rectifier.

• Therefore, fundamental frequency of the output voltage is 6*grid frequency.

• Whenever a diode conducts, voltage across it becomes equal to zero.

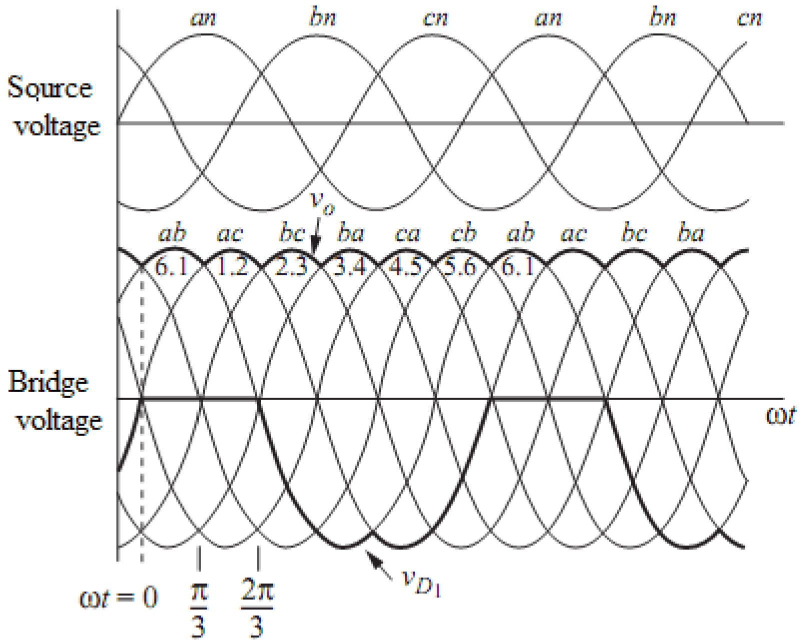

Figure-3.4: Waveforms of Source Voltage and Bridge Voltage of a Three Phase Rectifier

Table-3.1 depicts the diode state functions. Waveforms of state function of diode D_1, D_2, D_3, D_4, D_5 and D_6 are shown in Figure-3.5, Figure-3.6, Figure-3.7, Figure-3.8, Figure-3.9 and Figure-3.10, respectively.

Table-3.1: Diode State Functions

SEGMENT	$D_1(wt)$	$D_2(wt)$	$D_3(wt)$	$D_4(wt)$	$D_5(wt)$	$D_6(wt)$
0<wt<60°	1	0	0	0	0	1
60°<wt<120°	1	1	0	0	0	0
120°<wt<180°	0	1	1	0	0	0
180°<wt<240°	0	0	1	1	0	0
240°<wt<300°	0	0	0	1	1	0
300°<wt<360°	0	0	0	0	1	1

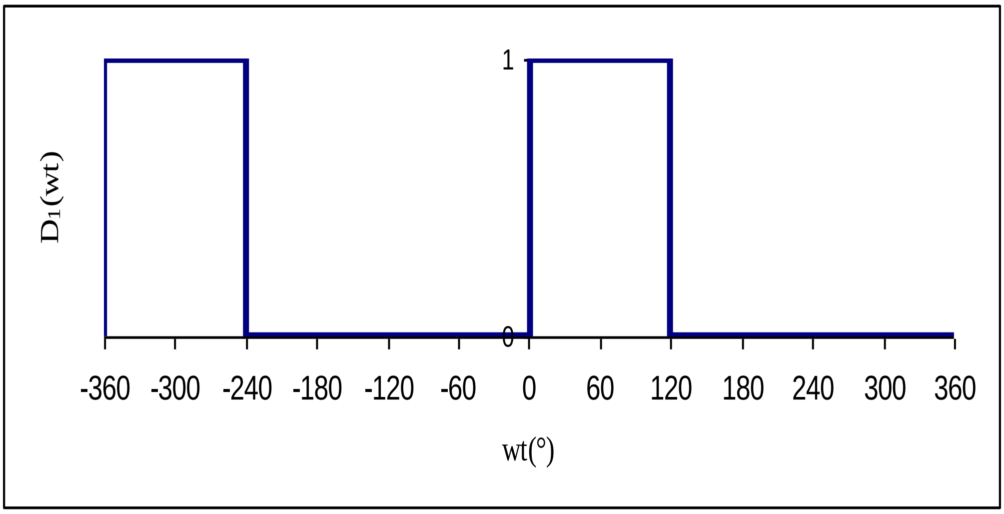

Figure-3.5: Waveform of the State Function of Diode D_1

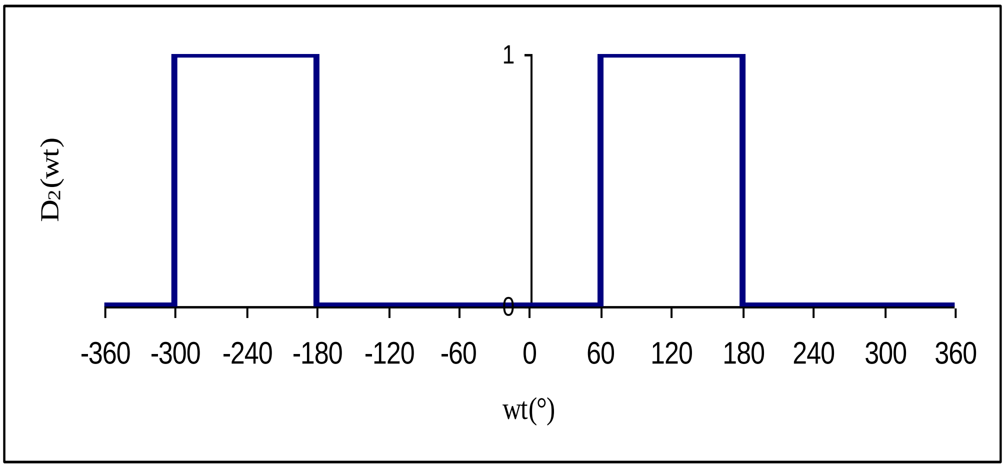

Figure-3.6: Waveform of the State Function of Diode D_2

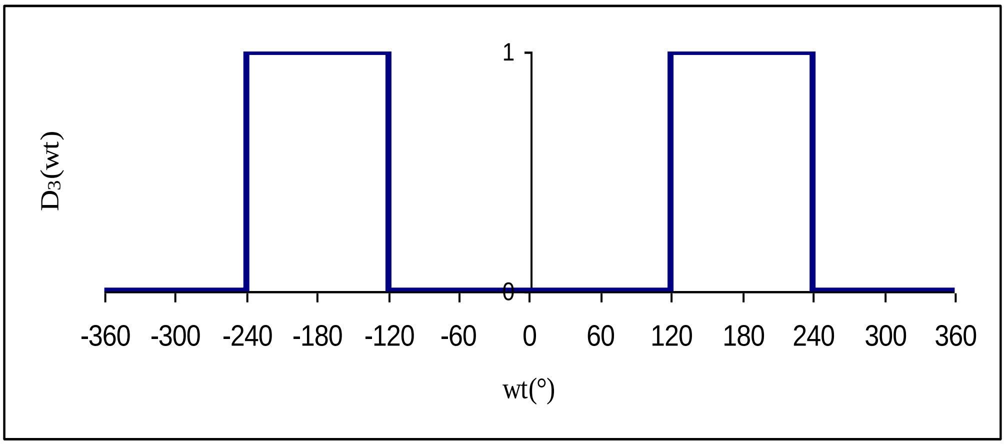

Figure-3.7: Waveform of the State Function of Diode D_3

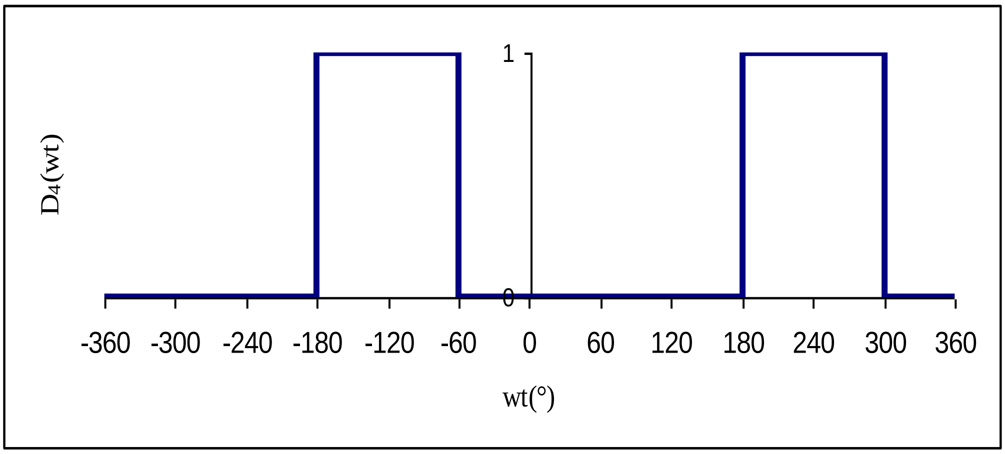

Figure-3.8: Waveform of the State Function of Diode D_4

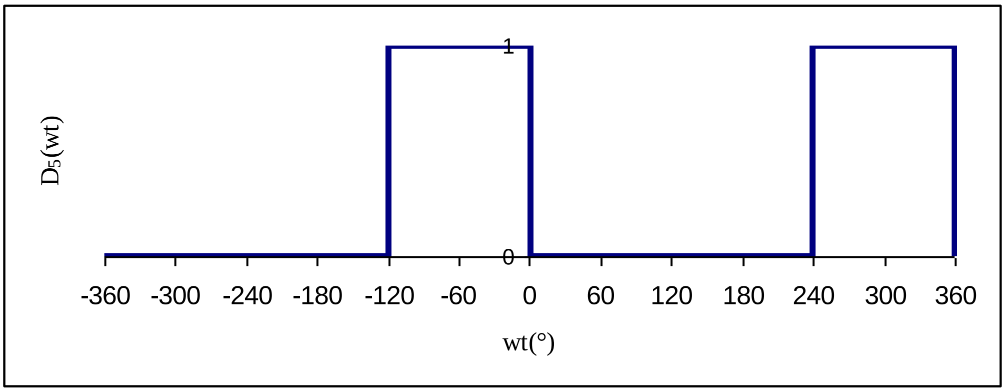

Figure-3.9: Waveform of the State Function of diode D_5

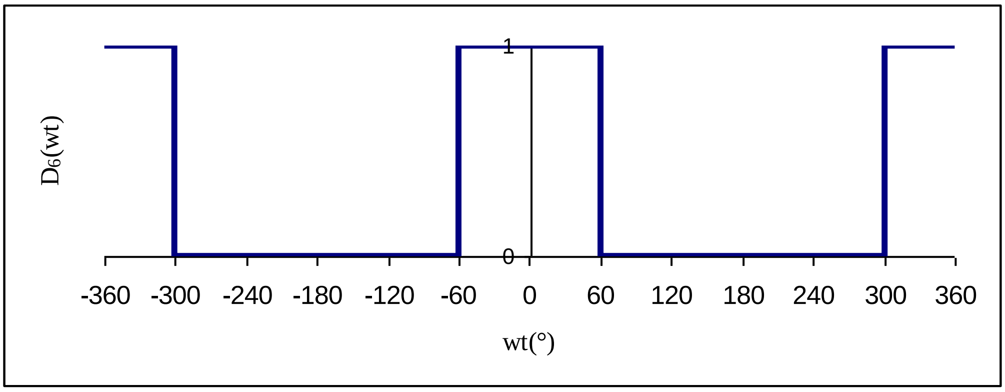

Figure-3.10: Waveform of the State Function of Diode D_6

3.3.3 FILTER

A filter circuit is used to filter out the ac components from the rectifier circuit. Basically, it is a device that removes the ac component from the rectified output but allows the dc component to pass through and reach the load. Generally, it consists of a combination of a series connected inductor (L) and a shunt connected capacitor (C). This combination is referred to as LC filter circuit. It is shown in Figure-3.11. Capacitor allows only ac component to pass through whereas an inductor allows only dc component to pass. Hence, a suitable L and C network can be used to effectively filter out the ac component from the rectified wave. This filter is popular, because of its low cost, small size, less weight and good characteristics. Such filters are used in radars and communication transmitters.

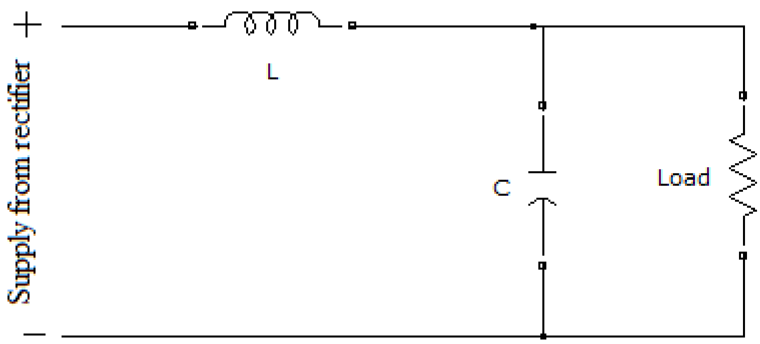

Figure-3.11: LC Filter

An inductor provides opposition to any change in current. The variation in current through an inductor produces a varying electromagnetic field. The varying electromagnetic field cuts the windings of the wire in the inductor and leads to the production of a Counter Electromotive Force (CEMF). It is this CEMF that causes the inductor to oppose the change in current. Opposition to variation in current at a specific frequency is referred to as inductive reactance (X_L). It is measured in ohms. The inductive reactance (X_L) of an inductor is determined by the value of the applied frequency and the value of the inductance of the inductor. Mathematically, it can be expressed as:

$$X_L = 2\pi fL \tag{3.1}$$

If the value of f or L is increased then X_L is also increased. For a dc signal, frequency is zero and as a result X_L also corresponds to zero. Hence, no opposition is provided to a dc signal but it obstructs the path for an ac signal. The capacitive reactance can be determined by the frequency (f) of the applied voltage and the capacitance (C) of the capacitor.

$$X_C = \frac{1}{2\pi fC} \tag{3.2}$$

From the above formula, we can observe that for a dc signal, infinite capacitive reactance is provided. Hence, it does not allow dc signal to pass through it but allow ac signal to pass through. The ripple frequency rate determines the charging and discharging of the capacitor. The charging rate for a capacitor is determined by impedance of the ac source, small resistance of the diode and the CEMF developed by the inductive coil. The RC charge time constant should be lower than the discharge time. After getting charged, the capacitor must be able to hold the charge as long as possible.

Hence, whenever a pulsating voltage appears across the filter circuit, CEMF produced by the inductor opposes the constantly increasing input voltage. As a result, rapid charging of the capacitor is avoided. Hence, capacitor charges only to the average value of the input voltage instead of charging up to the peak voltage. When the input voltage attains its peak value and starts decreasing then the capacitor would start discharging through load but it would discharge partially as it has a long discharge time constant. The value of the capacitor should be large in order to obtain better filtering action.

3.4 CANCELLATION OF HARMONICS

Input current harmonics for rectifier circuits depend on the pulse number and can be expressed by the following expression:

$$h = (np \pm 1) \tag{3.3}$$

where, n= 1, 2, 3,… and p = pulse number

The multipulse converters are formed by a number of converters which are phase shifted from each other so that harmonic currents required by one converter are supplied by the other converters.

The minimum phase shift required for harmonic cancellation can be expressed as:

$$\text{Phase shift} = \frac{60°}{\text{Number of 6-pulse converters}} \quad (3.4)$$

Switching function of 6-pulse and 12-pulse and 18-pulse converter is described as follows:

- **6-pulse converter**

The switching function for a 6-pulse converter for phase 'a' of the rectifier is depicted in Figure-3.12. A 6-pulse converter serves as a building block for higher order converters like 12-pulse, 18-pulse and so on. The switching function, S_a [16] for phase 'a' is given by:

$$S_{a1}(t) = \frac{2\sqrt{3}}{\pi}\left(\text{Sin } wt - \frac{1}{5}\text{Sin } 5wt - \frac{1}{7}\text{Sin } 7wt + \frac{1}{11}\text{Sin } 11wt + \frac{1}{13}\text{Sin } 13wt\ldots\right) \quad (3.5)$$

Hence, switching functions for phase 'b' and phase 'c' are given by:

$$S_{b1} = S_{a1} \angle -120° \quad (3.6)$$

$$S_{c1} = S_{a1} \angle +120° \quad (3.7)$$

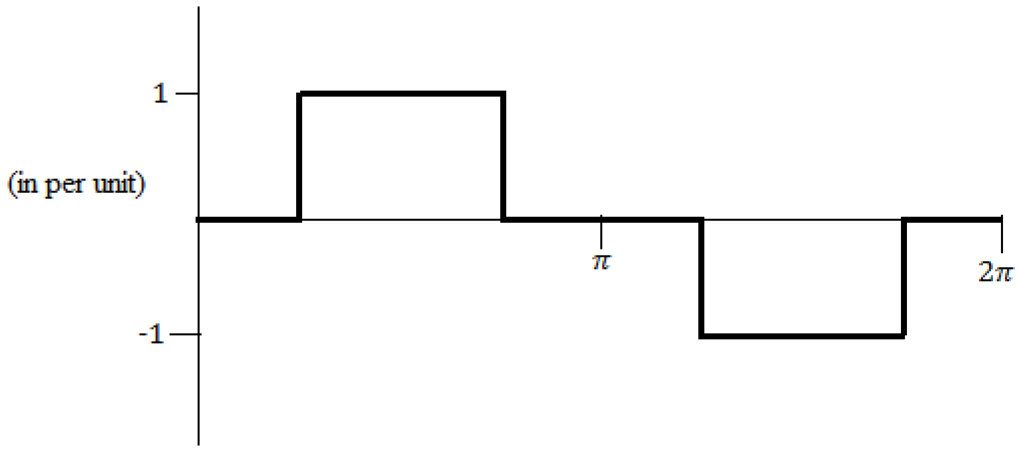

Figure-3.12: Switching Function, S_a [16]

- **12-pulse converter**

It consists of two 6-pulse converters which are phase shifted from each other by 30°.

➢ **Consider first rectifier**

The switching function S_a for phase 'a' is given by:

$$S_{a1}(t) = \frac{2\sqrt{3}}{\pi}(\text{Sin wt} - \frac{1}{5}\text{Sin 5wt} - \frac{1}{7}\text{Sin 7wt} + \frac{1}{11}\text{Sin 11wt} + \frac{1}{13}\text{Sin 13wt}....) \qquad (3.8)$$

Hence, switching functions for phase 'b' and phase 'c' are given by:

$$S_{b1} = S_{a1} \angle -120^{\circ} \qquad (3.9)$$

$$S_{c1} = S_{a1} \angle +120^{\circ} \qquad (3.10)$$

➢ **Consider second rectifier**

The switching function S_{a2} for phase 'a' is given by:

$$S_{a2} = S_{a1} \angle +30^{\circ} \qquad (3.11)$$

The switching function S_{b2} for phase 'b' is given by:

$$S_{b2} = S_{b1} \angle +30^{\circ} \qquad (3.12)$$

The switching function S_{c2} for phase 'c' of the second rectifier is given by:

$$S_{c2} = S_{c1} \angle +30^{\circ} \qquad (3.13)$$

- **18-pulse converter**

It consists of two 6-pulse converters which are phase shifted from each other by 20°.

➢ **Consider first rectifier**

The switching function S_a for phase 'a' is given by:

$$S_{a1}(t) = \frac{2\sqrt{3}}{\pi}(\text{Sin wt} - \frac{1}{5}\text{Sin 5wt} - \frac{1}{7}\text{Sin 7wt} + \frac{1}{11}\text{Sin 11wt} + \frac{1}{13}\text{Sin 13wt}....) \qquad (3.14)$$

Hence, switching functions for phase 'b' and phase 'c' are given by:

$$S_{b1} = S_{a1} \angle -120^{\circ} \qquad (3.15)$$

$$S_{c1} = S_{a1} \angle +120^{\circ} \qquad (3.16)$$

- **Consider second rectifier**

The switching function S_{a2} for phase ‘a’ is given by:

$$S_{a2} = S_{a1} \angle -20^{\circ} \qquad (3.17)$$

The switching function S_{b2} for phase ‘b’ is given by:

$$S_{b2} = S_{b1} \angle -20^{\circ} \qquad (3.18)$$

The switching function S_{c2} for phase ‘c’ is given by:

$$S_{c2} = S_{c1} \angle -20^{\circ} \qquad (3.19)$$

- **Consider third rectifier**

The switching function S_{a3} for phase ‘a’ is given by:

$$S_{a3} = S_{a1} \angle +20^{\circ} \qquad (3.20)$$

The switching function S_{b3} for phase ‘b’ is given by:

$$S_{b3} = S_{b1} \angle +20^{\circ} \qquad (3.21)$$

The switching function S_{c3} for phase ‘c’ is given by:

$$S_{c3} = S_{c1} \angle +20^{\circ} \qquad (3.22)$$

3.5 THEORY OF COMBINING SINE WAVES

The theory of combining sine waves can be achieved in two ways:

• By using the inherent phase angle displacement of the electrical wave shapes within the transformer which are then combined at the nodes or connection points, of the windings within the transformer.

• Sine waves at the common bus feeding two transformers of different phase shift can be combined.

CHAPTER-4

Z-SOURCE CONVERTER

4.1 INTRODUCTION [35]

Traditional converters consist of voltage source converters and current source converters. Figure-4.1 shows the diagram of a voltage source converter. A voltage source converter provides bidirectional current flow and unidirectional voltage blocking capability. This converter is used widely but it has some limitations which are described below:

➢ The ac output voltage is always less than the dc-rail voltage or the ac input voltage is always less than the dc-rail voltage. In case of dc to ac power conversion, voltage source inverter behaves as a buck inverter or step-down inverter. However, in case of ac to dc power conversion, voltage source converter behaves as a boost rectifier or a step-up rectifier. For the applications where the availability of dc voltage is limited, a dc-dc boost converter is required to achieve the required ac output. This extra circuitory adds up to the cost and cause reduction in the efficiency.

➢ The switching devices connected across each of the phase legs cannot be turned on simultaneously else a shoot-through would occur which would destroy the devices. Hence, a dead time has to be provided between the the upper switching device and the lower switching device in each of the legs. This leads to the problem of waveform distortion.

➢ LC filter should be connected across its output so as to obtain a sinusoidal voltage compared to that obtained from a current source inverter. This increases the power loses and further and the control process becomes complex.

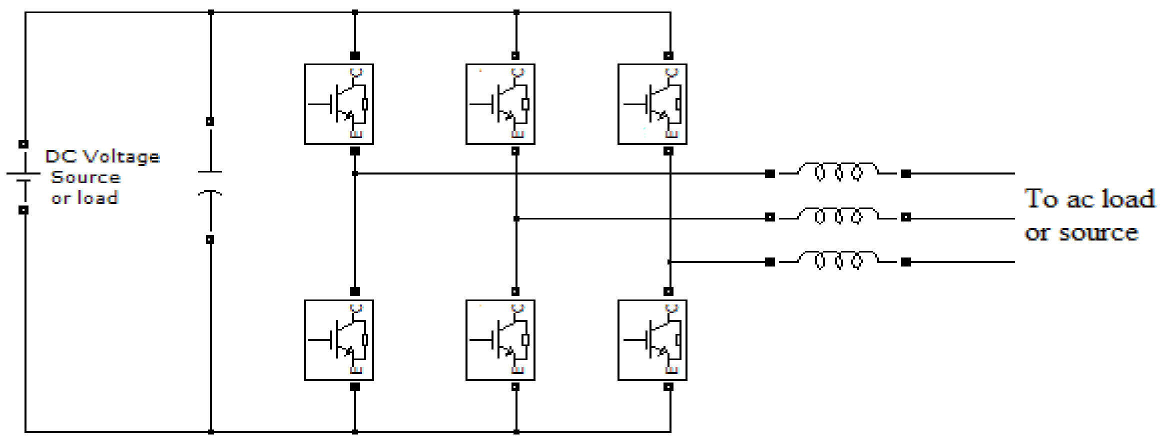

Figure-4.1: Voltage Source Converter

Figure-4.2 depicts a current source converter. A current source converter provides unidirectional current flow and bidirectional voltage blocking capability. Limitations of current source converters are as follows:

➢ AC output voltage always exceeds the dc voltage that is used to feed the inductor or the ac input voltage is always greater than the output dc voltage. In case of dc to ac power conversion, current source inverter behaves as a boost inverter or step-up inverter. However, in case of ac to dc power conversion, current source converter behaves as a buck rectifier or a step-down rectifier. For the applications where large voltage range is required, a dc-dc boost converter or a dc- dc buck converter is required. This extra circuitry adds up to the cost and cause reduction in the efficiency.

➢ One of the upper devices and one of the lower devices should be on at any instant of time else an open circuit of the dc inductor would take place which in turn would destroy the devices. Hence, in a current source inverter, overlap time is required for safe current commutation. However, this may lead to waveform distortion.

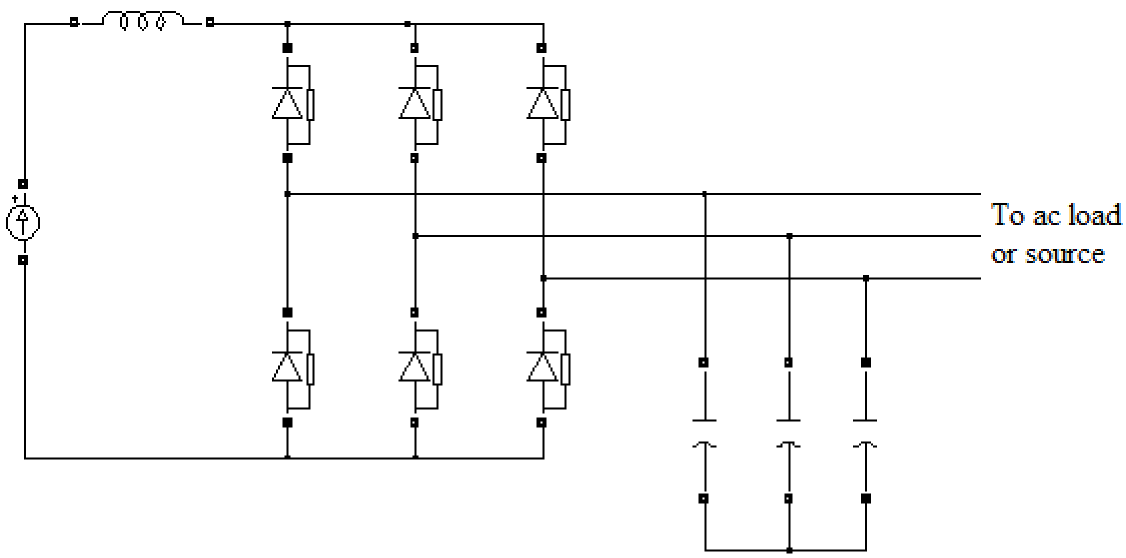

Figure-4.2: Current Source Converter

• **Common problems of voltage source converters and current source converters**

Some of the common problems faced by voltage source converters and current source converters are as follows:

➢ They can either behave as a buck converter or a boost converter. They cannot behave as a buck-boost converter.

➢ Their main circuits cannot be interchanged. In other words, the main circuit of the voltage source converter cannot be used for the current source inverter and vice versa.

➢ They are susceptible to electromagnetic noise and hence, the reliability of the system is affected.

All the drawbacks of voltage source converters and current source converters are overcome by Z-source converter. Z-source converter can be used for all power conversion concepts like dc to ac, ac to dc, ac to ac and dc to dc. General structure of a Z-source converter is depicted in Figure-4.3. Basically, it consists of a unique impedance network which is used to couple the main circuit with the power source, load or any other converter. Impedance network is formed by split-inductor L_1 and L_2 and capacitors C_1 and C_2. They are connected in X-shape. A battery, thyristor converter or a fuel cell can act as a dc source.

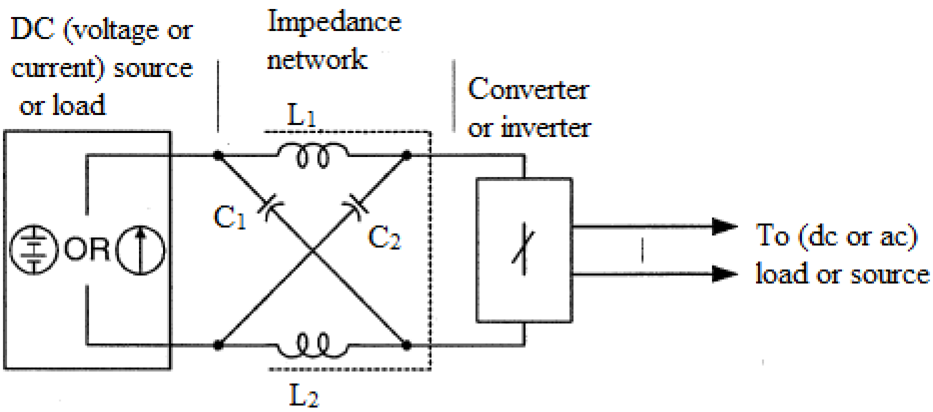

Figure-4.3: General Structure of a Z-Source Converter

Traditional three phase voltage source inverter have eight switching states i.e. 6 active switching states and two zero switching states. However, Z-source inverter consists of one extra zero state. This zero state occurs due to shorting of the load terminals by turning on the upper and lower switching devices on any one phase leg, two phase legs or all the three phase legs. This zero state is also referred to as shoot-through state which does not occur in voltage source inverters. This shoot-through state can be achieved in seven different ways i.e. by causing shoot-through in any one phase leg or in a combination of any two phase legs or in all the three phase legs. This shoot through provides the buck-boost feature to the Z-source inverter.

Voltage gain = MB = $\frac{V_{ac}}{\frac{V_o}{2}}$ (4.1)

Here, V_{ac} is the output peak phase voltage

V_o is the input dc voltage

M is the Modulation index

Boost factor, B = $\frac{1}{1-2\frac{T_o}{T}}$ (4.2)

Shoot-through duty ratio, $D_o = \frac{T_o}{T}$ (4.3)

Here, T_o is the shoot-through time interval over a switching cycle T.

4.2 CONTROL METHODS OF Z-SOURCE INVERTER

There are different control methods for a Z-source inverter which are as follows:

- **Simple boost control [36]**

This method involves the controlling of shoot-through duty ratio. Figure-4.4 shows the waveforms corresponding to simple boost control method. It consists of a straight line which is equal or higher than the maximum value corresponding to the three phase references, so as that the shoot-through duty ratio can be controlled in a traditional sinusoidal PWM. The six active states in the Z-source inverter are same as that in the traditional carrier PWM control. In this method, with the increase in value of M, the shoot-through duty ratio is reduced. The maximum shoot-through duty ratio corresponds to 1-M.

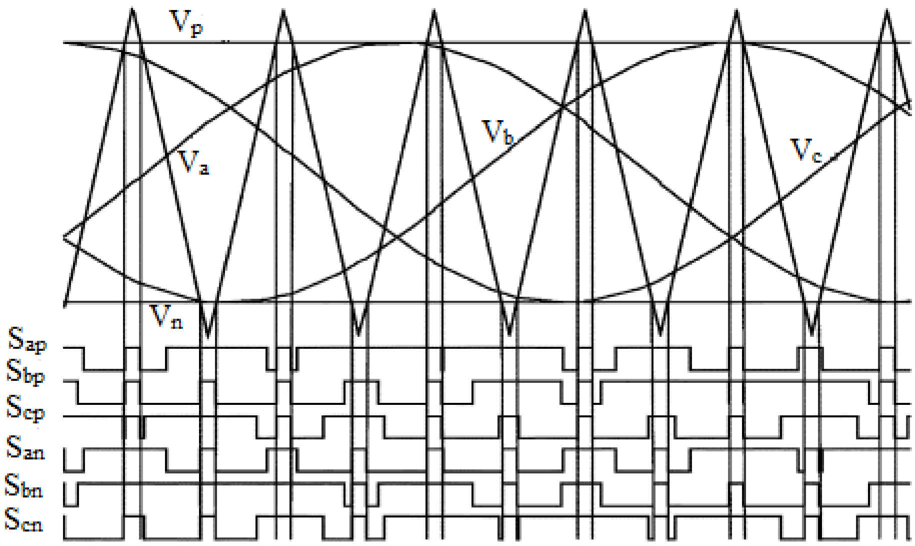

Figure-4.4: Waveforms of Simple Boost Control Method [36]

Voltage gain, G = MB = $\frac{V_{ac}}{\frac{V_o}{2}} = \frac{M}{2M-1}$ (4.4)

The maximum value of modulation index with respect to any value of G is shown below:

$M = \frac{G}{2G-1}$ (4.5)

Voltage stress across the switches, $V_s = BV_o = (2G-1)V_o$ (4.6)

In this method, the obtainable voltage gain is restricted due to high voltage stress across the switches. This is due to the fact that the device voltage rating is limited.

- **Maximum boost control [36]**

It is important to control to reduce the voltage stress for the desired value of voltage gain so as to control the Z-source inverter. To minimize the voltage stress, B should be minimized and M should be maximized. However, their product should be the desired value. At the same time, B should be maximized so as to obtain maximum voltage gain for any given value of modulation index. Also, the value of shoot-through duty ratio should be high. Figure-4.5 depicts the PWM signals for the maximum boost control method.

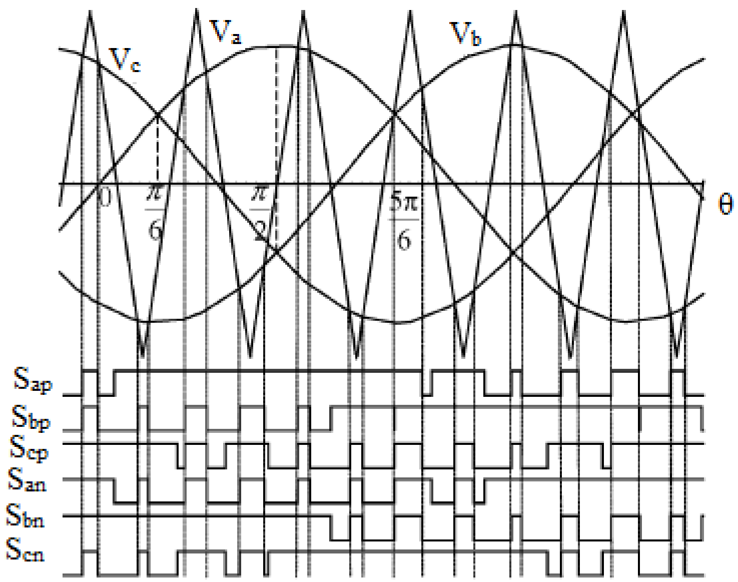

Figure-4.5: PWM Signals for Maximum Boost Control [36]

In this method, maximum value of T_o and B are obtained for any desired value of M such that no distortion is caused in the output waveform. From the Figure-4.5, it can be observed that the shoot-through state occurs whenever the triangular carrier wave attains higher value than the value corresponding to the maximum curve of the references (V_a, V_b, V_c) or lower value than the value corresponding to the maximum curve of the references. The shoot-through state would repeat itself after $\pi/3$ radians. The shoot-through duty ratio corresponding to one switching cycle for the interval ($\pi/6$,$\pi/2$) can be calculated with an assumption the value of the switching frequency is much higher than the value of the modulation frequency. It is given by:

$$\frac{T_o}{T} = \frac{2-(M\sin\theta - M\sin(\theta-\frac{2\pi}{3}))}{2} \quad (4.7)$$

The average duty ratio of shoot-through is shown below:

$$\frac{T_o}{T} = \int_{\pi/6}^{\pi/2} \frac{2-(M\sin\theta - M\sin(\theta-\frac{2\pi}{3}))}{2} d\theta = \frac{2\pi - M3\sqrt{3}}{2\pi} \quad (4.8)$$

$$\text{Boost factor, } B = \frac{1}{1-2\frac{T0}{T}} = \frac{\pi}{3M\sqrt{3}-\pi} \quad (4.9)$$

Voltage gain can be obtained by the modulation index. It can be expressed as:

$$\frac{V_{ac}}{\frac{V_o}{2}} = MB = \frac{\pi M}{3\sqrt{3}\,M-\pi} \quad (4.10)$$

Maximum value of modulation index for any voltage gain G is expressed by:

$$M = \frac{\pi G}{3\sqrt{3}\,G-\pi} \quad (4.11)$$

$$\text{Voltage stress, } V_s = BV_o = \frac{\pi V_o}{3\sqrt{3}\,M-\pi} = \frac{3\sqrt{3}\,G-\pi}{\pi} V_o \quad (4.12)$$

In this method, operation of the inverter may provide higher value of voltage gain because the value of voltage stress is much lower when compared with that obtained in simple boost control method.

- **Maximum constant boost control method [37]**

In order to reduce the cost and volume of the Z-source network, the low-frequency current ripple must be removed. For this, a constant shoot-through duty ratio is required. The voltage stress across the switches can be reduced if a high voltage boost for any desired modulation index is obtained. Figure-4.6 depicts the sketch map of maximum constant boost control method. In this method, maximum voltage gain is achieved while the shoot-through duty ratio is maintained constant. This method consists of five modulation curves which consists of three reference signals i.e. V_a, V_b and V_c, and two shoot-through envelope signals i.e. V_p and V_n. A shoot-through zero state would occur if the carrier triangular wave exceeds the upper shoot-through envelope V_p or attains a lower value than the lower shoot-through envelope V_n. In between, the inverter would behave in the similar manner as in the traditional PWM control. Shoot-through duty cycle determines the boost factor. It is necessary to maintain the shoot-through duty cycle constant from one switching cycle to another in order to maintain a constant boost. The main aim is to obtain the maximum value of B. At the same time, it should be kept constant. The upper envelope curve and the lower envelope curve are periodical in nature and have a frequency which is three times the output frequency.

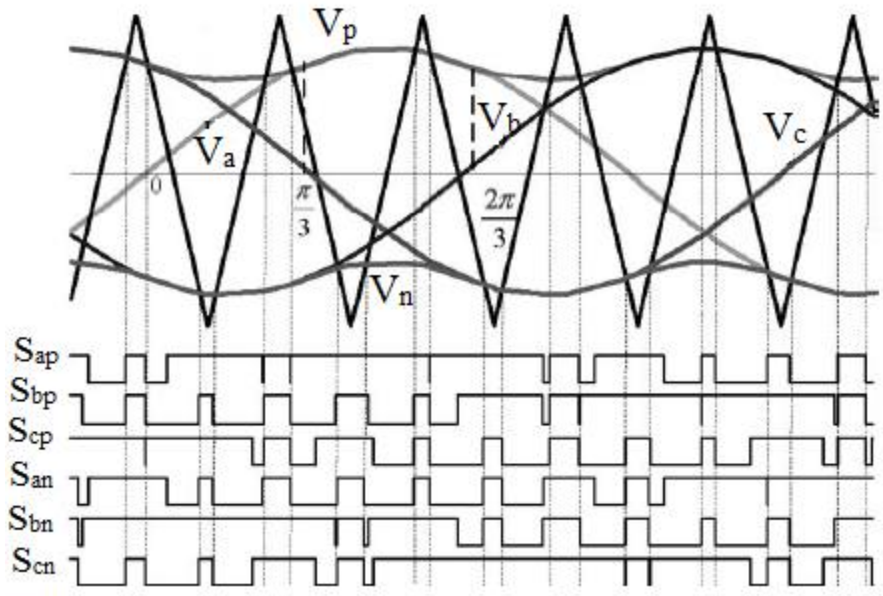

Figure-4.6: Sketch Map of Maximum Constant Boost Control [37]

A cycle consists of two half-periods for both the curves. The first half-period lies in the interval, $[0, \frac{\pi}{3}]$. In this interval, the upper envelope curve is given by:

$$V_{P1} = \sqrt{3}\ M + \sin(\theta - \frac{2\pi}{3})\ M \quad \text{for } 0 < \theta < \frac{\pi}{3} \tag{4.13}$$

The lower envelope curve is given by:

$$V_{n1} = \sin(\theta - \frac{2\pi}{3})\ M \quad \text{for } 0 < \theta < \frac{\pi}{3} \tag{4.14}$$

The second half-period lies in the interval, $[\frac{\pi}{3}, \frac{2\pi}{3}]$.In this interval, the upper envelope curve is given by:S

$$V_{P2} = \sin(\theta)M \quad \text{for } \frac{\pi}{3} < \theta < \frac{2\pi}{3} \tag{4.15}$$

The lower envelope curve is given by:

$$V_{n2} = \sin(\theta)M - \sqrt{3}\ M \quad \text{for } \frac{\pi}{3} < \theta < \frac{2\pi}{3} \tag{4.16}$$

The distance between the two curves which is used to obtain the shoot-through duty ratio is always maintained constant for a specified modulation index M, which is $\sqrt{3}$ M. Hence, the shoot-through duty ratio is maintained constant.

It can be represented as:

$$\frac{T_o}{T} = \frac{2 - M\sqrt{3}}{2} = 1 - \frac{M\sqrt{3}}{2} \qquad (4.17)$$

$$\text{Boost factor, } B = \frac{1}{1 - 2\frac{T_0}{T}} = \frac{1}{M\sqrt{3} - 1} \qquad (4.18)$$

$$\text{Voltage gain, } G = MB = \frac{V_{ac}}{\frac{V_o}{2}} = \frac{M}{\sqrt{3}\,M - 1} \qquad (4.19)$$

The maximum active state duty ratio can be represented as:

$$D_{a\ max} = \max\left(\frac{M\ \sin wt - M\ \sin(wt - \frac{2\pi}{3})}{2}\right) = \frac{\sqrt{3}}{2} M \qquad (4.20)$$

Where, $D_{a\ max}$ is the maximum duty ratio of the active states combined in a switching cycle. If active states remain unchanged such that the shoot through duty ratio is always constant, the maximum shoot-through duty ratio that can be obtained is given by:

$$D_{o\ max} = 1 - D_{a\ max} = 1 - \frac{\sqrt{3}}{2} M \qquad (4.21)$$

The shoot-through duty ratio can be expressed by:

$$\frac{T_o}{T} = \frac{2 - \sqrt{3}\ M}{2} = 1 - \frac{\sqrt{3}\ M}{2} \qquad (4.22)$$

CHAPTER-5

MATLAB BASED SIMULATION OF 6n-PULSE CONVERTERS

5.1 INTRODUCTION

In this thesis, MATLAB/SIMULINK software has been used for the simulation of 6n-pulse converters. Here, n=1, 2 and 3. 6n-pulse converters consist of a number of converters connected in series. The desired phase shift in the converters is obtained by using zig-zag phase shifting transformers. Simulation was carried out for the 6-pulse converter and its integral multiples which are as follows:

- **6-pulse converter**

Block diagram of the zig-zag phase shifting transformer based 6-pulse converter feeding R-load is shown in the Figure-5.1. The dc output obtained from the 6-pulse rectifier is fed to a LC filter which reduces the ripple content. Finally, the wave is fed to the load.

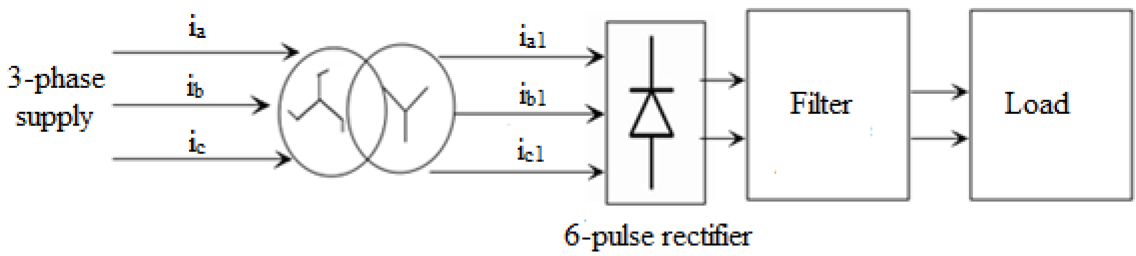

Figure-5.1: Block Diagram of the 6-Pulse Converter Feeding load

- **12-pulse converter**

Block diagram of zig-zag phase shifting transformer based 12-pulse converter feeding R-load is shown in the Figure-5.2. In this technique, rectification pulses are increased without major alterations in the installations. For harmonic elimination, phase shift of 30° is required. It involves two 6-pulse rectifiers connected in series. The phase shift between voltages of the rectifiers can be either of 0° and 30° or ±15°. To achieve this phase shift, two interconnected zig-zag phase shifting transformers are used. First zig-zag phase shifting transformer has its primary winding connected in zig-zag and its secondary winding is connected in star while the second zig-zag phase shifting transformer has its primary winding connected in zig-zag and its secondary winding is connected in delta. Each of the zig-zag phase shifting transformer feeds a 6-pulse rectifier. The dc output obtained from the series combination of the two converters is fed to the filter. Then the waveform is fed to the R-load.

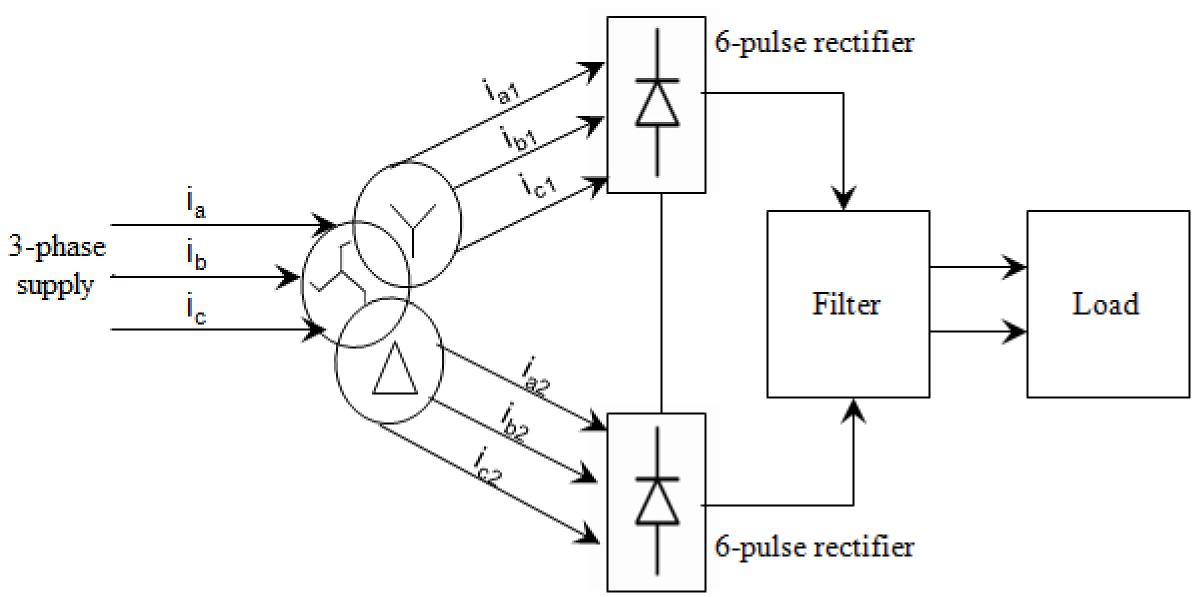

Figure-5.2: Block Diagram of the 12-Pulse Converter Feeding Load

- **18-pulse converter**

Block diagram of zig-zag phase shifting transformer based 18-pulse converter feeding R-load is shown in the Figure-5.3.

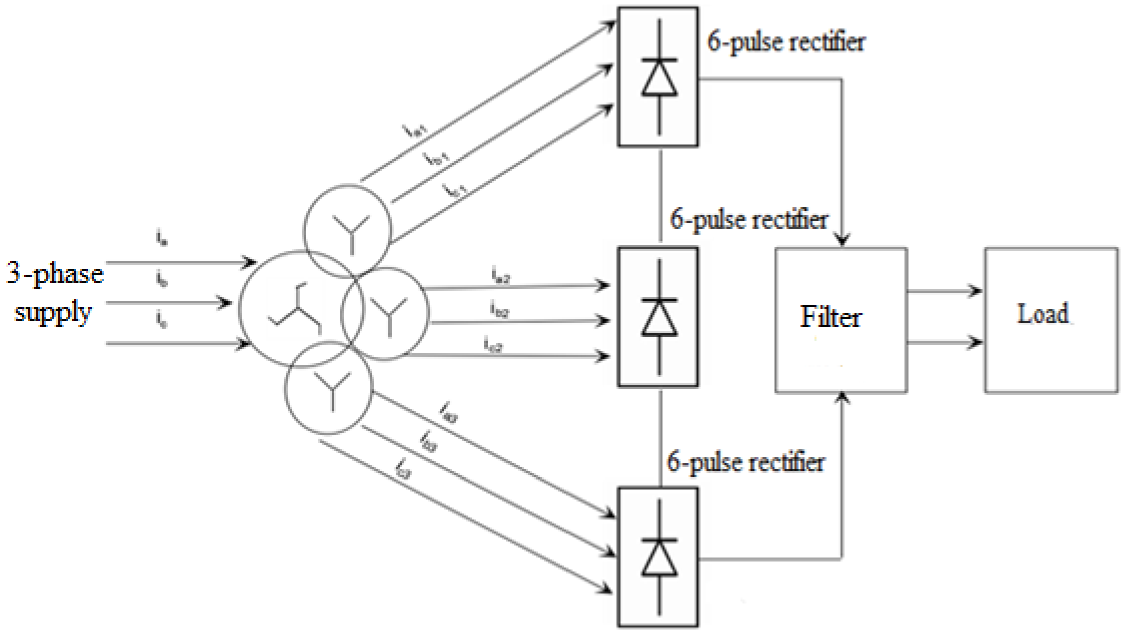

Figure-5.3: Block Diagram of the 18-Pulse Converter Feeding Load

In this technique, rectification pulses are further increased without many alterations in the installations. It involves, three 6-pulse rectifiers connected in series. The phase shift between the input voltages of rectifiers should be 20°. Three interconnected zig-zag phase shifting transformers are used for this purpose such that each one of them feeds one 6-pulse rectifier. All zig-zag phase shifting transformers have their primary windings connected in zigzag and their secondary windings connected in star such that a phase shift of 20° is achieved between the input voltages of rectifiers. The dc waveform obtained from the output of the rectifiers is the average value of the waveform of each of the rectifier. This resultant waveform is then fed to the filter which removes the ripples from the waveform. Finally, the waveform is fed to the R-load.

5.2 SYSTEM PARAMETERS

The system parameters considered for the simulation of 6n-pulse converters are depicted in Table-5.1.

Table-5.1: System Parameters

Parameters	Value
Phase to phase rms voltage across the ac mains	415 V
System frequency	50 Hz
Source resistance	0.8929 Ω
Source inductance	16.58 Mh
Resistive load	50 Ω
Filter inductance	5 H
Filter capacitance	1 μF

5.3 SIMULATION RESULTS AND DISCUSSIONS

Comparative analysis of 6-pulse, 12-pulse and 18-pulse converter has been performed. THD in input current, THD in input voltage, ripple content in output current and ripple content in output voltage has been measured for R-load which is depicted in Table-5.2.

Table-5.2: THD in Input Current, THD in Input Voltage, Ripple Content in Output Current and Ripple Content in Output Voltage for 6n-Pulse Converters Feeding R-Load

Topology	THD in input current (%)	THD in input voltage (%)	Ripple content in the output current (%)	Ripple content in the output voltage (%)
6-pulse	22.08	5.37	0.05	0.05
12-pulse	7.43	2.98	0.01	0.01
18-pulse	2.86	1.64	0	0

For a 6-pulse converter, waveforms of input voltage and input current are depicted in Figure-5.4 and Figure-5.5, respectively. Also, waveforms of output voltage and output current are depicted in Figure-5.6 and Figure-5.7, respectively.

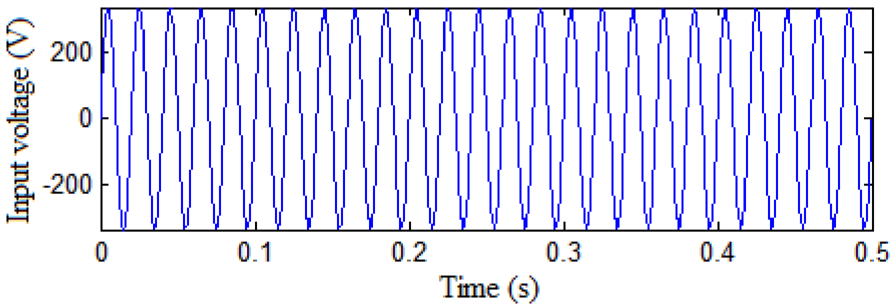

Figure-5.4: Input Voltage Waveform of a 6-Pulse Converter Feeding R-Load

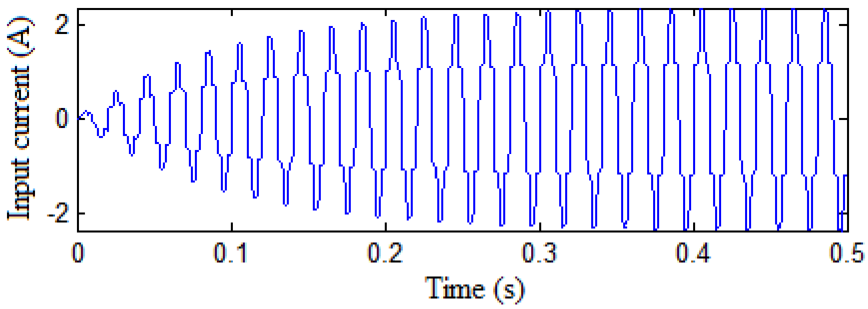

Figure-5.5: Input Current Waveform of a 6-Pulse Converter Feeding R-Load

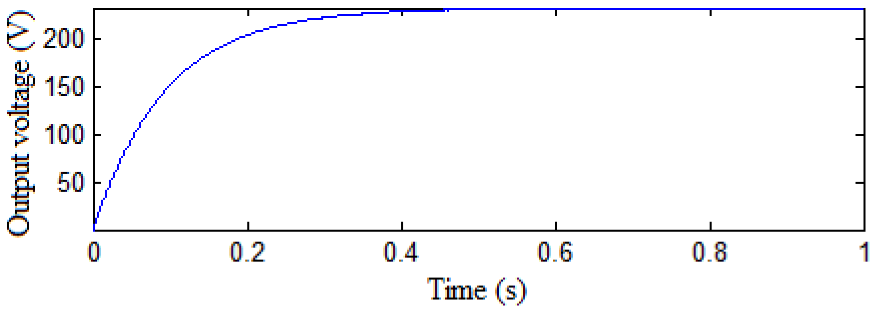

Figure-5.6: Output Voltage Waveform of a 6-pulse Converter Feeding R-Load

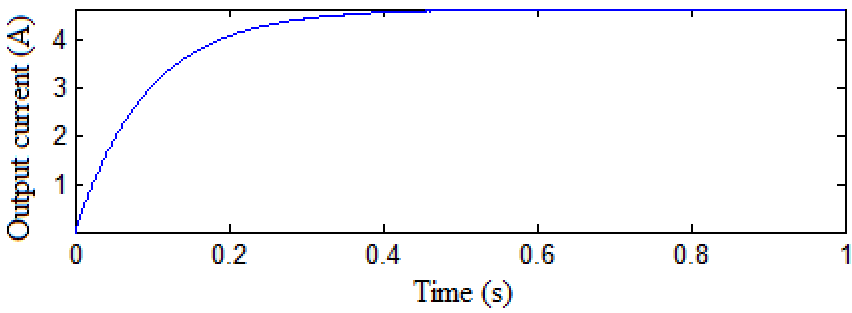

Figure-5.7: Output Current Waveform of a 6-Pulse Converter Feeding R-Load

For a 12-pulse converter, waveforms of input voltage and input current are depicted in Figure-5.8 and Figure-5.9, respectively. Also, waveforms of output voltage and output current are depicted in Figure-5.10 and Figure-5.11, respectively.

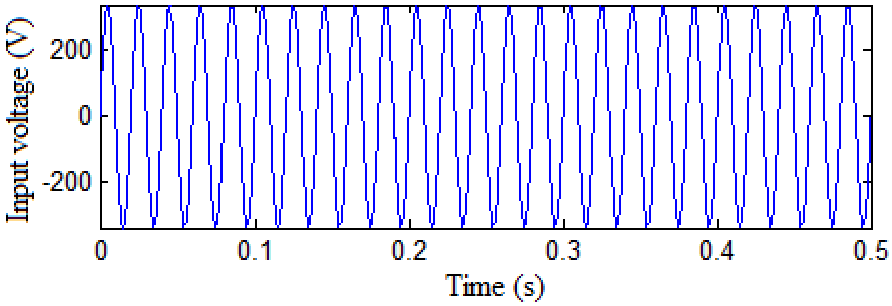

Figure-5.8: Input Voltage Waveform of a 12-Pulse Converter Feeding R-Load

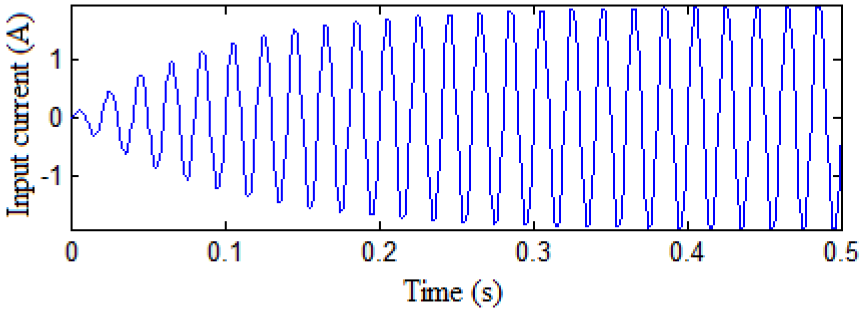

Figure-5.9: Input Current Waveform of a 12-Pulse Converter Feeding R-Load

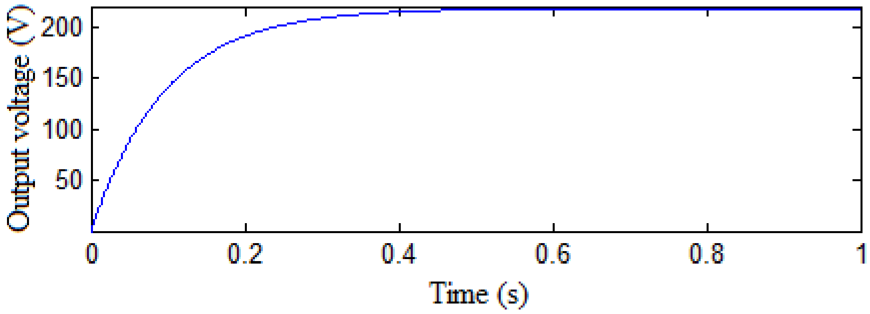

Figure-5.10: Output Voltage Waveform of a 12-Pulse Converter Feeding R-Load

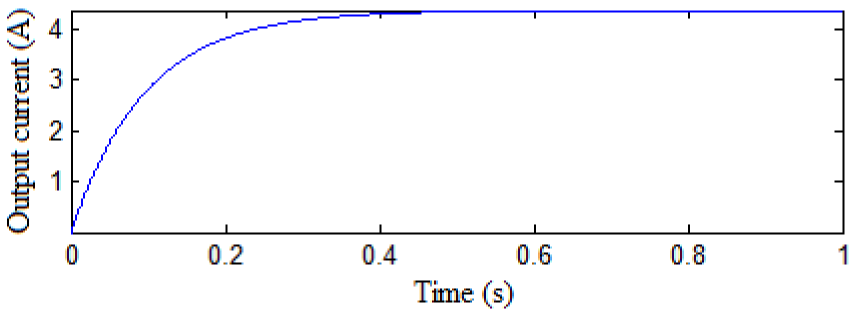

Figure-5.11: Output Current Waveform of a 12-Pulse Converter Feeding R-Load

For an 18-pulse converter, waveforms of input voltage and input current are depicted in Figure-5.12 and Figure-5.13, respectively. Also, waveforms of output voltage and output current are depicted in Figure-5.14 and Figure-5.15, respectively.

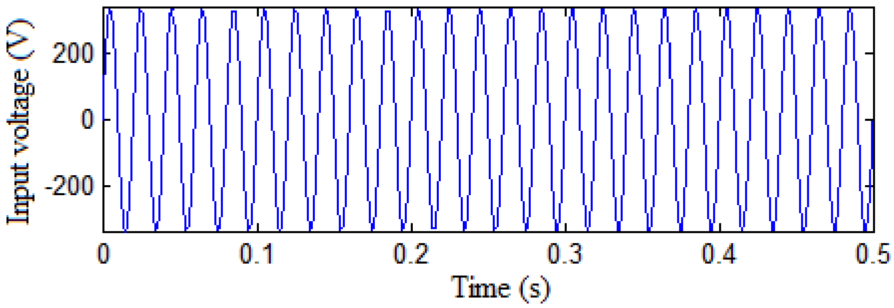

Figure-5.12: Input Voltage Waveform of an 18-Pulse Converter Feeding R-Load

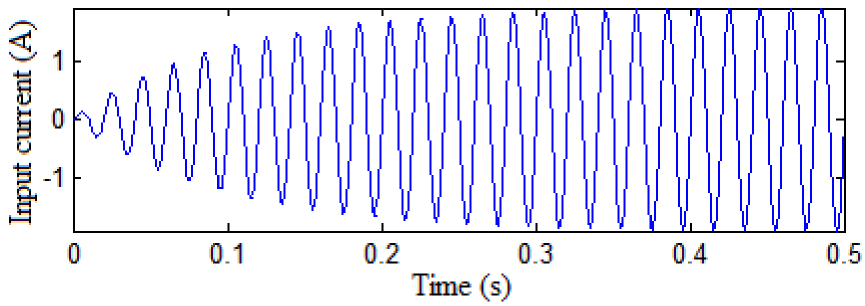

Figure-5.13: Input Current Waveform of an 18-Pulse Converter Feeding R-Load

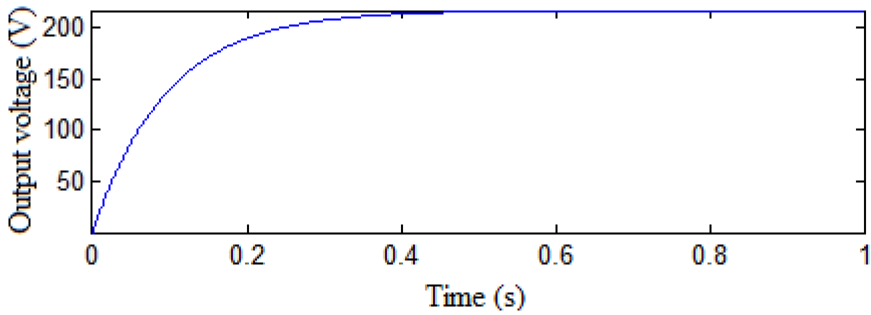

Figure-5.14: Output Voltage Waveform of an 18-Pulse Converter Feeding R-Load

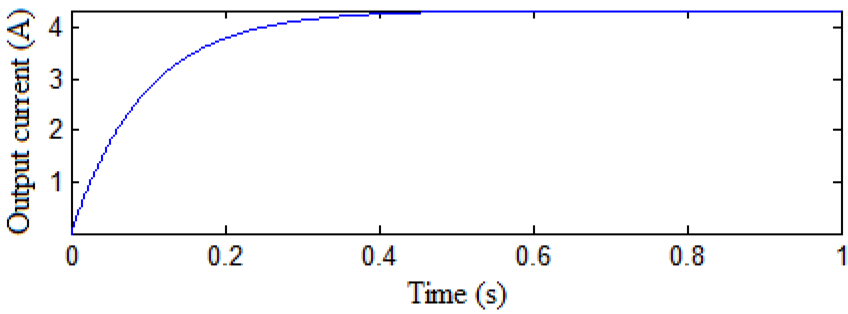

Figure-5.15: Output Current Waveform of an 18-Pulse Converter Feeding R-Load

CHAPTER-6

PERFORMANCE COMPARISON OF MULTIPULSE CONVERTER AND Z-SOURCE INVERTER DUOS

6.1 INTRODUCTION

DTC induction motor drive is a non-linear load which leads to the introduction of harmonics into the power system and thereby causing high distortion in supply voltage and supply current. It is due to this reason that a DTC induction motor drive cannot be connected directly across the supply side. For this purpose, multipulse converters are used. They prevent the non-linear load to directly inject the harmonics in supply voltage and supply current. Also, they themselves contribute to the reduction in the harmonic distortion at the supply side. For feeding the DTC induction motor drive, the dc voltage obtained at the output of the converter should be transformed into ac voltage. The combination of multipulse converter and Z-source inverter forms a duo which acts as an interface between the supply side and the DTC induction motor drive. Basically, this duo is used to couple the non-linear load with the supply. The DC voltage obtained at the output of the multipulse converter can be converted into ac voltage by using the following methods:

- Traditional inverter
- Z-source inverter based on maximum constant boost control method

6.2 SYSTEM PARAMETERS

Simulation models were developed for a 6- pulse, 12-pulse and 18-pulse converters feeding DTC induction motor drive in MATLAB/SIMULINK. System parameters are depicted in Table-6.1. Figure-6.1 depicts the test system.

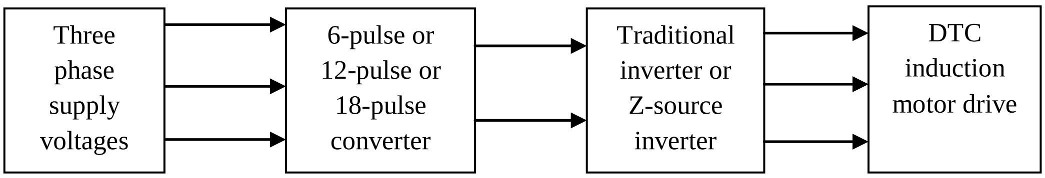

Figure-6.1: Test System

Table-6.1: System Parameters

S.No.	Parameters	Value
1	Phase to phase rms voltage across the ac mains	415 V
2	System frequency	50 Hz
3	Source resistance	0.8929 Ω
4	Source inductance	16.58 mΩ
5	Voltage across the DTC induction motor drive (rms)	460 V

6.3 SIMULATION RESULTS AND DISCUSSIONS

THD in input current and input voltage has been measured for each of the duos consisting of traditional inveter as well as Z-source inverter, which is depicted in Table-6.2.

Table-6.2: THD in Input Voltage and Input Current for 6n-Pulse Converters Feeding DTC Induction Motor Drive

Topology of the converter	Traditional Inverter		Z-source inverter based on maximum constant boost control method	
	THD in input voltage (%)	THD in input current (%)	THD in input voltage (%)	THD in input current (%)
6-pulse	66.61	10.55	4.69	0.42
12-pulse	43.29	10.50	2.23	1.03
18-pulse	29.62	10.26	0.95	0.06

- **When traditional inverter is used to convert dc voltage into ac voltage:**

Waveforms of input voltage and input current for a 6-pulse converter are shown in Figure-6.2 and Figure-6.3, respectively. Waveforms of input voltage and input current for a 12-pulse converter are shown in Figure-6.4 and Figure-6.5, respectively. Waveforms of input voltage and input current for an 18-pulse converter are shown in Figure-6.6 and Figure-6.7, respectively.

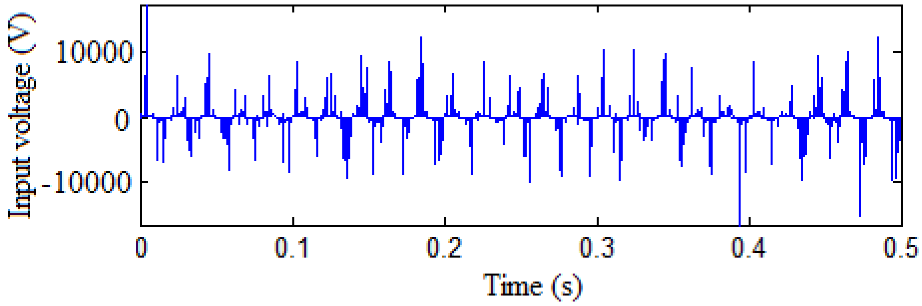

Figure-6.2: Input Voltage Waveform of the 6-Pulse Converter Using Traditional Inverter

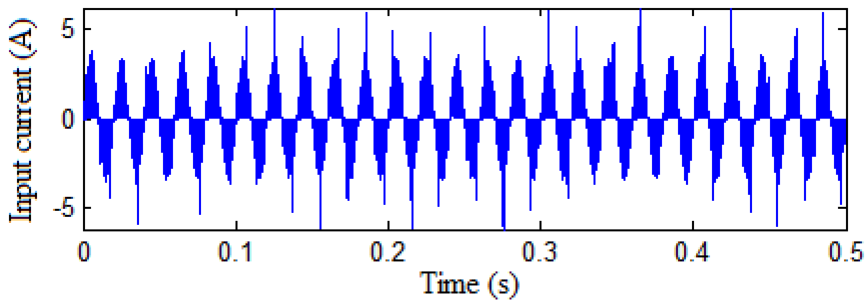

Figure-6.3: Input Current Waveform of the 6-Pulse Converter Using Traditional Inverter

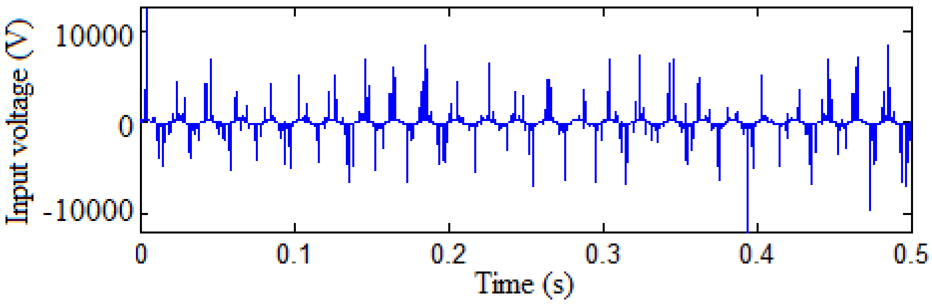

Figure-6.4: Input Voltage Waveform of the 12-Pulse Converter Using Traditional Inverter

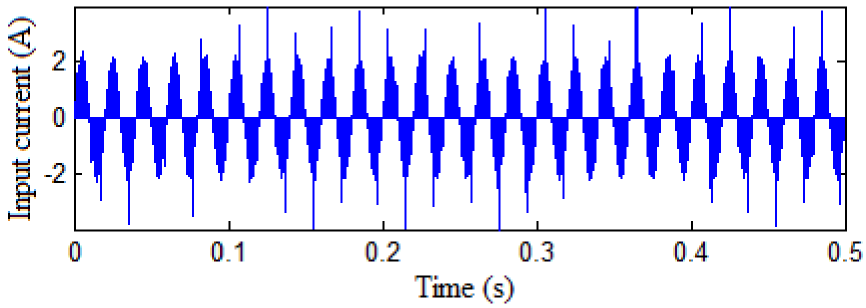

Figure-6.5: Input Current Waveform of the 12-Pulse Converter Using Traditional Inverter

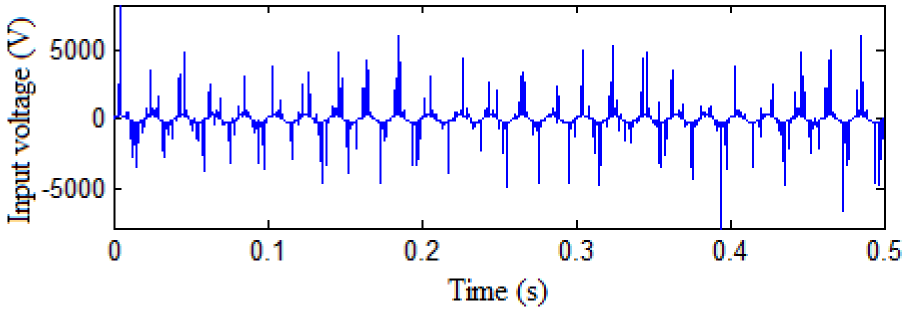

Figure-6.6: Input Voltage Waveform of the 18-Pulse Converter Using Traditional Inverter

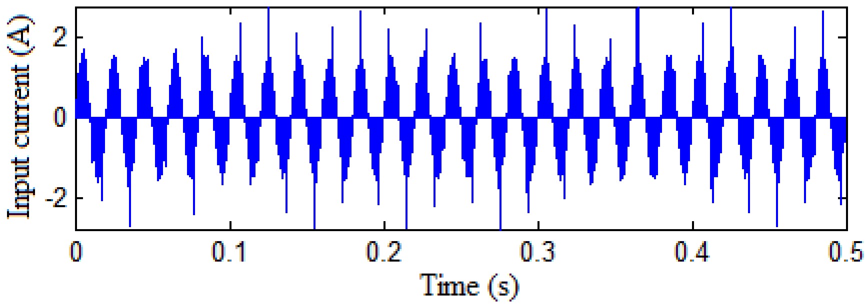

Figure-6.7: Input Current Waveform of the 18-Pulse Converter Using Traditional Inverter

• **When Z-source inverter based on maximum constant boost control method is used to convert dc voltage into ac voltage:**

Waveforms of input voltage and input current for a 6-pulse converter are shown in Figure-6.8 and Figure-6.9, respectively. Waveforms of input voltage and input current for a 12-pulse converter are shown in Figure-6.10 and Figure-6.11, respectively. Waveforms of input voltage and input current for an 18-pulse converter are shown in Figure-6.12 and Figure-6.13, respectively.

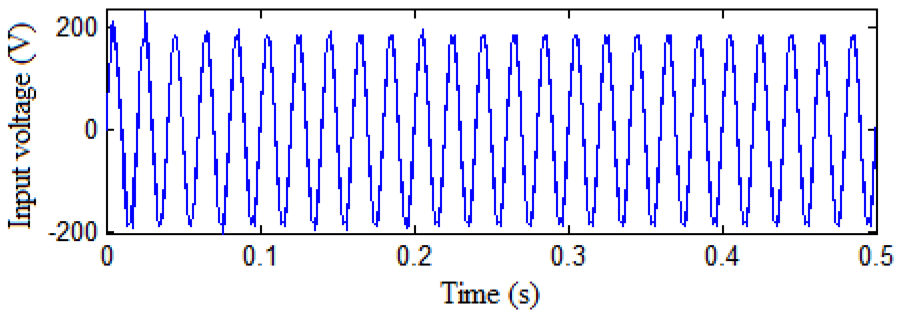

Figure-6.8: Input Voltage Waveform of the 6-Pulse Converter Using Z-Source Inverter Based on Maximum Constant Boost Control Method

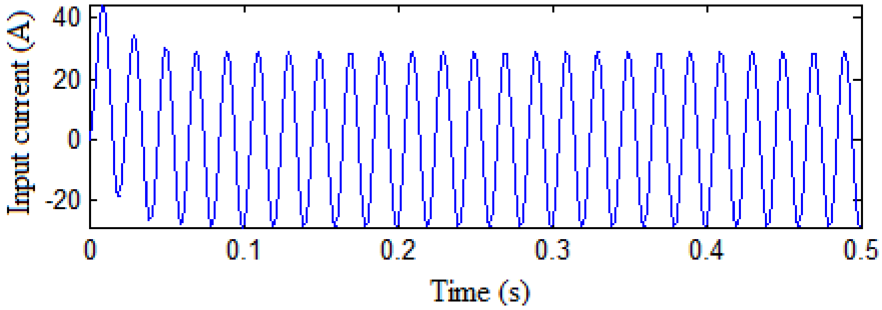

Figure-6.9: Input Current Waveform of the 6-Pulse Converter Using Z-Source Inverter Based on Maximum Constant Boost Control Method

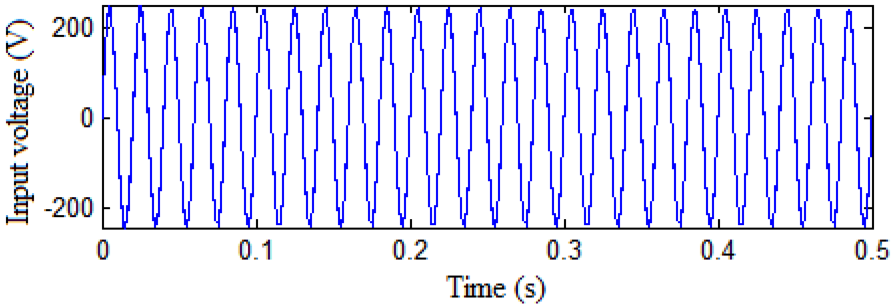

Figure-6.10: Input Voltage Waveform of the 12-Pulse Converter Using Z-Source Inverter Based on Maximum Constant Boost Control Method

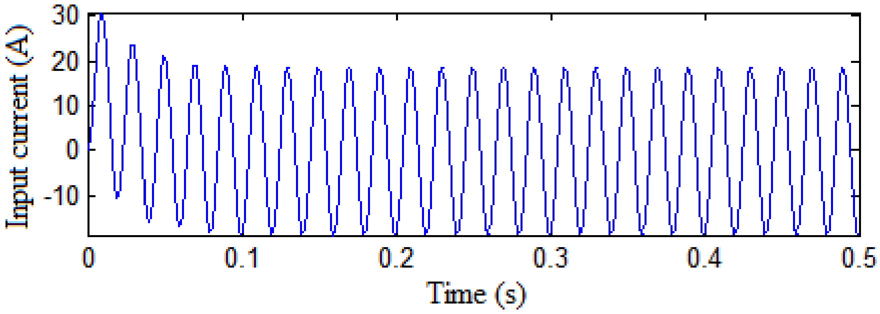

Figure-6.11: Input Current Waveform of the 12-Pulse Converter Using Z-Source Inverter Based on Maximum Constant Boost Control Method

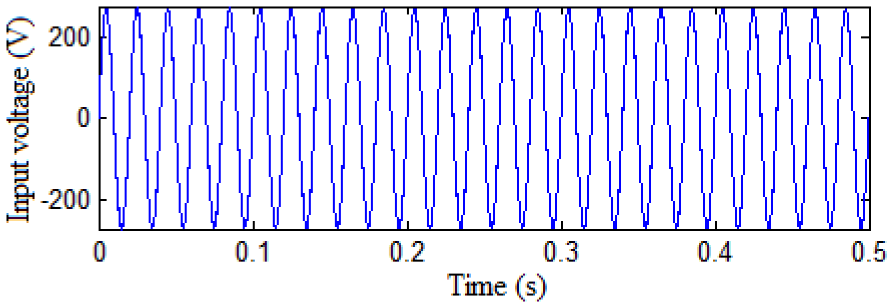

Figure-6.12: Input Voltage Waveform of the 18-Pulse Converter Using Z-Source Inverter Based on Maximum Constant Boost Control Method

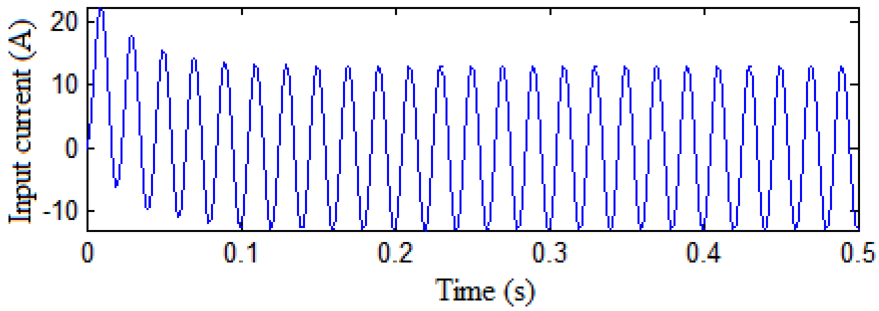

Figure-6.13: Input Current Waveform of the 18-Pulse Converter Using Z-Source Inverter Based on Maximum Constant Boost Control Method

CHAPTER-7

MATLAB BASED SIMULATION OF PROPOSED 14n-PULSE CONVERTERS

7.1 INTRODUCTION

In this thesis, MATLAB/SIMULINK software has been used for the simulation of 14n-pulse converters. Here, n=1, 2 and 3. 14n-pulse converters are described below:

- **14-pulse converter**

Figure-7.1 depicts the block diagram of a 14-pulse ac-dc converter feeding RL-load. For a 14-pulse converter, 7 phase supply voltage is required which is obtained by connecting each of the phase by single phase supply. Each of the phase is having a phase shift of $360^{o} / 7 = 51.42^{o}$ from one another. Each of these voltages is then fed to multi-winding transformers which are used as an isolation transformer. The dc output obtained from the 14-pulse rectifier is then fed to a LC filter which reduces the ripples. Finally, the dc wave is fed to the load.

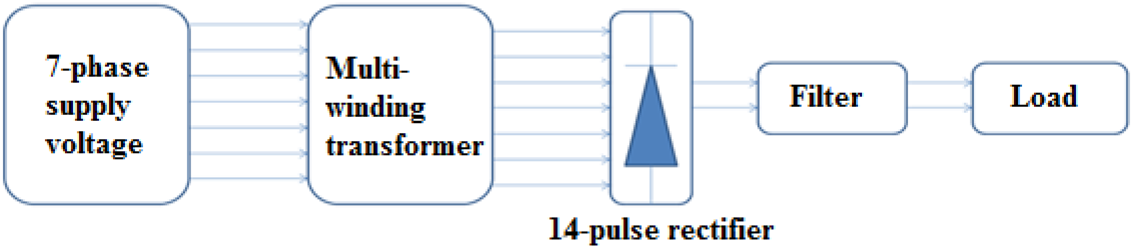

Figure-7.1: Block Diagram of a 14-Pulse Converter Feeding RL-Load

- **28-pulse converter**

Proposed 28-pulse ac-dc converter feeding RL-load is shown in Figure-7.2. For a 28-pulse converter, 14 phase supply voltage is required such that each of the phases is having a phase shift of $360^{o} / 14 = 25.714^{o}$ from one another. These voltages are then fed to a 28-pulse rectifier via multi-winding transformers.

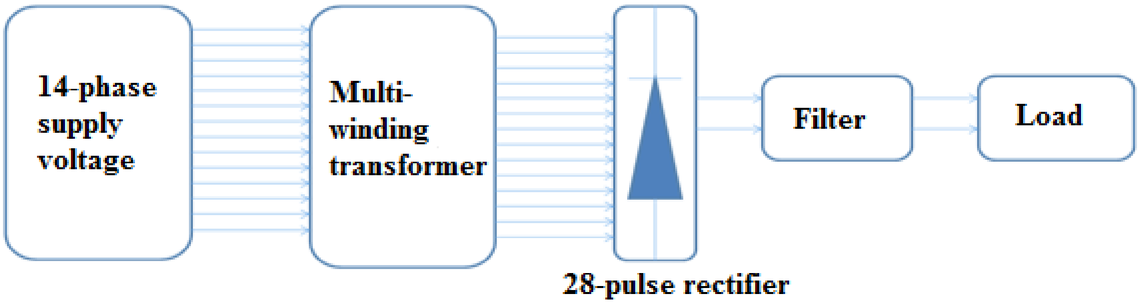

Figure-7.2: Block Diagram of a 28-Pulse Converter Feeding RL-Load

• **42-pulse converter**

Proposed 42-pulse ac-dc converter feeding RL-load is shown in Figure-7.3. For a 42-pulse converter, 21 phase supply voltage is required such that each of the phases is having a phase shift of $360^o / 21 = 17.142^o$ from one another. These voltages are then fed to a 42-pulse rectifier via multi-winding transformers.

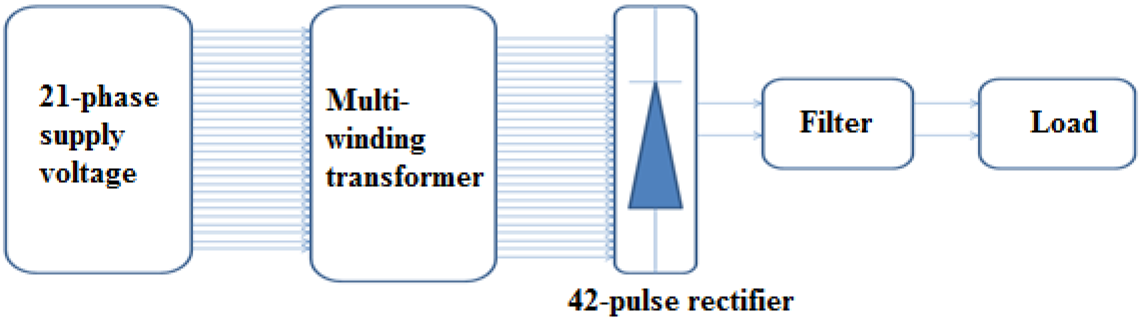

Figure-7.3: Block diagram of a 42-pulse converter feeding RL-load

7.2 SYSTEM PARAMETERS

Simulations were conducted for a 14-pulse, 28-pulse and 42-pulse converter with the system parameters depicted in Table-7.1.

Table-7.1: System Parameters

PARAMETER	VALUE
Peak amplitude	339 V
System frequency	50 Hz
Source resistance	0.8929 Ω
Source inductance	16.58e-3 Ω
RL-load	(500+jw0.5) Ω

7.3 SIMULATION RESULTS AND DISCUSSIONS

Comparative analysis of 14-pulse, 28-pulse and 42-pulse converter has been performed. THD in input current, THD in input voltage, ripple content in output current and ripple content in output voltage has been measured for RL-load which is depicted in Table-7.2.

Table-7.2: THD in Input Current, THD in Input Voltage, Ripple Content in Output Current and Ripple Content in Output Voltage for 14n-Pulse Converters Feeding RL-Load

Topology	THD in input current (%)	THD in input voltage (%)	Ripple content in output current	Ripple content in output voltage	DC voltage (V)
14-pulse	7.67	3.53	0.2229	0.2182	562
28-pulse	5.95	2.93	0.2219	0.2172	568.3
42-pulse	4.40	2.25	0.2218	0.2171	569

For a 14-pulse rectifier, waveforms of input voltage, input current, output voltage and output current are shown in Figure-7.4, Figure-7.5, Figure-7.6 and Figure-7.7, respectively.

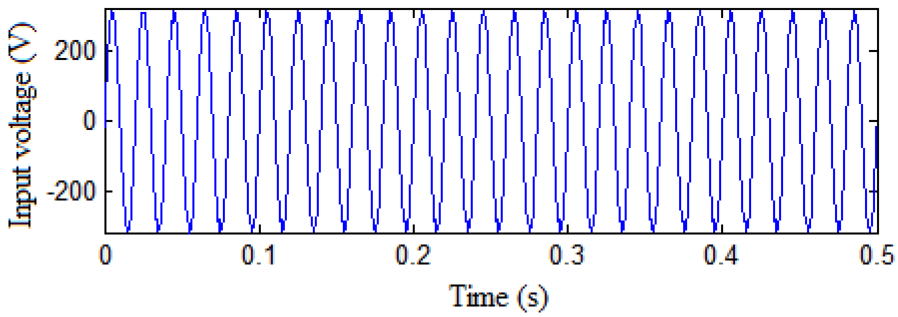

Figure-7.4: Input Voltage Waveform of the 14-Pulse Converter Feeding RL-Load

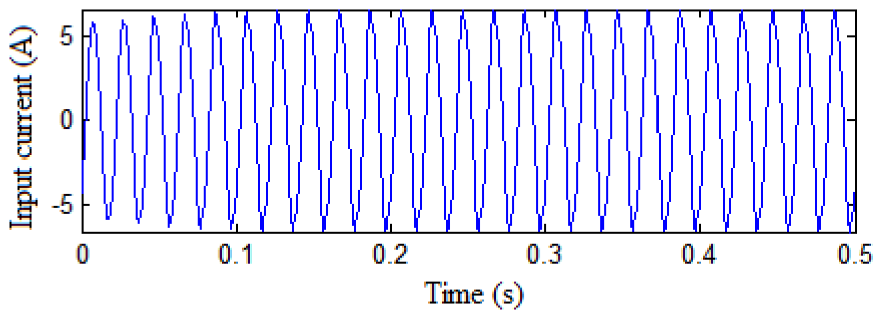

Figure-7.5: Input Current Waveform of the 14-Pulse Converter Feeding RL-Load

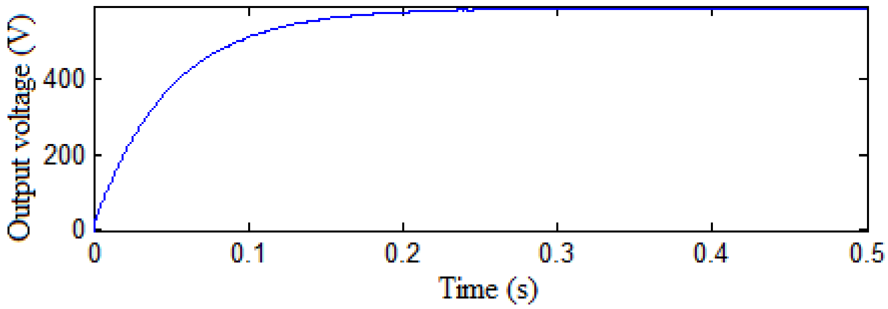

Figure-7.6: Output Voltage Waveform of the 14-Pulse Converter Feeding RL-Load

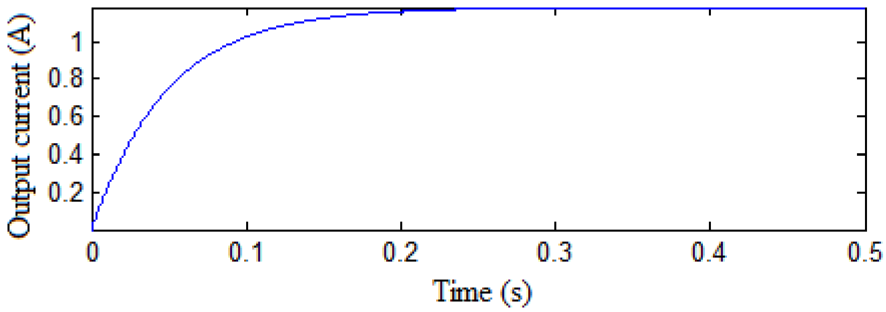

Figure-7.7: Output Current Waveform of the 14-Pulse Converter Feeding RL-Load

For a 28-pulse rectifier, waveforms of input voltage, input current, output voltage and output current are shown in Figure-7.8, Figure-7.9, Figure-7.10 and Figure-7.11, respectively.

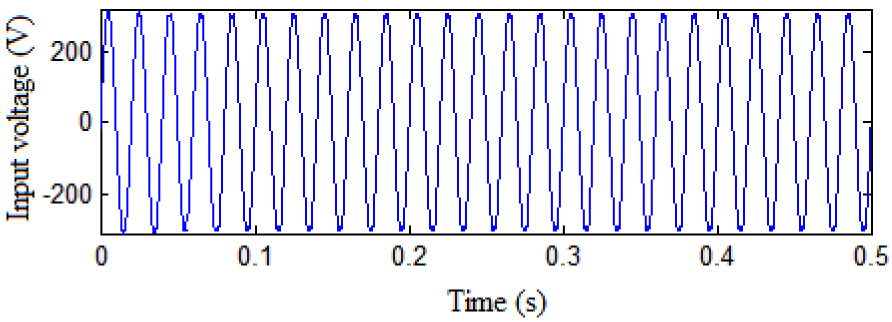

Figure-7.8: Input Voltage Waveform of the 28-Pulse Converter Feeding RL-Load

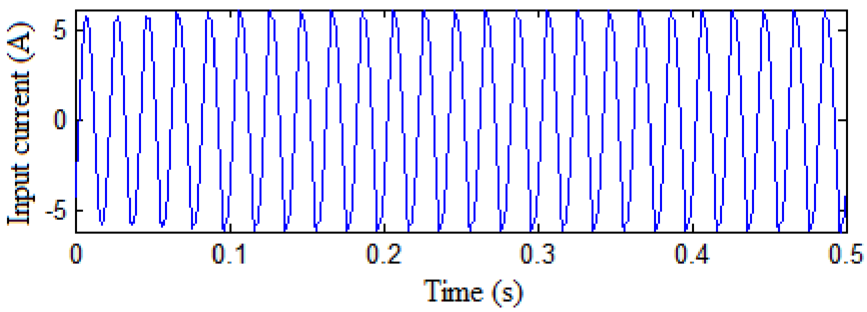

Figure-7.9: Input Current Waveform of the 28-Pulse Converter Feeding RL-Load

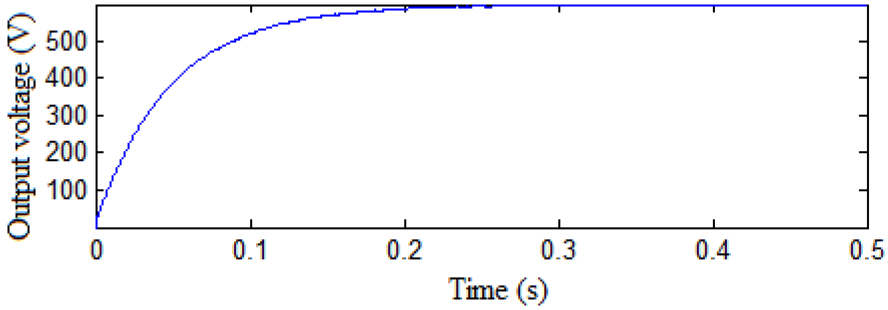

Figure-7.10: Output Voltage Waveform of the 28-Pulse Converter Feeding RL-Load

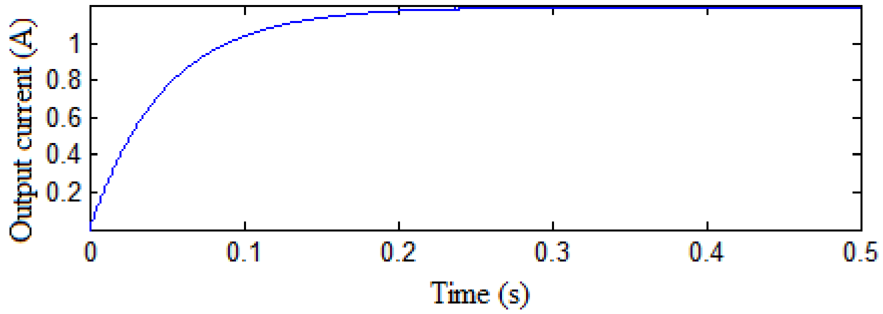

Figure-7.11: Output Current Waveform of the 28-Pulse Converter Feeding RL-Load

For a 42-pulse rectifier, waveforms of input voltage, input current, output voltage and output current are shown in Figure-7.12, Figure-7.13, Figure-7.14 and Figure-7.15, respectively.

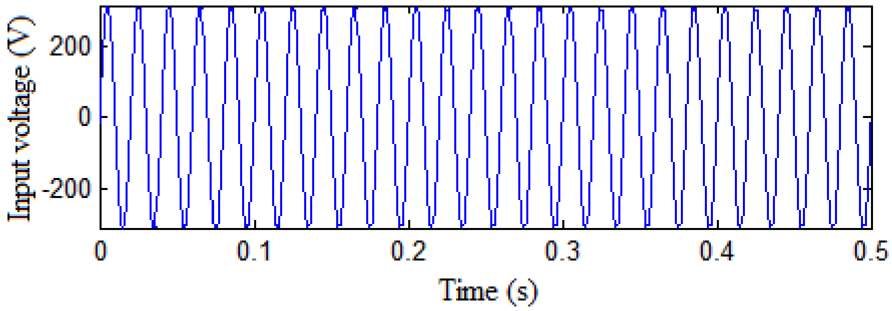

Figure-7.12: Input Voltage Waveform of the 42-Pulse Converter Feeding RL-load

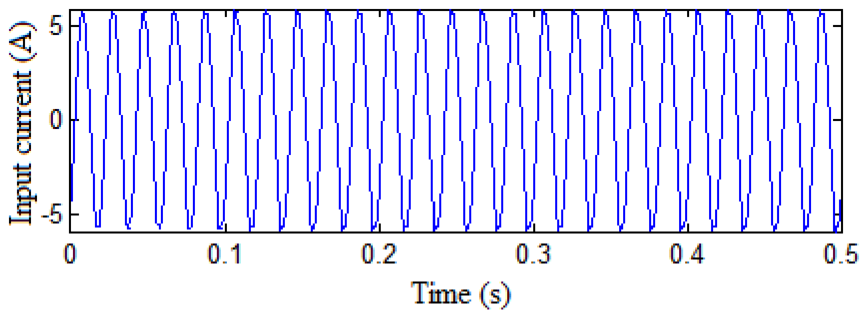

Figure-7.13: Input Current Waveform of the 42-Pulse Converter Feeding RL-Load

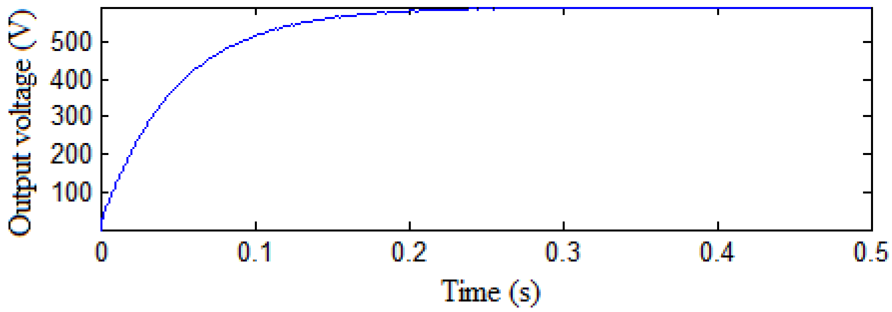

Figure-7.14: Output Voltage Waveform of the 42-Pulse Converter Feeding RL-Load

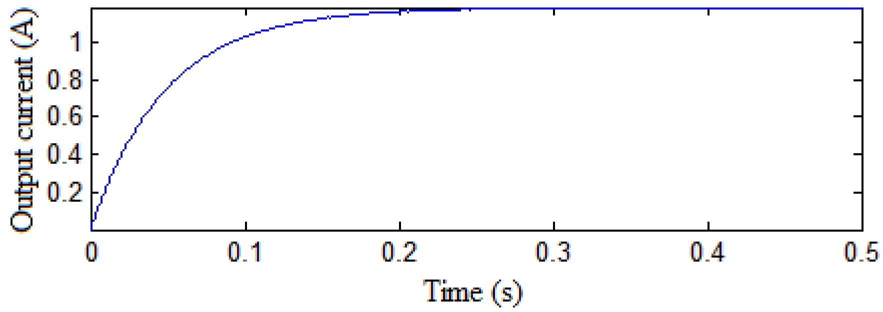

Figure-7.15: Output Current Waveform of the 42-Pulse Converter Feeding RL-Load

CHAPTER-8

CONCLUSIONS AND FUTURE SCOPE OF WORK

8.1 CONCLUSIONS

According to IEEE Std. 519-1992, the THD levels in voltage and current waveforms should be less than 5%. The conclusions of different problems considered in this work are summarized as follows:

- **For 6n-pulse converters feeding R-load**

➢ In 6n-pulse converters, it has been observed that as the pulse number of a converter is increased, THD in input current and input voltage is reduced.

➢ Also, the ripple content in output voltage and output current is also reduced with the increase in pulse number.

➢ A 6-pulse converter serves as a basic building block for higher order converters. 12-pulse and 18-pulse converters can replace the existing 6-pulse converters without many changes in the existing system layout and equipment.

- **For 14n-pulse converters feeding RL-load**

➢ In 14n-pulse converters, it has been observed that as the pulse number of a converter is increased, THD in input current and input voltage is reduced considerably.

➢ However, significant improvement is not observed in the ripple content in output voltage and output current with the increase in pulse number.

- **For multipulse converter and Z-source inverter duos**

➢ With the increase in the pulse number of a converter, THD in input current and input voltage is reduced in case of multipulse converter and traditional inverter duos.

➢ Similar trend can be observed in case of multipulse converter and Z-source inverter duos.

➢ If the performance of traditional inverter and Z-source inverter is compared then it has been observed that the THD in input current and input voltage is found to be much lower in case of multipulse converter and Z-source inverter duos when compared with that of multipulse converter and traditional inverter duos.

➢ Also, the Z-source inverter has additional advantages that it improves the reliability of the system and the system becomes less vulnerable to EMI noise when compared with the traditional inverters.

➢ As the pulse number of a converter increases, its cost also rises. Hence, a balance has to be maintained between the performance of the converter and the cost which in turn depends upon the application for which the converter is being used.

8.2 FUTURE SCOPE OF WORK

The work carried out in this thesis can be advanced in the following directions:

- A new control technique for Z-source converter can be explored to further improve its performance.
- A Z-source based multipulse converter can be applied in different custom power devices like Battery Energy Storage System (BESS), DVR etc so that the performance of the custom power devices can be improved.
- A combination of 14n-pulse converter and Z-source inverter duo can also be formed so as to feed the ac load.

LIST OF PUBLICATIONS

The list of publications is as follows:

- **Conference**

➢ Shokhand, A.; Nijhawan, P., "Simulation and Performance Comparison of Multipulse Converters", National Conference on Integrated Computational Techniques in Electrical Engineering, 18-19 Jan. 2014, Thapar University, Patiala.

➢ Shokhand, A.; Nijhawan, P., "Performance Comparison of Multipulse Converters Feeding Non-Linear Loads", National Conference on Recent Advances in Power Systems, 28 June 2014, PEC University of Technology, Chandigarh.

- **Journal**

➢ Shokhand, A.; Nijhawan, P., "Performance Comparison of Different Control Techniques Based Z-source Inverter and Multipulse Converters Duo Feeding DTC Induction Motor Drive" , Ciencia E Tecnica Vitivinicola, Vol. 29, No. 6, pp. 254-283, 2014.

- **Communicated in Journal**

➢ Shokhand, A.; Nijhawan, P., "Performance Comparison of Multipulse Converters", Turkish Journal of Electrical Engineering and Computer Sciences. (April, 2014).

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