INTIGRATING DSTATCOM WITH PHOTOVOLTAIC ENERGY STORAGE SYSTEM FOR POWER TRANSIENT STABILITY

Thesis submitted in partial fulfilment of the requirements for the award of degree of

MASTER OF ENGINEERING

IN

POWER SYSTEMS & ELECTRIC DRIVES

Submitted by:

GURJOT SINGH

Registration No- 821141005

Under the supervision of:

Dr. PRASENJIT BASAK

Assistant Professor, EIED

JULY 2014

ELECTRICAL & INSTRUMENTATION ENGINEERING DEPARTMENT

THAPAR UNIVERSITY PATIALA- 147004

CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled "**Integrating DSTATCOM with Photovoltaic Energy Storage System forPower System Transient Stability**" in partial fulfilment of requirement for the award of the master degree in POWER SYSTEM AND ELECTRIC DRIVES engineering submitted in the ELECTRICAL AND INSTRUMENTATION ENGINEERING department, Thapar University, Patiala is an authentic record of my own work carried out under the guidance of Dr. **PRASENJIT BASAK** (Assistant Professor EIED, Thapar University).

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

Gurjot Singh 16/07/2014
(GURJOT SINGH)
Regn.No.821141005

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

16/7/14
(Dr. PRASENJIT BASAK)
Assistant Professor
Electrical & Instrumentation Engg. Department
Thapar University, Patiala

Countersigned by:

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

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

ACKNOWLEDGEMENT

My words in full measure can't reciprocate the kindness shown and contribution made by several people in this endeavour of mine. I would like to express my sincere gratitude to all of them. Foremost, I would like to express my sincere thanks to my thesis supervisor **Dr. PRASENJIT BASAK**, Assistant Professor in Electrical & Instrumentation Engineering Department, for the continuous support, valuable guidance, scholarly inputs and consistent encouragement throughout my work. I would forever be indebted to him &his guidance that helped me in all the time of research and writing of this thesis. It has been a great honour to have **Dr. PRASENJIT BASAK** as supervisor.

I would like to thank **Dr. RAVINDER AGARWAL**, Professor & Head, Electrical & Instrumentation Engineering Department, Thapar University for his valuable suggestions and providing a good working environment. I wish also to extend my acknowledgements to all staff members in the department and my friends for their insights & helpful thoughts.

Last but not the least, I would like to thank my parents for supporting me spiritually throughout my life.

Gurjot Singh

GURJOT SINGH

ABSTRACT

Recently, with the growth of industry manufacturers and population, electric power quality becomes more and more important. The growing amount of power electronics-based equipment has had a profound impact on the quality of electric power supply. Now a day, consumers require high quality power supply for their sensitive loads. Voltage flicker has therefore been an important power quality concern for supply utilities, regulatory agencies and customers. Erratic variation in reactive power demands lead to a fluctuating voltage drops across the impedance of a distribution system which results in voltage fluctuation at the point of common coupling (PCC). Voltage sags are one of the most dominating power quality problem, which has drawn the attention of many researchers as the demand for sensitivity of loads are increasing due to extensive usage of power electronic devices. Fault at distribution level, sudden increase of loads, motor starting are some of the causes of the voltage sags. Such sudden variations of voltage are undesirable for sensitive loads. Traditionally, for mainly inductive supply system, power quality can be improved by using reactive power control methods. These undesirable power quality problems can be mitigated by connecting controlled devices either in series or shunt to the load. A few of such devices are dynamic voltage restorer (DVR) and Distribution Static Compensator (DSTATCOM). Both these devices require voltage source converters to satisfactory operation. Many topologies have been proposed in recent past for voltage source converters in many published literatures.

A DSTATCOM is a fast response, solid-state power controller that provides flexible voltage control at the point of coupling (PCC) to the utility distribution feeder for mitigations of power quality improvement. If it is coupled with energy storage system (ESS), it can exchange both active and reactive power with the distribution system by varying the amplitude and phase angle of the converter voltage with respect to the system voltage. The result is a controlled current flow through the interfacing inductance between DSTATCOM and the distribution system. The DSTATCOM can instantaneously compensate voltage sags by regulating the load voltage using the injected current from the converter and the voltage across equivalent inductance.

In this work, DSTATCOM has been modeled with Photovoltaic Energy Storage System and simulated in MATLAB/SIMULINK environment for improving the power quality of distribution systems with linear loads and static non-linear loads and the results are discussed.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ASD	Adjustable Speed Drive
BESS	Battery Energy Storage System
CBEMA	Computer Business Equipment Manufacturers Association
CPD	Custom Power Device
DSTATCOM	Distribution Static Compensator
DTC	Direct Torque Control
DVR	Dynamic Voltage Restorer
EMTDC	Electromagnetic Transients Including DC
ESS	Energy Storage System
EPQ	Electric Power Quality
FACTS	Flexible AC Transmission System
FFT	Fast Fourier Transform
FLC	Fuzzy Logic Controller
FOC	Field Oriented Control
GTO	Gate Turn-Off Thyristor
HVDVR	High Voltage Dynamic Voltage Restorer
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IGCT	Insulated Gate Commutated Thyristor
IPFC	Interline Power Flow Conditioner
IPM	Intelligent Power Module
IRPT	Instantaneous Reactive Power Theory
MOSFET	Metal-Oxide Semi-conductor Field effect Transistor
PI	Proportional Integral
PLC	Programmable Logic Controller
PLL	Phase Locked Loop
PQ	Power Quality
PSCAD	Power System Computer Aided System
PWM	Pulse Width Modulation
SA	Surge Arrester
SMESS	Super Magnetic Energy Storage System
SSSC	Static Synchronous Series Compensator

STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
SVPWM	Space Vector Pulse Width Modulation
TCSC	Thyristor Controlled Series Compensator
THD	Total Harmonic Distortion
UPFC	Unified Power Flow Conditioner
UPQC	Unified Power Quality Conditioner
VSC	Voltage Source Converter

CHAPTER 1

INTRODUCTION

1.1Overview on DSTATCOM

Electricity supply plays an important role in the economic development and technology advancement throughout the world. Recently, with the growth of industry manufacturers and population, electric power quality becomes more and more important. The quality and reliability of power supplies relates closely to the economic growth of a country. However, power quality disturbances such as sags, swells, flicker, harmonics, voltage imbalance etc., create a lot of problems in achieving a reliable and quality power supply.

Now a day, consumers require high quality power supply for their sensitive loads. In modern industries, load equipment uses electronic controller, which are sensitive to poor voltage quality and will shut down if supply voltage is depressed and may mal-operate in other ways, if harmonic distortion of the supply voltage is excessive. Distribution systems are more prone to load perturbations and faults due to the weak nature of isolated systems [1]. They receive no support from grid and the systems even more susceptible to load variations and faults. As a result, compensators are required to meet real and reactive power needs of the system during steady state and transient conditions.

Custom Power Devices are used in distribution systems to mitigate power quality problems and a number of configurations are increasing in use world-wide. A custom power device can be series connected, shunt connected or both simultaneously across the system. The amount of compensation offered by the device depends on the design of voltage source converter (VSC) i.e. DC link capacitor, device rating of IGBT switches and interface inductors. Distribution Static Compensator (DSTATCOM), Dynamic Voltage Regulator (DVR), Unified Power Quality Conditioner (UPQC), BESS are some of the custom power devices used at distribution level [3].

A distribution static compensator or DSTATCOM is a fast response, solid-state power controller that provides flexible voltage control at the point of coupling (PCC) and it is a voltage source converter (VSC) based power electronic device which is connected in parallel with the system to the utility distribution feeder for mitigations of power quality problem. If it is coupled with energy storage system (ESS), it can exchange both active and reactive power with the distribution system by varying the amplitude and phase angle of the converter voltage with respect to the system voltage. The result is a controlled current flow through the interfacing inductance between DSTATCOM and the distribution system.

In this thesis work, among the different custom power devices, the role of DSTATCOM has been investigated to improve the quality of power under different conditions.

A DSTATCOM is a voltage source converter (VSC) based power electronic device which is connected in parallel with the system. Usually, it is supported by energy storage device like capacitor. When a DSTATCOM is associated with a particular load, it injects compensating current, so that total demand meets the specifications for utility connections. DSTATCOM generates capacitive and inductive reactive power internally. Its control is very fast and has the capability to provide adequate reactive compensation to the system. DSTATCOM can be effectively utilized to regulate voltage for a series of small induction motors loads, which draw large starting currents (5-6 times) of full rated current and may affect working of other sensitive loads, connected to the system [5].

1.2 Literature Survey

A large amount of research is carried out in the field of custom power. A brief literature review related to DSTATCOM is presented as follows:

D.G. Flinn, *et al.* [1] discussed about various power quality problems that could exist in the power system. They also discussed the methods to identify the power quality problems. The electric utilities are receiving an increased number of customer complaints due to these types of problems. A systematic plan is needed to identify power quality problems in industrial, commercial or residential facilities. This paper explains about on site field measurements and routine checks on the system, that can help identify these problems most of the time. The data collected from the measurements can help in identifying the nature of the existing problem and also help to correlate the events to the problems.

J. Sun, *et al.* [2] explain Voltage flicker, a phenomenon of annoying light intensity fluctuation, which is caused by large rapid industrial load changes, it has been a major concern for both power companies and customers in the area of power quality. Distribution Static Compensator (DSTATCOM) has fast response which makes it the efficient solution for improving power quality in distribution systems. A voltage flicker phenomena in a distribution system is modelled and simulated and Voltage flicker mitigation studies with a current controlled PWM-based DSTATCOM are discussed

A. El Mofty, *et al.* [3] discussed about real time industrial power quality disturbances. Power quality disturbances are usually caused by non-linear loads, load switching, system faults, motor starting, load variations, intermittent loads and arc furnaces. These cause many electrical disturbances like voltage surge, voltage dip, harmonic distortions, interruptions and flicker. This paper presents analysis of the real time industrial electrical disturbances, power disturbance log and some suggestions to minimize or prevent inconveniences caused by power disturbances.

Walmir Freitas, *et al.* [4] presents a dynamic study about the influences of ac generators (induction and synchronous machines) and distribution static synchronous compensator (DSTATCOM) devices on the dynamic behaviour of distribution networks. The performance of a DSTATCOM as a voltage controller or a power factor controller is analyzed. The impacts of these controllers on the stability and protection system of distribution networks with distributed generators are determined. Computer simulation results show that a DSTATCOM voltage controller can improve the stability performance of induction generators significantly. On the other hand, a DSTATCOM power factor controller may adversely affect the stability performance of synchronous generators. It has also been observed that a DSTATCOM has no influence on short-circuit currents provided by ac generators during faults.

Bhim Singh, *et al.* [5] discuss DSTATCOM (Distribution Static Compensator) for load balancing, neutral current elimination, power factor correction and voltage regulation in three-phase, four-wire distribution system feeding commercial and domestic consumers. A four leg voltage source inverter (VSI) configuration with a dc bus capacitor is employed as DSTATCOM. The modified instantaneous reactive power theory (IRPT) is used in the control of DSTATCOM

M. G. Molina, *et al.* [6] describes the dynamic modelling and the control design of a distribution static compensator (DSTATCOM) coupled with ultra-capacitor energy storage (UCES) for improving the power quality of power systems. Three modes of operation are considered, i.e. voltage control for voltage fluctuations ride-through, current/voltage harmonics mitigation and dynamic active power control.

V. B. Virulkar, et al. [7] describes mitigation of flicker due to electric arc welder by using DSTATCOM with Battery Energy Storage System (BESS) and shows that control of active power along with reactive power control helps to mitigate the voltage flicker problem more effectively. Furthermore the voltage flicker mitigation of Electric Arc Welder with

DSTATCOM along with Battery Energy Storage System (BESS) is analyzed using the PSCAD/EMTDC software.

Cristian A. Sep´ulveda, et al. [8] illustrates that Power Quality disturbances have been faced through Custom Power Devices such as Static Series Compensator (SSC) and Distribution Static Compensator (DSTATCOM), each one provide part of the compensation capabilities required. To provide total functionality, it is possible to operate both equipments mentioned before, or to use a Unified Power Quality Conditioner (UPQC) which integrates both topologies not only providing full compensation capabilities but also improving compensation characteristics**.**

Sumate Naetiladdanon, et al. [9] demonstrates compensation performance of voltage sag by using DSTATCOM. The steady state performance for voltage sag compensation by DSTATCOM along with series inductor as well as energy storage has been studied in this paper. Three current injection schemes for voltage sag compensation with different purposes were discussed. Simulation results confirmed that DSTATCOM system with additional series inductor and energy storage could improve voltage sag compensation performance. Thus, DSTATCOM is a prominent feature in power system in mitigating power quality related problems in the next decades.

P. N. Boonchiaml, et al. [10] discussed the use of an energy storage device linked to a DSTATCOM to provide real power as well as reactive power flow. This paper presents the design, control and analysis of a DSTATCOM enhanced with an energy storage device when coupled with a wind farm comprising fixed speed induction generator. This demonstrates that the DSTATCOM, controlled via a decoupled vector control technique, is an effective method of decreasing voltage flicker emissions at the point of common coupling, removing the wind speed fluctuations and improving the transient stability of wind.

Sumate Naetiladdanon, et al. [11] describe that DSTATCOM can compensate voltage sags by injecting the reactive power into the distribution system. However, the false compensation due to the interaction with system could occur. In this the design considerations of DSTATCOM for voltage sag compensation were analysed. Also the voltage sag compensation performance with different current injection schemes was briefly explained and the interaction was described. After that the design of DSTATCOM system with controller for voltage sag compensation is proposed. Simulation results confirmed that the proper design of DSTATCOM system can achieve the good voltage sag compensation performance without interaction with the system.

M. G. Molina, et al. [12] describes the control design and the Dynamic Modelling of a distribution static compensator (DSTATCOM) coupled with ultra-capacitor energy storage (UCES) for reliability of the power quality in power systems. The control technique used in this is based upon on the instantaneous power theory on the synchronous-rotating *dq* reference frame. The fast response device shows to be very efficient in enhancing the distribution power quality, successfully mitigation of disturbances like voltage swell, voltage sag and voltage/current harmonic distortion, among other transients.

M. G. Molina, et al. [13] discusses the dynamic performance of a distribution static compensator (DSTATCOM)integrated with an energy storage system (ESS) to reduce transients and to improve the power quality of distribution systems. The presented integrated DSTATCOM/ESS compensator is considered as a voltage controller, a power factor controller and an active power controller. Dynamic system simulation studies demonstrate the effectiveness of the proposed multi-level control approaches in the synchronous-rotating dq reference frame. The result obtained shows the good performance of the multilevel controller along with the benefits of its use in the distribution level power quality (PQ).

Vasudeo Virulkar, et al.[14] discuss the dynamic performance of a DSTATCOM coupled with BESS for mitigation of flicker due to electric arc furnace . The modelling of DSTATCOM with BESS and is controlled by the controller acting on battery energy storage system, the dc-link voltage and the voltage at PCC. Moreover its results indicates that mitigation of flicker with DSTATCOM and BESS are much accurate than DSTATCOM used alone by supporting the active and reactive power at the particular time improves power quality in electric distribution systems. It is effective in compensating reactive power and improving the power factor of the distribution system.

Marcelo G. Molina, et al [15] proposes the use of superconducting magnetic energy storage (SMES) along with a distribution static synchronous compensator (DSTATCOM) as an operational controller of tie-line power flow of micro grids incorporating wind generation. The high penetration of wind generation causes fluctuations of tie-line power flow and significantly affects power system operations. This could generate severe problems, like system frequency oscillations, and/or violations of lines capability. The multi-level control scheme check fast controllability of the DSTATCOM-SMES operating in the four-quadrant modes, which enables to effectively increase the transient and dynamic stability of the micro grid.

Suvire Gastón O, et al [16] investigate the use of a Distribution Static Synchronous Compensator (DSTATCOM) with a Flywheel Energy Storage System (FESS) to mitigate problems, mainly in power quality, introduced by wind generation in the electric system .The control technique used in system has one control mode for active power and two control modes for reactive power, power factor correction, and voltage control. And from the results obtained, it can be evaluated that with the proposed device and control mode, the power fluctuations coming from a WG are effectively compensated. It shows that the WG-DSTATCOM/FESS system can deliver a constant active power for a specified time range of seconds or more, as per the storage capacity.

G. V. R. Satyanarayana, et al [17] proposed a cascaded multilevel inverter type DSTATCOM to compensate power quality problems in utility voltages in power distribution system. With results it has been observed that with cascaded multilevel inverter dc voltage requirement decreases as with low dc voltage higher ac voltages can be produced. Moreover filter at the output of the inverter can be eliminated with multilevel topology hence reducing the cost of the filter also the total harmonic distortion came within the acceptable limits.

Marcelo G. Molina, et al [18] proposes the use of ultra capacitor energy storage (UCES) system in combination with a DSTATCOM as effective distributed energy storage for stabilization and control of the tie-line power flow of micro grids incorporating wind generation. A multilevel control algorithm based on a decoupled current control strategy in the synchronous-rotating *d-q* reference frame was proposed. This scheme ensures fast controllability of the DSTATCOM-UCES, which enables to increase the transient and dynamic stability of the micro grid.

Alka Singh, et al [19] discussed the application of Distribution Static Compensator (DSTATCOM) to a small distribution System from 42.SkVA diesel generator (DG). The isolated system was not supported from the grid and it was prone to a variety of system disturbances and faults. The performance of DST ATCOM installed with isolated system has been exhibited for linear loads and for load side disturbances especially different types of faults. The battery energy storage system (BESS) is so designed and modelled so that it can act as a source of leading or lagging source current. Although the DG system receives no support from the grid, an effective controller design provides load compensation and system support during faults. The work in the paper will boost the research in small dispersed generation and application of compensators under disturbances and faults. It is concluded that DST A TCOM can be used for power quality improvement on small isolated system.

S. H. Hosseini, et al [20] validates the performance of a D-STATCOM system for improving distribution system performance under all types of fault. In this scheme the 12-pulse DSTATCOM configuration with IGBT was designed and the graphic based models of the DSTATCOM were developed using the PSCAD/EMTDC electromagnetic transient simulation program. Simulation results proved the reliability and robustness of the control scheme in the system response to the voltage sags caused by all types of faults such as Single Line to Ground (SLG) fault and Double Phase to Ground (DPG) fault and three-phase fault.

G.O. Suvire , et al [21] discussed the incorporation of distribution static synchronous compensator (DSTATCOM) coupled with a flywheel energy storage system (FESS) is used to mitigate problems in transient stability introduced by wind generation in the electric system **.** The control technique used is based on fuzzy logic and a special filter. The complete system (DSTATCOM/FESS plus WG) generates a smoother power response than that of the system without the DSTATCOM/ FESS. This smoothing effect of the output power increases with the number of flywheels. Finally, it is concluded that the active power control proposed for the DSTATCOM/ FESS achieved a good management of the stored energy because the wind-power fluctuations were corrected with the storage device never being discharged or overloaded**.**

Annapooma Chidurala ,et al [22] describes various PQ problems such as overvoltage, voltage unbalance, dip/swells and harmonics and proposes a novel perception of operating PV inverter as a Solar-DST ATCOM with a new control topology to enhance PQ. Simulation results confirm that voltage rise, VU, voltage dips, swells and THO levels at various operating scenarios with the proposed Solar-OSTATCOM are well within proposed IEEE standards.

C. H. Lin, et al [23] discusses the use of distribution static compensator (DSTATCOM) to compensate reactive power during peak solar irradiation to prevent voltage violation so that the PV penetration level of a distribution feeder can be increased to fully utilize solar energy. The voltage control scheme of DSTATCOM is applied to mitigate system voltage violation due to excessive PV power generation during peak solar irradiation periods so that solar energy can be fully utilized.

1.3 Scope of Work

It was observed from the literature survey that, the field of power quality and custom power devices plays an important role in power system. For the improvement of power quality, DSTATCOM is one of the custom power device used in distribution system. This work proposes the MATLAB SIMULINK model of DSTATCOM which is used for the improvement of power quality at distribution level. The major objectives of this work are summarized as follows:

- To study the model of DSTATCOM along with energy storage system as Photo Voltaic Cell.
- To investigate the performance of DSTATCOM for different fault conditions like single line to ground fault, double line to ground fault under static linear loads and non-linear loads.

1.4 Organization of Thesis

The work carried out in the thesis has been compiled in six chapters.

- **Chapter1** highlights the overview, literature review and scope of work. It also contains the organization of thesis. The outline of the thesis is also given in this chapter.
- **Chapter2** explains the power quality, various power quality problems and their causes.
- **Chapter3** describes custom power, need of custom power and brief introduction of custom power devices.
- **Chapter4** describes the DSTATCOM in detail with energy storage as Photo Voltaic Cell.
- **Chapter5** presents parameter of the test system. Simulink models of the test system with linear loads & non-linear loads and their results are also discussed in this chapter.
- **Chapter6** contains the conclusion and future scope of work.

CHAPTER 2

POWER QUALITY PROBLEMS

2.1 Power Quality

Power Quality is a term that means different to different people. Power quality is “The provision of voltages and system design so that the user of electric power can utilize electric energy from the distribution system successfully without interference or interruption”. Institute of Electrical and Electronic Engineers (IEEE) standard IEEE 1100 defines power quality as “the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment” [2]. A broad definition of power quality borders on system reliability, dielectric selection on equipment and conductors, voltage unbalance in three-phase systems, long-term outages, power electronics and their interface with the electric power supply and many other areas.

Power quality in electric networks is one of today's most concerned areas of electric power system. The power quality has serious economic implications for consumers, utilities and electrical equipment manufacturers .A simpler word power quality is a set of electrical boundaries that allow a piece of equipment to function in its intended manner without significant loss of performance or life expectancy [4]. This definition embraces two things that we demand from an electrical device which are performance and life expectancy.

2.2 Problems Regarding Power Quality

Power Quality (PQ) related issues are of most concern nowadays. The ideal power supply voltage would maintain a steady magnitude and a sinusoidal wave shape without any interruptions. Any phenomena that will alter this ideal situation are classified as a disturbance. The growing amount of power electronics based equipments has had a profound impact on the quality of electric power supply. The widespread use of electronic equipments, such as information technology equipments, power electronics such as programmable logic controllers (PLC), Adjustable speed drives (ASD) and energy-efficient lighting cause harmonics in the network voltages [2]. Furthermore, conventional loads such as large arc-furnaces and welding machines cause voltage fluctuation, voltage imbalance and flicker.

These loads are simultaneously the major causes and the major victims of power quality problems.

Along with advance technology, the organization of the worldwide economy has evolved towards globalisation and the profit margins of many activities tend to decrease. The increased sensitivity of the vast majority of processes (industrial, services and even residential) to PQ problems turns the availability of electric power with quality a crucial factor for competitiveness in every activity sector. The most critical areas are the continuous process industry and the information technology services. When a disturbance occurs, huge financial losses may happen with the consequent loss of productivity and competitiveness.

Although many efforts have been taken by utilities, some consumers require a level of PQ higher than the level provided by modern electric networks. This implies that some measures must be taken in order to achieve higher levels of Power Quality. It is used to define various types of disturbances to the normal power system voltage. A variety of disturbances such as harmonics, transients, outages, faults, sags, swells, dips and flicker can be associated with the term "Power Quality". Various types of disturbances are defined below:

2.2.1 Voltage Sag (Or Dip) [1]

Voltage sag is defined as a decrease in the normal voltage level between 10 and 90% of the nominal rms voltage at the power frequency, for durations of 0. 5 cycle to 1 minute. It is clear from fig.2.1 that due to voltage sag the magnitude of voltage is reduced. Voltage sags are mostly caused by connection of heavy loads, start-up of large motors and faults in consumer's installation. Starting of large induction motors can result in voltage dip as the motor draws a current up to 10 times the full load current during the starting. The consequences of voltage sag are disconnection and loss of efficiency in electric rotating machines, tripping of electro-magnetic relays and malfunction of information technology equipment namely microprocessor-based control systems.

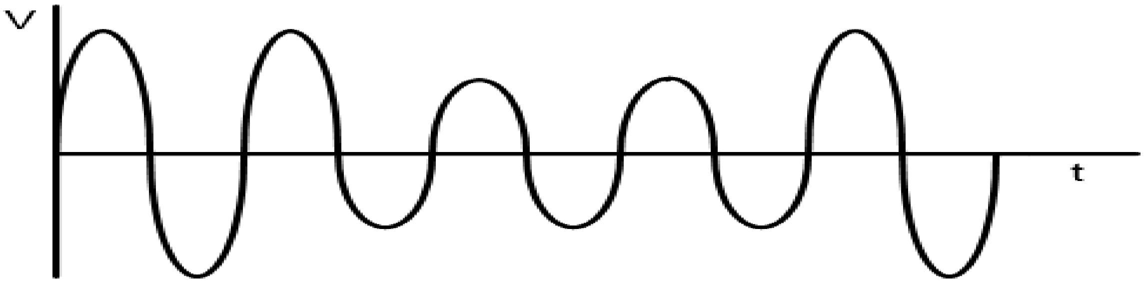

Fig.2.1: Voltage Sag [1]

2.2.2 Voltage Swell

Voltage swell is defined as momentary increase of the voltage at the power frequency, outside the normal tolerances, with duration of more than one cycle and typically less than a few seconds [2]. Fig.2.2 shows the increase in voltage magnitude due to voltage swell. Voltage swell is caused due to line faults, badly dimensioned power sources and incorrect tap settings in tap changers in sub stations. A SLG (single line to ground) fault can result in a voltage swell in the healthy phases. Swell can also result from energizing a large capacitor bank. The consequences of voltage swell are flickering of lighting and screens, data loss and stoppage or damage of sensitive equipment.

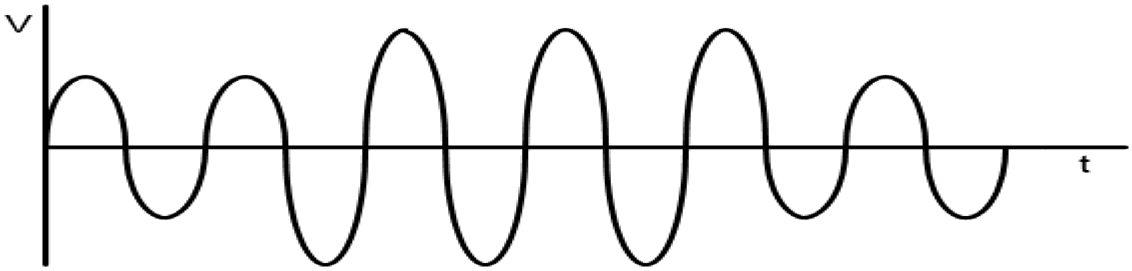

Fig. 2.2: Voltage Swell [2]

2.2.3 Interruption

An interruption is defined as a reduction in line voltage or current to less than 10 percent of the nominal value, not exceeding 60 seconds in length. Interruption can be of two types as given below:

2.2.3.1 Very Short Interruption [3]

Very short interruption is defined as total interruption of electrical supply for duration from few milliseconds to one or two seconds. It is shown in fig.2.3. It is caused due to insulation failure, lightning, system faults, equipment failures and insulator flashover. The consequences of very short interruption are loss of information and malfunction of data processing equipment, tripping of protection devices and stoppage of sensitive equipment.

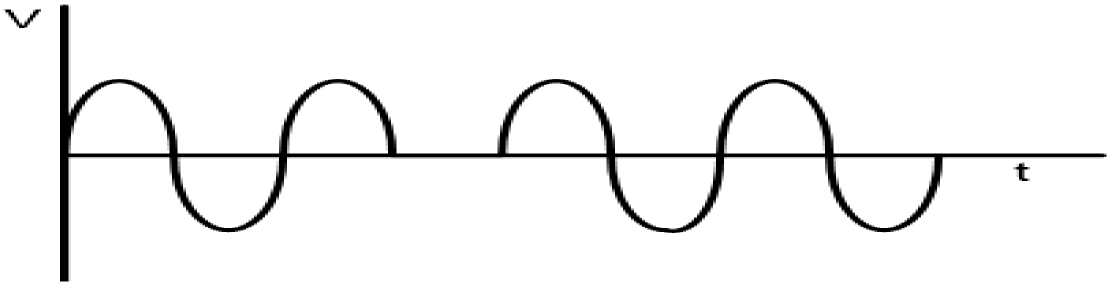

Fig.2.3: Very Short Interruptions [3]

2.2.3.2 Long Interruptions:

Long interruptions are defined as loss of utility power lasting more than 2 minutes due to major local area or regional electrical events. These are shown in fig.2.4. These are caused by equipment failure in the power system network, storms and objects striking lines or poles, power system faults and control malfunctioning. The consequences of long interruptions are stoppage of all equipment.

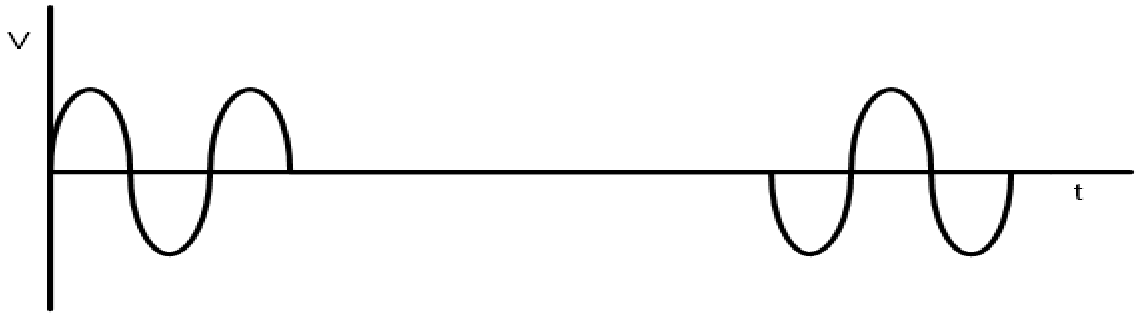

Fig.2.4: Long Interruptions

2.2.4 Transients

Transients are defined as very fast variation of the voltage values for durations from a several microseconds to few milliseconds. These variations may reach thousands of volts, even in low voltage. Transients are of two types which are given below:

2.2.4.1 Impulsive Transients [1]

An impulsive transient is a brief, unidirectional variation in voltage, current, or both on a power line as shown in fig.2.5.These are caused due to lightning, switching of inductive loads and disconnection of heavy loads. The consequences of impulsive transients are destruction of electronic components, failure of insulation materials, data processing errors and electromagnetic interference.

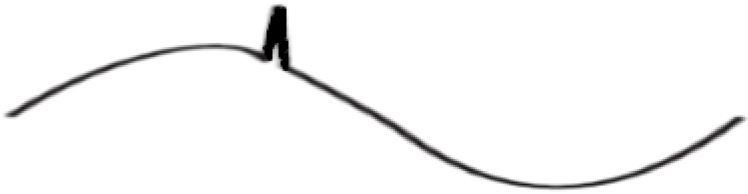

Fig.2.5: Impulsive Transients

2.2.4.2 Oscillatory Transients

An oscillatory transient is a brief, bidirectional variation in voltage, current, or both on a power line as shown in fig.2.6. These are caused due to power factor correction capacitors, switching of inductive loads and transformer Ferro-resonance. The consequences of oscillatory transients are failure of insulation materials, overheating of all cables, equipment and electromagnetic interference.

Fig.2.6: Oscillatory Transients [3]

2.2.5 Harmonic Distortion [2]

Harmonics can be defined as steady state distortion of voltage and current waveforms due to non-linear loads in the power system. Non-linear loads include adjustable-speed drives, arc furnaces and electronic power converters. The waveform corresponds to the sum of different sine-waves with different magnitude and phase, having frequencies that are multiples of power system frequency as shown in fig.2.7. Harmonics are caused due to electric machines working above the knee of the magnetization curve (magnetic saturation), arc furnaces, welding machines, rectifiers, DC brush motors and non-linear loads (such as power electronics equipment including ASDs, switched mode power supplies, data processing equipment and high efficiency lighting). The consequences of harmonics are increased probability in occurrence of resonance, overheating of all cables and equipment, neutral overload in 3-phase systems, loss of efficiency in electric machines and electromagnetic interference with communication systems.

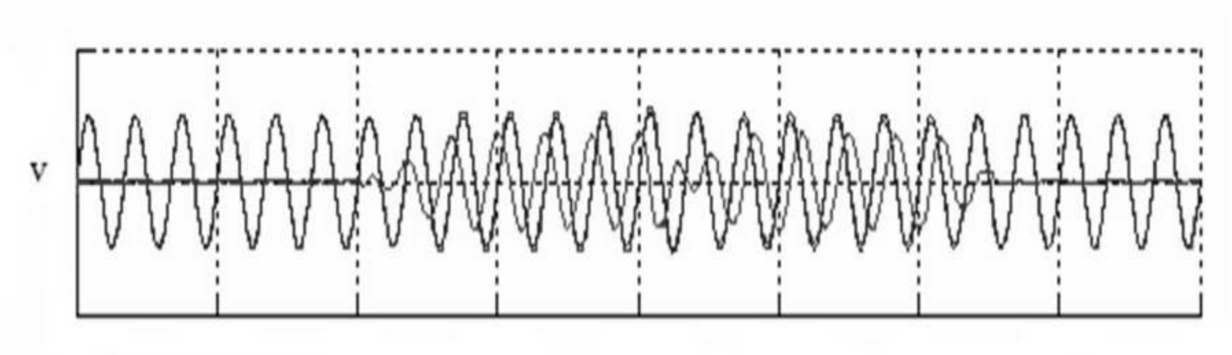

Fig.2.7: Harmonic Distortion

Harmonic distortion levels can be described by calculating total harmonic distortion (THD) which measures the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. THD is represented as the square-root of sum of the squares of each individual harmonic component. Voltage THD is given by

$$V_{THD}=\frac{\sqrt{\sum_{n=2}^{\infty}V_n^2}}{V_1} \qquad (2.1)$$

Where $V_1$is the rms magnitude of the fundamental component and $V_n$is the rms magnitude of component n, where n=2,……,∞.

The problem with this approach is that THD become infinity if no fundamental component is present. A way to avoid this ambiguity is to use an alternate definition that represents the harmonic distortion. This is called the distortion index (DIN) and is defined as

$$DIN=\frac{\sqrt{\sum_{n=2}^{\infty}V_n^2}}{\sqrt{\sum_{n=1}^{\infty}V_n^2}} \qquad (2.2)$$

THD and DIN are interrelated by the following equations

$$DIN=\frac{THD}{\sqrt{1+THD^2}} \qquad (2.3)$$

$$THD=\frac{DIN}{\sqrt{1-DIN^2}} \qquad (2.4)$$

2.2.6 Voltage Fluctuation [3]

Voltage fluctuations are systematic variation of voltage or a series of random changes in voltage magnitude which lies in the range of 0.9 to 1.1p.u as shown in fig.2.8 [4].Voltage fluctuations are caused due to frequent start or stop of electric motors, oscillating loads and arc furnaces. The consequences of voltage fluctuations are under voltages and flickering of lighting and screens.

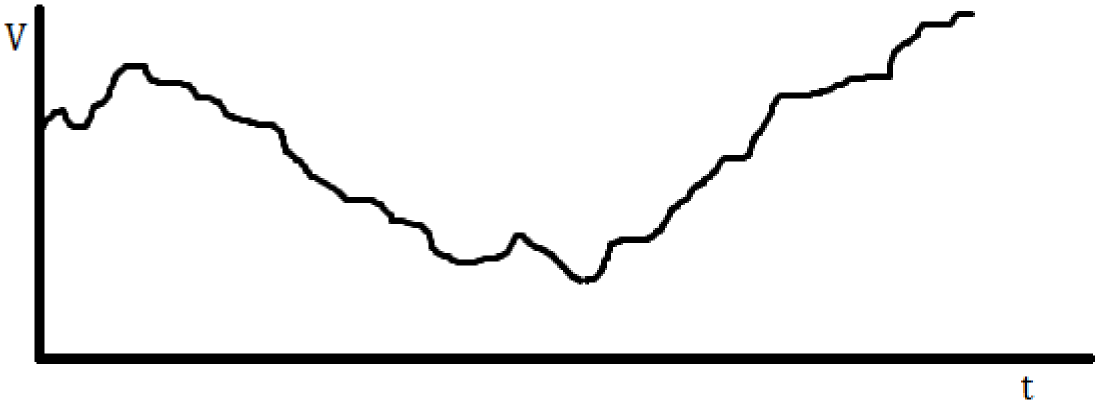

Fig.2.8: Voltage Fluctuation

2.2.7 Noise

Noise is defined as superimposing of high frequency signals on the waveform of the power-system frequency. Fig.2.9 shows the waveform due to noise. Noise is caused due to television diffusion and radiation due to welding machines, electromagnetic interferences provoked by hertzian waves such as microwaves, arc furnaces and electronic equipment and improper grounding. The consequences of noise are disturbances on sensitive electronic equipment and data processing errors.

Fig.2.9: Noise

2.2.8 Voltage Unbalance

Voltage unbalance is defined as voltage variation in a three-phase system in which the three voltage magnitudes or the phase angle differences between them are not equal. It is shown in fig.2.10. Voltage unbalance is caused due to large single-phase loads (induction furnaces, traction loads) and incorrect distribution of all single-phase loads by the three phases of the system (this may be also due to a fault). The consequences of voltage unbalance are unbalanced systems imply the existence of a negative sequence that is harmful to all three phase loads. The most affected loads are three-phase induction machines.

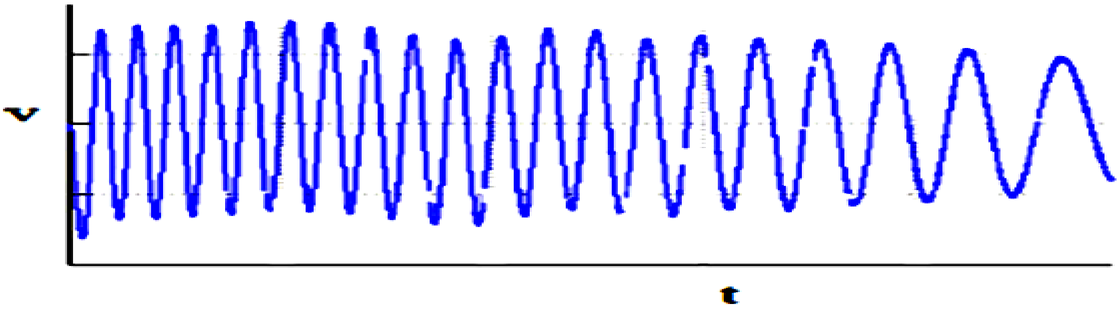

Fig.2.10: Voltage Unbalance

2.3 Effects of Poor Quality on Power System Devices [4]

The power quality has serious economic implications for consumers, utilities and electrical equipment manufacturers. Modernization and automation of industry involves increasing use of computers, microprocessors and power electronic systems such as adjustable speed drives. Therefore, insight into how disturbances are generated and interact into how they affect components is important for preventing failures. Even if failure does not occur, poor power quality and harmonics increase losses and decrease the lifetime of power components and end-use devices. Some of the main detrimental effects of poor power quality include the following:

- Heating, noise and reduced life on capacitors, rotating machines, surge suppressors, fuses, cables and customer’s equipment.
- Harmonic instability may be caused by large and unpredicted harmonic sources such as arc furnaces.
- Additional losses of transmission lines, cables, generators, AC motors and transformers may occur due to harmonics.
- Failure of power system components and customer loads may occur due to unpredicted disturbances such as voltage and or current magnifications due to parallel resonance and Ferro-resonance.
- Malfunction of controllers and protective devices such as fuse and relays is possible.
- Utility companies are particularly concerned that distribution transformer may need to be derated to avoid premature failure due to over-heating.
- Inter harmonics may occur which can perturb ripple control signals and can cause flicker at sub-harmonic levels.

CHAPTER 3
CUSTOM POWER DEVICES

3.1 Introduction

In 1995 N.G. Hingorani introduced the concept of custom power which was an extension of the FACTS concept to distribution systems. The key objective is to improve power quality (PQ) and enhance reliability of power supply. The concept of FACTS was also proposed by Hingorani in 1988. The term `custom power' describes the value-added power that electric utilities will offer their customers. The value addition involves the application of high power electronic controllers (similar to FACTS) to distribution systems, at the supply end of industrial, commercial customers and industrial parks. The provision of custom power devices (CPD) is complementary to the individual end-use equipment at low voltages (such as UPS (Uninterruptible Power Supply) or standby generators) [4].

The power quality has serious economic implications for customers, utilities and electrical equipment manufacturers. With modernization and automation of industry involves increasing use of electronic devices like computers, microprocessors and power electronic systems such as adjustable speed drives. Integration of non-conventional generation technologies such as fuel cells, wind turbines and photo voltaic with utility grids often requires power electronic interfaces. The power electronic systems also contribute to power quality problems (generating harmonics).

3.2 Need of Custom Power

Nowadays, electric power systems are under growing stress, more unstable with uncontrolled power flows and higher losses. The reason behind this is greater load demand, less generation, changing trends and constraints on the construction of new lines. As electric power is need of every industry. In modern industries, load equipment uses electronic controllers which are sensitive to poor voltage quality and will shut down if the supply voltage is depressed and may mal-operate in other ways if harmonic distortion of the supply voltage is excessive.

The widespread use of electronic equipment, such as information technology equipment, adjustable speed drives (ASD), arc furnaces, electronic fluorescent lamp ballasts and programmable logic controllers (PLC) have completely changed the electric loads nature. These loads are the major victims of power quality problems. Due to the non-linearity of these loads, they cause disturbances in the voltage waveform. The increased sensitivity of the vast majority of processes (industrial, services and even residential) to PQ problems turns the availability of electric power with quality a crucial factor for competitiveness in every activity sector. The most critical areas are the information technology services and the continuous process industry. When a disturbance occurs, huge financial losses may happen, with the consequent loss of productivity and competitiveness.

Every industry has different types of loads. Some of the loads are very sensitive and need pure power or good quality of power otherwise the loads are effective by power quality of power for example; the problem of voltage sags can affect sensitive loads. Except in the case of data processing equipment, there are no specific standards for different categories of equipment. Only Computer Business Equipment Manufacturers Association (CBEMA) has developed the CBEMA curve which describes the tolerance of main frame computers to the magnitude and duration of voltage variations on the power systems. CBEMA curve is shown in fig.3.1. Most of the Computer companies have their different tolerance, but the CBEMA curve has become a standard design target for sensitive equipment and also a common format for reporting power quality variations [5].

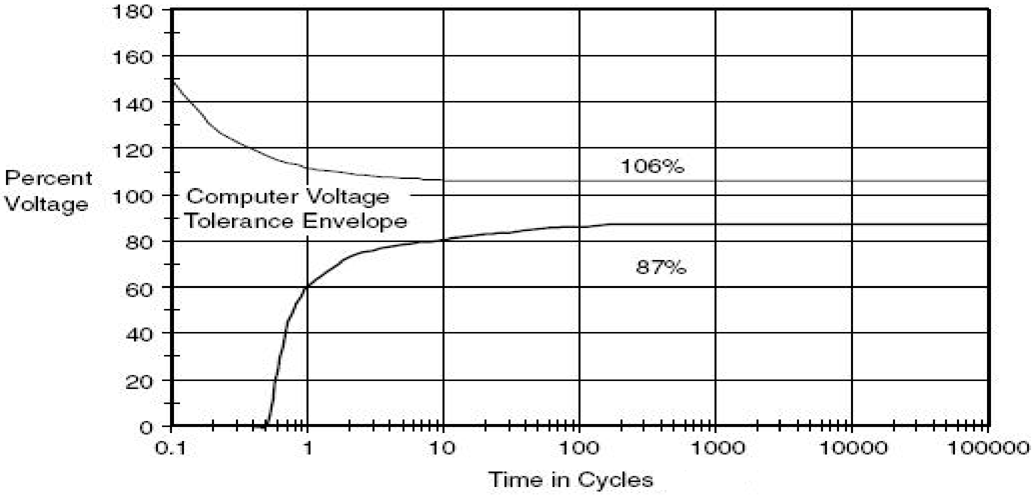

Fig.3.1: CBEMA curve

There are standards for the current and voltage harmonics based on THD. Typically, the voltage THD should not be more than 5% as per IEEE-519 standards. The previous discussion indicates the requirement for compensating equipment to improve power quality and meet the specified standards. The major problems relate to voltage are magnitude and waveform distortion. It is essential to provide reactive power compensation to improve power factor or regulate voltage under dynamic conditions.

So, to improve the quality of power, we require compensating equipment, which can help to fulfil the standards.

3.3 Custom Power Devices [6]

The introduction of power electronic loads has raised much concern about power quality problems caused by harmonics, distortions, interruptions, and surges. The use of electronic devices increase the power quality problem Equipment such as large industrial drives (e.g., cycloconverters) generate significantly high voltage and current (inter-, sub-) harmonics and create extensive voltage fluctuation. The addition of electronic devices is addition to power quality problem.

The application of harmonic filters and SVCs to radial transmission systems can offer partial solution to high THD levels and voltage fluctuations. Yet, the lack of dynamic capabilities of these devices limits them to bulk correction. In addition, they might be effective in one application but fail to correct other power quality issues.

Hingorani introduced the concept of custom power as the solution to V, P, and Q (voltage, active power, reactive power) compensation and power quality problems at the expense of high cost and network complexity. As FACTS controllers improve the reliability and quality of power transmission by simultaneously enhancing both power transfer capacity and stability custom power devices enhance the quality and reliability of power delivered to the customer. With a custom power device, a customer (e.g., a sensitive load) will be able to receive a pre specified quality of electric power with a combination of specifications including but not limited to:

- Magnitude and duration of over and under voltages with specified limits,
- Low harmonic distortion in the supply, load voltages, and currents.
- Small phase imbalance,
- Low flicker in the supply voltage,
- Control of power interruptions, and
- Control of supply voltage frequency within specified limits.

Classification of Custom power devices are based on their power electronic controllers, which can be either of the network reconfiguration type or of the compensation type. The network reconfiguration devices also called switchgear include the solid state and or static versions or current limiting, current breaking, and current transferring components. The compensation type custom power devices either compensate a load (e.g., correct its power factor, imbalance) or improve the quality for the supply voltage (e.g., eliminate its harmonics). They are either connected in shunt or in series or a combination of both. Custom power devices are classified as follows:

- Network – reconfiguration custom power devices include
- Solid state current limiter (SSCL),
- Solid – state breaker (SSB), and
- Solid state transfer switch (SSTS)

Compensation-custom power devices include

- Distributions STATCOM (DSTATCOM),
- Dynamic voltage restorer / regulator (DVR), and
- Unified power quality conditioner (UPQC).

Custom power devices are designed to improve the quality of power at their point of installation of the power distribution system. They are not primarily designed to improve the power quality of the entire system.

3.3.1 Distribution STATCOM (DSTATCOM) [6]

A DSTATCOM is a voltage source converter based compensating device which is connected in parallel with the distribution system to control the flow of reactive power. In its most basic form, the DSTATCOM configuration consists of a dc capacitor, one or more inverter modules and a transformer to match the inverter output to the line voltage. Fig.3.2 shows the schematic representation of DSTATCOM. In this arrangement, the steady state power exchange between the device and the AC system is mainly reactive. The VSC converts the DC voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the AC system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the DSTATCOM output voltages allows effective control of active and reactive power exchanges between the DSTATCOM and the AC system.

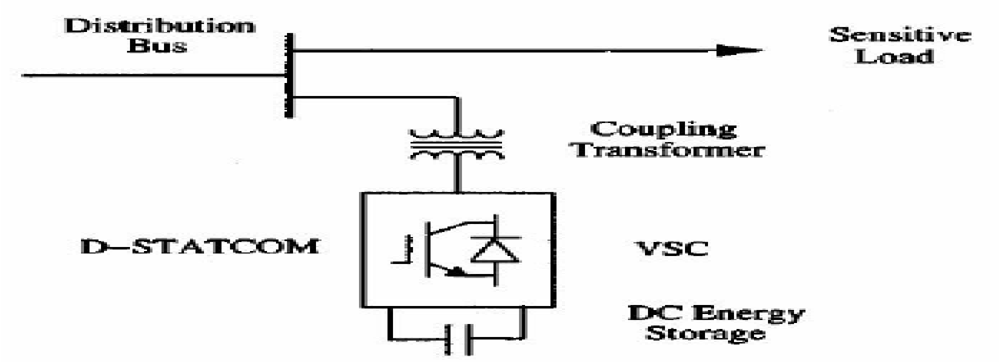

Fig.3.2: Schematic Diagram of DSTATCOM [6]

3.3.2 Dynamic Voltage Restorer (DVR)

The Dynamic Voltage Restorer (DVR) is a series connected device analogous to a SSSC. The main function of a DVR is to eliminate or reduce voltage sags seen by sensitive loads such as semiconductor manufacturing plant or IT industry. DVR that have been installed so far are modular with ratings of 2 MVA per module. They have been designed to compensate three phase voltage sags up to 35% for duration of time less than half a second (depending on the requirement). If the voltage sag occurs only in one phase (caused by SLG faults) then the DVR may be designed to provide compensation for sags exceeding 50%. The energy storage required in capacitors is typically in the range of 0.2 to 0.4 MJ per MW of load served. A DVR is connected in series with the feeder using a transformer. The low voltage winding is connected to the converter. If the objective of a DVR is mainly to regulate the voltage at the load bus, it remains for most of the time in stand-by mode during which the converter is bypassed (no voltage is injected). Only when sag is detected, the DVR injects a series voltage of the required magnitude. It is necessary to protect a DVR against the fault currents (as in the case of a SSSC). Fig.3.3 shows the schematic representation of DVR. A DVR with IGBT/IGCT devices can be controlled to act as a series active filter to isolate the load from voltage harmonics on the source side. It is also possible to balance the voltage on the load side by injecting negative and/or zero sequence voltages in addition to harmonic voltages.

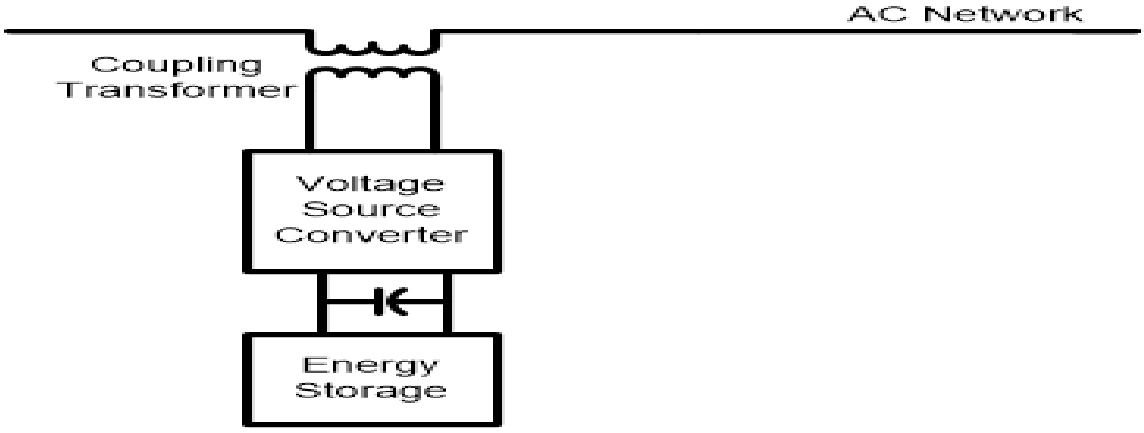

Fig.3.3: Schematic Diagram of DVR

3.3.3 Unified Power Quality Conditioner (UPQC)

Unified power quality conditioners (UPQC) allow the mitigation of voltage and current disturbances that could affect sensitive electrical loads while compensating the load reactive power. Unified power quality conditioners UPQC consist of combined series and shunt active power filters for simultaneous compensation of voltage and current disturbances and reactive power. The basic structure of this equipment is shown in fig.3.4.

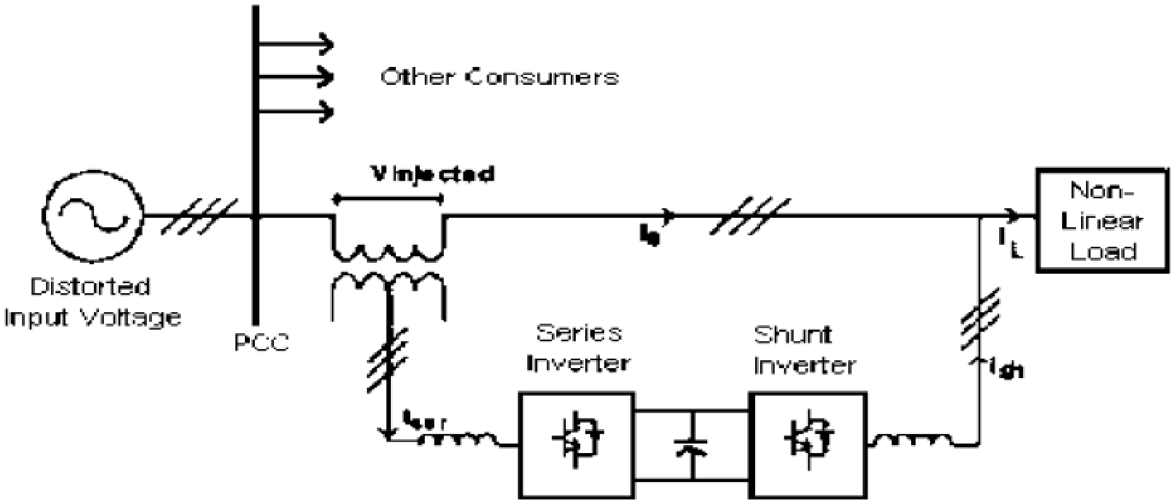

Fig.3.4: Schematic Diagram of UPQC [7]

CHAPTER 4

DISTRIBUTION STATCOM

4.1 Introduction

In 1999 the first SVC with Voltage Source Converter called STATCOM (STATIC COMPENSATOR) went into operation. The characteristic of STATCOM are a similar to the synchronous condenser, the difference is that it is an electronic device, due to that it has no inertia and it is superior to the synchronous condenser in so many ways, such as better dynamics, a lower investment cost and lower operating and maintenance cost [8].

A STATCOM is build with Thyristors with turn off capability like GTO or to day IGCT or with more and more IGBTs. The structure and operational characteristic is shown in Figure-4.1. The static line between the current limitations has a certain steepness determining the control characteristic for the voltage. The advantage of a STATCOM is that the reactive power provision is independent from the actual voltage on the connection point.

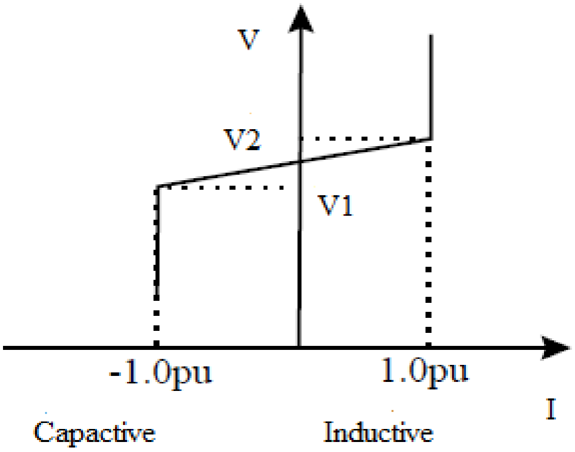

Figure-4.1: V-I characteristic of a STATCOM

In the distributed energy sector the usage of Voltage Source converters for grid interconnection is common practice today. The next step in STATCOM development is the combination with energy storages on the DC-side. The performance for power quality and balanced network operation can be improved much more with the combination of active and reactive power.

4.2 Basic Configuration of DSTATCOM

Schematic representation of the DSTATCOM is shown in fig.4.2.The general configuration of DSTATCOM consists of:

- Voltage Source Converter
- Energy Storage Device
- L-C Passive Filter
- Coupling Transformer
- Control Block

4.2.1 Voltage Source Converter

A voltage-source converter is used to create an output voltage wave, which is controlled in magnitude and phase angle to produce either leading or lagging reactive current, depending on the compensation required. It converts the DC voltage across storage devices into a set of three phase AC output voltages. It could be a 3-phase, 3- wire VSC or 3- phase, 4-wire VSC. VSC may be two level converters or a three level converter. Here, a two level VSC is used in this work.

4.2.2 Energy Storage Device

The function of storage devices is to supply the required energy to the VSC via a dc link for the generation of injected voltages. DC source is connected in parallel with the DC capacitor. It carries the input ripple current of the converter and it is the main reactive energy storage element. This DC capacitor could be charged by a battery source or could be recharged by the converter itself.

4.2.3 L-C Passive Filter

The LC filter is used to reduce harmonics and matches inverter output impedance to inverter to share current. The LC filter is chosen in accordance with the type e of the system and the harmonics present at the output of the inverter.

4.2.4Coupling Transformer

Coupling transformer is used to couple the output voltage of voltage source converter with the AC system. These voltages are coupled with AC system through the reactance of coupling transformer.

4.2.5 Control Block

The basic functions of Control block are the detection of fault, voltage sag and voltage swell in the system; computation of voltage, generation of trigger pulses to the sinusoidal PWM based DC-AC inverter and termination of the trigger pulses when the event has passed. They can control external devices such as mechanically switched capacitor banks too. These control blocks are designed based on the various control theories and algorithms like instantaneous DQO theory, synchronous frame theory etc.

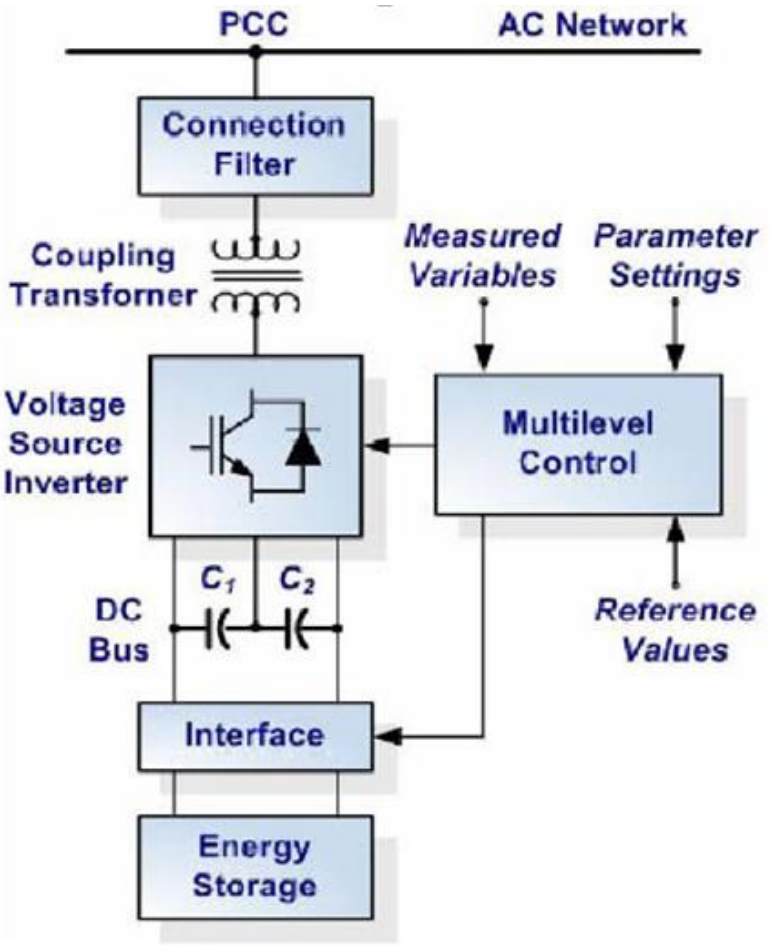

Fig.4.2: Schematic Representation of the DSTATCOM [10]

4.3 Location of DSTATCOM

The DSTATCOM is connected in shunt with distribution system as shown in fig.4.3.Here in this figure three distribution feeders are considered. These feeders are feeding different sensitive loads. DSTATCOM is connected at the point of common coupling to inject current into the system when any non-linearity occurs due to these loads.

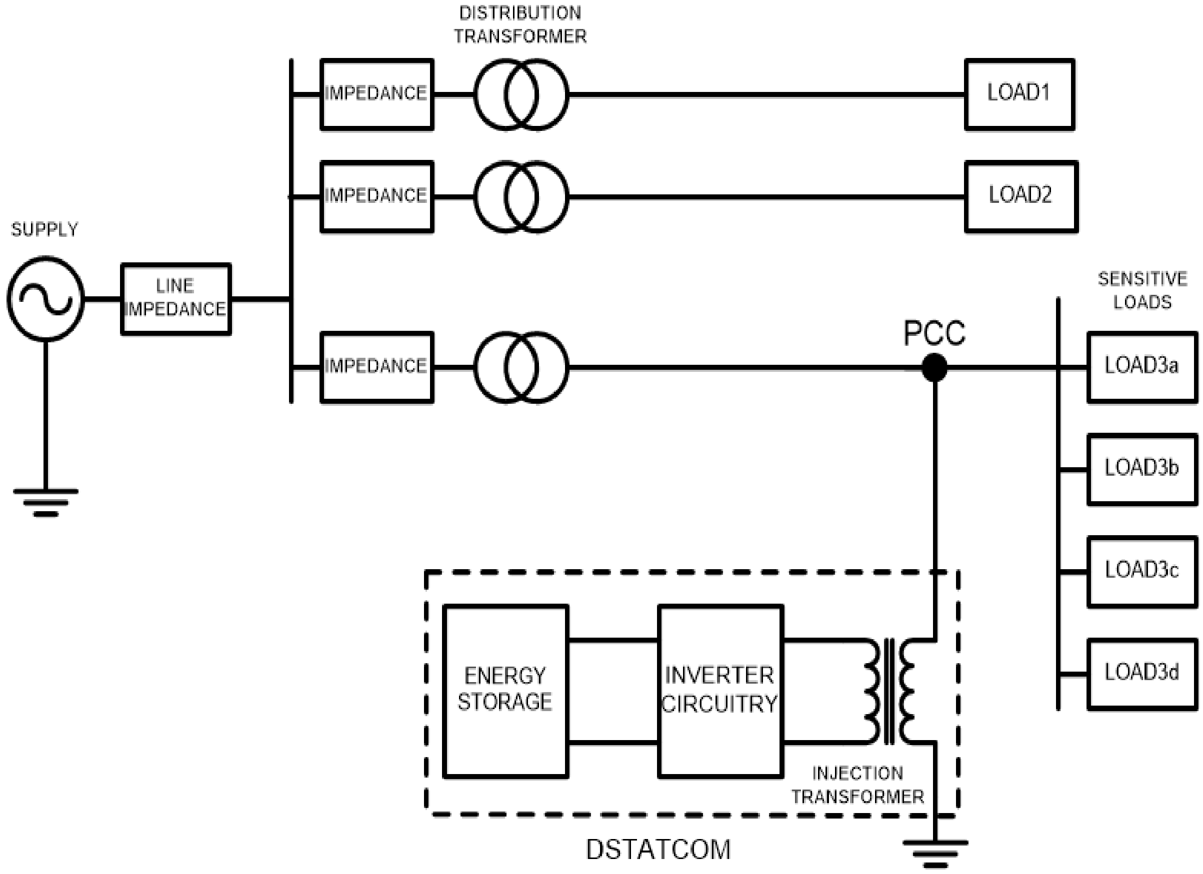

Fig.4.3: Typical Location of DSTATCOM in Distribution System

4.4 Principle of DSTATCOM

A single line diagram of a DSTATCOM is shown in fig.4.4. A DSTATCOM is a solid state power electronics switching device consisting of either GTO or IGBT, a capacitor bank as an energy storage device, a coupling transformer and a controller. Basic operating principle of a DSATCOM is similar to that of synchronous machine. The synchronous machine will provide lagging current when under excited and leading current when over excited. DSTATCOM can generate and absorb reactive power similar to that of synchronous machine and it can also exchange real power if provided with an external device DC source. The DSTATCOM is connected to the power networks at a PCC, where the voltage-quality problem is a concern. All required voltages and currents are measured and are fed into the controller to compare with the commands. The controller then performs feedback control and outputs a set of switching pulses to drive the main semiconductor switches (IGBT's, which are used at the distribution level) of the power converter accordingly [12].

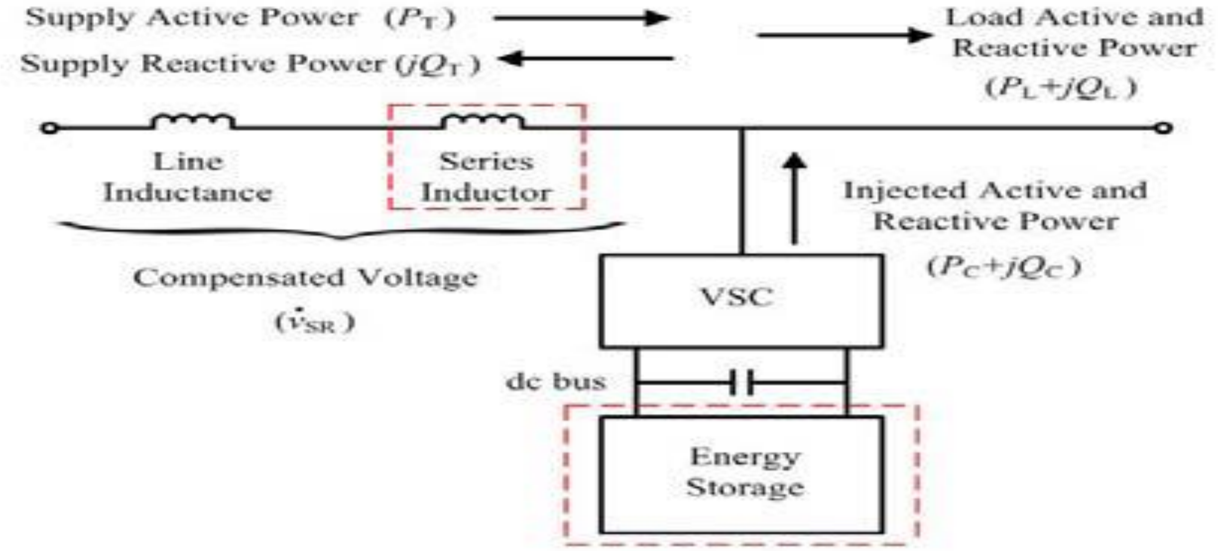

Fig.4.4: Single Line diagram of DSTATCOM [12]

The IGBT based VSC converts the DC voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the AC system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the DSTATCOM output voltages allows effective control of active and reactive power exchanges between the DSTATCOM and the AC system.

4.4.1 Exchange of Reactive Power [15]

Regulating the amplitude of the DSTATCOM output voltage controls the reactive power exchange of the DSTATCOM with the AC system. The reactive power supplied by the DSTATCOM is given by-

$$Q= \frac{(V_i - V_s) * V_s}{X}$$

Where,

Q is the reactive power.

V_i is the magnitude of DSTATCOM output voltage.

V_s is the magnitude of system voltage.

X is the equivalent impedance between DSTATCOM and the system.

Reactive power exchange between DSTATCOM and AC system is explained through following cases:

Case I: If the amplitudes of the DSTATCOM output voltage which is V_i and the AC system voltage which is V_s are equal, the reactive current is zero and the DSTATCOM does not generate/absorb reactive power. It is shown in fig.4.5.

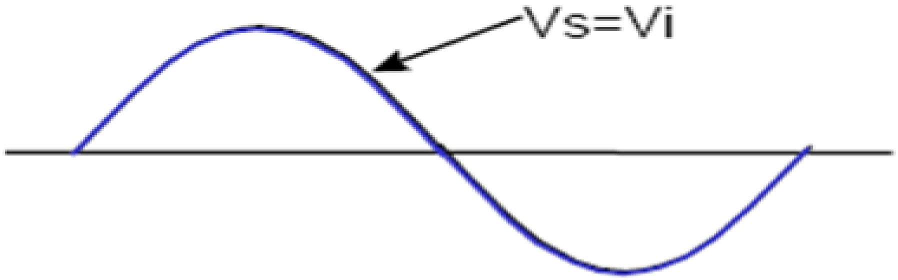

Fig.4.5: No Load Operation

Case II: If the amplitude of the DSTATCOM output voltage is increased above the amplitude of the AC system voltage, the lagging current flows through the transformer reactance from the DSTATCOM to the AC system, and the device generates capacitive reactive power. It is shown in fig.4.6.

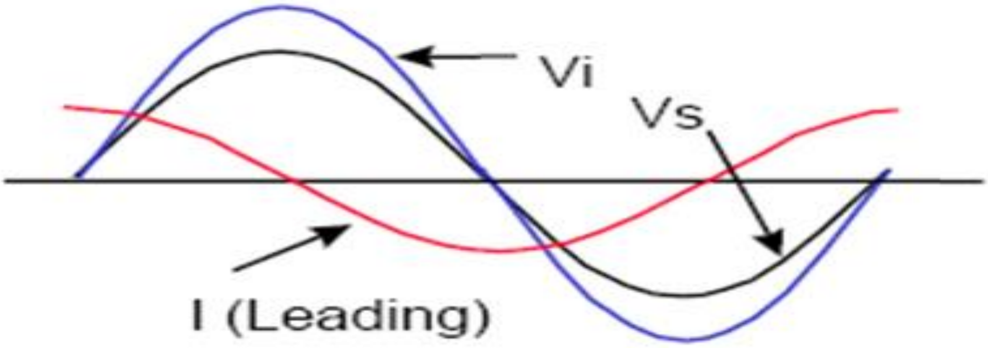

Fig.4.6: Capacitive Operation

Case III: If the amplitude of the DSTATCOM output voltage is decreased to a level below that of the AC system, then the leading current flows from the AC system to the DSTATCOM, resulting in the device absorbing inductive reactive power. It is shown in fig.4.7.

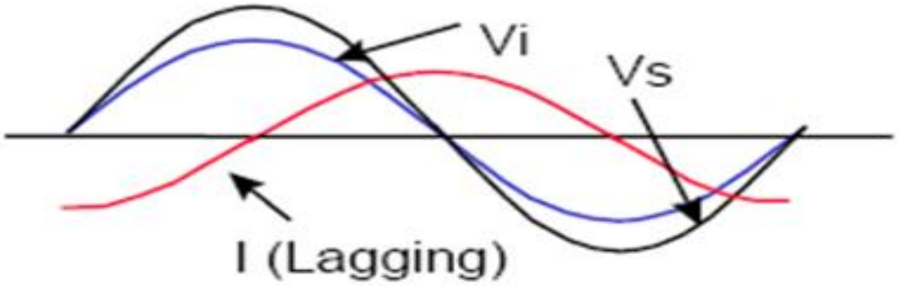

Fig.4.7: Inductive Operation

4.4.2 Exchange of Active Power [13] [18]

Due to the use of greater switching devices, there is a need for the DC capacitor to provide the required real power to the switches. In case of direct voltage control, there is a need for real power exchange with an AC system to make the capacitor voltage constant. Incase of very low voltage in the distribution system or in case of faults, there is a real power exchange with the AC system if DSTATCOM is provided with an external DC source to regulate the voltage. If the VSC output voltage leads the system voltage then the real power from the capacitor or the DC source will be supplied to the AC system to regulate the system voltage equal to 1p.u or to make the capacitor voltage constant.V-I characteristic of the DSTATCOM is shown in fig.4.8. The DSTATCOM smoothly and continuously controls voltage from V_1 to V_2.

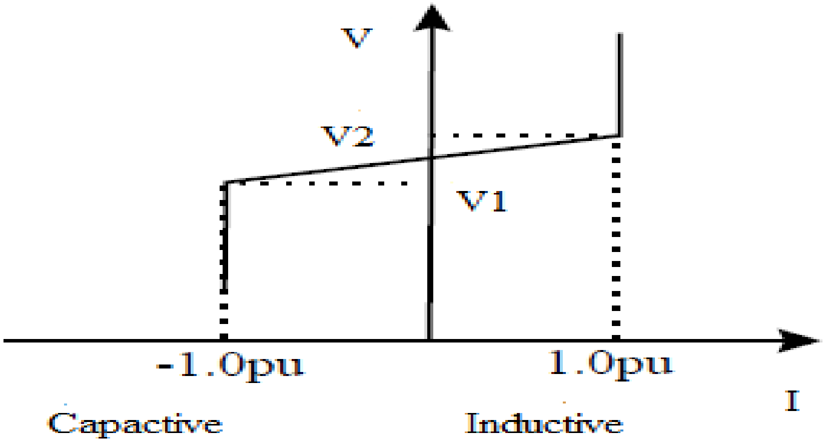

Fig.4.8: V-I Characteristic of a DSTATCOM

4.5 Load Compensation using DSTATCOM [14]

The schematic diagram of a distribution system compensated by DSTATCOM is shown in fig.4.9. Here it is assumed that the DSTATCOM is operating in current control mode. It is assumed that Load-1 is non-linear, reactive and unbalanced. In the absence of the compensator, the current I_s flowing through the feeder will be unbalanced and distorted, and as a consequence, bus-1 voltage will also be unbalanced.

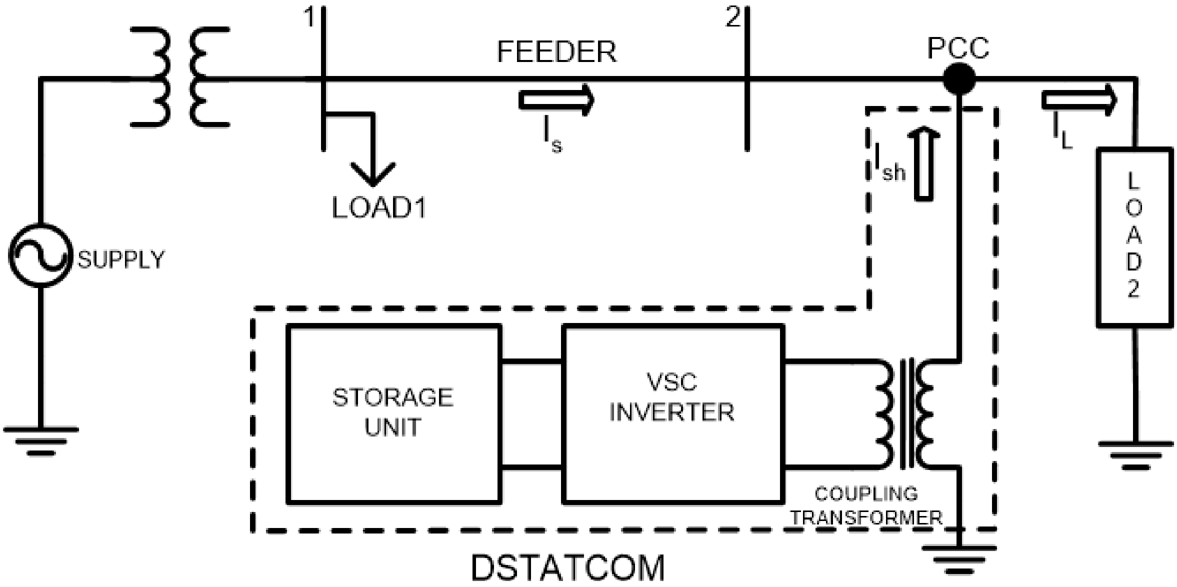

Fig.4.9: Schematic Diagram of Ideal Load Compensation

To remove this problem, DSTATCOM injects I_{sh} current such that the current I_s, becomes fundamental and positive sequence. In addition, DSTATCOM can also force the current I_s to be in phase with the bus-1 voltage. This fashion of operating the DSTATCOM is also called load compensation since in this connection the DSTATCOM is compensating the load current. From the utility point of view, it will look as if the compensated load is drawing a unity power factor, fundamental and strictly positive sequence current. The point at which the compensator is connected is called the utility customer point of common coupling (PCC). Denoting the load current by I_L, the KCL at the PCC yields:

$$I_s + I_{sh} = I_L \tag{1}$$

So, from above equation I_{sh} is written as:

$$I_{sh} = I_L - I_f \tag{2}$$

The desired performance from the compensator is that it generates a current I_{sh} that it cancels the reactive component, harmonic component and unbalance of the load current.

4.6 Photo Voltaic Energy Storage System [22] [23]

Recent research shows that the PV inverter has the capability of acting as DSTATCOM – a Flexible AC Transmission System (FACTS) device and is pronounced as PV-STATCOM. With the use of this STATCOM capability, the PV inverter is demonstrated to improve the connectivity of neighbouring wind farms, improve the power transfer capacity over long transmission line. In these control strategies, the PV-STATCOM utilize the entire solar inverter capacity during night time and the remnant inverter capacity after real power generation during daytime and exchange reactive power with the grid to accomplish different objectives such as voltage control, reactive power control etc.

Disadvantages of battery connected system:-

1. Battery can be used only for limited time and large size battery bank is required for the power quality equipment system.
2. In normal operating conditions the battery bank takes a considerable amount of supply from the grid.
3. Some equipment (high consuming power equipment) becomes heavier when using batteries.
4. Some batteries are dangerous and can lead to fire, explosion, chemical pollution...etc.
5. Life of battery is very less and we have to replace whole backup system either they used or not which causes heavy amount of money.
6. Battery connected system required large land size for installation purpose and having huge construction and installation cost.

Photovoltaic cells are the main ingredient of all photovoltaic solar energy systems, turning sunlight directly into electricity. Since the first silicon photovoltaic cells were discovered in the 1950s, technological developments have improved performance and transformed solar energy capabilities. An increasingly viable and popular renewable energy source, grid-connected photovoltaic systems grabbed a 75 percent share of U.S. installations in 2009, up from 31 percent.

Solar Energy Advantages

- The power source of the sun is absolutely free.
- The production of solar energy produces no pollution.
- The technological advancements in solar energy systems have made them extremely cost effective.
- Most systems do not require any maintenance during their lifespan, which means you never have to put money into them.
- Most systems have a life span of 30 to 40 years.
- Most systems carry a full warranty for 20 to 30 years or more.
- Unlike traditional monstrous panel systems, many modern systems are sleeker such as Uni-Solar rolls that lay directly on the roof like regular roofing materials.
- In 35 states, solar energy can be fed back to the utilities to eliminate the need for a storage system as well as eliminating or dramatically reducing your electric bills.

- Solar energy systems are now designed for particular needs. For instance, you can convert your outdoor lighting to solar. The solar cells are directly on the lights and can't be seen by anyone. At the same time, you eliminate all costs associated with running your outdoor lighting.

In this research another new application of PV-DSTATCOM to provide voltage support to a critical voltage sensitive distribution system connected in the vicinity of the solar farm is demonstrated. A fast fault detection technique is integrated with the PV system to sense any fault on the grid. Upon detection of any fault the PV solar farm inverter turns into a PV-DSTATCOM and provides the voltage support by disconnecting its DC side from the inverter while the inverter still remains connected with the grid. As a result, during day time real power generation curtailment is required to utilize the whole inverter capacity and provide sufficient amount of reactive power to the grid for a short duration of time during post fault recovery period.

Recent work tends to focus on assessing how distributed generation can be integrated into existing grids without affecting the system stability. However, the effect of a potentially rising penetration of DG upon the distribution systems has attracted much less attention. Very little work has examined its impact on distribution network. Moreover, the effects of voltage rise under fault condition with different penetration of DG are also analyzed and to enhance the voltage profile a comparative study between shunt capacitor and D-STATCOM is provided through nonlinear simulations.

4.7 Applications of DSTATCOM

When the STATCOM is connected in distribution system is called DSTACOM and its configuration is the same, or with small modifications, oriented to a possible future amplification of its possibilities in the distribution network at low and medium voltage, implementing the function so that we can describe as flicker damping, harmonic filtering and short interruption compensation. Applications of DSTATCOM are discussed below:

- DSTATCOM exhibits high speed control of reactive power to provide voltage stabilization, flicker suppression, and other types of system control.
- The DSTATCOMprotects the utility distribution system from voltage sags and/or flicker caused by rapidly varying reactive current demand. In utility applications, a DSTATCOMprovides leading or lagging reactive power to achieve system stability during transient conditions.

- The DSTATCOM can also be applied to industrial facilities to compensate for voltage sag and flicker caused by non-linear dynamic loads, enabling such problem loads to co-exist on the same feeder as more sensitive loads. The DSTATCOM instantaneously exchanges reactive power with the distribution system without the use of bulky capacitors or reactors.
- In most applications, a DSTATCOM can use its significant short-term transient overload capabilities to reduce the size of the compensation system needed to handle transient events. The short-term overload capability is up to 325% for periods of 1 to 3 seconds, which allows applications such as wind farms and utility voltage stabilization to optimize the system’s cost and performance. The DSTATCOM controls traditional mechanically switched, capacitors to provide optimal compensation on a both a transient and steady state basis.
- DSTATCOM can also be applied to utilities with weak grid knots or fluctuating reactive loads.
- It can be applied to the system delivering unbalanced loads (like arc furnace load, wood chippers, welding operations, car crushers & shredders etc.).
- DSTATCOM has many applications in wind farms and industrial mill for power quality improvement.

CHAPTER 5

Modelling and Simulation of DSTATCOM based System

5.1 Introduction

In recent years, Power engineers are increasingly concerned over the quality of the electrical power. In an increasing number of problems like voltage swells, voltage sags, flicker, harmonic distortion, transients and interruption of power supply, where conventional equipment cannot solve these problems, PWM converter-based shunt connected power conditioners named DSTATCOM have been introduced. Basically, DSTATCOM consists of PWM voltage source inverter circuit and a DC capacitor connected at one end. Due to lower switching losses and reduced size, the switching element is usually the integrated gate bipolar transistor (IGBT), which is used for the distribution voltage level. In this thesis work, Simulink model of test system is analyzed. In this test model two similar loads with different feeders are considered. One of the feeders is connected to DSTATCOM and the other is kept as it is. This test system is analyzed with linear and non linear load under same fault conditions under different fault conditions.

In this work, effectiveness of DSTATCOM to compensate the load current harmonics in distribution networks under various operating conditions of following distribution networks is carried out:

- Distribution network having static linear load
- Distribution network having static non-linear load

5.2 Parameters of the Test System

The modelled system has been tested with linear and non-linear load on different fault conditions. The system is employed with three phase generation source with configuration of 11KV, 50 Hz. The source is feeding two distribution lines through a three-phase, three-winding transformer with power rating 200kVA, 50 Hz. System test parameters are listed below in table 1:

Table 1: SYSTEM PARAMETERS

Serial number	System Quantities	Parameters
1.	Source	3-phase, 11kV rms (phase-phase), 50Hz, 500MVA, Short circuit level(VA), 11kV Base voltage, $\frac{X}{R}$= 0.5.
2.	Convertor	IGBT based, 3-arms, 6-pulse, $R_{on} = 1m\Omega$.
4.	Linear Load	400V rms (phase-phase), 50 Hz, 10kW, 10kVar.
5.	Non Linear Load	Non-linear Resistance (100Ω), Inductance (50mH), 400V rms (phase-phase), 50 Hz.
6.	Transformer	Nominal power 200kVA, 50Hz, Δ/Y/Y(grounded)11000/400/400V, $(R_1/R_2/R_3, L_1/L_2/L_3) =$ (0.002/0.002/0.002,0.08/0.08/0.08) p.u.

5.3 SIMULINK Model of Test System with Static Linear Load

SIMULINK model of the test system is given in fig.5.1. In this model, the system consists of two parallel feeders with similar type of linear loads of same rating. One of the feeders is connected to DSTATCOM and the other feeder is kept as it is. This system is analyzed under three different fault conditions, which are single line to ground fault, double line to ground fault and three phase fault.

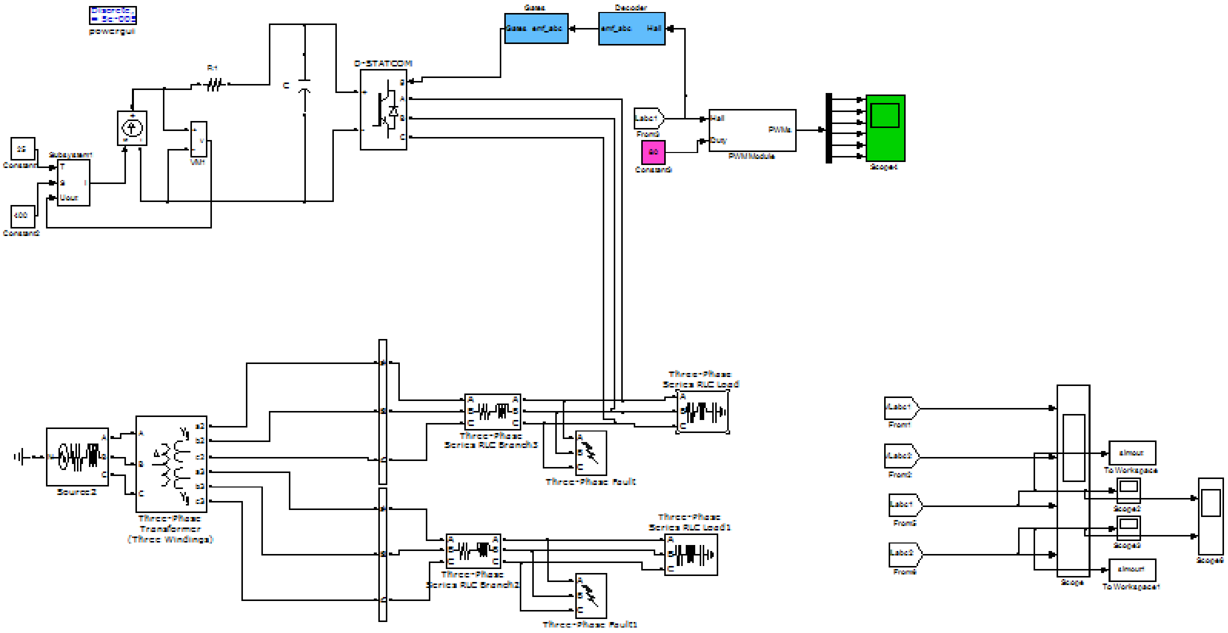

Fig.5.1: SIMULINK Model of Test System with Linear Load

5.3.1 Results for Linear Loads under Different Fault Conditions

CASE I: Single Line to Ground Fault Condition

In this case, a single line to ground fault is considered for both the feeders feeding linear load. Here the fault resistance is 0.001 ohm and the ground resistance is 0.001 ohm. The fault is created for the duration of 0.05s to 0.1s. The output wave for the load current with compensation and without compensation is shown in Figure-5.2, Figure-5.3 respectively. Here it is clear from the output wave shapes that the current in the phase where fault is created is increasing during the fault duration in the uncompensated feeder. So, here the unbalancing in the system where DSTATCOM is connected is reduced clearly.

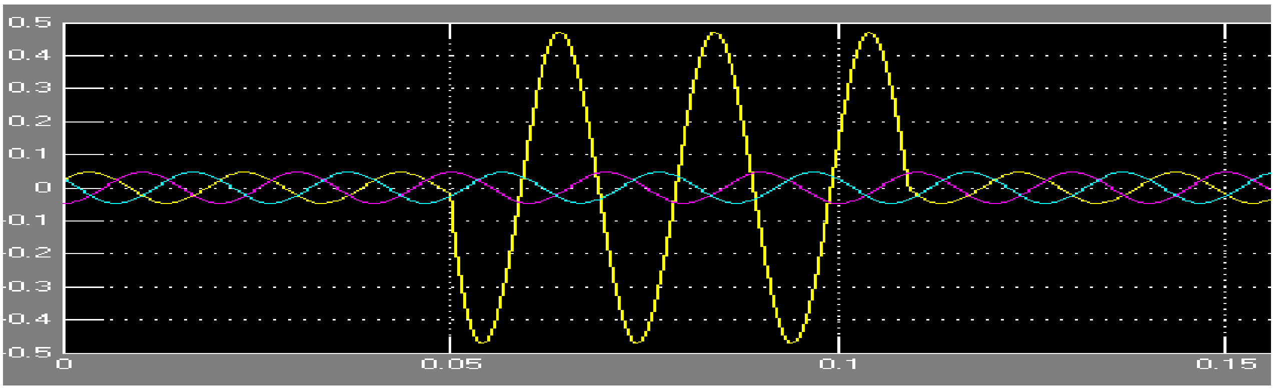

Fig.5.2: Load Current (p.u.) vs Time waveform (without compensation)

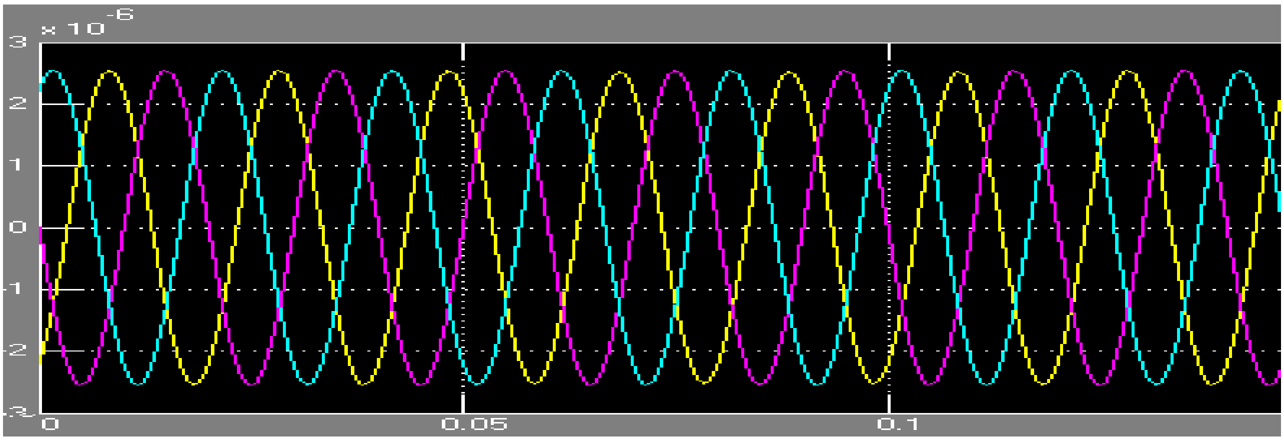

Fig.5.3: Load Current (p.u.) vs Time waveform (with compensation)

CASE II: Double Line to Ground Fault Condition

In this case, a double line to ground fault is considered for both the feeders feeding linear load. Here the fault resistance is 0.001 ohm and the ground resistance is 0.001 ohm. The fault is created for the duration of 0.05s to 0.1s. The output wave for the load current with compensation and without compensation is shown in Figure-5.4, Figure-5.5 respectively. Here it is clear from the output wave shapes that the current in the phases where fault is created is increasing during the fault duration in the uncompensated feeder. So, here the unbalancing in the system where DSTATCOM is connected is reduced clearly.

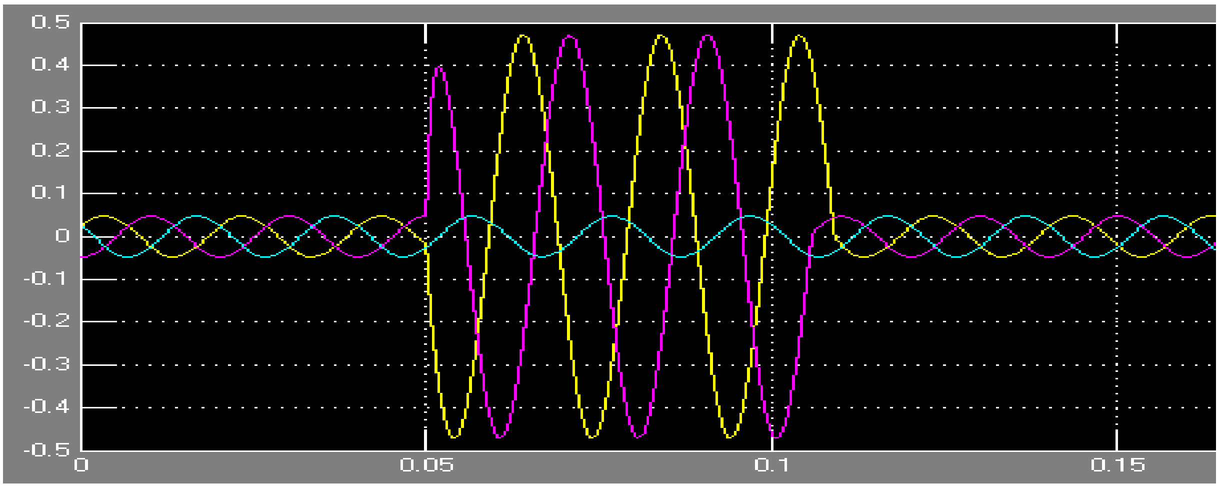

Fig.5.4: Load Current (p.u.) vs Time waveform (without compensation)

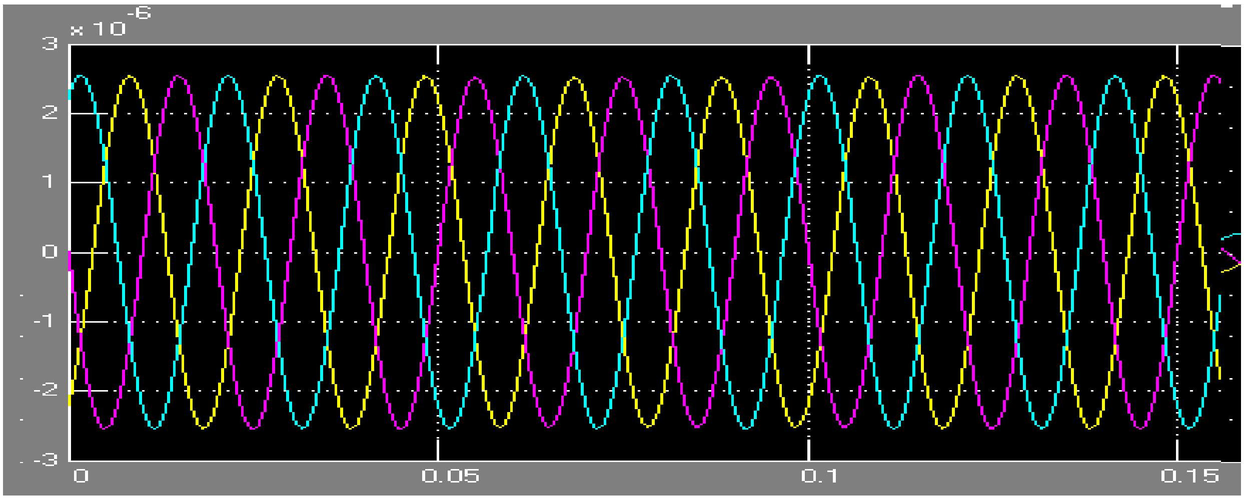

Fig.5.5: Load Current (p.u.) vs Time waveform (with compensation)

CASE III: Three Phase Fault Condition

In this case, a three fault is considered for both the feeders feeding linear load. Here the fault resistance is 0.001 ohm and the ground resistance is 0.001 ohm. The fault is created for the duration of 0.05s to 0.1s. The output wave for the load current with compensation and without compensation is shown in Figure-5.6, Figure-5.7 respectively. Here it is clear from the output wave shapes that the current in the phases where fault is created is increasing during the fault duration in the uncompensated feeder. So, here the unbalancing in the system where DSTATCOM is connected is reduced clearly.

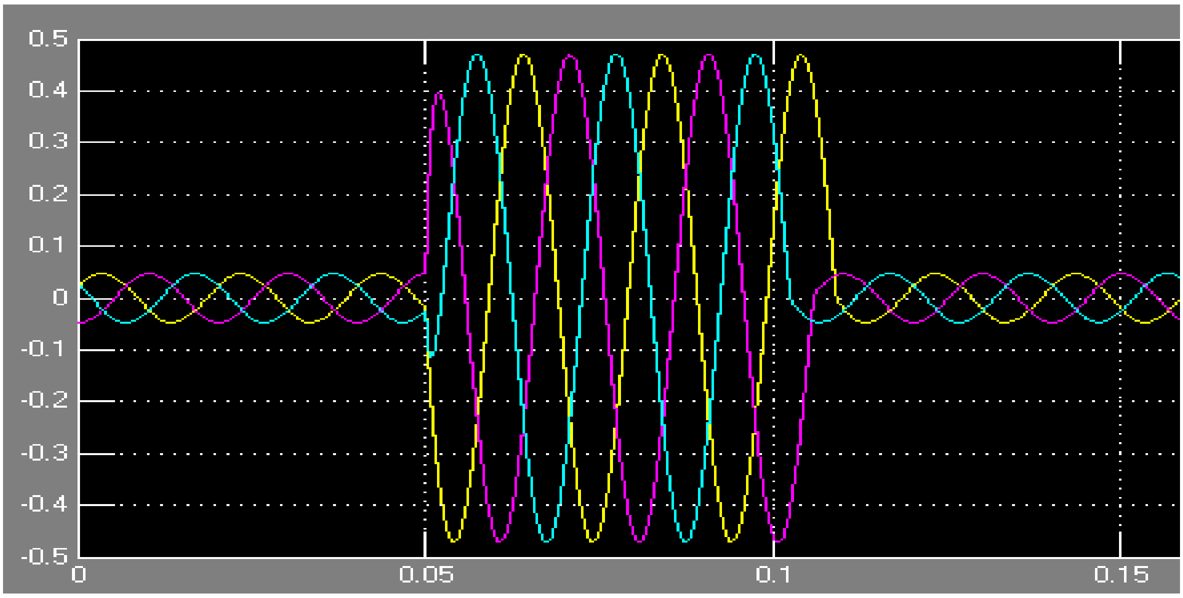

Fig.5.6: Load Current (p.u.) vs Time waveform (without compensation)

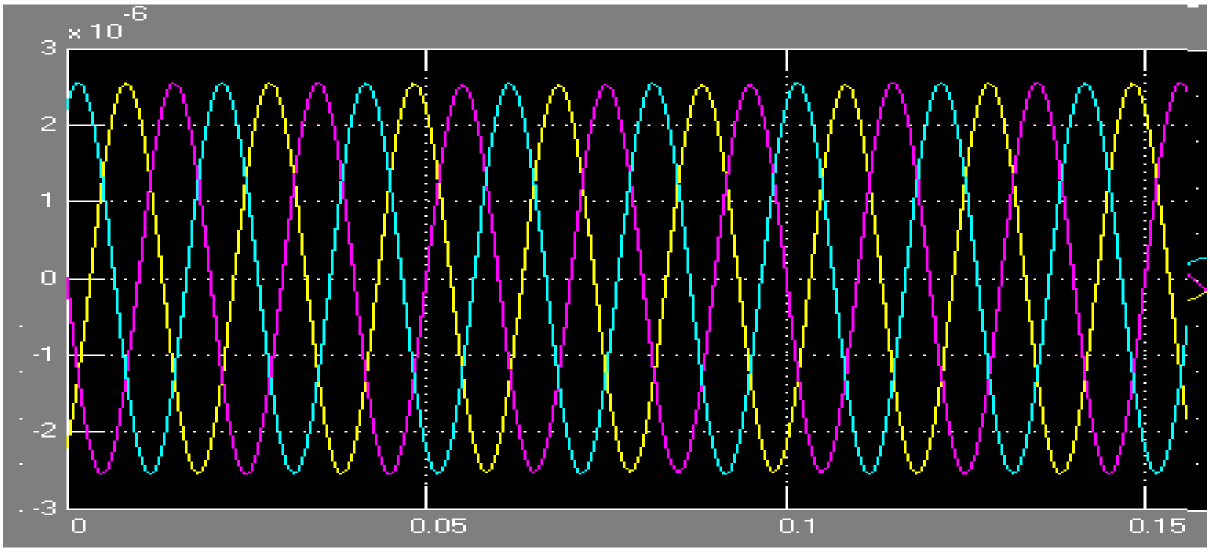

Fig.5.7: Load Current (p.u.) vs Time waveform (with compensation)

5.4 SIMULINK Model of Test System with StaticNon-Linear Load

SIMULINK model of the test system with static non-linear load is given in fig.5.8. The system consists of two parallel feeders with similar non-linear load of same rating. One of the lines is connected to DSTATCOM and the other line is kept as it is. This system is analyzed under normal operating condition and three different fault conditions, which are single line to ground fault, double line to ground fault and three phase fault.

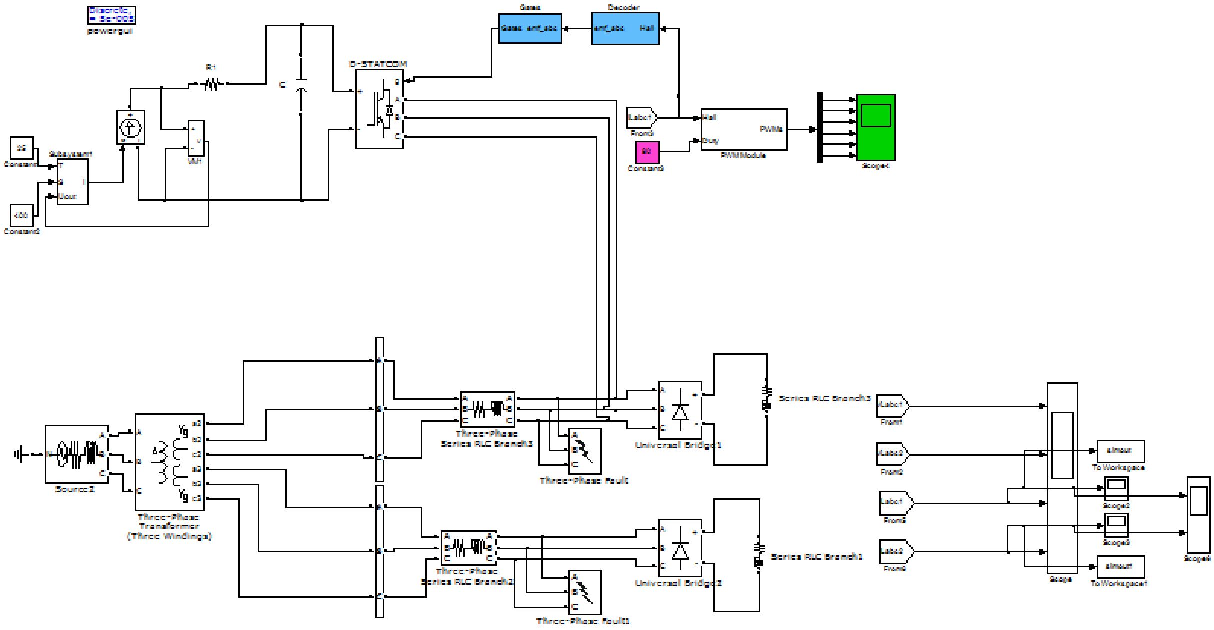

Fig.5.8: SIMULINK Model of Test System with Non-Linear Load

5.4.1 Results for Non-Linear Loads under Normal Condition

Here test system is considered under normal conditions. Due to non-linear load connected to the system, harmonics are produced in load current waveform as shown in fig.5.9. The frequency spectrum graph of load current for uncompensated feeder is shown in fig.5.10. When DSTATCOM is connected to the system it effectively reduces the harmonics from load current as shown in fig.5.11. Also frequency spectrum graph of load current for compensated feeder is shown in fig.5.12. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 27.22% to 0.00% when DSTATCOM is connected to the system.

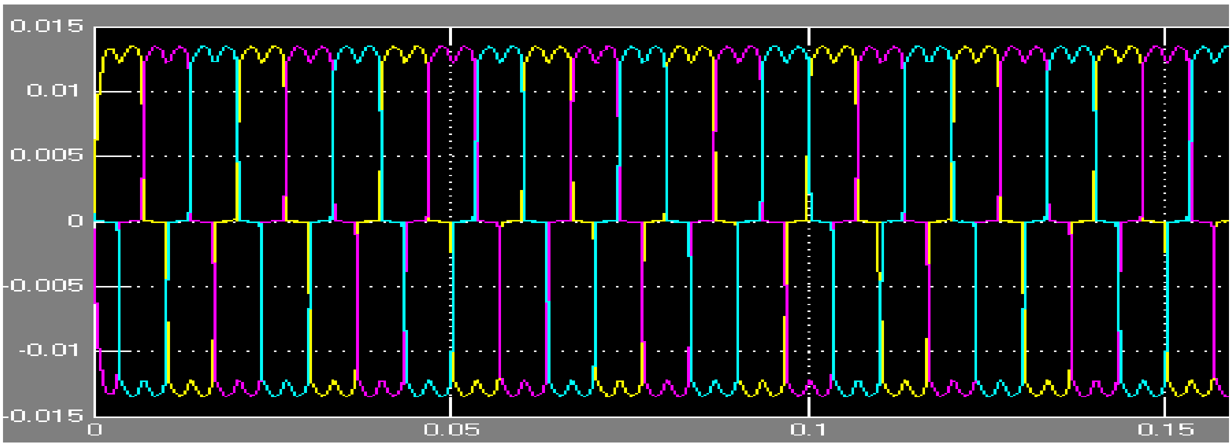

Fig.5.9: Load Current (p.u.) vs Time waveform (without compensation)

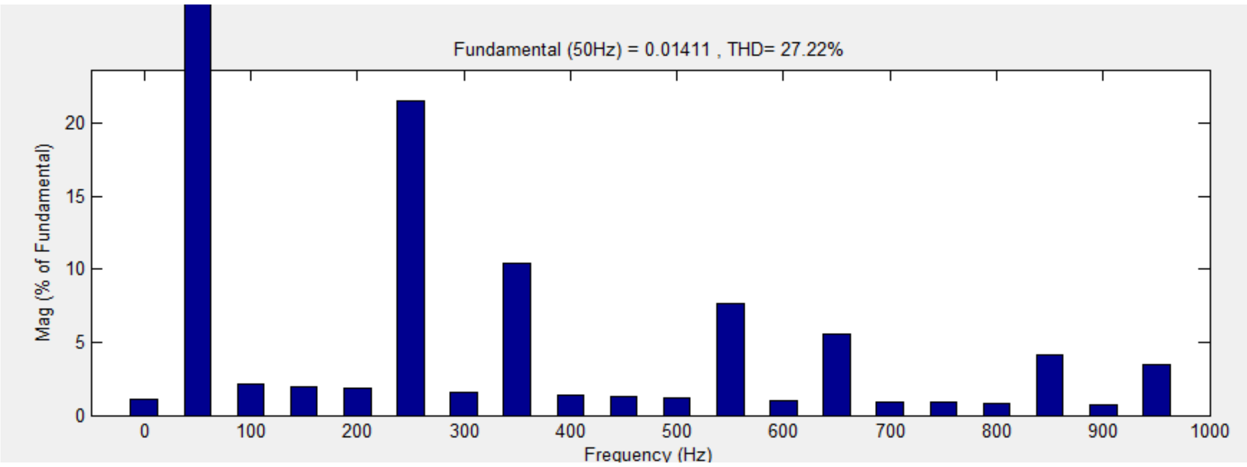

Fig.5.10: Frequency Spectrum of Load Current (without compensation)

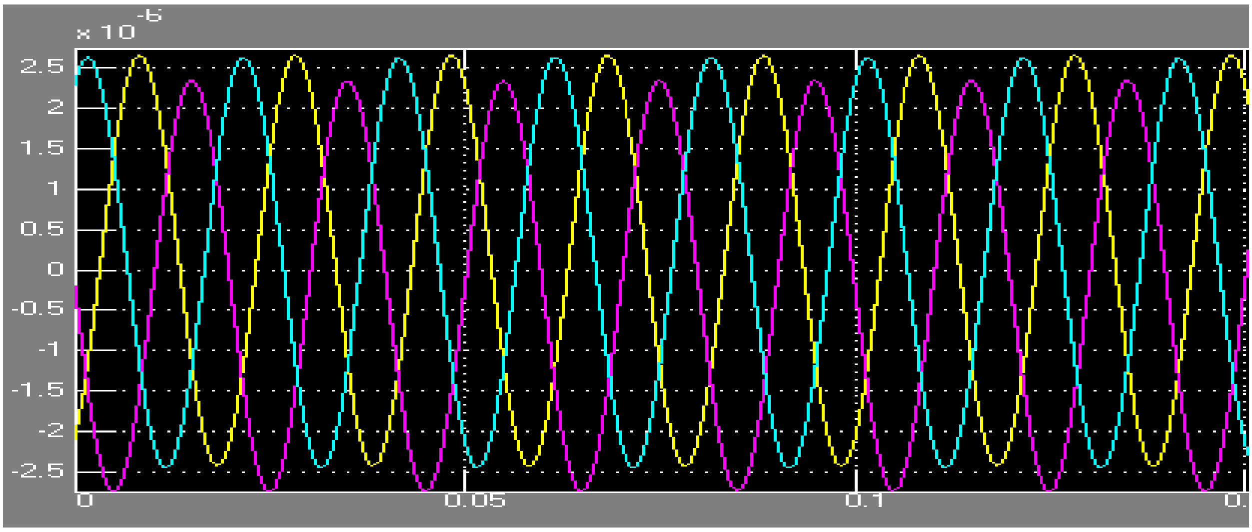

Fig.5.11: Load Current (p.u.) vs Time waveform (with compensation)

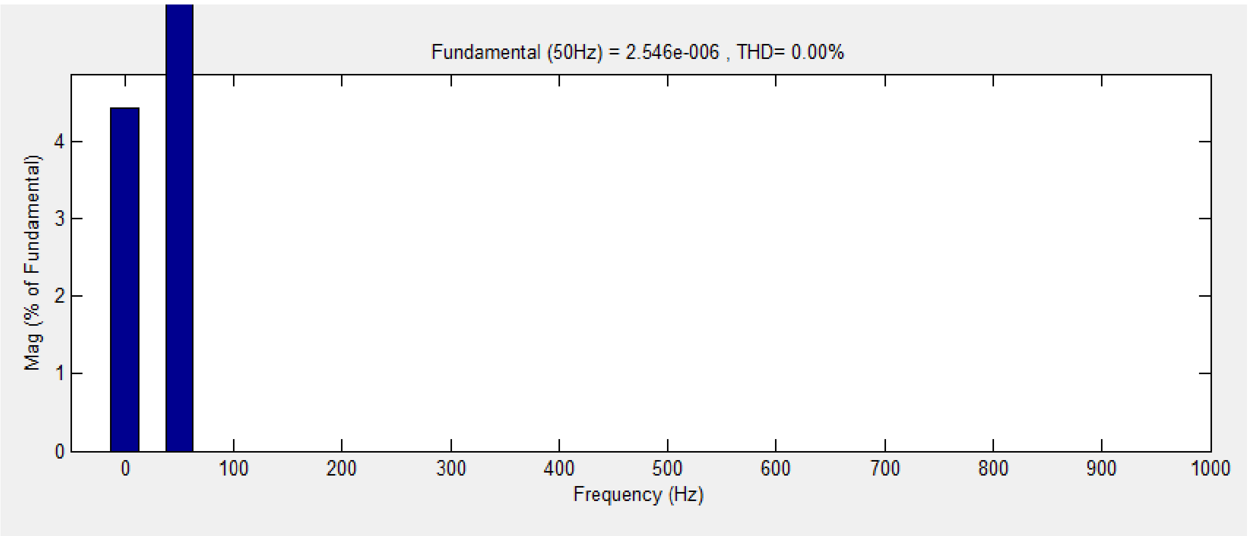

Fig.5.12: Frequency Spectrum of Load Current (with compensation)

5.4.2 Results for Non-Linear Loads under Different Fault Conditions

CASE I: Single Line to Ground Fault Condition

In this case, a single line to ground fault is considered for both the feeders feeding static non-linear load. Here the fault resistance is 0.001 ohm and the ground resistance is 0.001 ohm. The fault is created for the duration of 0.05s to 0.1s. The output wave for the load current without compensation is shown in fig.5.13. It is clear from the output wave shape that the current in the phase where fault is created is increasing during the fault duration in the uncompensated feeder, when DSTATCOM is connected in the system the unbalancing is reduced clearly as shown in fig.5.14. These results become clear from the frequency spectrum graphs, which are taken one by one for non-compensated and compensated feeders with static non-linear load as shown in fig.5.15 and fig.5.16. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 27.22% to 0.00% when DSTATCOM is connected to the system.

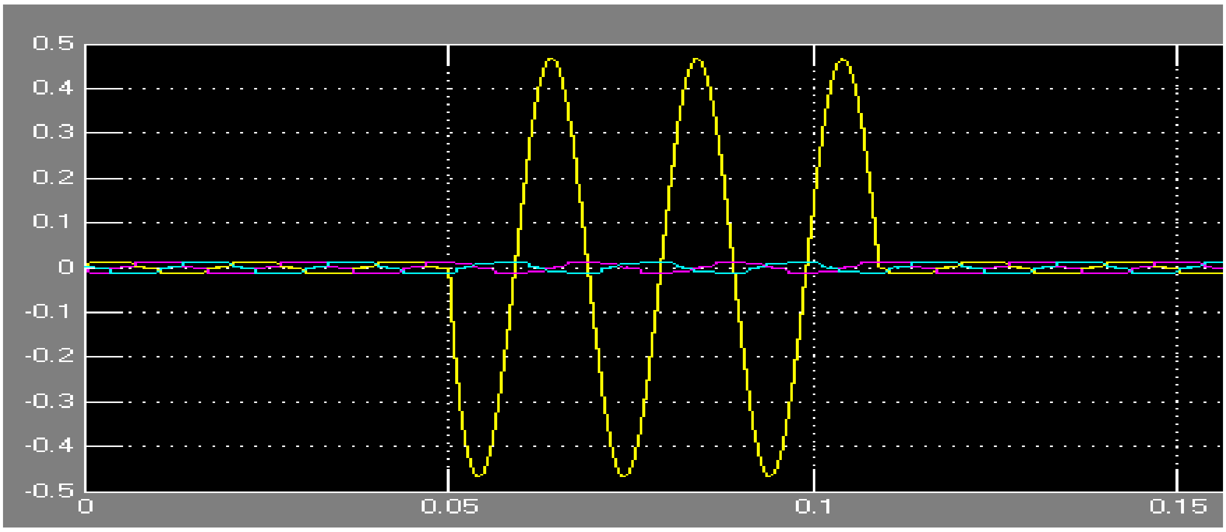

Fig.5.13: Load current (p.u.) vs Time waveform (without compensation)

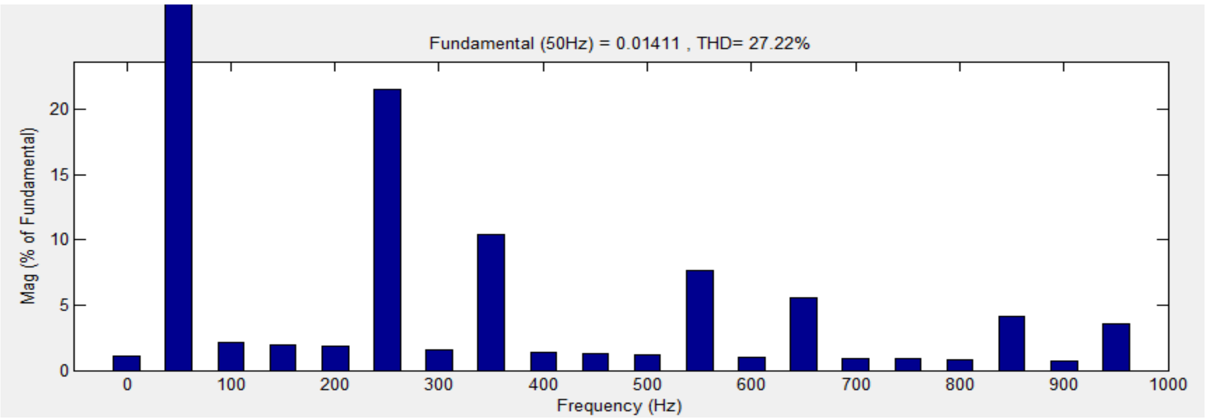

Fig.5.14: Frequency Spectrum of Load Current (without compensation)

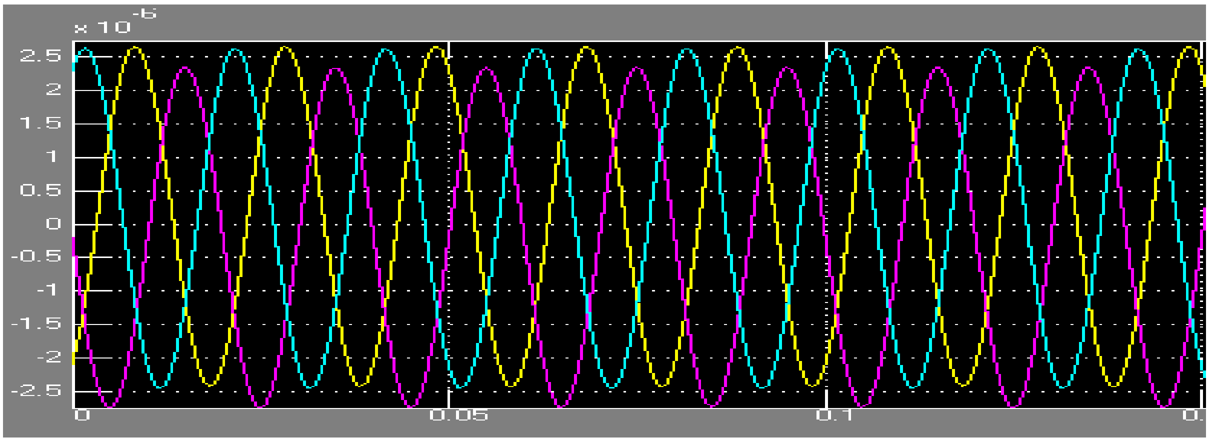

Fig.5.15: Load current (p.u.) vs Time waveform (with compensation)

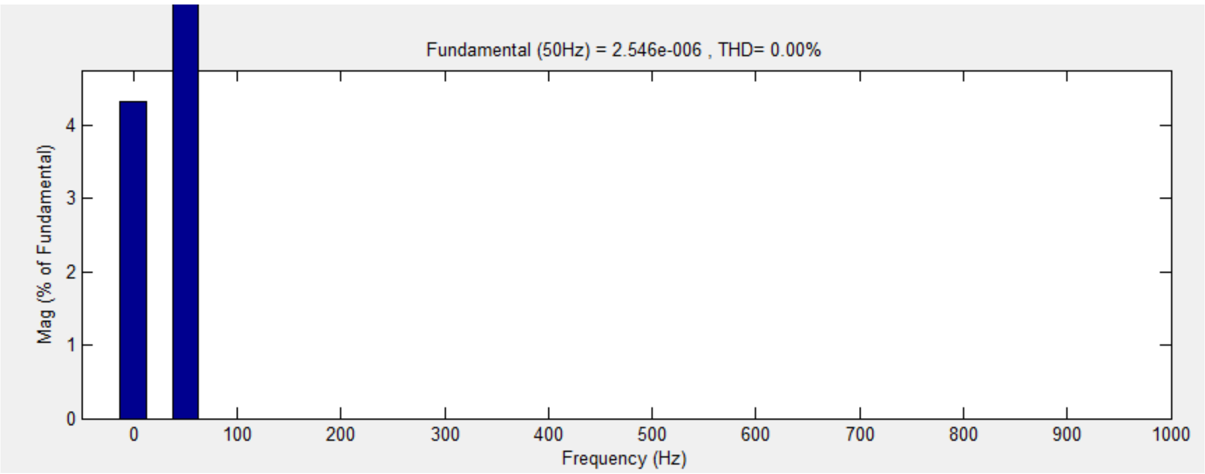

Fig.5.16: Frequency Spectrum of Load Current (with compensation)

CASE II: Double Line to Ground Fault Condition

In this case, a double line to ground fault is considered for both the feeders feeding static non-linear load. Here the fault resistance is 0.001 ohm and the ground resistance is 0.001 ohm. The fault is created for the duration of 0.05s to 0.1s. The output wave for the load current without compensation is shown in fig.5.17. It is clear from the output wave shape that the current in the phases where fault is created is increasing during the fault duration in the uncompensated feeder, when DSTATCOM is connected in the system the unbalancing is reduced clearly as shown in fig.5.18. These results become clear from the frequency spectrum graphs, which are taken one by one for non-compensated and compensated feeders with static non-linear load as shown in fig.5.19 and fig.5.20. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 27.22% to 0.00% when DSTATCOM is connected to the system.

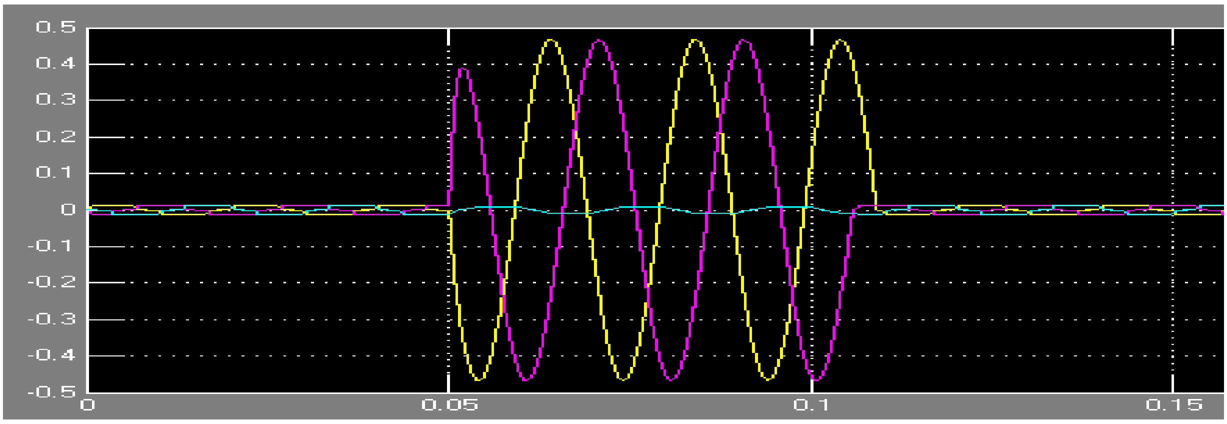

Fig.5.17: Load Current (p.u.) vs Time waveform (without compensation)

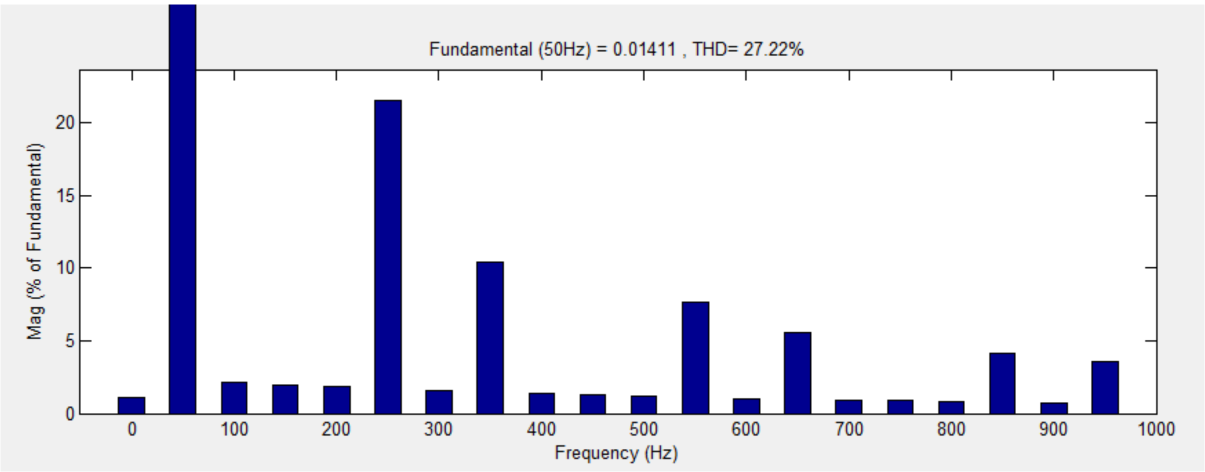

Fig.5.18: Frequency Spectrum of Load Current (without compensation)

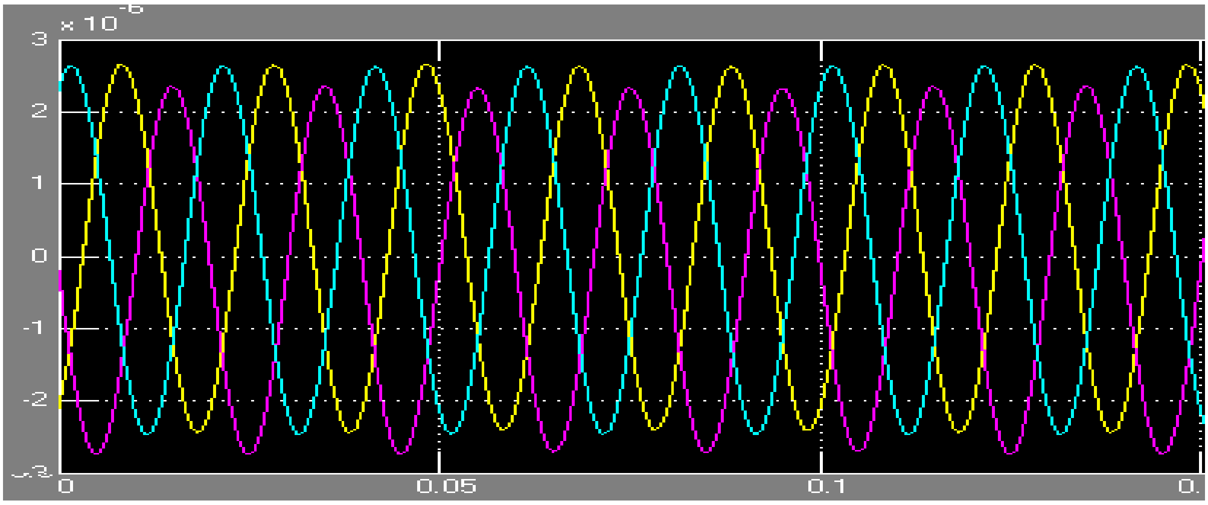

Fig.5.19: Load Current (p.u.) vs Time waveform (with compensation)

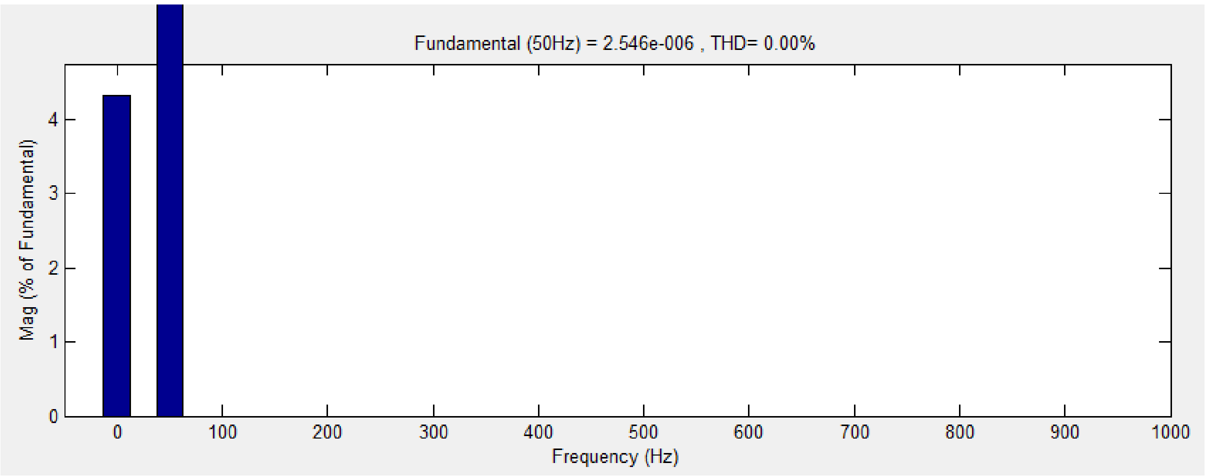

Fig.5.20: Frequency Spectrum of Load Current (with compensation)

CASE III: Three Phase Fault Condition

In this case, three phase fault is considered for both the feeders feeding static non-linear load. Here the fault resistance is 0.001 ohm and the ground resistance is 0.001 ohm. The fault is created for the duration of 0.05s to 0.1s. The output wave for the load current without compensation is shown in fig.5.21. It is clear from the output wave shape that the current in the phases where fault is created is increasing during the fault duration in the uncompensated feeder, when DSTATCOM is connected in the system the unbalancing is reduced clearly as shown in fig.5.22. These results become clear from the frequency spectrum graphs, which are taken one by one for non-compensated and compensated feeders with static non-linear load as shown in fig.5.23 and fig.5.24. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 27.22% to 0.00% when DSTATCOM is connected to the system.

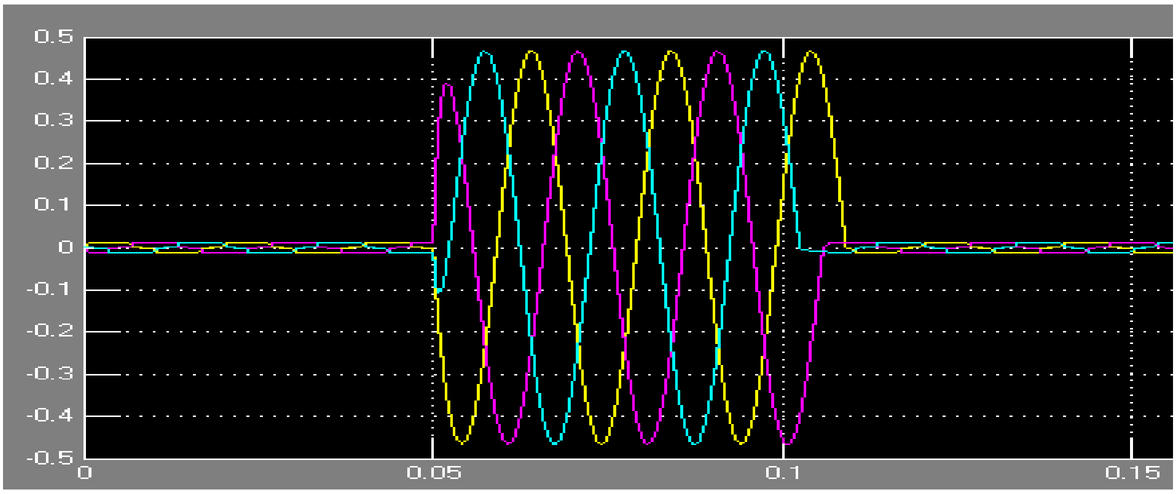

Fig.5.21: Load Current (p.u.) vs Time waveform (without compensation)

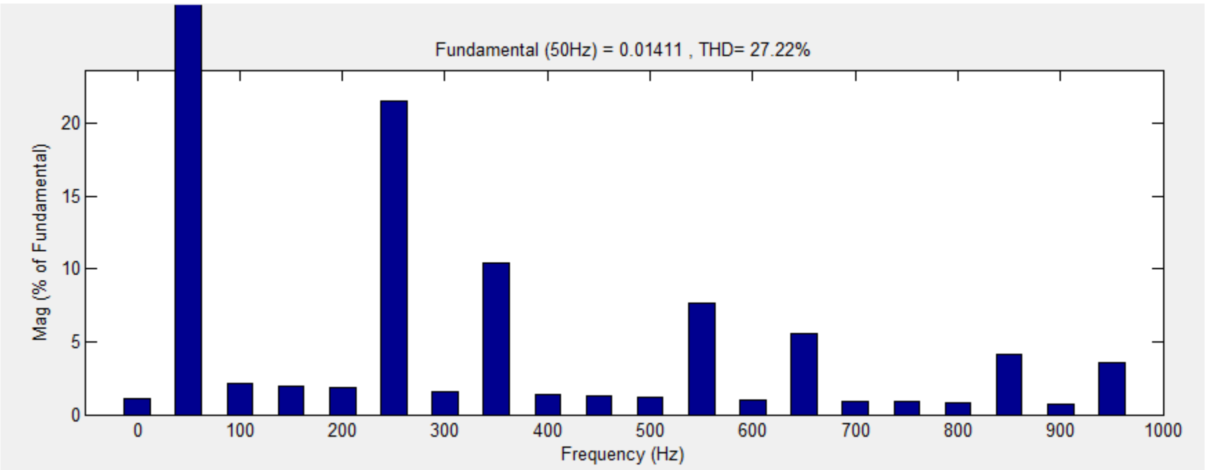

Fig.5.22: Frequency Spectrum of Load Current (without compensation)

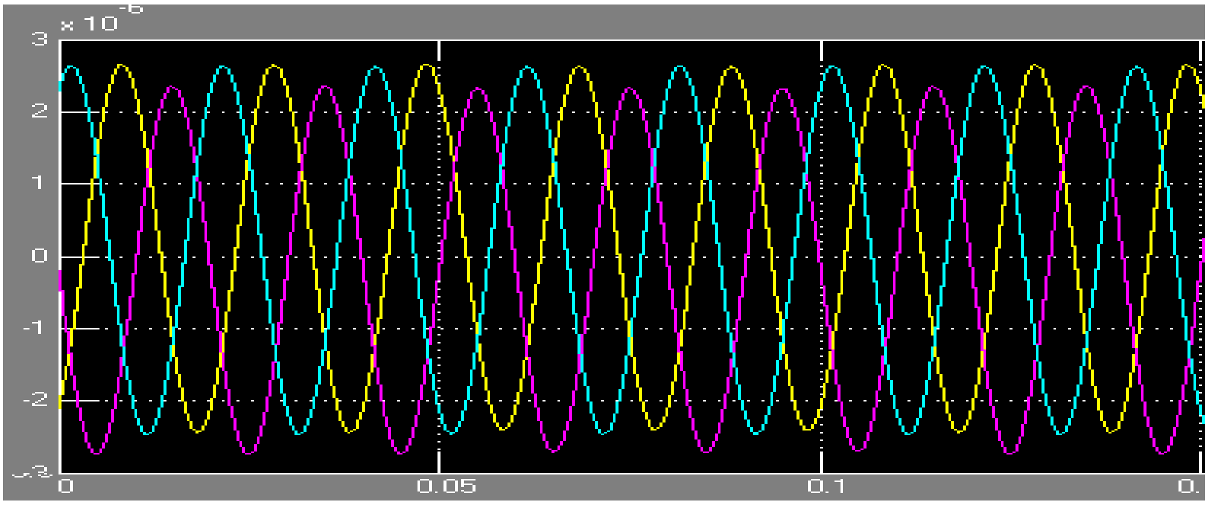

Fig.5.23: Load Current (p.u.) vs Time waveform (with compensation)

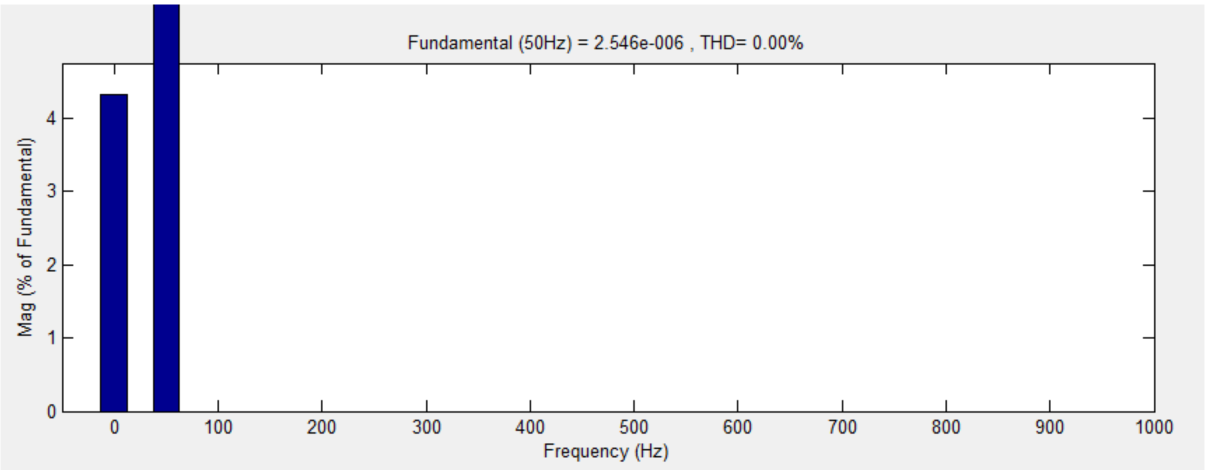

Fig.5.24: Frequency Spectrum of Load Current (with compensation)

CHAPTER 6

CONCLUSIONS AND FUTURE SCOPE OF WORK

6.1 Conclusions

In this work, DSTATCOM has been modeled with Photovoltaic Energy Storage System and simulated in MATLAB/SIMULINK environment. The performance of DSTATCOM has been analyzed for linear loads and static non-linear loads. DSTATCOM has been found to regulate PCC current under varying load conditions and load unbalancing. According to IEEE-519 standards the THD level must remain below 5% and DSTATCOM effectively reduces THD level of load current below 5% in all cases presented in this work. It is clear from comparison of THD analysis for different types of loads under normal and various faults conditions that DSTATCOM effectively compensate current harmonics. It is therefore, concluded that DSTATCOM has a huge scope in improving power quality levels in distribution systems.

6.2 Future Scope of Work

In this work, it is shown that DSTATCOM can effectively compensate harmonics from load current. The work can be extended in the following area:

- Other advanced controllers like fuzzy controller, artificial intelligence based adaptive fuzzy controller and state space vector technique can be employed with DSTATCOM to increase the effectiveness of DSTATCOM in distribution networks.
- The effectiveness of DSTATCOM can be established for distribution networks with other types of non-active loads like arc furnace, and active loads like FOC induction motor drive using dqo transformation technique and wind turbine system.

REFERENCES

[1] D.G. Flinn, C. Gilker and S.R. Mendis, "Methods for Identifying Potential Power Quality Problem", *Conference on Rural Electric Power,* February 3, 1991.

[2] J. Sun, D. Czarkowski and Z. Zabar, "Voltage Flicker Mitigation Using PWM-Based Distribution STATCOM", *Conference on Power Engineering Society Summer Meeting, Publication,* vol.1 ,pp. 616 – 621,2002.

[3] A. El Mofty and K. Youssef, "Industrial Power Quality Problems", *Conference on Electrical Distribution,* vol.2,pp. 18-21, June 2001.

[4] Walmir Freitas, Andre Morelato, Wilsun Xu and Fujio Sato, "Impacts of AC Generators and DSTATCOM Devices on the Dynamic Performance of Distribution Systems", *Conference on IEEE Transactions on Power Delivery,* pp. 1493 – 1501, 2005.

[5] Bhim Singh, Alka Adya, A.P. Mittal and J.R.P Gupta, "Modelling and Control of DSTATCOM for Three-Phase, Four-Wire Distribution Systems", *Conference on Industry Applications Conference,* vol. 4, pp: 2428 - 2434, 2005.

[6] M. G. Molina and P. E. Mercado, "Dynamic Modelling and Control Design of DSTATCOM with Ultra-Capacitor Energy Storage for Power Quality Improvements", *Conference on Transmission and Distribution conference and Exposition: Latin America, IEEE/PES,* pp. 1 – 8, 2008.

[7] Virulkar, V, and Aware, M, "Analysis of DSTATCOM with BESS for mitigation of flicker", *International Conference on Control, Automation, Communication and Energy Conservation, 2009. INCACEC 2009,* 4-6 June 2009.

[8] Sepulveda, C.A, Espinoza, J.R., Landaeta, L.M., and Baier, C.R. "Operating Regions Comparison of VSC-based Custom Power Devices", *32nd Annual Conference on IEEE Industrial Electronics, IECON 2006,* 6-10 Nov. 2006.

[9] Naetiladdanon Sumate, "Voltage Sag Compensation Performance by DSTATCOM with Series Inductor and Energy Storage*", 7th International Conference on Power Electronics and Drive Systems, 2007. PEDS '07,* 27-30 Nov. 2007.

[10] Aodsup, K., Boonchiam, P.N., Sode-Yome, A., Kongsuk, P. and Mithulananthan, N. "Response of DSTATCOM under Voltage Flicker in Farm Wind*", 7th International*

Conference on Power Electronics and Drive Systems, 2007. PEDS '07, 27-30 Nov. 2007.

[11] Naetiladdanon, S, “Design considerations of DSTATCOM for voltage sag compensation without interaction”, *Electrical Engineering/Electronics, 5th International Conference on Computer, Telecommunications and Information Technology,* vol. 2, 14-17 May 2008.

[12] Molina, M.G. and Mercado, P.E. “Dynamic modelling and control design of DSTATCOM with ultra-capacitor energy storage for power quality improvements”, *Transmission & Distribution Conference and Exposition: Latin America, 2006.* 15-18 Aug. 2006.

[13] Molina, M.G. and Mercado, P.E. “Control Design and Simulation of DSTATCOM with Energy Storage for Power Quality Improvements”, *Transmission & Distribution Conference and Exposition: Latin America, 2006.* 15-18 Aug. 2006.

[14] Virulkar, V.B. and Aware, M, “Analysis of DSTATCOM with BESS for mitigation of flicker”, *International Conference on Control, Automation, Communication and Energy Conservation, 2009. INCACEC 2009,* 27-29 Dec. 2009.

[15] Molina, M.G. and Mercado, P.E. “Control of tie-line power flow of micro grid including wind generation by DSTATCOM-SMES controller”, *Energy Conversion Congress and Exposition, 2009. ECCE 2009. IEEE,* 20-24 Sept. 2009.

[16] Suvire, G.O. and Mercado P.E, “Improvement of power quality in wind energy applications using a DSTATCOM coupled with a Flywheel Energy Storage System”, *Power Electronics Conference, 2009. COBEP '09. Brazilian*, Sept. 27 2009-Oct. 2009.

[17] Satyanarayana, G. V R and Ganesh, S. N V “Cascaded 5-level inverter type DSTATCOM for power quality improvement”, *Students' Technology Symposium (TechSym), 2010 IEEE,* 3-4 April 2010.

[18] Molina, M.G. and Mercado, P.E. “Power flow control of micro grid with wind generation using a DSTATCOM-UCES”, *International Conference on Industrial Technology (ICIT), 2010 IEEE,* 14-17 March 2010.

[19] Singh, A. Singh, B. and Singh, S., “Customized solution for real and reactive power compensation for small distribution systems”, *Conference on the European Energy Market (EEM), 2010 7th International,* 23-25 June 2010.

[20] Hosseini, S.H.andNazarloo, A., “Application of D-STATCOM to improve distribution system performance with balanced and unbalanced fault conditions”, *Electric Power and Energy Conference (EPEC), 2010 IEEE,* 25-27 Aug. 2010.

[21] Suvire, G.O. and Mercado, P.E, “Active power control of a flywheel energy storage system for wind energy applications”, *Renewable Power Generation, IET* vol. 6, issue-1, pp. 9-16, Jan 2012.

[22] C. H. Lin, C. S. Chen, W. L. Hsieh, C. T. Hsu, H. J. Chuang, and C.Y. Ho, “Optimization of Photovoltaic Penetration with DSTATCOM in Distribution Systems”, *in 2012 IEEE Power Engineering Society General Meeting, Toronto, Canada,* July 2012.

[23] Annapooma Chidurala, Tapan Kumar Saha and N. Mithulananthan “Power Quality Enhancement in Unbalanced Distribution Network using Solar-DSTATCOM”, *Australasian Universities Power Engineering Conference, AUPEC 2013, Hobart, T AS, Australia,* 29 September - 3 October 2013.

[24] Singh, B. and Niwas, R, “Power quality improvements in diesel engine driven induction generator system using SRF theory”, *Power India Conference, 2012 IEEE Fifth,* ,pp. 1-5, 19-22 Dec. 2012.

[25] Singh, A., Bhowmick, S. and Shukla, K, “Load compensation with DSTATCOM and BESS”, *5th India International Conference on Power Electronics (IICPE), 2012 IEEE,* vol. 2, pp. 1-6, 6-8 Dec. 2012.