ROLE of DC-MLI based D-STATCOM in DISTRIBUTION NETWORK with FOC INDUCTION MOTOR DRIVE

A Dissertation

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Certificate

I hereby certify that the work which is being presented in this thesis entitled "**ROLE of DC-MLI based D-STATCOM in DISTRIBUTION NETWORK with FOC INDUCTION MOTOR DRIVE**" in partial fulfilment of the requirement for the award degree of Master of Engineering in Power System submitted in Electrical and Instrumentation Engineering Department, Thapar University, Patiala is an authentic record of my own work carried out under the guidance of Dr. Parag Nijhawan, Assistant Professor, EIED, Thapar University.

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

Surbhi Agg 26/7/17

(Surbhi Aggarwal)

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

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Abstract

The main objective of Power System engineers is to meet the consumers demand. Rated voltage and rated frequency supply should be supplied to the consumer end.With the introduction of many non-linear loads at the consumer end, Power Quality problem is a serious threat to the Power System. Power Quality problem is any occurrence in voltage, current or frequency deviation that may result in failure or mis-operation of electrical appliances.Common Power Quality problems that can be observed in daily life are voltage sag, voltage swell, voltage flickering, over-voltage and under-voltage. Impulsive transients, oscillatory transients and harmonics are also some of the Power Quality problems.

The potency of D-STATCOM using SRF control theory in a Distribution Network with Field Oriented Control (FOC) Induction Motor drive as non-linear load with Diode-Clamped Multilevel inverter is examined. The FOC induction motor drive is a non-linear load which introduces harmonics into the distribution network when operated. D-STATCOM is a shunt linked device used for the reactive power compensation, for harmonic elimination and load balancing. D-STATCOM is a Custom Power device used at the distribution end to counteract the Power Quality problem.

The conceptualization of Multilevel inverters came around 1975. For high-power and medium-power applications, Multilevel inverters are used as they can extract input current and produce output voltage with very low distortion. They even reduce the *dv/dt* stress and can operate at both fundamental switching frequency and high switching frequency. All these benefits cannot be retained through conventional VSI and CSI. These can generate output voltages with mature medium-power semi conductor technology with lower distortion. As the number of levels increases, the output waveform approaches more towards sinusoidal wave with a reduced harmonic distortion.

Simulation of D-STATCOM using SRF control theory with 7 level Diode-Clamped Multilevel Inverter has been performed in MATLAB/SIMULINK.

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List of Abbreviations

APOD	Alternative Phase Opposite Dissipation
BESS	Battery Energy Storage System
CP	Custom Power device
CSI	Current Source Inverter
DC-MLI	Diode-Clamped Multilevel Inverter
D-STATCOM	Distribution Synchronous Compensator
DVR	Dynamic Voltage Restorer
FACTS	Flexible AC Transmission System
FFT	Fast Fourier Transform
FOC	Field Oriented Control
IEC	International Electro technical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IRP	Instantaneous Reactive Power theory
MLI	Multilevel Inverter
PCC	Point of Common Coupling
PD	Phase Dissipation
POD	Phase Opposition Dissipation
PQ	Power Quality
PWM	Pulse Width Modulation
STATCOM	Synchronous Compensator
SRF	Synchronous Reference Frame theory
THD	Total Harmonic Disorder
UPQC	Unified Power Quality Compensator
VSI	Voltage Source Inverter

Chapter- 1

Overview

1.1 Introduction

Power System is a subsystem of Electrical Engineering which composes of the generating, transmiting and distributing sections of the electric power.It is the chief duty of Power System engineers is to meet the consumers electric power demand. Rated voltage and rated frequency supply should be supplied to the end user. With the advance need of energy, Renewable energy is included in the subsisting Power System. With the beginning of the Power Electronics into the subsisting system, the consumer demand is fulfilled upto a certain extent but the Power Quality problem is now one of the chief concerns of Power engineers.

With the introduction of many non-linear loads at the consumer end, Power Quality problem is a serious threat to the Power System. As per*IEEE*,“*Power Quality is the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment*”. Common Power Quality problems that can be observed in daily life are Voltage Sag, Voltage Swell, Voltage Flickering, Over-Voltage and Under-Voltage. Impulsive transients, Oscillatory transients and Harmonics are also Power Quality problems.

For the Harmonic elimination, passive, active and hybrid power filters are used. At the distribution side, Custom Power devices are used which mainly include Unified Power Quality Conditioner (UPQC), Distribution Static Compensators (D-STATCOM) and Dynamic Voltage Restorer (DVR).

D-STATCOM, a shunt linkedCustom Power deviceemployed for the reactive power compensation at the distribution side whereas STATCOM is also a shunt linked device employed in the transmission system for the power factor improvement and the voltage stability.

D-STATCOM is also used for elimination of harmonic level and balancing of the loads at the distribution end. Various control algorithms for extracting the reference source current components are defined in the literature to analyze the performance of D-STATCOM such as Instantaneous Reactive Power (IRP) theory, Adaline Based Control Algorithm, Load balancing,Synchronous Reference Frame (SRF) theory, Symmetrical Component Theory and many others. Among from all, IRP and SRF control algorithms are usually used.

Inverter, one of the Power Electronic conversion device from DC input to AC output. AC output serves as an input to Adjustable Speed Drives (ASDs); Flexible AC Transmission System (FACTS); Static VAR Compensators (SVCs); Active Filters; and many more. These could be classified as Voltage Source Converters (VSIs) and Current Source Inverters (CSIs) and are basically used for low and medium voltage applications. But for high-power applications, conventional VSIs and CSIs cannot be used because of their high device rating issues and more switching losses.

Multilevel inverter finds usage in many industrial high power applications. Multilevel inverters were introduced in 1975 beginning with3 level Multilevel inverter. Multilevel inverters produce output with more number of voltage levels, producing a more sinusoidal voltage waveform and however reducing the harmonic distortion in the system. Multilevel inverters are superior to conventional VSIs and CSIs due to their low distortion in the output voltage waveform and reducing the *dv/dt* stress on the switches. Operating at fundamental and high switching frequency, Multilevel inverters extracts very low distorted value of input current. One negative point is that Multilevel inverters depend on more number of switching devices and separate control circuitry is required for each switch which however increases the cost and complexity of the system.

1.2 Literature Survey

In recent years, usage of non-linear loads like ASDs, SPS, arc furnaces and other equipments is greater than before. Due to the running of non-linear loads, Power Quality problem arises in Power System. Many researcheshave been done onCustom Power devices to enhance the current and voltage quality. A brief literature review related to Power Quality, its improvement using D-STATCOM is presented here:

Francois D. M., *et al.*[1]presented the detailed summary of the surveys conducted in last two decades showing about the different origins and types of disturbances Rated voltage and rated frequency supply has to be supplied to the consumers. Also, different types of monitoring instruments are described.

D.G. Flinn, *et al.* [2] presented a paper focussing on various Power Quality problems that subsist in the Power System alongside with their method to identify these problems. The data collected from routine checks and on- site field measurements help to recognize the nature of the Power Quality problem and the method to clarify that problem.

D.J. Ward, *et al.* [3] studied about the two different perspectives of Power Quality problems. Power Quality problem viz. Short duration transients or momentary disturbances affect both the utility side and consumer side. One aspect is from utility side meter which covers any of the Power System disturbances that originates at the utility side and affects the customer's equipment whereas second aspect is from the customer side meter in which the problems are restricted to the customer end only. This paper surveys into the power interrelated problems which are in the direct of the utility and by the user itself.

A. Sannino, *et al.* [4] presentedaboutPower Quality problem reduction using FACTS controllers such as STATCOM and D-STATCOM. Various power electronic devices are used to mitigate Power Quality issues, for example, low power factor, poor voltage, current and voltage harmonics and many more. These Power Quality problems mainly arise because of swiftadjustments in the field excitation of Synchronous generator, unexpected increment in the load or abrupt occurrence of faults in the Power System.

B. Singh, *et al.* [5] surveyed about the Custom Power devices along with their advantagesand drawbacks. Power electronics based devices are being used to mitigate the Power Quality problem. Various mitigating appliancesare used at the distribution end known as Custom Power devices as well as at the transmission side classified as FACTS devices. Also some comparisons are done between the traditional mitigation methods and some Custom Power devices. Shunt devices are used to protect the source from the load whereas series devices are used to protect load from the source.

A.A. Peter, *et al.* [6] surveyed about the impact of Power Quality issue on the execution of an Induction motor drive.Induction Motor is not a linear load which utilized mostly at the consumer end.With the help of MATALB Simulink, the execution of the Induction Motor is predicted. Simulink results show the difference between execution of an induction motor in case of unbalanced voltagesources and balanced voltagesources.

N.S. Rao, *et al.* [7] presented the Modelling and Simulation of D-STATCOM for compensation of voltage sag problem. The present Power System is in the direction of distributed and dispersed generation; Power Quality problem is one of the significant concerns of Power Engineers. To mitigate the Power Quality problem at distribution end,Custom Power devices are used. Various control algorithms are used for Simulation of D-STATCOM. This paper focuses on the functioning of D-STATCOMon occurrence of a single–line to ground (SLG) fault and measures to be taken to enhance the Power Quality problem.

N. Kaur, *et al.* [8] studied about the switching transients originated at the distribution end due to the usage of inductive load.With the increase in demand of power supply, present Power System network is operated at its full capacity. Huge power loss and security issues are there. The present Power System has to be smart and aware, fault-tolerant and self-healing. This paper analyses the performance of D-STATCOM for 2 inductive loads viz. 2095.91kW and 3424.31kW. The different transient conditions are generated by connecting and disconnecting the loads at different intervals of time.

B. Singh, *et al.* [9] surveyed about thecomparison of 3 control algorithms of DSTACOM viz. IRP theory, SRF theory and Adaline based algorithm. Different control algorithms of D-STATCOM for reparation of reactive power and unbalanced produced by various loads in Power System are defined in literature.Diverse simulation and tests are done to exhibit the performance of these control algorithms.

E. Varghese, *et al.* [10] presented the design, analysis and comparison of D-STATCOM in MATALB Simulink for various types of loads like linear, non-linear and unbalanced load.D-STATCOM, a shunt attacheddeviceemployed for reactive power compensation, source current balancing at distribution end. IRPT, SRF, Adaline based algorithm, Back propagation are some of the control algorithms for the analysis of D-STATCOM.

T. Rakesh, *et al.* [11] surveyed the SRF control of Diode-Clamped MLI basedD-STATCOMwith Synchronous organization based management for harmonic mitigation.IRP theory, SRF theory and Adaline based algorithm are some of the mostly used control algorithms for D-STATCOM. In place of two level inverters Multilevel inverters are being used nowadays. Comparison is done between two-level, 3-level MLI and five-level MLI.

R Sharma, *et al.* [12] presented the functioning of D-STATCOM with FOC Induction Motor drive as load with dq0 transformation to investigate the performance of D-STATCOM.Nowadays mostly used loads at distribution end are non-linear loads. Induction Furnace load is one of the common non-linear loads used in the industries. FOC Induction motor drive introduces obvious measure of load current harmonics, which additionally influences the alternate loads linked in the system.

R.B. Vasa [13] presented the SRF control algorithm for Power Quality improvement using MATALB Simulink to demonstrate the satisfactory behaviour of D-STATCOM.Poor voltage regulation, high reactive power, load balancing, voltage sag-swell are some of the Power Quality problems. Various control algorithms like IRPT, SRF theory, Adaline based algorithm are used to overcome these Power Quality problems.

P. Nijhawan, *et al.*[14] surveyed about the Multilevel inverter based D-STATCOM.FOC-Induction furnace load is one of the common non linear loads used in various industries at the consumer end. Induction furnace load when operated introduces a substantialamount of load current harmonics which have an effect on the other equipments linked to the system. On conventional basis, two phase VSIwere employed in the model of D-STATCOM but nowadays Multilevel inverters have replaced the conventional inverters. This paper shows the comparison ofPWM based D-STATCOM andCarrier Phase Shift (CPS)PWM 5 level inverter based D-STATCOMand results are inferred on comparison basis.

M. Bansal, *et al*. [15] presented about Instantaneous Reactive Power theory i.e. conversion of *a-b-c* coordinates to *α-β-0* coordinates to mitigate the current harmonics when induction furnace drive used as non-linear load. Nowadays Power Quality problem is an important subject for Power System network as well as to Power System engineers. Power Quality problem includes voltage sag, voltage swell, interruptions, harmonics and many more which may lead to interruption or failure of equipments. Various control algorithms are used to overcome these Power Quality problems.

A. Singh, *et al.* [16] presentedthe improved performance of D-STATCOM and Battery Energy Storage System (BESS) by modelling and controlto improve Power Quality.SRF theory is used as the control algorithm forD-STATCOM and BESS for linear and non-linear loads under balanced and dynamic conditions.

K.S.Varaprasad, *et al.* [17] presented the comparison between D-STATCOM and DVR using MATALAB Simulink with the help of PI controller at the distribution side for static linear and non-linear loads under different fault conditions. About 90% of the average customer interruptions occur at distribution side which accounts for a huge amount of financial losses and loss of productivity.

J.A. Barrena *et al.* [18] presented the two different design methodologies of D-STATCOMMultilevel topologies. Neutral Point Clamped (NPC) Multilevel topology and Cascaded H-Bridge Multilevel topology for D-STATCOM relevance have been presented. Special consideration is given on the capacitor value of DC bus and inductance value of output filter.

B. Singh *et al.* [19] presented the application of D-STATCOM for easing of Power Quality problems at distribution end. D-STATCOM, linked in shunt with an isolated alternator system (42.5 kVA, 400V) feeding non-linear load is modelled in MATLAB/SIMULINK and PSB.

Voltage dip problem arises on the sudden application of induction motor at load end. Comparison between with and without D-STATCOM controller is done.

L.M. Tolbert *et al.* [20] presented the transformerless Multilevel converters for high-power drives and/or high-voltage electric motor drives. These converters are better than conventional VSIs and CSIs as they can operate on high switching frequency and on fundamental switching frequency. Simulation and comparison of Cascaded Multilevel inverter and back-to-back Diode-ClampedMultilevel inverter is presented.

S. Iyer, *et al.* [21] surveyed about the distinctive topologies of inverters for performing a D-STATCOM. A Voltage Source Inverter (VSC) is one of the main components of the D-STATCOM model. The compensation provided by inverter depends on the configuration of the inverter. Simulation study of 3-stage inverter with a single DC capacitor, 3- stage inverter with Neutral Point Clamped DC capacitors, 4-stage inverter and 3-single phase inverters with common DCcapacitor is described.

J.S. Lai, *et al.* [22] discussed 3 designs available for the Multilevel inverters namely FC-MLI, DC-MLI, Cascaded H-Bridge MLI for high power applications. At the output terminals of Multilevel inverter, more than two voltage levels are available which can be approximated as sine wave as compared to the output of a traditional VSI or CSI. Multilevel inverters are used to solve harmonics distortion and to reduce*dv/dt* induced due to motor failures.

J. Rodriguez, *et al.* [23] surveyed about the different topologies, controls and applications of Multilevel inverters. DC-MLI, FC-MLI and Cascaded H-Bridge MLI topologies are compared and surveyed according to the applicationsMultilevel inverters uses high switching frequency as compared to conventional VSI and CSI and have a number of advantages over two-level inverters. Multilevel inverters output voltages are low distorted output voltages and have lessen*dv/dt* stress.

T.A. Meynard, *et al.* [24] presented the modelling and simulation of Multilevel converters with the utilization of several switches connected in series arrangement. These converter switches have lower voltage ratings, reduced conduction losses and higher switching frequency as compared to conventional switches.

C. Rech, *et al.* [25] presented the Binary hybrid Multilevel inverter and Trinary hybrid Multilevel inverter comparison to decrease the number of series-linked inverters and to cut down the THD level of output voltage. Hybrid Multilevel inverters when used for high power applications, usually DC bus voltages in the ratio of 2:1 are set for series linked inverters.

H.K. Chiang, *et al.* [26] presented the test and employmentof a Neutral Point Clamped based D-STATCOMMultilevel inverter for the aberrant voltage conditions. D-STATCOM is used at the distribution end to deliver or absorb the reactive power as require by the system. Several Multilevel inverters are introduced in the literature since 1975. Multilevel inverter is used to eradicate out the harmonics from the load current and to counteract for reactive power. To trace the compensated current, hysteresis current controller is used.

I. Colak, *et al.* [27] reviewed about the different basic and hybrid Multilevel voltage source inverter topologies. For average and high power applications,these Multilevel inverters offer less common mode voltage, cut*dv/dt*ratio and less harmonics to the load currents.Also, various control schemes for Multilevel inverters are also discussed.

C. Gomathi, *et al.* [28] presented the comparison of various modulating schemes for Multilevel inverter in MATLAB/SIMULINK. Basically, Multilevel inverters are used to reduce the THD level by keeping the inverter output voltage constant. By rising the level of Multilevel inverter, the switching stress will be increased due to the rise in the number of switching components.

A. Nami, *et al.* [29] presented the comparison of single phase Symmetrical and Asymmetrical DC-MLI. A 4 level asymmetrical MLI inverter is compared with conventional MLI inverter. The asymmetrical MLI performs well with the same number of components as it yields higher number of output voltage levels in comparison to conventional 4 level VSI.

1.3 Scope of Work

Power Quality problem is a foremost issue to the present Power System network. Rated voltage and rated frequency supply has to be supplied to customers. Different types of FACTS devices and Custom Power devices are analysed and recommended to overcome the Power Quality problems. About 90% of the average customer interruptions occur at distribution side which accounts for a huge amount of financial losses and loss of productivity. So, more intentness is given to the Power Quality problems occurring at distribution side. A Custom Power device, D-STATCOM is used to enhance the quality of power at distribution side along with a Multilevel inverter to obtain a more sinusoidal output. FOC-Induction Motor drive is used as the non-linear load to show the effectiveness of D-STATCOM. Test and results are obtained by using MATLAB/ SIMULINK R2015b software.

1.4 Objective of Thesis

The presented work comes up with MATLAB/ SIMULINK model of D-STATCOMalong with Multilevel inverter at the distribution end. The main objectives of the presented work are:

- To analyse the model of D-STATCOM with SRF control theory.
- To analyse the working of D-STATCOM for Field Oriented Control (FOC) Induction Motor Drive as non-linear load.
- To study the performance of 7 level DC-MLI.

1.5 Organization of Thesis

- Chapter 1 contains the overview of the proposed work including the introduction, literature review and scope of the work. Objective and organization of thesis is also presented.
- Chapter 2 explains about the Custom Power devices giving the brief description about all of the Compensating devices.
- Chapter 3 mainly focuses on the D-STATCOM model configuration, its applications and advantages with the control strategy used for D-STATCOM.
- Chapter 4 presents the Multilevel converters introduction with a brief discussion on 3 types of Multilevel inverters. Detailed description about DC-MLI is also presented.
- Chapter 5 presents the system test and results. Parameters of the test system and MATLAB/SIMULINK models of test system for non-linear load and their results are included.
- Chapter 6 contains the conclusions and future scope.

Chapter- 2

Custom Power devices

2.1 Introduction

The notion of Custom Power devices was made known by N. G. Hingorani in the Power System. At the distribution end, Custom Power devices are used whereas FACTS device are used at the transmission end. For improving the system reliability and power transfer quality at the transmission end, FACTS devices are used whereas the Custom Power devices are employed for Power Quality improvement that is transmitted to the end user. Rated voltage and rated frequency power has to be supplied to the consumers having low flicker and low harmonic distortion.

Custom Power Park is defined as the consolidation of different CP devices in a particular area to improve both the current quality and voltage quality for both linear and non-linear loads. To achieve high Power Quality, DVR,Static Transfer Switches, Active Power Filters (APF)and backup generator are used. Customer Power Park serve the consumers who are in a request of high grade of power and areeager to pay an extra charge sum for the services provided to them.

Custom Power devices are classified into current breaking devices and compensating power devices. SSB, SSCL and SSTS are some of the current breaking or solid state devices. Compensating devices are either used to compensate the load power factor, unbalance load, etc. or to enhance supplied voltage. D-STATCOM, DVR and UPQC are the Compensating devices.

2.2 Compensating Devices

2.2.1 Distribution Static Compensator (D-STATCOM)

A Distribution STACOM is a shunt linked device similar to Transmission STATCOM coupled with the help of a coupling transformer with the system. It is a Custom Power device which can giveor take reactive power to\from the system. A simple schematicplan of a DSATCOM is shown in Figure 2.1.

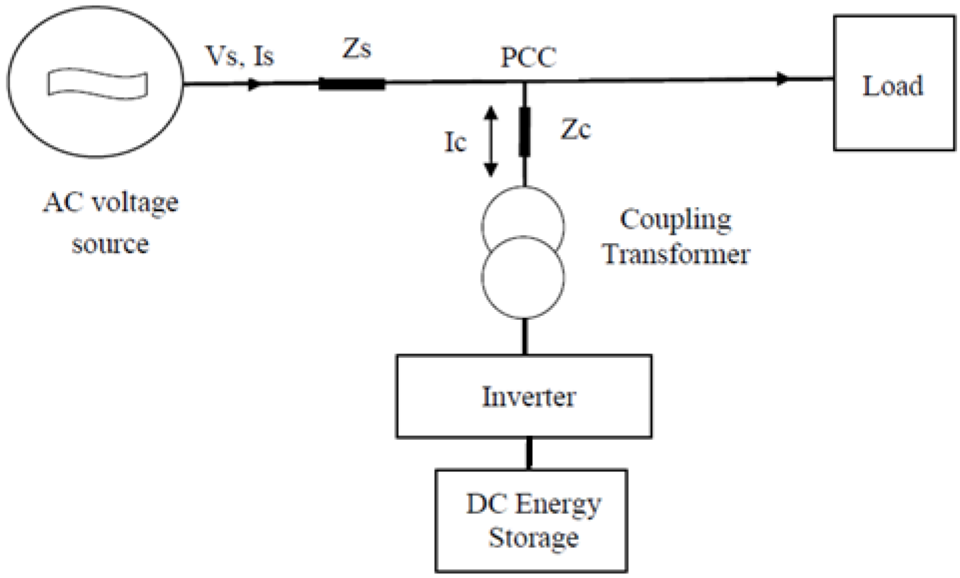

Figure 2.1: Schematicplan of D-STATCOM

The main components of D-STATCOM are Coupling Transformer, LC Filter,Voltage Source Converter (VSC) and DC energy storage system. The flow of Reactive power depends on the voltage conditions at PCC and at the inverter output.

- When voltage level at PCC is equal to the inverter output voltage, no reactive power transfer is there.
- When voltage level at PCC is greater than the inverter output voltage, the reactive power transfers from the system to the D-STATCOM i.e D-STATCOM acts as an inductor and consumes reactive power.
- When voltage level at PCC is less than the inverter output voltage, the reactive power transfers from D-STATCOM to the system i.e. D-STATCOM acts as a capacitor and supplies reactive power.

2.2.2 Dynamic Voltage Restorer (DVR)

DVR, a series linkedCustom Power device similar to one of the FACTS devices i.e. Static Synchronous Series Compensator (SSSC). DVR is used to eliminate the Voltage Sag problem occurred due to the sensitive loads at the consumer end. Figure 2.2 show the Basic Schematicplan of DVR.

It is basically used to maintain the load side voltage even when there is some distortion at the source side voltage. DVR is linked in series to the arrangement with the help of a transformer.

Voltage source inverter injects AC voltage to the system as when required. To maintain constant DC voltage, a DC energy storage system is used with the inverter.

Basically, DVR injects 50% of the nominal voltage due to which DVRs are used to provideprotection against 50% of sags upto a duration of 0.1 seconds.

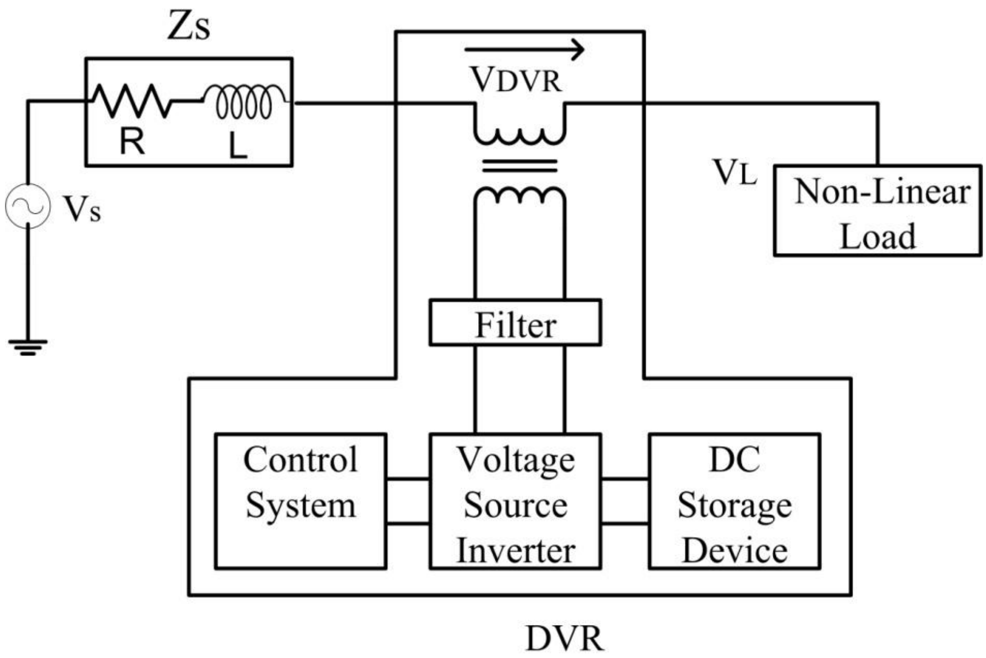

Figure 2.2:Schematicplan of DVR

2.2.3 Unified Power Quality Compensator (UPQC)

UPQC is a combo arrangement of series and shunt compensatorslinked at the DC side.

Figure 2.2 show the Basic Schematic plan of UPQC.

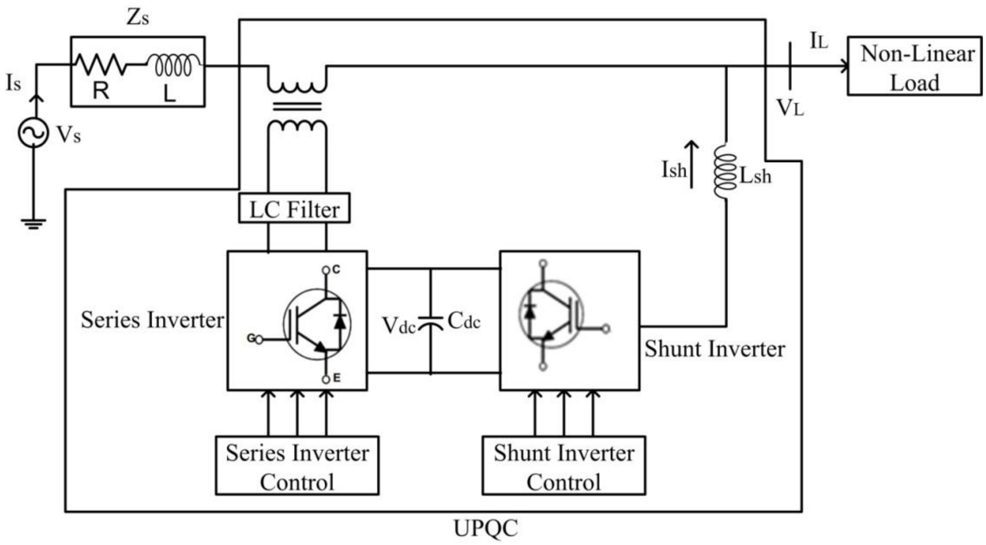

Figure 2.3:Schematicplan of UPQC

UPQC is similar to the FACTS device Unified Power Flow Controller (UPFC). UPQC are useful in those conditions when both the sending side and receiving side voltage are unbalance and distorted.

The series inverter coupled to the common DC link is used for the harmonic isolation along with the voltage regulation and imbalance compensation. The shunt inverter on the other side provides DC link voltage control alongside with harmonic and negative sequence current compensation.

In present work, D-STATCOM as Custom Power device with SRF control theory has been presented. D-STATCOMbeing a shunt linked device used at the distribution side to compensate for the Power Quality problems.

A detailed description about D-STATCOM has been discussed in the next chapter.

Chapter- 3

Distribution Static Compensator (D-STATCOM)

3.1 Introduction

D-STATCOM, a Custom Power device on the whole is a Voltage Source Converter (VSC)linked in shunt at PCC at the distribution end of the Power System network.Custom Power device used for load current harmonics compensation and to control unity power factor load. To maintain the isolation between the D-STATCOM system and the distribution end of the network system, a coupling transformer is used linking the two. D-STATCOM provides fast and continuous inductive reactive power compensation and capacitive reactive power compensation.

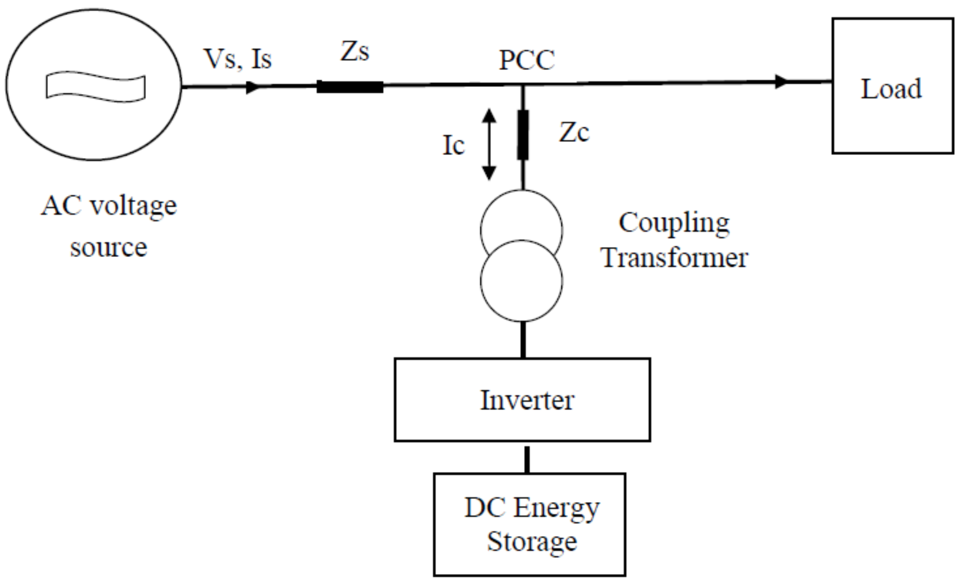

Figure 3.1: Basic structure of D-STATCOM

Nowadays, many utilities and industries face the voltage sag problem which is one of the most common Power Qualityissues caused due to the use of non-linear loads like motors, pumps, fans etc. at the distribution end. These loads draw excessively lagging power factor currents which reduce the flow of active power through the network and increase the losses on the system.

Voltage sag is described as the fall in the rms voltage value from 10% to 90% of thestandard voltage value at power frequency for atimeextent of one-half cycle to few seconds. Also, to mitigate the Voltage swell D-STATCOM is used.

Due to the boost in the usage of non-linear loads such as spot welders, arc furnaces , etc. Voltage flickering problem also arises in the system. SVCs are traditionally used to mitigate the voltage flicker produced by arc furnaces. But nowadays, D-STATCOM gives better results than SVC in mitigating flicker problem.

Load Balancing; IRP theory;Adaline based algorithm; SRF theory are some of the control techniques for D-STATCOM.

3.2 Configuration of D-STATCOM

D-STATCOM mainly constitute of:

1. Voltage Source Converter
2. Coupling Transformer
3. DCCapacitor Voltage
4. LC PassiveFilter

3.2.1 Voltage Source Converter

A VSC is used for the conversion ofthe storedDC energy to 3 phase AC energy as required by the system. This AC output voltage is required to be in phase with the AC system and is coupled with the help of coupling transformer. It is used to generate required leading or reactive power for compensation.

3.2.2 Coupling Transformer

Coupling transformer is used to maintain the isolation between the distribution network and D-STATCOM. The AC output voltage from the VSC is linked with the AC system with the help of coupling transformer.

3.2.3 DC-Capacitor Voltage

The voltage at the Point of Common Coupling (PCC) determines the value of the voltage at the DC bus. The DC bus voltage V_{DC} is defined as:

$$V_{DC} = (2\sqrt{2}\ V_L)/(\sqrt{3}n)$$

where, V_L is the AC output voltageof D-STATCOM and *'n'* is the modulation index.

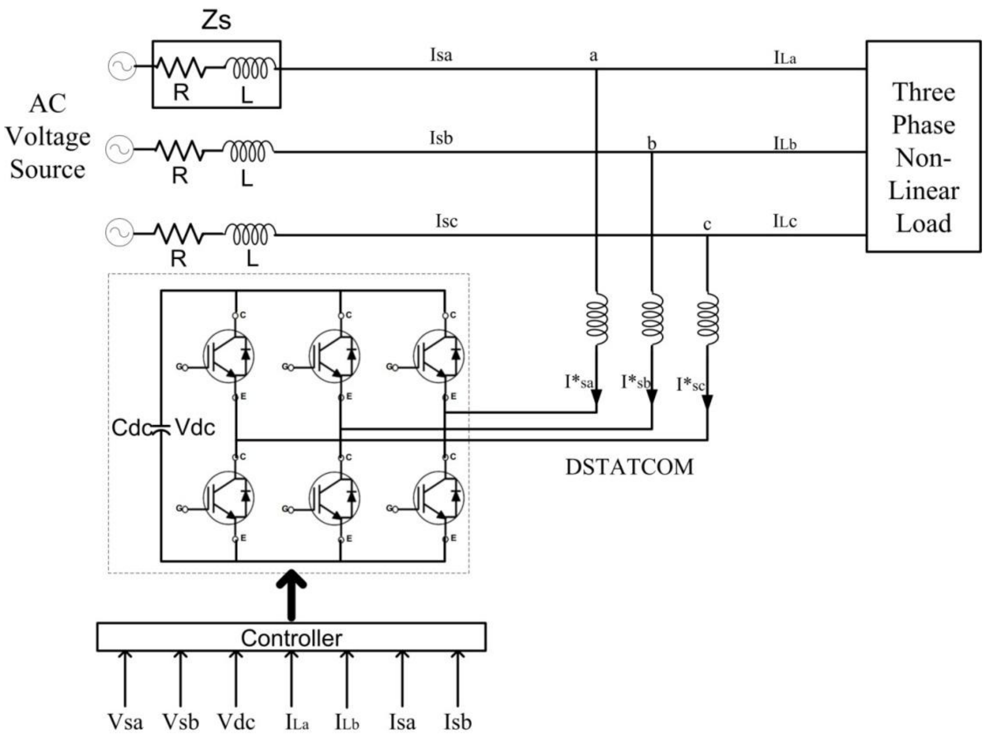

Figure3.2: Configuration of D-STATCOM

3.2.4 LC Passive Filter

LC passive filters are used to dispose of the harmonic content. The value of L and C in the filter is based on the type of system and the harmonics present.

3.3 Applications/ Advantages of D-STATCOM

D-STATCOM, shunt linked device used at the distribution side for voltage adjustment and for power factor modification.

Several applications and advantages of D-STATCOM are:

- D-STATCOM can supply both leading and lagging reactive power as and when required by the system.
- Voltage Sag and Flickering are easily defended by D-STATCOM that are caused by non-linear loads.
- For various wind farms and industrial mills applications, D-STATCOM is used for various Power Quality improvements.
- Unbalanced loads can be easily satisfied by using D-STATCOM.

- D-STATCOM has high efficiency and can provide single phase control for unbalanced load.
- D-STATCOM allows continuous and dynamic voltage control and full grid control.

3.4 Control Strategy for D-STATCOM- SRF Theory

D-STATCOM is employed for harmonic easing; reactive power compensation or load balancing at the distribution end of the network. Different control theories or algorithms are used for extracting reference source currents. Some of the strategies SRF theory, IPR theory, Adaline Based algorithm, DC bus regulation for current compensation and some schemes based on artificial intelligence. Amongst from these schemes, SRF based theory is used to study the performance of the DSATCOM with Field Oriented Control (FOC) induction motor drive as a non-linear load is examined.

Synchronous Reference Frame (SRF) Theory

SRF theory, a *d-q* control theory is based on the conversion of 3 phase current frame *a-b-c*to synchronously rotating *d-q* frame. Schematicplan of SRF theory is explained in Figure3.3. To the Phase Locked Loop (PLL) block, voltage signals V_a, V_b and V_c are applied to obtain sine and cosine signals.

Load current signals I_{La}, I_{Lb} and I_{Lc} are converted from 3 phase quantities to 2 phase quantities i.e I_α and I_β with the help of ***Clark's transformation*** following the equations:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \qquad (2)$$

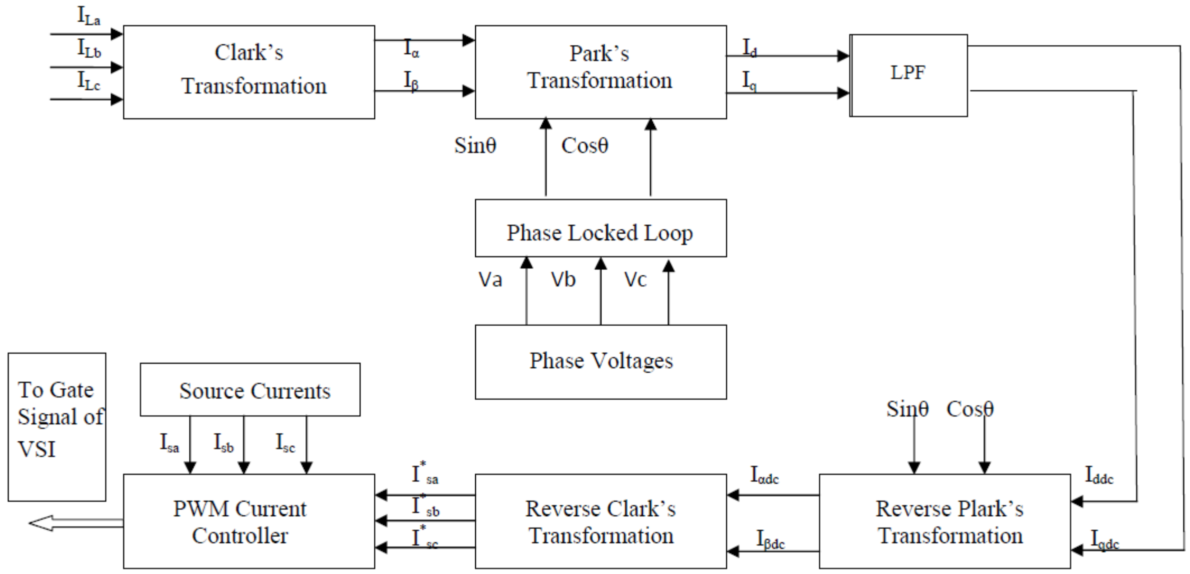

Figure3.3:Schematicplan of SRF based theory

Park's transformation is used for converting balanced two-phase stationary quantities to 2-phase rotating reference frame. The 2-phase stationary quantities i.e $I_\alpha$and I_β are perpendicular to each other and two-phase rotating reference frame quantities i.e. $I_d$and I_q. $I_d$is rotated at a rotation angel θ to the α axis whereas I_q remains perpendicular to $I_d$axis. The reference frames are shown in the Figure3.4.

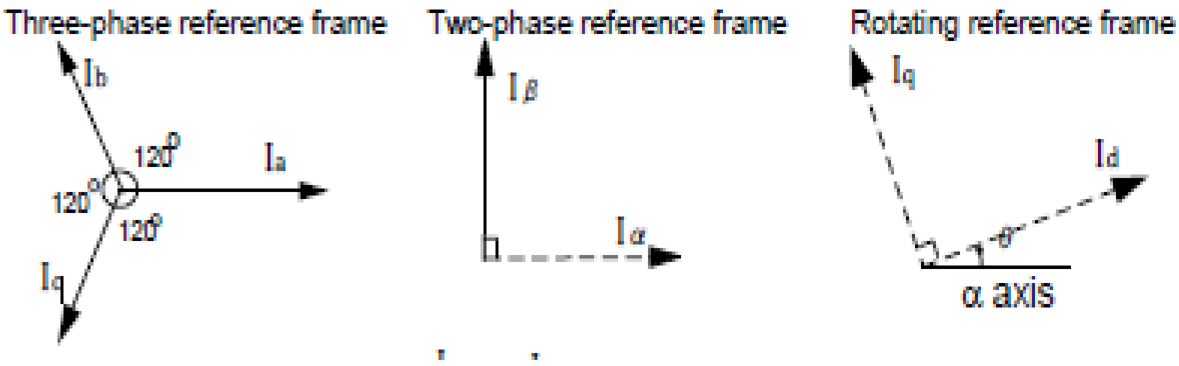

Figure 3.4: Reference Frames

After ***Clark's Transformation, Park's Transformation*** is done by using the following equation:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \qquad (3)$$

For extraction the DC component from the synchronously rotated currents, Low pass filter is used. These extracted DC currents are altered back into $I_{\alpha DC}$ and $I_{\beta DC}$using ***Reverse Park's Transformation*** equation:

$$\begin{bmatrix} I_{\alpha dc} \\ I_{\beta dc} \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} I_{ddc} \\ I_{qdc} \end{bmatrix} \quad (4)$$

Reverse Clark's Transformation is applied to obtain 3-phase Reference Source Currents I^*_{sa}, I^*_{sb} and I^*_{sc} from the derived DCcurrents using the equation:

$$\begin{bmatrix} I^*_{sa} \\ I^*_{sb} \\ I^*_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I^*_0 \\ I^*_{\alpha dc} \\ I^*_{\beta dc} \end{bmatrix} \quad (5)$$

PWM controller is employed for the comparison of Reference Source Currents and the actual source currentsand the derived gating signals are applied to the gates of Voltage Source Inverter.

Chapter- 4

Multilevel Converters

4.1 Introduction

Converter is a conversion device used to alter the nature of electric supply i.e. from DC to AC and vice-versa, DC to DC as well as AC to AC. As a rectifier, AC input to DC output conversion is done. As an inverter, it converts DC input to AC output. As a chopper, DC to DC conversion is there and as a cyclo converter, AC to AC conversion is there.

Voltage source inverters (VSI) are basically two-level inverters. By increasing the switching frequency of VSI, better output voltage waveform can be obtained. Various PWM switching strategies are used to control harmonics in VSI.

Figure 4.1 shows the Flowchart for High Power Factor Converters.

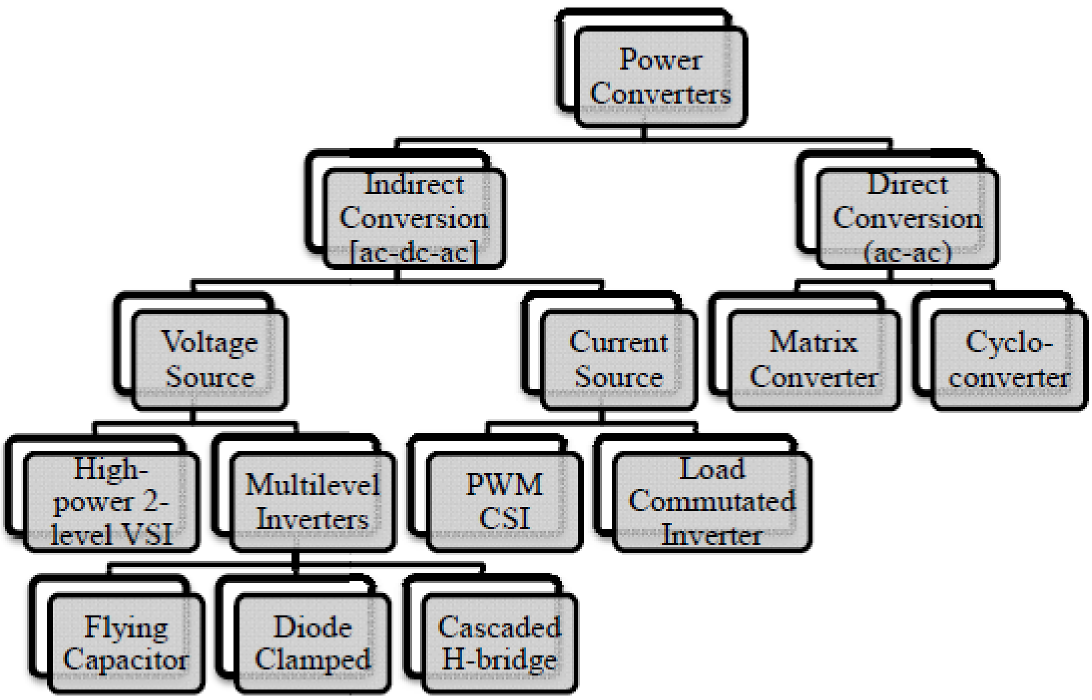

Figure 4.1: Flowchart for High Power Factor Converters

In the year 1975, the concept of Multilevel inverters was introduced. Basically, Multilevel inverter began with 3 level inverter.Multilevel inverters are fundamentally used to obtain sinusoidal voltage from several levels of voltage extracting input current with very low distortion operating at lower switching frequency; generate smaller torque ripples in the motor. These can generate output voltages with mature medium-power semi conductor technology with lower distortion. The output waveforms access a more sinusoidal wave with a reduced harmonic distortion when numbers of level are increased.

Multilevel inverters havereplaced the conventional VSIs because it is difficult to use conventional VSIs in high voltage appliances due to their high device rating constraints and increased switching losses. Also, the series/parallel combination of devices is a great problem.

The basic topology of the Multilevel inverter is toobtain a more sinusoidal voltage waveform from several level ofvoltages. The unique structure of MLI allows them to attain more number of voltage levels with lower harmonics without using a transformer or Series-linkedSynchronized Switching devices.

Basically Multilevel Inverters are used for Static VAR compensators, for Adjustable Speed Drives (ASD), back to back high voltages inter tie and many more.

A disadvantage of Multilevel inverter is the constraint of more number of power semiconductor switches. Though the switches used in MLIs are of low voltage rating but every switch involve a separate gate drive circuit which however makes the whole system more expensive with increase in the complexity.

Figure 4.2 shows the General topology for Multilevel Inverter.

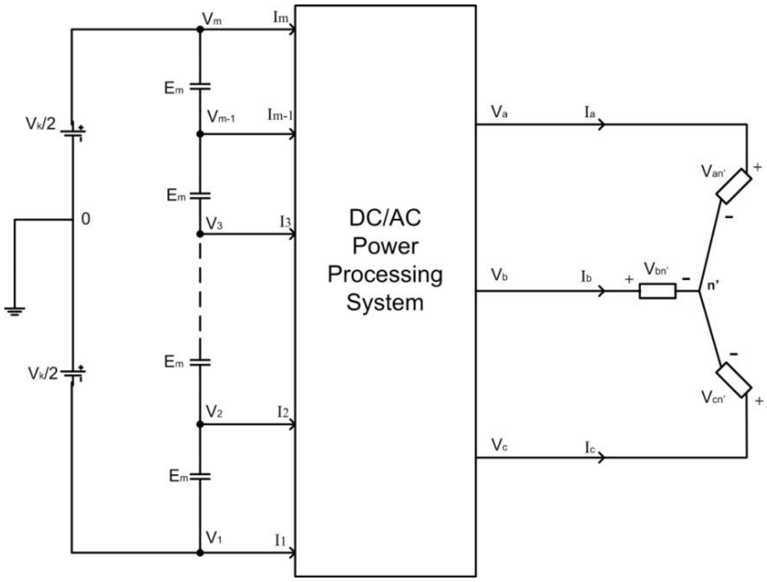

Figure 4.2: General topology for Multilevel Inverter

4.2 Multilevel Inverters

The basic standard Multilevelinverter are:

- DC-MLI
- FC-MLI
- Cascaded H-Bridge MLI

The brief description and basic layout of different Multilevel inverters are explained below.

4.2.1 DC-MLI: Diode-ClampedMultilevel Inverter

- For *p*-level inverter, (*p*-1) capacitors are required on the DC bus.
- *p*-level of phase voltage and (2*p*-1) levels of output line voltage are produced. For example, a 5 level inverter will produce 9 level output line voltage.
- In each phase, (*p*-1)*(*p*-2) number clamping diodes are required.
- Blocking diodes of high-voltage rating are required.

Figure 4.3 shows the simple layout of 3 level Diode-Clamped Inverter.

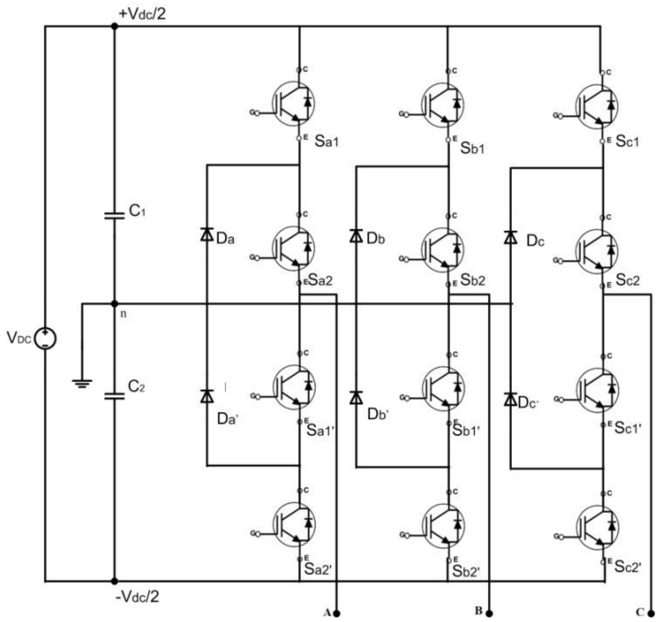

Figure 4.3: 3-level Diode-ClampedMultilevel Inverter

4.2.2 FC-MLI: Flying Capacitor Multilevel Inverter

- For *p*-level inverter, (*p*-1) numbers of capacitors are required at the DC bus.
- Control of both real and reactive power flow can be done.
- {(*p*-1)*(*p*-2)}/2 number of auxiliary capacitors are required per phase in DC bus.

Figure 4.4 shows the simple layout of 3 level Flying Capacitor Multilevel inverter.

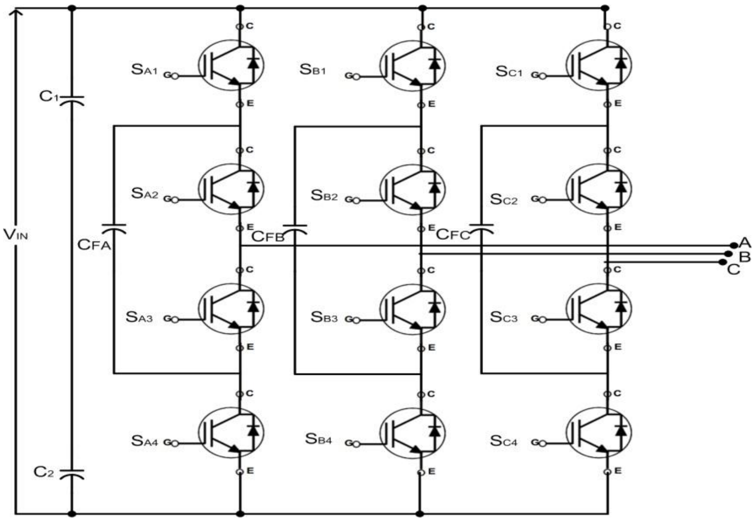

Figure 4.4: 3 level Flying Capacitor Multilevel Inverter

4.2.3 Cascaded H-Bridge Multilevel Inverter

- If *p* number of DC sources are used, (2*p*+1) number of output phase voltage will be generated.
- For real power conversion, separate DC sources are required.
- No extra capacitor is required.

Figure 4.5 shows the simple layout of 3 level Cascaded H-Bridge Multilevel Inverter.

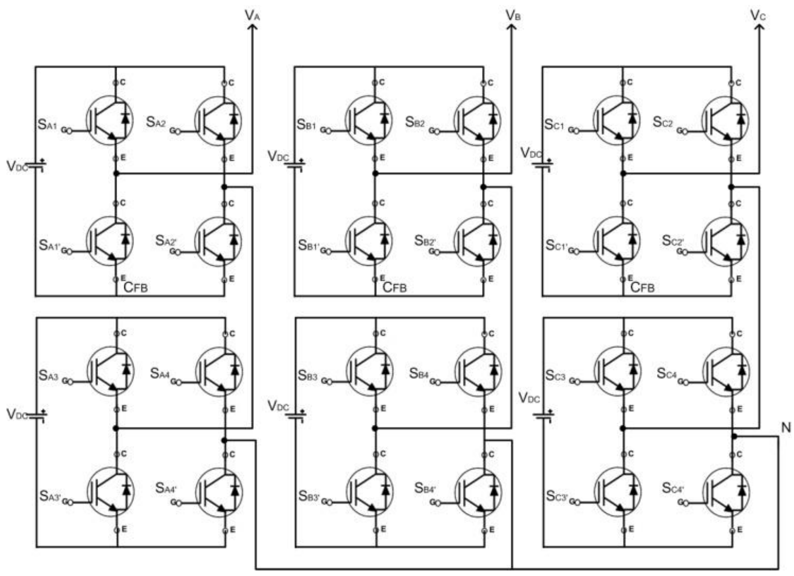

Figure 4.5: 3 level Cascaded H-BridgeMultilevel Inverter

In presented work, DC-MLI has been explained in detail in next section.

4.3DC-MLI: Diode-Clamped Multilevel Inverter

Nabae, Takahashi and Akagi put forward the first 3 levelDC-MLI in year 1981. The DC- MLI is also acknowledged as Neutral Point Clamped (NPC) Multilevel Inverter. Without requiring exact voltage match condition, it doubles the device voltage level.DC-MLI is basically used for Static VAR compensation,for inter- connection of high-voltage systems, Variable speed motor drives, mills, conveyors and so on.

For *p*-level inverter, at the DC bus (*p*-1) capacitors are requiredproducing*p* level of phase voltage with (2*p*-1) levels of output line voltage. Blocking diodes of high voltage rating are required for DCMLI with (*p*-1)*(*p*-2) number of clamping diodes required in each phase. Available commercial ratings of DCMLI are 2.2 to 6.6 kV, 3.7 to44MVA.

For our work, Simulation of 7-level DC-MLI is implemented on MATLAB/Simulink R2015b. Simulation of 7-level DC-MLI is shown in Figure 4.6.

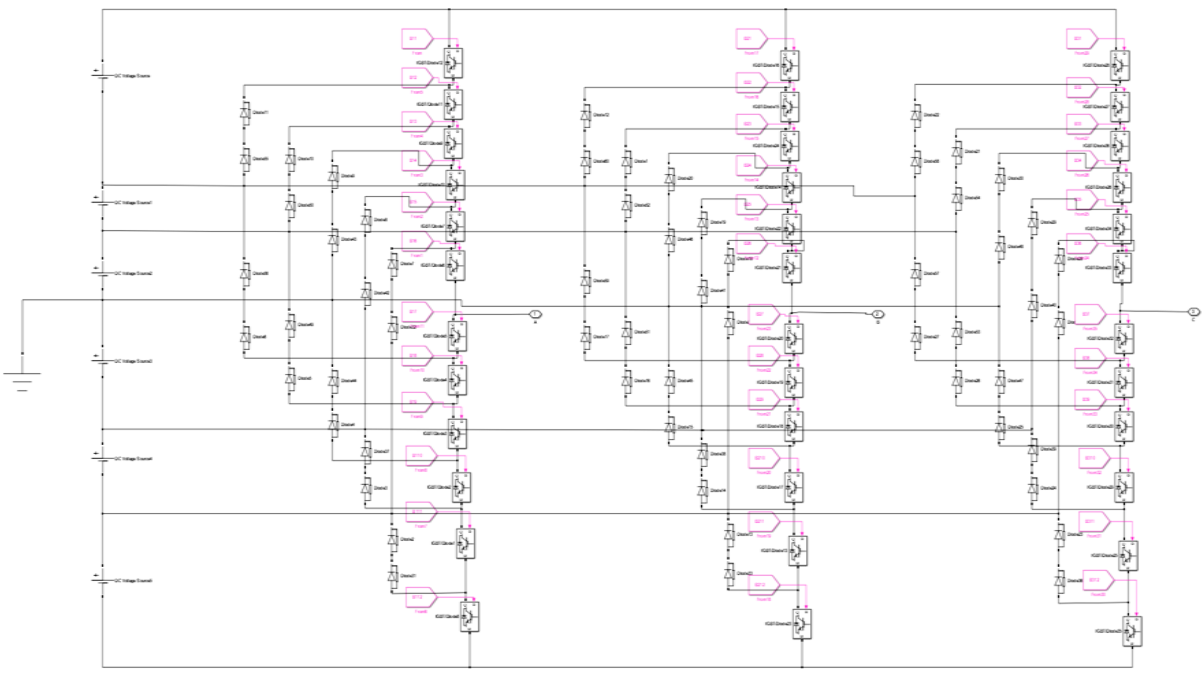

Figure 4.6: Simulation of 7- level Diode-Clamped MLI

Output levels of a 7 level Diode-Clamped MLI are +3V_{DC}, +2V_{DC},+V_{DC}, 0, -V_{DC}, -2V_{DC}, -3$V_{DC..}$ DC-MLI topology is one of the generally used topology because of its high voltage levels and high efficient operation.

A common DC bus is used for all 3 legs of the inverter and ($V_{DC}/6$) is the voltage across each capacitor. Each leg of inverter consists of six complimentary switch pairs such that only one switch is operated during the operation.

Figure 4.7 depicting 7 level DC-MLI output waveform.

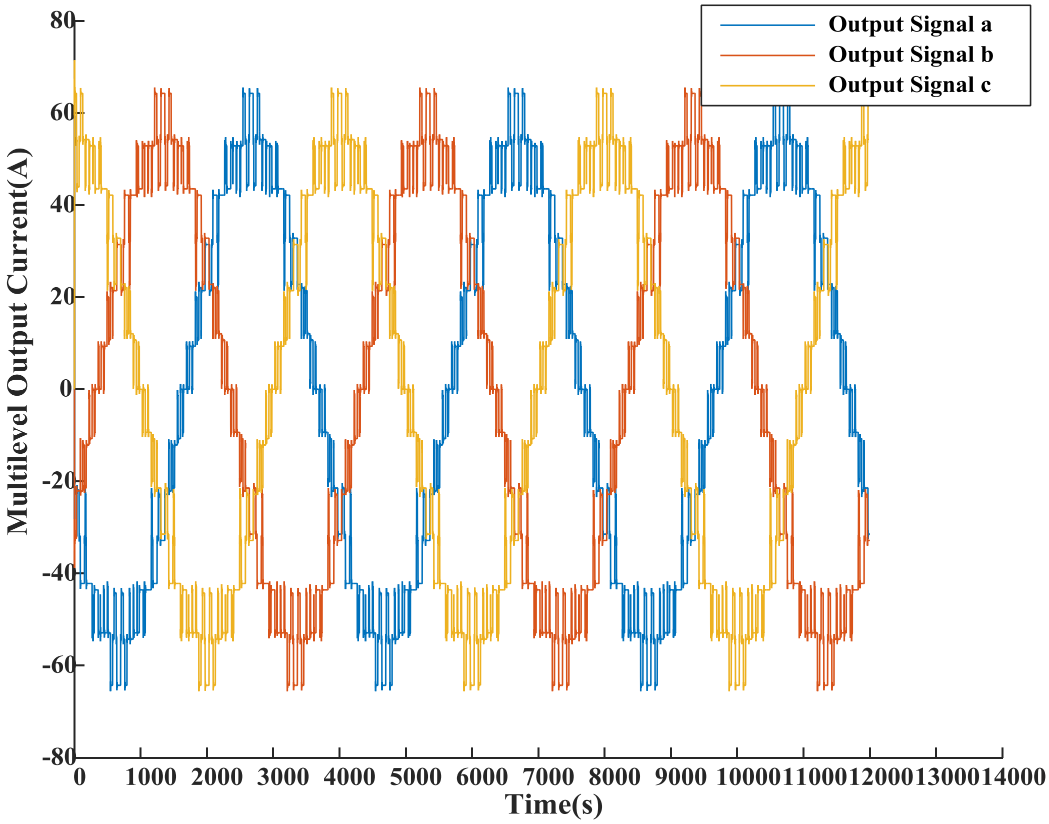

Figure 4.7: Output Waveform of 7-level DC-MLI

Multilevel Sinusoidal PWM is the comparison of the carrier wave and sinusoidal wave. Vertical carrier distribution techniques and horizontal carrier distribution techniques are the two types of Modulation techniques. The shifting of the carrier wave in the vertical direction comes under vertical carrier distribution techniques.POD, PD and APOD comes under vertical carrier distribution techniques whereas the shifting of the carrier wave in horizontal direction comes under horizontal carrier distribution techniques.

The method available for this 7-level Diode-Clamped MLI is Phase Dissipation Modulation technique.

4.3.1 Advantages of DC-MLI

- Control method for back-to-back inter tie system is simple.
- Efficiency is high due to fundamental switching frequency.
- Controlling of reactive power is easy.
- Filter requirement is avoided as harmonic content will reduce when the number of levels is increased.

4.3.2 Disadvantages of DC-MLI

- With the increase in level, the requirement of diodes also increases.
- For individual converter, real power flow control is a difficult task.
- Sometimes unequal device rating and capacitor voltage unbalance also cause some issues

Chapter- 5

System Test and Results

5.1 Introduction

Power Quality concern issues like Voltage Sag, transients, interruption of power supply, Voltage Swell, harmonic distortions and many more problems are introduced into the system owed to the usage of non-linear loads. Harmonics are injected into the power network, distortion of voltage at the PCC, insulation failure of the machines due to the overheating and over voltages, malfunctioning of sophisticated electronic equipment and many more problems arise due to the deteriorated Power Supply. Conventional equipments like passive filters including of R,L,C components are unable to solve Power Quality problems. Active Power Filters are better than passive filters as they can be used for reactive power compensation, flicker mitigation and unbalance compensation.

D-STATCOM, Custom Power device used for power factor correction at the distribution end. A voltage source converterlinkedat one end and a DC capacitor linked at the other end. IGBTs are used due to their lower switching losses and higher conduction rate. Multilevel inverters are used to obtain sinusoidal waveform with more number of voltage levels thereby reducing theTHD value. In this thesis, MATLAB/SIMULINK R2015b software has been used to design the D-STATCOM model based upon *dq0* transformation and a 7 level DC-MLI. This system is analysed for an Induction Furnace Drive non-linear load under working conditions. The SRF control technique is employed for D-STATCOM which observes the difference between the load current and reference current. Consequently, the gating signals for Multilevel inverter are produced.

5.2 Parameters of the Test System

The proposed model system is tested for FOC induction motor drive load. The system is equipped with 3 phase programmable voltage source with 338 Vrms, 50 Hz and a 7 level DC-MLI is linked with the system.

Parameters of the test system are indexed in Table 5.1.

Table5.1: System Parameters

Serial No.	System Quantities	Parameters
1.	Voltage Source side	3-phase, 338Vrms (Line Voltage), 50 Hz.
2.	FOC Induction Motor Drive (Machine)	Nominal Power -200e3 VA, Stator Resistance -14.85 mΩ, Rotor Resistance -9.295 mΩ,, Leakage Inductance (Stator &Rotor) – 0.3027 mH Mutual Inductance – 10.46 mH
3.	FOC Induction Motor Drive (Converters)	Snubber Circuit - C- 20 pF R-10 KΩ Inverter- IGBT/Diodes, On-state Resistance -1mΩ
4.	Diode-ClampedMultilevel Inverter	IGBT/Diodes, 3 arms

The proposed test system model and the various test results in MATLAB/SIMULINK are shown in the next sub-section.

5.3 MATLAB/SIMULINK Results

The test system is designed on MATLAB/SIMULINK R2015b with FOC Induction Motor Drive as non-linear load and a Diode-ClampedMultilevel Inverter. SRF control theory is used for D-STATCOM. Figure 5.1 shows the Simulink model of the proposed work.

In the test system, it is observed that due to the usage of FOC Induction Motor Drive, the THD level of 3.84% is observed in the load current whereas for the Compensating Current provided by the D-STATCOM is 3.61%. The THD level for supply current is 0% due to the coupling of D-STATCOM in the network. The presence of 0% THD level in source current shows that the designed D-STATCOM efficiently compensates for the load current harmonics.

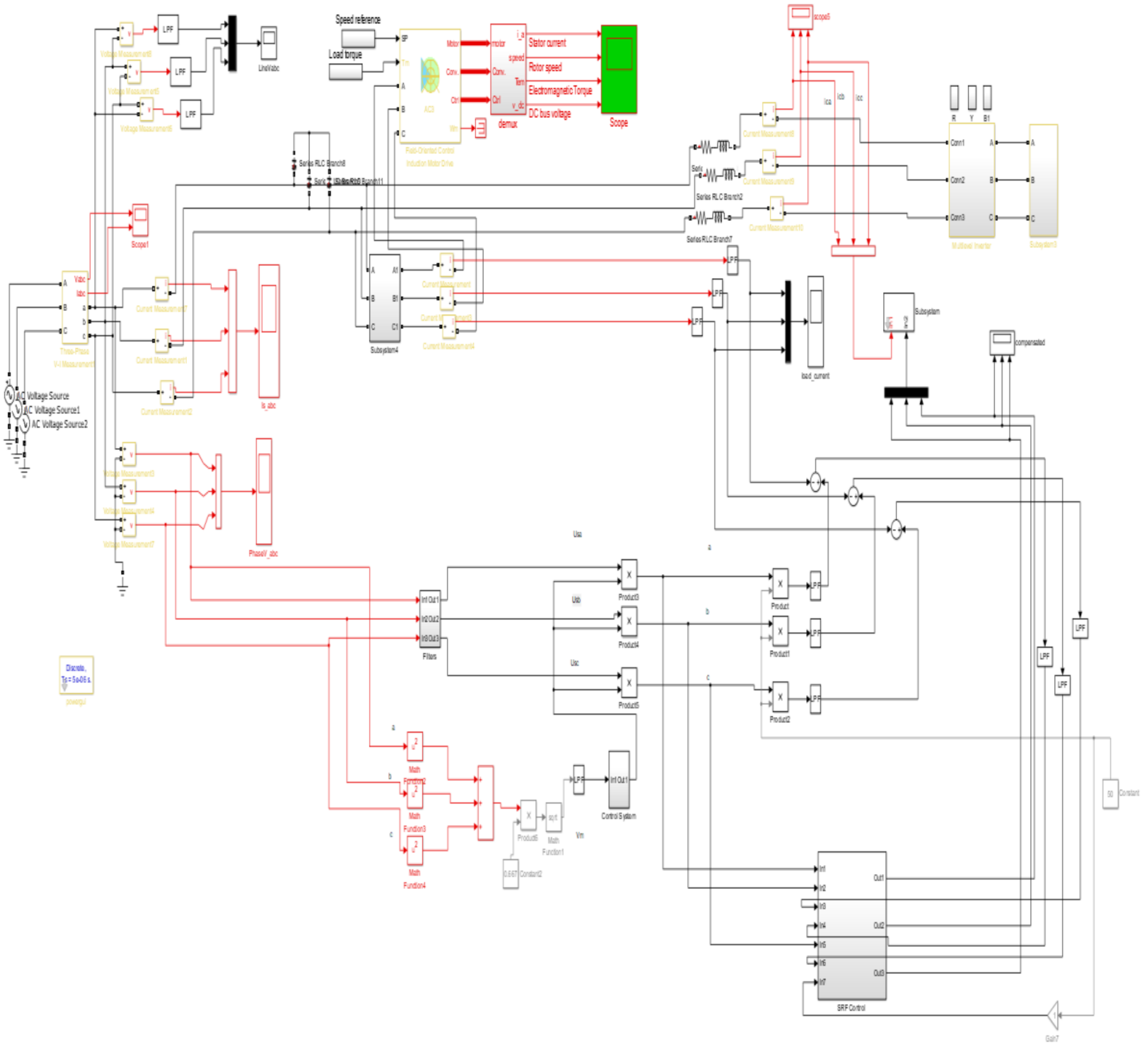

Figure 5.1: MATLAB\SIMULINK of Test System

The output waveforms for source phase voltage, source current, load current and compensating current with their FFT Analysis are shown below.

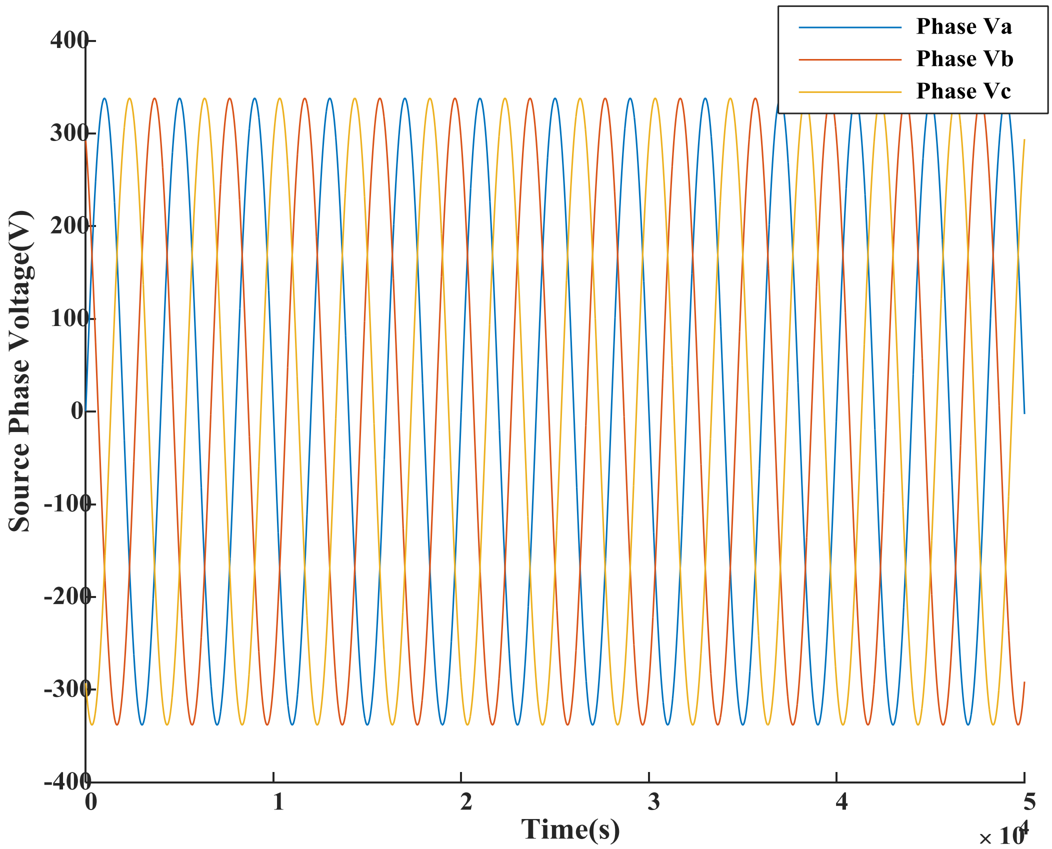

Figure 5.2: Output Waveform of Source Phase Voltage

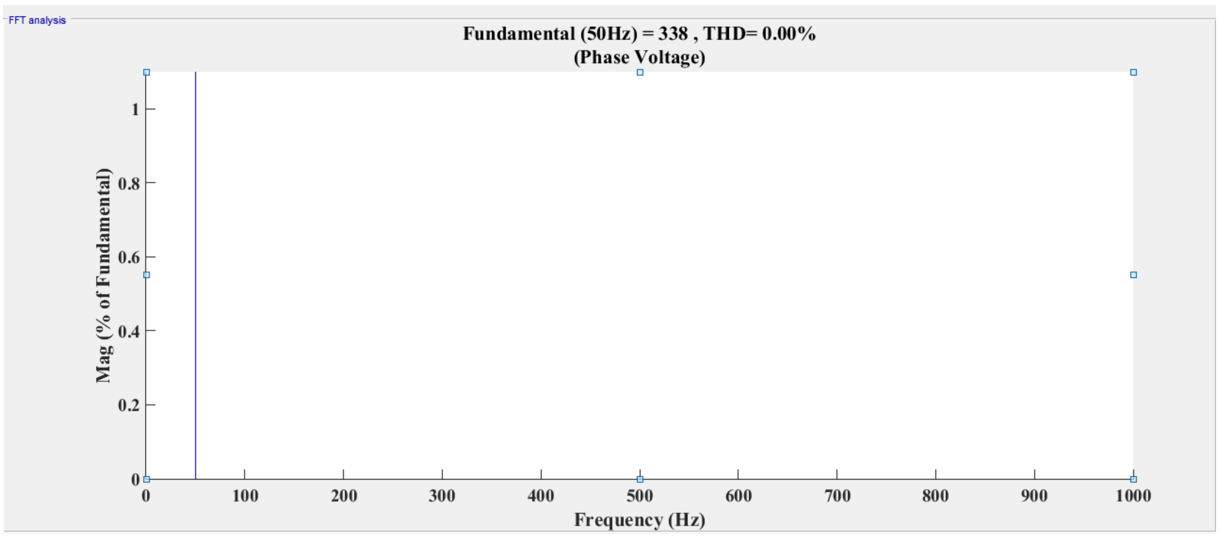

Figure 5.3: Frequency Spectrum of Source Phase Voltage

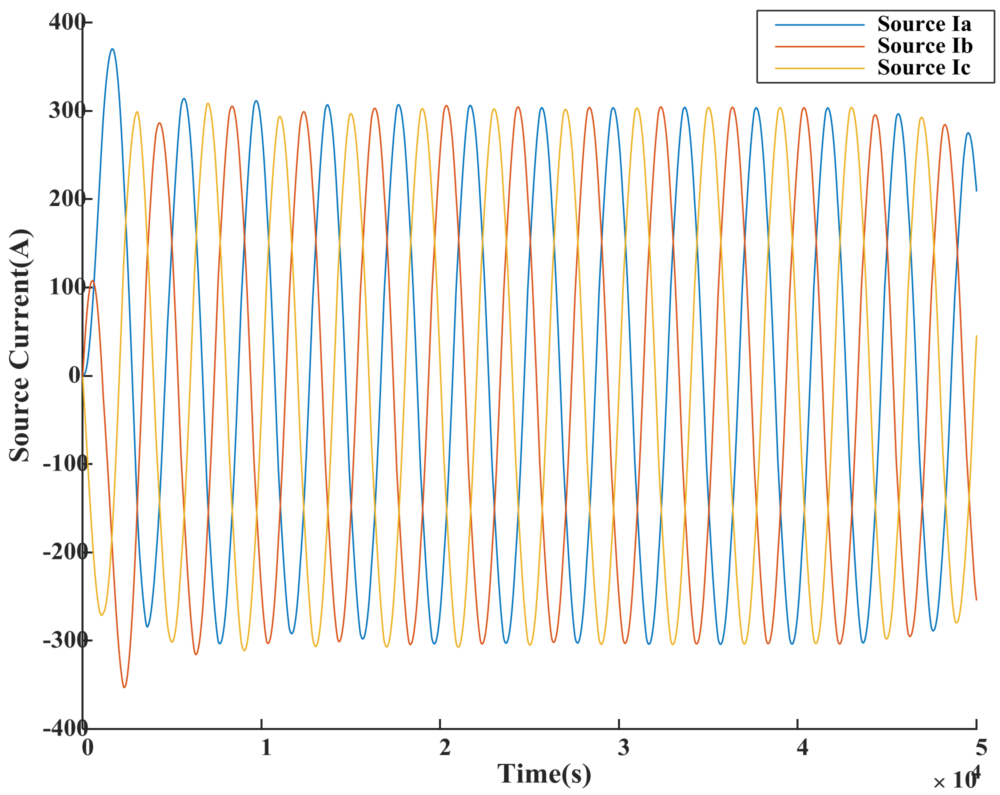

Figure 5.4: Output Waveform of Source Current

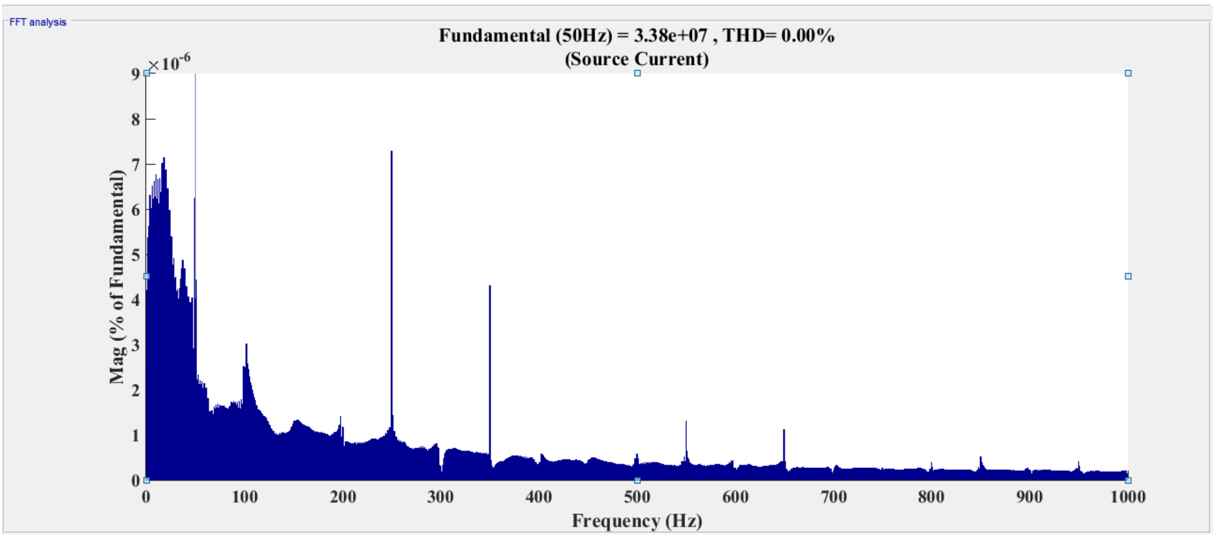

Figure 5.5: Frequency Spectrum of Source Current

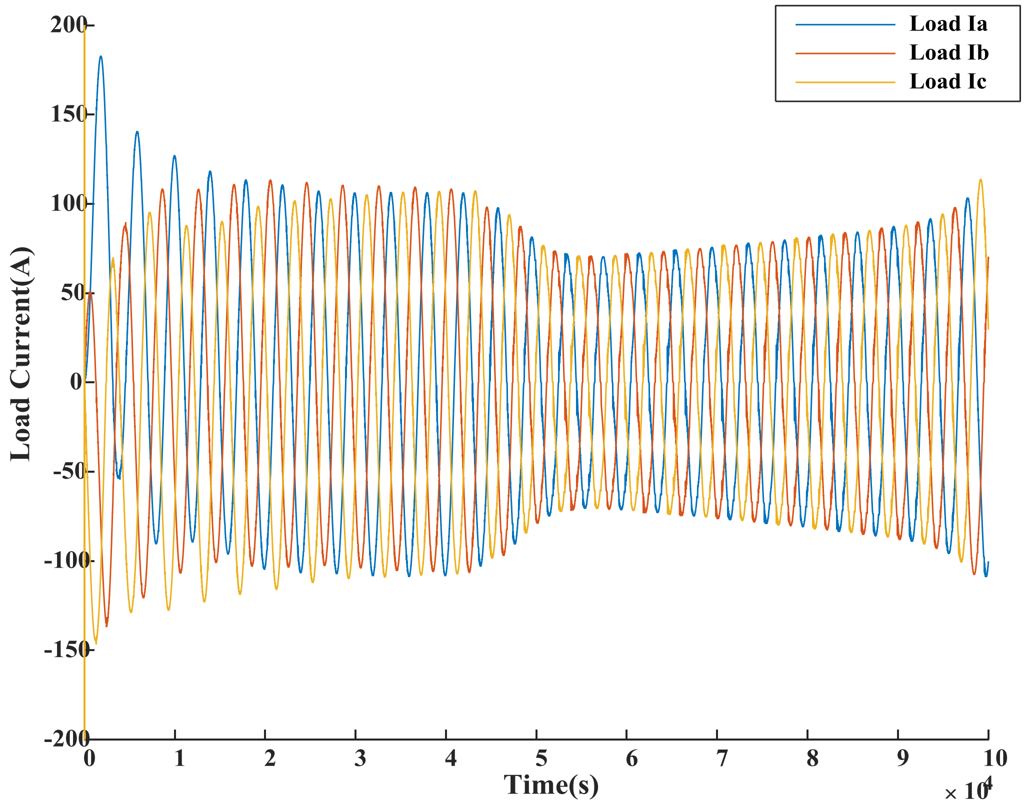

Figure 5.6: Output Waveform of Load Current

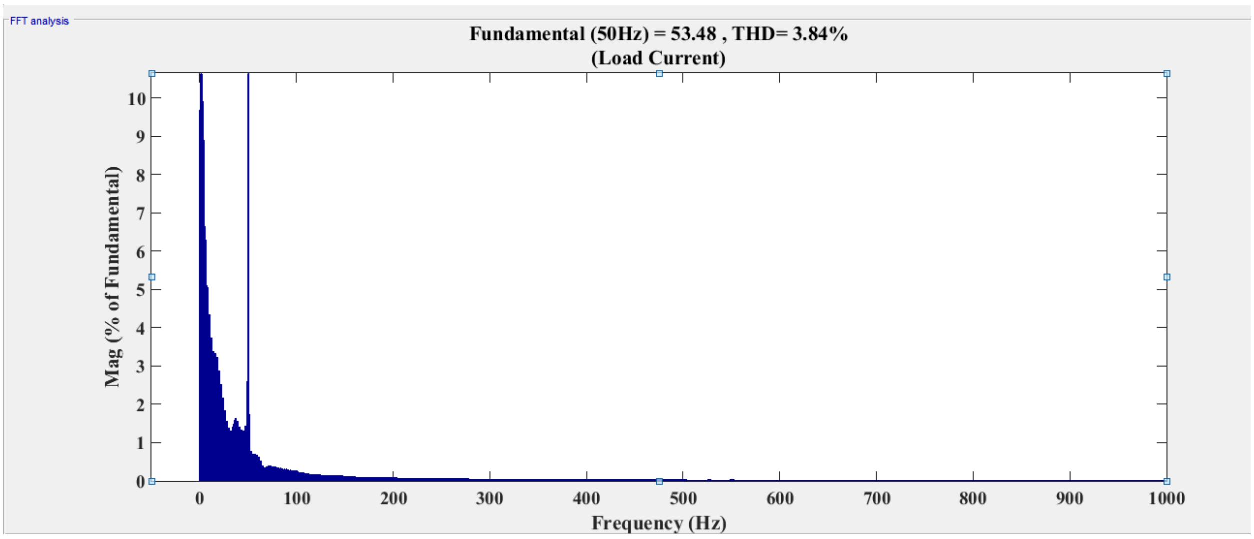

Figure 5.7: Frequency Spectrum of Load Current

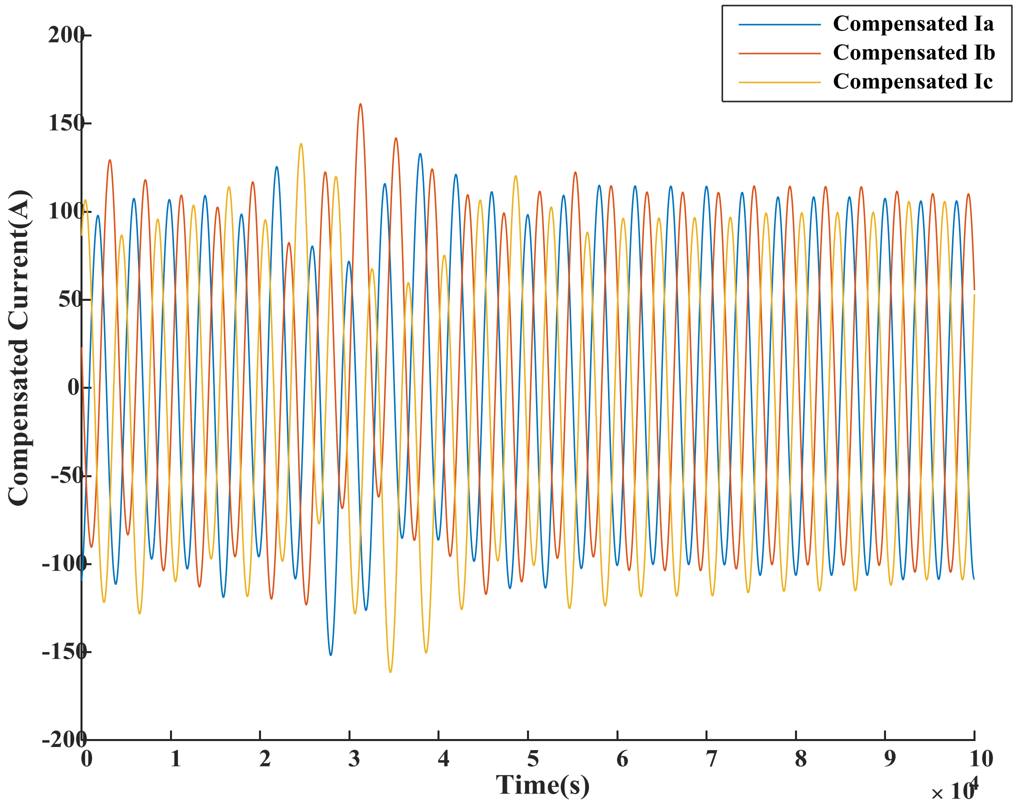

Figure 5.8: Output Waveform of Compensated Current

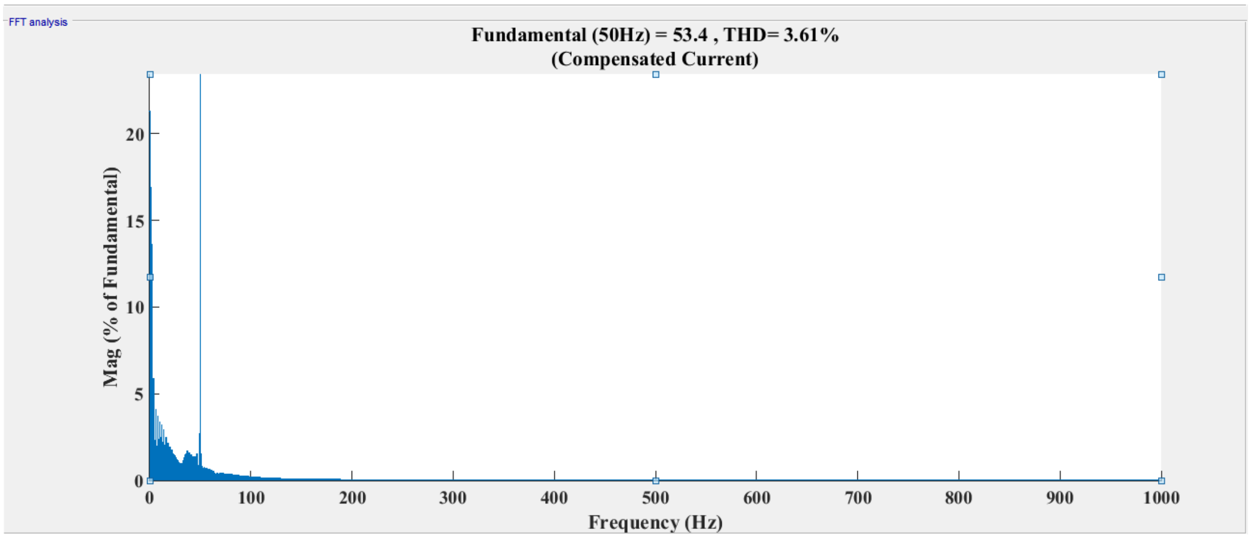

Figure 5.9: Frequency Spectrum of Compensated Current

Chapter- 6

Conclusions and Future Scope

6.1 Conclusions

In the present work, Power Quality and its problems has been discussed with their mitigation techniques. Different types of Custom Power devices are discussed in which particularly MATLAB/SIMULINK model of D-STATCOM has been modelled and simulated for Field Oriented Control (FOC) Induction Motor drive using the Synchronous Reference Frame (SRF) control theory. MATLAB/SIMULINK model of 7 level DC-MLI has also been developed. It is clearly observed from the test results that D-STATCOM efficiently eliminates the harmonics from source current making the 0% THD level for source current. With the use of Multilevel inverter, the output waveform is more sinusoidal with reduced harmonic distortion. From the present work, it can be concluded that D-STATCOM finds applications in effectively enhancing the Power Quality level at distribution side of the Power System.

6.2 Future Scope

In the present work, D-STATCOM effectively eliminates harmonic content from the load current. Present work can be extended in the following ways:

- To mitigate Power Quality problems using D-STATCOM for Renewable Energy based distribution system.
- D-STATCOM with hybrid Multipulse converter based system can be implemented.
- Hybrid Multilevel inverter based D-STATCOM system can be explored.

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