

Performance Analysis of Different Control Methods of Z-Source Inverter Feeding Industrial Drives

Thesis

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

**MASTER OF ENGINEERING
IN
POWER SYSTEMS**

Submitted By:

**PREETI
Regn. No.: 801241017**

Supervised By:

**Mr. PARAG NIJHAWAN
Assistant Professor, EIED**



JUNE 2014

**ELECTRICAL & INSTRUMENTATION ENGINEERING
DEPARTMENT, THAPAR UNIVERSITY, PATIALA-147004**

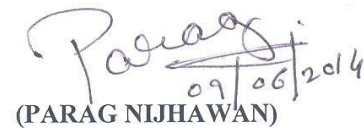
CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled “**Performance Analysis of Different Control Methods of Z-Source Inverter Feeding Industrial Drives**” 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.



(PREETI)


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


(PARAG NIJHAWAN)

Assistant Professor
Electrical & Instrumentation Engineering Department
Thapar University, Patiala

Countersigned By:


(Dr. RAVINDER AGARWAL)
Professor & Head
Electrical & Instrumentation Engineering Department
Thapar University, Patiala


(Dr. S.K. MOHAPATRA)
Dean of Academics Affairs
Thapar University,
Patiala

ACKNOWLEDGEMENT

I am grateful to the Electrical and Instrumentation Engineering Department for giving the opportunity to execute this thesis which is an integral part of the curriculum in M.E. Power Systems at the Thapar University.

This work would not have been possible without the encouragement and able guidance of my supervisor, Mr. Parag Nijhawan. Their enthusiasm and optimism made this experience both rewarding and enjoyable. Most of the novel ideas and solution found in this thesis are the result of our numerous stimulating discussions. Their feedback and editorial comments were invaluable for the writing of this thesis.

I would like to express my deep sense of gratitude toward Dr. Ravinder Agarwal, Professor and Head, EIED, Thapar University, Patiala who has been a constant source of inspiration for me throughout this work.

I would also like to thank all the faculty members of the department and my friends who have directly or indirectly helped me in completion of my thesis.

(Preeti)

Roll No. 801241017

ABSTRACT

This thesis highlights the comparative performance analysis of different control methods of Z-source inverter (ZSI) feeding industrial drives. It compares the fundamental output voltage, fundamental output current and their THD level of different control methods for ZSI. These results are then compared with conventional SPWM converter. The control methods of ZSI investigated in this work are simple boost control, maximum boost control and constant maximum boost control. The ZSI employs a unique impedance network that couples the converter main circuit to the dc source or load or another converter. The ZSI advantageously utilizes the shoot-through switching states in addition to active and zero states. The Z-source network makes the shoot-through states possible unlike traditional inverters and provides the unique buck-boost feature to the inverter. It overcome all the limitations and conceptual barriers of VSI and CSI and provides a new power conversion concept. Simulations of the circuit configuration and the control methods of the ZSI and conventional SPWM converter have been performed in MATLAB/SIMULINK.

LIST OF ABBREVIATIONS

VSI	Voltage Source Inverter
CSI	Current Source Inverter
ASD	Adjustable Speed Drives
EMI	Electromagnetic Interference
GTO	Gate-Turn-off Thyristor
SCR	Silicon-Controlled Rectifier
IGBT	Insulated Gate Bipolar Transistors
IPM	Intelligent Power Modules
PWM	Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
PID	Proportional Integral Derivative
ZSI	Impedance Source Inverter
THD	Total Harmonic Distortion
FOC	Field Orientation Control
DTC	Direct Torque Control
DFOC	Direct Field Orientation Control
DSC	Direct Self Control
DSVM	Discrete Space Vector Modulation Technique
MATLAB	Matrix Laboratory
PSB	Power System Block
PLC	Programmable Logic Control

PQ

Power Quality

IEEE

Institute of Electrical and Electronics
Engineers

RMS

Root Mean Square

LIST OF FIGURES

Figure No.	Caption of Figure	Page No.
Figure-1.1	Traditional Voltage Source Inverter	1
Figure-1.2	Traditional Current Source Inverter	3
Figure-1.3	Structure of Z-Source Inverter	5
Figure-3.1	Equivalent Circuit of Z-Source Inverter when viewed from dc link	15
Figure-3.2	Equivalent Circuit of Z-Source Inverter in Shoot-through state	16
Figure-3.3	Equivalent Circuit of Z-Source Inverter in active state	16
Figure-3.4	Simple Boost Control	19
Figure-3.5	Maximum Boost Control	21
Figure-3.6	Constant Maximum Boost Control	23
Figure-4.1	Block Diagram of FOC Scheme	25
Figure-4.2	Block Diagram of DTC Scheme	26
Figure-5.1	Block Diagram of ZSI based Test System feeding load	28
Figure-5.2	Waveform of Output Voltage for Simple Boost Control Strategy of ZSI feeding FOC induction motor drive	30
Figure-5.3	Waveform of output current for Simple Boost Control strategy of ZSI feeding FOC induction motor drive	30

Figure-5.4	Waveform of output voltage for Maximum Boost Control strategy of ZSI feeding FOC induction motor drive	31
Figure-5.5	Waveform of output current for Maximum Boost Control strategy of ZSI feeding FOC induction motor drive	31
Figure-5.6	Waveform of output voltage for Constant Maximum Boost Control strategy of ZSI feeding FOC induction motor drive	32
Figure-5.7	Waveform of output current for Maximum Boost Control strategy of ZSI feeding FOC induction motor drive	32
Figure-5.8	Waveform of output voltage for Simple Boost Control strategy of ZSI feeding DTC induction motor drive	33
Figure-5.9	Waveform of output current for Simple Boost Control strategy of ZSI feeding DTC induction motor drive	33
Figure-5.10	Waveform of output voltage for Maximum Boost Control strategy of ZSI feeding DTC induction motor drive	34
Figure-5.11	Waveform of output current for Maximum boost control strategy of ZSI feeding DTC induction motor drive	34
Figure-5.12	Waveform of output voltage for Constant Maximum boost control strategy of ZSI feeding	35

	DTC induction motor drive	
Figure-5.13	Waveform of output current for Constant Maximum boost control strategy of ZSI feeding DTC induction motor drive	35
Figure-5.14	Waveform of output voltage for conventional SPWM converter feeding FOC induction motor drive	36
Figure-5.15	Waveform of output current for conventional SPWM converter feeding FOC induction motor drive	36
Figure-5.16	Waveform of output voltage for conventional SPWM converter feeding DTC Induction motor Drive	37
Figure-5.17	Waveform of output current for conventional SPWM converter feeding DTC induction motor drive	37

LIST OF TABLES

Table No.	Caption of Table	Page No.
Table-4.1	Switching Table	27
Table-5.1	Variations of fundamental output voltage, output current and their THD level for FOC induction motor drive	38
Table-5.2	Variations of fundamental output voltage, output current and their THD level for DTC induction motor drive	39

TABLE OF CONTENTS

DECLARATION	i
ACKNOWLEDGEMENT	ii
ABSTRACT	iii
LIST OF ABBREVIATIONS	iv
LIST OF FIGURES	vi
LIST OF TABLES	ix
TABLE OF CONTENTS	x
1. INTRODUCTION	1-10
1.1 CONVENTIONAL INVERTER	1
1.2 Z-SOURCE INVERTER	4
1.3 LITERATURE SURVEY	5
1.4 SCOPE OF WORK	9
1.5 OBJECTIVE OF THESIS	9
1.6 ORGANIZATION OF THESIS	9
2. POWER QUALITY	11-13
2.1 INTRODUCTION	11
2.2 POWER QUALITY PROBLEMS	11
2.2.1 SHORT DURATION VOLTAGE DEVIATION	11
2.2.2 LONG DURATION VOLTAGE DEVIATION	12
2.2.3 TRANSIENTS	12
2.2.4 WAVEFORM DISTORTION	13
2.3 SOLUTIONS TO IMPROVE THE POWER QUALITY	13

3. Z-SOURCE INVERTER	14-23
3.1 INTRODUCTION	14
3.2 OPERATING PRINCIPLE	14
3.3 ADVANTAGES	17
3.4 CONTROL TECHNIQUES OF Z-SOURCE INVERTER	17
3.4.1 SIMPLE BOOST CONTROL	17
3.4.2 MAXIMUM BOOST CONTROL	19
3.4.3 CONSTANT MAXIMUM BOOST CONTROL	21
4. INDUSTRIAL DRIVES	24-27
4.1 INTRODUCTION	24
4.2 FIELD ORIENTATION CONTROL	24
4.3 DIRECT TORQUE CONTROL	25
5. MATLAB BASED SIMULATION AND RESULTS	28-39
5.1 SIMULATION RESULTS	28
5.2 PARAMETERS OF ZSI BASED TEST SYSTEM	28
6. CONCLUSIONS AND FUTURE SCOPE OF WORK	40
6.1 CONCLUSSIONS	40
6.2 FUTURE SCOPE OF WORK	40
REFERENCES	41-43

OVERVIEW

1.1 INTRODUCTION

Inversion is the change of dc power to ac power at a desired output voltage or current and frequency. A static semiconductor inverter circuit does this electrical energy inverting transformation. The terms voltage-fed and current-fed are used in relation with the output from inverter circuits. Conventionally, inverters are classified into two broad categories – voltage source inverter (VSI) and current source inverter (CSI).

A VSI is one in which the dc input voltage would have to keep constant and independent of the load current drawn. The inverter dictates the load voltage while the drawn current shape is specified by the load. These topologies are widely used because they behave as voltage sources naturally as required in many industrial applications, such as adjustable speed drives (ASDs), which are the most famous application of inverters. Similarly, these structures can be used as CSIs, where the independently controlled ac output is a current waveform. These structures are widely used in medium-voltage applications, where good-quality voltage waveforms are required. Static power converters, mainly inverters, are constructed from power switches and the ac output waveforms are therefore constructed of discrete values. This leads to the formation of waveforms that features fast transition rather than smooth ones.

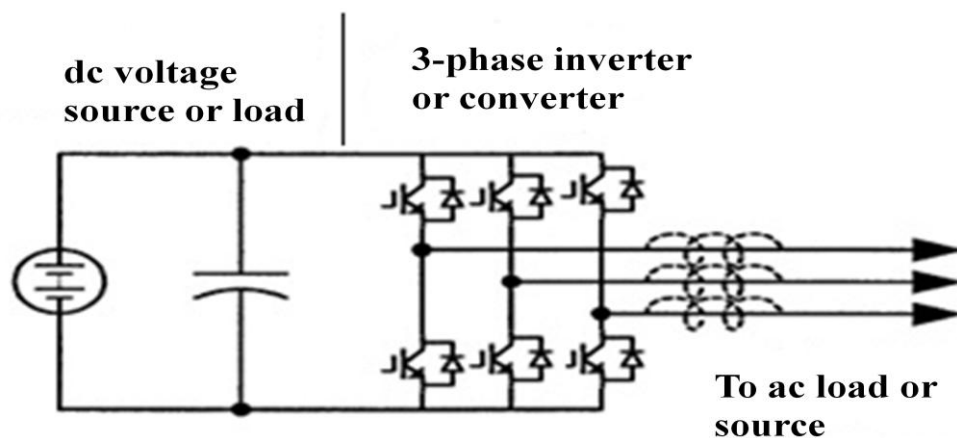


Figure-1.1: Traditional VSI

Figure-1.1 depicts the traditional or conventional three-phase voltage-source converter (that can be abbreviated as VSC) structure. A dc voltage source which is supported by a large capacitor feeds the main converter circuit, a three-phase bridge. This dc voltage source can be a battery, fuel-cell stack, diode rectifier, or capacitor. Six switches which are represented by IGBTs with an anti-parallel diode are used in the main circuit; to provide bidirectional current flow and unidirectional voltage blocking capability. The VSC is commonly used. However it has following limitations [10]:

- ✓ The ac output voltage is limited below and cannot cross the dc-rail voltage. Therefore, the VSC is a buck inverter for dc-to-ac power conversion and the VSC is a boost rectifier for ac-to-dc power conversion.
- ✓ For applications where over drive is required and the available dc voltage is not sufficient then an additional dc-dc boost converter is required to get the desired ac output. These additional converter stages raise the system cost and lower down the efficiency%.
- ✓ The upper and lower devices of each phase leg cannot be gated on simultaneously otherwise, a shoot-through would occur which would destroy the devices. The shoot-through problem by electromagnetic interference (EMI) noise's miss-gating-on is one of the main problems in terms of reliability of the converter.
- ✓ An output LC filter is required to provide a sinusoidal voltage compared with the CSI, which causes additional power loss.

A CSI is one in which the source and therefore the load current is predetermined and the load impedance decides the output voltage. The supply current cannot change rapidly. This current is controlled by series inductance which control sudden changes in current. The magnitude of load current is controlled by varying the input dc voltage to the large inductance, hence inverter response to changing load is slow. Being a current source, the inverter may survive a short circuit thereby offering fault ride-through properties.

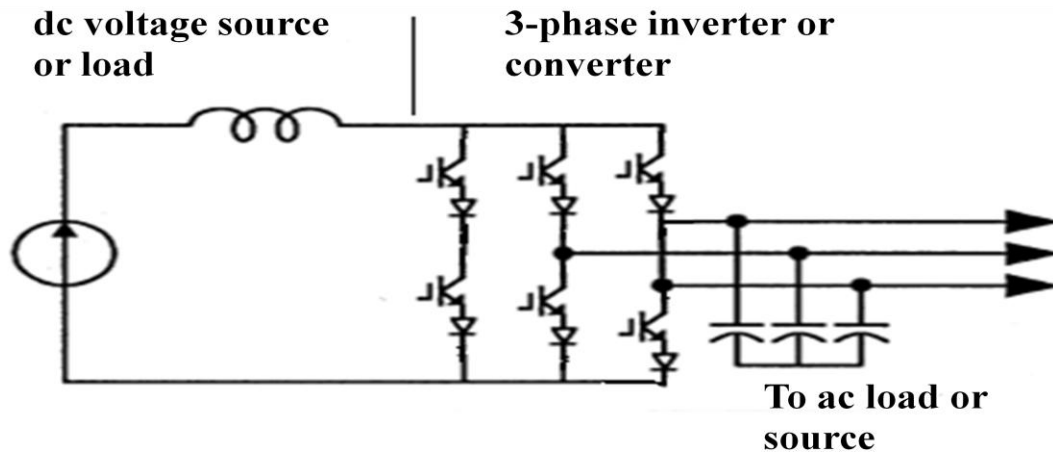


Figure-1.2: Traditional CSI

Figure-1.2 depicts the traditional three-phase current-source converter (that can be abbreviated as CSC) structure. A dc current source feeds the main converter circuit, a three-phase bridge. The dc current source can be a large dc inductor fed by a voltage source. This voltage source can be a battery, fuel-cell stack, diode rectifier, or thyristor converter. Six switches are used in the main circuit. In Figure-1.2 insulated gate bipolar transistors (IGBTs) with a series diode represent the switches. A gate-turn-off thyristor (GTO) or Silicon-Controlled Rectifier (SCR) or a power transistor with a series diode can also be used as switch to give unidirectional current flow and bidirectional voltage blocking capability. However, the CSC has the following limitations:

- ✓ The output ac voltage has to be more than the original dc voltage which feeds the dc inductor. Therefore, the CSC is a boost inverter for dc-to-ac power conversion and the CSC is a buck rectifier (or buck converter) for ac-to-dc power conversion.
- ✓ For applications where a wide voltage range is required, an additional dc–dc buck (or boost) converter is needed. The additional power conversion stage raises system cost and lowers down the efficiency.
- ✓ At least one of the upper devices and one of the lower devices have to be gated on or turned on and maintained on at any time. Otherwise, an open circuit of the dc inductor would occur which would destroy the devices. The open-circuit problem by EMI noise miss-gating-off is a main concern in terms of reliability of the converter.

- ✓ The main switches of the CSC have to block reverse voltage which needs a series diode to be used together with high-speed and good- quality performance transistors like IGBTs. This would prevent the direct use of low-cost and good-performance IGBT modules and intelligent power modules (IPMs).

Apart from the above limitations, both the VSC and the CSC have the following common problems [10]:

1. They are either a buck converter or boost converter means they do not have buck-boost feature i.e. their obtainable output voltage range is restricted to either greater or smaller than the input voltage.
2. Their main circuits cannot be interchangeable means, neither the VSC main circuit can be used for the CSC, nor vice versa.
3. They are prone to EMI noise in terms of reliability [10].

To overcome the above mentioned limitation of conventional inverter, an improved converter topology named Z-source converter (ZSC) is proposed in the literature.

1.2 Z-SOURCE INVERTER

To overcome the limitations and problems of the traditional or conventional source converters, an impedance-source (or impedance-fed) power converter (that can be abbreviated as ZSC) is introduced. Figure-1.3 depicts the general structure of ZSC.

It employs a special impedance network (or circuit) that connect the voltage source converter and current converter main circuit to the power source, load, or another converter, for providing special features that cannot be seen in the conventional voltage source and current source converters where a capacitor and inductor are used, respectively [10]. ZSC structure using the series combination of switching devices like IGBT and diode is depicted in Figure-1.3, The Z-source concept is applicable on all dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion.

The configuration of a ZSI consists of the following components:

1. Two Inductors
2. Two Capacitors
3. DC source
4. Inverter or Converter
5. Load or Converter

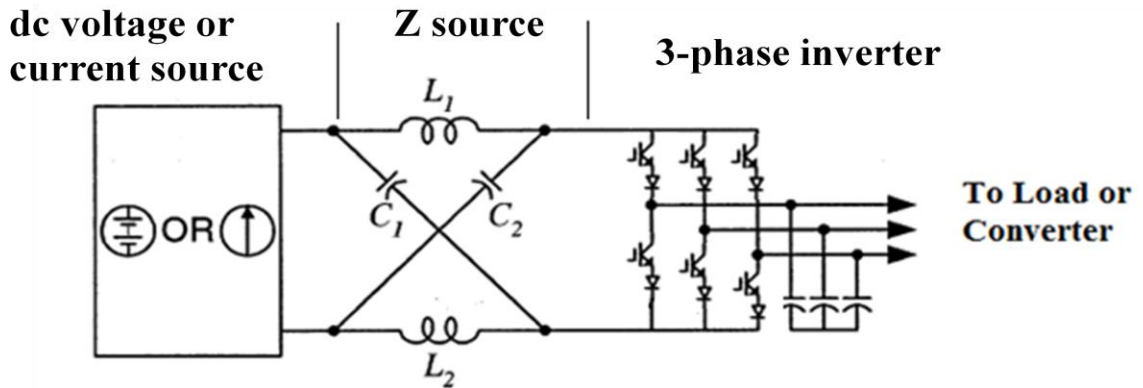


Figure-1.3: Structure of ZSI

Figure-1.3 depicts the general structure of the ZSI. A ZSI structure uses the series combination of IGBT and diode. It overcomes all the theoretical barriers and limitations of the traditional VSI and CSI and gives rise to a new power conversion concept. Figure-1.3 depicts a two-port network that consists of two split-inductors L_1 , L_2 and capacitors C_1, C_2 connected in X shape to provide an impedance source (Z-source) coupling the converter (or inverter) to the dc source, load, or another converter [10]. The dc source/or load may be either a voltage or a current source/or load. Hence, the dc source can be a battery, diode rectifier, thyristor converter, fuel cell, an inductor, a capacitor, or any combination of these. Series combination of IGBTs and diode are used as switches in the converter circuit. The inductance L_1 and L_2 can be provided by a split inductor or two separate inductors.

1.3 LITERATURE SURVEY

Power quality [1] is one of the most concerned areas in electric power system. The power quality has serious implication for consumers, utilities and manufacturers. The technological advancement led to complete change in the nature of electric load. The impact of power quality problem is increasingly sensed by industrial, commercial and residential consumers [2]. Some power quality and voltage quality problems such as voltage sag, voltage swell, transients, harmonics [3] etc. have been presented. The solution to the problems can be done either from customer side or from utility side by using custom power devices.

On the other hand, recent developments in power electronics [4-6] and semiconductor technology have led improvements in power electronic systems. Hence, different circuit configurations namely multilevel inverters [7-9] have become popular and considerable interest

by researcher are given on them. A static semiconductor inverter circuit performs electrical energy inverting transformation.

The terms voltage-fed and current-fed are used in connection with output from inverter circuit. Variable voltage and frequency supply to ac drives is invariably obtained from a three-phase voltage source inverter. A number of Pulse width modulation (PWM) schemes are used to obtain variable voltage and frequency supply. The most widely used PWM schemes for three-phase voltage source inverters are carrier-based sinusoidal PWM (SPWM) and space vector PWM (SVPWM). Inverter output waveforms (either voltage or current) are usually rectilinear in nature and as such contain harmonics which may lead to reduced load efficiency and performance. Load harmonic reduction can be achieved by either filtering, selected harmonic-reduction chopping or pulse-width modulation. Voltage source inverters and current source inverters are used widely but they have certain theoretical and conceptual barriers and limitations like problem of shoot-through, do not have buck-boost feature etc.

An impedance fed power converter i.e. ZSC has been presented [10]. Z-source concept is applicable for all ac to dc, dc to ac, ac to ac, and dc to dc power conversion. Z-source concept is applicable for entire spectrum of power conversion. It has employed a special impedance network coupling the converter main circuit to the dc source or load or another converter. It has overcome the limitations of traditional converters. An example of ZSI for dc to ac power conversion in fuel cell application has been given. By this example operating principle of ZSI has been described.

The three control methods of ZSI namely simple boost control [10], maximum boost control [11] and constant maximum boost control [12] have been discussed. Comparison of voltage gain of control methods for ZSI under a given boost factor has been done. ZSI has utilized shoot through switching states in addition to active states and zero states. It has provided a special feature of buck–boost which was not possible in traditional VSC and CSC.

It has been found that a ZSI at a given boost factor, the maximum boost control method has the greatest modulation index and thus maximum boost control technique has the highest voltage gain [11]. It has been found that there are two maximum constant boost control methods for the ZSI which have achieved maximum voltage gain at any given modulation index without generating any low-frequency ripple that is connected to the output frequency [13]. So, the Z-

network requirement would be independent of the output frequency and ascertained only by the switching frequency.

It has been discussed that the analysis of ZSI which was available in literature was based on assumption that inductor current is rather large, continuous and has small ripple. These assumptions have become irrational for low load power factor and for small inductances. A simple method to eliminate the new operating modes by superseding the diodes with a switch has also been proposed. This configuration has also provided bidirectional power flow ability [14].

It has been presented that by using conventional SPWM in case of inductive load the output voltage and current of ZSI suffered from distortion and hence power inverting quality also gets affected. According to the principle of ZSI the control method has been applied to dc-ac by inserting a fixed D into zero state of SPWM. Upgraded SPWM has not only reduced the distortion but also decreases the switch times and quantities in each cycle. Thus Total Harmonic Distortion (THD) has been reduced expertly and hence efficiency has been upgraded [15].

ZSI has been used widely in many applications due to its buck-boost nature and single stage power conversion. For a split-phase grid-connected photo voltaic system, a ZSI system has been nominated. The nominated system has realized the boost and inversion with power tracking in one single power stage thus minimized the number of switching devices. All the merits of ZSI have been combined with six-switch split-phase inverter to develop a reliable PCS system [16].

Another application has been shown by developing a new ASD system based on ZSI [17]. By regulating the open-circuit duty cycle, the ZSI could generate any desired output ac voltage, even less than the line voltage. ZSI has given superior low speed characteristics than conventional CSI fed adjustable speed drives.

Several controllers have been implemented on ZSI to enhance the system performance. A direct peak dc-link boost voltage like-PID fuzzy controller in ZSI has been presented [18]. With the help of this technique a constant peak dc-link voltage could be retrieved with good transient performance which increases the rejection of disturbance, including the input voltage and load current variation, and has also facilitated the design of controller. It has also given a phase plan to show the control effort transient response, examine the system stability and modify the rule matrices.

In comparison with ZSI, a switched inductor ZSI has increased the voltage boost inversion ability to large extent. It has employed only a very short shoot through zero states to retrieve high voltage conversion ratios and hence upgraded the output power quality. An example for dc 36V input and ac 110V output has been given under two different PWM control. Nominated inverter could be used in distributed system, hybrid electric vehicles etc. [19].

Performance analysis of four control strategies namely simple boost control, maximum boost control, maximum constant boost control and third harmonic injected maximum constant boost control of ZSI feeding induction furnace load has been presented [20]. Simulation results have been shown which have illustrated the comparison of all the four strategies of ZSI for reducing the harmonic distortion in the load current with induction furnace load.

In today's era industrial drives are the major causers and the major victims of power quality problems. There are different types of industrial drives such as Field Orientation Control (FOC) induction motor drives and Direct Torque Control (DTC) induction motor drives [21]. Induction machines have been widely used in industry because of their advantages like- simple in construction, ruggedness, reliability, low cost, less maintenance. But due to their highly coupled non-linear structure high performance of these machines is quiet challenging.

Several control strategies have been developed for induction machine drives. These are FOC, DTC. The performance of two control strategies namely, Direct Field Orientation Control (DFOC) and DTC has been evaluated and compared. Simulation results have shown that both the methods give very good performance with faster dynamics. It has been shown that DTC is less sensitive to machines parameters and FOC has been demonstrated superior under steady state [22].

Also it has been found that DTC although gives better dynamic applications but it has higher current and torque ripple. This analysis has been done by using numerical simulation. But the drawback of torque ripple could be compensated to some extent by the use of new scheme i.e. Discrete Space Vector Modulation technique (DSVM) [23].

Switching characteristics of an inverter feeding DTC induction drive [24] have been presented. These characteristics have been assessed in steady state. It has been analyzed that the total time of application of each vector in half a sextant depends only on frequency. Effects of motor parameters have been neglected. It has also formed equations to illustrate the number of

commutation for all the three phases of the inverter along with zero band of hysteresis flux and torque controller. After this, switching frequency of the inverter has been calculated whose value depends on the sampling interval and control delay which has been aroused from the microprocessor implementation on DTC. In the end sensitivity of switching frequency of an inverter feeding DTC with the control delay, sampling interval and inverter dc link voltage has been discussed.

A comparative study for a cascaded H-bridge multilevel DTC induction motor drive has been explained. Symmetrical and asymmetrical arrangements of five-level and seven-level H-bridge inverters have been compared in order to find the most conducive arrangement with lesser switching losses and optimized output voltage quality. Conducted experiments have shown that asymmetrical configuration gives almost sinusoidal voltage with low distortion. Furthermore torque ripples have also been reduced [25].

1.4 SCOPE OF WORK

From the literature survey, it has been observed that the work done to overcome the drawbacks of traditional inverters is very much diversified. However, it is observed that there is scope to investigate the effectiveness of ZSC using different control techniques in the distribution networks with the practical industrial drives.

1.5 OBJECTIVE OF THESIS

The dissertation proposes the MATLAB/SIMULINK model of different control techniques of ZSI feeding industrial drives. The major objectives are summarized as follows:

- To study of the model of ZSI using different control techniques namely, simple boost control, maximum boost control and constant maximum boost control reported in literature.
- To prepare the model of ZSI using different control techniques namely, simple boost control, maximum boost control and constant maximum boost control in MATLAB/SIMULINK.
- Comparative analysis of different control techniques of ZSI feeding practical industrial drives.
- To establish the effectiveness of ZSI over VSI feeding practical industrial drives.

1.6 ORGANIZATION OF THESIS

This thesis has been compiled in six chapters as per the details given below:

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

Chapter-2 explains the power quality, different types of power quality problems and the various solutions that can be implemented to improve the power quality in distribution network.

Chapter-3 presents the concept of ZSI operating principle of ZSI, advantages and different control methods of ZSI.

Chapter-4 presents the introduction of industrial drives, different schemes of induction motor drives which include FOC induction motor drives and DTC induction motor drives.

Chapter-5 presents the ZSI based test system, parameters of test system and discusses the simulation results of ZSI based test system feeding FOC induction motor drive, DTC induction motor drive and conventional SPWM inverter feeding the same loads.

Chapter-6 presents the conclusions of the work presented in thesis and future scope of this work.

POWER QUALITY

2.1 INTRODUCTION

Power Quality (PQ) related issues are of most concern nowadays. The extensive use of electronic equipments, such as information technology equipment, power electronics such as adjustable speed drives (ASD) [17], [19], induction motor drives, programmable logic controllers (PLC), energy-efficient lighting, led to a complete reorient in the essence of electric loads. These loads are simultaneously the major causers and the major victims of power quality problems. Industrial surroundings depend on electronic equipment to supersede in today's highly ruthless, efficiency-driven business world. Computers, drives, motion controllers and sensors have become indispensable for peerless productivity, consistency and quality. However, these receptive components require clean and unfluctuating electrical quality to perform properly. Even though, there is yet no solution is found to completely deal with this burning issue. Power quality issues, such as voltage fluctuations, harmonic distortion, noise and power outages, disturb the production and damage equipments.

Institute of Electrical and Electronics Engineers (IEEE) Standard IEEE 11000 defines power quality as “the concept of powering and grounding perceptive electronic equipment in an aspect relevant for the equipment” [1].

2.2 NEED OF POWER QUALITY

Power quality is of great concern because of the following reasons [2]:

1. Modern generation load equipments with microprocessor based control and power electronics devices are more susceptible to power quality mutation than was equipments used previously.
2. The expanding insistence on power system proficiency has led to the growth in the utilization of devices such as ASDs and shunt capacitor for power factor improvement to reduce losses. As a consequence harmonic level is increasing on power system and has many people distressed about the forthcoming concussion on system capabilities.

3. Many things or systems are linked in a distribution network. Consolidated operation means that the collapse of any intrinsic has much more severe outcomes.

2.3 POWER QUALITY PROBLEMS

Power quality problems are shown in voltage, current and frequency disparity that result in collapse of end users equipments. Table-2.1 depicts the classification of spectral content, duration and voltage magnitude of Power System Electromagnetic Phenomena which is subjected for power quality problems.

Table-2.1: Classification and Characteristics of Power System Electromagnetic Phenomena [2]

S.No.	Categories	Typical spectral content	Typical span	Typical Voltage Magnitude
1.	TRANSIENTS			
	i) Impulsive			
	Nanoseconds	5-ns rise	<50 ns	
	Microseconds	1- μ s rise	50 ns-1ms	
	Milliseconds	0.1-ms rise	>1ms	
	ii) Oscillatory			
	Low frequency	< 5kHz	0.3-50 ms	0-4 pu
	Medium frequency	5-500kHz	20 μ s	0-8 pu
	High frequency	0.5-5MHz	5 μ s	0-4 pu
2.	SHORT DURATION VOLTAGE DEVIATION			
	i) Instantaneous			
	Sag		0.5-30 cycles	0.1-0.9
	Swell		0.5-30 cycles	1.1-1.8 pu
	Interruption		0.5-30 cycles	< 0.1 pu
	ii) Momentary			
	Sag		30 cycles-3sec	0.1-0.9
	Swell		30 cycles-3sec	1.1-1.8 pu
	Interruption		30 cycles-3sec	< 0.1 pu
	iii) Temporary			
	Sag		3sec-1min	0.1-0.9
	Swell		3sec-1min	1.1-1.2 pu
	Interruption		3sec-1min	< 0.1 pu
3.	LONG DURATION VOLTAGE DEVIATION			
	i) Over voltage		>1min	1.1-1.2 pu
	ii) Under voltage		>1min	0.8-0.9 pu
	iii) Sustained interruption		>1min	0.0 pu

4.	WAVEFORM DISTORTION			
	i) DC offset Voltage		Steady State	0-0.1%
	ii) Harmonics	0-100 th harmonics	Steady State	0-20%
	iii) Inter harmonics	0-6kHz	Steady State	0-2%
	iv) Sub harmonic		Steady State	
	v) Notching		Steady State	
	vi) Noise	Broadband	Steady State	0-1%
5.	VOLTAGE FLUCTUATION	< 25Hz	Intermittent	0.1-7% 0.2-2P _{st}
6.	VOLTAGE IMBALANCE		Steady State	0.5-2%
7.	POWER FREQUENCY VARIATION		< 10 sec	

2.3.1 SHORT DURATION VOLTAGE DEVIATION

These are caused by fault conditions, stimulation of large loads which involve high starting current or intermittent loose connection in power wiring. Depending on the fault position and the system constraints the fault can produce temporary voltage sags, voltage swells or a complete loss of voltage (interruptions) [2]. The fault condition can be close to or distant from the point of concern. These are categorized into three types:

- a) Voltage Sag-** It is also referred to as a voltage dip or voltage drop as shown in Figure-2.1. This is one of the most customary power quality problems. It is defined as a reduction of RMS voltage to a value between 0.1 pu to 0.9 pu and lasts for duration between 0.5 cycles to 1 minute. The magnitude of voltage sag relies on various components like the type of fault, the position of the fault and the fault impedance of fault. The time span of voltage sag basically dependent on how quickly the fault is cleared by the protective devices.



Figure-2.1: Voltage Sag

b) **Voltage Swell-** It is originated by a sudden decrease in load with a poor or destructive voltage regulator. It can also be generated by damaged or untied neutral connection. It is explained as an increase in RMS voltage level to 110% to 180% of real value, at the power frequency duration of ½ cycles to 1 minute. Figure-2.2 shows the waveform of voltage swell.

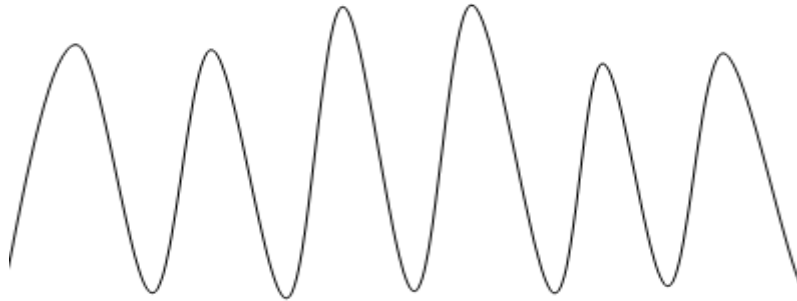


Figure-2.2: Voltage Swell

c) **Interruption-** A voltage interruption [3] as shown in Figure-2.3 is a large reduction in RMS voltage to less than a small percentile of the actual voltage, or a complete collapse of voltage. Voltage interruptions may be caused by accidents like faults and component malfunctions, or from listed downtime. Short voltage interruptions are usually caused by malfunction of a switching device or prearranged or reckless operation of a fuse, circuit breaker, or re-closure in acknowledgement to faults and disturbances.

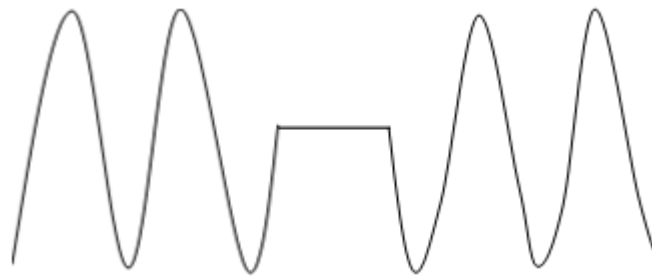


Figure-2.3: Interruptions

2.3.2 LONG DURATION VOLTAGE DEVIATION

They appear when RMS voltage deviations at output frequency exist longer than one minute. They can be either over voltages (greater than 1.1 pu) or under voltages (less than 0.9 pu). Over voltages and under voltages generally are not caused by system faults but they are the result of load displacement on the system and system switching operations.

a) **Over voltages-** It is defined as the rise in the RMS ac voltage greater than 110% at the power frequency for time span longer than 1 minute. They are usually the after effects of load switching or wrong transformer tap setting.

b) **Under voltages-** It is defined as the reduction in the RMS ac voltage to less than 90% at the power frequency for time span longer than 1 minute. A load switching-on or a capacitor switching-off can cause an under voltage until voltage regulation equipment on the system restore the voltage back to within tolerance limits.

c) **Sustained interruption-** When the supply voltage has been zero for duration in excess of 1 minute, the long duration voltage deviation is considered as sustained interruption.

2.3.3 TRANSIENTS

Transients are power quality perturbations which involve destructive high magnitudes of current and voltage or even both. It is that part of the variance in a variable that escape during alteration from one steady state operating condition to another. Transients are of two types:

a) **Impulsive Transients-** As shown in Figure-2.4, it is a small unidirectional change in voltage, current or both on a power line. The main stimulations of impulsive transients are lightning strikes, switching of inductive loads or switching in power distribution system.

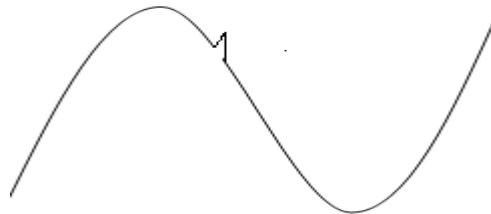


Figure-2.4: Impulsive Transients

b) **Oscillatory Transients-** As shown in Figure-2.5, it is a small unidirectional change in voltage, current or both on a power line. These are mainly stimulated by switching of power factor improvement capacitors and transformer ferroresonance.

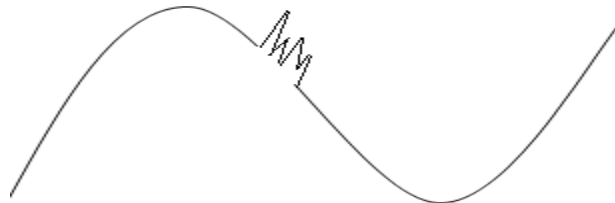


Figure-2.5: Oscillatory Transients

2.3.4 WAVEFORM DISTORTION

Any undesirable signal other than supply frequency produces waveform distortion. Waveform distortion can be of following types:

- a) **DC offset-** It is defined as the presence of a dc voltage or current in an ac power system.
- b) **Harmonics-** It can be defined as voltages or currents having frequencies that are integral multiples of fundamental frequency. Total Harmonic Distortion (THD) is ordinarily used to measure the efficacy of harmonic distortion. Protections from high level of harmonics include phase multiplication, pulse width modulation, use of active or passive filters etc.
- c) **Inter Harmonics-** It is that frequency component which is not integral multiple of fundamental frequency. The main sources of inter harmonics waveform distortion are static frequency converters, cycloconverter and arcing devices.
- d) **Sub harmonics-** It is defined as frequency components in voltage and current waveform less than the power frequency. The main sources of sub harmonics waveform distortion are arc furnace, cycloconverter, ASDs, wind generators.
- e) **Notching-**It can be explained as an iterative power quality disruption due to normal operation of power electronic devices when current is commutated from one phase to another. It is the uncommon case which lies between harmonics and transients. Figure2.6- shows the waveform of notching [4].



Figure-2.6: Notching

- f) **Noise-** It is defined as an unwanted electrical signal with broad band spectral content lower than 200 kHz superimposed upon the power system voltage or current in phase conductors or found on neutral conductors or signal lines. It can be caused due to power electronic devices, arcing equipments, control circuits, and load with solid state rectifiers.

2.3.5 VOLTAGE FLUCTUATIONS

These are comparatively small (less than 5%) changes in the RMS line voltage. These are stimulated by cycloconverter, arc furnace and other systems that do not draw current in synchronization with line frequency.

2.3.6 VOLTAGE IMBALANCE

It is a change in the amplitude of three phase voltages in comparison to one another. It is stimulated due to the existence of different loads on the phase which outgrowth in different voltage drop through the phase-line impedances.

2.3.7 POWER FREQUENCY VARIATIONS

These are defined as the variation of power system fundamental frequency from its stated normal value. Power system frequency is directly proportional to rotational speed of generators supplying the system [4].

2.4 SOLUTIONS TO IMPROVE THE POWER QUALITY

The solution to the power quality [3] can be done from customer side or from utility side. Approaches that are used to improve the power quality are as follows:

- **Load conditioning:** It make certain that the equipment is less responsive to power disturbances, allowing the operation even under large voltage distortion.
- **Line conditioning systems:** They overcome or redress the power system disruptions. To achieve improve power quality is to use passive filters connected at the sensitive load terminals. The objection is to administer the sensitive load terminal voltage so that its magnitude remains same and any harmonic distortion is reduced to an adequate level.

Z-SOURCE INVERTER

3.1 INTRODUCTION

ZSI can be used for dc-to-ac, ac-to-dc, dc-to-dc or ac-to-ac power conversion. It employs a special impedance network to combine the converter main circuit to the dc power supply. ZSI structure is already shown in Figure-1.3. The two port network consists of split-inductors L_1 and L_2 and capacitors C_1 and C_2 connected in X-shape [10]. Unlike traditional inverters [4-7] it provides special buck-boost feature to inverter by utilizing the shoot-through zero states by gating on both upper and lower switches of a phase leg. Therefore the ZSI can boost voltage and produce a required output voltage that is greater than the available dc bus voltage. In addition to this, the reliability of the inverter is greatly improved because the shoot through due to miss-gating can now no longer destroy the circuit. Thus it gives a low-cost, reliable, and high efficiency single stage structure for buck and boost power conversion [14].

3.2 OPERATING PRINCIPLE OF ZSI

The special feature of the ZSI is that its output ac voltage can be any value between zero and infinity. That is, the ZSI is a buck–boost inverter that has a wide obtainable voltage area [15]. The traditional VSIs and CSIs do not provide such characteristics. Unlike the traditional or conventional three-phase VSI that has eight switching states the ZSI bridge has nine permissible switching states (vectors).

- The six active vectors when the dc voltage is connected across the load.
- Two zero vectors when the load terminals are shorted through either the upper or lower three devices, respectively.
- One more zero state (or vector) when the load terminals are shorted through both the upper and lower devices of any one of the phase leg (i.e., both devices are gated on), any two phase legs, or all three phase legs.

This shoot-through zero state (or vector) is not present in the traditional VSI, otherwise shoot-through would occur [10]. This extra zero state (vector) is called the shoot through zero state (or vector). This shoot-through zero state can be produced in seven different ways:

- shoot-through via any one phase leg
- combinations of any two phase legs
- all three phase legs

The Z-source network has accomplished the shoot-through zero state. This shoot-through zero state gives the special buck-boost feature to the inverter. Figure-3.1 depicts the equivalent circuit of the ZSI when seen from the dc link [18]. The inverter bridge is similar to a short circuit when the inverter bridge is in the shoot-through zero state, as depicted in Figure-3.2, whereas the inverter bridge becomes an equivalent current source as depicted in Figure-3.3 when it is in one of the six active states [10]. The inverter bridge can also be illustrated by a current source with zero value (i.e., an open circuit) when it is in one of the two conventional zero states.

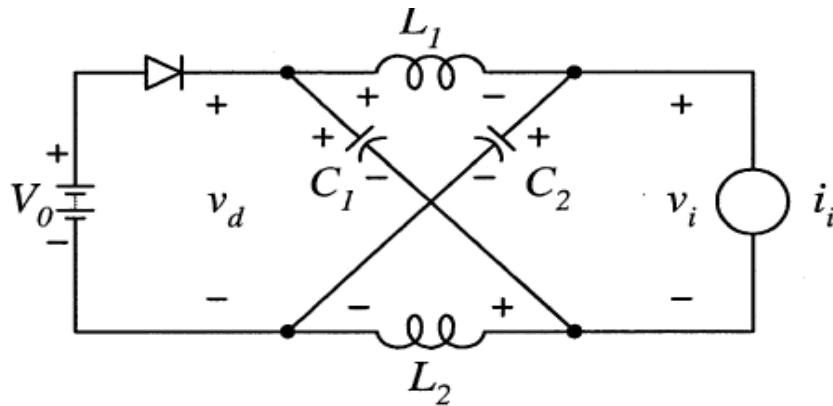


Figure-3.1: Equivalent Circuit of ZSI when viewed from dc link [10]

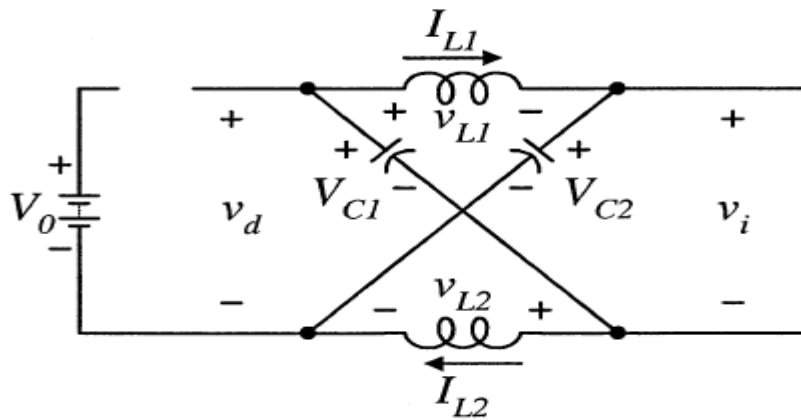


Figure-3.2: Equivalent Circuit of ZSI in Shoot-through state [10]

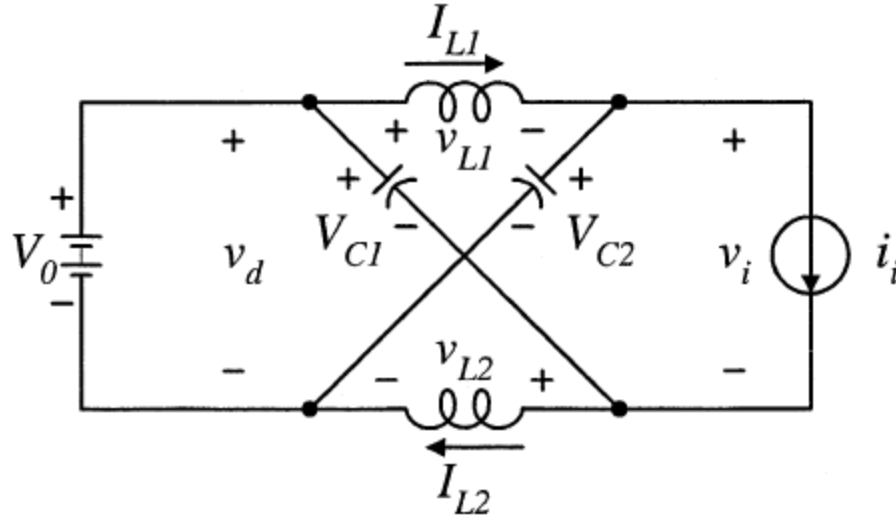


Figure-3.3: Equivalent Circuit of ZSI in Active State [10]

It is supposed that $L1 = L2$, and $C1 = C2$. The output ac voltage equation of PWM based ZSI is given by:

$$\frac{V_{ac}}{V_0/2} = MB \quad (1)$$

Where V_{ac} is maximum sinusoidal inverter output voltage, B is boost factor, M is the modulation index and V_0 is input dc voltage. The product (B.M) is called inverter gain and is expressed by G. So, equation (1) can be written as

$$V_{ac} = GV_0/2 \quad (2)$$

Boost factor is decided from the given relation

$$B = \frac{1}{1-2\frac{T_o}{T}} \quad (3)$$

Where T_o is the shoot-through time interval over a switching cycle T. Therefore, in the 3-phase ZSI there are nine permissible switching states – six active states or vectors, two zero states and one extra zero state (when the both devices of any one of the phase leg are gated on) called shoot through state.

3.3 ADVANTAGES OF Z-SOURCE INVERTER

ZSI is preferred over traditional or conventional VSI and CSI [16]:

- Boost -buck the voltage

- Minimize component count
- Increase efficiency
- Reduces cost
- Reliable

3.4 CONTROL TECHNIQUES OF Z-SOURCE INVERTER

There are several reformed PWM control methods for ZSI over traditional or conventional inverter:

- i) Simple boost control method
- ii) Maximum boost control method
- iii) Constant Maximum boost control method

3.4.1 SIMPLE BOOST CONTROL METHOD

This is very easy method to be utilized. There are two straight lines envelope equal to or greater than the maximum value of the three phase references to control shoot-through duty ratio in a conventional sinusoidal PWM [8-9]. When the carrier triangular wave is more than the upper shoot-through envelope V_p or lower than the bottom shoot-through envelope V_n , the inverter is switched to a shoot-through state as shown in Figure-3.4. In between, the inverter switches act in the same manner as in the traditional carrier based PWM control [10].

But this simple boost control method produces high voltage stress or tension across the switches as the maximum shoot-through duty ratio is extended to $(1-M)$. Thus shoot-through duty ratios become zero when modulation becomes equal to one. For the entire switching period, T is total switching period, T_o is the zero state time period and D_o is the shoot-through duty ratio. The duty ratio and modulation index are accounted of:

$$D_o = 1-M \quad (4)$$

$$G = MB = \frac{M}{1-2D_o} \quad (5)$$

$$G = \frac{M}{1-2D_o} = \frac{M}{1-2(1-M)} = \frac{M}{2M-1} \quad (6)$$

$$V_{out} = \frac{MV_o}{2} \quad (7)$$

The voltage stress or tension across the inverter switches is given by:

$$V_{inv} = BV_o \quad (8)$$

$$B = 2G-1 \quad (9)$$

$$V_{inv} = (2G-1) V_o = V_o/(2M-1) \quad (10)$$

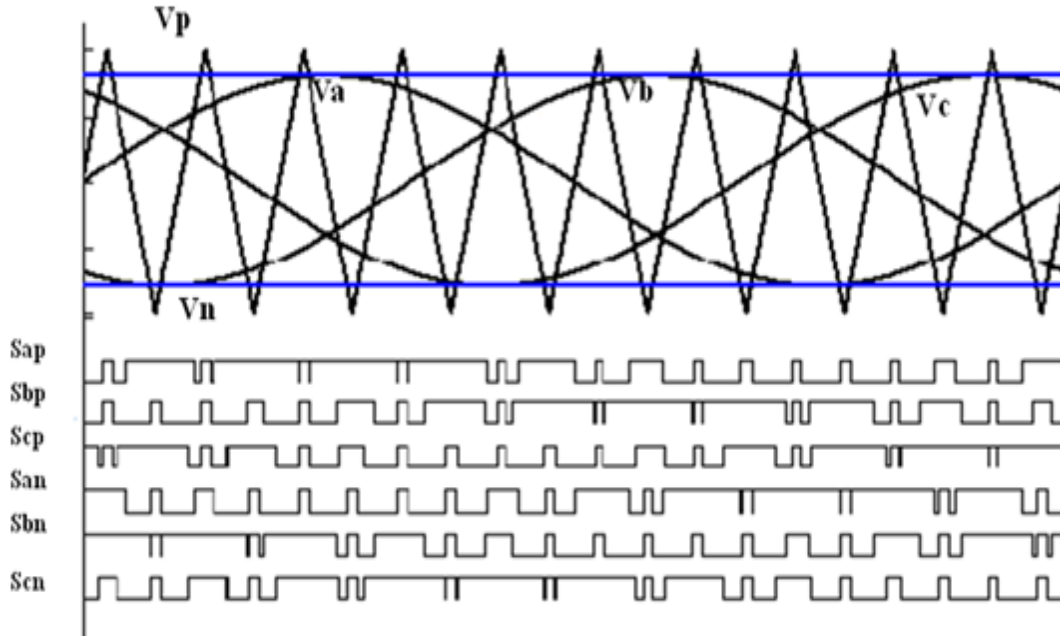


Figure-3.4: Simple Boost Control [10]

3.4.2 MAXIMUM BOOST CONTROL METHOD

It is alike to the traditional or conventional carrier-based PWM control method. In this control method the six active states remain as it is and all zero states get switched into shoot-through states [11]. Thus maximum T_o and B are achieved for any given modulation index M without deforming the output waveforms. As can be viewed from Figure-3.5, the circuit is in shoot-through state when the triangular carrier wave is either more than the maximum curve of the citations (V_a , V_b , V_c) or smaller than the minimum of the citations. To determine the voltage gain it is desired to find out average shoot-through duty cycle [12]. The shoot through state iterate periodically every $\pi/3$. It is supposed that the switching frequency is much greater than the modulation frequency; the shoot-through duty ratio over one switching cycle in the interval $(\pi/6, \pi/2)$ can be illustrated as

$$\frac{T_o}{T} = \frac{2-(M \sin \theta - M \sin(\theta - \frac{2\pi}{3}))}{2} \quad (11)$$

The average shoot-through duty ratio can be determined by integrating Eq. (11)

$$\frac{T_o}{T} = \int_{\pi/6}^{\pi/2} \frac{2-(M \sin \theta - M \sin(\theta - \frac{2\pi}{3}))}{2} dV \quad (12)$$

$$= \frac{2-M3\sqrt{3}}{2\pi} \quad (13)$$

From equation (13) the boost factor is given by:

$$B = \frac{T}{T_1 - T_o} = \frac{1}{1 - 2T_o} = \frac{2\pi}{2 - M3\sqrt{3}} \quad (14)$$

The voltage gain can be calculated by modulation index M

$$\frac{V_{ac}}{V_o/2} = MB = \frac{\pi M}{3\sqrt{3} M - \pi} \quad (15)$$

This method has wider operating area as well as higher modulation index can be used as a result of which voltage stress or tension across the switches is reduced.

The maximum value of modulation index that can be employed for a given voltage gain is given by:

$$M = \frac{\pi G}{3\sqrt{3} G - \pi} \quad (16)$$

Thus voltage stress or tension becomes

$$V_s = BV_o = \frac{\pi V_o}{3\sqrt{3} M - \pi} = \frac{3\sqrt{3} G - \pi}{\pi} V_o \quad (17)$$

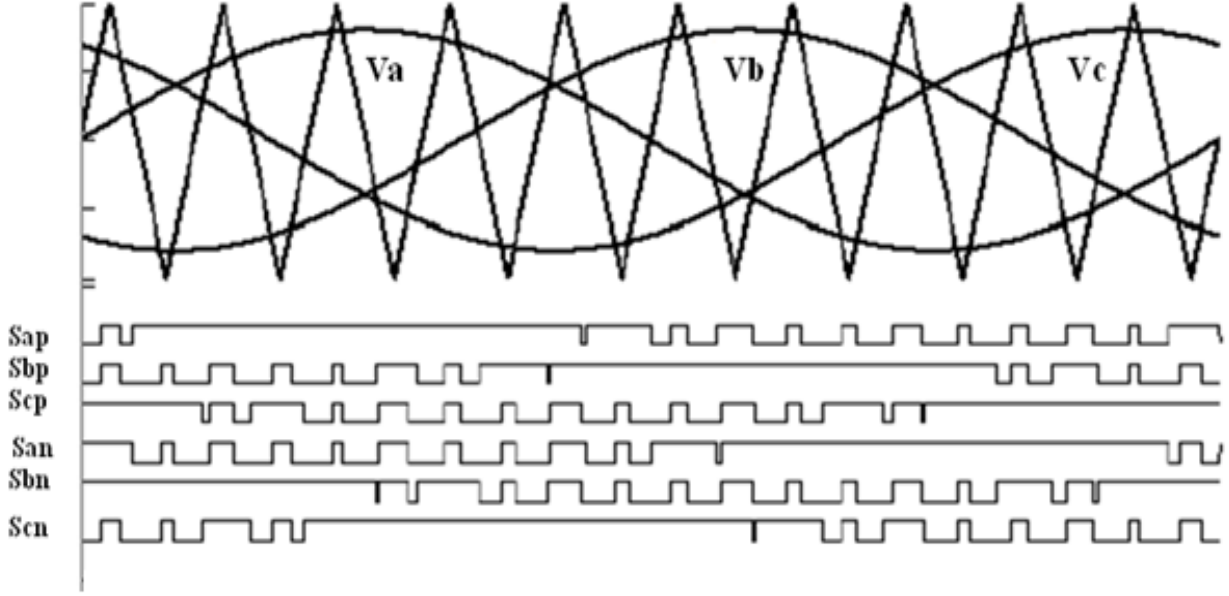


Figure-3.5: Maximum Boost Control [11]

Maximum boost control is convenient for applications that have a fixed or correspondingly high output frequency. However for applications with variable and low output frequency, this method may need a large dc inductor. So, this method is convenient only for high frequency & large current rating.

3.4.3 CONSTANT MAXIMUM BOOST CONTROL

This control technique overcomes the hitches of maximum boost control. In this method low frequency current ripple are removed by using constant duty ratio. This method consists of five modulation curves -three reference signals V_a , V_b , and V_c , and two shoot-through envelope signals V_p and V_n . For V_p some positive bias value is provided while for V_n negative bias value is provided. When the triangular carrier wave is more than the top most shoot-through envelope V_p or lower than the rear end shoot-through envelope V_n , the inverter is switched to a shoot-through zero state as shown in Figure-3.6 [13]. The essential point is to get the maximum B while keeping it constant all the time. The top most and rear end envelope curves are periodical and are three times the output frequency [12], [20]. There are two half-periods for both curves in a cycle. For the first half-period, $(0, \pi/3)$ in Fig. 7, the top most and rear end envelope curves can be illustrated as given below:

$$V_{P1} = \sqrt{3} M + \sin\left(\theta - \frac{2\pi}{3}\right) M \quad \text{for } 0 < \theta < \frac{\pi}{3} \quad (18)$$

$$V_{n1} = \sin\left(\theta - \frac{2\pi}{3}\right) M \quad \text{for } 0 < \theta < \frac{\pi}{3} \quad (19)$$

$$V_{p2} = \sin(\theta) M \quad \text{for } \frac{\pi}{3} < \theta < \frac{2\pi}{3} \quad (20)$$

$$V_{n2} = \sin(\theta) M - \sqrt{3} M \quad \text{for } \frac{\pi}{3} < \theta < \frac{2\pi}{3} \quad (21)$$

The distance between these two curves deciding the shoot-through duty ratio is always kept constant for a given modulation index M , that is, $\sqrt{3}M$. Therefore, the shoot through duty ratio is constant and can be written as

$$\frac{T_o}{T} = \frac{2-M\sqrt{3}}{2} = \frac{1-M\sqrt{3}}{2} \quad (22)$$

The boost factor B , and voltage gain G is expressed as:

$$G = \frac{V_o}{V_{dc}/2} = MB = \frac{M}{-1+M\sqrt{3}} \quad (23)$$

For modulation index M , the maximum active-state duty ratio $D_{a\max}$ can be written as

$$D_{a\max} = \max\left(\frac{M \sin \omega t - M \sin\left(\omega t - \frac{2\pi}{3}\right)}{2}\right) = \frac{\sqrt{3}}{2} M \quad (24)$$

In order to maintain the active states unaffected while keeping the shoot-through duty ratio always constant, the maximum shoot-through duty ratio that can be obtained is

$$D_{o\max} = 1 - D_{a\max} = 1 - \frac{\sqrt{3}}{2} M \quad (25)$$

For a given modulation index M , the most lengthy shoot through period is

$$T_o = \left(1 - \frac{\sqrt{3}}{2} M - \left(\frac{1-M}{2}\right)\right) T_s \quad (26)$$

Where T_s is the switching cycle

The maximal switching frequency current ripple I_r is represented by:

$$I_r = \frac{V_{cap}}{L} \frac{1+M(1-\sqrt{3})}{2} T_s \quad (27)$$

$$= \frac{\frac{\sqrt{3}}{2} M V_{dc}}{-1+M\sqrt{3}} \frac{1+M(1-\sqrt{3})}{2L} T_s \quad (28)$$

Where V_{cap} is the voltage across capacitor of the Z-source network.

This control method generates the maximum constant boost while miniaturizing the voltage stress or tension while keeping the shoot through ratio constant so as to produce of no dc voltage & current ripples.

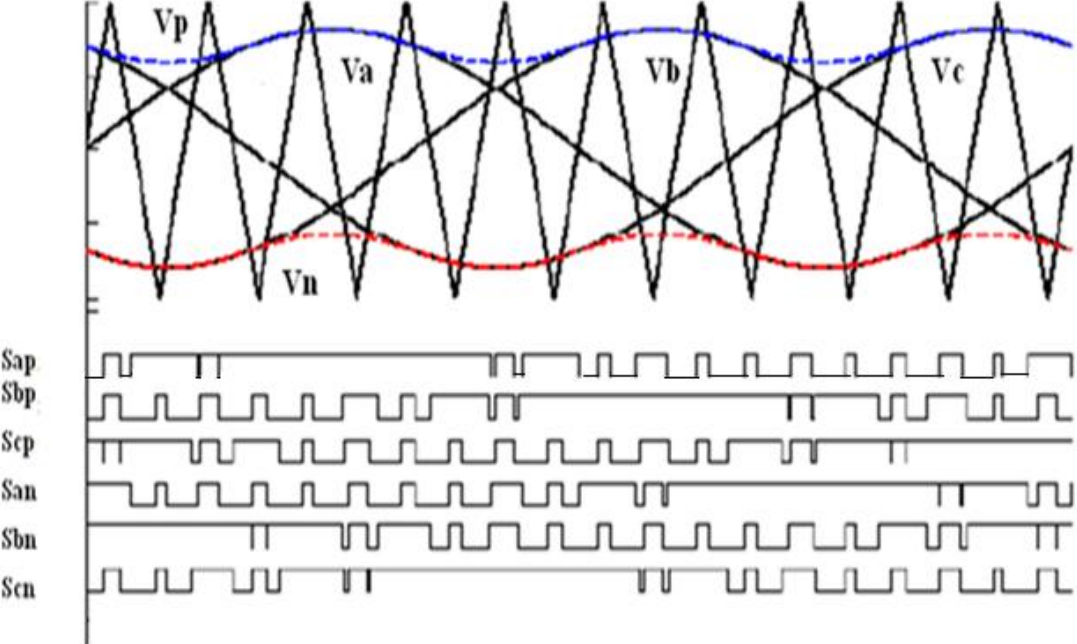


Figure-3.6: Constant Maximum Constant Boost Control [12]

INDUSTRIAL DRIVES

4.1 INTRODUCTION

Industrial drives are causes as well as victims of power quality problem. This work deals with two commonly used industrial drives- [21] FOC induction motor drives and DTC induction motor drive. These induction motor drives are customarily used in concomitant industry as loads. Being non-linear in nature, these loads are responsible for the increased THD levels in voltages and currents, noises which ultimately affect the power quality. The mathematical models of the FOC and DTC industrial drives have been presented in the subsequent sub-sections.

4.2 FIELD ORIENTATION CONTROL

The block diagram of FOC induction motor drive is shown in Figure-4.1. It is a technique which is commonly used in ac synchronous and induction motor applications. The FOC appears to be analogous to the dc machine over a wide range of speed and load conditions. It has the advantage of generating the full torque at zero speed and is capable of fast acceleration and deceleration. But the only drawback is that its performance depends critically on a very accurate coordinate transformations and flux angle estimation, which are complicated and depend on the variation of machine parameters.

The concept of field oriented control was introduced by Blaschke in 1972. Since then, it has been the widely popular control method for induction motor drives. This technique has allowed independent control of the torque and flux of the dynamic machine. This could be done by direct or indirect flux orientation. In the DFOC, both the instantaneous magnitude and position of the rotor flux are supposed to be directly measured [23]. The condition for flux orientation is $\varphi_{qr} = 0$. So, the FOC performance equations become

$$\varphi_r = \varphi_{dr} \tag{26}$$

$$T = p \frac{M}{L_r} \varphi_r i_{qs} \tag{27}$$

$$\varphi_r = \frac{M}{1+sT_r} i_{ds} \tag{28}$$

$$\omega_r = \omega_s - \omega = \frac{M}{T_r} \frac{i_{qs}}{\varphi_r} \tag{29}$$

$$V_{ds}^* = \sigma L_S \frac{di_{ds}}{dt} + R_S i_{ds} - \sigma L_S \omega_s i_{qs} + \frac{M}{L_r} \frac{d\phi_r}{dt} \quad (30)$$

$$V_{qs}^* = \sigma L_S \frac{di_{qs}}{dt} + R_S i_{qs} - \sigma L_S \omega_s i_{ds} + \frac{M}{L_r} \omega_s \phi_r \quad (31)$$

Where

$$T_r = \frac{L_r}{R_r} \text{ and } \sigma = 1 - \frac{M^2}{L_r L_S} \quad (32)$$

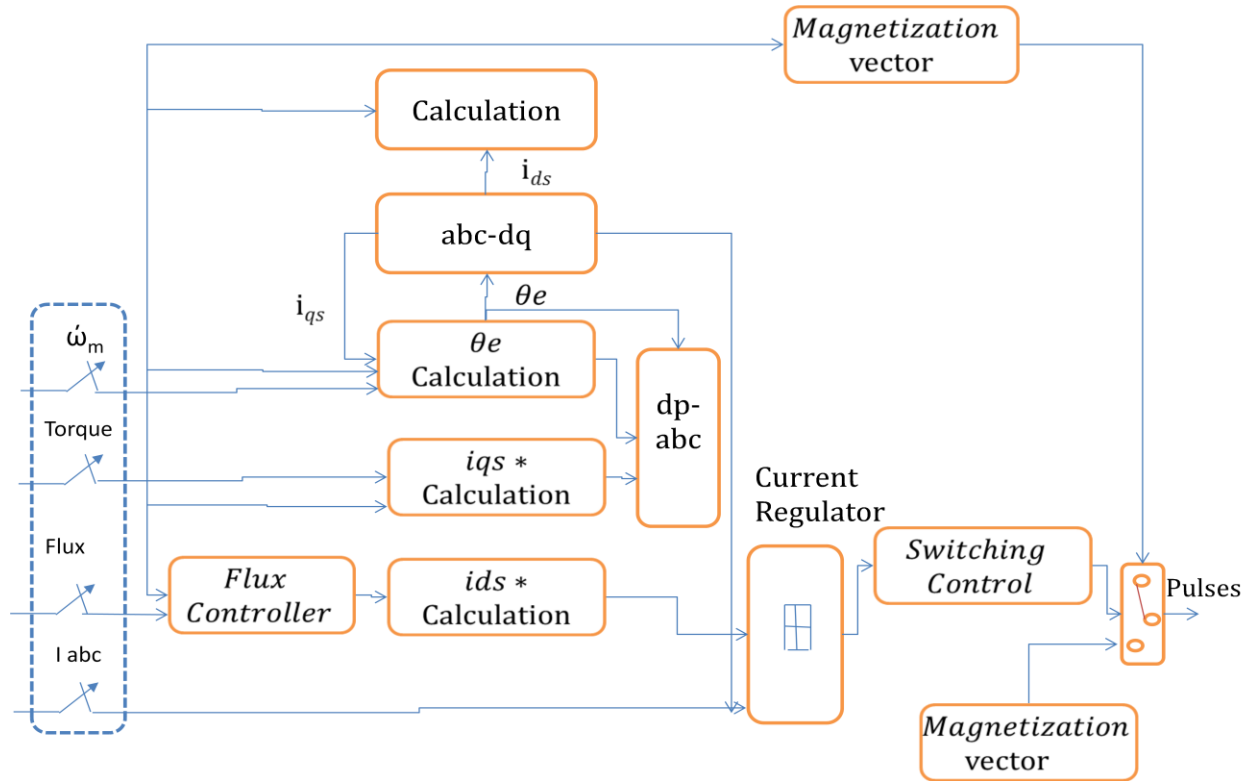


Figure-4.1: Block Diagram of FOC Scheme

4.3 DIRECT TORQUE CONTROL

DTC [21-22] is the typical method used by industries in modern days. This method is used for controlling the induction motor torque and its speed. The block diagram of DTC is shown in Figure-4.2. The main characteristic of DTC is that position of inverter switches are determined directly thus refrained from using any modulation techniques like pulse width modulation (PWM), space vector modulation (SVM) unlike other control methods [24]. This involves an estimation of the motor's magnetic flux and torque based on the measured voltage and current of the motor. The main objective is to keep motor's torque and stator flux within pre specified limits. The inverter gets triggered by hysteresis controllers to switch whenever bounds are

violated. The choice of the new switch has made using a pre designed look up table that has been designed using a geometric insight in the problem and additional heuristics.

The other main features of DTC induction motor drive are:

1. Torque and flux can be changed fast by changing the reference.
2. Absence of mechanical transducers.
3. Very simple control scheme and low computational time.
4. PI controller, coordinate of torque and flux, no modulator are required.

The DTC [25] has the merits of fast dynamic torque response and has good robustness to the changes of rotor parameters etc. But the only disadvantage is torque ripple. The pulsation becomes more apparent especially in the low-speed operating conditions.

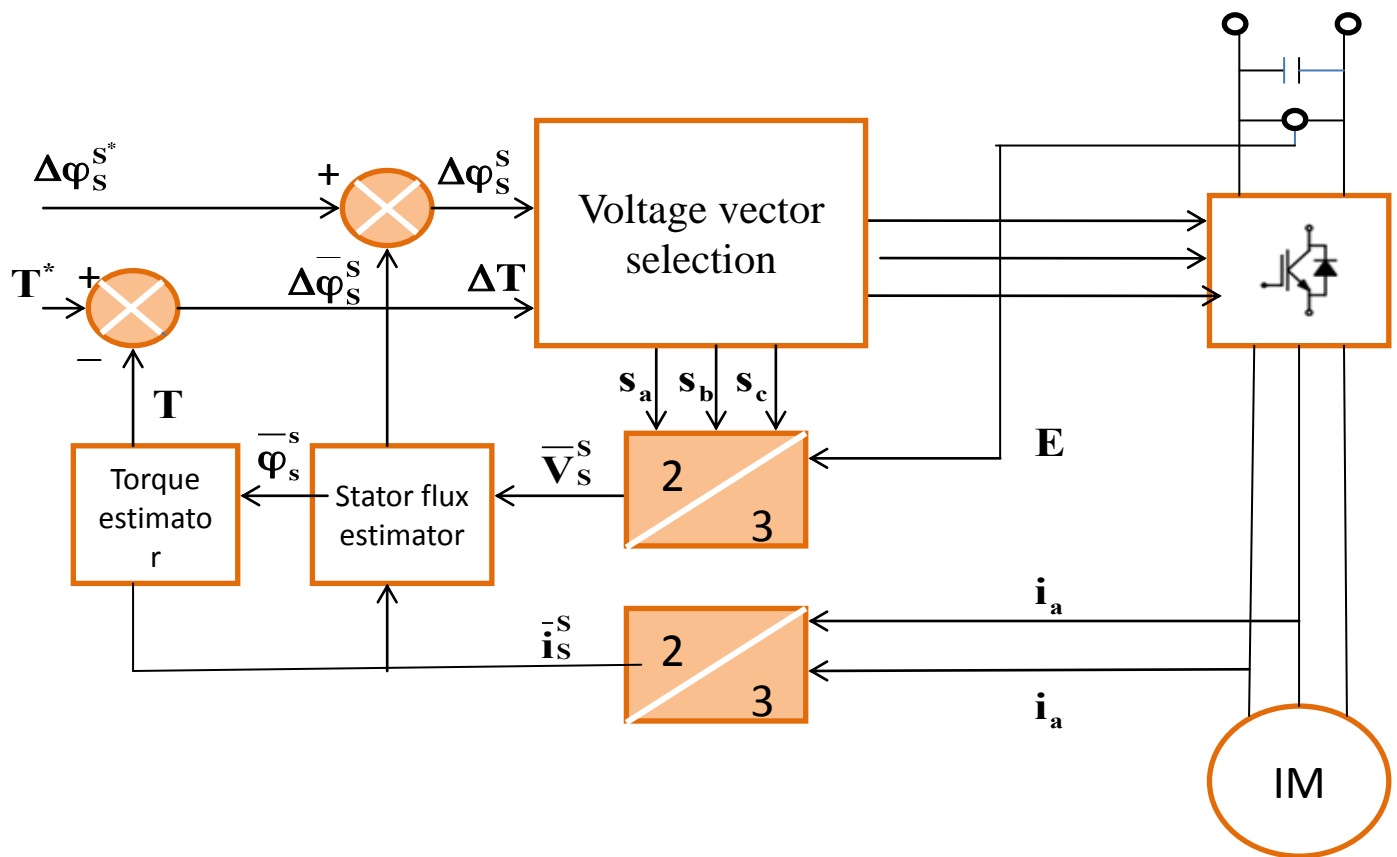


Figure-4.2: Block diagram of DTC Scheme

The basic idea of DTC for induction motor is to control the voltage space vectors properly, which is based on the interconnection between the slip frequency and torque by using a α - β

stationary stator reference frame [23], the stator flux linkage φ_s and electromagnetic torque T are calculated by using:

$$\varphi = \sqrt{(\varphi_{\alpha s})^2 + (\varphi_{\beta s})^2} \quad (33)$$

$$\text{Where, } \varphi_{\alpha s} = \int_0^t (V_{\alpha s} - R_S i_{\alpha s}) dt \quad (34)$$

$$\varphi_{\beta s} = \int_0^t (V_{\beta s} - R_S i_{\beta s}) dt \quad (35)$$

$$\text{The angle } \theta_s = \text{artg} \frac{\varphi_{\beta s}}{\varphi_{\alpha s}} \quad (36)$$

$$T = p [\varphi_{\alpha s} i_{\beta s} - \varphi_{\beta s} i_{\alpha s}] \quad (37)$$

The stator flux φ_s is calculated by integrating the stator voltage and torque T is calculated by the cross product of stator flux linkage vector and motor current. The error between the estimated stator flux magnitude φ_s and the reference stator flux magnitude φ_s^* is the input of a two level hysteresis comparator [23]. The alternative of the appropriate voltage vector is based on the switching table given in Table-4.1.

Table-4.1: Switching Table [23]

Output of hysteresis comparator		Sector					
		1	2	3	4	5	6
$C_\varphi = -1$	$C_T = -1$	V_2	V_3	V_4	V_5	V_6	V_1
	$C_T = 0$	V_7	V_0	V_7	V_0	V_7	V_0
	$C_T = +1$	V_6	V_1	V_2	V_3	V_4	V_5
$C_\varphi = +1$	$C_T = -1$	V_3	V_4	V_5	V_6	V_1	V_2
	$C_T = 0$	V_0	V_7	V_0	V_7	V_0	V_7
	$C_T = +1$	V_5	V_6	V_1	V_2	V_3	V_4

4.4 PROBLEMS ASSOCIATED WITH INDUSTRIAL DRIVES

Industrial drives are customarily used in concomitant industry as loads. These being non-linear in nature are responsible for the increased THD levels in currents which ultimately affect the power quality in a power distribution system. These harmonic currents when flow in the distribution network result in voltage distortions and increased heating in consumer and/or system equipment(s). These unbalance load current with large reactive components produces voltage fluctuations and imbalance due to system impedance. The industrial drives in a distribution network lead into substantial harmonic contents resulting in restraining the power quality level. The performance of other loads connected in the distribution network may also get distressed due to the subsistence of industrial drives.

MATLAB BASED SIMULATION AND RESULTS

5.1 SIMULATION RESULTS

In this thesis, MATLAB/SIMULINK (version 11) software has been used to design and develop the ZSI feeding industrial drives and analyze simulation in MATLAB environment along with SIMULINK and power system block set (PSB) toolboxes. The block diagram of ZSI based test system feeding load is depicted in Figure-5.1. Here, ZSI is triggered by different techniques namely simple boost control, maximum boost control and constant maximum boost control. The simulation has been carried out for different loads which are as follows:

1. FOC induction motor drive
2. DTC induction motor drive

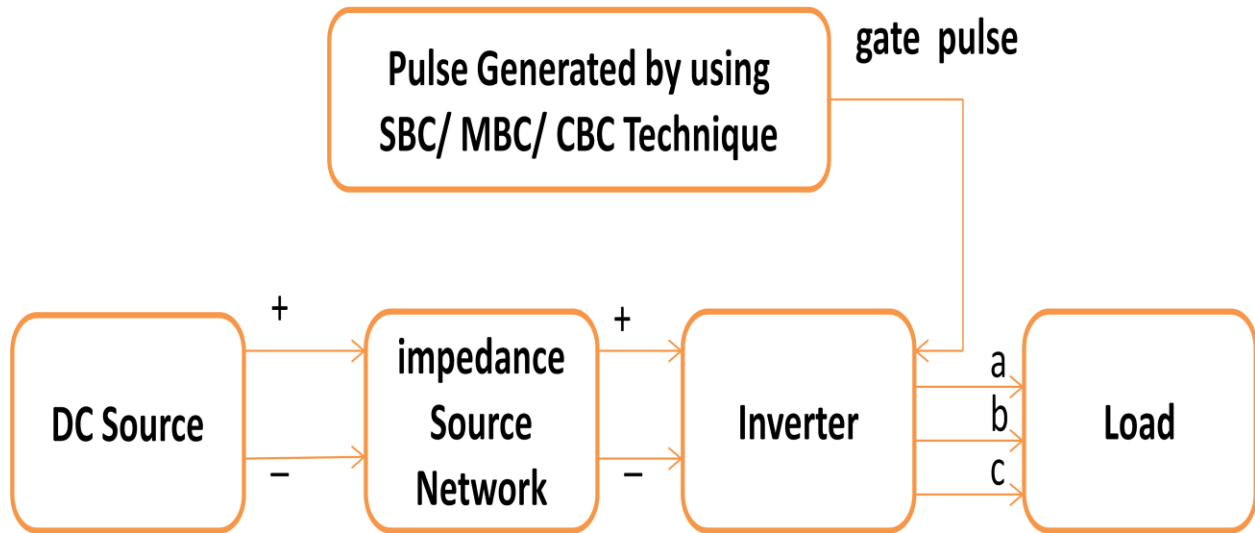


Figure-5.1: Block Diagram of ZSI based Test System feeding load

5.2 PARAMETERS OF ZSI BASED TEST SYSTEM

Block diagram of ZSI based test system is shown in Figure-5.1. Following parameters are considered in the ZSI based test system.

$$L1 = L2 = 1.0 \text{ mH}$$

$$C1 = C2 = 1.3 \text{ mF}$$

Input Voltage = 260 V

Cut off frequency = 1 kHz

Modulation index for Simple Boost Control & Constant Maximum Boost Control = 0.812

Modulation index for Maximum Boost Control = 1

DTC Drive 2238 VA, 286 V, 50 Hz

Stator Resistance $R_s = 0.435 \Omega$

Stator Leakage Reactance $X_s = 2 \text{ mH}$

Rotor Resistance $R_r = 0.816 \Omega$

Rotor Leakage Reactance $X_r = .002 \Omega$

Mutual Inductance = 69.31 mH

FOC Drive 2238 VA, 286 V, 50 Hz

Stator Resistance $R_s = 0.435 \text{ Ohm}$

Stator Leakage Reactance $X_s = .002 \Omega$

Rotor Resistance $R_r = 0.816 \Omega$

Rotor Leakage Reactance $X_r = .002 \Omega$

Mutual Inductance = 69.3 mH

Case-1: ZSI based Test System feeding FOC Induction Motor Drive

In this case, SIMULINK model has been developed in which FOC induction motor drive is fed by ZSI based test system. Simulations are conducted for different ZSI configurations. Output voltage waveform and output current waveform for simple boost control using FOC are depicted in Figure-5.2 and Figure-5.3. Output voltage waveform and output current waveform for maximum boost control using FOC are depicted in Figure-5.4 and Figure-5.5. Similarly, output voltage waveform and output current waveform for constant maximum boost control using FOC are depicted in Figure-5.6 and Figure-5.7.

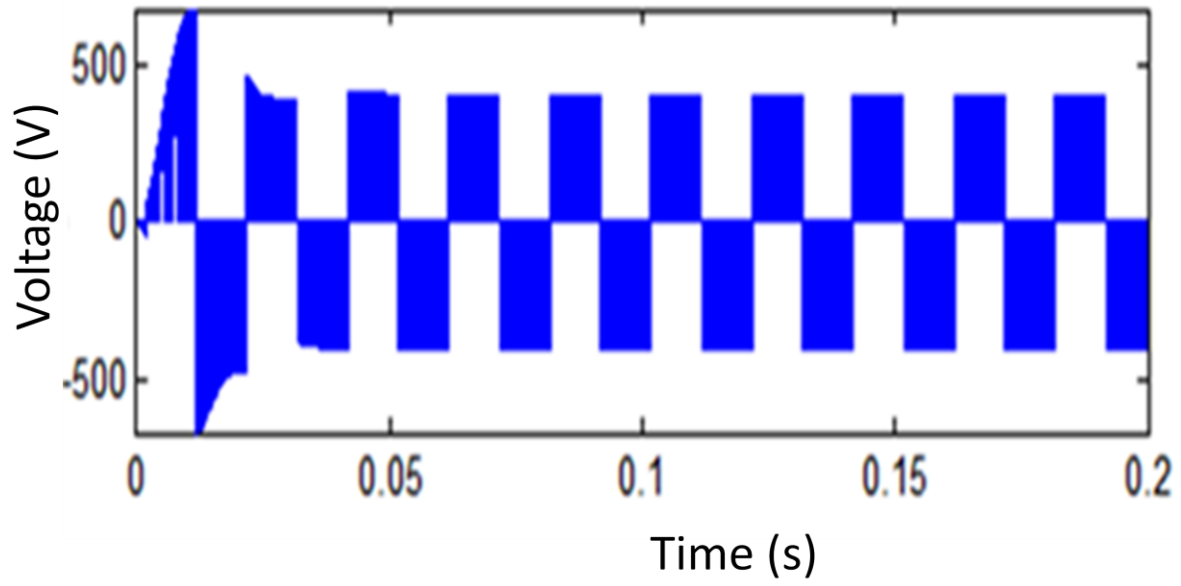


Figure-5.2: Waveform of output voltage for simple boost control strategy of ZSI feeding FOC induction motor drive

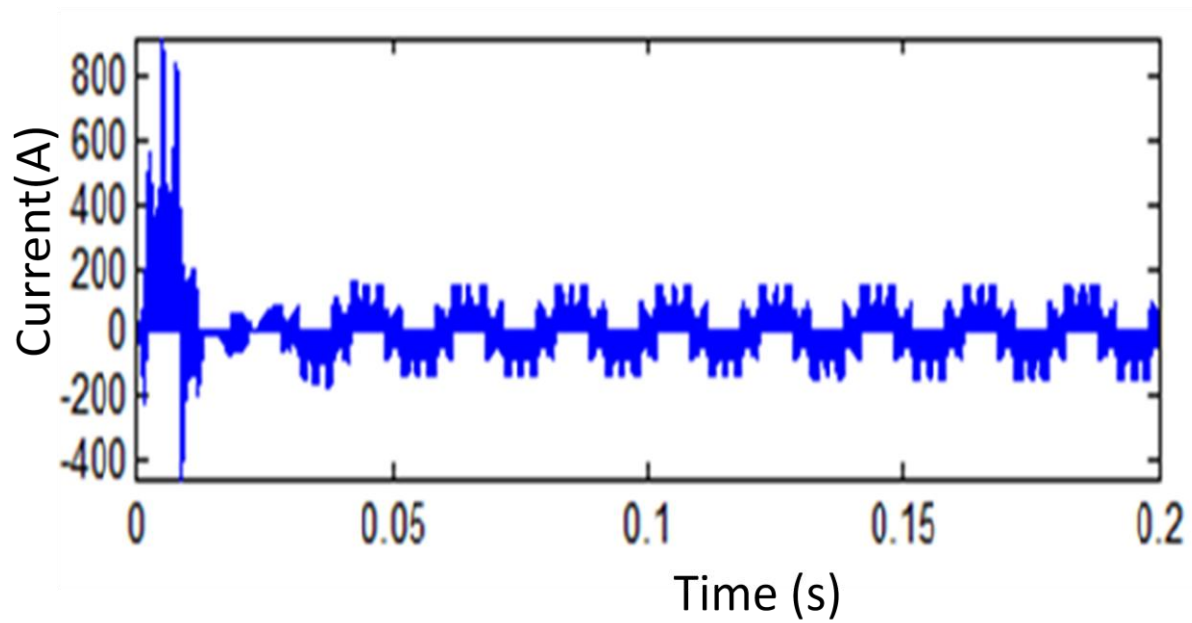


Figure-5.3: Waveform of output current for simple boost control strategy of ZSI feeding FOC induction motor drive

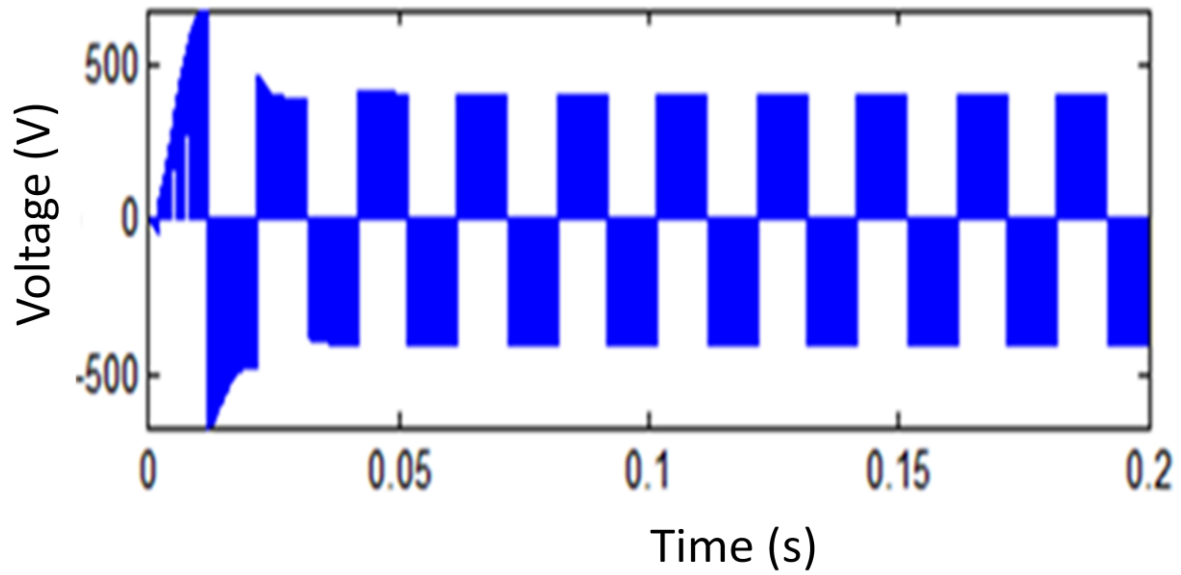


Figure-5.4: Waveform of output voltage for maximum boost control strategy of ZSI feeding FOC induction drive

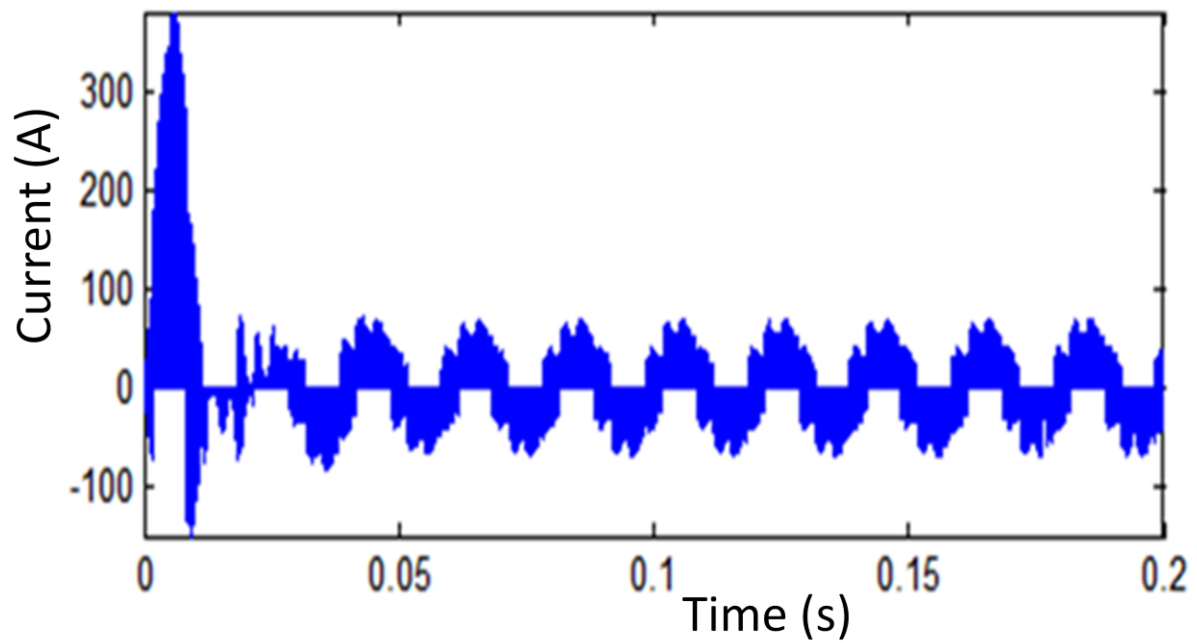


Figure-5.5: Waveform of output current for maximum boost control strategy of ZSI feeding FOC induction motor drive

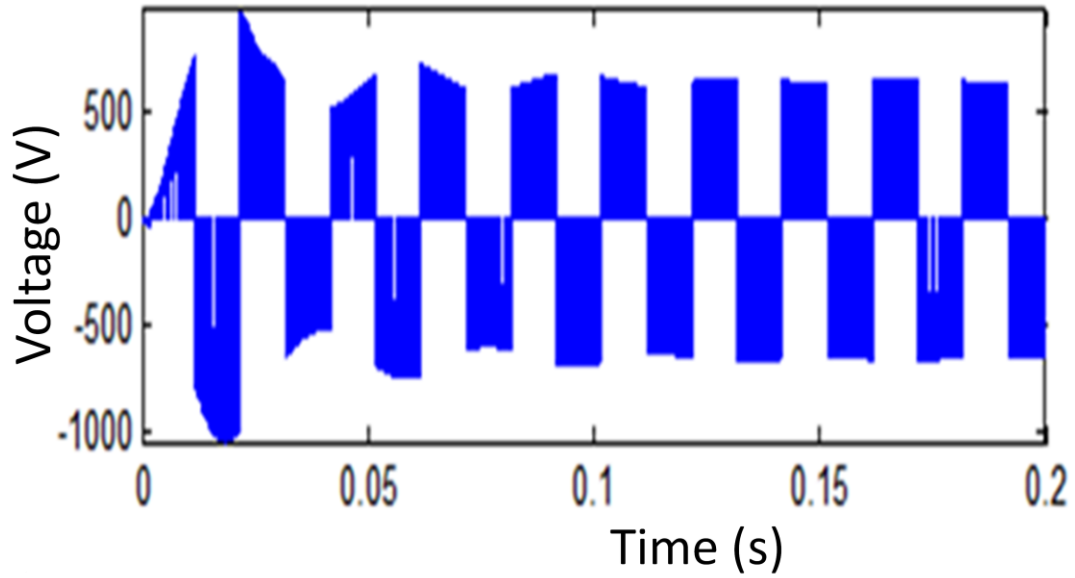


Figure-5.6: Waveform of output voltage for constant maximum boost control strategy of ZSI feeding FOC induction motor drive

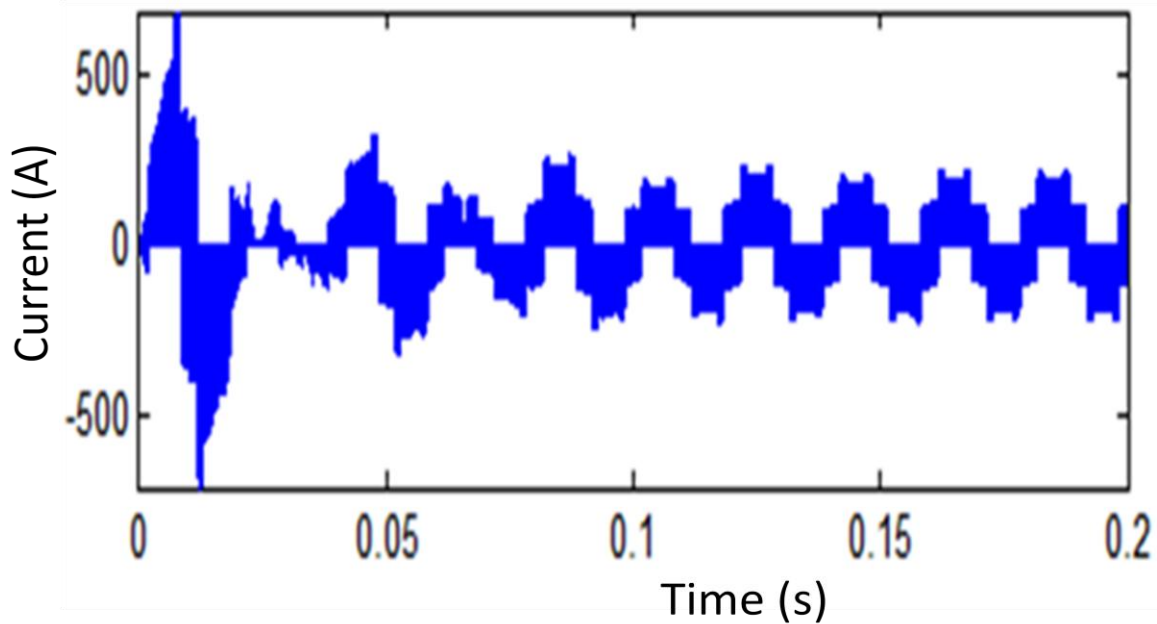


Figure-5.7: Waveform of output current for constant maximum boost control strategy of ZSI feeding FOC induction motor drive

Case-2: ZSI based Test System feeding DTC Induction Motor Drive

In this case, SIMULINK model has been developed in which DTC induction motor drive is fed by ZSI based test system. Simulations are conducted for different ZSI configurations. Output voltage waveform and output current waveform for simple boost control using DTC are shown in

Figure-5.8 and Figure-5.9. Output voltage waveform and output current waveform for maximum boost control using DTC are shown in Figure-5.10 and Figure-5.11. Similarly, output voltage waveform and output current waveform for constant maximum boost control using DTC are depicted in Figure-5.12 and Figure-5.13.

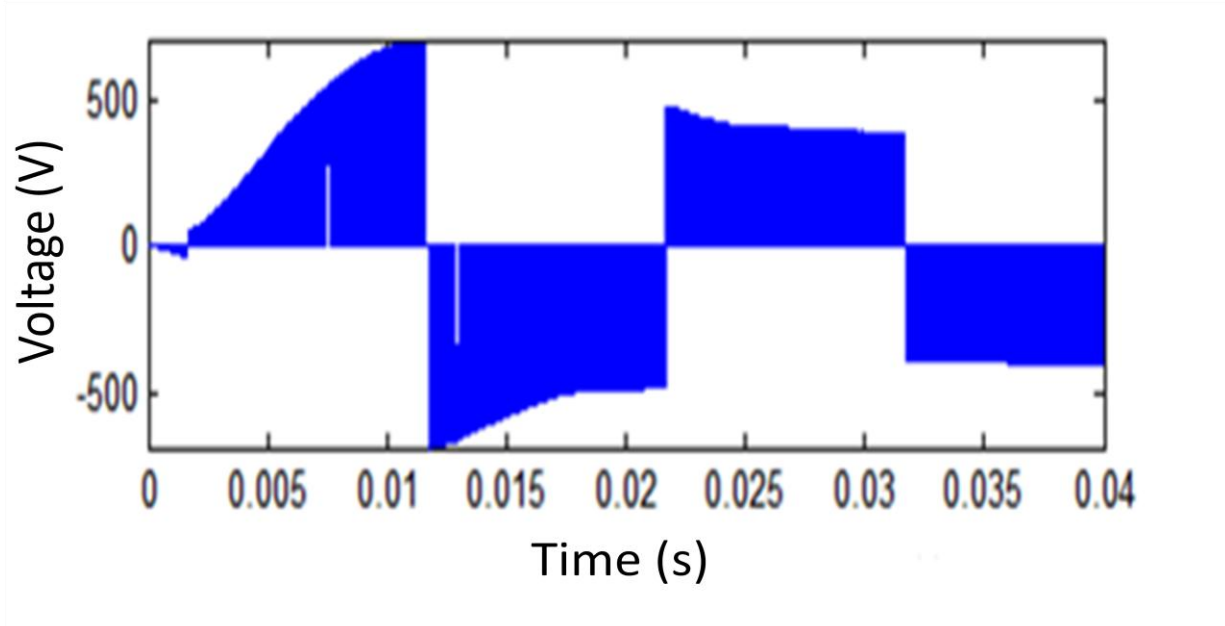


Figure-5.8: Waveform of output voltage for simple boost control strategy of ZSI feeding DTC induction motor drive

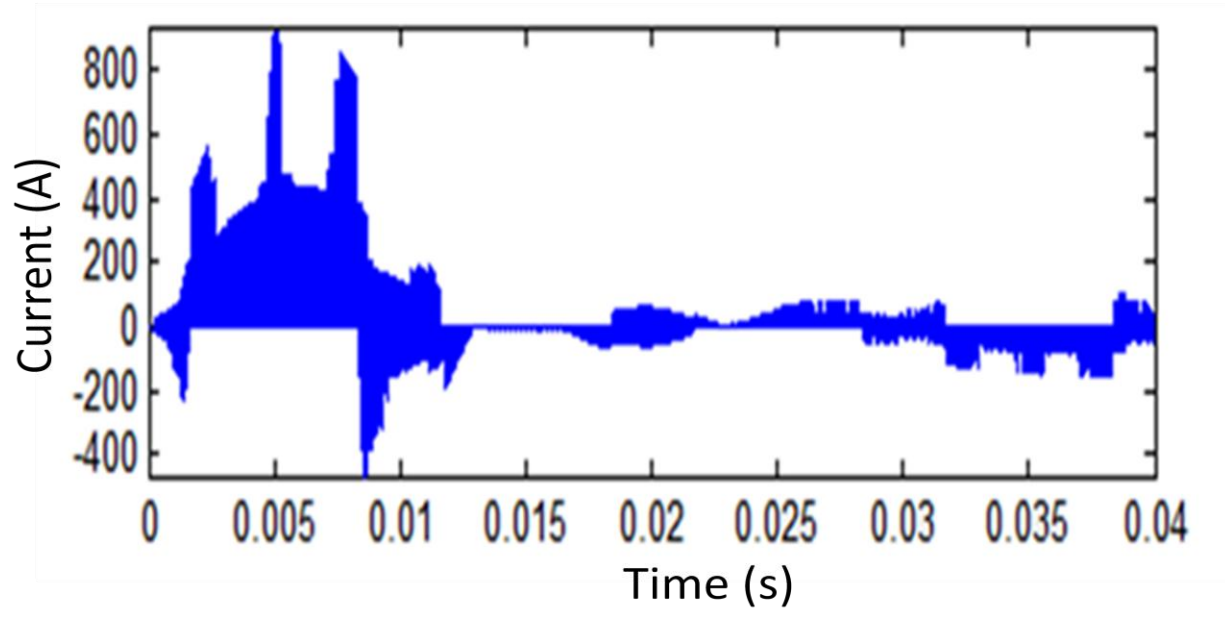


Figure-5.9: Waveform of output current for simple boost control strategy of ZSI feeding DTC induction motor drive

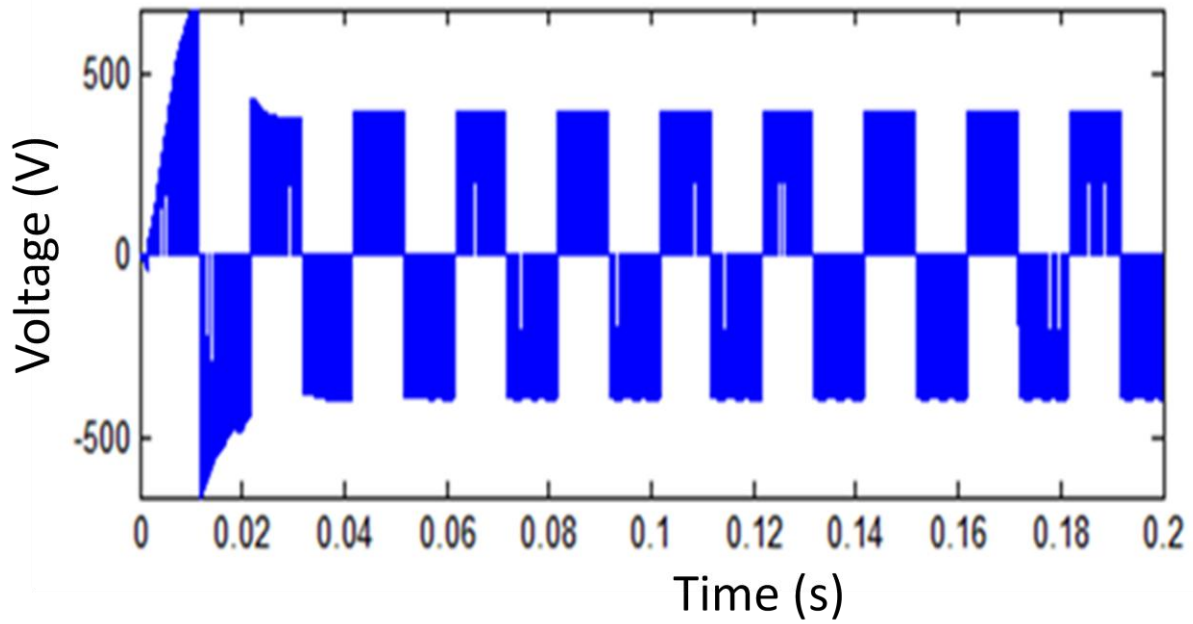


Figure-5.10: Waveform of output voltage for maximum boost control strategy of ZSI feeding DTC induction motor drive

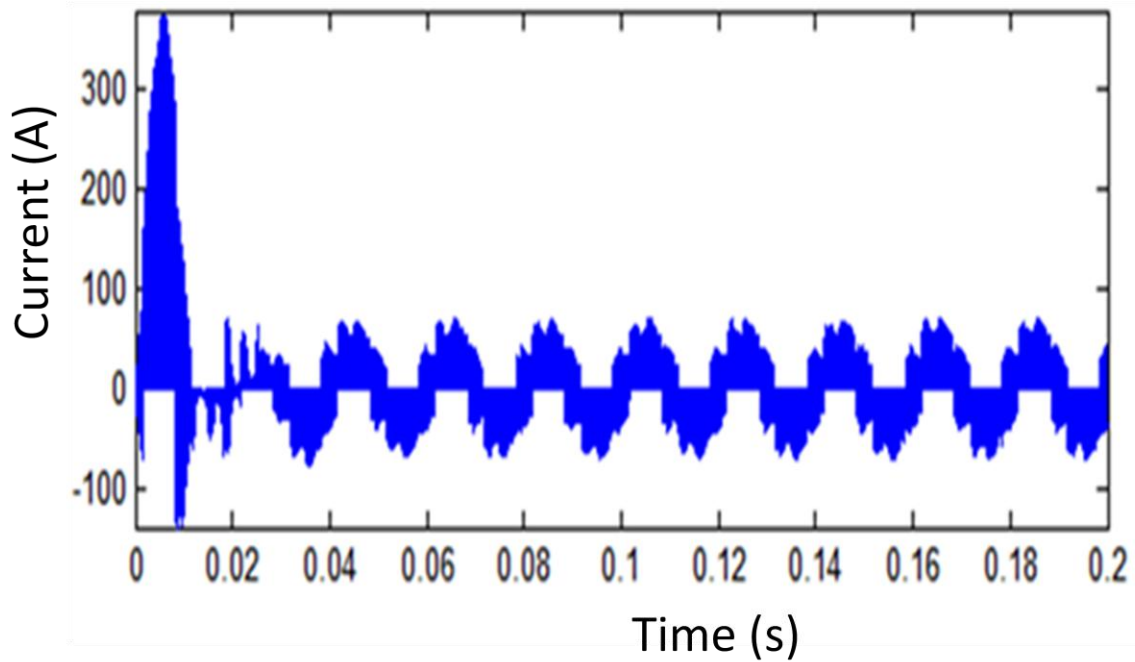


Figure-5.11: Waveform of output current for maximum boost control strategy of ZSI feeding DTC induction motor drive

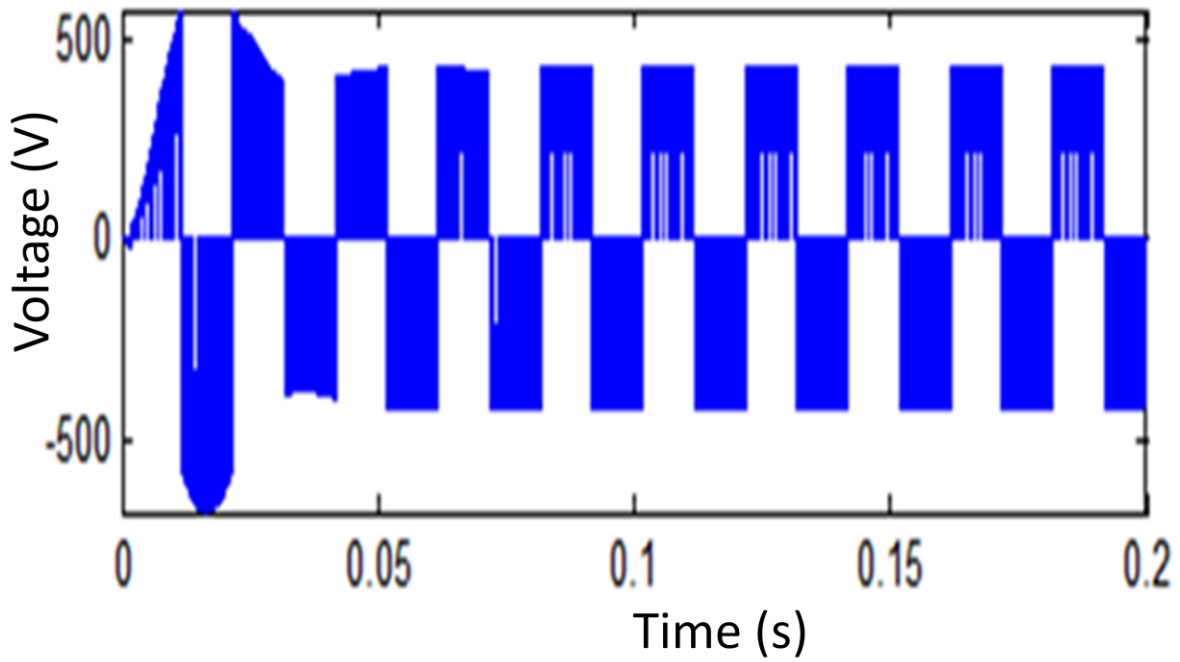


Figure-5.12: Waveform of output voltage for constant maximum boost control strategy of ZSI feeding DTC induction motor drive

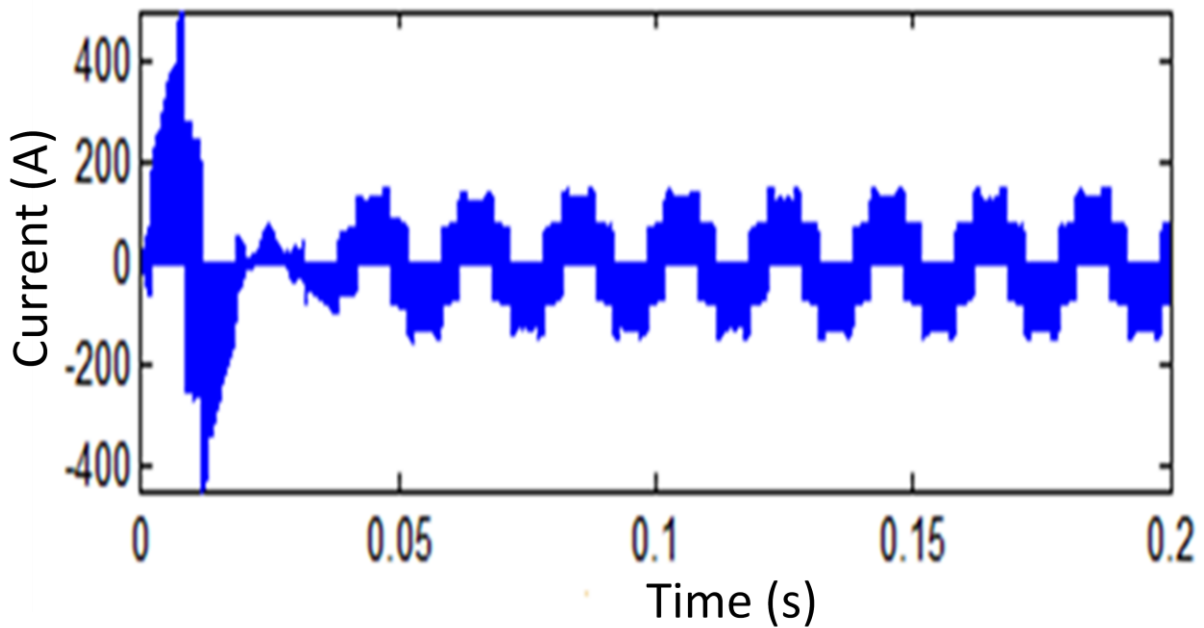


Figure-5.13: Waveform of output current for constant maximum boost control strategy of ZSI feeding DTC induction motor drive

Case-3: SPWM inverter based Test System feeding FOC Induction Motor Drive

In this case, SIMULINK model has been developed in which FOC induction motor drive is fed by SPWM inverter based test system. Simulations are conducted for SPWM inverter feeding FOC induction motor drive and its output voltage and output current waveforms are shown in Figure-5.14 and Figure-5.15

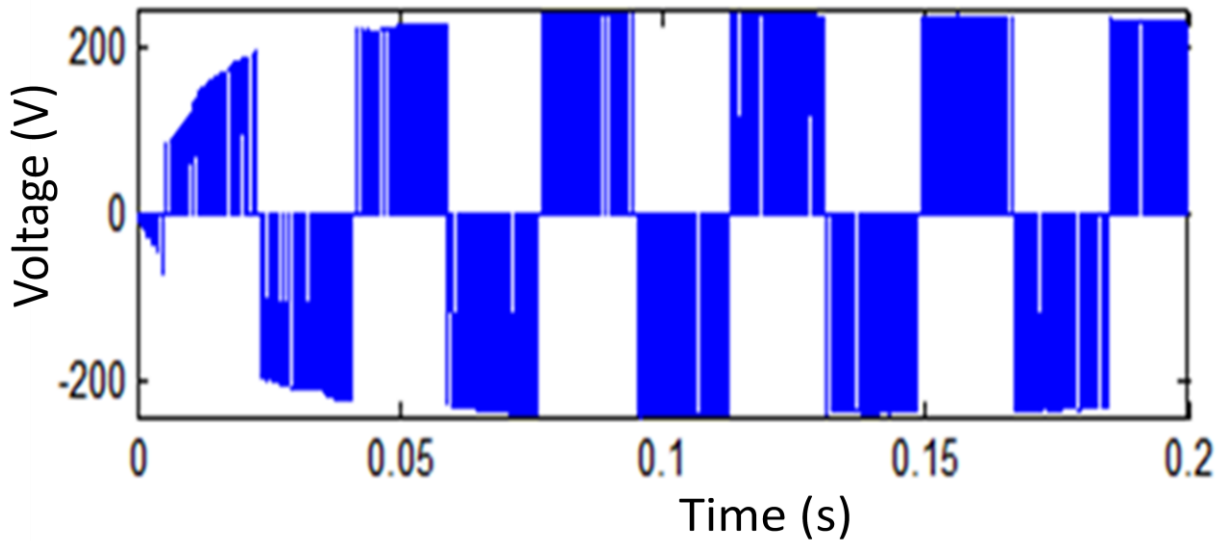


Figure-5.14: Waveform of output voltage for conventional SPWM inverter feeding FOC induction motor drive

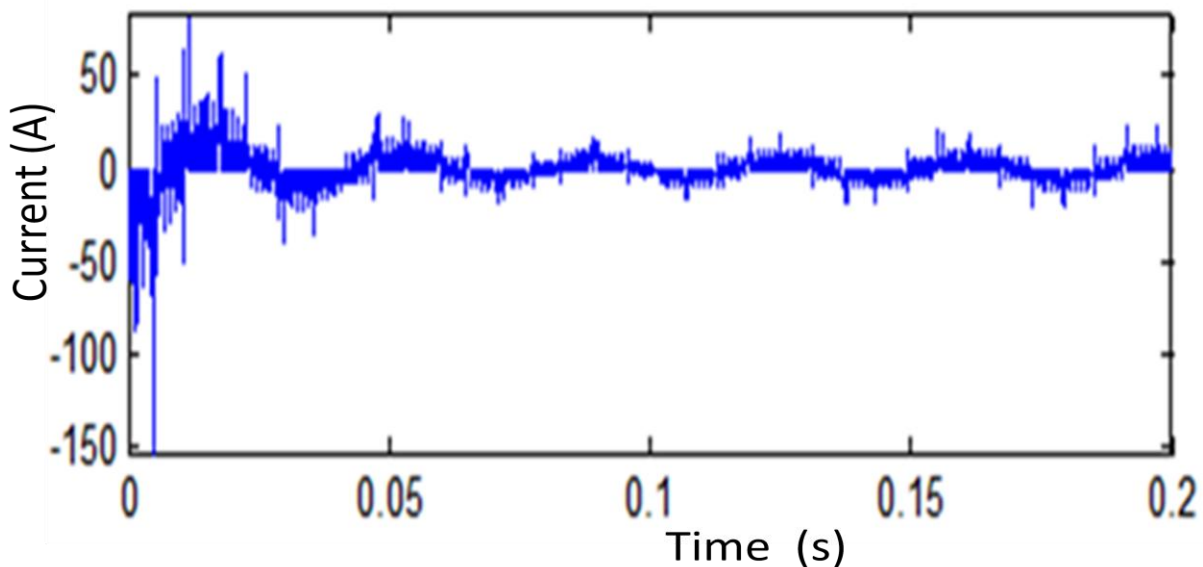


Figure-5.15: Waveform of output current for conventional SPWM inverter feeding FOC induction motor drive

Case-4: SPWM inverter based Test System feeding DTC Induction Motor Drive

In this case, SIMULINK model has been developed in which DTC induction motor drive is fed by SPWM inverter based test system. Simulations are conducted for SPWM inverter feeding DTC induction motor drive and its output voltage and output current waveforms are shown in Figure-5.16 and Figure-5.17.

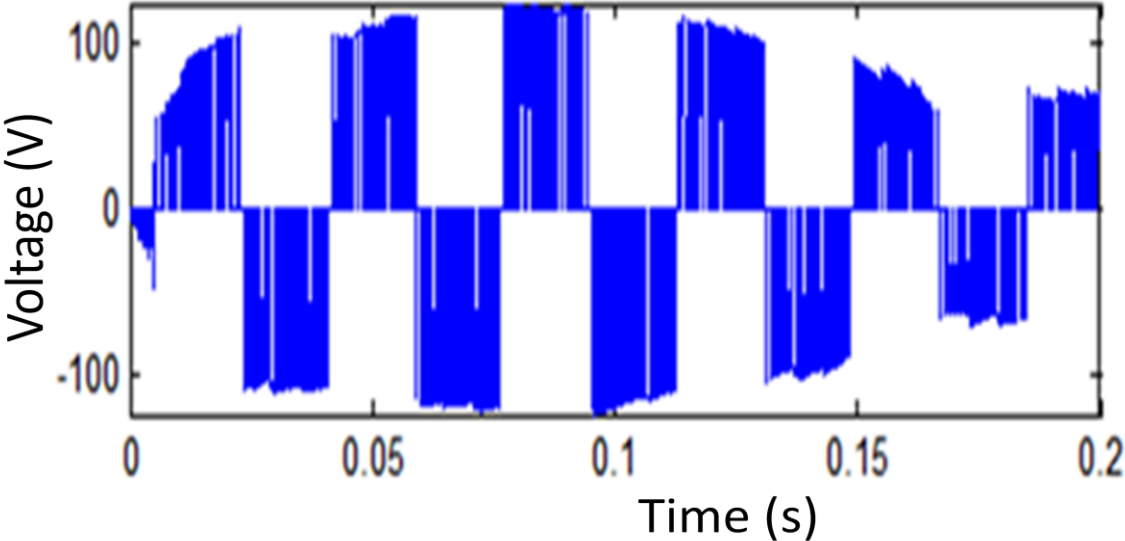


Figure-5.16: Waveform of output voltage for conventional SPWM inverter feeding DTC Induction motor Drive

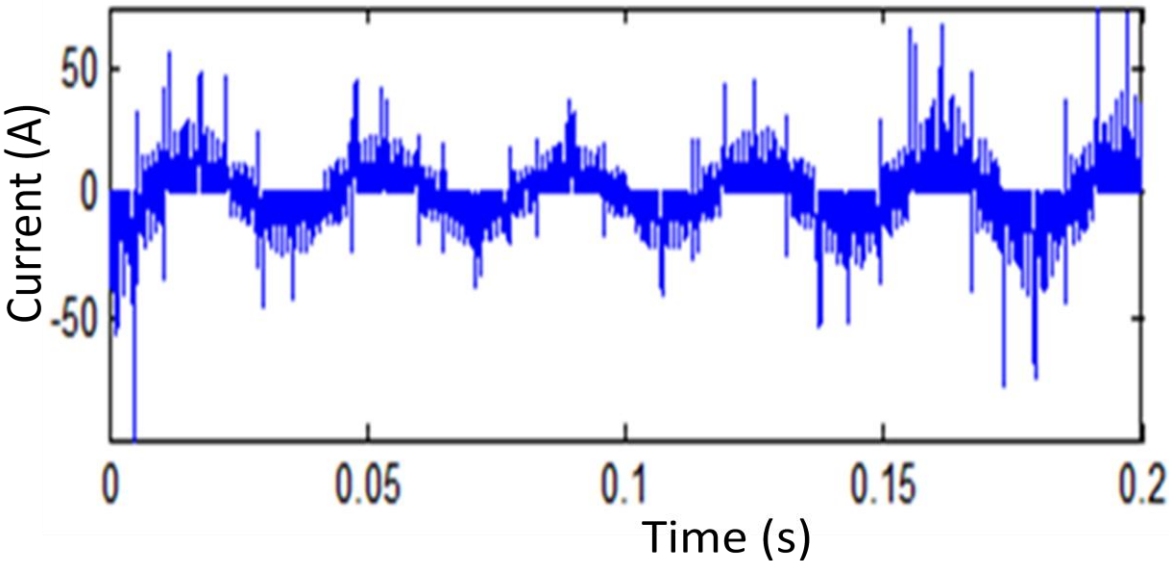


Figure-5.17: Waveform of output current for conventional SPWM inverter feeding DTC induction motor drive

Results of ZSI for different control strategies have been compared with SPWM inverter. The Table-5.1 shows the variations of fundamental output voltage, output current and their THD level for the various inverter configurations feeding FOC induction motor drive. Similarly, Table-5.2 shows the variations of fundamental output voltage, output current and their THD level for the various inverter configurations feeding DTC induction motor drive.

Table-5.1: Variations of fundamental output voltage, current and their THD level for FOC induction motor drive

Inverter	Output voltage (V)	THD (%)of Output Voltage	Output current (A)	THD (%)of Output Current
Simple boost control ZSI	285.3	89.96	39.17	105.67
Maximum boost control ZSI	341	68.45	34.28	82.48
Constant Maximum boost control ZSI	452.4	91.53	76.12	120.69
Conventional SPWM inverter	26.65	202.10	0.7914	275.45

Table-5.2: Variations of fundamental output voltage, current and their THD level for DTC induction motor drive

Inverter	Output Voltage (V)	THD (%) of Output Voltage	Output Current (A)	THD (%) of Output Current
Simple boost control ZSI	285.1	89.94	39.1	105.58
Maximum boost control ZSI	341	68.45	34.44	82.80
Constant Maximum boost control ZSI	452.3	91.53	76.18	120.69
Conventional SPWM inverter	12.06	239.41	1.09	390.39

CONCLUSIONS AND FUTURE SCOPE OF WORK

6.1 CONCLUSIONS

In this work, simulation of Z-source inverter configurations schemes and conventional SPWM inverter feeding industrial drives has been done in MATLAB/SIMULINK. From the results obtained, following conclusions have been drawn:

- In case of constant maximum boost control, it has been observed that fundamental output voltage is highest. Output voltage has increased to almost 1.5 times that of input supply voltage.
- Also, fundamental output current is highest in constant maximum boost control and almost same in simple boost control and maximum boost control.
- In case of maximum boost control, the fundamental output voltage is more whereas its THD level is observed to be lower than any other method.
- In case of conventional SPWM inverter, fundamental output voltage is very less and its THD level is very high as compared to any control strategy of Z-source inverter. So, Z-source inverter definitely proves to be a better equipment/device than conventional SPWM inverter.

6.2 FUTURE SCOPE OF WORK

Only three methods of ZSI namely simple boost control, maximum boost control and constant maximum boost control have been considered in this thesis. All these methods have certain limitations. Simple boost control can be implemented simply, but this method results in high voltage stress and high inductor current ripple. Maximum boost control reduces the voltage stress but it introduces low frequency current ripple related with line frequency. Maximum constant boost control reduces the voltage stress and eliminates the low frequency ripple.

The work presented in this thesis may be extended as per the horizons or directions given below.

- Some better SPWM and /or SVPWM based control technique(s) for ZSI may be explored to improve its performance.
- ZSI based custom power devices can be made use of in the distribution network to improve the PQ level.

REFERENCES

- [1] Sankaran, C., “*Power Quality*”, CRC Press LLC, 2002.
- [2] Dugan, Roger C.; McGranaghan, Mark F.; Santoso, Surya; Beaty, H. Wayne, “*Electrical Power System Quality*”, The McGraw-Hill, 2007.
- [3] Mohammed, Shazly A; Cerrada, Aurelio G; A Abdel-Moamen M; Hasanin B, “Dynamic Voltage Restorer (DVR) System for Compensation of Voltage Sags, State-of-the-Art Review”, *International Journal of Computational Engineering Research*, vol. 3, issue:1, pp.177- 183, 2013.
- [4] Rashid, M.H., “*Power Electronics*”, 2nd ed. Englewood Cliffs, NJ, Prentice Hall, 1993.
- [5] Mohan, N., Robbin, W.P.; Undeland, T., “*Power Electronics: Converters, Applications, and Design*”, 2nd ed. New York, Wiley, 1995.
- [6] Thorobog, K., “*Power Electronics*”, Prentice Hall International, 1998.
- [7] Krein, P.T., “*Elements of Power Electronics*”, Oxford University Press, 1998.
- [8] Trzynadlowski, A.M., “*Introduction to Modern Power Electronics*”, New York, Wiley, 1998.
- [9] Bose, B.K., “*Modern Power Electronics and AC Drives*” Upper Saddle River, Prentice Hall, 2002.
- [10] Peng, F.Z. “Z-Source Inverter”, *IEEE Transactions on Industry Applications*, vol. 39, issue: 2, pp.501-510, March/April 2003.
- [11] Peng, F.Z.; Shen, Miaosen; Qian, Zhaoming, “Maximum Boost Control of the Z-Source Inverter”, *IEEE Transaction on Power Electronics*, vol. 20, issue: 4, pp. 833-838, July 2005.
- [12] Rostami, H.; Khaburi, D.K., “Voltage Gain Comparison of Different Control Methods of the Z-source inverter”, *Iran University of Science and Technology*, Tehran, Iran.
- [13] Shen, M.; Wang, J.; Joseph, A.; Peng, F.Z.; Tolbert, L.M.; Adams, D.J., “Maximum Constant Boost Control of the Z-Source Inverter”, *IEEE/IAS*, pp.142-147, Seattle, 2004.

- [14] Shen, Miaosen; Peng, F.Z., "Operation Modes and Characteristics of Z- Source Inverter with Small Inductance or Low Power Factor", *IEEE Transaction on Industrial Electronics*, vol. 55, issue: 1, pp. 89-96, January 2008.
- [15] Gao, Zhiqiang; Wang, Jianze; Chen, Qichao, "An Improved Control Method for Inductive Load of Z- Source Inverter", *School of Electrical Engineering and Automation Harbin Institute of Technology*, Harbin, China.
- [16] Huang, Yi; Shen, Miaosen; Peng, F.Z., "Z- Source Inverter for Residential Photovoltaic Systems", *IEEE Transactions on Power Electronics*, vol. 21, issue: 6, pp. 1776-1782, November 2006.
- [17] Fang, Xu-Peng; Qian, Zhao-ming; Qi-Gao, Bin-Gu, Fang-Zheng Peng; Xiao-ming Yuan, "Current Mode Z-Source Inverter-Fed ASD System", *35th Annual IEEE Power Electronics Specialists Conference*, 2007.
- [18] Ding, Xinping; Qian, Zhaoming; Yang, Shuitao; Cui, Bin; Peng, F.Z., "A Direct DC-link Boost Voltage PID-like Fuzzy Control Strategy in Z-Source Inverter", *IEEE Power Electronic Specialist Conference*, 2008.
- [19] Zhu, Miao; Yu, Kun; Luo, Lin, Fang, "Switched Inductor Z-Source Inverter", *IEEE Transaction on Power Electronics*, vol. 25, issue: 8, pp. 2150-2158, August 2008.
- [20] Nijhawan, Parag; Bhatia, R.S.; Jain, D.K., "Performance Analysis of Different Control Methods of Z-Source Inverter Feeding Induction Furnace Load", *International Review of Automatic Control*, vol.7, issue: 2, pp.166-175, March 2014.
- [21] Takahashi, I.; Noguchi T., "A new quick-response and high-efficient control strategy of an induction motor", *IEEE Transaction on Industrial Application*; vol. 22, pp. 820-827, September / October 1986.
- [22] Chaikhy, Hamid; Khafallah, Mohamed; Saad, Abdallah, "Evaluation of two control strategies for induction machine". *International Journal of Computer Application*; vol. 35, issue: 5, pp. 51-52, December 2011.
- [23] Casadei, Domenico; Profumo, Francesco; Serra, Giovanni; Tani, Angelo, "FOC and DTC: Two Variable Schemes for Induction Motors Torque Control", *IEEE Transactions on Power Electronics*, vol. 17, issue: 5, pp. 779-787, September 2002.

[24] Ambrozic, Vanja; Bertoluzzo, Manuele; Buja Giuseppe, S.; Menis, Roberto, “An assessment of the inverter switching characteristics in DTC induction motor drive”, *IEEE Transaction on Power Electronics*; vol. 20, pp. 457-465, March 2000.

[25] Khoucha, Farid; Lagoun, Mouna Soumia; Kheloui, Abdelaziz; Benbouzid, Mohamed El Hachemi, “A Comparison of Symmetrical and Asymmetrical Three-Phase H-Bridge Multilevel Inverter for DTC Induction Motor Drives”, *IEEE Transactions On Energy Conversion*, vol. 26, issue: 1, pp. 64-72, March 2011.