INVESTIGATIONS ON THE EFFECTIVENESS OF DSTATCOM IN DISTRIBUTION NETWORKS

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MASTER OF ENGINEERING
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CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled **"INVESTIGATIONS OF THE EFFECTIVENESS OF DSTATCOM IN DISTRIBUTION NETWORKS"** 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 **Mr.PARAG NIJHAWAN,** (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.

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ABSTRACT

Utility and customer-side disturbances result in terminal voltage fluctuation, transients and waveform distortions on the distribution system. In recent years, power quality engineers are becoming increasingly concerned over the quality of electrical power. 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. Also 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. Due to the non-linearity of these loads, they cause disturbances in the voltage waveform. In modern industries, FOC induction motor drives and DTC induction motor drives are used, which produce distortion in load current and harmonics distortion. It is expected that a utility will supply a low distortion balanced voltage to its customers, especially those with sensitive loads.

A Distribution Static Compensator (DSTATCOM) is a voltage source converter (VSC) based custom power device for the enhancement of power quality due to its quick response, high reliability and nominal cost. A DSTATCOM is connected in parallel with the system to compensate voltage sag, voltage swell, voltage unbalance and harmonics. 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.

In this work, DSTATCOM has been modeled and simulated in MATLAB/SIMULINK environment. The performance of DSTATCOM has been analyzed for linear loads, static non-linear loads, DTC induction motor drive and FOC induction motor drive using dqo transformation technique. DSTATCOM has been found to regulate PCC current under varying load conditions and load unbalancing. The control technique implements a dqo transformation which starts from the difference between the load current and reference current that determines the reference voltage of the inverter (modulating reference signal). The simulation results show that the DSTATCOM effectively compensate load current harmonics.

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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

1.1 Overview

Utility and customer-side disturbances result in terminal voltage fluctuation, transients and waveform distortions on the distribution system. In recent years, power quality engineers are becoming increasingly concerned over the quality of electrical power. 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 [1]. Much of these modern load equipment's themselves use electronic switching devices which then can contribute to poor network voltage quality.

In present days, power distribution systems are suffering from severe power quality problems. Current power distribution systems are experiencing increased installation of distributed generators and application of custom power devices. The most common type of distributed generation employs ac rotating machines. In modern industries, FOC induction motor drives and DTC induction motor drives are used, which produce distortion in load current and harmonics distortion [5-6]. It is well known that these drives have some disadvantages that can be summarized in the following points:

- High current and torque ripple;
- Variable switching frequency behaviour;
- High noise level at low speed;
- Lack of direct current control.

Power quality issues are gaining significant attention due to the increase in number of sensitive loads. Also 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 [3]. 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. It is expected that a utility will supply a low distortion balanced voltage to its customers, especially those with sensitive loads.

In last two decades, various schemes of load compensation have been proposed. These schemes can cancel the effect of unbalance and distortion in current and can also correct the power factor at the load bus. The FACTS devices offer a fast and reliable control over the transmission parameters, i.e. voltage, line impedance and phase angle between the sending end voltage and receiving end voltage [8-9]. On the other hand the custom power is for low voltage distribution and improving the poor quality and reliability of supply affecting sensitive loads. DVR, DSTATCOM and UPQC are most widely used custom power devices.

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 [10]. 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.

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.

S. V. Ravi Kumar, *et al*. [2] discussed about the various power quality problems and described a PI controller based technique to correcting the voltage sag, swell and interruption in a distributed system. At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications. Among these, the distribution static compensator and the dynamic voltage restorer are most effective devices. Both DSTARCOM and DVR are based on the VSC principle. A DVR injects a voltage in series with the AC system voltage and a DSTATCOM injects a current into the AC system to correct the voltage sag, swell and interruption.

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.

A. De Almeida, *et al.* [4] discussed the main Power Quality (PQ) problems with their associated causes and consequences. The economic impacts associated with PQ are characterized and some solutions to mitigate the PQ problems are presented in this paper.

Domenico Casadei, *et al.* [5] discussed about field oriented control and direct torque control of induction motor drives. This paper is aimed to give a contribution for a detailed comparison between the two control techniques. The performance of the two control schemes is evaluated in terms of torque and current ripple. This paper also explained about advantages and disadvantages of induction motor drives.

R. Toufouti, *et al.* [6] proposed two approach intelligent techniques of improvement of Direct Torque Control (DTC) of Induction motor such as fuzzy logic and artificial neural network. The comparison with conventional direct torque control show that the use of the DTC fuzzy logic and DTC artificial neural network reduces the torque, stator flux and current ripples. The validity of the proposed methods is confirmed by the simulative results.

Alexander Domijan, *et al.* [7] discussed about three major power quality devices which are an advanced static VAR compensator, a dynamic voltage restorer and a high-speed transfer switch. This paper presents a simulation study about the coordination and interaction of advanced power electronic devices working in close electrical proximity. It explained a first approach to the custom power park concept, using well-demonstrated performance PQDs, i.e. a DVR, an ASVC and an HSMTS.

T. Devaraju, *et al.* [8] discussed about custom power devices like DSTATCOM, DVR and UPQC. The configurations, working and significant functions of each custom power devices are also explained in this paper. This study presents the power quality problems such as voltage sags, swells and interruptions. A new PWM-based control scheme has been implemented to control the electronic valves in the two-level VSC used in the DSTATCOM and DVR.

Afshin Lashkar Ara, *et al.* [9] discussed the comparison of the FACTS equipment operation in transmission and distribution systems. This paper reviewed the technology industry and new attachments on power components, power controllers and various topologies of the power components. The FACTS devices offer a fast and reliable control over the transmission parameters, i.e. voltage, line impedance and phase angle between the sending end voltage and receiving end voltage. On the other hand the custom power is for low voltage distribution and improving the poor quality and reliability of supply affecting sensitive loads. DVR, DSTATCOM and UPQC are most widely used custom power devices. The principal operating modes and applications whichever one of equipment in transmission and distribution system (such as STATCOM, SSSC, UPFC, DSTATCOM, DVR and UPQC) are discussed and compared in this paper.

Bhim Singh, *et al.* [10] focused on power quality development of power electronic technology which rises to aspects like power factor correction, voltage regulation and load balancing of linear load. DSTATCOM is realized using a three leg IGBT static and dynamic performance. In this paper, a hysteresis rule based carrier-less PWM current controller is used to derive gating pulses for the IGBT switches. It is observed that DSTATCOM effectively improves power quality in electric distribution systems. It is effective in compensating reactive power and improving the power factor of the distribution system.

J. Sun, *et al.* [11] discussed Voltage flicker, which is a phenomenon of annoying light intensity fluctuation. It is caused by large rapid industrial load changes and has been a major concern for both customers and power companies in the area of power quality. The fast response of the DSTATCOM makes it the efficient solution for improving power quality in distribution systems. In this paper, voltage flicker mitigation studies with a current controlled PWM-based DSTATCOM are also performed and discussed. In this paper, the voltage flicker problem in a 69/13.8 kV distribution system is investigated.

Dinesh Kumar, *et al.* [12] described the modeling and analysis of DSTATCOM, which is capable of balancing the source current and power factor correction caused due to unbalanced and non-linear load currents. In this paper, a hysteresis band based PWM current controller is used. The theory of instantaneous symmetrical components is used here to extract the three-phase reference currents. These reference currents are tracked using voltage source inverter (VSI), operated in a hysteresis band control technique. The two-level and three-level inverter topologies are used to realize the compensator in this paper. It is observed that three level inverter gives less THD in source currents as compare to two level inverter.

Arindam Ghosh, *et al.* [13] discussed the concept of a mini custom power park in which the voltage inside the park is tightly regulated by a DSTATCOM. In this paper, it is discussed that solid state protection devices, along with the DSTATCOM will eliminate many transients in all the loads of the park during disturbances. During the total line outages the DSTATCOM backed by a diesel generator, will supply the most sensitive loads and made them both transient and interruption free. Digital computer simulation studies are used to verify the proposed operation of the custom power park in this paper.

Walmir Freitas, *et al.* [14] presented a dynamic study about the influences of induction and synchronous machines on the dynamic behaviour of distribution networks. The performance of a DSTATCOM as a voltage controller or a power factor controller is analysed in this paper. Also the impacts of these controllers on the stability and protection system of distribution networks with distributed generators are determined in this paper. It is shown by Computer simulation results that a DSTATCOM voltage controller can significantly improve the stability performance of induction generators and a DSTATCOM power factor controller may adversely affect the stability performance of synchronous generators.

Rodda Shobha Rani, *et al.* [15] proposed that a VSC with pulse width modulation provides a faster control for flicker mitigation purpose. By installing a shunt compensator the voltage regulation in the distribution feeder is improved very effectively. DSTATCOM is modelled and simulated to verify the power factor correction and voltage regulation along with neutral current compensation, harmonic elimination and load balancing with linear loads and non-linear loads. The three-phase, three-wire DSTATCOM is proposed for power quality improvement in this paper.

Bhim Singh, *et al.* [16] discussed DSTATCOM for load balancing, power factor correction, neutral current elimination 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, in this paper.

Su Chen, *et al.* [17] proposed an alternative control structure which is based on the simultaneous control of line current and dc-link voltage by means of instantaneous power control. DSTATCOMs are viable solution for improving power quality in distribution systems, including mitigation for temporary interruptions, harmonics, voltage flicker and voltage dip. Conventional DSTATCOMs are implemented using two cascaded loops, an ac current control loop and a dc-bus voltage loop. In this paper, the instantaneous real and imaginary power calculation is derived and explained using the controller, which is implemented using two hysteresis comparators and an optimum switching table. This paper describes mitigation of voltage flicker and load harmonics using a DSTATCOM.

Arindam Ghosh, *et al.* [18] discussed load compensation using a DSTATCOM. The compensator is designed such that it not only cleans the distortion created by the load, but also improves the voltage quality at the point of common coupling (PCC). Specifically, a compensator passive filter structure is proposed for this paper. The other aspect of the proposal is for a linear quadratic regulator (LQR) based switching controller scheme that tracks reference using the proposed compensator filter structure. It proposes a new switching control scheme and demonstrates its suitability for this problem and also proposes a scheme in which the fundamental sequence components of a three-phase signal can be computed from its samples. This paper discusses the issues for correction of load unbalance and distortion at a weak ac bus using DSTATCOM.

M. G. Molina, *et al.* [19] investigated the dynamic performance of a DSTATCOM coupled with energy source system (ESS) for improving the power quality of distribution systems. In this paper, three modes of operation are considered, i.e. voltage control, power factor correction and active power control. The multi-level control technique is proposed, which is based on the instantaneous power theory on the synchronous rotating dq reference frame.

K. N. Choma, *et al.* [20] described the application of a DSTATCOM to an existing industrial facility for voltage flicker mitigation during the starting of a large motor. The DSTATCOM performs well, should have acceptable reliability and is cost competitive with other solutions. Since the cost of a DSTATCOM is expected to be comparable to the addition of onsite generation, it is the only solution that meets all of the requirements.

M. B. C. Salle, *et al.* [21] presented a comparative analysis between a SVC and a DSTATCOM for improvement of induction generator stability. This study is based on transient stability simulations. The dynamic performance of a distribution network with an induction generator and a SVC or a DSTATCOM during balance and unbalance faults is analysed in this paper. Simulation results showed that a DSTATCOM with the same power capability of a SVC allows the critical power injection from an induction generator to assume higher values.

S. H. Hosseini, *et al.* [22] proposed a control method that enables DSTATCOM to mitigate all types of fault, intelligently (such as single line to ground fault, double phase to ground fault and three-phase fault). In this paper, a 12-pulse DSTATCOM configuration with IGBT is designed and the graphic based models of the DSTATCOM are developed using the PSCAD/EMTDC. It validates the performance of a DSTATCOM system for improving distribution system performance under all types of fault. The reliability and robustness of the control scheme in the system response to the voltage sags caused by single line to ground, double line to ground and three-phase faults is proved in the simulation results.

I. Papic, *et al.* [23] discussed about PWM converter based shunt and series connected Power Conditioners named DSTATCOM and DVR to solve the power quality problems like voltage sags, harmonic distortion, flicker and interruption of power supply. Computer and process control equipment as well as drive converters are sensitive to deviations of the line voltage from the ideal sinusoidal. With energy storage added to the Power Conditioner even more flexibility in system operation and planning is provided for utilities and industry. In this paper, the application areas of DSTATCOM with energy storage are discussed in detail, followed by the derivation of the converter level control system of the device enabling fast dynamic active power compensation.

Sung Min Woo, *et al.* [24] discussed about FACTs and Custom Power devices. FACTs use power electronic devices and methods to control the high voltage side of the network for improving the power flow. Custom Power is for low voltage distribution and improving the poor power quality and reliability of supply affecting factories, offices and homes. Custom Power Devices is classified into three categories by their structures such as DVR, DSTATCOM and UPQC. The proposed control technique is applied to DSTATCOM for protecting voltage sags, swell and momentary interruption. This paper presents the performance of a shunt type compensator a1so called DSTATCOM with fast dynamic response designed to support the voltage for voltage sag and swell. The proposed system is able to compensate the voltage sag and swell even the long term faults.

Walmir Freitas, *et al.* [25] discussed the behaviour of a DSTATCOM to improve the voltage stability performance of distribution systems with induction generators based on three-phase non-linear dynamic simulations. The usage of distributed generation and devices based on power electronics has significantly increased in electric power distribution systems. In this context, induction generators have received more attention and such machines draw very large reactive currents during fault occurrence, which depresses the network voltage further and can lead to voltage instability. Two control strategies for a DSTATCOM are analysed: voltage and power factor control. In such studies, a DSTATCOM is simulated through a model based on controllable three-phase voltage sources, which has shown to be suitable for stability studies.

W. Srisongkram, *et al*. [26] described analysis and control design of a DSTATCOM to control the voltage at the PCC in order to keep the power constant at the load from intermittent wind speeds. A feed forward compensation scheme is derived and employed in this paper, for fast response requirement. Use of a current controlled PWM inverter as the power stage of the DSTATCOM generates needed compensation currents for real time load compensation. It illustrated that the DSTATCOM could regulate the voltage coming from the network wind turbine. The dq detection with RDFT is applied to detect system voltage quickly and could immune any undesired signals.

Kiran Kumar Pinapatruni, *et al*. [27] discussed that DSTATCOM is a compensating device which is used to control the flow of reactive power in the distribution systems. In this paper, decoupled theory using the PI controller is used to control the DSTATCOM. Analyses of the different types of control strategies use for the control of DSTATCOM are discussed in this paper. The control scheme maintains power balance at the PCC to regulate the dc capacitor voltages. Extensive simulations were conducted to gain insight into the impact of capacitor size on DSTATCOM harmonic generation, speed of response of the PWM control and transient overshooting. It is concluded that a DSTATCOM though is conceptually similar to a STATCOM at the transmission level; its control scheme should be such that in addition to complete reactive power compensation, power factor correction and voltage regulation and for achieving improved power quality levels at the distribution end.

M. Abul Masrur, *et al*. [28] discussed about automotive industry PWM inverter controlled drive systems which find extensive applications in Electric Vehicles and other motion control systems. In this paper, the ABC-DQ current transformations vector based PWM inverter controller is used to control brushless synchronous motor drive. Among the major peripheral devices in the drive system are the A/D and D/A converters, analog or digital filters and position encoder. These devices deal with signals and other quantities which have to undergo digitization and quantization. All the above processes and the devices introduce non-linearities and errors in the drive system.

Alka Singh, *et al*. [29] discussed modeling & control of DSTATCOM and BESS using SIMULINK in MATLAB environment. They proposed a control system based on dqo technique. The results are presented for a test system with/without DSTATCOM for a wide variety of system disturbances. The modeled DSTATCOM is also tested for load compensation of linear and non-linear loads in both steady state and dynamic conditions.

Wei Neng Cheng, *et al.* [30] proposed a feed forward based dqo transformation compensation scheme for the control of DSTATCOM in faulty conditions. In this paper, compensation technique of the DSTATCOM is derived with symmetrical component method and a current regulated PWM inverter is used to generate needed compensation current. The results are presented for a test system with/without DSTATCOM for a wide variety of system disturbances.

Soo Bin Han, *et al.* [31] analysed the static and dynamic characteristics of buck-type three-phase PWM rectifier which are fully based on the dc and ac circuit models developed by the circuit DQ transformation. In this paper, various static converter characteristics such as gain, real and reactive power, power factor and unity power factor conditions are completely analysed.

Mithilesh Singh, *et al.* [32] discussed about the artificial neural network technique with which the voltage sag is detected then trained data and neural network output simulated in neural network block set, then it will be mitigated using DSTATCOM with neural network control block. Here different aspects or power line status were considered and simulated using artificial neural network to get the response under changed operating conditions.

A. Elnahdy, *et al.* [33] discussed an effective control technique for DSTATCOM, as a custom power conditioner to mitigate the current fluctuation and voltage flicker in industrial distribution systems. The proposed control depends on a current vector control technique for generating the required reactive power and is newly utilized for a single-phase DSTATCOM. It is known that the current vector control is commonly implemented on a three-phase system to operate the three-phase DSTATCOM. The novelty in this paper is articulated in the implementation of the current vector control on a single-phase circuit to operate a single-phase DSTATCOM.

Pirooz Javanbakht, *et al.* [34] presented the comparative studies which evaluate the effects of SVC and DSTATCOM on dynamic and transient performance of common shaft cascaded induction motors, which are commonly used in deep well digging plants. The dynamic and transient events include system starting, supply voltage sag and swell as well as supply disconnection and reconnection

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 its controller.
- To investigate the performance of DSTATCOM using dqo transformation control scheme for different fault conditions like single line to ground fault, double line to ground fault under static linear loads, non-linear loads, DTC induction motor drive load and FOC induction motor drive load.

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 and outlines the control scheme used for simulation of it.
- **Chapter5** presents parameter of the test system. Simulink models of the test system with linear loads, non-linear loads, DTC induction motor drive load and FOC induction motor drive load 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 [3] as "the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment". 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 [11]. 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. 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" [3]. 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.

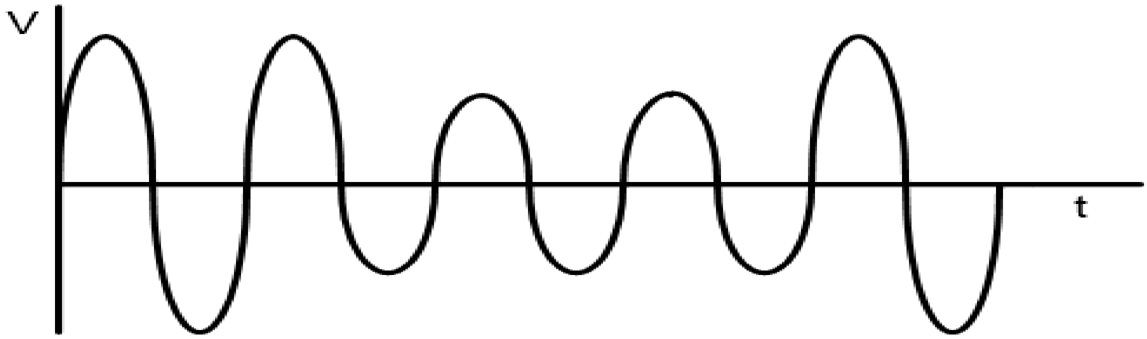

Fig.2.1: Voltage Sag

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 substations. 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.

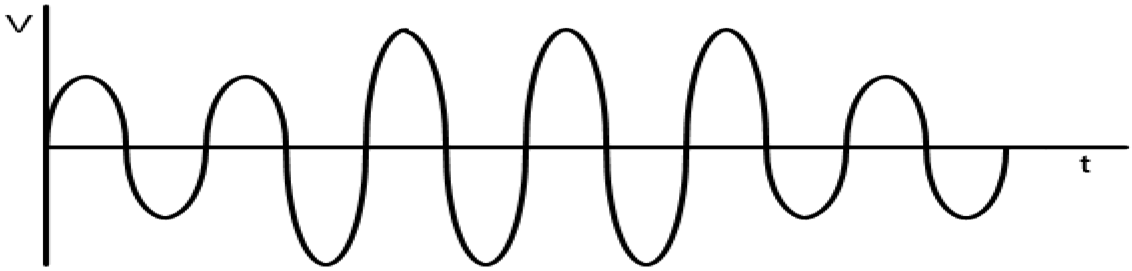

Fig. 2.2: Voltage Swell

2.2.3 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.

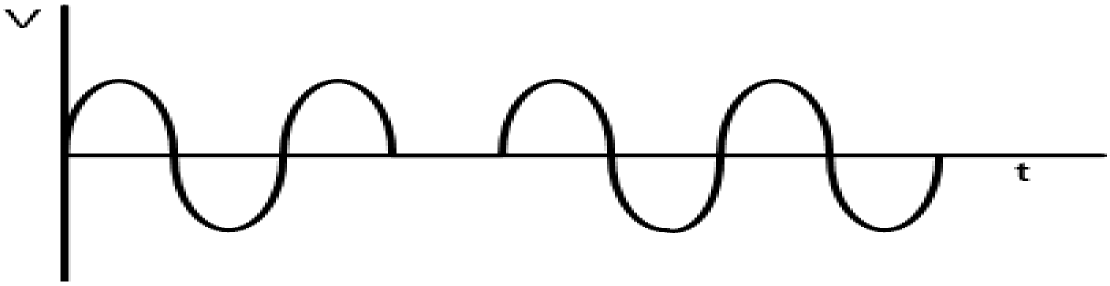

Fig.2.3: Very Short Interruptions

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 [3]. 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.

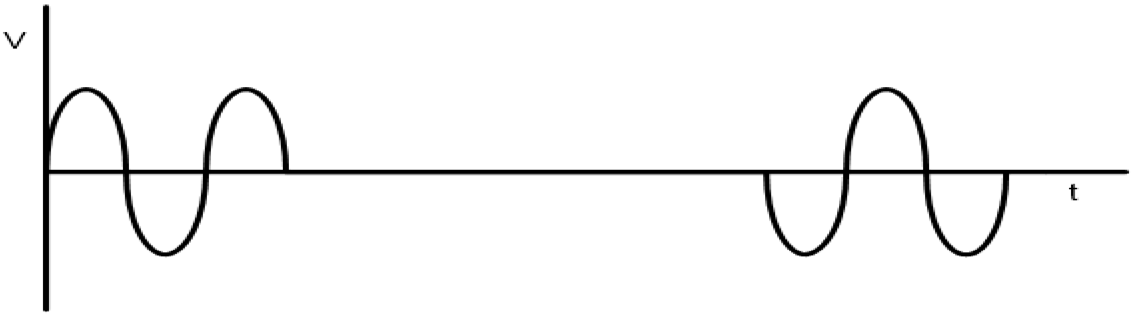

Fig.2.4: Long Interruptions

2.2.4 Transients

Transients are defined as very fast variation of the voltage values for durations from a several microseconds to few milliseconds [1]. 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

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 [4]. The consequences of impulsive transients are destruction of electronic components, failure of insulation materials, data processing errors and electromagnetic interference.

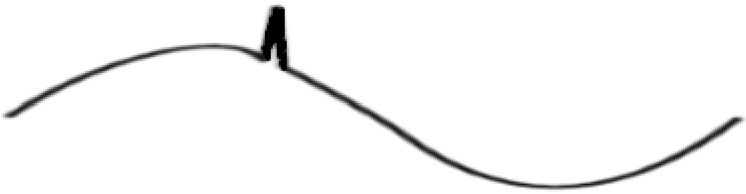

Fig.2.5: Impulsive Transients

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

2.2.5 Harmonic Distortion

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 [1, 4]. 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.

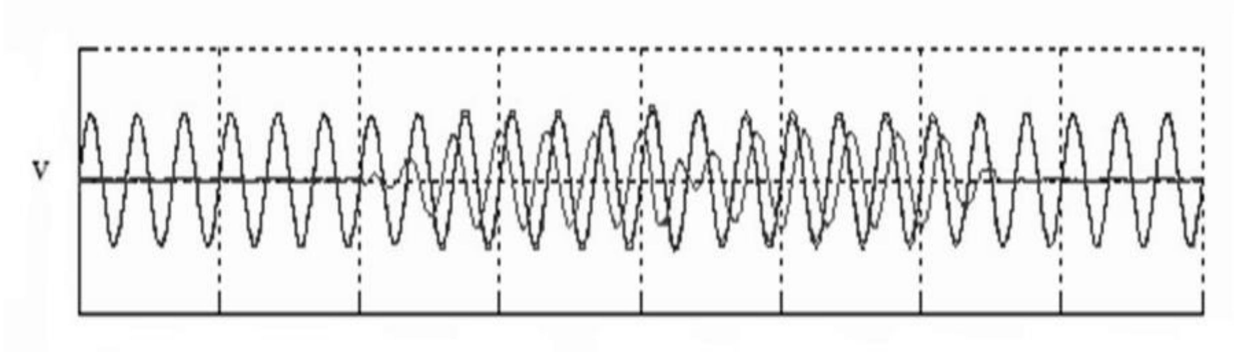

Fig.2.7: Harmonic Distortion

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

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.

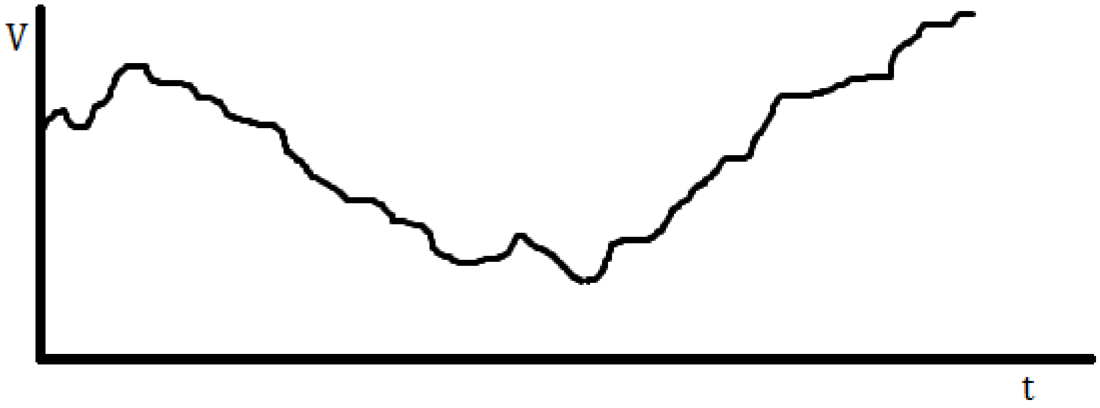

Fig.2.8: Voltage Fluctuation

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 [4]. 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.

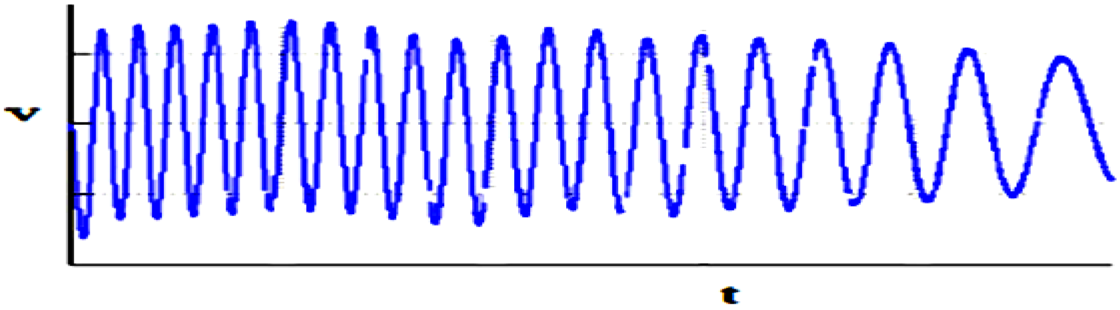

Fig.2.10: Voltage Unbalance

2.3 Effects of Poor Quality on Power System Devices

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

The concept of custom power was introduced by N.G. Hingorani in 1995 for improving the system performance for distribution network. Like flexible ac transmission systems (FACTS) for transmission systems, Custom Power is a concept based on the use of power electronic controllers in the distribution system to supply value-added, reliable, high quality power to its customers [7]. Just as FACTS improves the reliability and quality of power transmission by simultaneously enhancing both power transfer volume and stability, the custom power enhances the quality and reliability of power that is delivered to customers. Due to increasing load demands and the rapid development of power semiconductor devices, the custom power devices are taking place very fast. A custom power specification may include provision for:-

- Tight Voltage regulation including short duration sags or swells,
- Low harmonic Voltages,
- No power interruption,
- Acceptance of fluctuating and non-linear loads without effect on terminal voltage [8].

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 [8].

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 [4]. 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 [35]. 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.

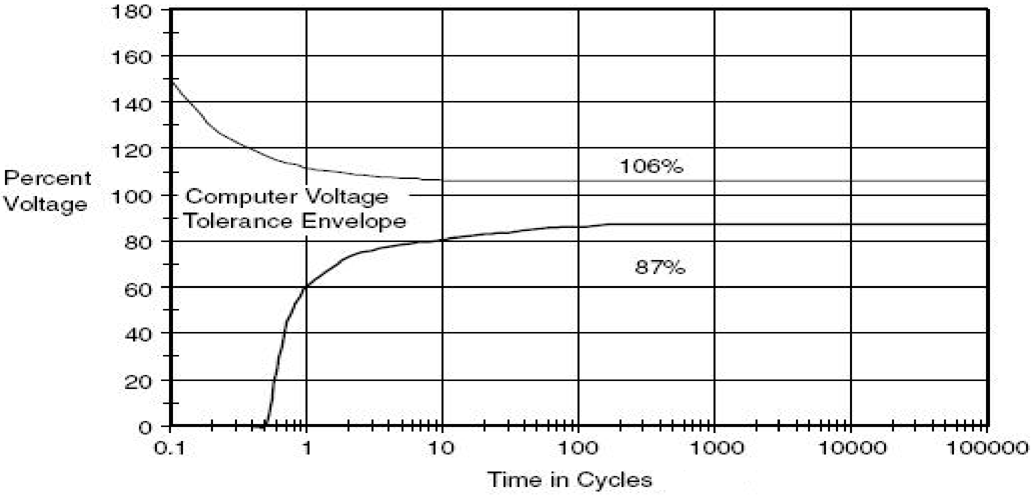

Fig.3.1: CBEMA curve

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

In last two decades, various schemes of load compensation have been proposed. These schemes can cancel the effect of unbalance and distortion in current and can also correct the power factor at the load bus. The FACTS devices offer a fast and reliable control over the transmission parameters, i.e. voltage, line impedance and phase angle between the sending end voltage and receiving end voltage [7-8]. On the other hand the custom power is for low voltage distribution, improving the poor quality and reliability of supply affecting sensitive loads.

There are many types of custom power devices. Some of these devices include Surge Arrester, Active Power Filter, Super Conducting Magnetic Energy Systems, Static Electronic Tap Changer, Solid State Fault Current Limiter, Solid State Transfer Switch, Static Var Compensator, Distribution Series Capacitor, Distribution Static Compensator, Dynamic Voltage Restorer and Unified Power Quality Conditioner [9].

Classification of Custom power devices (CPDs) are based on their power electronic controllers, which can be either of the network reconfiguration type or of the compensation type [8]. The network reconfiguration devices also called switchgear devices, which include the solid state or static versions or current limiting, current breaking and current transferring components. The compensating type devices are used for active filtering, load balancing, power factor correction and voltage regulation. They are either connected in shunt or in series or a combination of both. 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. The classification of CPDs is shown in fig.3.2.

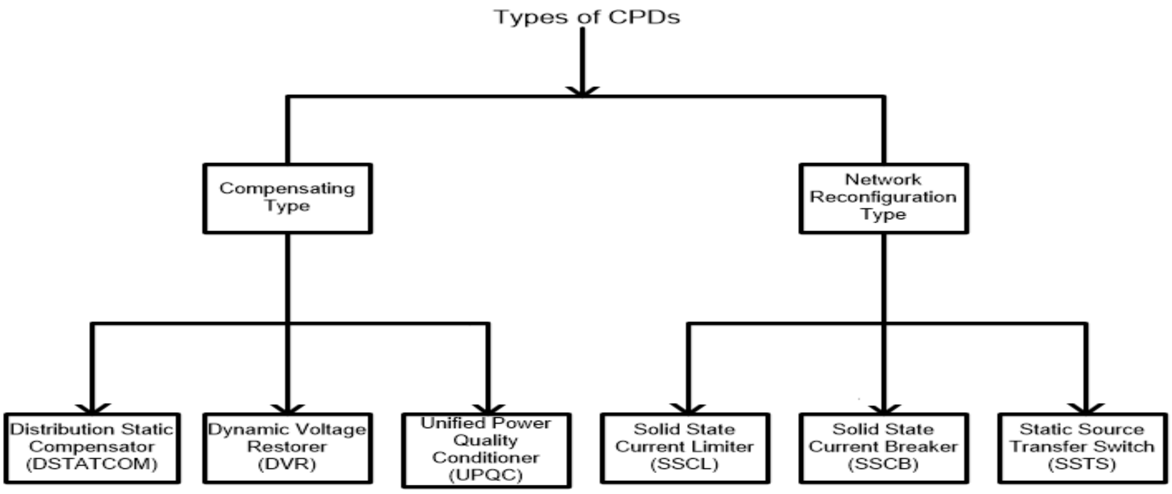

Fig.3.2: Classification of Custom Power Devices

3.3.1 Distribution STATCOM (DSTATCOM) [11]

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.3.3 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.

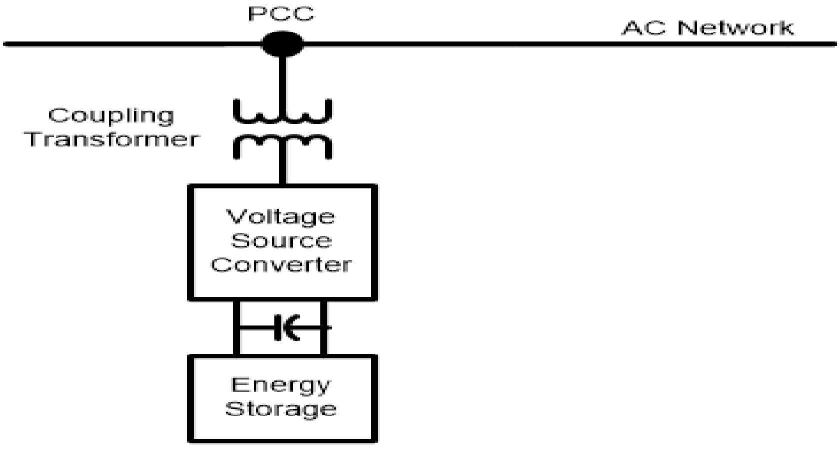

Fig.3.3: Schematic Diagram of DSTATCOM

3.3.2 Dynamic Voltage Restorer (DVR)

The DVR is a powerful controller that is commonly used for voltage sags mitigation at the point of connection. The DVR employs the same blocks as the DSTATCOM, but in this application the coupling transformer is connected in series with the ac system [2]. Fig.3.4 represents the schematic diagram of DVR. The main functions of DVR are reactive power compensation, voltage regulation, compensation for voltage sags and swells and unbalance voltage compensation (for 3-phase systems). The VSC generates a three phase ac output voltage which is controllable in phase and magnitude. These voltages are injected into the ac distribution system in order to maintain the load voltage at the desired voltage reference.

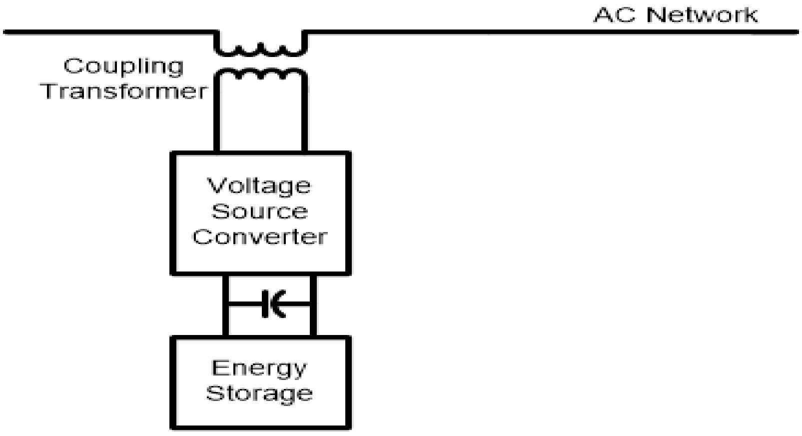

Fig.3.4: Schematic Diagram of DVR

3.3.3 Unified Power Quality Conditioner (UPQC) [8]

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.3.5.

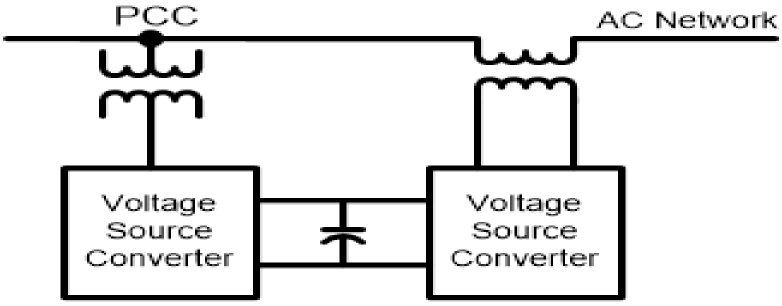

Fig.3.4: Schematic Diagram of UPQC

CHAPTER 4

DISTRIBUTION STATCOM

4.1 Introduction

DSTATCOM is basically one of the custom power devices, which is generally a shunt connected solid state device, installed at the Distribution level system in order to regulate the load side disturbances. In 1999, the first SVC with Voltage Source Converter called DSTATCOM went into operation. It has many advantages over the synchronous condenser, such as lower investment cost, better dynamics, no inertia, lower operating and maintenance cost. The basic component of the DSTATCOM is a power VSC that is based on high power electronics technologies [15]. It is a versatile device which provides reactive compensation in ac networks. The control of reactive power is achieved via the regulation of a controlled voltage source converter behind the leakage impedance of a transformer. It continuously checks the line waveform with respect to a reference ac signal and therefore, it can provide the correct amount of leading or lagging reactive current compensation to reduce the voltage fluctuations. A STATCOM at the transmission level handles only fundamental reactive power and provides voltage support while as a DSTATCOM is employed at the distribution level or at the load end for power factor improvement and voltage regulation. Other than voltage sags and swells compensation, DSTATCOM is also used to reduce the total harmonic distortions [18]. Additionally, a DSTATCOM can also behave as a shunt active filter, to eliminate unbalance or distortions in the source current or the supply voltage.

4.2 Basic Configuration of DSTATCOM

Schematic representation of the DSTATCOM is shown in fig.4.1. 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 [16]. 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 converter 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 of the system and the harmonics present at the output of the inverter.

4.2.4 Coupling 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.

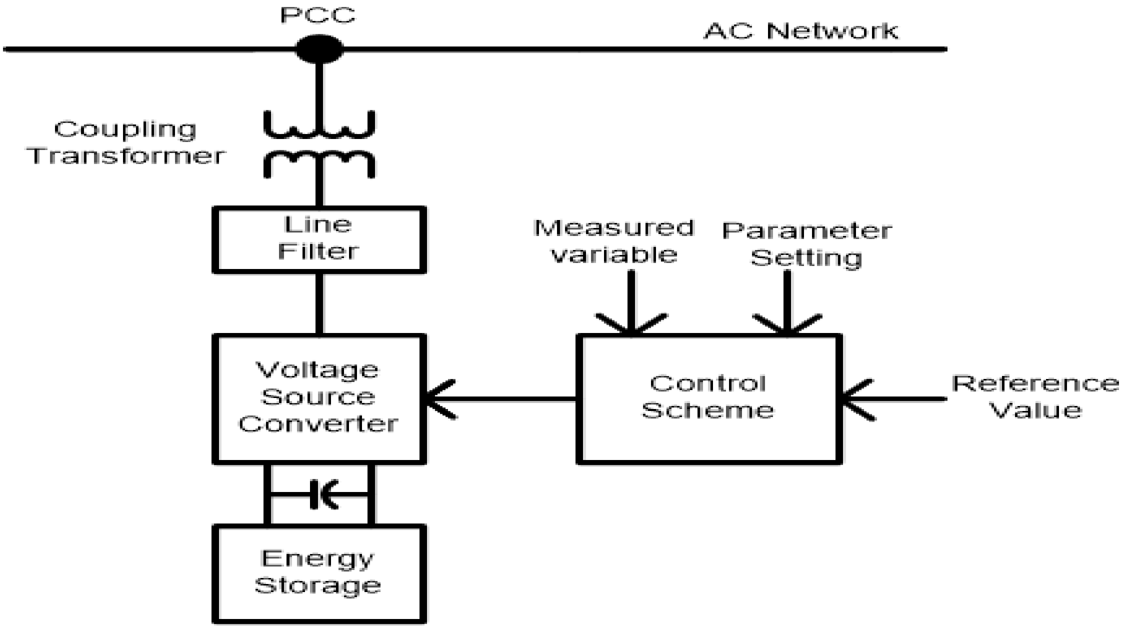

Fig.4.1: Schematic Representation of the DSTATCOM [19]

4.3 Location of DSTATCOM

The DSTATCOM is connected in shunt with distribution system as shown in fig.4.2.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.

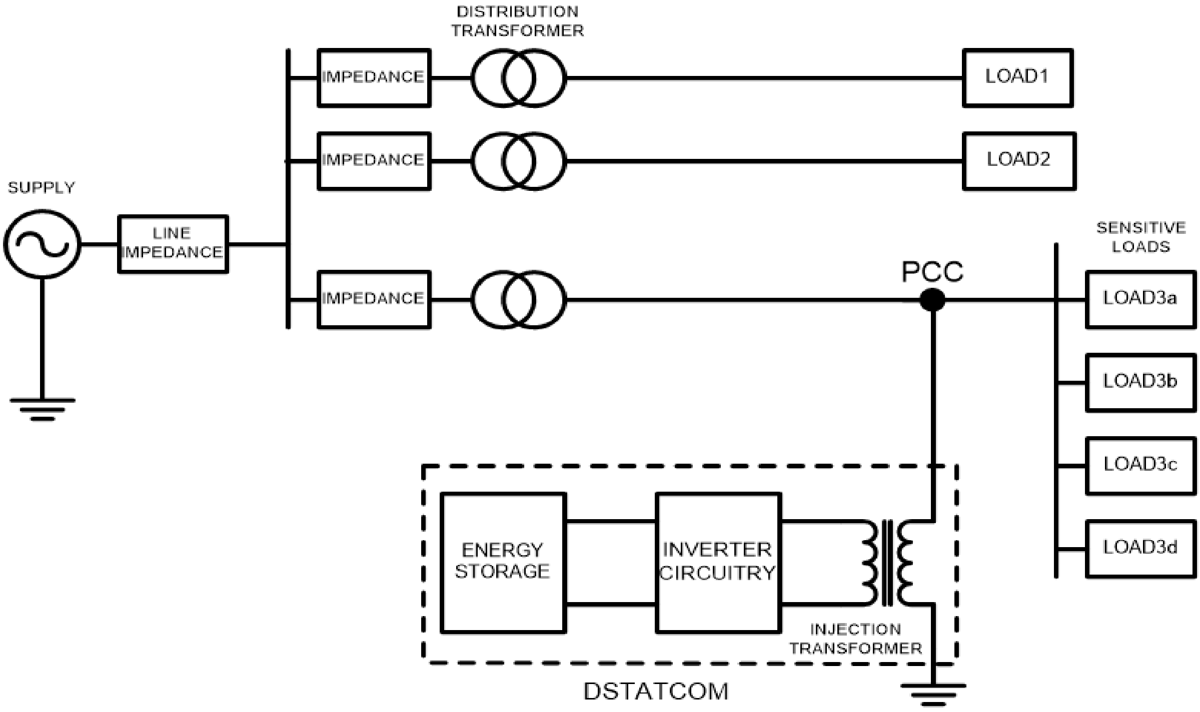

Fig.4.2: Typical Location of DSTATCOM in Distribution System

4.4 Principle of DSTATCOM

A single line diagram of a DSTATCOM is shown in fig.4.3. 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 [19-20]. 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.

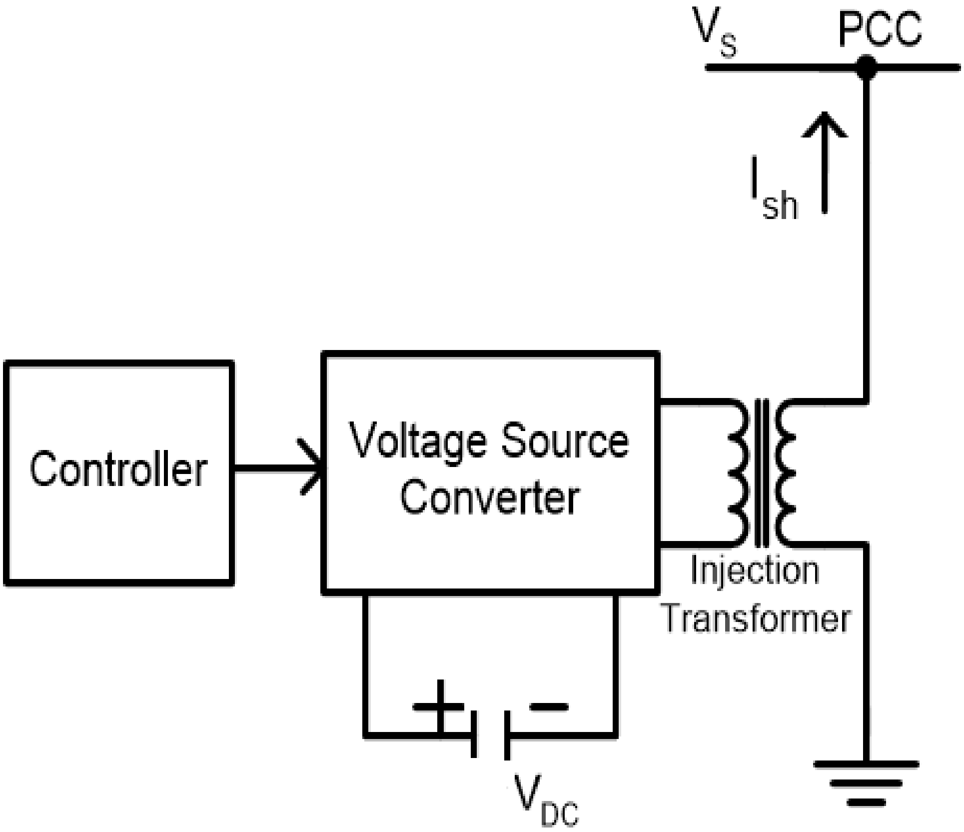

Fig.4.3: Single Line diagram of DSTATCOM [22]

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

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.4.4.

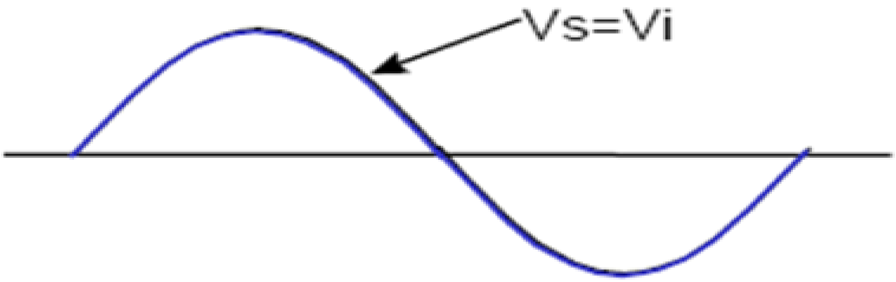

Fig.4.4: No Load Operation

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.4.5.

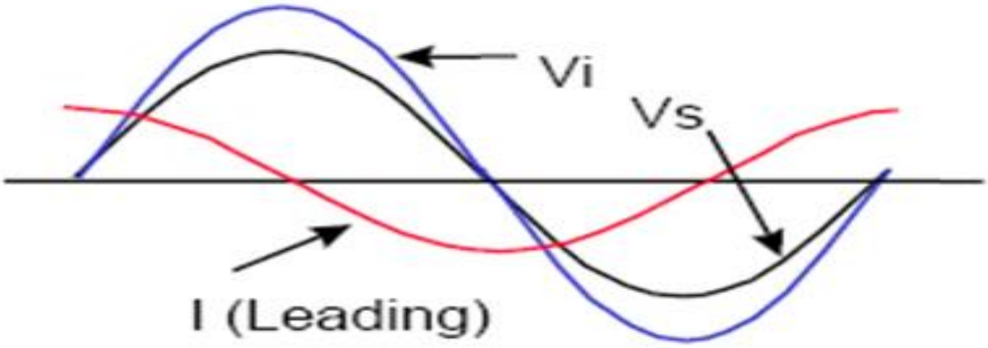

Fig.4.5: Capacitive Operation

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.4.6.

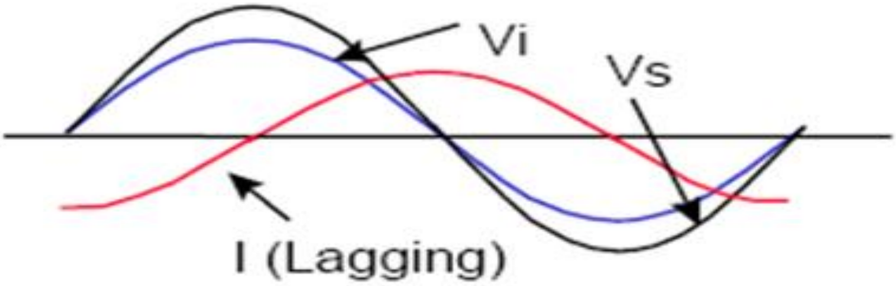

Fig.4.6: Inductive Operation

4.4.2 Exchange of Active Power

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. In case 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.4.7. The DSTATCOM smoothly and continuously controls voltage from V_1 to V_2.

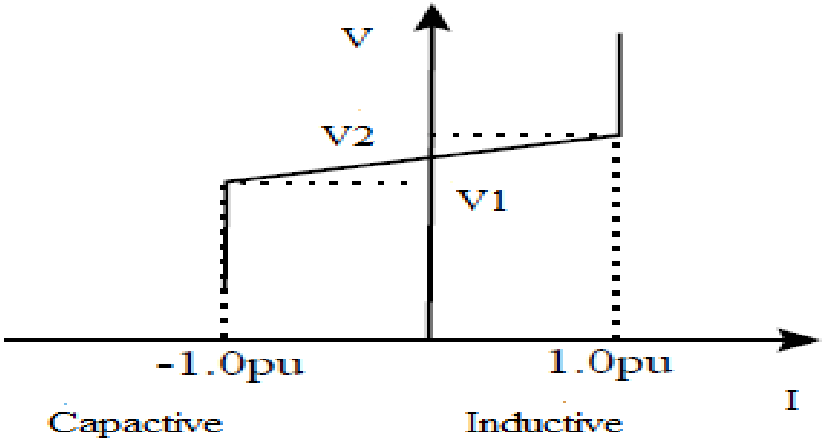

Fig.4.7: V-I Characteristic of a DSTATCOM

4.5 Load Compensation using DSTATCOM

The schematic diagram of a distribution system compensated by DSTATCOM is shown in fig.4.8. 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 [35].

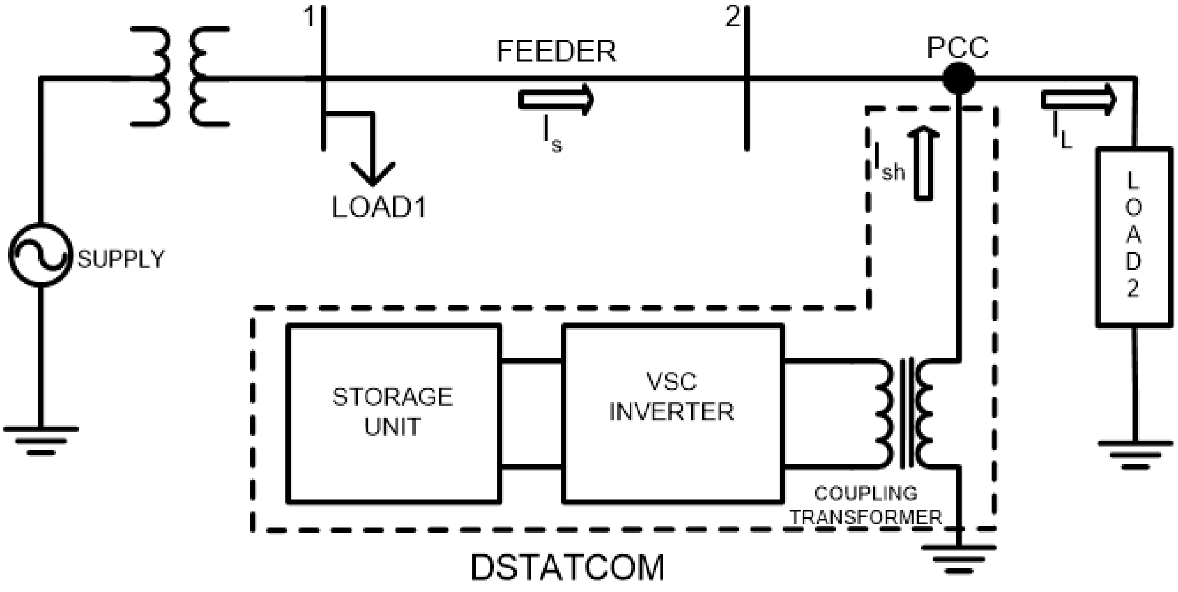

Fig.4.8: Schematic Diagram of Ideal Load Compensation

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:

$$I_s + I_{sh} = I_L \quad (1)$$

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

$$I_{sh} = I_L - I_f \quad (2)$$

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 Principle of Voltage Regulation

4.6.1 Voltage Regulation without DSTATCOM [27]

Consider a simple circuit as shown in fig.4.9. It consists of a source Voltage E; V is the voltage at a PCC and a load drawing the current I_L. Without a voltage compensator, the PCC voltage drop caused by the load current I_L, is shown in fig.4.9. ΔV is given by equation (1):

$$\Delta V = E - V = Z_S * I_L \quad (1)$$

Also

$$S = VI_L^*$$

So, $$S^* = V^* I_L \quad (2)$$

From equation (2)

$$I_L = \frac{P_L - jQ_L}{V} \quad (3)$$

Put the value of I_L from equation (3) into equation (1)

$$\Delta V = (R_S + jQ_L)\left(\frac{P_L - jQ_L}{V}\right)$$

$$= \frac{(R_S\ P_L - X_S\ Q_L)}{V} + j\frac{(X_S\ P_L + R_S\ Q_L)}{V}$$

$$= \Delta V_r + \Delta V_s \quad (4)$$

The voltage change has a component ΔV_r in phase with V and component ΔV_s, which are illustrated in fig.4.10. It is clear that both magnitude and the phase of V, relative to the supply voltage E, are functions of the magnitude and phase of the load current namely the voltage drop depends on both the real and reactive power of the load. The component ΔV is rewritten as

$$\Delta V = I_s R_s + jI_s X_s \qquad (5)$$

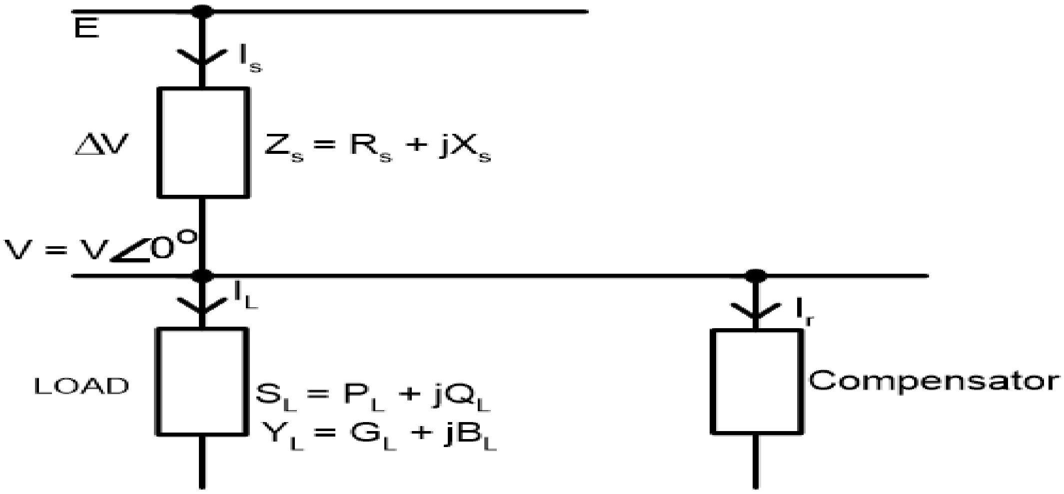

Fig.4.9: Circuit for Demonstrating the Voltage Regulation Principle

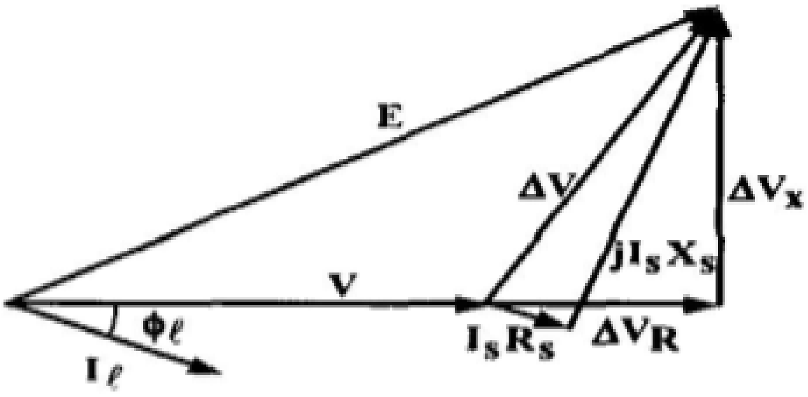

Fig.4.10: Phasor Diagram for Voltage Regulation without DSTATCOM

4.6.2 Voltage Regulation with DSTATCOM

Now consider a compensator connected to the system. It is as shown in fig.4.11 shows vector diagram with voltage compensation. By adding a compensator in parallel with the load, it is possible to make E=V by controlling the current of the compensator.

$I_s = I_r + I_L$

Where I_r is the compensating current.

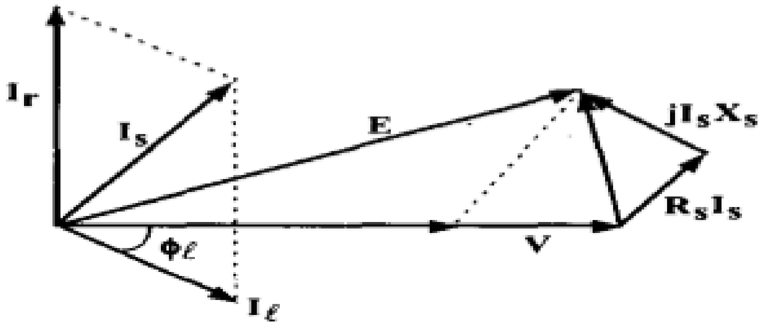

Fig.4.11: Phasor Diagram for Voltage Regulation with DSTATCOM

4.7 Advantages of DSTATCOM

The main advantages of using DSTATCOM are as follows:

- Better dynamics, no inertia, lower operating, lower investment cost and maintenance cost than synchronous condenser.
- Continuous and dynamic voltage control.
- It enables grid control compliance.
- A DSTATCOM has high dynamic and quicker step response of 8 ms to 30 ms. This helps with compensation of negative phase current and with the reduction of voltage flicker.
- Active power control is possible with a DSTATCOM (with optional energy storage on dc circuit). This could further help with system stability control.
- Maximum reactive current over extended voltage range.
- High efficiency.
- Single phase control for unbalanced loads.
- No potential for creating a resonance point. This is because no capacitor banks or reactors are required to generate the reactive power for a DSTATCOM.

4.8 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 DSTATCOM protects the utility distribution system from voltage sags and/or flicker caused by rapidly varying reactive current demand. In utility applications, a DSTATCOM provides 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.

4.9 DQO Transformation [27, 30]

The dqo transformation or Park's transformation is used to control of DSTATCOM. The advantage of using dqo method is that it gives information about current unbalance, phase faults and phase shift with start and end times. The quantities are expressed as the instantaneous space vectors. The load currents which are in a-b-c frame are transformed into dqo frame using Park's transformation as shown in equation (1).

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

Here θ is the transformation angle which is provided by PLL.

Inverse Park's transformation can now be made to obtain three phase reference currents in a-b-c coordinates from the i_d, i_q dc components given by equation (2).

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos\theta & -\sin\theta & \frac{1}{\sqrt{2}} \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \tag{2}$$

The flow chart of the feed forward dqo transformation is shown in fig.4.12.

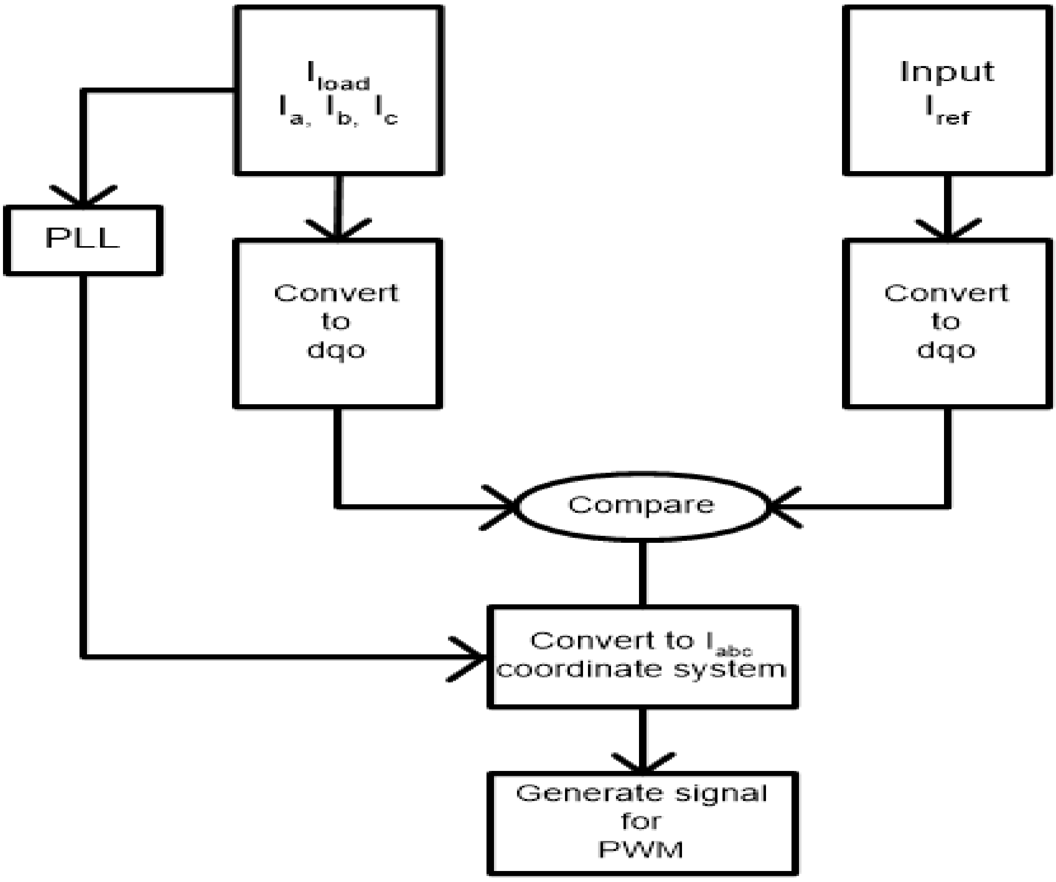

Fig.4.12: Flow Chart of DQO Transformation

4.10 Control Scheme

The basic function of a controller in a DSTATCOM is the detection of faults in the system, computation of correcting voltage, generation of trigger pulses to sinusoidal PWM based DC-AC inverter and termination of the trigger pulses when the event has passed [29]. When fault is detected, DSTATCOM should react as fast as possible and inject an ac current to the grid. It can be implemented using a control technique based on the current reference and load current. The basic control scheme is shown in fig.4.13.

The load current is connected to a transformation block which converts stationary a-b-c frame to dqo frame. Also, the load current is connected to a phase lock loop (PLL) which provides transformation angle θ. These signals are provided to fault detection block which detects fault in load current [29-30]. The fault detection block generates the reference supply current whenever fault is generated. The injection current is also generated by difference between the reference current and load load current. Now i_d, i_q dc components are converted into three phase reference currents in a-b-c coordinates using Inverse Park's transformation and applied to converter to produce required current, with the help of pulse width modulation(PWM).

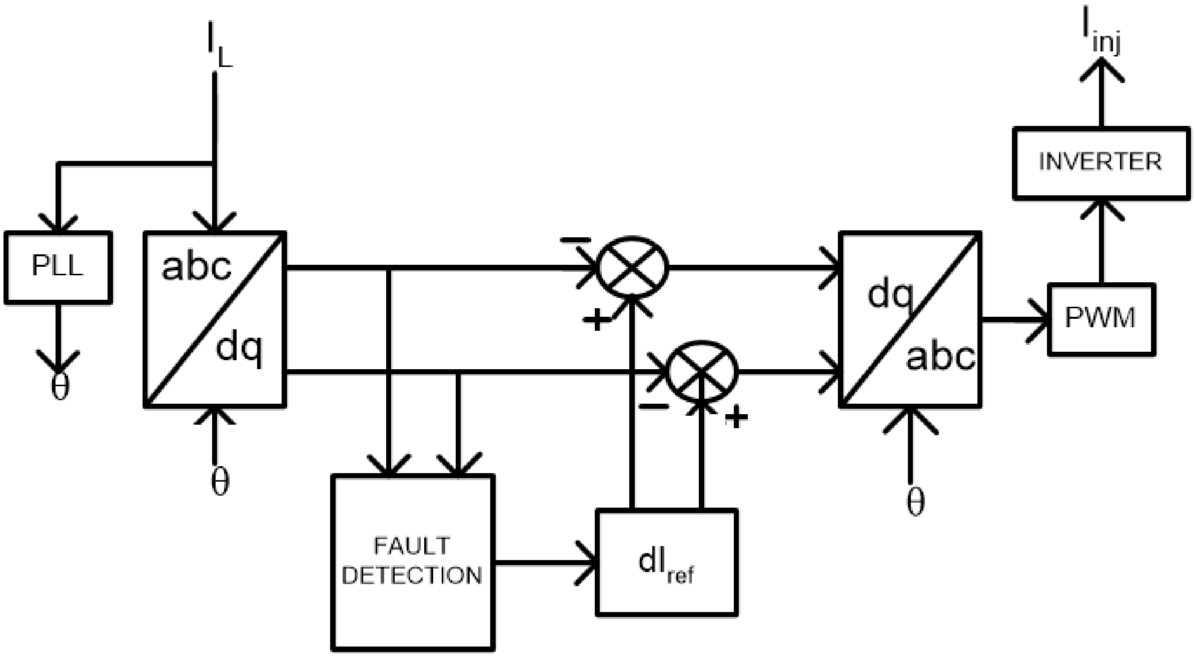

Fig.4.13: Control Scheme

CHAPTER 5

SIMULATION AND RESULTS

5.1 Introduction

In an increasing number of problems like voltage sags, voltage swells, flicker, harmonic distortion 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. Consequently, the output voltage control may be executed through the pulse width modulation (PWM) switching method. Energy storage added to the power conditioner provides even more flexibility in system operation and planning for utilities and industry. Here, SIMULINK model of test system is considered with two different feeders having two similar loads. This test system is analysed under normal and various fault conditions. One of the feeders is connected to DSTATCOM, which is known as compensated feeder and the other is kept as it is, which is known as an uncompensated feeder. The control technique implements a dqo transformation which starts from the difference between the load current and reference current that determines the reference voltage of the inverter (modulating reference signal).

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
- Distribution network having DTC induction motor drive load
- Distribution network having FOC induction motor drive load

5.2 Parameters of the Test System

The modeled system has been tested on different fault conditions with linear load, non-linear load, DTC induction motor drive load and FOC induction motor drive load. 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, $R_{on} = 1m\Omega$.
3.	Discrete 3-phase PLL	$K_P = 20, K_i = 50$, sampling time 50µs.
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.	DTC Induction Motor Drive	Stator Resistance (14.85mΩ), Rotor Resistance (9.295mΩ), Leakage Inductance (0.3027mH), Mutual Inductance (10.46mH), Nominal power 200 kVA, 400V rms (phase-phase), 50 Hz.
7.	FOC Induction Motor Drive	Nominal power 200 kVA, 400V rms (phase-phase), 50 Hz, Stator Resistance (14.85mH), Rotor Resistance (9.295mH), Leakage Inductance (0.3027mH), Mutual Inductance (10.46mH).
8.	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.

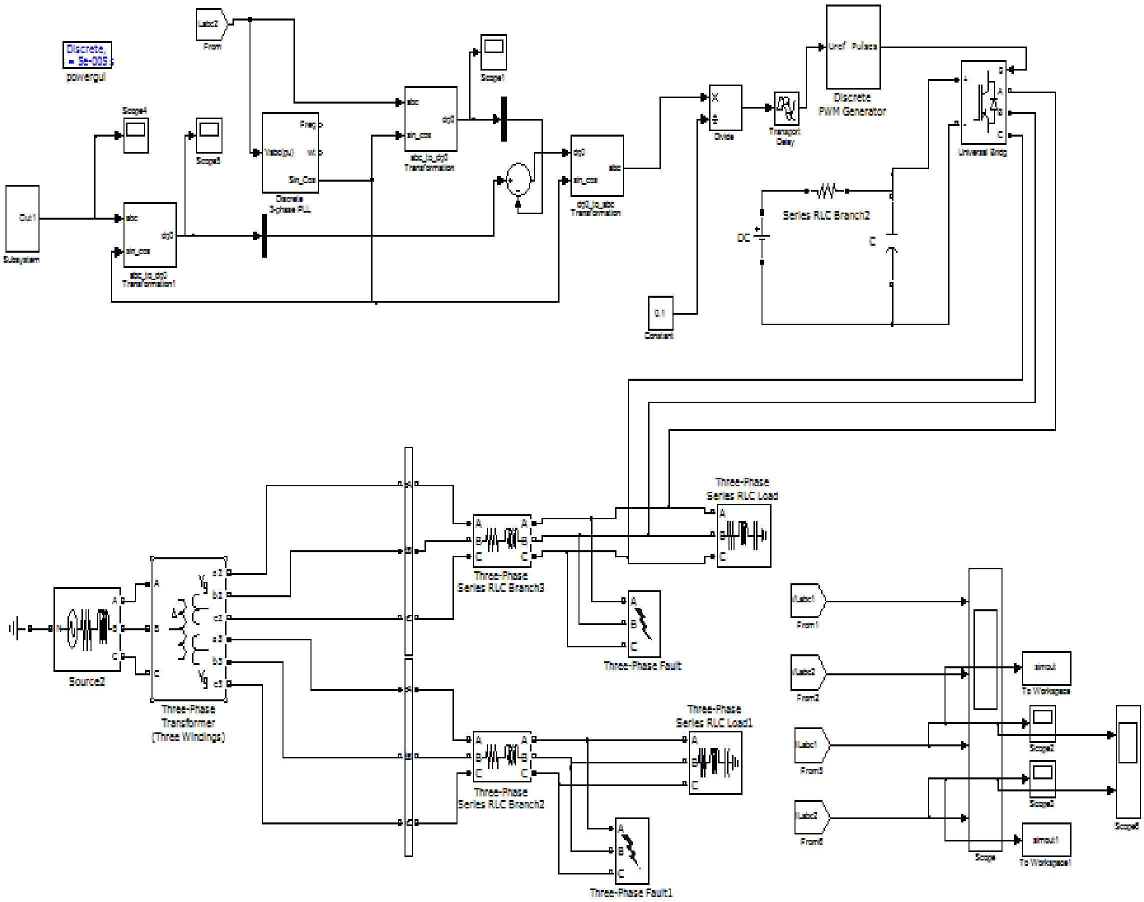

Fig.5.1: SIMULINK Model of Test System with Linear Load

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 static 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.5.2. 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.5.4. These results become clear from the frequency spectrum graphs, which are taken one by one for non-compensated and compensated feeders with static linear load as shown in fig.5.3 and fig.5.5. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 4.47% to 0.00% when DSTATCOM is connected to the system.

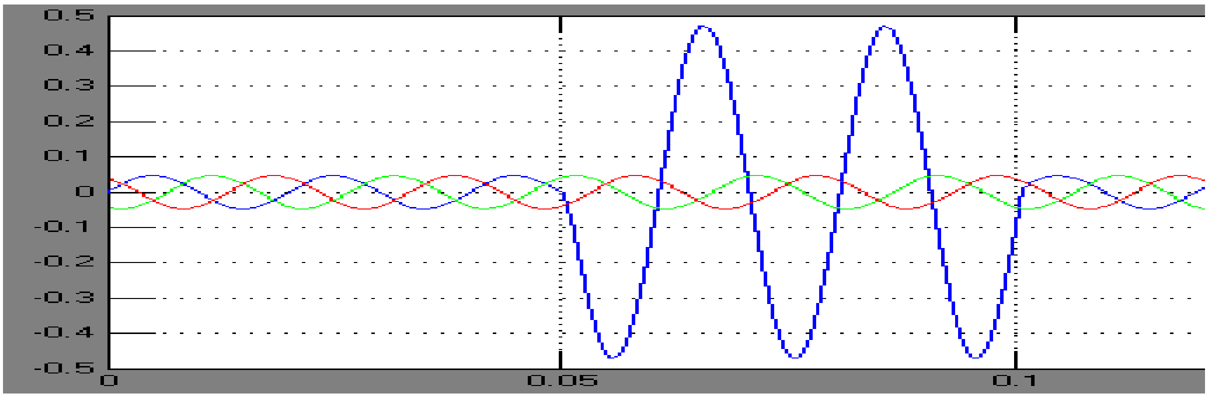

Fig.5.2: Load Current vs Time waveform (without compensation)

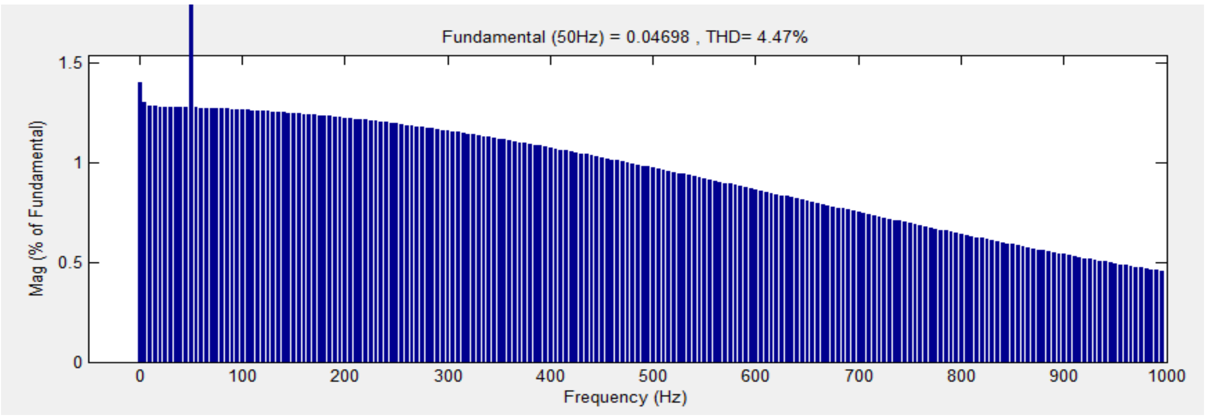

Fig.5.3: Frequency Spectrum of Load Current (without compensation)

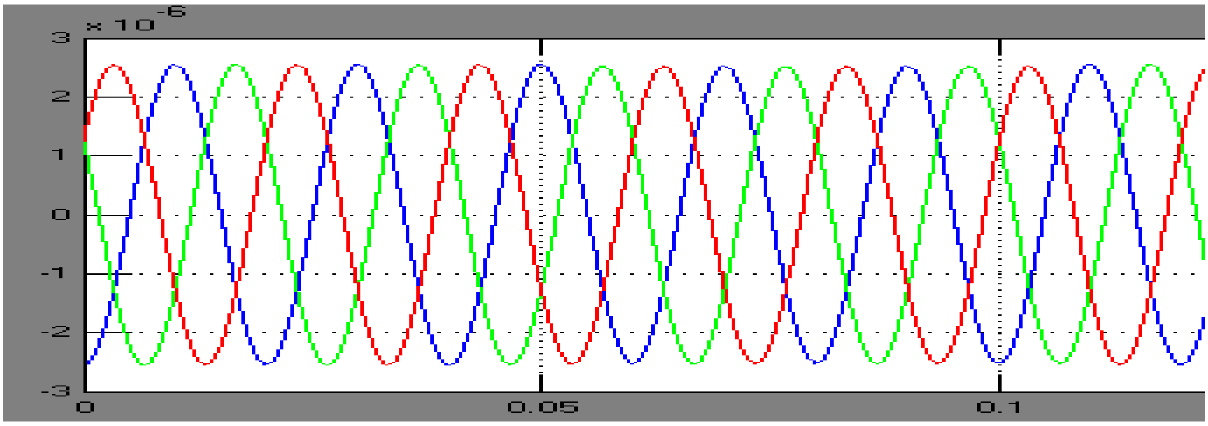

Fig.5.4: Load Current vs Time waveform (with compensation)

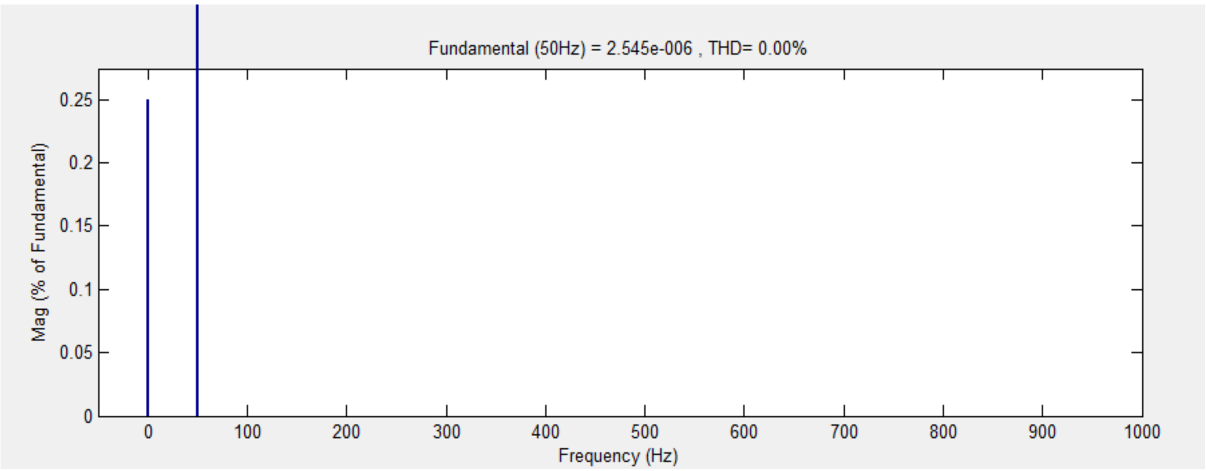

Fig.5.5: Frequency Spectrum of Load Current (with compensation)

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 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.5.6. 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.5.8. These results become clear from the frequency spectrum graphs, which are taken one by one for non-compensated and compensated feeders with static linear load as shown in fig.5.7 and fig.5.9. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 4.47% to 0.00% when DSTATCOM is connected to the system.

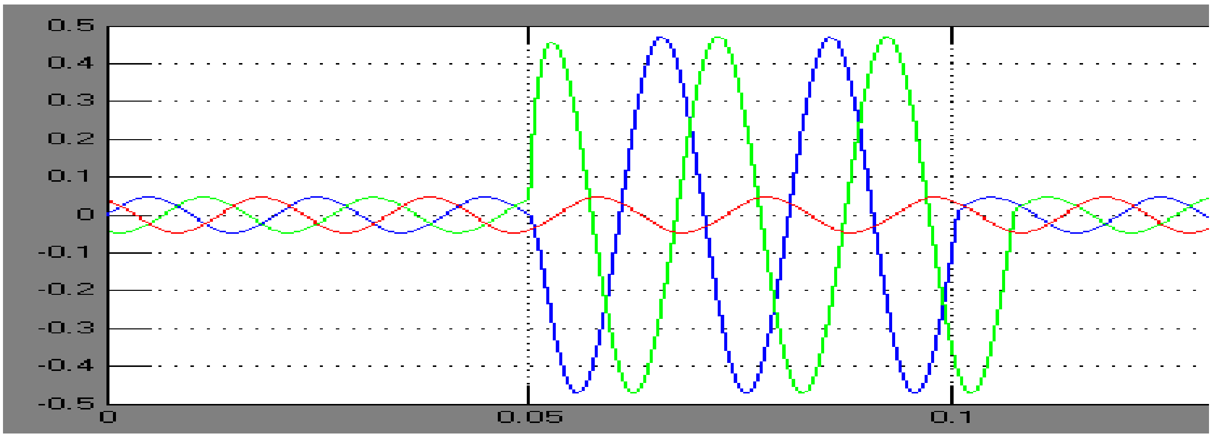

Fig.5.6: Load Current vs Time waveform (without compensation)

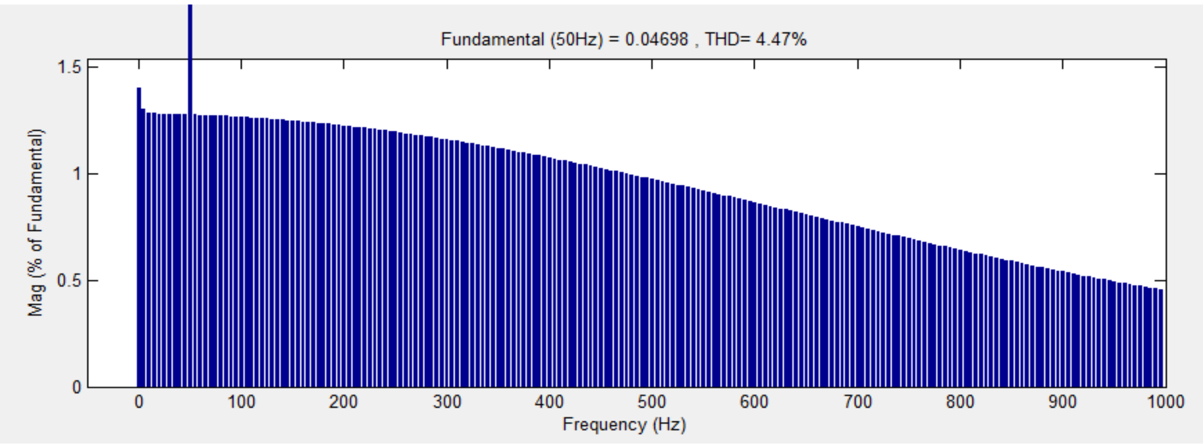

Fig.5.7: Frequency Spectrum of Load Current (without compensation)

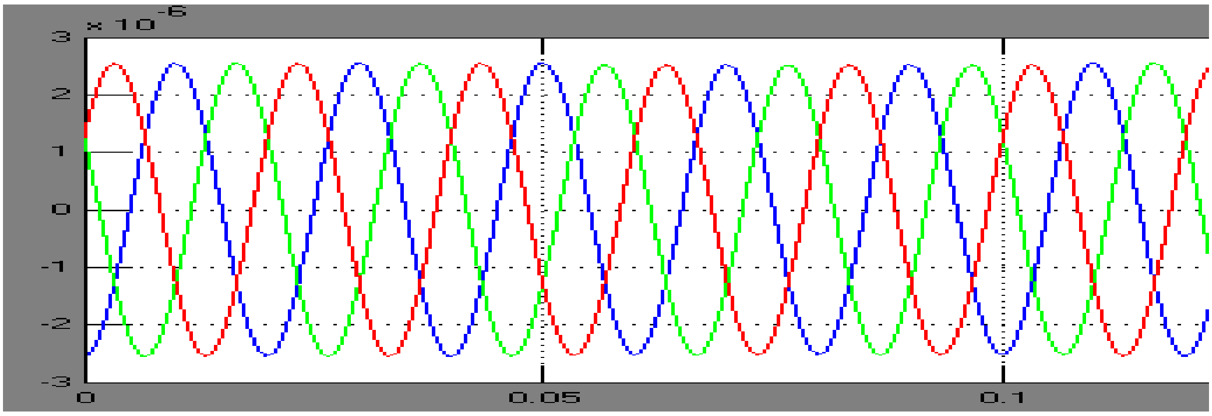

Fig.5.8: Load Current vs Time waveform (with compensation)

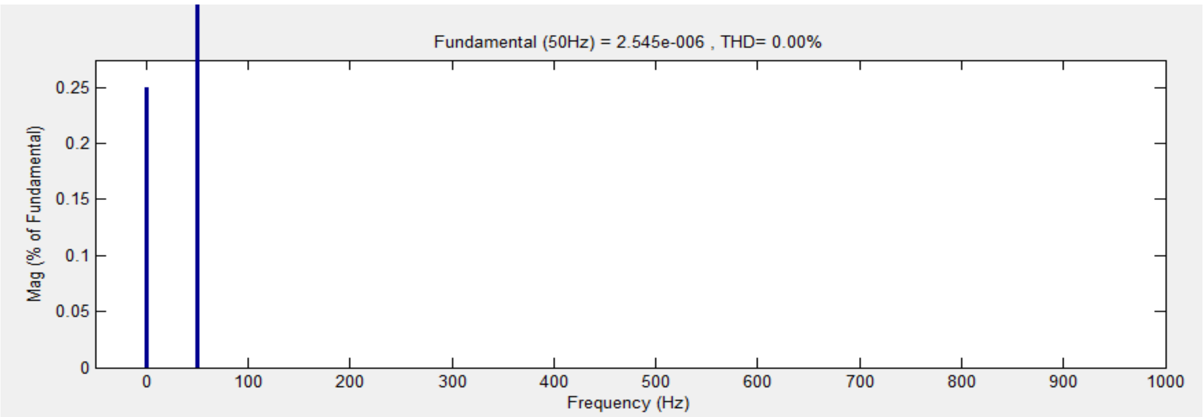

Fig.5.9: Frequency Spectrum of Load Current (with compensation)

CASE III: Three Phase Fault Condition

In this case, three phase fault is considered for both the feeders feeding static 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.5.10. 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.5.12. These results become clear from the frequency spectrum graphs, which are taken one by one for non-compensated and compensated feeders with static linear load as shown in fig.5.11 and fig.5.13. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 4.48% to 0.00% when DSTATCOM is connected to the system.

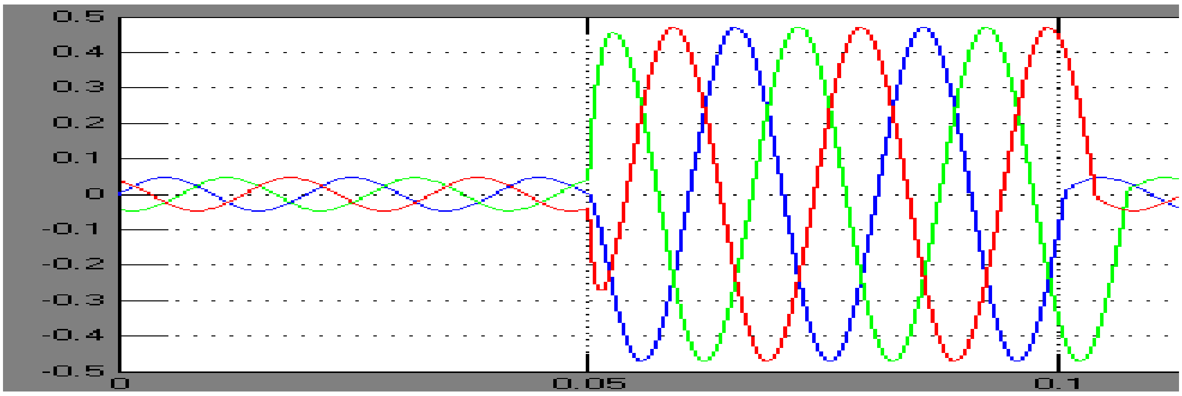

Fig.5.10: Load Current vs Time waveform (without compensation)

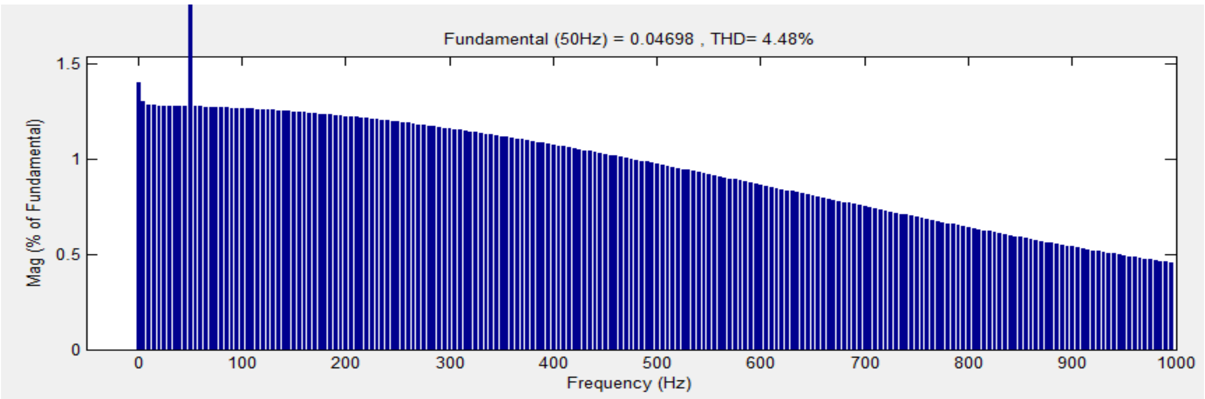

Fig.5.11: Frequency Spectrum of Load Current (without compensation)

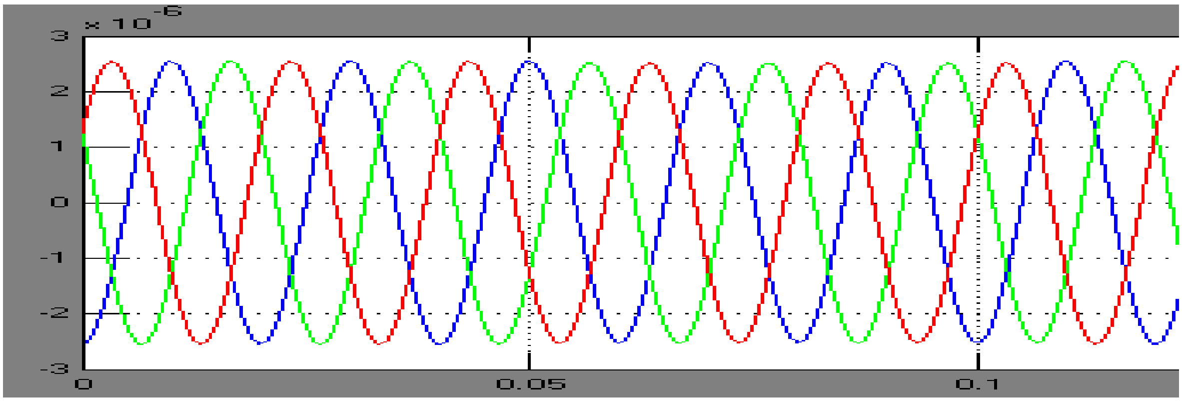

Fig.5.12: Load Current vs Time waveform (with compensation)

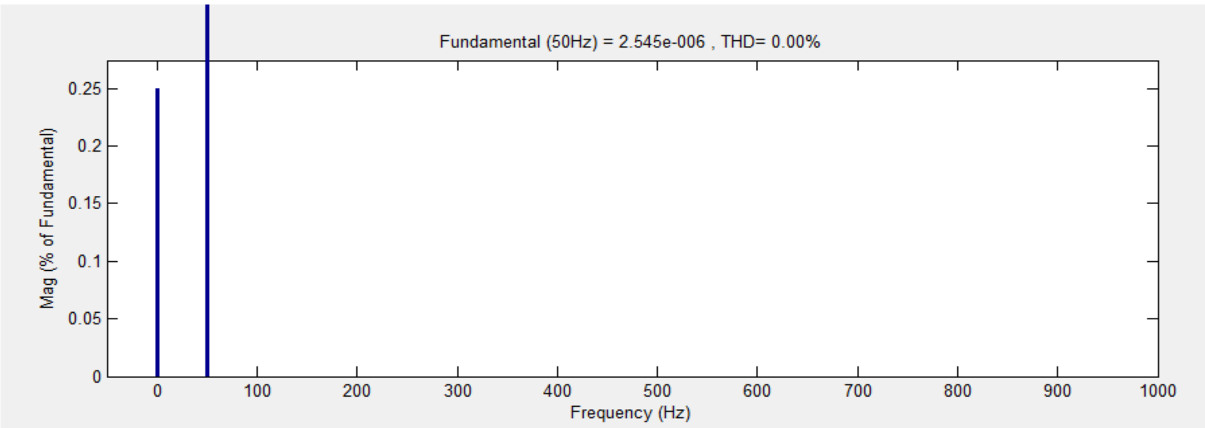

Fig.5.13: Frequency Spectrum of Load Current (with compensation)

5.4 SIMULINK Model of Test System with Static Non-Linear Load

SIMULINK model of the test system with static non-linear load is given in fig.5.14. 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.

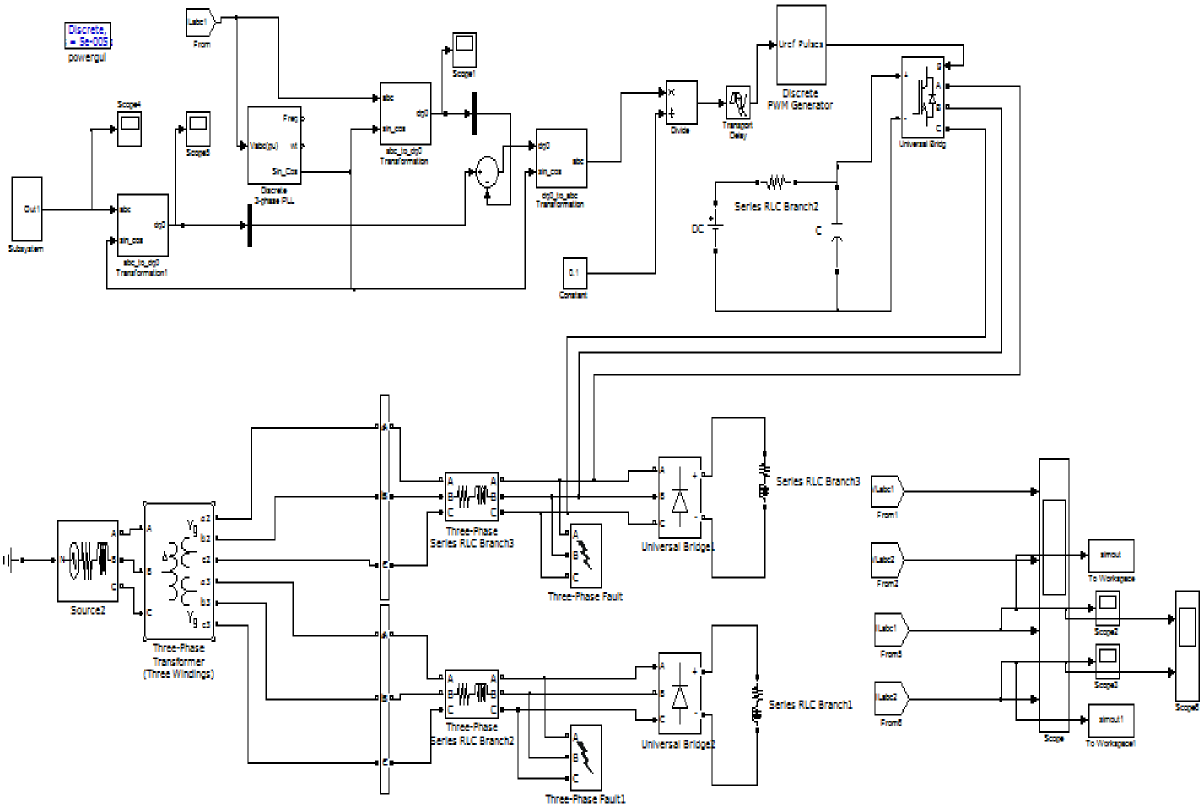

Fig.5.14: SIMULINK Model of Test System with Non-Linear Load

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.5.15. The frequency spectrum graph of load current for uncompensated feeder is shown in fig.5.16. When DSTATCOM is connected to the system it effectively reduces the harmonics from load current as shown in fig.5.17. Also frequency spectrum graph of load current for compensated feeder is shown in fig.5.18. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 28.09% to 0.07% when DSTATCOM is connected to the system.

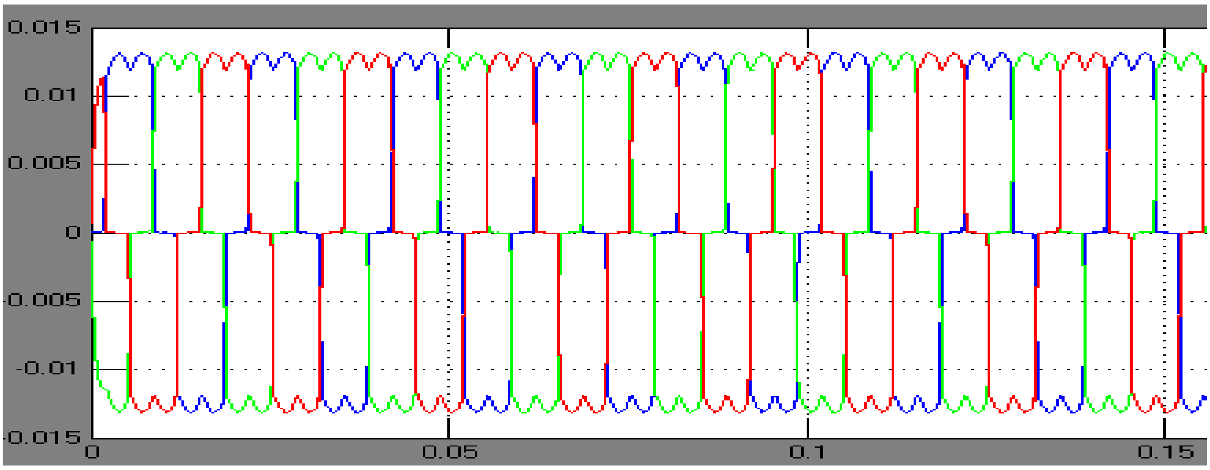

Fig.5.15: Load Current vs Time waveform (without compensation)

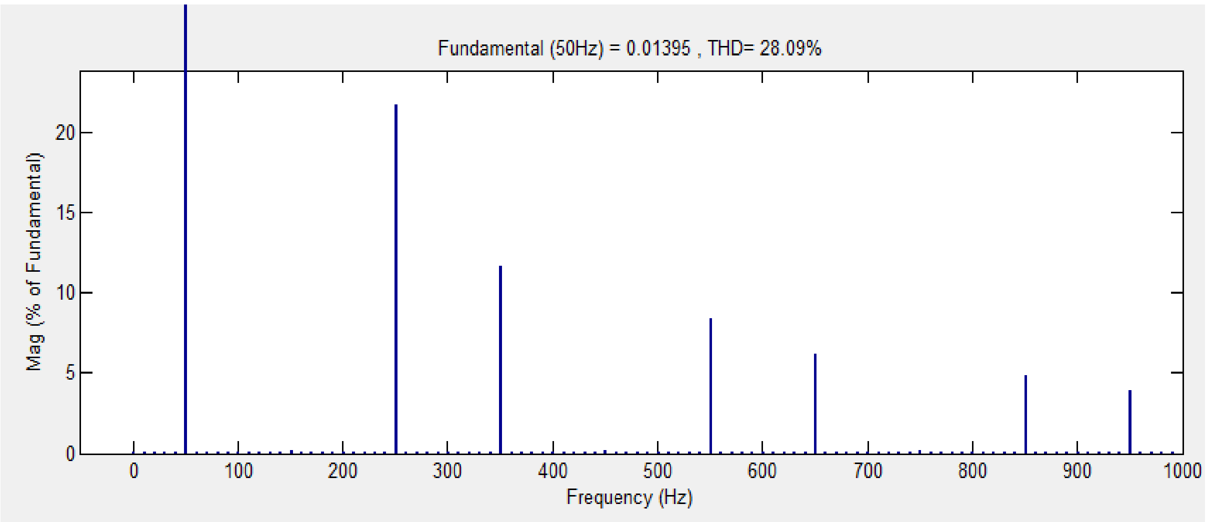

Fig.5.16: Frequency Spectrum of Load Current (without compensation)

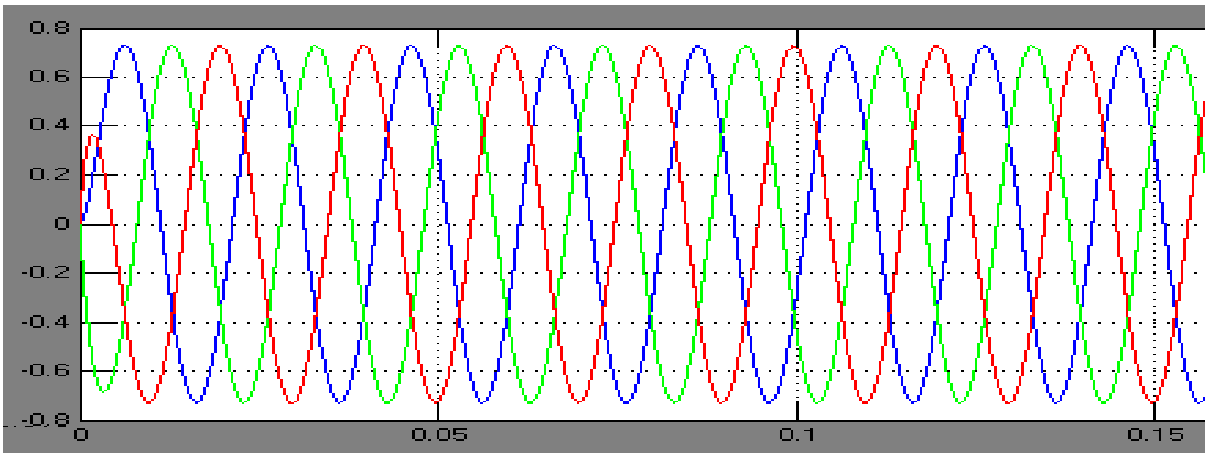

Fig.5.17: Load Current vs Time waveform (with compensation)

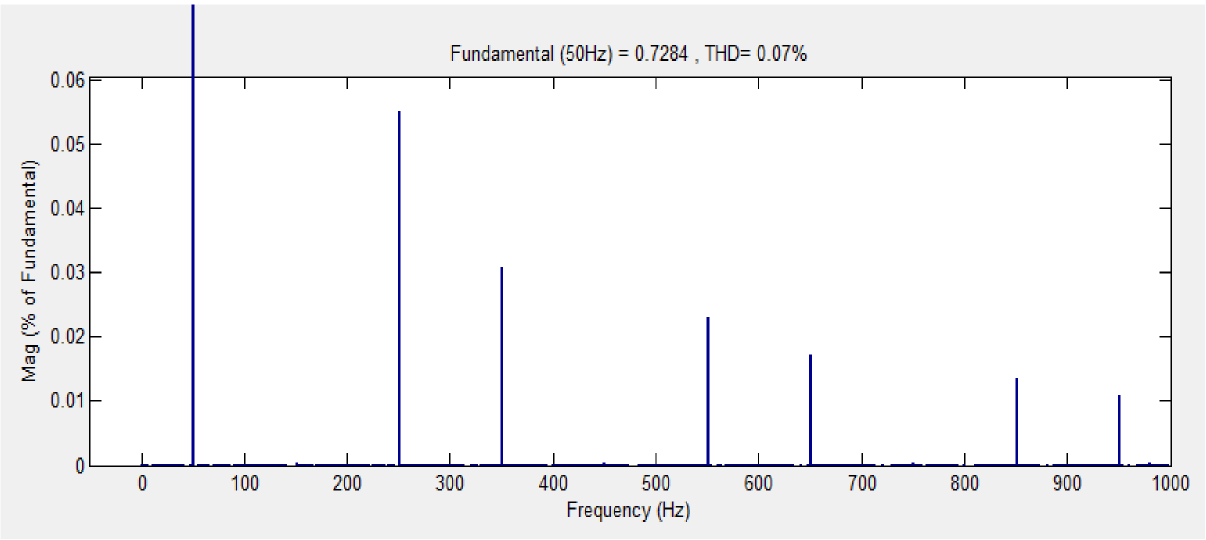

Fig.5.18: Frequency Spectrum of Load Current (with compensation)

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.5.19. 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.5.21. 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.5.20 and fig.5.22. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 29.13% to 0.07% when DSTATCOM is connected to the system.

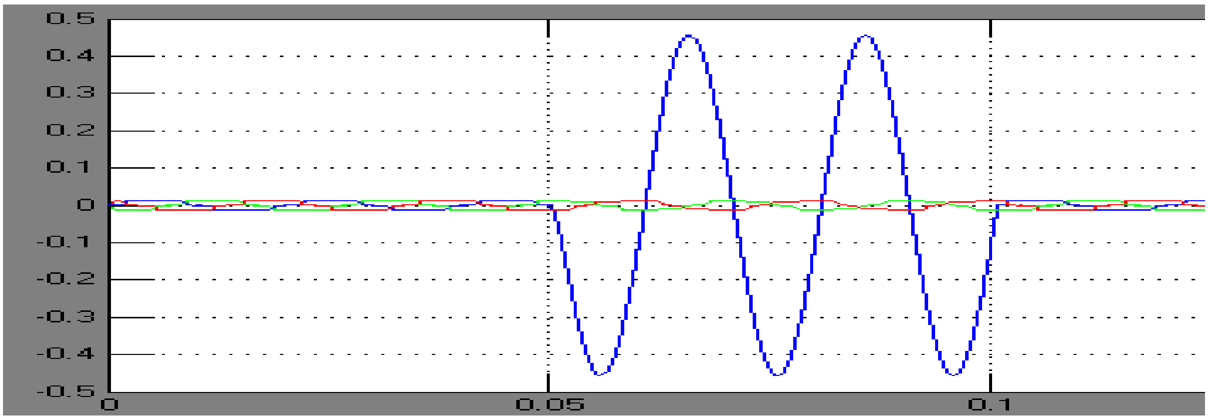

Fig.5.19: Load current vs Time waveform (without compensation)

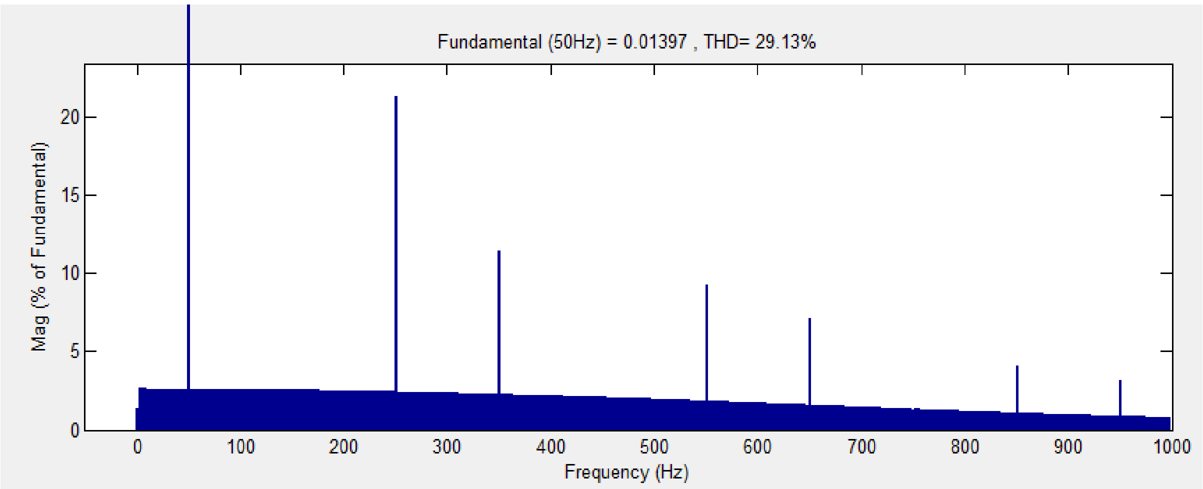

Fig.5.20: Frequency Spectrum of Load Current (without compensation)

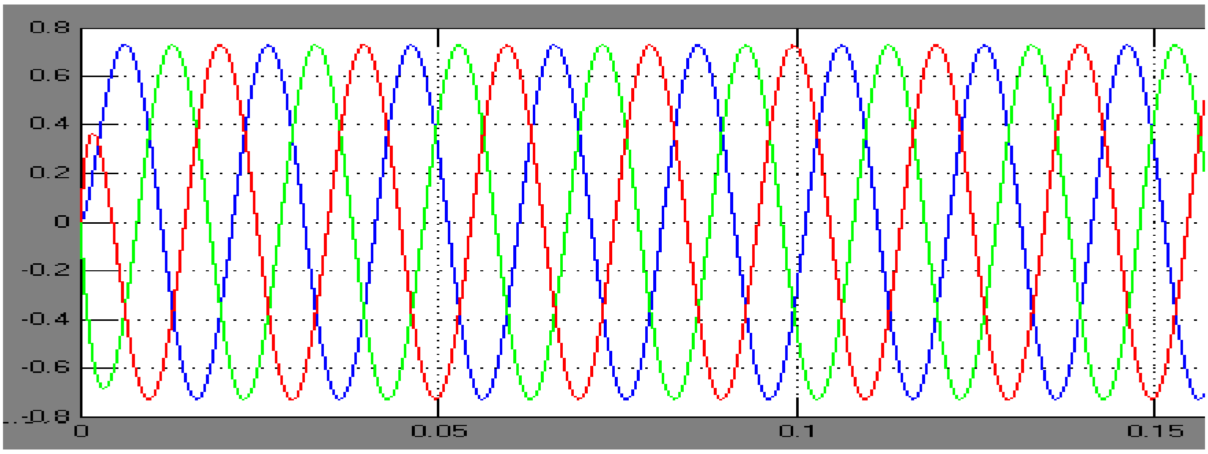

Fig.5.21: Load current vs Time waveform (with compensation)

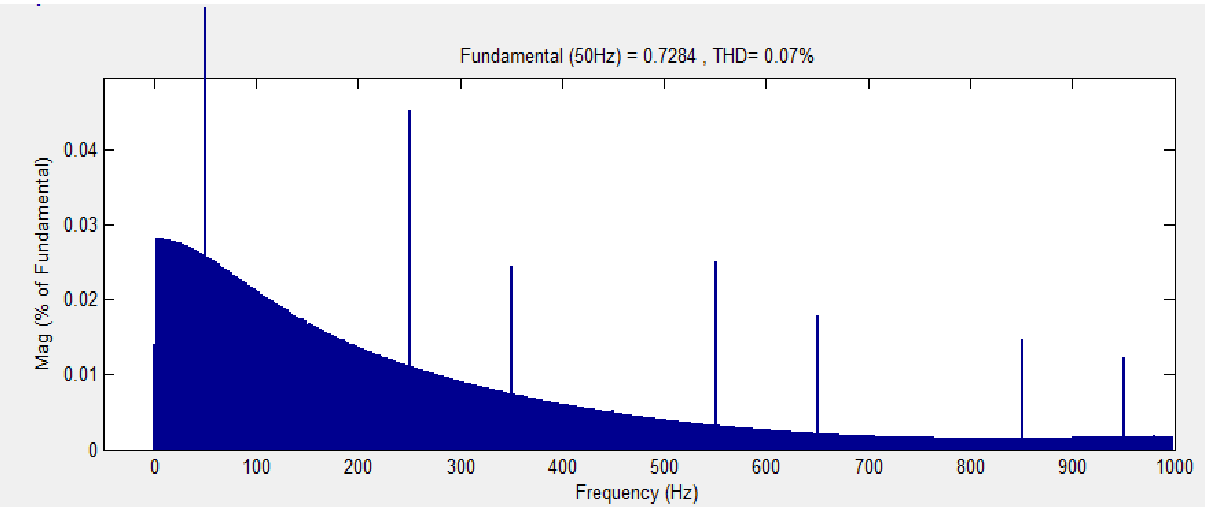

Fig.5.22: Frequency Spectrum of Load Current (with compensation)

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.5.23. 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.5.25. 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.5.24 and fig.5.26. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 29.07% to 0.08% when DSTATCOM is connected to the system.

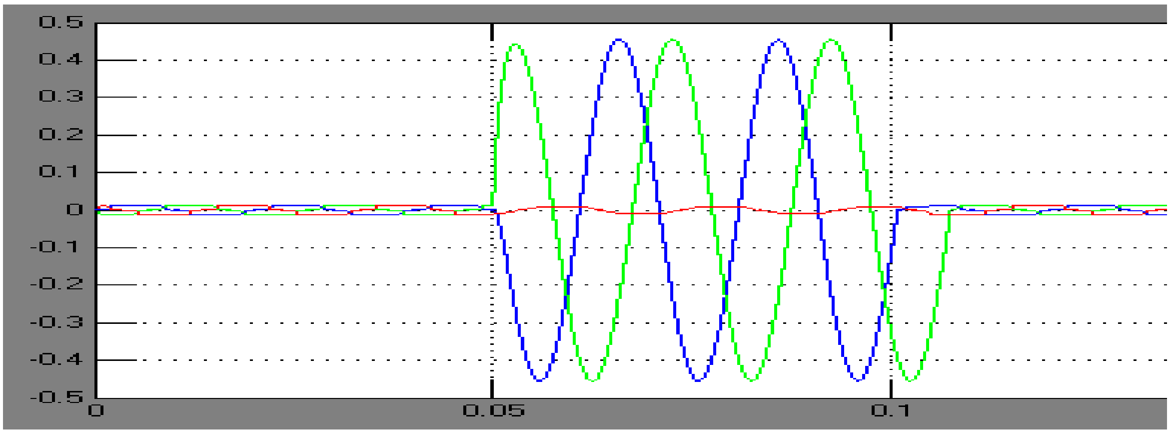

Fig.5.23: Load Current vs Time waveform (without compensation)

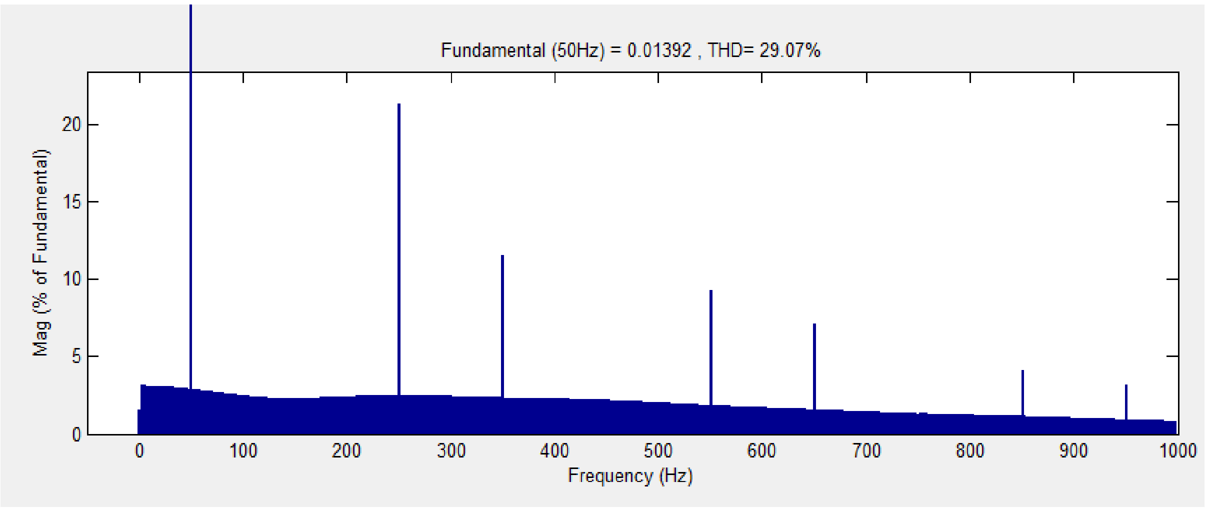

Fig.5.24: Frequency Spectrum of Load Current (without compensation)

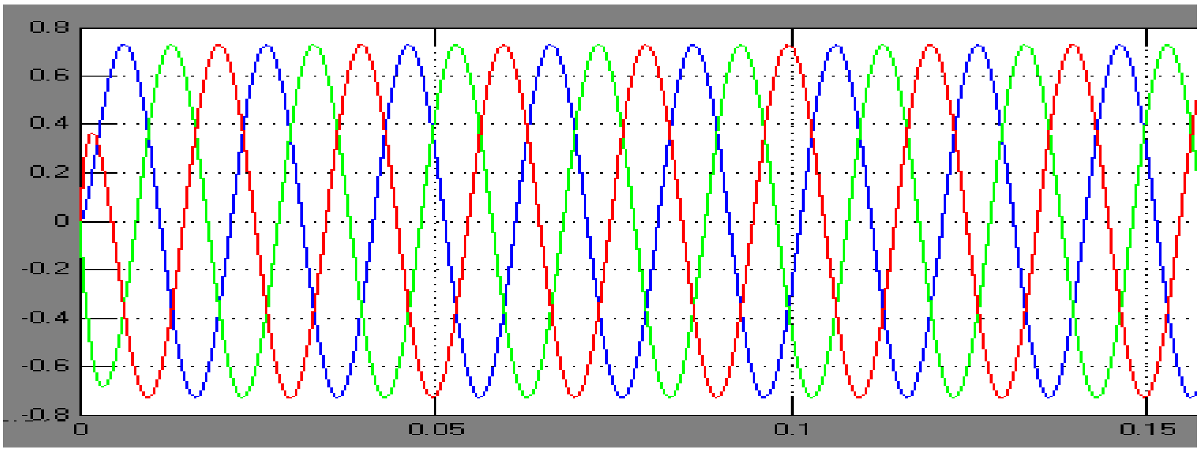

Fig.5.25: Load Current vs Time waveform (with compensation)

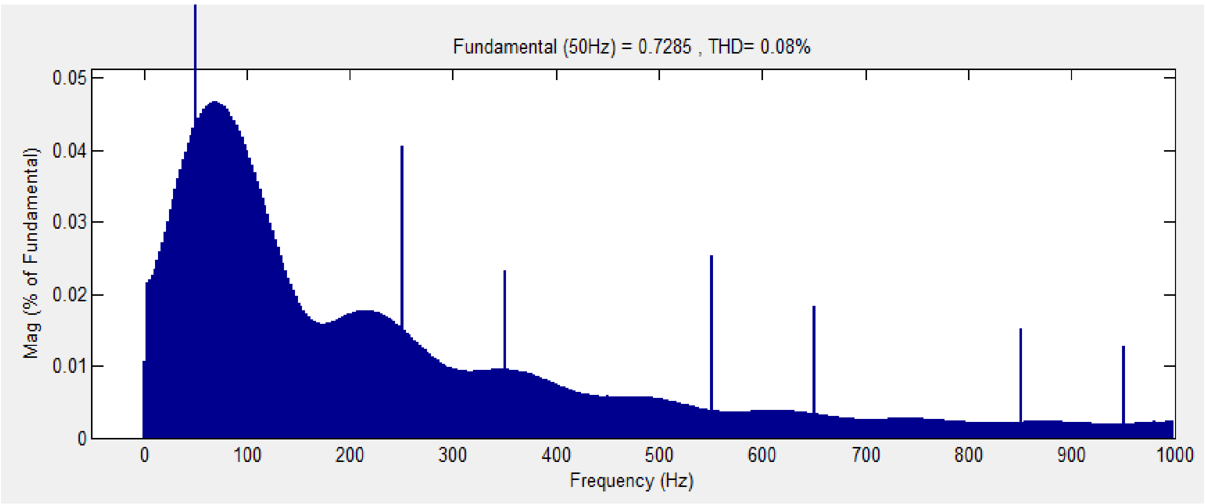

Fig.5.26: Frequency Spectrum of Load Current (with compensation)

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.5.27. 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.5.29. 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.5.28 and fig.5.30. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 28.90% to 0.08% when DSTATCOM is connected to the system.

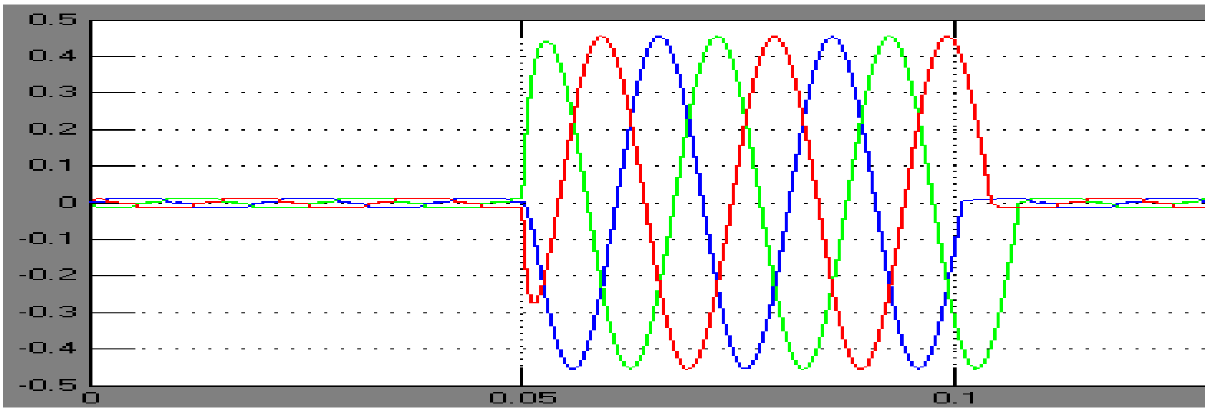

Fig.5.27: Load Current vs Time waveform (without compensation)

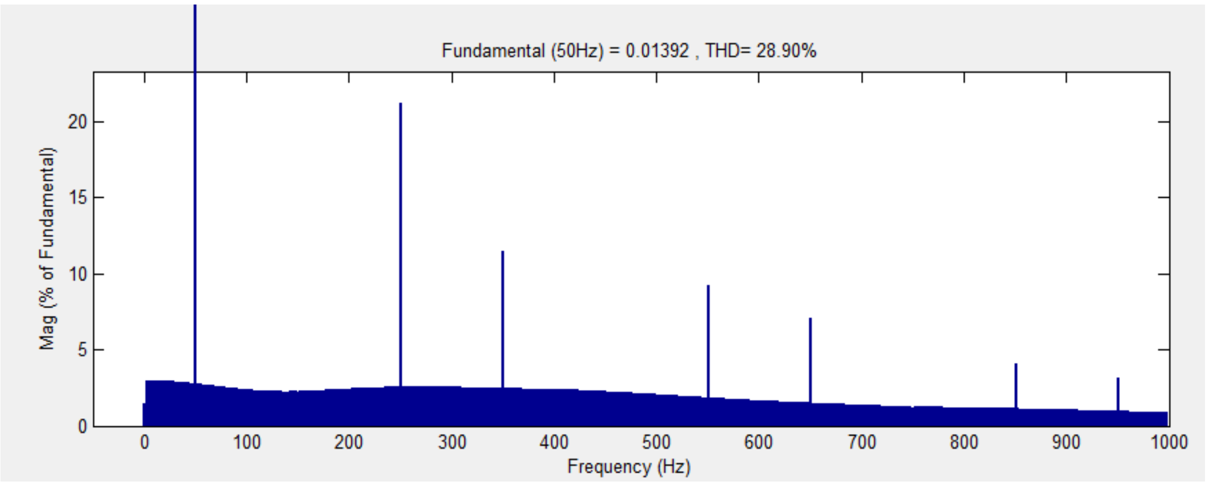

Fig.5.28: Frequency Spectrum of Load Current (without compensation)

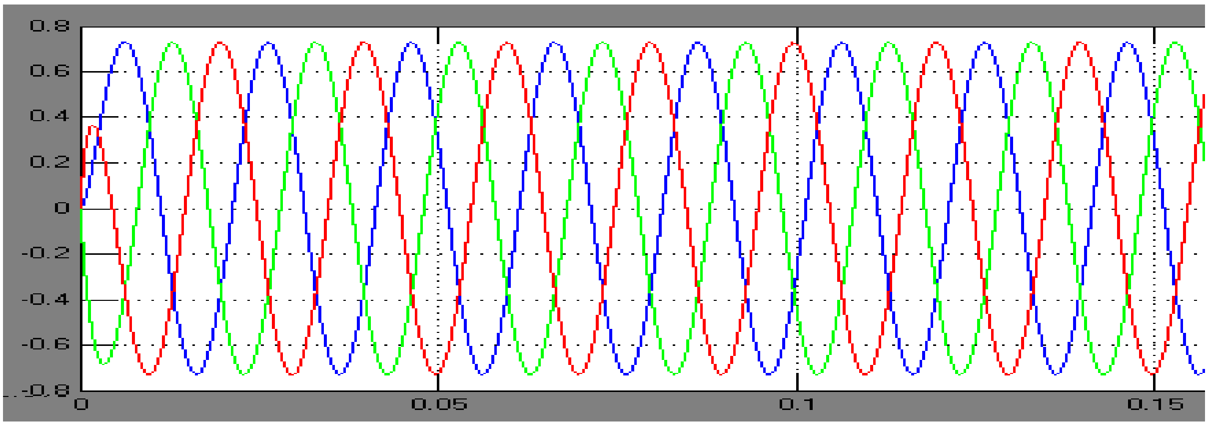

Fig.5.29: Load Current vs Time waveform (with compensation)

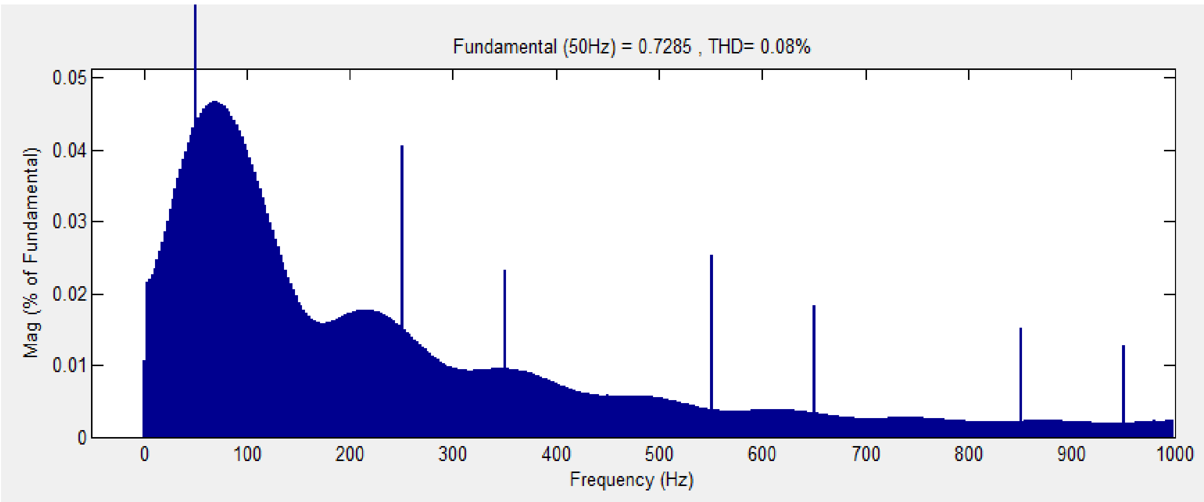

Fig.5.30: Frequency Spectrum of Load Current (with compensation)

5.5 SIMULINK Model of Test System with DTC Induction Motor Drive

SIMULINK model of the test system with DTC induction motor drive as load is given in fig.5.31. The system consists of two parallel feeders with similar DTC induction motor drive load of same rating. One of the feeders 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.

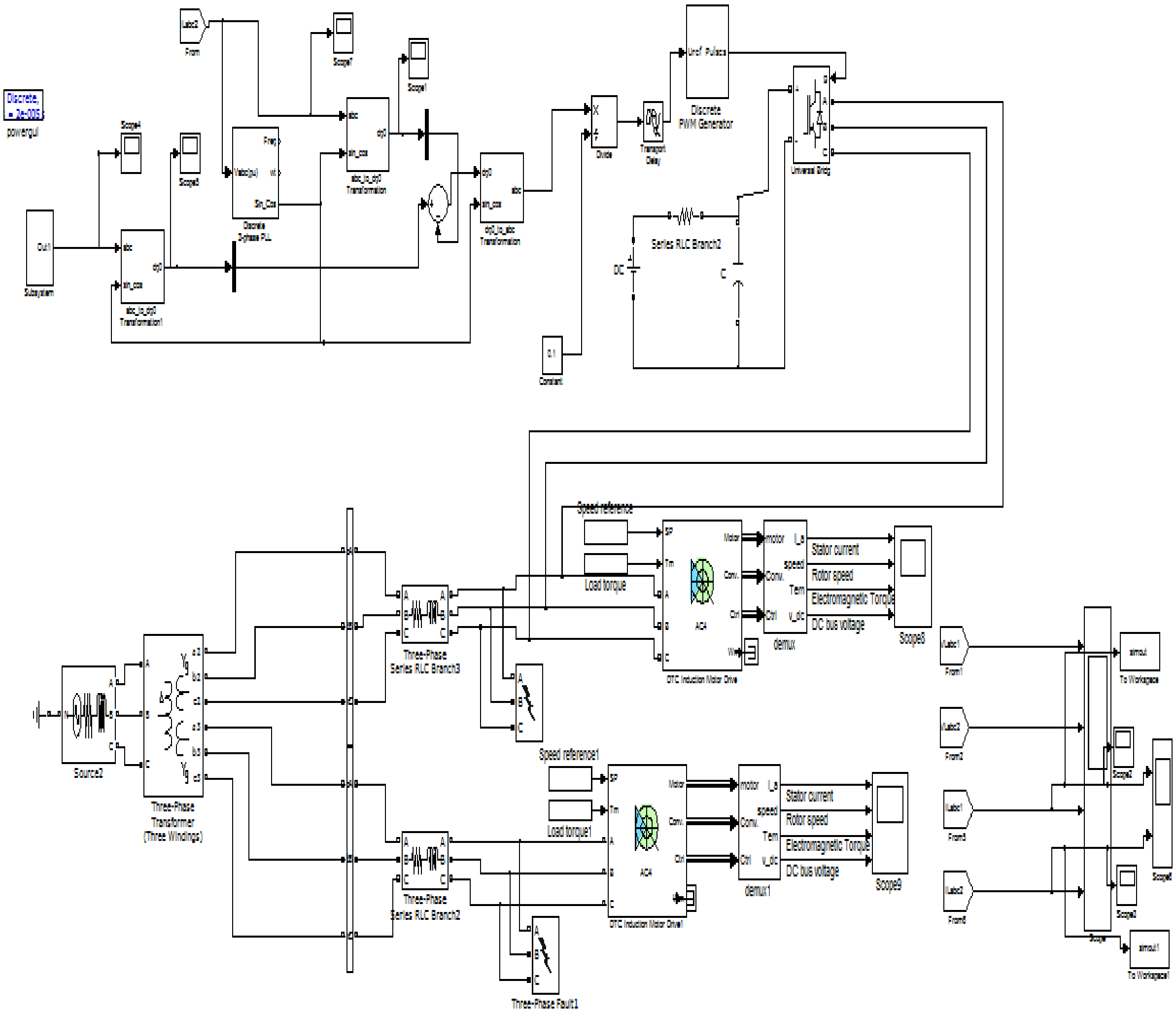

Fig.5.31: SIMULINK Model of Test System with DTC Induction Motor Drive

5.5.1 Results for DTC Induction Motor Drive under Normal Condition

Here test system is considered under normal conditions. Due to DTC induction motor drive connected to the system, harmonics are produced in load current waveform as shown in fig.5.32. The frequency spectrum graph of load current for uncompensated feeder is shown in fig.5.33. When DSTATCOM is connected to the system it effectively reduces the harmonics from load current as shown in fig.5.34. Also frequency spectrum graph of load current for compensated feeder is shown in fig.5.35. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 44.37% to 0.29% when DSTATCOM is connected to the system.

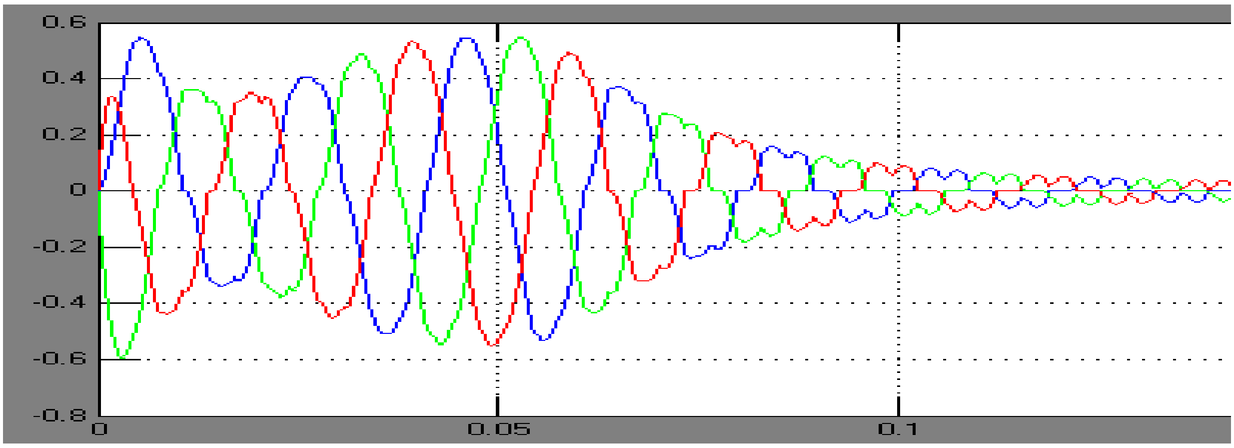

Fig.5.32: Load Current vs Time waveform (without compensation)

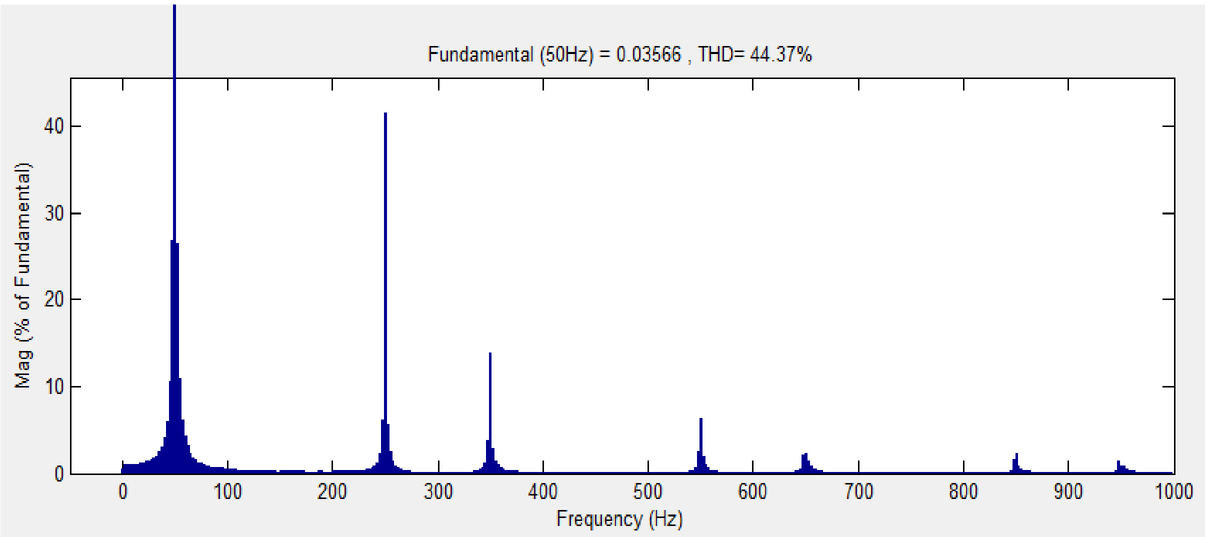

Fig.5.33: Frequency Spectrum of Load Current (without compensation)

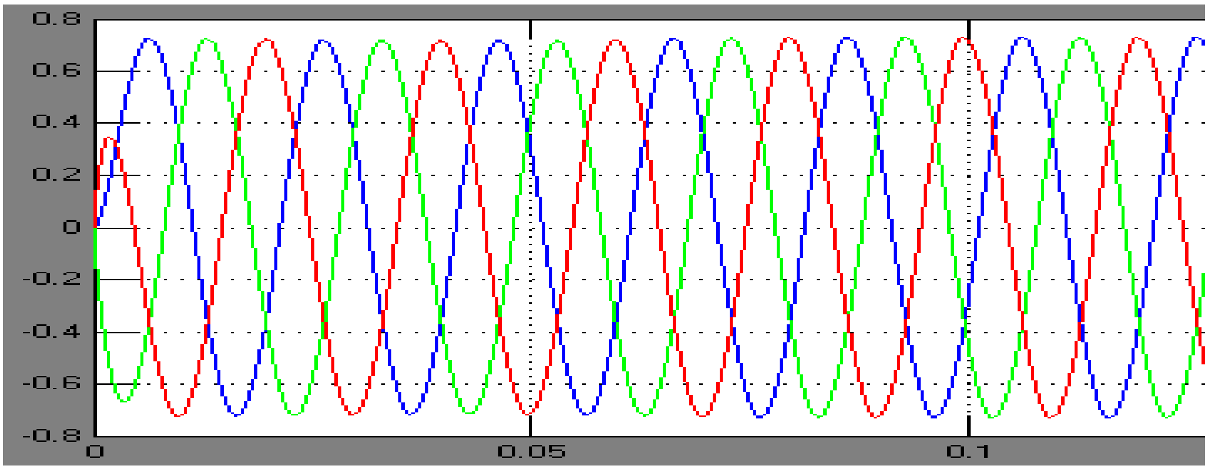

Fig.5.34: Load Current vs Time waveform (with compensation)

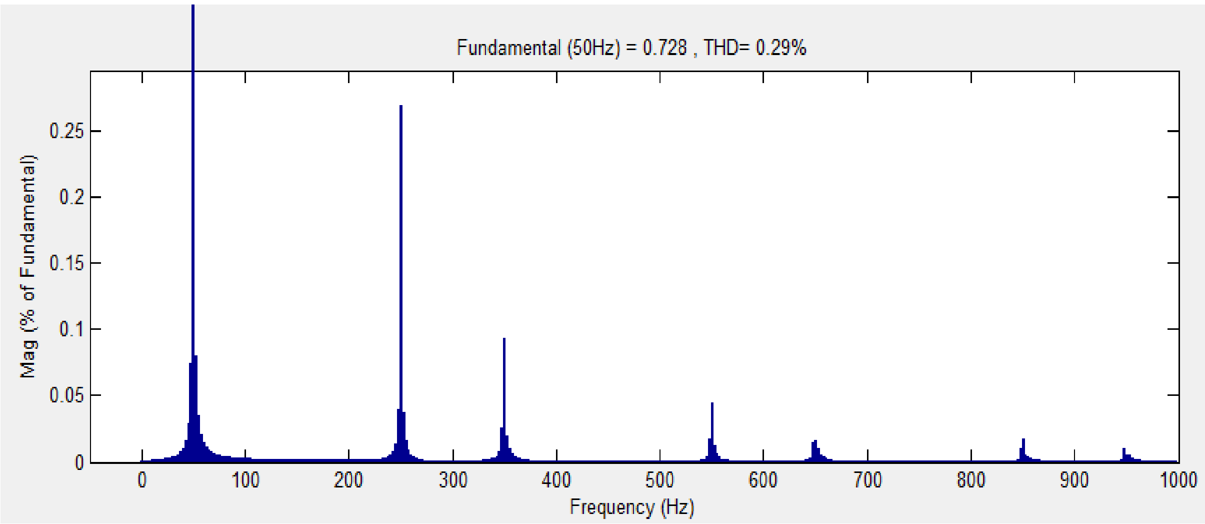

Fig.5.35: Frequency Spectrum of Load Current (with compensation)

5.5.2 Results for DTC Induction Motor Drive 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 DTC induction motor drive 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 0.12s to 0.18s. The output wave for the load current without compensation is shown in fig.5.36. 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.5.38. These results become clear from the frequency spectrum graphs, which are taken one by one for non-compensated and compensated feeders with DTC induction motor drive load as shown in fig.5.37 and fig.5.39. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 13.93% to 0.26% when DSTATCOM is connected to the system.

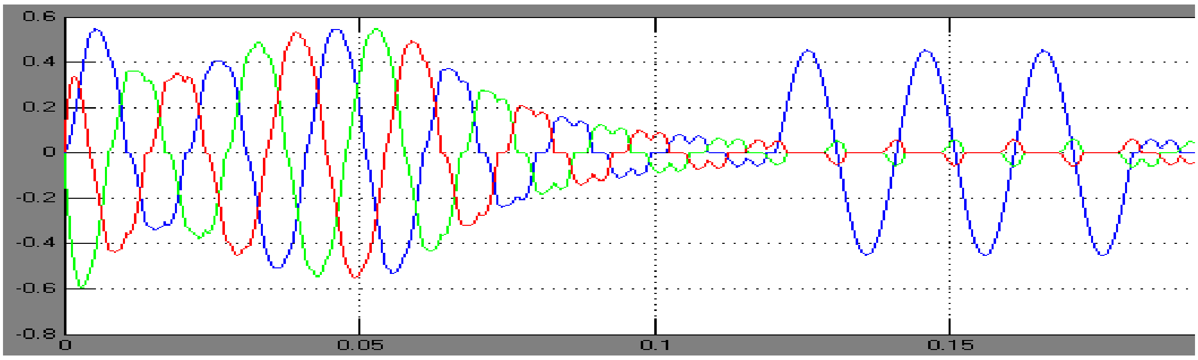

Fig.5.36: Load Current vs Time waveform (without compensation)

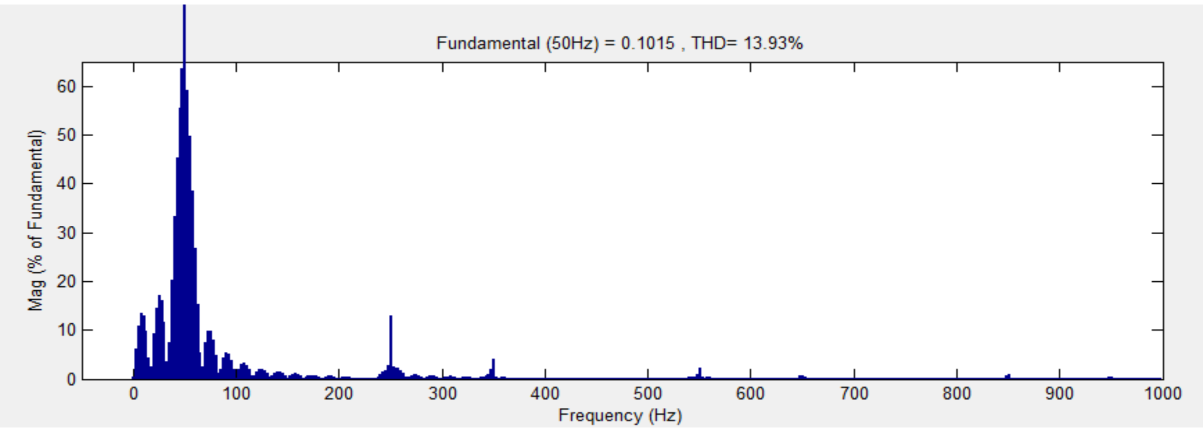

Fig.5.37: Frequency Spectrum of Load Current (without compensation)

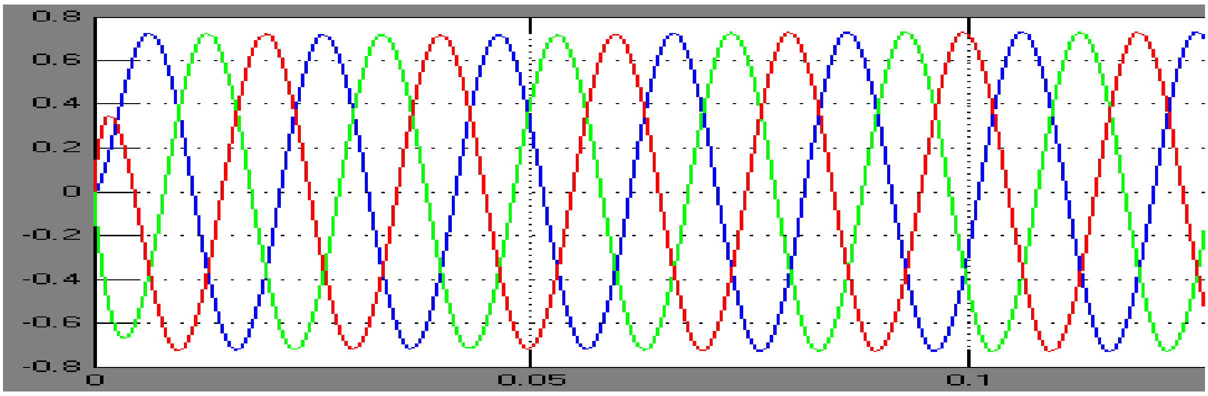

Fig.5.38: Load Current vs Time waveform (with compensation)

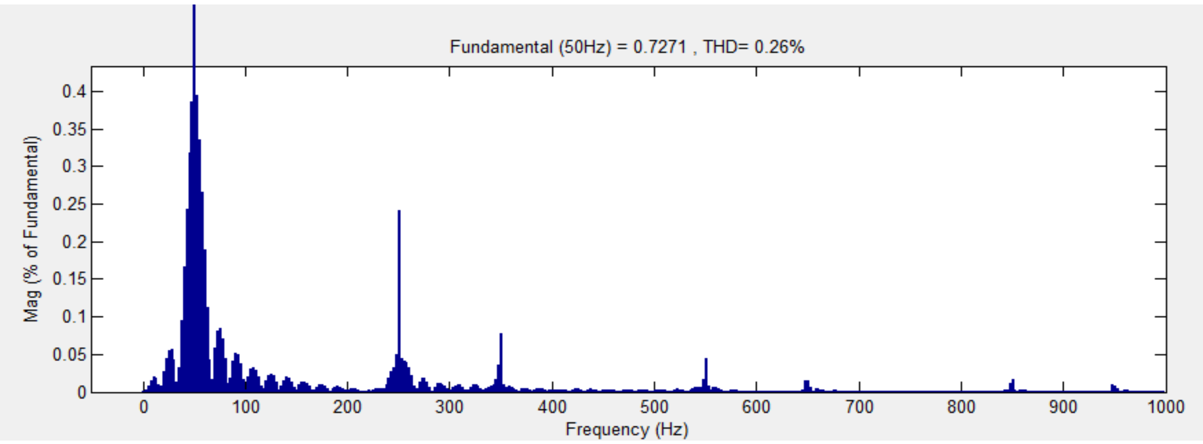

Fig.5.39: Frequency Spectrum of Load Current (with compensation)

CASE II: Double Line to Ground Fault Condition

In this case, a double line to ground fault is considered for both the feeders feeding DTC induction motor drive 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 0.12s to 0.18s. The output wave for the load current without compensation is shown in fig.5.40. 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.5.42. These results become clear from the frequency spectrum graphs, which are taken one by one for non-compensated and compensated feeders with DTC induction motor drive load as shown in fig.5.41 and fig.5.43. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 14.03% to 0.26% when DSTATCOM is connected to the system.

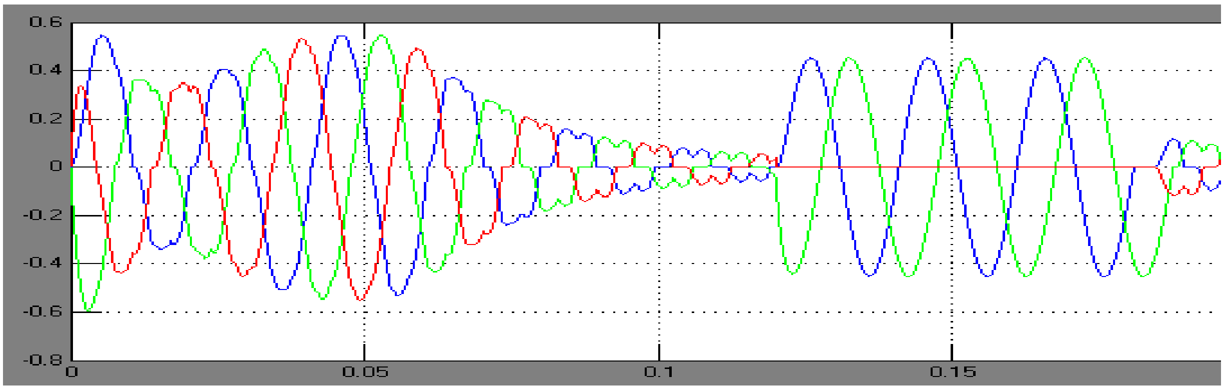

Fig.5.40: Load Current vs Time waveform (without compensation)

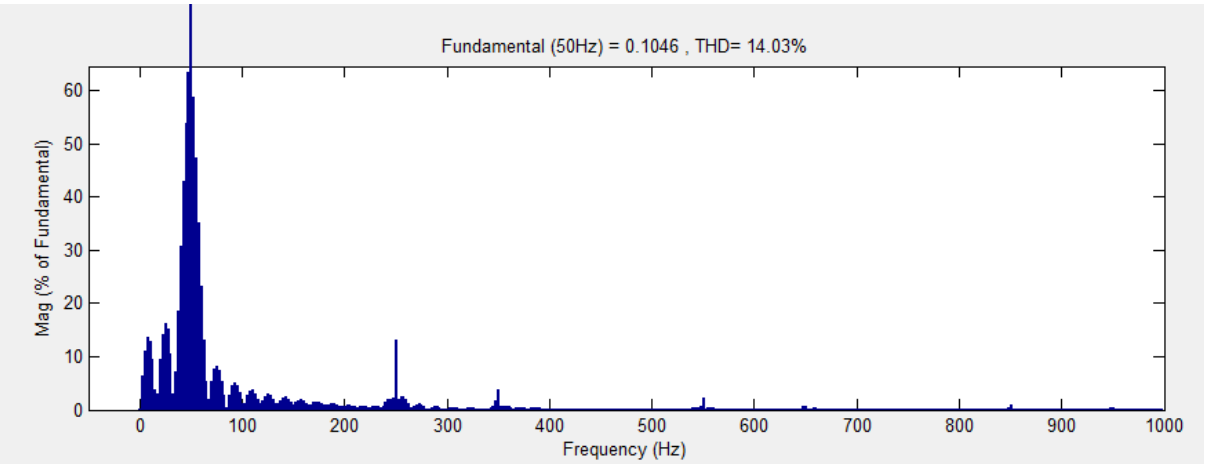

Fig.5.41: Frequency Spectrum of Load Current (without compensation)

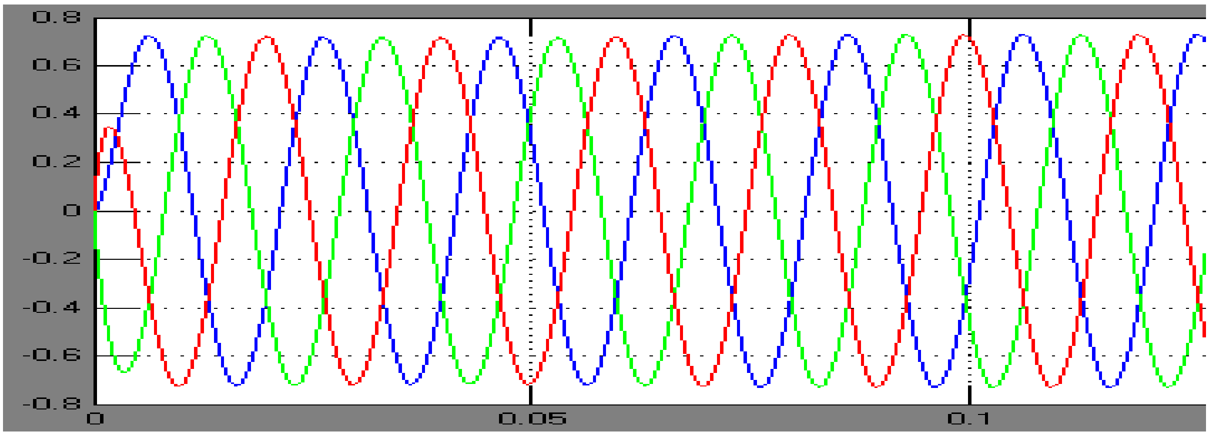

Fig.5.42: Load Current vs Time waveform (with compensation)

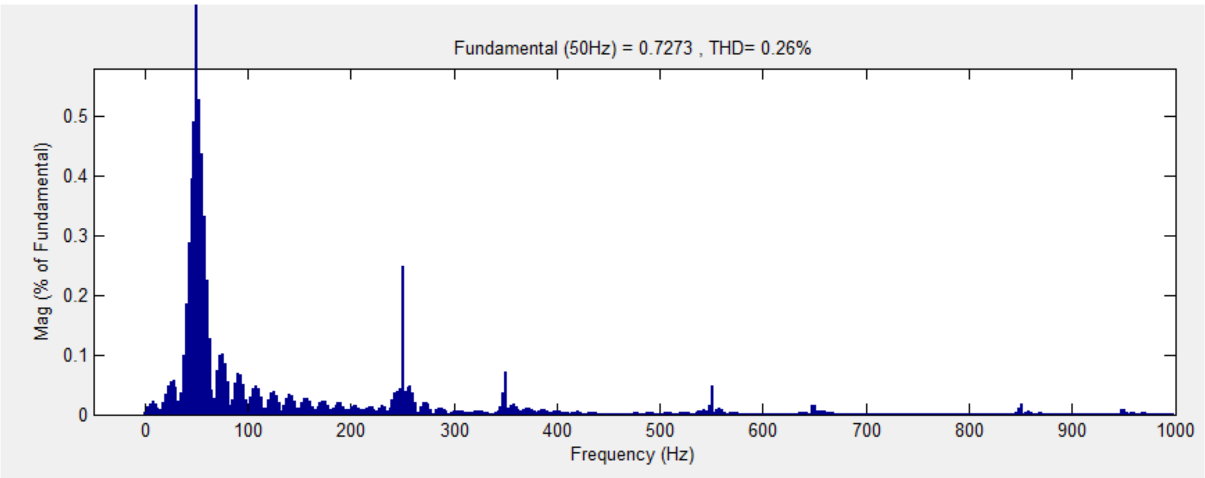

Fig.5.43: Frequency Spectrum of Load Current (with compensation)

CASE III: Three Phase Fault Condition

In this case, three phase fault is considered for both the feeders feeding DTC induction motor drive 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 0.12s to 0.18s. The output wave for the load current without compensation is shown in fig.5.44. 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.5.46. These results become clear from the frequency spectrum graphs, which are taken one by one for non-compensated and compensated feeders with DTC induction motor drive load as shown in fig.5.45 and fig.5.47. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 14.02% to 0.27% when DSTATCOM is connected to the system.

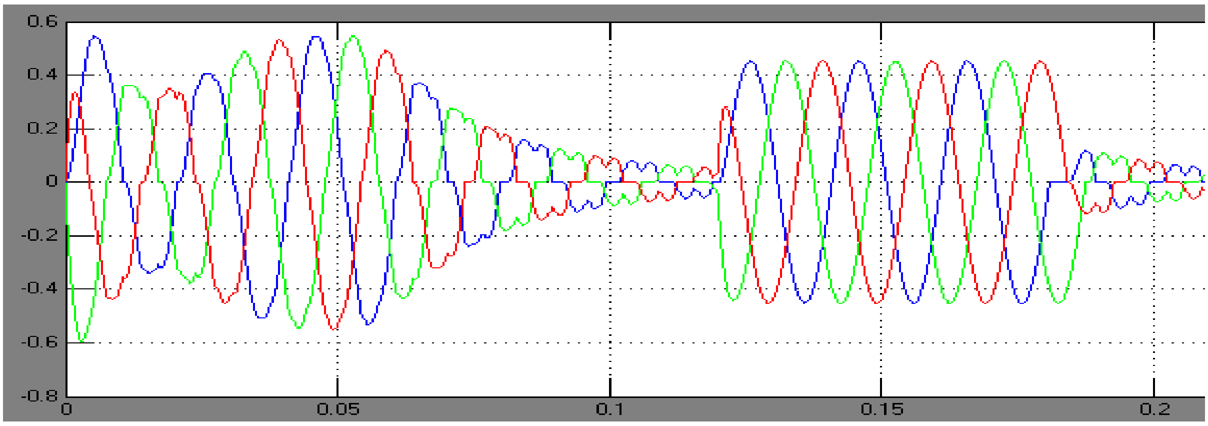

Fig.5.44: Load Current vs Time waveform (without compensation)

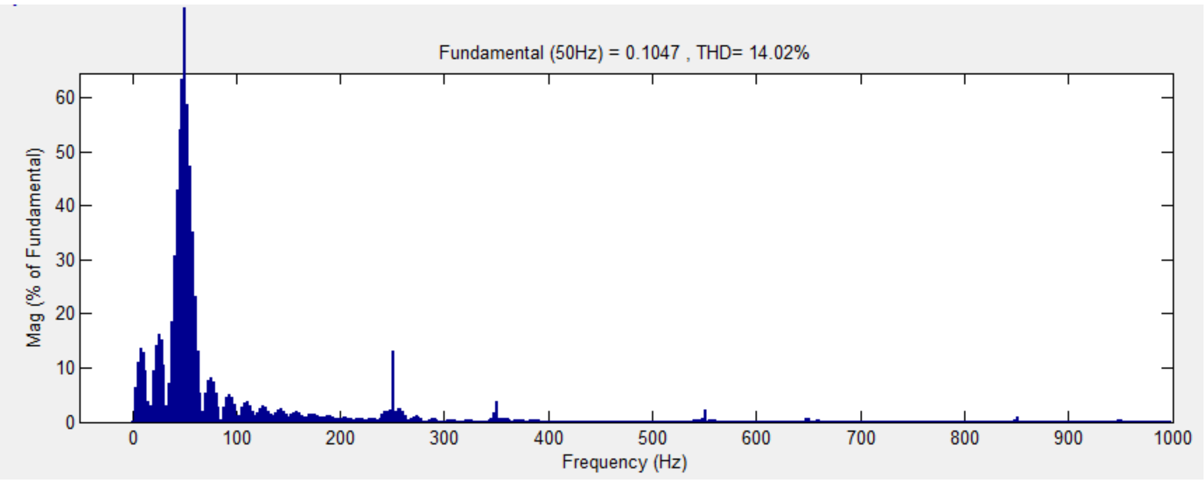

Fig.5.45: Frequency Spectrum of Load Current (without compensation)

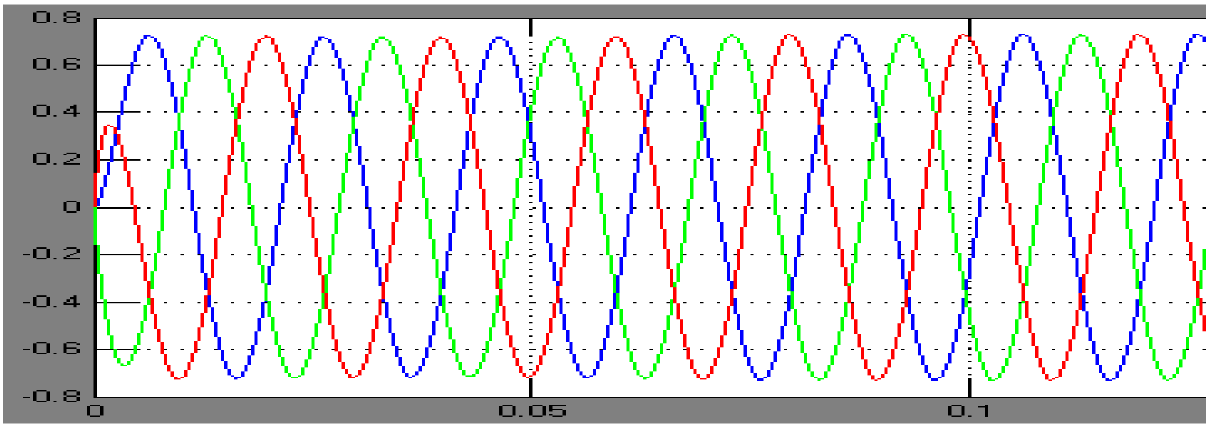

Fig.5.46: Load Current vs Time waveform (with compensation)

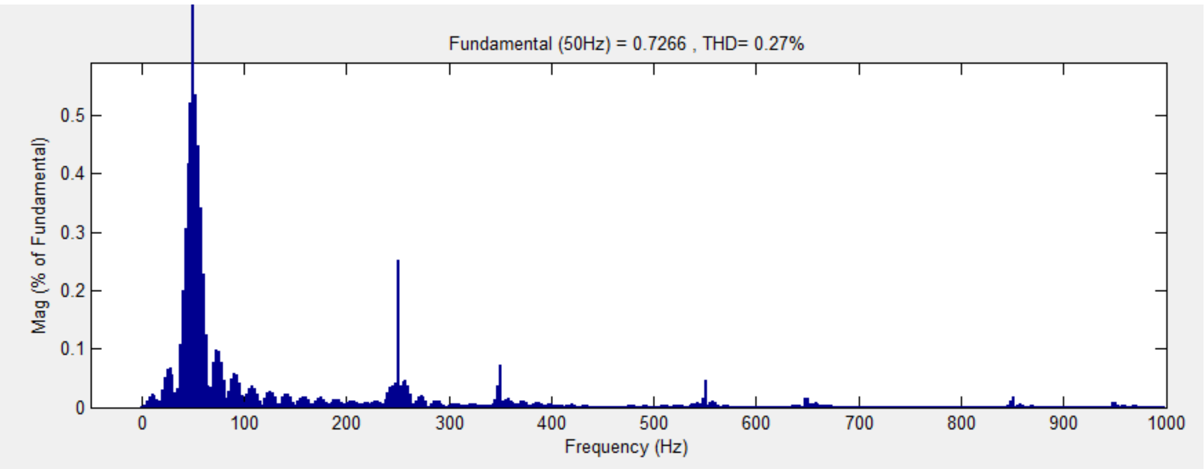

Fig.5.47: Frequency Spectrum of Load Current (with compensation)

5.6 SIMULINK Model of Test System with FOC Induction Motor Drive

SIMULINK model of the test system with FOC induction motor drive as load is given in fig.5.48. The system consists of two parallel feeders with similar FOC induction motor drive load 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 normal operating condition and three different fault conditions, which are single line to ground fault, double line to ground fault and three phase fault.

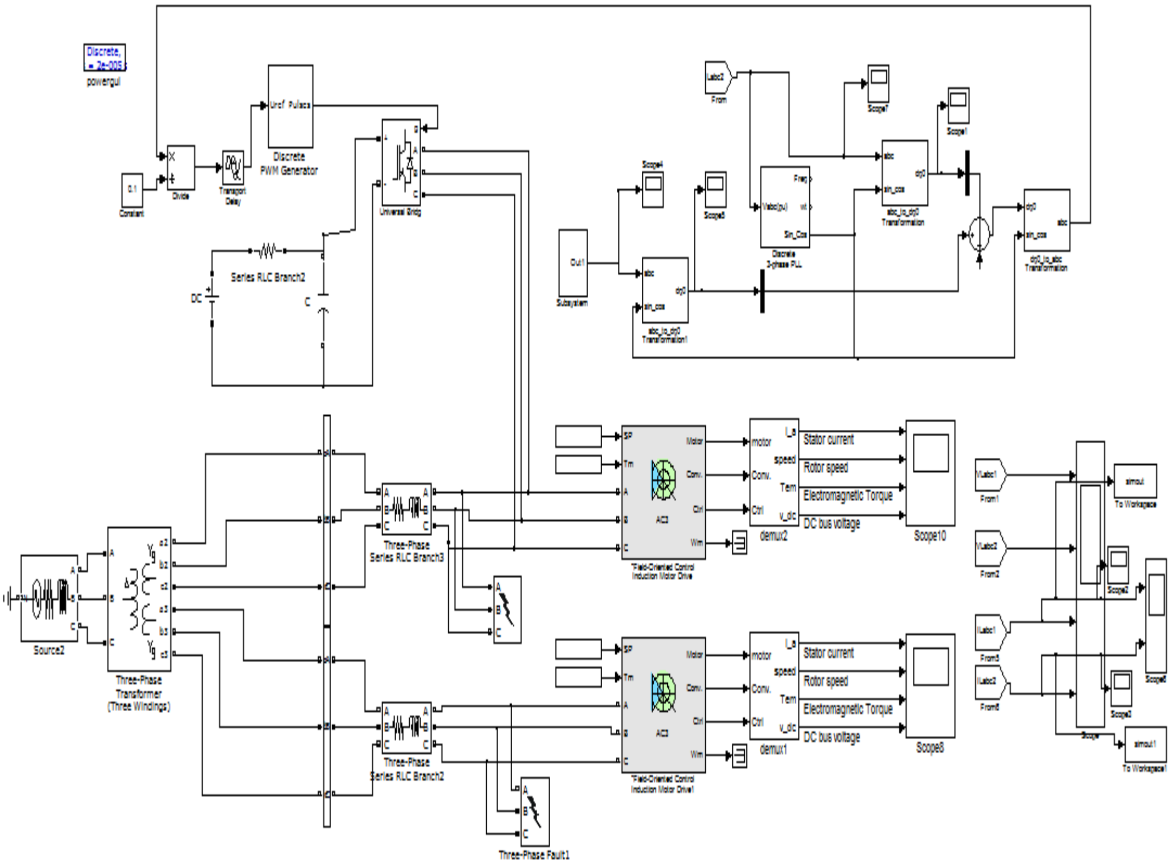

Fig.5.48: SIMULINK Model of Test System with FOC Induction Motor Drive Load

5.6.1 Results for FOC Induction Motor Drive under Normal Condition

Here test system is considered under normal conditions. Due to FOC induction motor drive connected to the system, harmonics are produced in load current waveform as shown in fig.5.49. The frequency spectrum graph of load current for uncompensated feeder is shown in fig.5.50. When DSTATCOM is connected to the system it effectively reduces the harmonics from load current as shown in fig.5.51. Also frequency spectrum graph of load current for compensated feeder is shown in fig.5.52. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 26.99% to 0.23% when DSTATCOM is connected to the system.

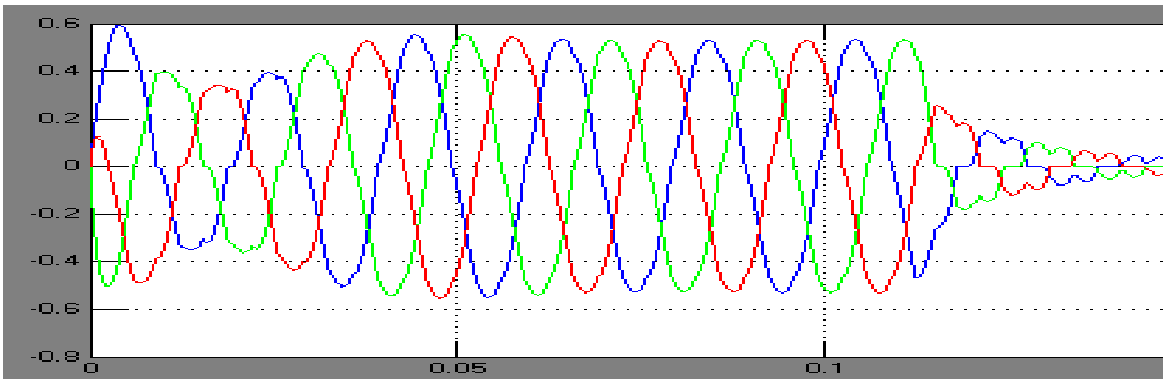

Fig.5.49: Load Current vs Time waveform (without compensation)

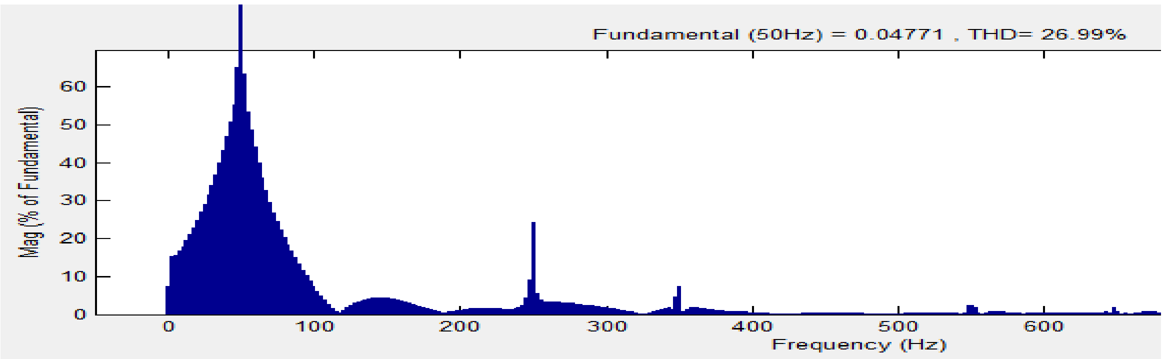

Fig.5.50: Frequency Spectrum of Load Current (without compensation)

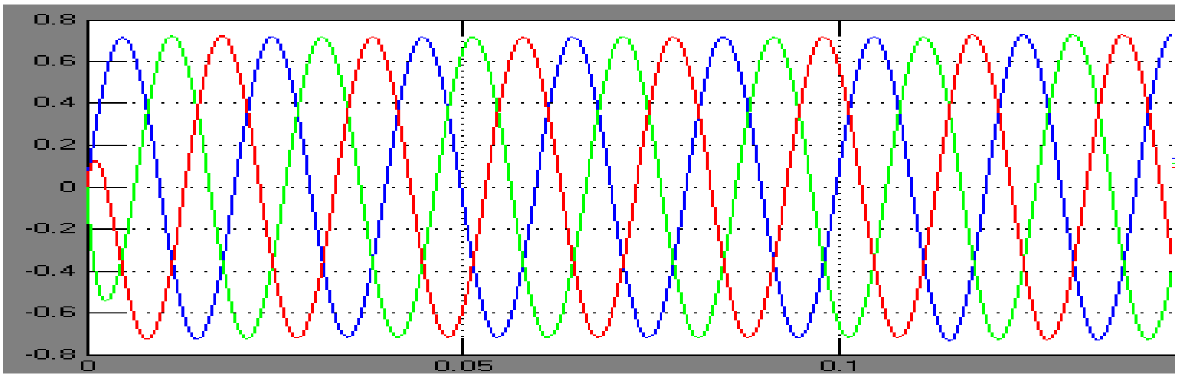

Fig.5.51: Load Current vs Time waveform (with compensation)

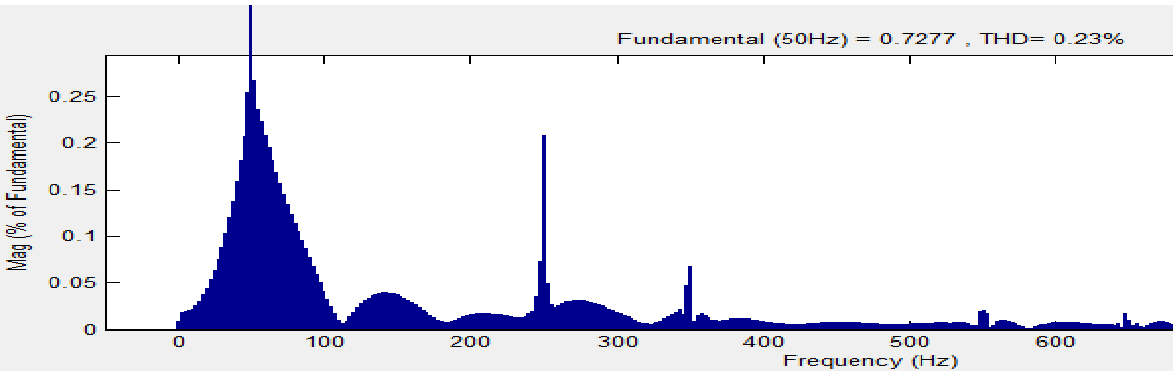

Fig.5.52: Frequency Spectrum of Load Current (with compensation)

5.6.2 Results for FOC Induction Motor Drive under Different Fault Conditions

Case I: Results for Single Line to Ground Fault

In this case, a single line to ground fault is considered for both the feeders feeding FOC induction motor drive 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 0.12s to 0.18s. The output wave for the load current without compensation is shown in fig.5.53. 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.5.55. These results become clear from the frequency spectrum graphs, which are taken one by one for non-compensated and compensated feeders with FOC induction motor drive load as shown in fig.5.54 and fig.5.56. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 11.07% to 0.22% when DSTATCOM is connected to the system.

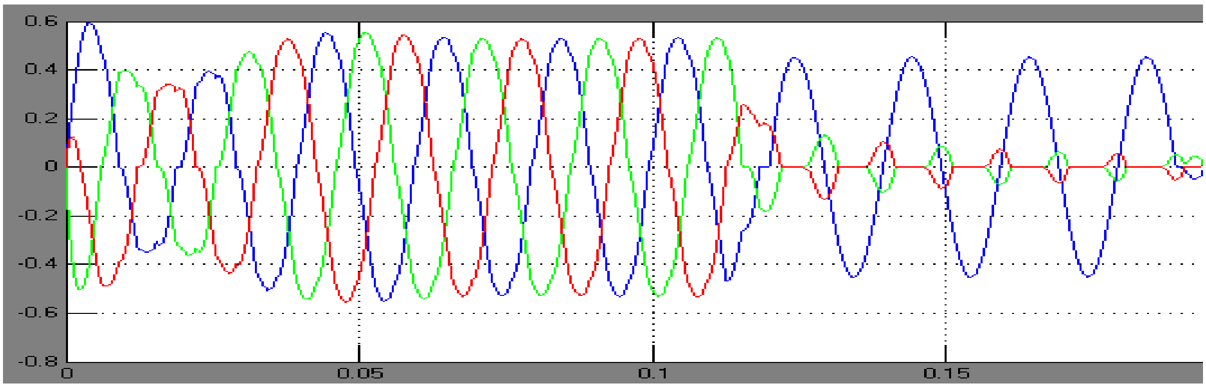

Fig.5.53: Load Current vs Time waveform (without compensation)

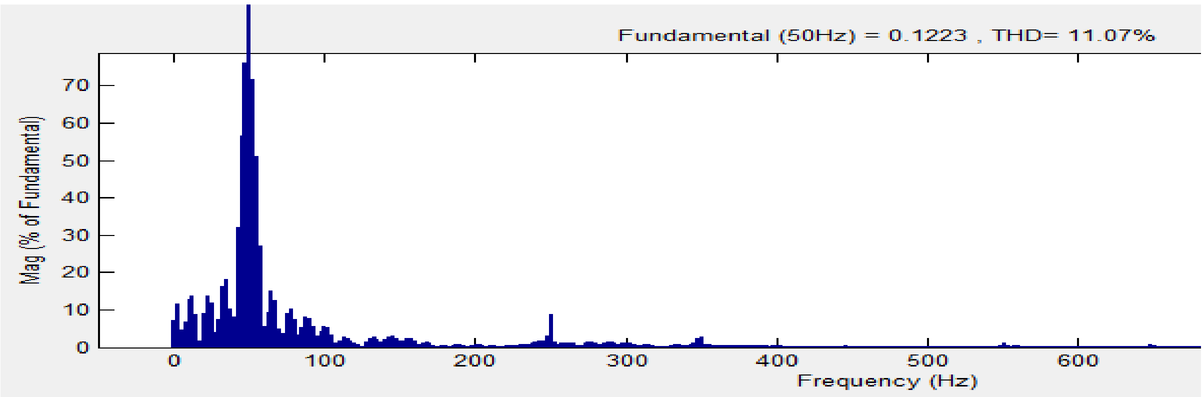

Fig.5.54: Frequency Spectrum of Load Current (without compensation)

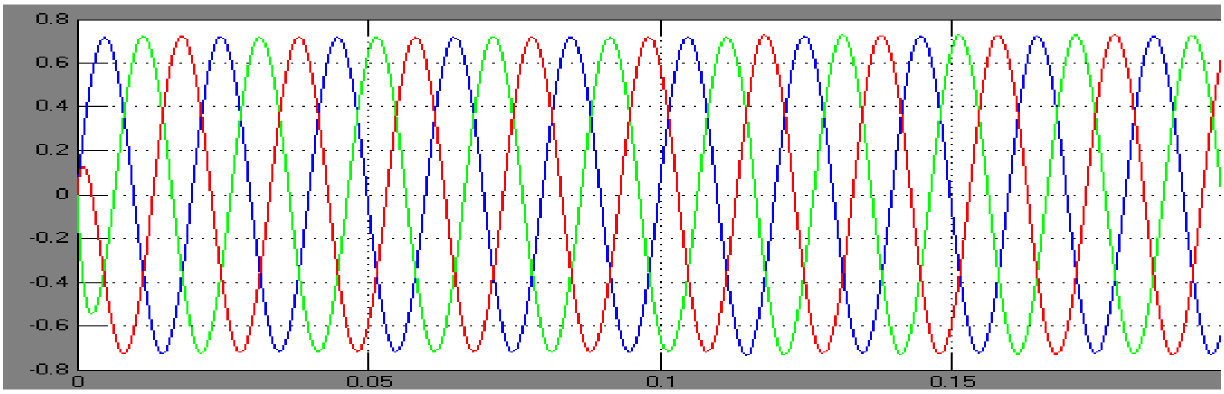

Fig.5.55: Load Current vs Time waveform (with compensation)

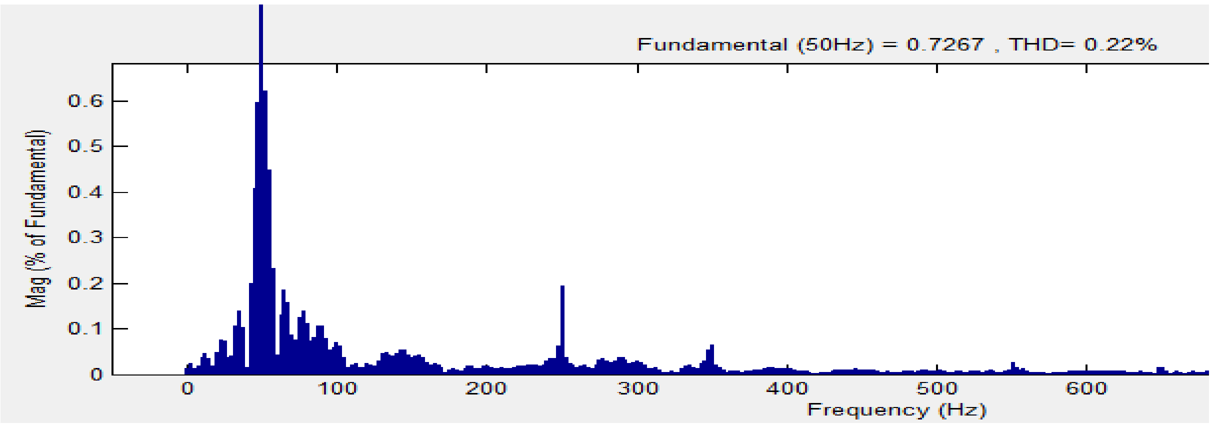

Fig.5.56: Frequency Spectrum of Load Current (with compensation)

Case II: Results for Double Line to Ground Fault

In this case, a double line to ground fault is considered for both the feeders feeding FOC induction motor drive 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 0.12s to 0.18s. The output wave for the load current without compensation is shown in fig.5.57. 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.5.59. These results become clear from the frequency spectrum graphs, which are taken one by one for non-compensated and compensated feeders with FOC induction motor drive load as shown in fig.5.58 and fig.5.60. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 11.20% to 0.24% when DSTATCOM is connected to the system.

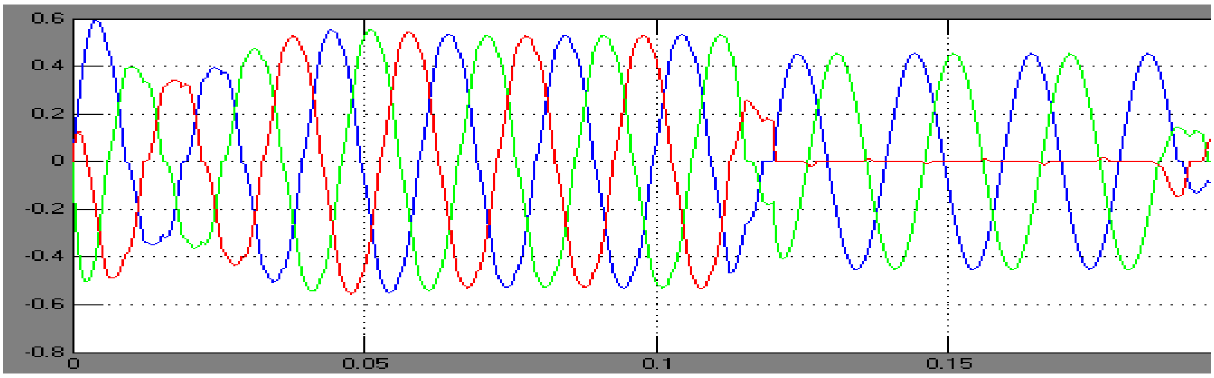

Fig.5.57: Load Current vs Time waveform (without compensation)

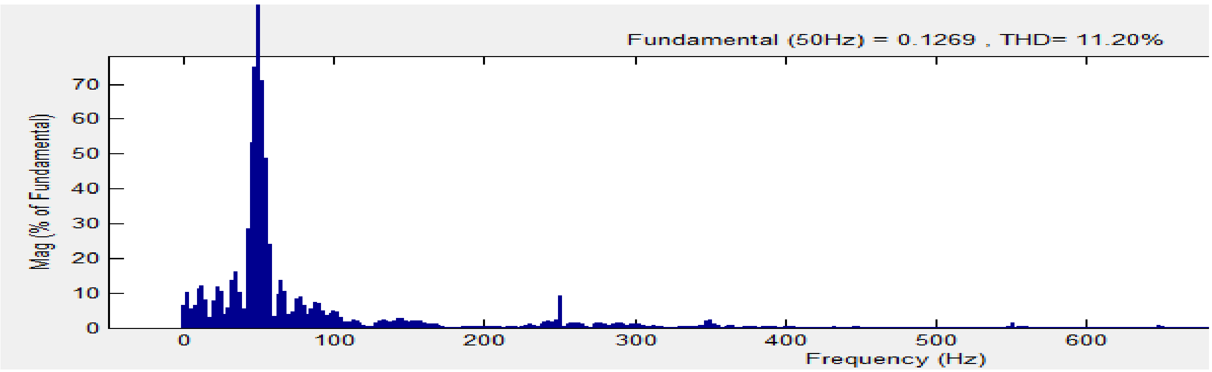

Fig.5.58: Frequency Spectrum of Load Current (without compensation)

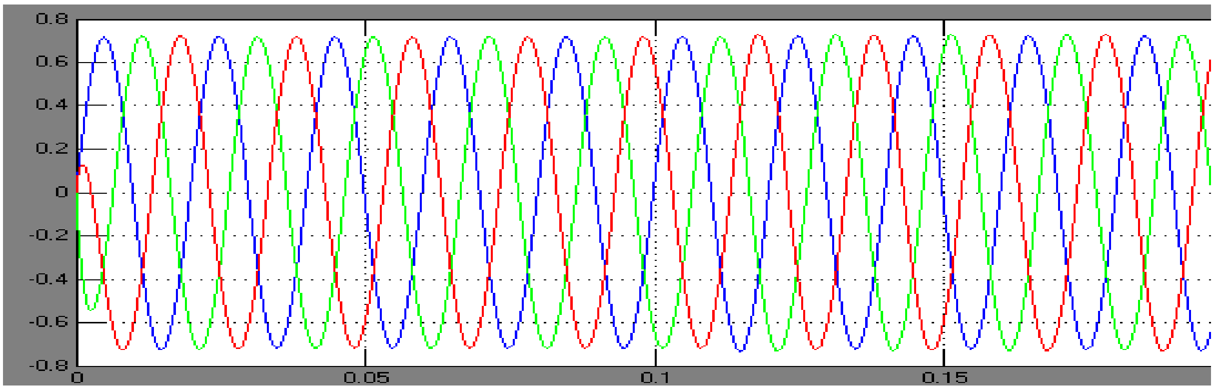

Fig.5.59: Load Current vs Time waveform (with compensation)

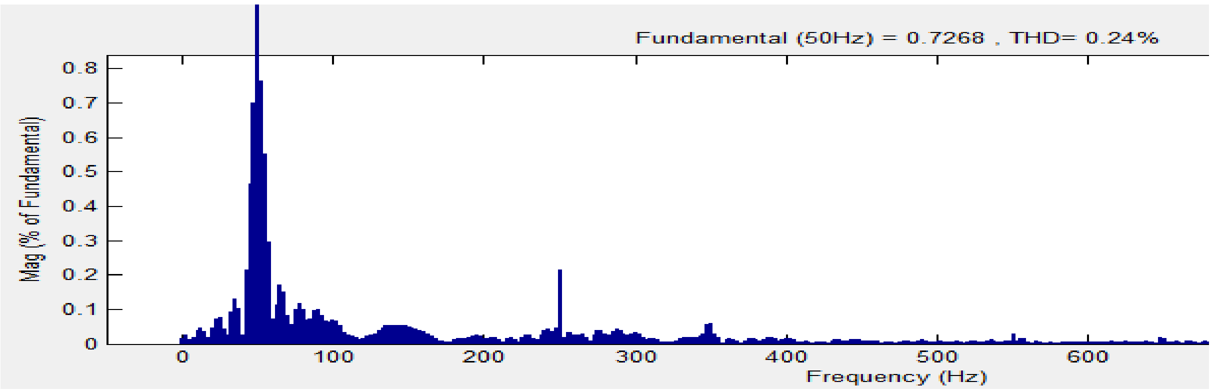

Fig.5.60: Frequency Spectrum of Load Current (with compensation)

Case III: Results for Three Phase Fault

In this case, three phase fault is considered for both the feeders feeding FOC induction motor drive 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 0.12s to 0.18s. The output wave for the load current without compensation is shown in fig.5.61. It is clear from the output wave shape of load current 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.5.63. These results become clear from the frequency spectrum graphs, which are taken one by one for non-compensated and compensated feeders with FOC induction motor drive load as shown in fig.5.62 and fig.5.64. It is clear from the frequency spectrum graphs that THD level of load current is reduced from 11.23% to 0.25% when DSTATCOM is connected to the system.

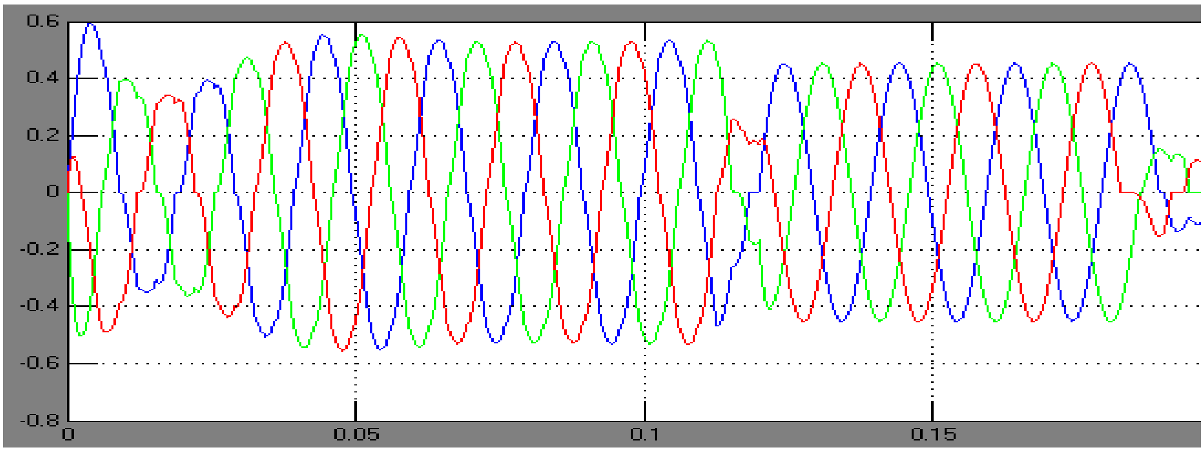

Fig.5.61: Load Current vs Time waveform (without compensation)

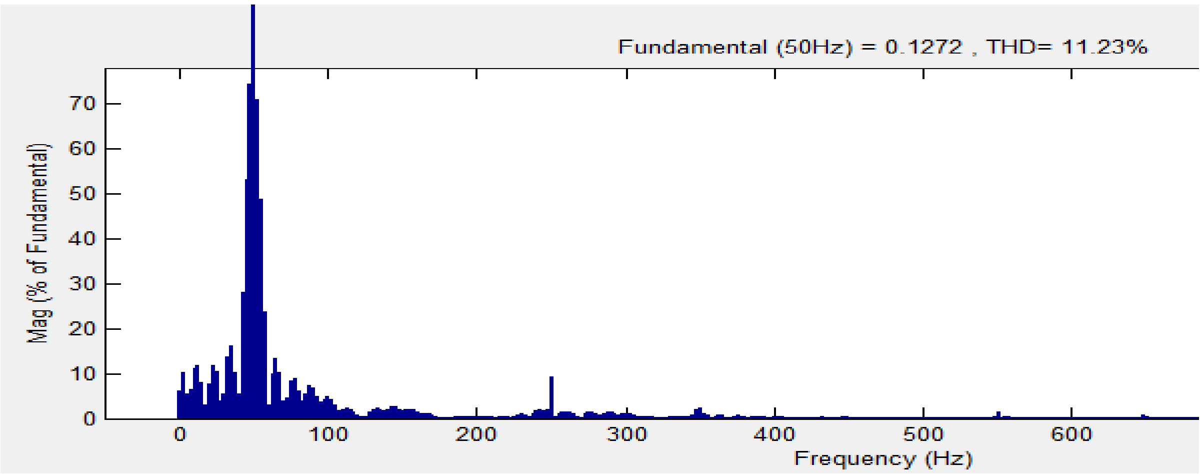

Fig.5.62: Frequency Spectrum of Load Current (without compensation)

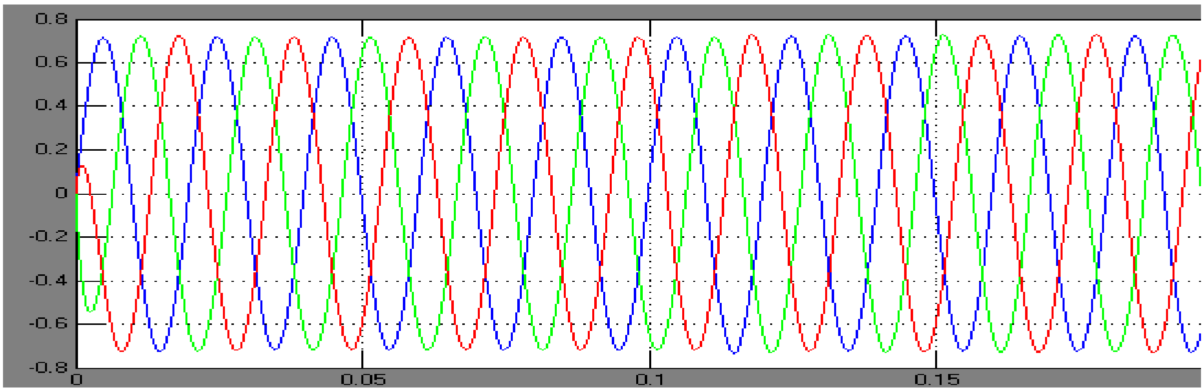

Fig.5.63: Load Current vs Time waveform (with compensation)

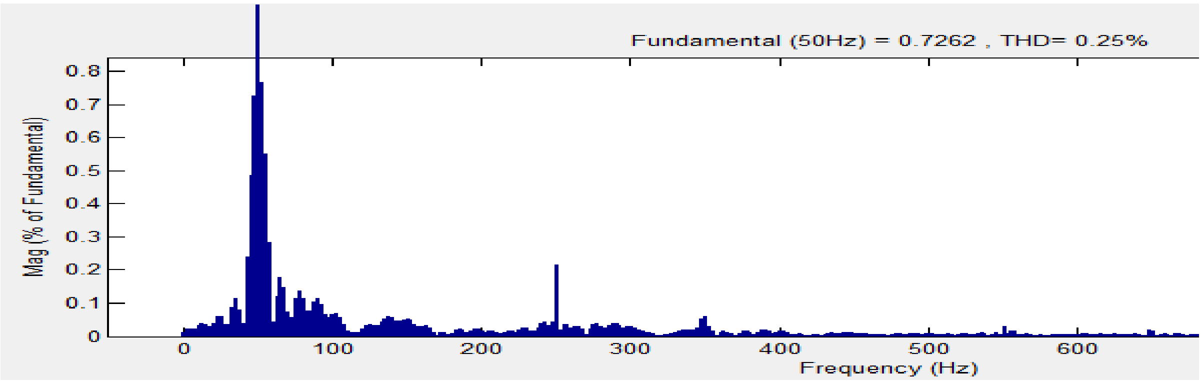

Fig.5.64: Frequency Spectrum of Load Current (with compensation)

5.7 Comparison of THD Levels for Different Types of Load

The Comparison of THD levels for different types of loads under normal and various faults conditions with or without DSTATCOM is shown in table 2. It is clear from the THD analysis of load current that DSTATCOM effectively removes harmonics from load current and makes it smooth.

Table 2: THD LEVLS OF TEST SYSTEMS

Sr. No.	**System Conditions**	**Without DSTATCOM**		**With DSTATCOM**	
		Load Current (Fundamental) in p.u.	**THD**	**Load Current (Fundamental) in p.u.**	**THD**
1.	Linear Load				
	a) Single Line to Ground fault	0.04698	4.47%	2.545e-6	0%
	b) Double Line to Ground fault	0.04698	4.46%	2.545e-6	0%

	c) Three Phase fault	0.04698	4.48%	2.545e-6	0%
2.	Non-Linear Load				
	a) Normal Condition	0.01395	28.09%	0.7284	0.07%
	b) Single Line to Ground fault	0.01397	29.13%	0.7284	0.07%
	c) Double Line to Ground fault	0.01392	29.07%	0.7285	0.08%
	d) Three Phase fault	0.01392	28.90%	0.7285	0.08%
3.	DTC Induction Motor Drive				
	a) Normal Condition	0.03566	44.37%	0.728	0.29%
	b) Single Line to Ground fault	0.1015	13.93%	0.7271	0.26%
	c) Double Line to Ground fault	0.1046	14.03%	0.7273	0.26%
	d) Three Phase fault	0.1047	14.02%	0.7266	0.27%
4.	FOC Induction Motor Drive				
	a) Normal Condition	0.04771	26.99%	0.7277	0.23%
	b) Single Line to Ground fault	0.1223	11.07%	0.7267	0.22%
	c) Double Line to Ground fault	0.1269	11.20%	0.7268	0.24%
	d) Three Phase fault	0.1272	11.23%	0.7262	0.25%

CHAPTER 6

CONCLUSIONS AND FUTURE SCOPE OF WORK

6.1 Conclusions

In this work, DSTATCOM has been modeled and simulated in MATLAB/SIMULINK environment. The performance of DSTATCOM has been analyzed for linear loads, static non-linear loads, DTC induction motor drive and FOC induction motor drive using dqo transformation technique. 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 PV cell and wind turbine system.

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