

**COMPARATIVE PERFORMANCE ANALYSIS OF VSI AND ZSI
BASED DVRs IN A DISTRIBUTION NETWORK WITH WELDING
LOAD**

A Dissertation submitted in fulfillment of the requirements for the Degree
of

MASTER OF ENGINEERING
in
Power Systems

Submitted by

Manila Garg
Regd. No.: 801341009

Under the Guidance of

Mr. PARAG NIJHAWAN
Assistant Professor, EIED



2015

Electrical and Instrumentation Engineering Department
Thapar University, Patiala

(Declared as Deemed-to-be-University u/s 3 of the UGC Act., 1956)

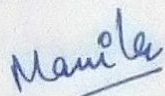
Post Bag No. 32, Patiala – 147004
Punjab (India)

CERTIFICATE

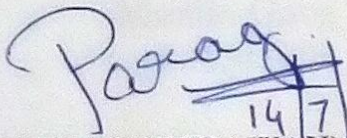
I hereby certified that the dissertation entitled, "**COMPARATIVE PERFORMANCE ANALYSIS OF VSI AND ZSI BASED DVRs IN A DISTRIBUTION NETWORK WITH WELDING LOAD**", which is being submitted by Manila Garg in fulfillment of the requirements for the award of the M.E. (Power Systems) in EIED Thapar University, Patiala, is a bona-fide record of the candidate's own work carried out by her under my supervision and guidance. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other university or institute for award of any degree.

Place: Patiala

Date: 14/July/2015


(MANILA GARG)

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

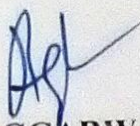

(PARAG NIJHAWAN)

Assistant Professor

Electrical & Instrumentation Engineering Department

Thapar University, Patiala

Countersigned By:

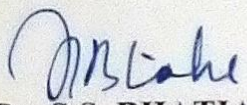

(Dr. RAVINDER AGGARWAL)

Professor & Head

Electrical & Instrumentation Engineering Department

Thapar University, Patiala

Patiala


(Dr. S.S. BHATIA)

Sr. Professor & Dean

Academic Affairs

Thapar University,

ACKNOWLEDGEMENT

I would like to thank Thapar University, Patiala for giving me the opportunity to use their resources and work in such a challenging environment. First and foremost I take this opportunity to express my deepest sense of gratitude to my guide Mr. Parag Nijhawan, for his able guidance during my seminar work. This seminar would not have been possible without his help and the valuable time that he has given me amidst of his busy schedule.

I would also like to extend my gratitude to my friends and senior students of this department who have always encouraged and supported me in doing my work.

Last but not the least I would like to thank all the staff members of Department of Electrical Engineering who have been very cooperative with us.

Manila Garg
801341009

ABSTRACT

Power quality is the most distressed areas in electrical power system. It has become important especially with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply. Power quality is signalized by parameters that reveal harmonic pollution, load disturbance and reactive power. One of the major problems which we deal here is power sag. To improve the power quality issues, custom power devices are used. The device considered here is DYNAMIC VOLTAGE RESTORER (DVR). DVR is the one who restore the voltage timely and provides best solution to power quality problems. DVR has very effective solution for mitigation of voltage sag and voltage swell in the distribution network. Here, the comparative study of Voltage Source Inverter (VSI) and Z-Source Inverter (ZSI) topologies based DVR to mitigate the power quality problems introduced into distribution network by welding power supply are introduced using MATLAB/SIMULINK. ZSI has both buck and boost capabilities as they allow inverters to be operated through shoot through state. This will provide ride through during voltage sag without any additional circuit and improve the power factor by reducing the harmonic current and common-mode voltage which will finally increase the reliability and extends the output voltage range. For unity power factor, pulse width modulation technique is developed.

TABLE OF CONTENTS

CERTIFICATE	i
ACKNOWLEDGEMENT	ii
TABLE OF CONTENTS	iv
LIST OF ABBREVIATIONS	vi
LIST OF FIGURES	viii
LIST OF TABLES	ix
CHAPTER1. INTRODUCTION	1-11
1.1 INTRODUCTION	1
1.2 LITERATURE SURVEY	2
1.3 SCOPE OF WORK	10
1.4 OBJECTIVE OF THESIS	11
1.5 ORGANIZATION OF THESIS	11
CHAPTER2. POWER QUALITY	12-25
2.1 INTRODUCTION	12
2.2 PERSPECTIVES OF POWER QUALITY	12
2.3 IMPORTANCE OF POWER QUALITY	13
2.4 POWER QUALITY PROBLEMS & ISSUES	13
2.5 POWER QUALITY ISSUES	14
2.5.1 SHORT-DURATION VARIATION	16
2.5.2 LONG DURATION VARIATION	17
2.5.3 TRANSIENTS	18
2.5.4 VOLTAGE IMBALANCE	20
2.5.5 WAVEFORM DISTORTION	20
2.5.6 SPIKES	23
2.5.7 FLICKER	24
2.6 SOLUTION TO POWER QUALITY PROBLEMS	24
CHAPTER3. DYNAMIC VOLTAGE RESTORER	26-36
3.1 INTRODUCTION	26
3.2 PRINCIPLE OF DVR OPERATION	26
3.3 BASIC ARRANGEMENT OF DVR	27
3.4 EQUATION RELATED TO DVR	31
3.5 OPERATING MODE OF DVR	32
3.6 VOLTAGE INJECTION METHODS	33
3.6.1 PRE-SAG/DIP COMPENSATION METHOD	33
3.6.2 IN-PHASE COMPENSATION METHOD	34
3.6.3 IN-PHASE ADVANCE COMPENSATION METHOD	34
3.6.4 VOLTAGE TOLERANCE METHOD WITH MINIMUM	35

ENERGY INJECTION	
3.7 CONTROL TECHNIQUES	36
3.7.1 LINEAR CONTROLLERS	36
3.7.2 NON-LINEAR CONTROLLERS	36
CHAPTER4. ARC WELDING POWER SOURCES	37-45
4.1 INTRODUCTION	37
4.2 PRINCIPLE OF OPERATION	38
4.2.1 WELDING TRANSFORMER	38
4.2.2 SOLID – STATE INVERTER	40
4.3 MATHEMATICAL MODELLING OF WELDING SUPPLY	42
CHAPTER5. MATLAB BASED SIMULATION AND RESULTS	47-57
5.1 SIMULATION RESULTS	46
5.2 MODULATION METHODS	48
5.3 RESULTS and DISCUSSIONS	49
CHAPTER6. CONCLUSIONS AND FUTURE SCOPE OF WORK	58
6.1 CONCLUSIONS	58
6.2 FUTURE SCOPE OF WORK	58
REFERENCE	59-63

LIST OF ABBREVIATIONS

CV - Constant Voltage

CC - Constant Current

PWM – Pulse Width Modulation

SPWM - Sinusoidal Pulse Width Modulation

IEEE - Institute of Electrical and Electronics Engineers

DVR - Dynamic Voltage Restorer

CCM – Continuous Conduction Mode

DCM – Discontinuous Conduction Mode

PFC - Power Factor Correction

THD – Total Harmonic Distortion

ZSI – Z-Source Inverter

VSI - Voltage Source Inverter

CSI – Current Source Inverter

EPQ - Electric Power Quality

RMS – Root Mean Square

PCC - Point of Common Coupling

SMES - Superconductive Magnetic Energy Storage

ANN - Artificial Neural Networks

SMAW - Shielded Metal Arc Welding

GMAW - Gas Metal Arc Welding

FCAW - Flux Cored Arc Welding

GTAW - Gas Tungsten Arc Welding

SAW - Submerged Arc Welding

ESW – Electro Slag Welding

EGW – Electro Gas Welding

PAW - Plasma Arc Welding

ASW - Arc Stud Welding

TRC - Time Ratio Control

LIST OF FIGURES

Figure No.	Caption of Figure	Page No.
2.1	Voltage Sag	16
2.2	Voltage Swell	16
2.3	Interruptions	17
2.4	Impulsive Transient	19
2.5	Oscillatory Transient	19
2.6	Harmonics	20
2.7	Notching	22
2.8	Noise	22
2.9	Flicker	24
3.1	Location of DVR	26
3.2	Principle of DVR system	27
3.3	Schematic diagram of DVR	28
3.4	Two level switch mode inverter	29
3.5	Three-Phase Z-Source Inverter	30
3.6	Equivalent circuit diagram of DVR	31
3.7	Pre-Sag Compensation	34
3.8	In-phase Compensation	35
3.9	Voltage Tolerance Method with Minimum Energy Injection	35
4.1	Principal Electrical Elements of a Transformer Power Supply	39
4.2	Welding Transformer with Tapped Secondary Winding	39
4.3	Series Impedance Control of Output Current	40
4.4	Inverter Diagram Showing Power Supply Section and Voltage Waveform	42
4.5	A Schematic Diagram of GTA Welding Process	43

LIST OF TABLES

Table No.	Caption	Page No.
2.1	Categories and Characteristics of Electromagnetic Phenomenon in Power Systems as Defined by IEEE-1159	14
2.2	Spectral Components of Waveforms (of Frequency f)	23

1.1 INTRODUCTION

In this fast developing technology world, high current and low voltage welding power supply with more efficiency has been used in the industries in present era. Welding is an art of joining two metals usually metals or thermoplastics together. During welding the pieces which have to be joined are melted at joining surfaces and the filler material has to be added which makes the pool of molten metal and strong the joint by solidifying.

Welding device supplies high current at low voltage which is in the range of 50 V. It is very much simple as car battery and as knowledgeable as modern machines which are based on SCR (silicon controlled rectifier) technology. Welding machines are usually of two types that is constant current (CC) or constant voltage (CV); a constant voltage machine will fluctuate its output current to maintain a set voltage while a constant current machine varies its output voltage to maintain a steady state current. Gas metal arc welding and flux-cored arc welding typically use constant voltage, gas tungsten and shielded metal arc welding will use a constant current sources but a constant current is also used with a voltage sensing wire feeder. If a welder is aimed to use a constant voltage machine to weld with SMAW (shielded metal arc welding) the small fluctuations in the arc distance would cause wide fluctuations in the machine. In case of constant current machine, the welder can count a fixed number of amperes current which are going into the material as too much distance will cause poor welding.

Welding power supply has been based on transformers. A metallic transformer changed it from high input voltage to current at lower output voltage. This voltage current is then rectified by the rectifier circuit to get the direct current (dc) at output end of welding supply. Transformers are generally inefficient operating at 50 or 60 hertz frequency. In inverter circuit same incoming power frequency is used which may be 50 or 60 hertz. The inverter circuit can also provide some additional features like flow of

power control and overload protection. The supply is being first fed to the rectifier instead of being directly fed to the transformer. Different techniques are used to control the gate pulses of inverter section. SPWM (sinusoidal pulse width modulation), SVPWM (state vector pulse width modulation), hysteresis band PWM etc have been used in controlling the gates of inverter section. This high voltage, high frequency dc is then fed to the transformer where it is transformed to low voltage according to the requirement of welding machines. At the end it is put on the filtering circuit. To filter this incoming voltage and current basically LC filter is used. Other filters may also be used like active filters, passive filters, high pass band filter, low pass filter etc according to the requirement of the circuit. The most significant advantage of the inverter power supply used is that it will chopped up the AC supply and finally convert it into steady state DC output without any ripples. This will finally result in smoother and more stable welding DC arc output.

1.2 LITERATURE SURVEY

Power quality [1] is the most distressed areas in electrical power system. The power quality has serious inference for customers, utilizers and manufacturers. Power quality is signalized by parameters that reveal harmonic pollution, load disturbance and reactive power. The influence of power quality problems are sensed by commercial, industrial and residential consumers [2]. Some power quality problems like voltage swell, voltage sag, voltage unbalance, fluctuations, harmonic interruptions has been presented. The solution to the problem can be done by taking various measures like using less sensitive equipments, installation of restoring technologies, distributed generation etc [3].

On the other hand, recent developments in semiconductor technology and power electronics have improved the power system. Now-a-days, a new concept of Custom Power Devices has been introduced for the customer satisfaction [4-5]. The concept of custom power in power distribution is to provide a good quality power which is demanded by sensitive customers [9-10].

Power quality is defined in the IEEE 100 Authoritative Dictionary of IEEE Standard Terms as given below:

The concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment Utilities may want to define power quality as reliability [6-7].

The CP (custom power) devices installed in distribution network to eliminate various power quality disturbances like voltage sag/swells, dip, flicker, power factor reduction, current harmonics. These devices have applied at the distribution system with purpose of protecting entire plant, feeder and loads. The DSTATCOM, connected in shunt has provide good power quality in both transmission and distribution level. This entire device integrated to form custom power park. The entire customers are benefit from high quality of power [8].

Multipulse converters have been implemented to develop robust controls for Flexible Alternating Current Transmission System (FACTS) and High Voltage Direct Current (HVDC) systems [11]. Power electronic based equipment, such as High-Voltage DC (HVDC), Flexible AC Transmission Systems (FACTS) and Custom Power technologies create some of the most-challenging technical advancements to address the new operating challenges which have been presented today [12-13].

The DVR has been presented in this paper which has the most efficient property for resolving power quality problems because of its fast response and high reliability. The DVR has effective equipment for the protection of sensitive loads from short duration voltage dips. The DVR has been placed both at the low voltage level and at medium voltage level. The series connection with the supply voltages makes it productive at locations where voltage dips have the primary problem. The role of a DVR in mitigating the power quality problems in terms of voltage swell, sag and interruptions has been described. The equations for calculating the voltages and power injected from each of the three DVR phases have given [14].

DVR has some additional features like harmonics and power factor correction capability because of which it has gained a universal importance. In this paper, the effectiveness of DVR (dynamic voltage restorer) for voltage balancing has been shown.

The dqo control algorithm between source side and its reference has been implemented to restore the absent cycles of voltage. The proposed method has compensated for most of the voltage faults like harmonics and any kind of voltage unbalance on the supply networks [15].

This paper sketches the problem of voltage swells and sags and its severe impact on non linear loads. The dynamic voltage restorer has become universal because of its cost effective solution for the protection of sensitive loads from power quality issues. The dqo algorithm control for the compensation voltages in DVR has been discussed. It resolves the power circuit of a dynamic voltage restorer system in order to control limitations and targets for the compensation of voltage [16].

The performance of proposed arc welding power supply using single phase full bridge converter has been presented over wide range of loads in CCM and DCM operations. This modular approach will increase the power expandability of power converter for welding applications. It has been observed that in modular approach for power factor correction, this will result in nearly unity power factor. Simple pulse width modulation technique is used DC-DC converter. There is no extra voltage stress on power devices when compared with the single phase modules based on welding power supply system. The simulation results show that the harmonic content is well below IEEE-519 standard. It has been observed that there is no need of second stage requirement because dynamic performance is fast enough. This system is capable of operating in short circuit conditions which is appropriate for welding applications. Irrespective of the load variations this maintains the good voltage regulation [17-18].

The isolated bridgeless AC-DC converter based on power factor correction (PFC) for welding applications has been discussed. The DCM operation helps in achieving fast dynamic response and nearly unity power factor. The input current has been observed to be in phase with input voltage and THD is less than 5% even during load variations [19].

The modeling of Sheppard-Taylor topology suitable for welding applications has been presented. The input inductance of this proposed converter works in discontinuous current mode (DCM). The converter functions well in short circuit conditions as well as

light load conditions. Simple control technique is used and THD calculated is less than 5% in line current [20].

A single-stage forward AC-DC converter for welding applications has been analyzed. This system has no extra voltage stress on power devices as compared to the single stage modules [21]. The power supply maintains the good voltage regulation irrespective of the load variations. At three- phase utility interface very low THD and a unity power factor is attained.

A gas tungsten arc welding power supply at constant voltage has been presented. Traditional power quality transformer with reduced size and weight is presented in this paper. The modular topology is used for the design which is basically based on dc-dc buck converter. Also matrix converter power electronic transformer based AC welding power supply for GTAW of aluminum is proposed. The power quality problems in traditional transformers are resolved by simulation. DC link in input side has replaced by three-phase to one-phase matrix converter. The harmonics of input voltage and current are having low value than that of conventional power electronic transformer topology [22].

A Power Factor Corrected two stage, bridgeless converter has been suggested for the welding applications. It has been designed with low input current total harmonic distortion. This topology offers excellent power factor correction features and the quality of weld has been enhanced by controlling output side parameters to regulate the heat. It has provided fast response and robustness and the THD calculated was below 5% for both full load and light load conditions. The power factor has also remained near to unity which in all observed that this topology meets the requirement of IEC 61000-3-2 international standard [23].

As the profitable industry continues to move with financial, deregulation and market forces are demanding moreover optimal and surplus operation of the power system with regard to generation, transmission and distribution [24]. Power electronics equipments such as Custom Power Technologies and Flexible AC Transmission Systems which is used to implement voltage source inverter based technology, constitute

advanced technology which addresses to the present day new challenges. The high performance capability of these equipments will result in improving the quality of power delivered [25].

Voltage source inverter or Current source inverter has been generated discrete output waveforms which require large inductance in series with the load so that it generated respective output current waveform. Distorted current and voltage waveform produces harmonic distortion, high frequency noise and additional power losses. It has discussed the minimization of THD with reference current generation based on multilevel inverter. Mainly DSP or microcontroller based controller are preferred over analog controller for implementing SPWM scheme for multilevel inverter [26].

Five major types of pulse width modulation control for ZSI has been explored and compared in this paper. Proper control method has been selected according to the requirement of different loads and demands. By comparing the results it has been noticed that the modified maximum boost control technique gives the best result for lower harmonics and better operation [27].

The Control techniques may vary according to the power demand of inverter. The terminal of voltage source inverter is substantially remains constant because of low internal impedance with the variation of load. That is why it is equally suitable for single motor drives and multi motor drives. Any short circuit across the voltage source terminals causes current to rise fast, because of low time constant of its internal impedance [28].

The term current-fed and voltage-fed have been used in connection with output from inverter circuit. Variable frequency and voltage supply to ac drives is invariably obtained from three-phase VSI. Output waveforms of inverter are usually rectilinear in nature and as such contain harmonics which may lead to reduce load efficiency and the performance of inverter [28]. Load harmonic reduction can be reached by either pulse width modulation, selected harmonic reduction chopping or filtering. Voltage source inverter (VSI) and current source inverter (CSI) are used widely but they have certain theoretical and conceptual barriers and limitations.

The effectiveness of different control techniques based on DVRs for static linear & static non-linear loads have been investigated in this paper. A PI controller with a linear structure offers satisfactory performance over a wide range of operation. Simulation results indicate that the non-linear control techniques provide better compensation to the system as compared to the linear PI technique based DVR connected to the feeder during static non-linear loads [29].

The modeling and simulation of a DVR using MATLAB/SIMULINK has been presented. This paper explained a low voltage DVR which is connected to adjustable speed drive load. The dqo control algorithm which has a scaled error between source side of the DVR and its reference was implemented to restore the missing cycles of the voltage [30].

Limitations and conceptual barriers in voltage source inverter include that it has a boost for ac-to-dc power conversion and buck converter for a dc-to-ac power conversion because the output voltage is restricted. An additional dc-dc boost converter had needed to obtain desired output where available dc has been limited and this has increase the cost and finally decrease the efficiency. The shoot-through has destroyed the converter if upper and lower devices of each phase leg have not been gated by EMI noise simultaneously. An additional LC filter is required for waveform distortion which will increase the power loss and control complexity [31].

A Z-source inverter with unique X-shaped impedance network has been presented. This impedance network couples the converter main circuit with the load or power source or converter. It has overcome the limitations of traditional converters i.e. VSI and CSI. 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 [32].

Three control methods of ZSI [33] are as follow:

- The simple boost control
- The maximum boost control
- The constant maximum boost control

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 insertion to active states and zero states. It has provided a special feature of buck-boost which was not possible in traditional voltage source and current source converters.

Comparison of voltage gain of control methods for the Z-source inverter under a given boost factor has been presented. The Z-source inverter excellently utilizes the shoot-through switching states besides the active and zero states. The Z-source network makes the shoot-through states possible and provides the unique buck-boost feature to the inverter [34].

It has been found that the maximum boost control method has the highest modulation index and voltage gain. There have two maximum boost control methods which has achieved maximum voltage gain at any modulation index without generating any ripples that is connected to the output frequency [35]. This shows that the Z-source network requirement has been independent of the output frequency and ascertained only by switching frequency.

ZSI has a following feature given below:

- Controlling the shoot-through duty cycle of IGBT inverter system which reduces the line harmonics
- Improves the power factor and extends output voltage range.

Five modified PWM techniques have been discussed in this paper. The main consideration to design parameters has dc link voltage stress. A common factor to PWM techniques has boosting of dc link voltage with the help of shoot-through state. A modified SVPWM technique showed that the output AC voltage has no longer limited value and has been boosted beyond the limit imposed by conventional voltage source inverter. This has shown the best result among all pulse width modulation techniques discussed for variable speed applications [36].

It has been presented the improved Z-source inverter used to control the speed of induction motor. This inverter has effectively reduced the voltage stress across the

capacitors in the impedance network. This topology has been used in many renewable energy sources where input voltage has unreliable in nature and keep varying from time to time [37]. The inrush current has been suppressed and topology had started with soft start capability.

It has been discussed that the unique impedance network has a special feature that the output ac voltage has any value between zero and large value despite of input voltage. Thus, the ZSI has both buck and boost capability that has a wide range of obtainable value at different pulse width which has been verified by SIMULINK model [38]. It has been found that the shoot-through zero state have not affect the PWM control of inverter because it finally produce the same zero voltage at load terminals. The shoot-through period has explained by the modulation index. The performance scheme has been evaluated and has found that the output voltage is of good quality and pure sinusoidal in nature.

The design and development of SPWM three-phase voltage source inverter has been discussed. It has been found that there are no. of PWM techniques used for obtaining variable voltage and frequency supply. The mainly used PWM techniques for three-phase voltage source inverters are carrier based PWM and space vector PWM. The SPWM has been tested for VSI in SIMULINK for different loads at different carrier frequencies. There has been increasing trend of using sinusoidal PWM because it has easily digital realized. It has been concluded that the THD for output current decreases with increase in carrier frequency up-to 13 KHz which shows that this design is well efficient in the range of 11-13KHz [39].

The concept of switched inductor and Trans Z-source among various topologies of Z-source has been discussed. The resulting topologies have enhanced the voltage boosting capabilities. Here, SVPWM (space vector pulse width modulation technique) has been used. SVPWM has optimized the output voltage waveform of the inverter. Comparative studies of ZSI have been performed and observed that ZSI has high voltage boost capability in switched inductor ZSI as compared to Trans ZSI. The THD value has reduced. ZSI has offered high reliability because the shoot-through caused by EMI had no longer destroyed the inverter circuit [40].

The novel Z-source PWM rectifier-inverter has been presented with following advantages:

- Z-source capacitor has lower dc voltage.
- The volume of capacitor has reduced and.
- The mechanical structure has simplified [35].

In order to decrease the switching losses and to increase the efficiency of Z-source rectifier-inverter it has proposed two novel PWM techniques called the novel Discontinuous Simple Control SVPWM and the novel Minimum Switching Number SVPWM. These proposed PWM have following advantages:

- EMI and switching loss is low.
- The Z-source network voltage, capacitor voltage and power switch voltage stress of the three Z-source novel rectifier-inverter circuit has been analyzed.
- This inverter has achieved the unity power factor [41].

1.3 SCOPE OF WORK

From the literature review, it has been observed that the work to mitigate the power quality problems introduced into distribution network by welding power supply is very much diversified. However, there is a scope to investigate the effectiveness of compensating devices for welding load and with different loading condition in the distribution system as the reliability of power supply mainly depends on the distribution system.

The objective of proposed work is to improve the power quality of distribution network with welding load by voltage source inverter and Z- source inverter based DVR. This will provide ride through during voltage sag without any additional circuit and improve the power factor by reducing the harmonic current and common-mode voltage which will finally increase the reliability and extends the output voltage range. The unity power factor is achieved using pulse width modulation technique.

1.4 OBJECTIVE OF THESIS

The dissertation proposes the MATLAB/SIMULINK model of VSI and ZSI based DVRs in a distribution network with welding load. The major objectives are summarized as follows:

- To prepare VSI feeding welding load.
- To prepare ZSI feeding welding load.
- To study and compare the model of VSI and ZSI based DVR feeding welding load in continuous conduction mode
- To establish the effectiveness of VSI based DVR in a distribution network with welding load for power quality improvement.
- To establish the effectiveness of ZSI based DVR in a distribution network with welding load for power quality improvement.

1.5 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 includes the power quality and its problem and also included various solutions that can be implemented to improve the power quality of distribution network.

Chapter 3 includes the operation, modeling and application of dynamic voltage restorer (DVR).

Chapter 4 includes the introduction, principle and mathematical modeling of welding power supply.

Chapter 5 includes the SIMULINK models and their results.

Chapter 6 includes conclusions of work presented in the thesis. It also presents the future scope of this work.

2.1 INTRODUCTION

The technology is developing at faster rate in all progressing areas. Power scenario has changed a lot. The issue of power quality has become very critical because of the loads which are sensitive to power quality disturbances. Different loads like adjustable speed drives, energy-efficient lighting etc are major causers and the major victims of power quality problems. Electronic devices like computers, process control and of equipments are sensitive to the disturbances in power quality. All of these devices and other reacts adversely to power quality problems, depending upon the severity of the problems [5]. The effect of power quality disturbance on equipment can be considered as susceptibility and vulnerability. The equipment is said to be vulnerable if the electric transients exceeds its insulation withstand level. The same phenomenon can be observed in rectifiers also as this device also fails if the transient voltage exceeds to certain level.

Institute of Electrical and Electronics Engineers (IEEE) standard IEEE 1100 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” [1].

2.2 PERSPECTIVES OF POWER QUALITY [5]

Perspectives of power quality are as follows:

- The first perspective concern with the customer’s side is of the electric meter. In this, focus is directly on the power disturbances that effect the equipments severely.
- The second perspective is also concerns with the meter of the customer’s side. In this, the manufacturer should be aware of the level of disturbances in the equipment and their frequencies of occurrences so as to determine the tolerance power of the equipment.
- The third and most important perspective is from the utility side. They are interested in power disturbances of the both sides of 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 [5]

Recently, a lot of focus has been put on improving the power quality problems. The issue of power quality concerns with the utility as well as the consumers. Because of the following reasons power quality is gaining importance day by day, the reasons are as follows:

- The dependency of our society on electric supply has been increasing day by day. Even the small power outage causes the industrial customers to bear heavy economic losses.
- Some 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 POWER QUALITY PROBLEMS & ISSUES [6]

A recent survey on Power Quality done by experts tells that the almost 50% of the power quality problems are related to ground bonds, grounding and neutral to ground voltages, ground loops, ground current or other ground related problems. Some of the symptoms of power quality issues are as follows:

- Failure of equipment during a thunderstorm.
- Misoperation of a piece of equipment.
- Stopping of automated system for no automated reason.

2.5 POWER QUALITY ISSUES [2]

Electromagnetic phenomenon can lead to power quality problems. Power quality problems are shown in voltage, current and frequency disparity that results in end users equipments. Table 2.1 depicts the classification of spectral content, duration and voltage magnitude of Power System Electromagnetic Phenomenon which is subjected for power quality problems. Power Quality issues can be classified as follows:

**Table-2.1: Categories and Characteristics of Electromagnetic Phenomenon in Power Systems as
Defined by IEEE-1159 [2]**

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

	• Interruption		3 sec- 1 min	<0.1 pu
3.	LONG DURATION VOLTAGE DEVIATION			
	i) Overvoltage		>1 min	1.1-1.2 pu
	ii) Under voltage		>1 min	0.8-0.9 pu
	iii) Sustained interruption		>1 min	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	0-6 KHz	Steady state	0-2 %
	iv) Sub harmonics		Steady state	
	v) Notching		Steady state	
	vi) Noise	Broadband	Steady state	0-1 %
5.	VOLTAGE FLUCTUATION	<25 Hz	Intermittent	0.1-7 %
6.	VOLTAGE IMBALANCE		Steady state	0.5-2 %
7.	POWER FREQUENCY VARIATION		<10 sec	

2.5.1 Short-Duration Variation

The Short-duration variation occurs for less than 1 minute. These variations depend upon the location of occurrence of fault and the conditions of system. These variations can lead to voltage sag or voltage drop, voltage swell or voltage rise and interruptions or complete loss of voltage, which are described as follows:

2.5.1.1 Voltage Sag

Voltage sag is also called as voltage dip. It is shown in Figure-2.1. It is defined as decrease of normal voltage level between 10-90 percent of the nominal Root Mean Square (rms) Voltage for duration between 0.5 cycles to 1 minute. The time period for which voltage sag depends on how faster the fault is cleared by the protective devices. The factors that may lead to voltage sag are starting of large induction motor, connection of heavy loads and fault in consumer's installation. It may also lead to malfunctioning of information technology equipments, tripping of contactors and electromechanical relays.

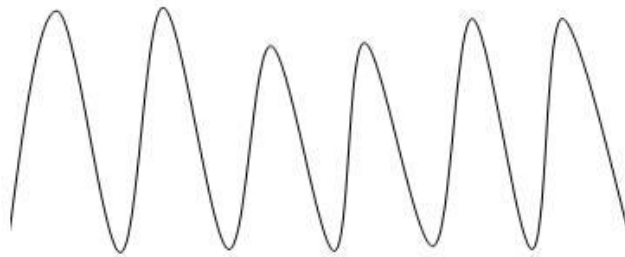


Figure-2.1: Voltage Sag

2.5.1.2 Voltage swell

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

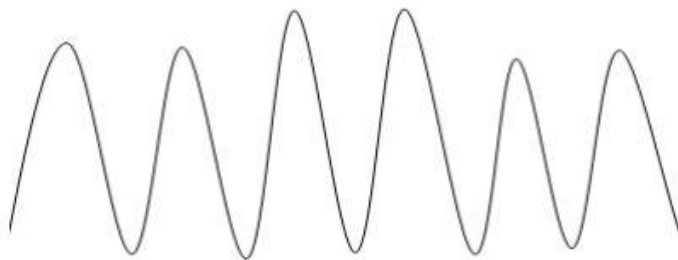


Figure-2.2: Voltage Swell

2.5.1.3 Interruption

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

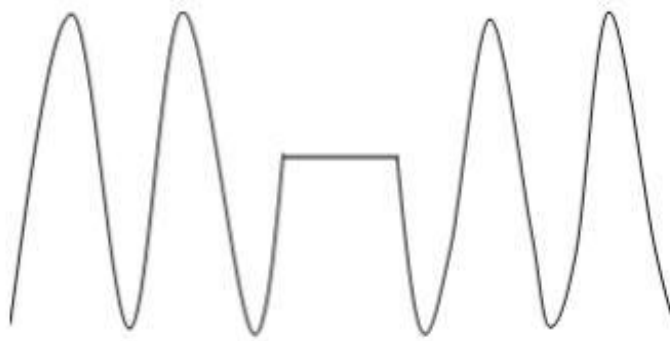


Figure-2.3 Interruptions

2.5.2 Long Duration Variation

These are basically root mean square variations at power frequencies. These variations exist for duration greater than 1 minute. Various types of overvoltage are described below:

2.5.2.1 Overvoltage

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

- Overvoltage is produced by lightning.
- Overvoltage which is produced due to ferroresonance, overcompensation, tap changer transformer, insulation fault etc.
- Overvoltage is produced due to switching operations like opening and closing of protective devices.

2.5.2.2 Undervoltage

It can be defined as a decrease in the rms (root mean square) ac voltage to less than 90 percent at power frequency which lasts for duration greater than 1 minute. Some factors which may lead to undervoltage are load switching or switching off.

2.5.2.3 Sustained Interruption

The long duration voltage variations are 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 a minute is 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. 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:

- Neighbouring facilities
- Switching of capacitor banks
- Error caused by humans
- Tap changing of transformers
- Bad weather conditions
- Loose connection in the distribution system may lead to the problem of arcing
- Operations related to reclosing

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

2.5.3.1 Impulsive Transient

It is defined as a sudden, unidirectional change in the steady state condition of current, voltage or both. It can cause the excitation of the natural frequency of the system. It is depicted in Figure-2.4.

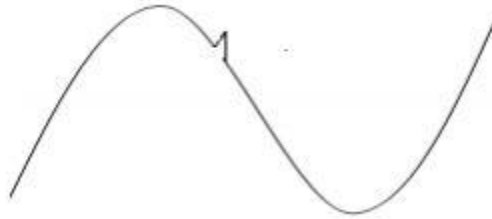


Figure-2.4: Impulsive Transient

2.5.3.2 Oscillatory Transient

It is defined as a sudden, non-power frequency change in the steady state condition of voltage, current or both which has positive and negative polarity values both as it is bidirectional in nature. It 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 the 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 defined as follows:

2.5.5.1 Harmonics

A harmonic can be defined as sinusoidal current or voltage having different frequencies which are whole multiple of the frequency at which power system is defined to operate. This frequency is called as fundamental frequency. In India, it is 50 Hz and in Foreign it is 60 Hz. Figure-2.6 depicts harmonics. Protection from harmonics includes the use of multiple converters, Pulse Width Modulation (PWM) rectifiers and application of passive or active harmonic filters [11]. 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 equipments.

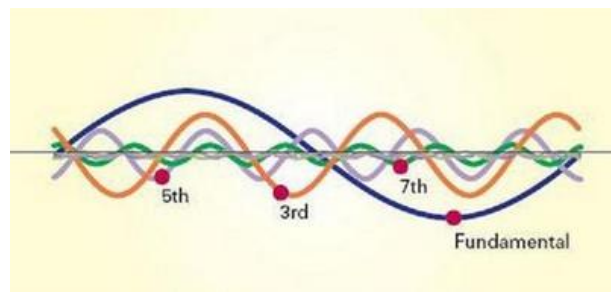


Figure-2.6: Harmonics

Harmonic distortion is measured by obtaining the whole harmonic spectrum. This harmonic spectrum consists of magnitudes and phase angles of each of the harmonic content. It measures the whole harmonic spectrum which consists of phase and magnitude angle of each of the harmonic component present in the signal. It is presented as follows:

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

Where, V_1 = rms magnitude corresponding to the fundamental component.

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

$n = 2, 3, 4, \dots, \infty$.

2.5.5.2 Consequences of harmonics

Some of the consequences of harmonics are as follows:

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

2.5.5.3 Notching

It is a periodic voltage disturbance which is due to the normal operations of power electronic devices when current is changed from one phase to another. It is depicted in Figure-2.7. It is the uncommon case which lies between harmonics and transients. Notching is caused by the converters which generate dc current continuously. It can be prevented by isolating the sensitive equipment from the source that causes power quality problems.



Figure-2.7: Notching

2.5.5.4 Noise

Noise is an unwanted electrical signal with broad band spectral content which is lower than 200 kHz. It may lead to data loss, disturbances in sensitive electronic equipments and error during data processing. The main causes of noise are as follows:

- ✓ Arcing equipments
- ✓ Corona
- ✓ Radiation due to welding machines
- ✓ Power electronic equipments
- ✓ Control circuits
- ✓ Load with solid state rectifiers
- ✓ Electromagnetic interferences

The effect of noise can be mitigated by using filters, line conditioners or transformers. Noise is shown in Figure-2.8.

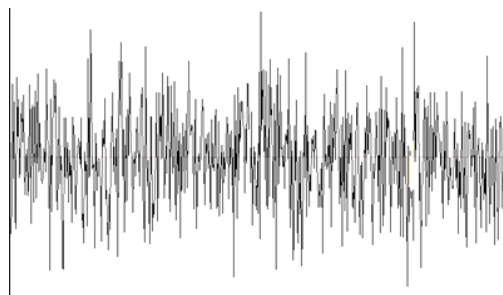


Figure-2.8: Noise

2.5.5.5 DC Offset

It can be defined as the presence of dc voltage or current in an ac power system. Main causes behind dc offset are the operation of electronic switching devices and geomagnetic disturbances. Various effects of dc offset on an alternating network are as follows:

- It may lead to electrolytic erosion of grounding electrodes.
- Even harmonics may also be generated in addition to odd harmonics.
- Lifetime of some equipments like transformers, electromagnetic devices and rotating machines may be reduced.
- **Interharmonics**

Interharmonics are those frequencies which are not the integer multiple of the frequency of supply system (50 or 60 Hz). Spectral components of waveforms are depicted in the Table-2.2 given below.

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 $n=0$
Interharmonic	$f \neq nf_1$ 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 sudden, short surge in voltage. The voltage peak may rise up to 6000 volts. It can be caused by lightning, power outages, tripping of circuit breakers, short circuits etc. It can lead to breakdown of isolation in transformers, loss of data, spurious operation of semiconductor devices and burned circuit boards.

2.5.7 Flicker

Flicker is also called as voltage fluctuation. It is explained as random changes in the voltage envelope which may occur because of sudden changes in the real or reactive power drawn by the load. This is characterized by type of load and the power system capacity. Here, voltage changes have been modulated in the sinusoidal form. The shape of voltage waveform after changes can be rectangular or irregular in nature. The current drawn by the fluctuating load determines the profile of voltage changes. An example of voltage fluctuation is shown in Figure-2.9. Two important parameters for voltage fluctuation are magnitude and frequency of fluctuation. It may lead to lamp flickering, spurious tripping of relays, stalling of induction motors which will operate at maximum load. Some examples of loads that produce voltage fluctuation are as follows:

- ✓ Arc furnaces
- ✓ Arc welders
- ✓ Motor drives which consist of cyclic operations like hoists, rolling mills etc.
- ✓ Device which consist of excessive changes in motor speed like wood chippers, car shredders etc.

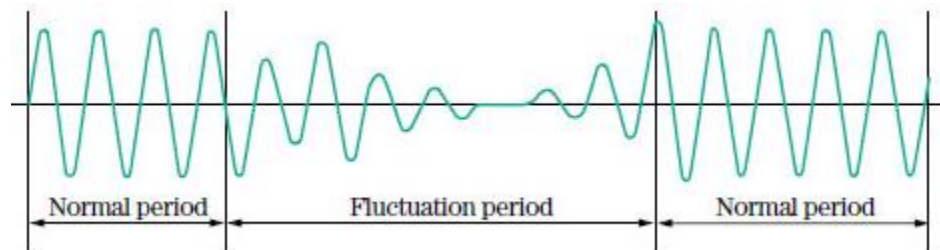


Figure-2.9: Voltage Fluctuations

2.6 SOLUTION TO POWER QUALITY PROBLEMS

The improvement in power quality can be done from consumer side as well as from the utility side. The methods which help in improving power quality are as follows:

- Load conditioning

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

- Line conditioning

In this method, systems are used to overcome or redress the disturbances that occur in the power system. This is achieved by using passive filters which are connected at sensitive load terminals. The series active filters can also be used which acts as controllable voltage source where as the shunt active filters work as a controllable current source.

3.1 INTRODUCTION

Among all power quality issues like voltage sag, voltage swell, interruptions etc, voltage sag is the most severe problem in the distribution network and to atone these problems, custom power devices have been introduced. The most effective and efficient custom power device introduced for distribution network is dynamic voltage restorer (DVR).

DVR is a solid state device connected in series which injects voltage into the system in order to regulate the load side voltage. It is generally installed between supply and the critical load feeder at the PCC (point of common coupling). A DVR can prevent the harmonics of the source side voltage and also provides voltage regulation.

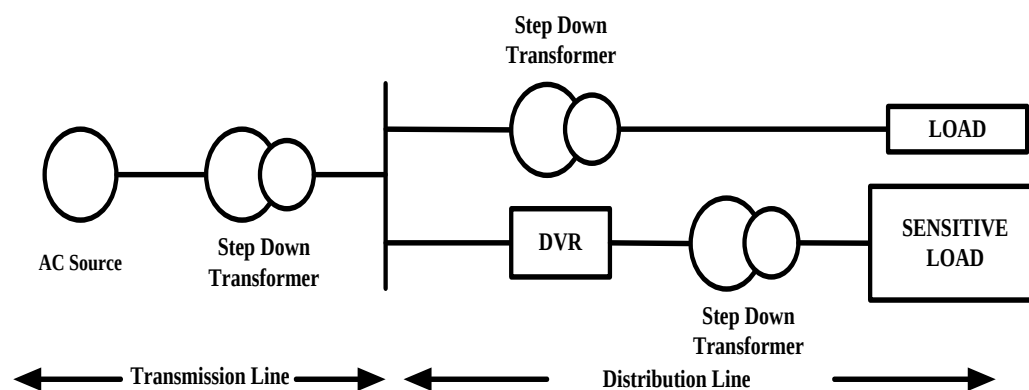


Figure 3.1: Location of DVR

3.2 PRINCIPLE OF DVR OPERATION

A DVR is a power electronic switching device which consists of either GTO or IGBT, capacitor bank as a energy storage device and injecting transformer. It is connected in series between the distribution network and the load which is depicted in Figure 3.2. A DVR injects a controlled voltage which is generated by forced commutated converter in series to the bus voltage by means of an injecting transformer. The sinusoidal pulse width modulation (SPWM) technique helps in regulating the voltage. All

through normal operating modes, the dynamic voltage restorer will inject only a small amount of operating voltage to compensate the voltage drop of injection transformer and the device losses. The dynamic voltage restorer system calculate and synthesize the voltage when voltage sag occurs in the network which is required to compensate the output voltage of the load by injecting controlled voltage within a certain magnitude and phase angle into distribution network to the sensitive load [29].

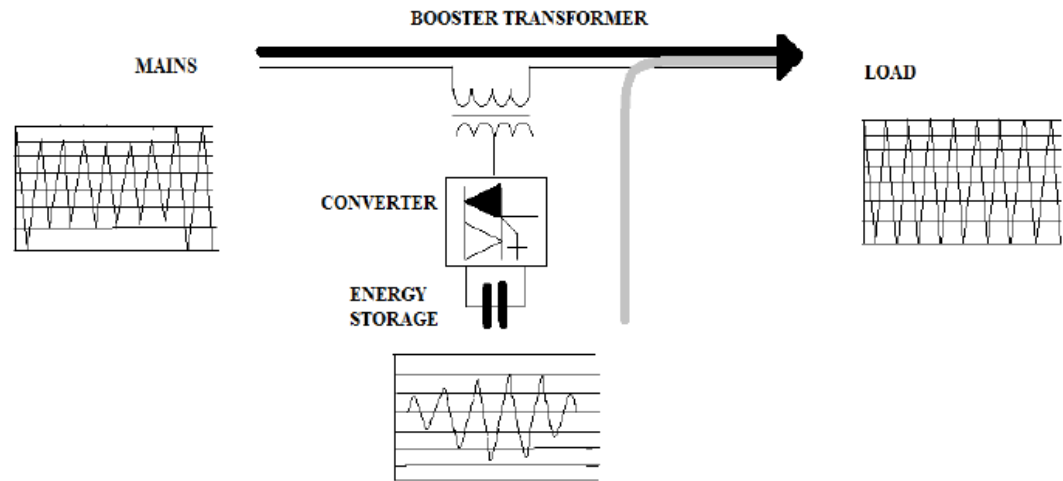


Figure 3.2: Principle of DVR system

Dynamic voltage restorer is capable of generating or absorbing reactive power but the active power injection is done by an external energy source system. The response time is very short and limited by power electronics device. The predictable response time is about 25 ms, which is very less than the traditional methods of voltage correction such as tap-changing transformer [30].

3.3 BASIC ARRANGEMENT OF DVR [29]

The DVR mainly consists of the following components:

- An injection transformer
- DC charging unit
- Storage devices

- Converters
- Harmonic filter
- Control and protection system

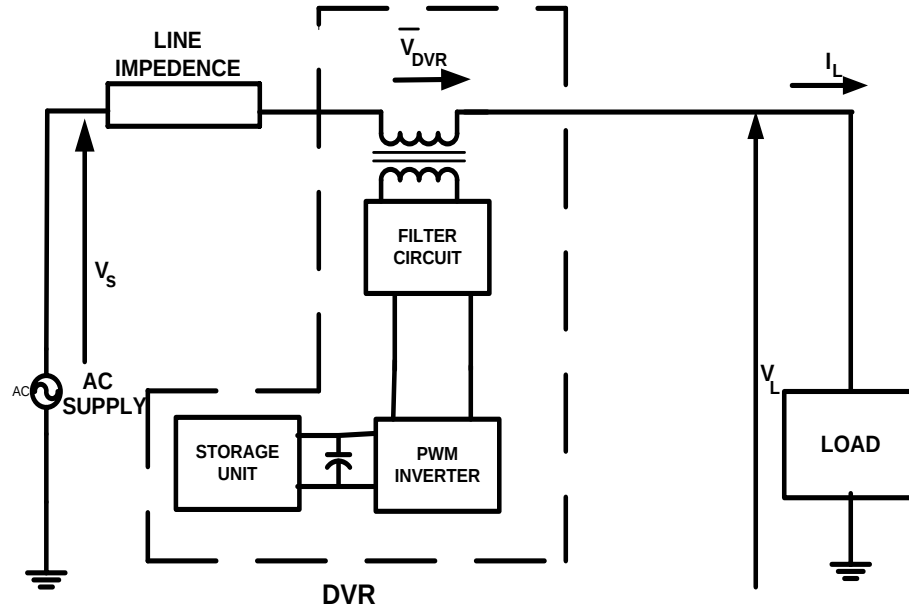


Figure 3.3: Schematic diagram of DVR

3.3.1 Injection Transformer

Three single phase transformers are connected in series with the distribution feeder network to couple the converter circuit with higher distribution level. It connects the dynamic voltage restorer to the distribution network with the help of high voltage winding transformer and couples with the injected compensating voltage which is generated by the converter for the incoming voltage supply. The injection transformer also fulfills the purpose of isolating load from the dynamic voltage restorer system (converter and control mechanism).

3.3.2 DC charging unit

The DC charging unit is used when the energy source is charged again through the direct current charging unit after voltage sag compensation. It is also used to maintain dc link voltage at the nominal voltage.

3.3.3 Converters

(a) Voltage Source Converter

It is a power electronic device consisting of storage device and switching device which can generate a sinusoidal voltage at any required frequency, magnitude and phase angle. It could be a three phase three-wire or three phase four-wire system. A conventional three-level converter is used. The voltage source converter is used to replace or generate the supply voltage which is absent. The storage device is used to supply the required energy to the voltage source converter with the help of a direct current link for the generation of injected voltages [25]. The different types of energy storage devices are like, capacitance, batteries and Superconductive magnetic energy storage (SMES).

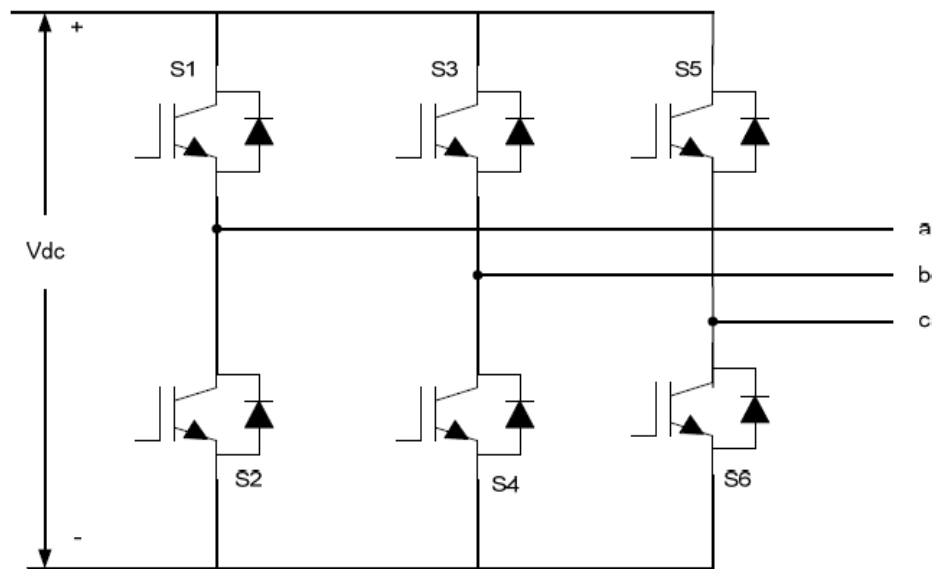


Figure 3.4: Two level switch mode inverter

(b) Z-Source Converter

The main circuit of Z-source inverter is shown in Figure 3.5. The Z-source network consists of diode, two inductors and two capacitors [32]. This impedance network act as a energy filtering element for the inverter. It provides a second order filter

which helps the circuit to reduce current and voltage ripples than the capacitor or inductor alone [33]. The dc voltage boost by Z-source network is changed into alternating current through three leg inverter with high frequency transformer and then finally changed into dc by the welding load. High frequency transformer isolation is lodge to reduce the cost, weight, size and volume of transformer used [35]. A high switching frequency is employed for effective PFC action and quick management of output DC voltage. The switching pairs are switched on alternatively during each half cycle of the switching period. The rectifier diodes at load side act as free-wheeling diodes when both switching pairs are switched off. A small L-C filter is provided at end of diode rectifier for ripple free output DC voltage.

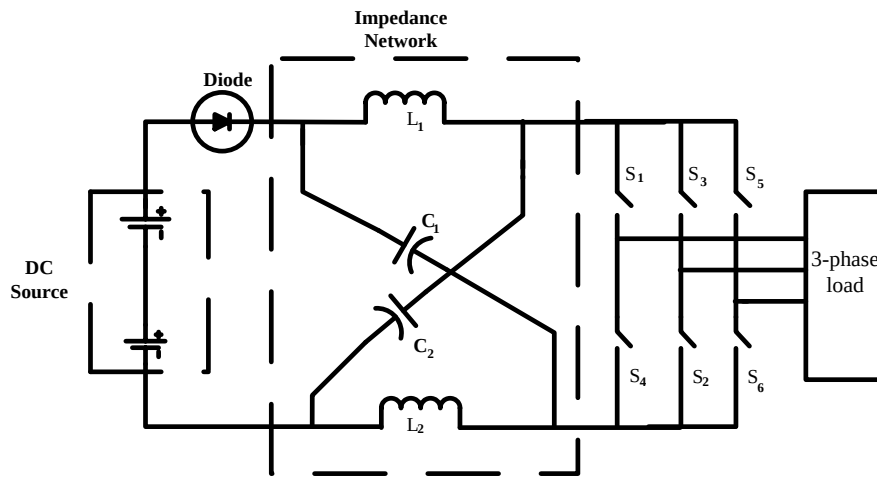


Figure 3.5: Three-Phase Z-Source Inverter

3.3.4 Harmonic Filter

The function of the harmonic filter is to keep the harmonic voltage content at the minimum level.

3.3.5 Control and Protection

A controller is also used for the proper working of dynamic voltage restorer. The load voltage is sensed and then passed through the sequence analyzer. The magnitude of load voltage is compared with the reference voltage. SPWM technique is used for controlling the gate pulses and generating sinusoidal voltage at load terminals. Chopping

frequency is set in the range of few Kilo Hertz. A fixed dc input voltage is given to the inverter and the controlled output voltage is received from the components of inverter. The triangular wave (carrier wave) in pulse width modulation technique fulfills such requirement [26].

3.4 EQUATION RELATED TO DVR

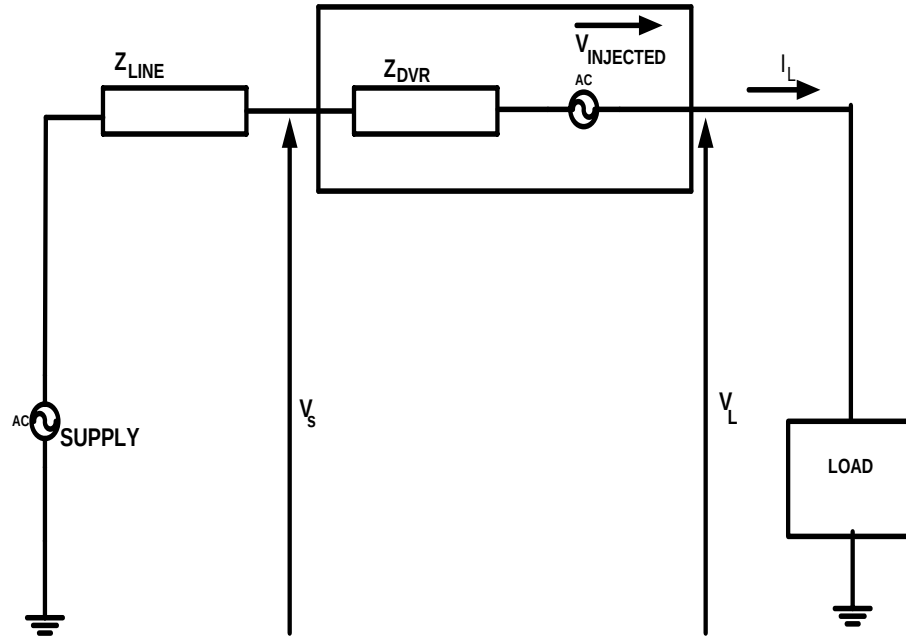


Figure 3.6: Equivalent circuit diagram of DVR

Here, the impedance Z_{LINE} depends on the fault level of the load. When the system voltage drops or reduced from any specific value, the DVR will inject a series voltage which means V_{DVR} maintained a desired load voltage through the injection transformer. Now the injected voltage of DVR can be written as

$$V_{DVR} = V_{LOAD} + Z_{LINE} I_{LOAD} - V_{SOURCE}$$

where

V_{LOAD} = desired load voltage

Z_{LINE} = line impedance

I_{LOAD} = load current

V_{SOURCE} = system voltage during any fault condition

If we take I_{LOAD} as I_L , V_{SOURCE} as V_{th} , V_{LOAD} as V_L , Z_{LINE} as Z_{th} then,

The load current is given by,

$$I_L = [P_L + jQ_L] / V$$

where V_L is considered as a reference equation and can be written as,

$$V_{\text{DVR}} \angle 0 = V_L \angle 0 + Z_{\text{TH}} \angle (\beta - \theta) - V_{\text{TH}} \angle \delta$$

α , β , δ are angles of V_{DVR} , Z_{TH} , V_{TH} respectively and θ is load power angle

$$\theta = \tan^{-1}(Q_L / P_L)$$

The complex power injection of DVR can be written as,

$$S_{\text{DVR}} = V_{\text{DVR}} I_L^*$$

It requires the injection of only reactive power and the DVR itself is capable of generating reactive power.

3.5 OPERATING MODE OF DVR

The dynamic voltage restorer is designed to inject the dynamically controlled voltage i.e. V_{dvr} , which is generated with the help of forced commutated converter. The injection transformer injects the voltage in series to a bus voltage. The momentary three phase amplitude of injected voltages is controlled so that it will remove the harmful effects of bus fault to the load voltage V_L . The DVR has three modes of operations [30] as given below:

- Protection mode
- Stand-by mode
- Injection/boost mode

In protection mode, if current on the load side exceeds a tolerable limit due to any fault or short-circuit on load side then the dynamic voltage restorer will isolate from the system automatically.

In stand-by-mode, the voltage winding on the injection transformer is short circuited through the converter.

In injection/boost mode, the dynamic voltage restorer injects a compensating voltage through the injection transformer due to disturbance in the supply voltage.

3.6 VOLTAGE INJECTION METHODS

Voltage injection or compensation methods by means of a DVR depend upon the limiting factors such as:

- Power rating of DVR
- Various conditions of load
- Different type of voltage sags

Some loads are sensitive towards phase angle jump and change in magnitude and some are tolerant to these. Therefore, the control strategies depend upon the type of load characteristics. There are four different methods of dynamic voltage restorer voltage injection which are as follows:

- Pre-sag compensation method
- In-phase compensation method
- In-phase advanced compensation method
- Voltage tolerance method with minimum energy injection

3.6.1 Pre-sag/Dip compensation method

The pre-sag method follows the voltage supply continuously and if it detects any problem then it will inject the different voltage between the voltage at point of common coupling (PCC) or sag and pre-fault condition, to restore the load voltage back into the pre-fault condition. The injected active power cannot be controlled and is determined by external means like different type of faults and load conditions.

$$V_{DVR} = V_{prefault} - V_{sag}$$

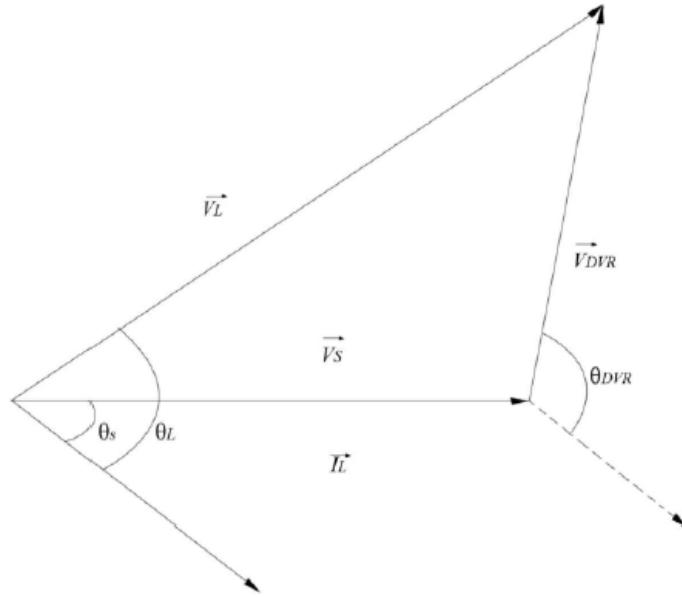


Figure 3.7: Pre-Sag Compensation

3.6.2 In-phase Compensation method

In this technique; the injected voltage is in phase with the supply voltage irrespective of the load current and pre-fault voltage. The phase angles of the pre-sag and load voltage are different but the most important standard for power quality is that the constant magnitude of load voltage must be satisfied. The advantage of this method is that the amplitude of dynamic voltage restorer injection voltage is minimum for the certain voltage sag in comparison of the other strategies.

3.6.3 In-phase Advance Compensation method

In this method, the real power spent by the dynamic voltage restorer is decreased by minimizing the power angle between the voltage sag and the load current. One of the most costly parts of dynamic voltage restorer is that the active power supplied is limited by stored energy in the DC links. The minimum injected energy is achieved by making the active power component zero and making the injection voltage phasor perpendicular to the load current phasor. In this method, the values of load current and the voltage are fixed in the system so it can change only the phase of the voltage sag. IPAC method uses only reactive power and unfortunately, real power cannot remove all voltage sag.

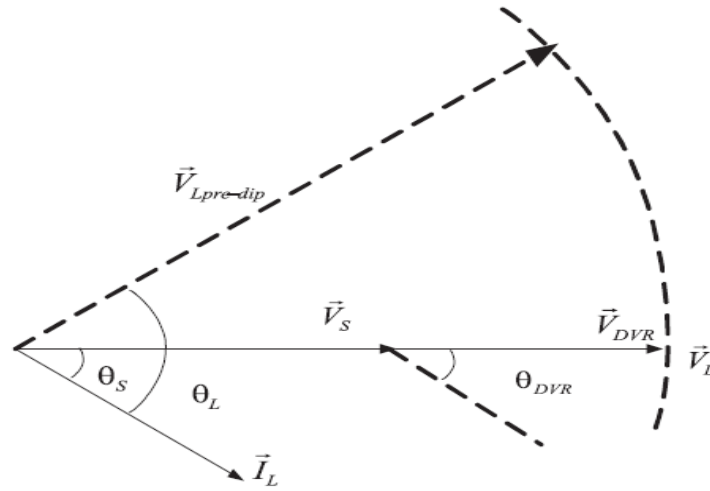


Figure 3.8: In-phase Compensation

3.6.4 Voltage Tolerance Method With Minimum Energy Injection

The injected voltage is in quadrature with the load current in this injection method because of which the power requirements of dynamic voltage restorer are zero, neglecting all losses. Minimum energy compensation strategy control the active power exchange between dynamic voltage restorer and the external means. The compensation capability of dynamic voltage restorer could be maintained by controlling the strategy not only when the injection voltage is under the voltage limitation. The control parameters are phase and magnitude which can be achieved with the help of small energy injection.

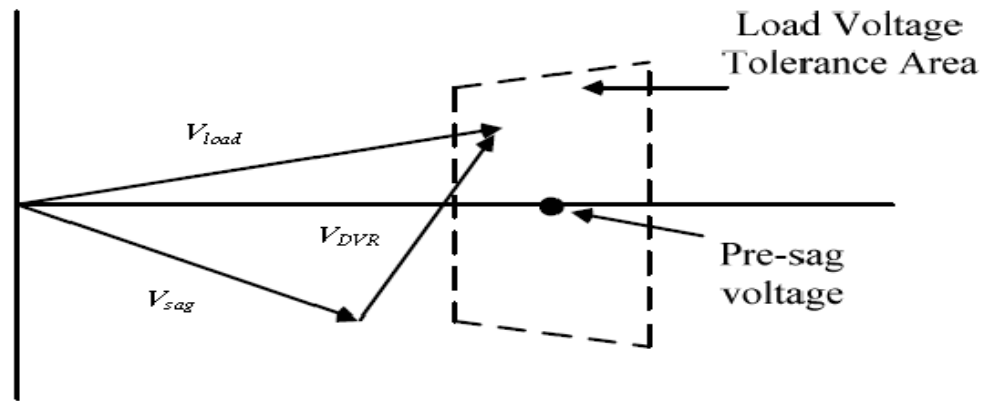


Figure 3.9: Voltage Tolerance Method with Minimum Energy Injection

3.7 CONTROL TECHNIQUES:

3.7.1 Linear controllers

The three main voltage controllers are Feed forward (open loop), Feedback (closed loop) and Multi-loop controller. The first choice for the dynamic voltage restorer is feed-forward voltage controller because it is simple and fast in nature. The supply voltage is continuously monitored and compared with the reference voltage and if the difference exceeds a certain value, the dynamic voltage restorer will inject the required voltage into the system. The drawback of the open loop controller is the high steady state error. In the feedback control, the load voltage is measured and compared with the reference voltage; the missing voltage is then supplied by the dynamic voltage restorer at the supply bus [6]. Multi-loop control is used with an outer voltage loop to control the dynamic voltage restorer voltage and an inner loop to control the load current. This method has the strength of feed-forward and feedback control strategies, on the expense of complexity and time delay.

3.7.2 Non-linear controllers

It suggest that the nonlinear controller is more suitable than the linear type since the dynamic voltage restorer is a non-linear system due to the presence of power semiconductor switches in the inverter bridge. The most non-linear controllers are the Artificial Neural Networks, Fuzzy Logic and SVPWM. The ANN has inherent learning capability that can give improved precision by interpolation. Fuzzy Logic controllers are the safest choice when precise mathematical formulations are not possible. When a Fuzzy Logic controller is used, transient overshoots of pulse width modulation can be reduced. Space Vector PWM control is used to inherent a space vector of the inverter voltage to get better performance in low switching frequency conditions.

ARC WELDING POWER SOURCES

4.1 INTRODUCTION

Many power sources are required to meet the electrical requirement of different arc welding processes. The arc welding sources include shielded metal arc (SMAW), gas metal arc (GMAW), flux cored arc (FCAW), gas tungsten arc (GTAW), submerged arc (SAW), electoslag (ESW), electrogas (EGW), plasma arc (PAW) and arc stud (ASW) welding. These power sources involve configurations which are either manually or automatically controlled. The steps for the process includes as follows:

- To determine the electrical requirements of the welding process
- Other factors include future requirements, maintenance, economic considerations, environment, available skills, safety, manufacturer's support, and standardization

The voltage supplied for industrial purposes to use directly in the arc welding by power companies is too high. Therefore, the purpose of arc welding power sources is to reduce the high input voltage to limit it into the output voltage range in 20 to 80 volts. A transformer, solid-state inverter and a motor-generator can be used to reduce the 120, 240, or 480 V utility power to the rated terminal voltage appropriate for arc welding process. The transformer or motor generator also provides a high welding current, generally ranging from 30 to 1500 amperes (A). The typical output of a power source may be ac, dc or both. It may also include the pulsing output mode. Some power source configurations deliver only certain type of current like transformer type power sources will deliver only alternating current. Transformer rectifier power sources may deliver either ac or dc. Power sources can be classified by subcategories such as a GTAW (gas tungsten arc welding) power source might be identified as transformer-rectifier, constant current, ac/dc. Special features included are as following:

- remote control
- high frequency stabilization
- current pulsing capability

- starting and finishing current versus time programming
- wave balancing capabilities
- line voltage compensation

4.2 PRINCIPLE OF OPERATION

Arc welding includes low voltage and high current arcs between an electrode and the work piece. The means of reducing power voltage may either be the transformer or an electric generator or an alternator driven by an electric motor. Electric generators built for arc welding usually designed for direct current welding only. Unlike generators, alternators will also provide alternating current output which must be rectified to get a direct current output. They may use a separate exciter which may either be differential or cumulative compounding for controlling and selecting volt-ampere output characteristics.

4.2.1 WELDING TRANSFORMER

Figure 4.1 depicts the basic elements of a welding transformer and its related components. For a transformer, the remarkable relationships between winding turns, input and output voltages and currents are as follows:

$$N_1 / N_2 = E_1 / E_2 = I_2 / I_1$$

where

N_1 = number of turns on the primary winding of the transformer

N_2 = number of turns on the secondary winding

E_1 = input voltage

E_2 = output voltage

I_1 = input current

I_2 = output {load} current.

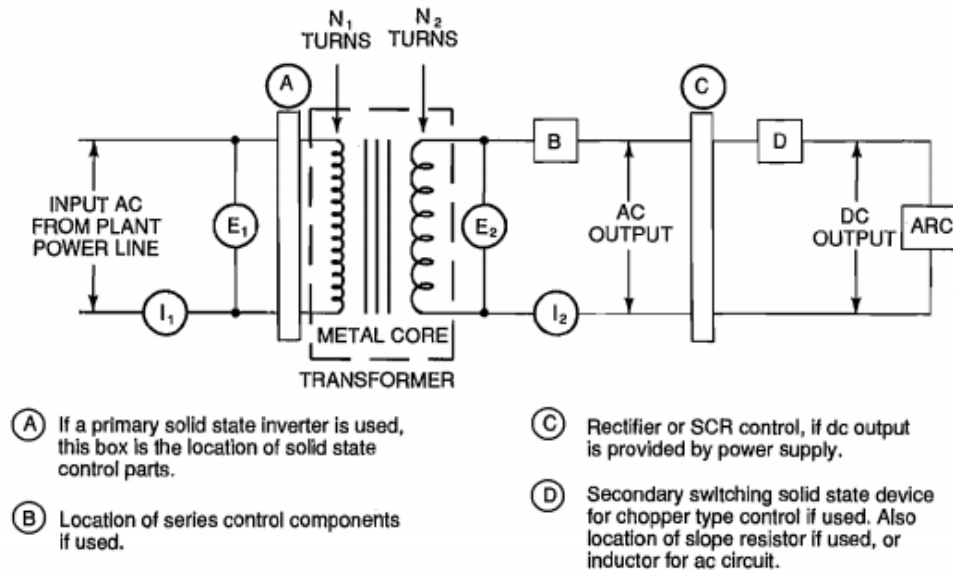


Figure 4.1: Principle Electrical Elements of a Transformer Power Supply

Tapping of secondary winding is used to change the number of turns in the secondary, as depicted in Figure 4.2, to change the no-load output voltage. In this case, the tapped transformer allows the CC or CV machine that provides both constant current and constant voltage.

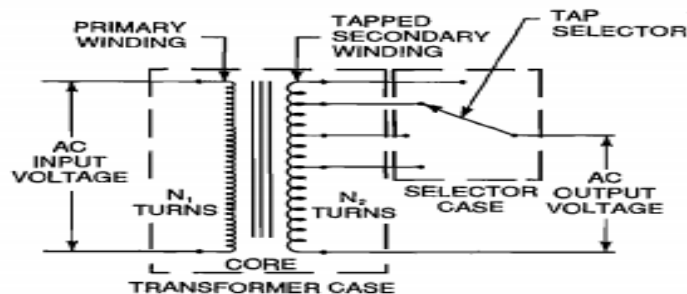


Figure 4.2: Welding Transformer with Tapped Secondary Winding

As shown below, the primary to secondary current ratio is inversely proportional to the voltage ratio. Thus, a large number of secondary currents can be obtained from low line currents. Moreover, an impedance source is added in series with the secondary windings of transformer to provide the characteristic, as shown in Figure 4.3. In CC power supplies, the voltage drop, E_x , across the impedance increases as the load current

increases. The increase in voltage drop, E_x , results in a large reduction in the arc voltage, E_A . This is called current control or slope control. In CV power sources, the output voltage is very close to the required arc voltage. The increase in load current causes a drop in voltage E_x , across the impedance. The load voltage is reduced by a small amount.

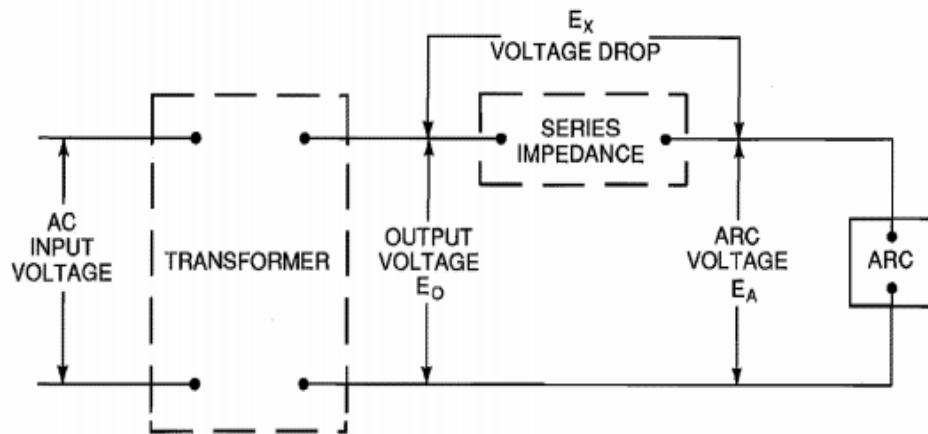


Figure 4.3: Series Impedance Control of Output Current

4.2.2 SOLID-STATE INVERTER

The primary contributors to weight or mass in any power source are the main transformer and filter inductor. Various attempts have been made to reduce their weight and size like the substitution of aluminum windings for copper. The use of an inverter circuit can produce reduction in size and weight as well as decrease the electrical losses. An inverter-based power source has following advantages:

- It is compact and its size is small.
- It requires less electricity as compared to other welding power sources.
- Also, it offers a faster response time.

An inverter circuit uses silicon controlled rectifier (SCR) or transistors to convert direct current into alternating current with frequency in the range of 1 kHz to 50 kHz. The output power of inverter circuits is based on the principle of TRC. The solid-state devices in the inverter act as switches with two states, i.e., on and off. This operation is known as switch mode operation. TRC is the regulation of the no. of times of fluctuation of the two states of the switches to control the output supply. When the switch is on, the

output voltage (V_{out}) is equal to the input voltage (V_{in}). $V_{out} = 0$ when the switch is off. The average value of V_{out} is as follows:

$$V_{out} = t_{on} \cdot V_{in} + 0 \cdot t_{off} / (t_{on} + t_{off})$$

Thus,

$$V_{out} = V_{in} \cdot (t_{on}/t_p)$$

where

t_{on} = on time (conducting)

t_{off} = off time (blocking)

$t_p = t_{on} + t_{off}$ or time of 1 cycle

V_{out} is controlled by regulating the time ratio t_{on}/t_p . Since the on/off cycle is repeated for every t_p interval, the frequency (f) of the on/ off cycles is defined as:

$$f = 1/t_p$$

Thus, the TRC formula can now be written as:

$$V_{out} = V_{in} \cdot t_{on} \cdot f$$

The time ratio control formula defines the two methods of controlling an inverter welding power source. By varying t_{on} , the inverter uses pulse-width modulated time ratio control. Figure 4.4 is a block diagram of an inverter used for dc welding. Incoming three-phase or single-phase 50/60 Hertz power is converted to dc by using the full wave rectifier. This dc is applied to the inverter which is directly used by semiconductor switches and changes it into high-frequency square wave ac. The inverter produces sine waves with the frequency modulation control in a resonant technology. Faster response time is related with the high switching and control frequencies which will result in more stable arcs. Inverter is used to get enhanced performance for alternating current welding power sources. Another application is direct current, CC power sources which is used for cutting the plasma.

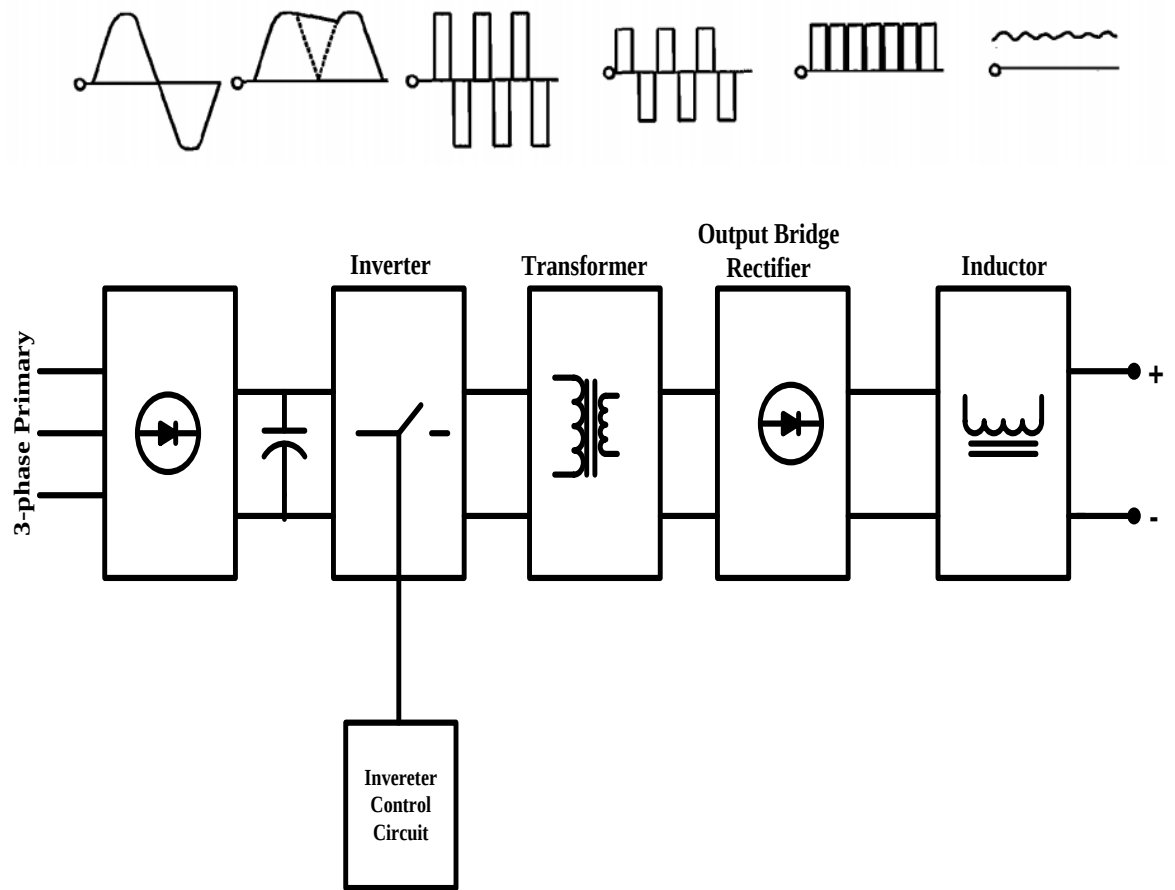


Figure 4.4: Inverter Diagram Showing Power Supply Section and Voltage Waveform

4.3 MATHEMATICAL MODEL OF WELDING LOAD [42]

Figure 4.5 shows a schematic diagram of the gas tungsten arc welding process. The flow of welding current from base metal to tungsten electrode causes the self-induced magnetic field and plasma arc forces. A plasma arc force acts as a distributed source of heat and the electric current. This provides an incident flux of current and thermal energy at the free surface of the weld pool. Mathematical model for weld pool has been developed to confirm the effect of alternate supply of shielding gas in the gas tungsten arc welding. In modeling system, the following assumptions were made such as:

- (1) The welding arc and weld pool model was axial symmetric
- (2) The arc plasma was in local thermodynamic equilibrium
- (3) Gas and metal liquid were incompressible

- (4) Arc plasma fluid was laminar
- (5) Surface of the weld pool is flat
- (6) Physical properties are constant except the thermal conductivity, the specific heat and the density in the buoyancy
- (7) The heat and current density distributions were obtained by the simulated results, which were calculated under the assumption of a steady state welding arc

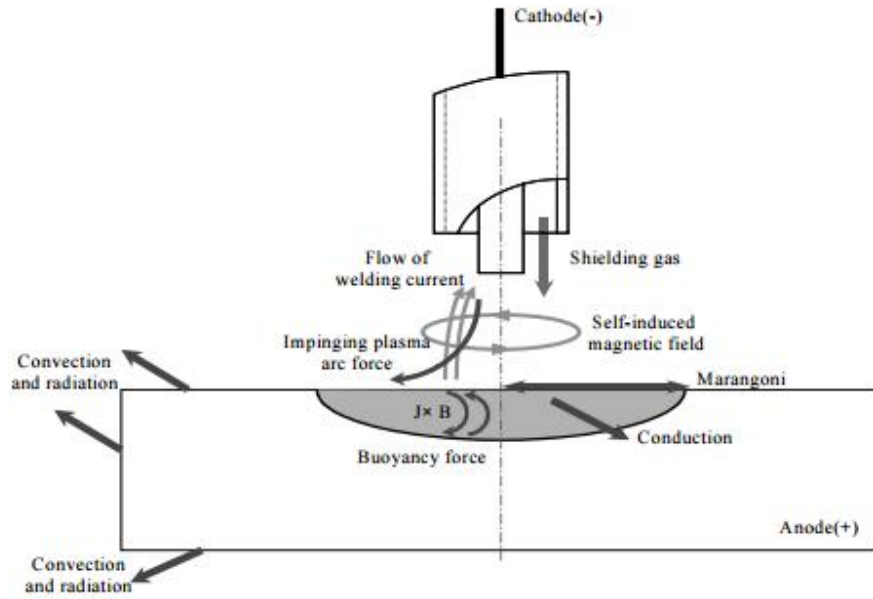


Figure 4.5: A Schematic Diagram of GTA Welding Process

The mass continuity equation is represented as:

$$\frac{1}{r} \frac{\partial}{\partial r} (r u) + \frac{\partial}{\partial z} (w) = 0 \quad (1)$$

The radial momentum equation is presented as:

$$\begin{aligned} \frac{\partial}{\partial t} (\rho u) + u \frac{\partial}{\partial r} (\rho u) + w \frac{\partial}{\partial z} (\rho u) = \frac{2}{r} \frac{\partial}{\partial r} (\mu r \frac{\partial u}{\partial r}) \\ + \frac{\partial}{\partial z} [u \{ (\rho w \frac{\partial u}{\partial r}) + (\rho u \frac{\partial w}{\partial z}) \}] - \frac{\partial p}{\partial r} - 2 \mu \frac{u}{r^2} - j_z B_0 \end{aligned} \quad (2)$$

The axial momentum equation is described as:

$$\begin{aligned} \frac{\partial}{\partial t} (\rho w) + u \frac{\partial}{\partial r} (\rho w) + w \frac{\partial}{\partial z} (\rho w) = 2 \frac{\partial}{\partial z} (\mu \frac{\partial w}{\partial z}) + \\ \frac{1}{r} \frac{\partial}{\partial r} [r u \{ \rho u \frac{\partial w}{\partial z} + \rho w \frac{\partial u}{\partial r} \}] - \frac{\partial p}{\partial z} - j_z B_0 \end{aligned} \quad (3)$$

The momentum equations consist of the transient term, two convective terms, pressure gradient term, the diffusive term and the Lorentz force term.

The energy equation can be expressed as:

$$\frac{\partial}{\partial t}(\rho C_p t) + u/r * (\frac{\partial}{\partial r}) * (\rho C_p r t) + w * \frac{\partial}{\partial z}(\rho C_p t) = \frac{\partial}{\partial z}(k * \frac{\partial T}{\partial z}) + 1/r * \frac{\partial}{\partial r}[kr(\frac{\partial T}{\partial r})] - \Delta H/C_p * \frac{\partial f_L}{\partial t} \quad (4)$$

The current continuity equation obtained from the definition of electric potential presented as:

$$1/r * (\frac{\partial}{\partial r})(\sigma r * (\frac{\partial \phi}{\partial r})) + (\frac{\partial}{\partial z})(\sigma * \frac{\partial \phi}{\partial z}) = 0 \quad (5)$$

The latent term is added to the conservation of thermal energy is can be expressed as:

$$\begin{aligned} f_L &= 1 && \text{at } T > T_L \\ f_L &= (T - T_s)/(T_L - T_s) && \text{at } T_s \leq T \leq T_L \\ f_L &= 0 && \text{at } T < T_s \end{aligned} \quad (6)$$

Surface tension force means the flow of liquid from a lower to a higher surface tension. At the surface of weld, the surface tension variation with temperature must be balanced by fluid shear stress. Therefore, the shear stress at the surface is equated to the gradient of surface tension. At the free surface, the shear stress due to the surface tension driven flow is included as a boundary condition for the momentum equation.

$$\mu * (\partial V_s / \partial z) = \partial \gamma / \partial T * (\partial T / \partial s) \quad (7)$$

where,

ρ = Density (kg/m³)

μ = Effective viscosity (kg/m·s)

σ = Electrical conductivity (1/Ωm)

ϵ = Emissivity of body surface

R = Gas constant (J/kg·mole·K)

ΔH = Latent heat of fusion (J/kg)

T_L = Liquid temperature (K)

T_s = Solid temperature (K)

μ_0 = Magnetic permeability of vacuum (H/m)

Φ = Axial and radial velocity, temperature, pressure

MATLAB BASED SIMULATION AND RESULTS

5.1 SIMULATION RESULTS

To demonstrate the performance of VSI and ZSI inverter based welding power supply, its model is developed in MATLAB environment along with SIMULINK and power system block set (PSB) toolboxes. The block diagrams of VSI and ZSI based DVR for improving power quality in a distribution network with welding load are depicted in Figure 5.1 and Figure 5.2, respectively. This configuration is accomplished in continuous conduction mode based on power factor correction technique which results in unity power factor and THD calculated is of low value of AC main current.

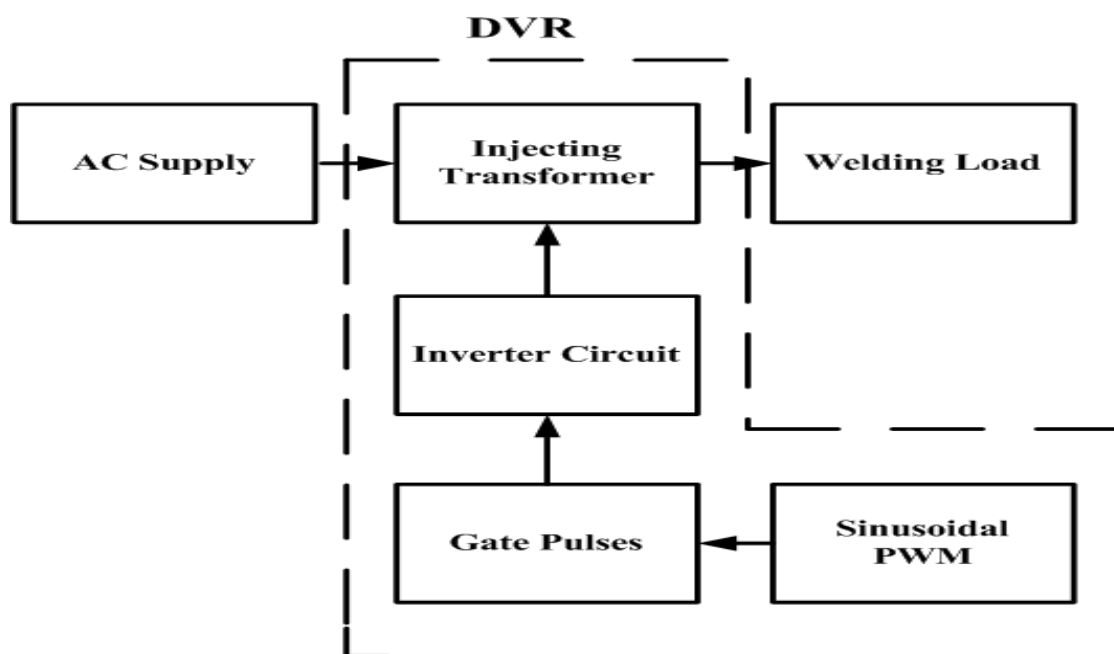


Figure 5.1: Block Diagram of VSI based DVR for welding load

The DC-DC converter plays an important role in removing current and voltage stresses in power switches when compared with single phase modules. The ZSI has a feature that it can operate under short circuit conditions also. The voltage regulation is maintained under various load variations of power supply. Based on the design specifications obtained above, simulated results are shown in Figure 5.5 & Figure 5.8.

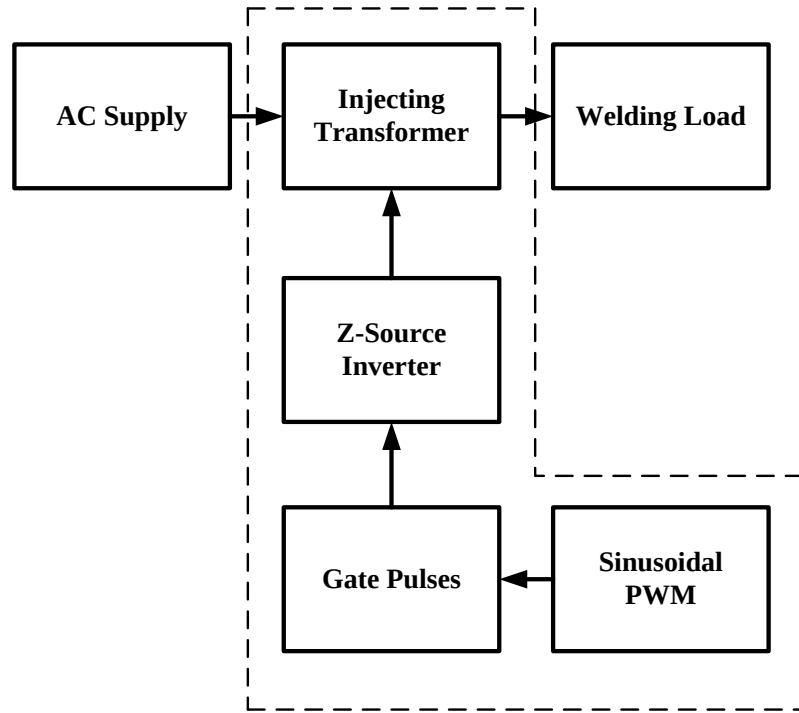


Figure 5.2: Block Diagram of ZSI for Welding Power Supply

Table 5.1: CIRCUIT SPECIFICATIONS FOR WELDING POWER SUPPLY

QUANTITY	VSI	ZSI
Input voltage (V_{rms}) @ 50 Hz	415V	415V
Inductor of Z-source inverter	-	5.8H
Capacitor of Z- source inverter	-	5.5mF
Carrier frequency	2KHz	2KHz
Value of filter, L	15 μ H	15 μ H
Value of filter, C	10F	10F

5.2 MODULATION METHODS

A number of pulse width modulation techniques are used to obtain variable voltage and frequency supply. The most widely used PWM technique used for Voltage Source inverter is carrier based sinusoidal pulse width modulation in which we compare two signals, sinusoidal wave and triangular wave with relational operator. A fixed dc input voltage is given to the inverter and controlled output voltage is obtained by switching on and off the components of inverter. The triangular wave (carrier wave) in PWM technique fulfills such requirement that it defines the on and off states by comparing modulating signal with the triangular waveform.

The Z-source utilizes shoot-through zero state to boost the dc voltage and output voltage is greater than the original dc voltage. But this will not affect the PWM of the inverter because it also produces same zero voltage at load terminals. For achieving high output voltage it is required to increase the shoot through duty ratio. Three sinusoidal reference signals and one triangular wave are compared to get firing pulses with shoot through state. The reference signals are displaced by 120° . When the carrier wave is greater than the upper envelope, or lower than the bottom envelope, the circuit turns into shoot-through state.

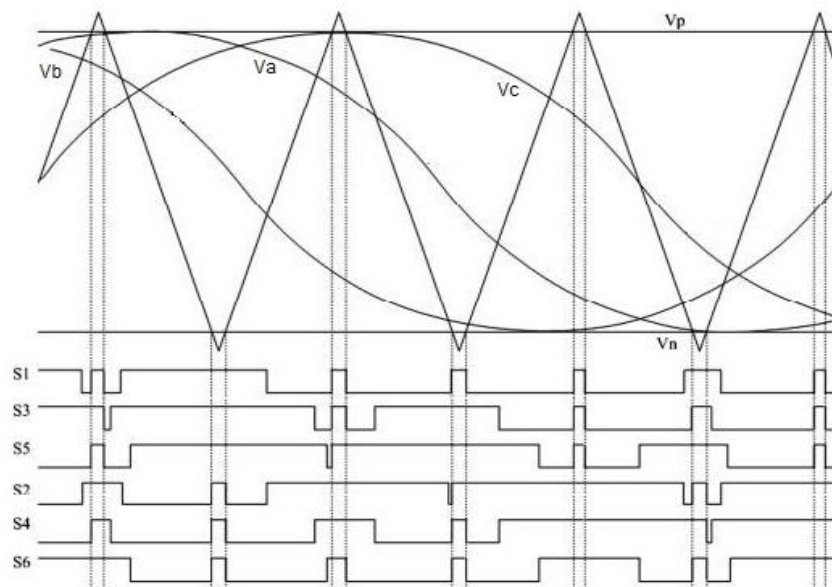


Figure 5.3: PWM Principle

5.3 RESULTS AND DISCUSSIONS

Simulation results of proposed welding power supply for VSI and ZSI are presented in this section. The simulated waveform of voltage source inverter and Z-source inverter at continuous conduction mode shown in Figure 5.5 and Figure 5.8, respectively. These figures shows the performance of welding power supply in terms of voltage and current waveforms along with the total harmonic distortion spectrum at 100% load.

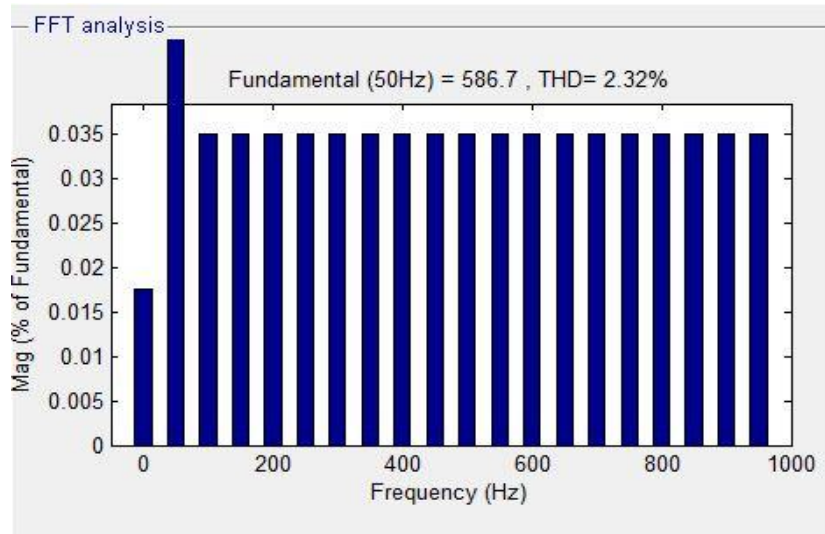


Figure 5.4: Harmonic Spectrum of Input AC Mains Voltage For VSI at Full Load Condition

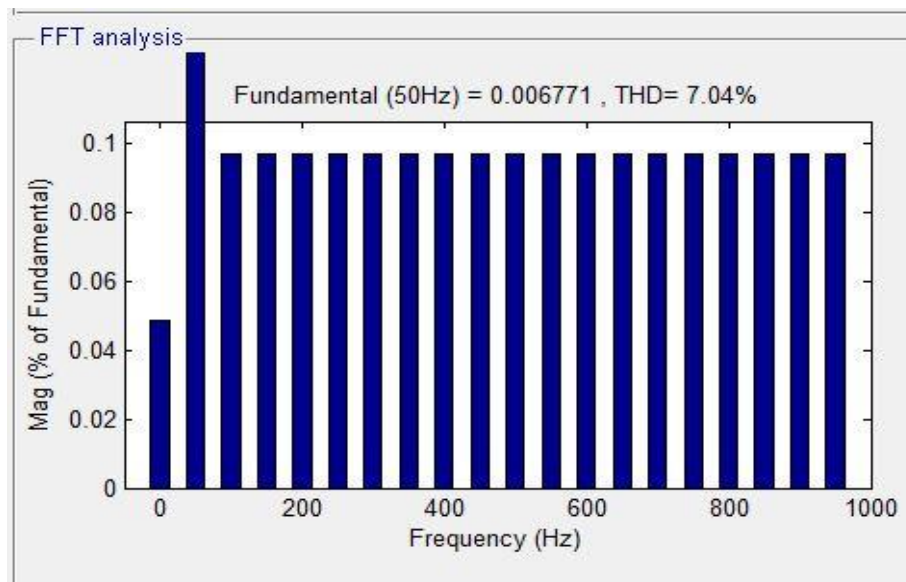


Figure 5.5: Harmonic Spectrum of Input AC Mains Current for VSI at Full Load Condition

It can be observed that the value of THD calculated for voltage and current is 2.32% and 7.04% respectively for voltage source inverter. Here the dc voltage is limited, we need an additional dc-dc boost converter which will increase the cost of the system and lowers the efficiency. Voltage source inverter is vulnerable to EMI noise. The output is limited either small or greater than the value of input voltage.

The modelling is done for Z-source inverter also and it can be observed from the simulation that the THD value for ac main current and voltage is 0% which shows that all the harmonics are eliminated at input side only which is very useful for high power applications. This is best suited for welding power supply as we can change the input voltage widely, output voltage can be any value between zero to infinity regardless of input voltage.

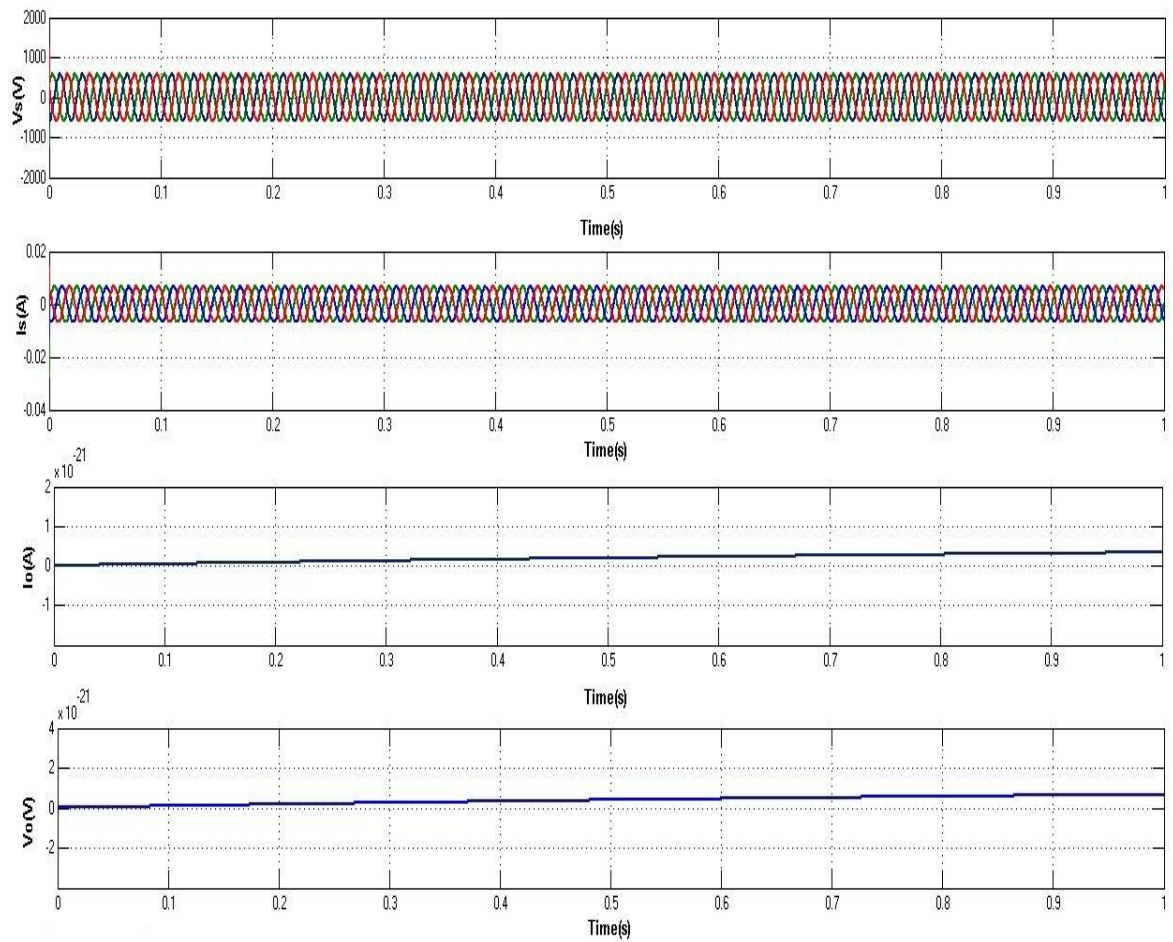


Figure 5.6: Performance of Proposed Welding Power Supply at 415 V AC Mains for VSI

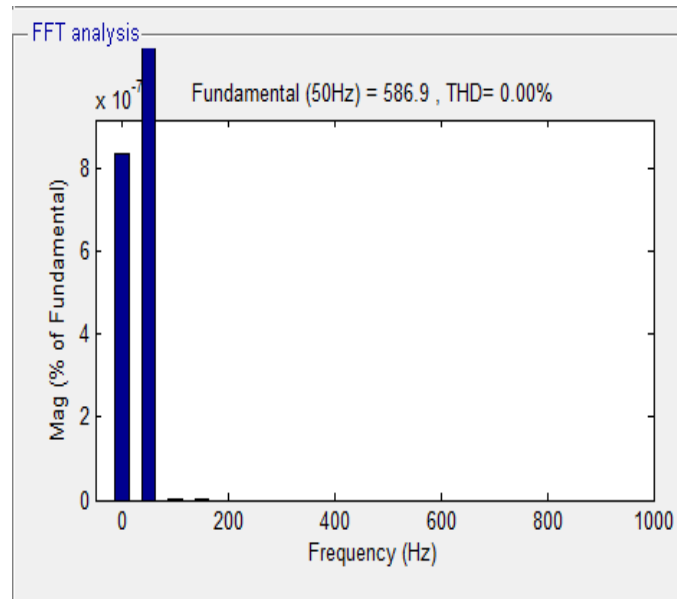


Figure 5.7: Harmonic Spectrum of Input AC Mains Voltage for ZSI at Full Load Condition

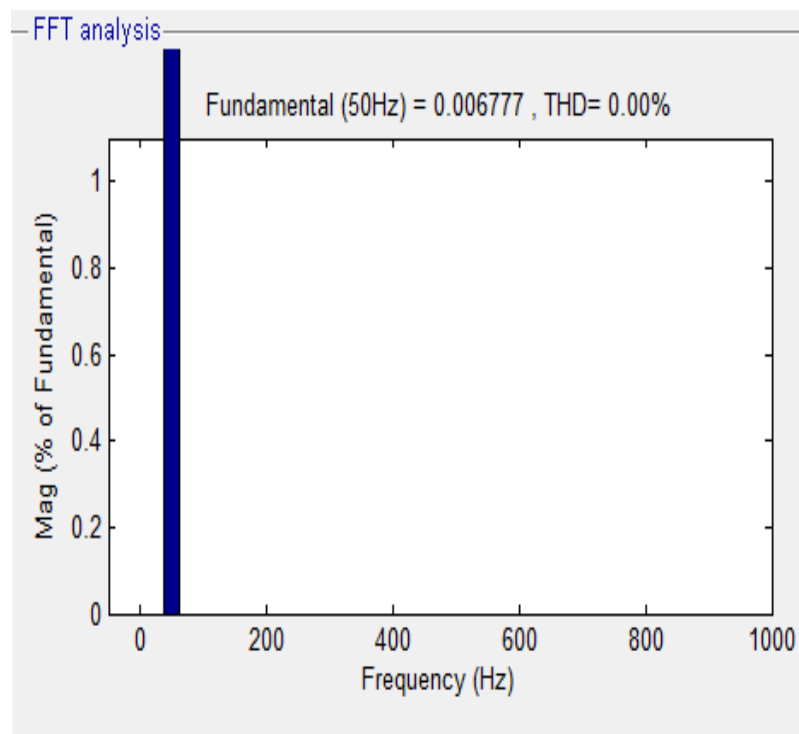


Figure 5.8: Harmonic spectrum of Input AC Mains Current for ZSI at Full Load Condition

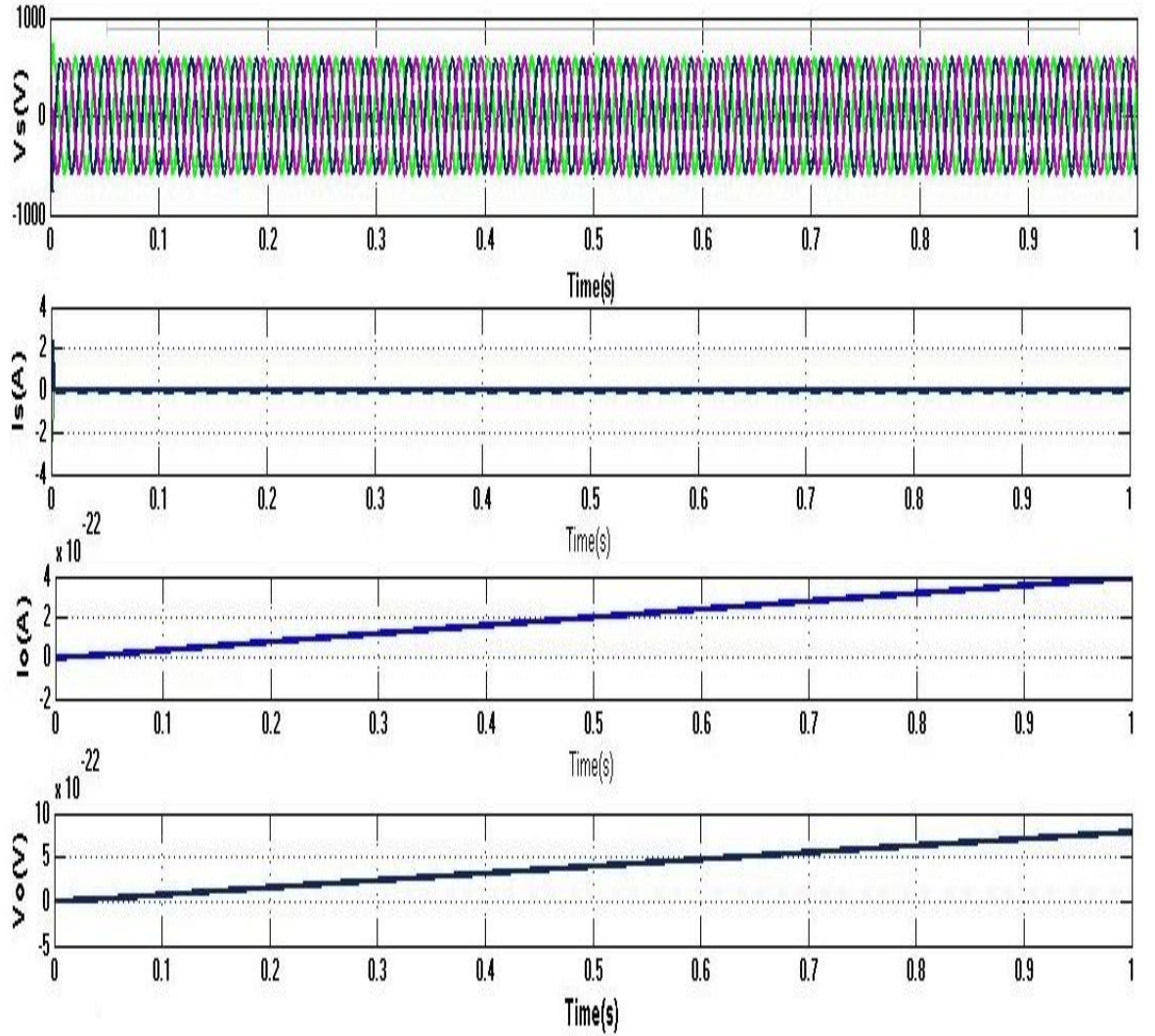


Figure 5.9: Performance of of Proposed Welding Power Supply at 415 V AC Mains for ZSI

Simulation results for proposed welding supply containing voltage sag, voltage swell and THD is discussed in this section. The voltage sag and swell is introduced by the programmable voltage source at the source side which initiates at 0.5 second and remains until 0.75 seconds and it can be observed that with the help of DVR all sag is removed and constant output current (I_o) and output voltage (V_o) is obtained at load side as shown in Fig 5.10 which is the basic requirement of welding.

A) Voltage Sags

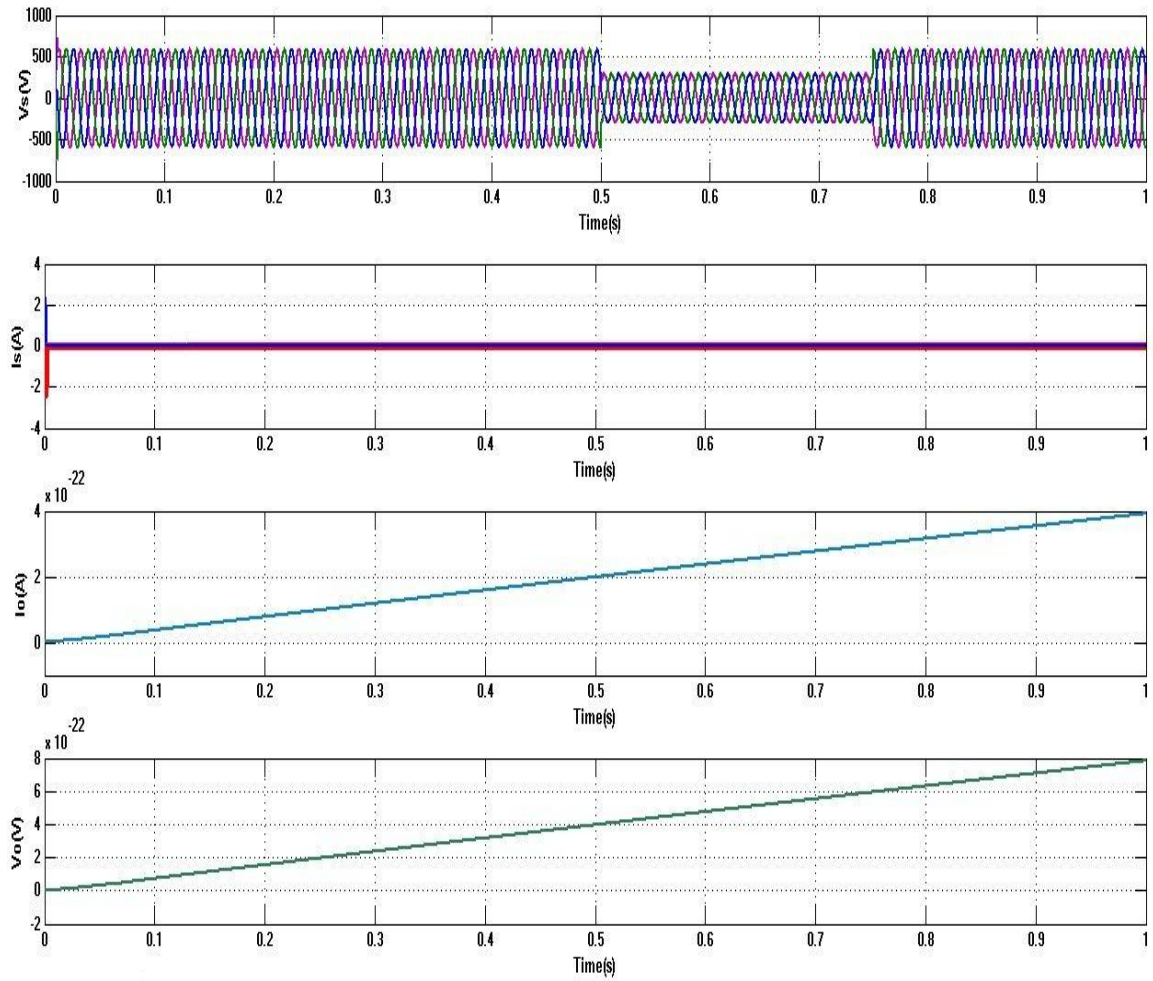


Fig 5.10: Performance of Proposed Welding Power Supply at 415 V AC Mains to Mitigate Voltage Sag with 0.5 magnitude

B) Voltage Swells

The voltage swells may not cause an overvoltage at the dc link. The voltage swell characteristics and the loading conditions are the main issues that determine the energy transfer status from the grid to the DVR. Two cases of measured voltage swells are presented here. As the measured voltage swells are not relatively large, they have not influenced the dc voltage.

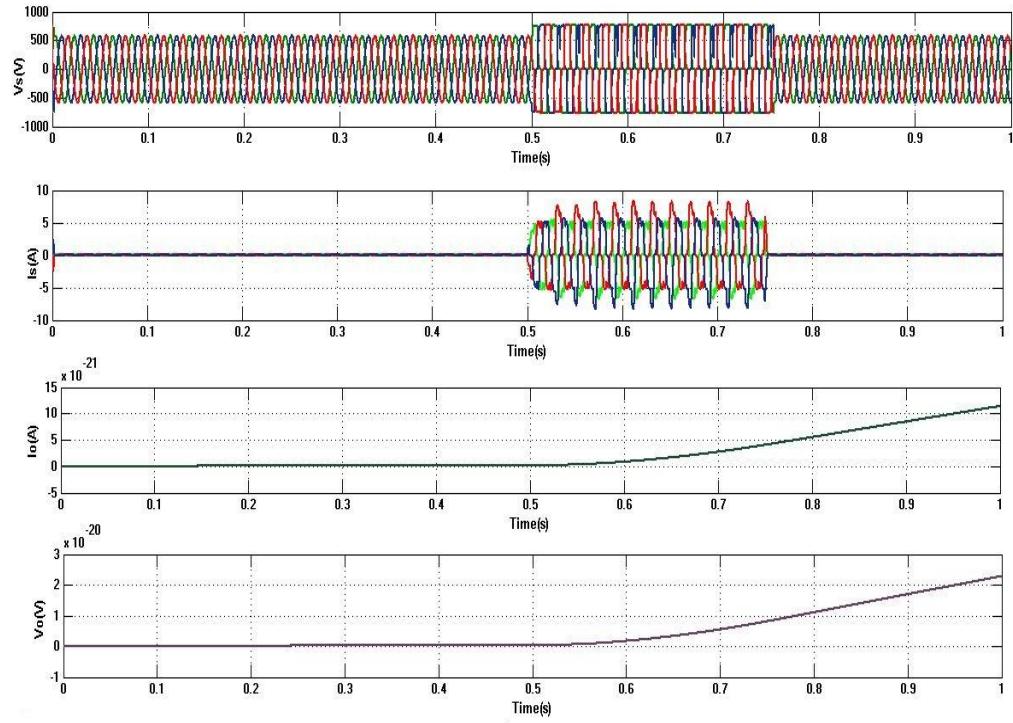


Fig 5.11: Performance of Proposed Welding Power Supply at 415 V AC Mains to Mitigate Voltage Swell with 0.5 magnitude

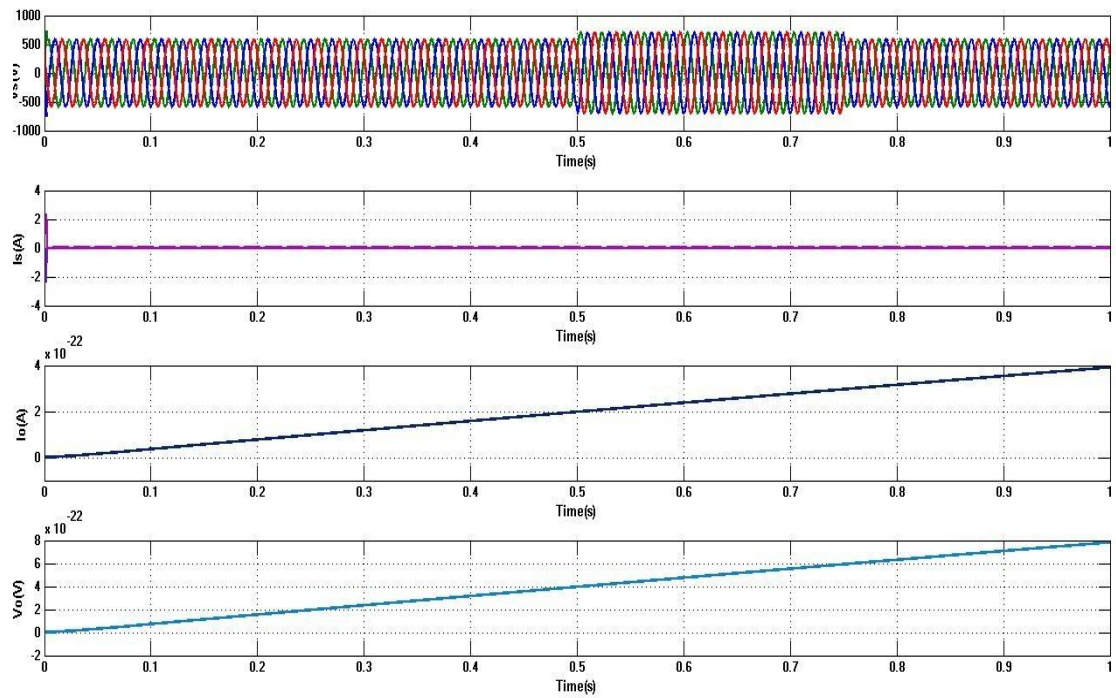


Fig 5.12: Performance of Proposed Welding Power Supply at 415 V AC Mains to Mitigate Voltage Swell with 0.6 magnitude

C) THD in Input Supply

After voltage sag and voltage swell, THD is introduced in the programmable voltage source. It is observed that by injecting different order of harmonics in the voltage source, distortionless output is obtained with constant output and current as shown in Fig 5.15. This is the best suited method for welding power supply as in this we can change the input voltage widely, and observed that the output voltage can be any value between zero to infinity regardless of input voltage.

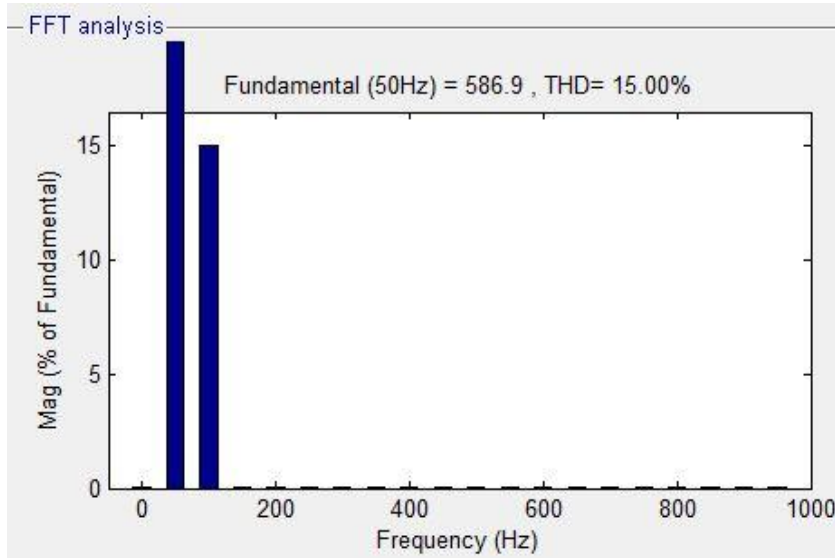


Fig 5.13: Harmonic Spectrum of input current with injection of 3rd Harmonics

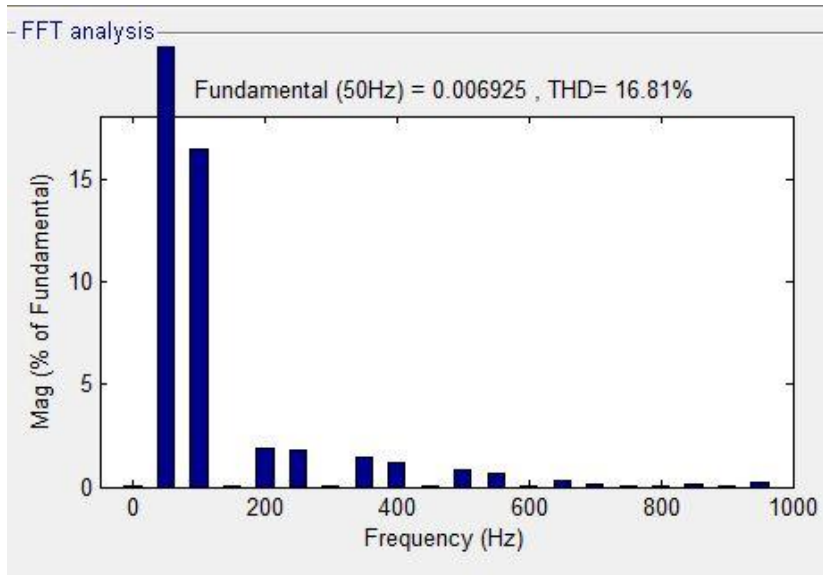


Fig 5.14: Harmonic Spectrum of input voltage with injection of 3rd Harmonics

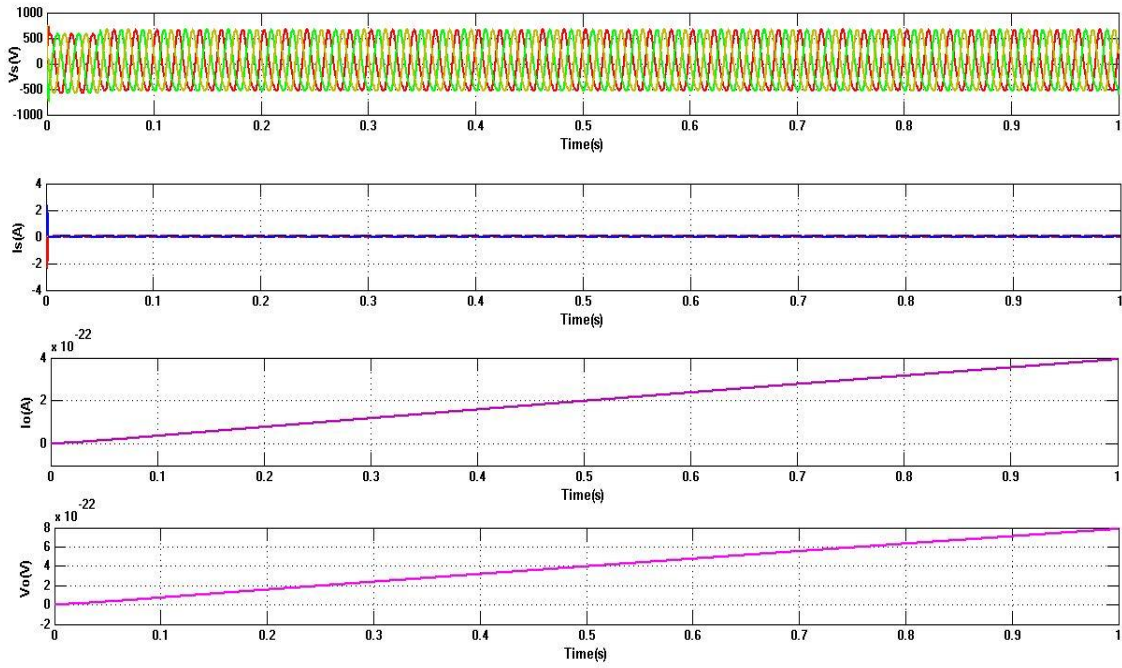


Fig 5.15: Performance of Proposed Welding Power Supply at 415 V AC Mains to Mitigate injection of 3rd Harmonic

TABLE 5.2: Type of injected Harmonics with P.U. magnitude

S.No.	Combination of harmonics with P.U. magnitude at source end	Value of THD without DVR (%)	Value of THD with DVR (%)
1.	3 rd (0.1) & 5 th (0.1)	20	0.00
2.	3 rd (0.2) & 5 th (0.2)	40	0.00
3.	3 rd (0.3) & 5 th (0.3)	60	0.00
4.	3 rd (1/3) & 5 th (0.1)	20	0.00
5.	3 rd (1/3) & 5 th (0.2)	40	0.00
6.	3 rd (0.1) & 5 th (0.2)	40	0.00
7.	3 rd (0.2) & 5 th (0.2)	60	0.00

CONCLUSIONS AND FUTURE SCOPE OF WORK

6.1 CONCLUSIONS

The performances of voltage source inverter and Z-source inverter based DVRs have been compared for welding load. The frequency spectrum and THD levels of various input and output quantities have been compared. It has been observed that the THD value of voltage source inverter is high as compared to ZSI. Voltage source inverter has no unique impedance network as Z-source inverter. By eliminating all harmonics at source side, ZSI has become a cost effective device and the efficiency has also improved. ZSI has no extra voltage stress on power devices. ZSI has been operated in short circuit conditions also which makes the circuit appropriate for welding applications. ZSI has a feature that the ac voltage can be controlled by modulation index. ZSI has enhanced the reliability of system because shoot-through has no longer destroyed the inverter. It has also been observed that the power supply maintains good voltage regulation.

6.2 FUTURE SCOPE OF WORK

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

- New control techniques for Z-source converter based DVR can be explored to further improve its performance.
- The effectiveness of the above mentioned ZSI based DVR in a distribution network with various practical type of loads can be investigated.
- A new hybrid Z-source multilevel converter based DVR for high voltage and high power applications can be developed.

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] A. de Almeida, L. Moreira. J. Delgado, “Problem Quality Problems”, *ISR*, 2002.
- [5] Kazibwe, W.E., “Electrical Power Quality Control Techniques”, *Van Nostrand Reinhold*, 1993.
- [6] S.Khalid, Bharti Dwivedi, “Power Quality Issues, Problems, Standards & Their Effects in Industry with Corrective Means”, *International Journal of Advances in Engineering & Technology*, vol. 1, issue 2, pp. 1-11, May 2011.
- [7] Kurt Schipman, Francois Delinse, “The Importance of Good Power Quality”, *ABB Power Quality Products, Belgium*.
- [8] Prafull A. Desale , Vishvadeep J. Dhawale, Ranjeet M. Bandgar, “Brief Review Paper on the Custom Power Devices for Power Quality Improvement”, *International Journal of Electronic and Electrical Engineering*, vol. 7, pp. 723-733, 2014.
- [9] Rashid, M.H., “Power Electronics”, *2nd ed. Englewood Cliffs, NJ, Prentice Hall*, 1993.
- [10] Thorobog, K., “Power Electronics”, *Prentice Hall International*, 1998.
- [11] Aredes, M., Aquino, A. F. C., Jr, G. S., “Multipulse Converters and Controls for HVDC and FACTS Systems”, *Journal of Electrical Engineering, Springer Berlin/Heidelberg*, vol. 83, no. 4, pp. 137-145, 2001.

- [12] John J. Paserba, Gregory F. Reed, Masatoshi Takeda, Tomohiko Aritsuka, "FACTS and Custom Power Equipment for the Enhancement of Power Transmission System Performance and Power Quality", *Symposium of Specialists in Electric Operational and Expansion Planning (VII SEPOPE) Curitiba, Brazil*, 2000, pp. 1-12, May 21-26.
- [13] N. G Hingorani, "Introducing Custom Power", *IEEE Spectrum*, vol. 32, pp. 41-48, 1995.
- [14] Venkateswara Sarma Mallela, P.S. Solanki and A. Chaturvedi, "Role of a Dynamic Voltage Restorer in Mitigation of Power Quality Problems", *International Conference on Communication, Computer & Power (ICCCP)*, pp. 161-166, 14-16 February 2005.
- [15] K. Chandrasekaran, P.A. Venkatachalam and Mohd Noh Karsiti, "Dynamic Voltage Restorer As A Sag Mitigator And Harmonic Restorer", *IEEE International Conference on Sustainable Energy Technologies*, pp 904-909, 2008.
- [16] Rosli Omar, Nasrudin Abd Rahim and Marizan Sulaiman, "Modeling and Simulation FOR Voltage Sags/Swells Mitigation Using Dynamic Voltage Restorer (DVR)", *Journal of Theoretical and Applied Information Technology*, pp. 464-470, 2009.
- [17] Yash Pal, A. Swarup, Bhim Singh, "A Review of Compensating Type Custom Power Devices for Power Quality Improvement", *IEEE Power India Conference*, pp. 1-8, 2008.
- [18] Bhim Singh, Swati Narula, G. Bhuvaneswari, "Power Quality Improvement Using Three Phase Modular Converter for Welding Power Supply", *IEEE fifth Power India Conference*, pp. 1-6, 2012.
- [19] Swati Narula, G. Bhuvaneswari, Bhim Singh, "Isolated Bridgeless Converter for Welding Power Supply with Improved Power Quality", *IEEE Student's Conference on Electrical, Electronics and Computer Science*, pp. 1-6, 2014.
- [20] Swati Narula, G. Bhuvaneswari, Bhim Singh, "Welding Power Supply With Improved Power Quality Using Sheppard-Taylor Converter", *Annual IEEE India Conference (INDICON)*, pp. 1-6, 2013.

- [21] Swati Narula, G. Bhuvaneswari, Bhim Singh, "A Modular Converter for Welding Power Supply with Improved Power Quality", *IEEE International Conference on Power Electronic, Drives and Energy System* ", pp. 1-4, December 2012.
- [22] R.Shiju Kumar, T.Ruban Deva Prakash, "Design of Gas Tungsten Arc Welding Power Supply using Power Electronic Transformer for Steel and Aluminium Welding", *International Journal of Current Engineering and Technology*, pp. 1484-1490, 19 October 2013.
- [23] Swati Narula, G. Bhuvaneswari, Bhim Singh, "A PFC Based Bridgeless Converter with Improved Power Quality for Welding Applications", *IEEE International Conference on Computational Intelligence & Communication Technology*, pp. 503-508, 2015.
- [24] Swati Narula, G. Bhuvaneswari, Bhim Singh, "Three-Phase Push-Pull Modular Converter Based Welding Power Supply with Improved Power Quality", *IEEE 5TH International Conference on Power Electronics (IICPE)*, pp. 1-5, 2012.
- [25] Gregory F. Reed, Masatoshi Takeda, Shinji Jochi, "Applications of Voltage Source Inverter (VSI) Based Technology for FACTS and Custom Power Installations", *IEEE International Conference on Power System and Technology*, vol. 1, pp. 381-386, 2000.
- [26] M.S.Aspalli, Anil Wamanrao, "Sinusoidal Pulse Width Modulation (SPWM) With Variable Carrier Synchronization for Multilevel Inverter Controllers", *International Conference on Control, Automation, Communication and Energy Conservation*, pp. 1-6, 2009.
- [27] S.Thangaprakash, A.Krishnan, "Comparative evaluation of modified pulse width modulation schemes of Z-source inverter for various applications and demands", *IJEST*, vol 2, pp. 103-115.
- [28] Rahul Dixit, Bindeshwar Singh, Nupur Mittal, "Adjustable Speed Drives: Review on Different Inverter Topologies", *International Journal of Reviews in Computing*, vol. 9, pp. 54-66, 2012.

- [29] Ramanpreet Kaur and Parag Nijhawan, "Simulation And Comparison Of Control Strategies Of DVR For Compensating Voltage Sags", *International Journal of Engineering Research & Technology (IJERT)*, vol. 2, no. 6, pp. 1993-2000, June 2013.
- [30] Anmol and Parag Nijhawan, "Application of Dynamic Voltage Restorer for Voltage Balancing with ASD Load Using DQO Transformation", *International Journal of Electrical Engineering*, vol. 4, no. 8, pp. 889-898, 2011.
- [31] A. Florescu, O. Stocklosa, M. Teodorescu, C. Radoi, D.A. Stoichescu, S. Rosu, "The Advantages, limitations and Disadvantages of Z-Source Inverter", *IEEE*, pp. 483-486, 2010.
- [32] Peng, F.Z., "Z-Source Inverter", *IEEE Transactions on Industry Applications*, vol. 39, issue 2, pp. 501-510, March/April 2003.
- [33] Peng F.Z., Shen Miaosenn, Qian, Zhaoming, "Maximum Boost Control of the Z-source Inverter", *IEEE Transactions on Power Electronics*, vol. 20, issue 4, pp. 833-838, July 2005.
- [34] 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.
- [35] 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, 2004.
- [36] Penchalababu.V, Chandrakala.B, Gopal Krishna, "A Survey on Modified PWM Techniques for Z-Source Inverter", *International Journal of Engineering and Advanced Technology (IJEAT)*, vol. 1, issue 5, pp. 556-562, June 2012.
- [37] D.Amudhavalli, L.Narendran, "Improved Z Source Inverter for Speed Control of an Induction Motor", *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. 2, issue 4, pp.1240-1247, April 2013.
- [38] Mohit Tyagi, Atul Kushwaha, Shubra Goel, Amit Kumar, Manoj Saini, "Modelling and Simulation of PWM based ZSource Inverter using MATLAB/SIMULINK", *IJEEE*,

International Journal of Electrical and Electronics Engineers, vol.6, issue 02, pp. 24-33, July-Dec., 2014.

[39] Rajesh Kumar Ahuja, Amit Kumar, “Analysis, Design and Control of Sinusoidal PWM Three Phase Voltage Source Inverter Feeding Balanced Loads at Different Carrier Frequencies Using MATLAB”, *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. 3, issue 5, pp. 9557-9563, May 2014.

[40] Ramya.C, Chinnaiya.S, Prabha.S.U, “Improved Z-Source Inverter with Switched-Inductor and Trans Z-Source Topology”, *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 3, Special issue 1, pp. 1625-1632, January 2014.

[41] Lei Shi, Haiping Xu, Zuzhi Zhang, Zhuoran Liu, “The Topology Analysis and PWM Method of the Novel Z-Source PWM Rectifier-Inverter”, *ITEC Asia-Pacific*, pp. 1-6, 2014.

[42] I.S. Kim, J.S. Son, H.J. Kim and B.A. Chin, “Development of a mathematical model to study on variation of shielding gas in GTA welding”, *Journal of Achievements in Material and Manufacturing Engineering (JAMME)*, vol. 19, issue 2, pp. 73-80, December 2006.