POWER QUALITY IMPROVEMENT OF DISTRIBUTION NETWORKS USING DYNAMIC VOLTAGE RESTORER

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IN

POWER SYSTEMS & ELECTRIC DRIVES

Submitted by:

AMANDEEP BANGAR
Roll No-800941002

Under the supervision of:

Mr. PARAG NIJHAWAN
Assistant Professor, EIED

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ELECTRICAL & INSTRUMENTATION ENGINEERING DEPARTMENT

THAPAR UNIVERSITY

PATIALA — 147004

CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled "POWER QUALITY IMPROVEMENT OF DISTRIBUTION NETWORKS USING DYNAMIC VOLTAGE RESTORER" in partial fulfillment of requirement for the award of the master degree in POWER SYSTEMS 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 other degree of this or any other university.

Amandeep Bangar
04/7/2011
(AMANDEEP BANGAR)

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

Parag
04/7/2011
(Mr. PARAG NIJHAWAN)
Assistant Professor
Electrical & Instrumentation Engg. Department
Thapar university, patiala

Countersigned by:

S. Ghosh
(Dr. S. GHOSH)
Professor & Head
Electrical & Instrumentation Engg. Department
Thapar University, Patiala

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

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Amandeep Bange
04/7/2011
AMANDEEP BANGAR
Roll No. 800941002

ABSTRACT

Power quality is one of major concerns in the present era. It has become important, especially, with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply. Power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure of end use equipments. One of the major problems dealt here is the power sag. Sensitive industrial loads and utility distribution networks all suffer from various types of outages and service interruptions which may result in a significant financial 1oss. To improve the power quality, custom power devices are used. The device considered in this work is DVR. This thesis presents modeling, analysis and simulation of a Dynamic Voltage Restorer (DVR) test systems using MATLAB. In this work, PI controller and Discrete PWM pulse generator are used for the control purpose. Here, different fault conditions are considered for linear as well as induction motor load. The role of DVR to compensate load voltage is investigated during the different fault conditions like voltage sag, single phase to ground, double phase to ground faults. In addition, the application of DVR to compensate the problem of starting voltage dip for induction motor is also investigated.

LIST OF ABBREVIATIONS

SLG - Single Line to Ground
IEEE - Institute of Electrical and Electronic Engineers
EMC - Electromagnetic Compatibility
CRT - Cardiac Resynchronization Therapy
AGC - Automatic Generation Control
PWM - Pulse Width Modulation
DC - Direct Current
SMES - Superconducting Magnet Energy Storage
FACTS - Flexible AC Transmission Systems
AC - Alternating Current
CPD - Custom Power Device
APF - Active Power Filters
BESS - Battery Energy Storage Systems
DSTATCOM - Distribution Static Synchronous Compensators
DVR - Dynamic Voltage Restorer
UPS - Uninterruptible Power Supplies
PQD - Power Quality Device
UPQC - Unified Power Quality Compensator
ESS - Energy Storage System
PI - Proportional Integral
SSSC - Static Synchronous Series Compensator
SVC - Static Var Compensator
ASVC - Advanced Static VAR Compensator
HSMTS - High-Speed Mechanical Transfer Switch
VSI - Voltage Source Inverter
CSI - Current Source Inverter
PCC - Point Of Common Coupling
IGBT - Insulated Gate Bipolar Transistors

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

The electric power system is considered to be composed of three functional blocks - generation, transmission and distribution. For a reliable power system, the generation unit must produce adequate power to meet customer's demand, transmission systems must transport bulk power over long distances without overloading or jeopardizing system stability and distribution systems must deliver electric power to each customer's premises from bulk power systems. Distribution system locates the end of power system and is connected to the customer directly, so the power quality mainly depends on distribution system. The reason behind this is that the electrical distribution network failures account for about 90% of the average customer interruptions. In the earlier days, the major focus for power system reliability was on generation and transmission only as these more capital cost is involved in these. In addition their insufficiency can cause widespread catastrophic consequences for both society and its environment. But now a day's distribution systems have begun to receive more attention for reliability assessment.

Initially for the improvement of power quality or reliability of the system FACTS devices like static synchronous compensator (STATCOM), static synchronous series compensator (SSSC), interline power flow controller (IPFC), and unified power flow controller (UPFC) etc are introduced. These FACTS devices are designed for the transmission system. But now a days more attention is on the distribution system for the improvement of power quality, these devices are modified and known as custom power devices. The main custom power devices which are used in distribution system for power quality improvement are distribution static synchronous compensator (DSTATCOM), dynamic voltage Restorer (DVR), active filter (AF), unified power quality conditioner (UPQC) etc.

In this thesis work from the above custom power devices, DVR is used with PI controller for the power quality improvement in the distribution system. Here two different loads are considered, one is linear load and the other is induction motor. Different fault conditions are considered with these loads to analyze the operation of DVR to improve the power quality in distribution system.

1.2 LITERATURE SURVEY

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. The impact of power quality problems is increasingly felt by customers - industrial, commercial and even residential. Some of the main power quality problems are sag, swell, transients, harmonic, and flickers etc [2].

By custom power devices, we refer to power electronic static controllers used for power quality improvement on distribution systems rated from 1 to 38 kV [9], [10]. This interest in the practice of power quality devices (PQDs) arises from the need of growing power quality levels to meet the everyday growing sensitivity of customer needs and expectations [7]. One of those devices is the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. Its application includes lower cost, smaller size, and its fast dynamic response to the disturbance.[12]

Several research papers and reports addressed the subject of improving power quality in distribution system by the use of custom power devices. The followings present a brief review of the work undertaken so far.

N.G. Hingorani, [5] presents the concept of custom power is now becoming familiar. The term describes the value-added power that electric utilities and other service providers will offer their customers in the future. The enhanced level of reliability of this power, in terms of reduced interruptions and less variation, will stem from an integrated solution to present problems, of which a prominent feature will be the application of power electronic controllers to utility distribution systems and/or at the supply end of many industrial and commercial customers and industrial parks.

Yash Pal, A. Swarup, et al. [11] presents a comprehensive review of compensating custom power devices mainly DSTATCOM (distribution static compensator), DVR (dynamic voltage restorer) and UPQC (unified power quality compensator). It is aimed at providing a broad viewpoint on the status of compensating devices in electric power distribution system to researchers and application engineers dealing with power quality problems.

Fawzi AL Jowder, et al. [15] presents three different system topologies for dynamic voltage restorers (DVRs) are modeled and tested using Simulink, SimPowerSystem Toolbox for power system quality studies. The DVR controls are based on hysteresis voltage control. Simulation tests on radial distribution system, equipped with the DVR under three-phase and single-phase voltage sags with phase jump, are used to verify the operation of different DVR topologies. The modeled DVR topologies can be used to develop and test different, control strategies and methods for the DVR. These models can also aid instructors in teaching power quality courses.

John Godsk Nielsen, et al. [16] presents different control strategies for dynamic voltage restorer are analyzed with emphasis put on the compensation of voltage sags with phase jump.. Different control methods to compensate voltage sags with phase jump are here proposed and compared. Two promising control methods are tested with simulations carried out and finally tested on a 10 kVA rated Dynamic Voltage Restorer in the laboratory. Both methods can be used to reduce load voltage disturbances caused by voltage sags with phase jump. One method completely compensates the phase jump, which is the best solution for very sensitive loads.

H.P. Tiwari, et al. [20] presents dynamic voltage restorer against voltage sag. A dynamic voltage restorer (DVR) is a custom power device used to correct the voltage sag by injecting voltage as well power into the system. The mitigation capability of these devices is generally influence by the maximum load; power factor and maximum voltage dip to be compensated. Voltage Dip on a feeder is an main task for DVR system operation and appropriate desired voltage sag compensation. This paper is intended to assimilate the amount of DC energy storage depends on voltage dip. It is available in a convenient manner for DVR power circuit.

D.N.Katole, et al. [19] presents the Dynamic Voltage Restorer (DVR) with ESS based PI Controller method to compensate balanced voltage sag. Voltage sag is one of the major power quality problem which results in a failure or a mis-operation of end use equipments. Sensitive industrial loads and Utility distribution networks all suffer from various types of outages and service interruptions which can cost significant financial 1oss per event. The aim therefore, is to recommend measures that can improve voltage sag.

Francisco Jurado, et al. [21] presents fuzzy logic control of dynamic voltage restorer.. Some basic concepts of the DVR arc presented. Also describes the fundamentals of fuzzy logic. He presented a briefly discusses the application of fuzzy logic control in the field of PWM converter. The voltage error and its derivative are the Fuzzy Logic controller input crisp values. When a Fuzzy Logic controller is used, the tracking error and transient overshoots of PWM can be considerably reduced. The simulations carried out show that the Dynamic voltage restorer provides excellent voltage regulation capabilities.

Paisan Boonchiaml et al. [22] presents detailed analysis of load voltage compensation for dynamic voltage restorer (DVR) that used for enhancing power quality. A technique of determining the accurate amount of voltage injection necessary to correct a specific voltage reduction with least power injection is described. Systematic expressions for both magnitude and angle of the injected voltage are also derived. It has been shown that a voltage reduction and power factor should be analyzed before compensating the voltage.

A.Teke, et al. [23] presents the design and analysis of a fuzzy logic (FL) controlled dynamic voltage restorer (DVR) are presented and extended to perform quick fault detection. A new control method for DVR is proposed by combining FL with a carrier modulated PWM inverter. The proposed control method is simple to design and has outstanding voltage compensation capabilities. The proposed method for voltage sag/swell detection has the ability of detecting different kinds of power disturbances faster than conventional detection methods. Effectiveness of the proposed detection method is shown by comparison with the conventional methods in the literature.

B. Ferdi, et al. [24] presents Adaptive PI Control of Dynamic Voltage Restorer Using Fuzzy Logic. PI controller is very common in the control of DVRs. However, one disadvantage of this conventional controller is the fact that by using fixed gains, the controller may not provide the required control performance, when there are variations in the system parameters or operating conditions. To overcome this problem, an adaptive PI controller using fuzzy logic is proposed. The controller is composed of fuzzy controller and PI controller. According to the error and error rate of the control system and fuzzy control rules, the fuzzy controller can online adjust the two parameters of the PI controller in order to be adapted to any variations in the operating conditions. The simulation results have proved that the proposed control method greatly improves the performance of the DVR compared to the conventional PI controller.

P.Ajay-D-Vimal Raj, et al. [25] presents DVR with pi and fuzzy logic controller. The growing interest in power quality has led to a variety of devices designed for mitigating power disturbances, primarily voltage sags. Among several devices, a Dynamic Voltage Restorer (DVR) is a novel custom power device proposed to compensate for voltage disturbances in a distribution system. The compensation capability of a DVR depends primarily on the maximum voltage injection ability and the amount of stored energy available within the restorer.

M.H.J Bollen, et al. [26] presents the various characteristics of voltage sags experienced by customers within industrial distribution systems. Special stress is paid to the influence of the induction motor load on the characterization of voltage sags. During a fault, an induction motor operates as a generator for a short period of time and causes a raise in sag magnitude. Its reacceleration after the fault clearance results in an extended post-fault voltage sag. For an imbalanced fault, the induction motor current contains only positive- and negative-sequence components. Induction motors form a low impedance path for the negative-sequence voltage due to an imbalanced fault. This causes a small sustained nonzero voltage with large phase-angle jump in the faulted phase and a voltage drop in the non faulted phases with a small phase-angle jump. The symmetrical components of the induction motor during the imbalanced sags have been studied.

C.S. Chang, et al. [27] presents performance of voltage sag mitigation devices such as the Dynamic Voltage Restorer (DVR) has been analyzed in highly simplified electrical environment consisting of simple line and load models. The negative influences of dynamic motor loads on the existing voltage disturbance, such as post-fault sags, further during-fault phase-angle deviations, during-fault and post-fault voltage fluctuations have often been unnoticed. First, the influence of induction motor operations on the during-fault and post-fault waveforms will be discussed. After which, the ability of the DVR to dynamically respond to the various types of voltage sag conditions at the terminals of a dynamic motor load and restore the sagging voltage to its pre-fault conditions is presented.

M.H.J Bollen [28] presented the influence of motor parameters on the number of sags that lead to an interruption of plant operation. The assumption that a voltage sag is rectangular is not correct in a power system with large induction motor loads. After fault-clearing, they will accelerate again, drawing a high reactive current from the supply, causing extended post fault voltage sag. This is aggravated by the removal of branches by the protection. The resulting shape of some voltage sags in an example power system is shown and discussed. The influence of faster protection and of reduced transformer impedance on the table is presented. A simple motor model is implemented in a method for including interruptions due to voltage sags in the reliability analysis of power systems.

H.P. Tiwari, et al. [29] presented the issues and the impact of various factors on performance of Dynamic Voltage Restorer (DVR) system. A DVR is connected in power system for series voltage compensation. Voltage sags have considerable affect on the performance of sensitive loads there in the distribution system. The impact of voltage, energy, power, DVR rating, maximum load, power factor, maximum depth and duration of voltage sag, efficiency & losses, harmonics, frequency and transformer on proper functioning of DVR system is studied

1.3 SCOPE OF WORK

From the literature review, it is observed that the work on the investigation on power with compensating devices is very much diversified. However it is observed that there is a scope to investigate the effectiveness of compensating devices for different loads and with different loading conditions in distribution system. As the distribution system locates the end of power system and is connected to the customer directly, so the reliability of power supply mainly depends on distribution system. As the customer's demand for the reliability of power supply is increasing day by day, so the reliability of the distribution system has to be increased. Electrical distribution network failures account for about 90% of the average customer interruptions. So it is highly required to increase the reliability of the distribution system.

The objective of the proposed work is to improve the power quality or reliability in the distribution system with the use of custom power device. Different fault conditions are considered with different loads to analyze the operation of DVR for the improvement the power quality in distribution system.

1.4 ORGANIZATION OF THESIS

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

Chapter-2 explains the fundamentals of power quality, power quality problems and their associated solutions.

Chapter-3 presents the concept and need of custom power devices.

Chapter-4 discusses the operation, modeling and applications of Dynamic voltage controller (DVR).

Chapter-5 presents of SIMULINK test models and their results.

Chapter-6 presents the conclusion of the work presented in this thesis. It also presents the future scope of this work.

CHAPTER 2

POWER QUALITY

2.1 INTRODUCTION

The IEEE Standard Dictionary of Electrical and Electronics defines power quality as “the concept of powering and grounding sensitive electronic equipment in a manner that is suitable to the operation of that equipment.” Power quality may also be defined as “the measure, analysis, and improvement of bus voltage, usually a load bus voltage, to maintain that voltage to be a sinusoid at rated voltage and frequency.”Another definition of power quality reported in the literature [1] is as follows:

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.” A broad definition of power quality borders on system reliability, dielectric selection on equipment and conductors, long-term outages, voltage unbalance in three-phase systems, power electronics and their interface with the electric power supply and many other areas.

2.2 POWER QUALITY- A BIG ISSUE

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. Modernization and automation of industry involves increasing use of computers, microprocessors and power electronic systems such as adjustable speed drives. Integration of non-conventional generation technologies such as fuel cells, wind turbines and photo-voltaic with utility grids often requires power electronic interfaces. The power electronic systems also contribute to power quality problems (generating harmonics). Under the deregulated environment, in which electric utilities are expected to compete with each other, the customer satisfaction becomes very important. The impact of power quality problems is increasingly felt by customers - industrial, commercial and even residential.

2.3 PROBLEMS ASSOCIATED WITH POWER QUALITY

2.3.1 MOMENTARY PHENOMENA

2.3.1.1 Transients

Transients are unwanted decay with time and hence not a steady state problem. A broad definition is that a transient is “that part of the change in a variable that disappears during transition from one steady state operating situation to the other". Another synonymous term which can be used is surge.

Transients are further classified into two categories:

(a) Impulsive

(b) Oscillatory

2.3.1.2 Long Duration Voltage Variations

When rms (root mean square) deviations at power frequency last longer than one minute, then we say they are long duration voltage variations. They can be either over voltages which is greater than 1.1p.u or under voltages which is less than 0.9p.u. Over voltage is due to switching off a load or energizing a capacitor bank. Also incorrect tap settings on transformers can result in over voltages. Under voltage are the results of actions which are the reverse of events that cause over voltages i.e. switching in a load or switching off a capacitor bank.

2.3.1.3 Sustained Interruptions

If the supply voltage becomes zero for a period of time which is greater than one minute, then we can say that it is a sustained interruption. Normally, voltage interruption lasting for more than one minute is often unending and requires human intervention to restore the supply. The term “outage” is also used for long interruption. However it does not bring out the true impact of the power interruption. Even an interruption of half a cycle can be disastrous for a customer with a sensitive load.

2.3.1.4 Short Duration Voltage Variations

The short duration voltage variations are generally caused by fault conditions like single line to ground or double line to ground and starting of large loads such as induction motors. The voltage variations can be temporary voltage dips i.e. sag or temporary voltage rise i.e. swells or a absolute loss of voltage which is known as interruptions [3].

- **Voltage Sags**

Voltage sag is defined as the reduction of rms voltage to a value between 0.1 and 0.9p.u and lasting for duration between 0.5 cycle to 1 minute. Voltage sags are mostly caused by system faults and last for durations ranging from 3 cycles to 30 cycles depending on the fault clearing time. It is to be noted that under-voltages (lasting over a minute) can be handled by voltage regulation equipment. 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. Also, the power factor of the starting current is generally poor.

- **Voltage Swells**

A voltage swell is defined as a raise in rms voltage which is between 1.1 and 1.8p.u for time duration between 0.5 cycles to 1 minute. A voltage swell is characterized by its magnitude (rms) and duration. As with sag, swell is associated with system faults. 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. On an ungrounded system, the line to ground voltages on the ungrounded phases is 1.73p.u during a SLG fault. However in a grounded system, there will be negligible voltage rise on the unfaulted phases close to a substation where the delta connected windings of the transformer provide low impedance paths for the zero sequence current during the SLG fault.

- **Interruption**

If the supply voltage or load current decreases to less than 0.1 p.u for a period of time not more than one minute is known as interruption. Interruption can be caused either by system faults, equipment failures or control malfunctions. The interruptions are measured by their duration alone. The duration due to a fault is determined by the operating time of the protective devices. Duration of an interruption due to equipment malfunction can be irregular. Some interruptions may also be caused by voltage sag conditions when there are faults on the source side.

2.3.2 STEADY STATE PHENOMENA

2.3.2.1 Waveform Distortion

This is defined as a steady-state deviation from an ideal sine wave of power frequency. There are five types of waveform distortion:

(a) DC offset

(b) Harmonics

(c) Inter harmonics

(d) Notching

(e) Noise

2.3.2.2 Voltage Imbalance

Voltage imbalance can be defined using symmetrical components. The ratio of the negative sequence or zero sequence component to the positive sequence component is a measure of unbalance. The main cause of voltage unbalance is single phase loads on a three phase circuit which resulting in load imbalance. Severe imbalance can be caused by single-phasing conditions in the system.

2.3.3 VOLTAGE FLUCTUATIONS AND FLICKER

Voltage fluctuations are systematic variations of the voltage or a series of random changes in the voltage magnitude which lies in the range of 0.9 to 1.1p.u. High power loads that draw fluctuating current, such as large motor drives and arc furnaces, cause low frequency cyclic voltage variations that result in flickering of light sources like incandescent and fluorescent lamps which can cause significant physiological discomfort or irritation in human beings. The voltage flicker can also affect stable operation of electrical and electronic devices such as motors and CRT devices. The typical frequency spectrum of voltage flicker lies in the range from 1 Hz to 30 Hz.

2.3.4 POWER FREQUENCY VARIATIONS

Power frequency variations are defined as the deviations of the system frequency from its particular value of 50 or 60 Hz. The variations in the frequency begin from the changes in the load and the response of the generators to meet the load. Thus the load characteristics which dependence on the frequency and the control characteristics of the generators change the shift in the frequency. In current interconnected power systems, frequency variations are insignificant most of the time unless governor and load frequency controls are disabled under a system of power shortages and a lack of grid discipline. Profitable incentives or disincentives that ensure balance between existing generation and load may help control over frequency variations under normal operating conditions. [2]

2.4 SOLUTION OF POWER QUALITY PROBLEMS

For the improvement of power quality there are two approaches. According to first approach the solution to the power quality problems can be done from the utility side. The first approach is called load conditioning, which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line conditioning systems that suppress the power system disturbances. In this approach the compensating device is connect to low and medium voltage distribution system in shunt or in series. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source. Both schemes are implemented preferable with voltage source PWM inverters, with a dc source having a reactive element such as a capacitor. However, with the restructuring of power sector and with shifting trend towards distributed and dispersed generation, the line conditioning systems or utility side solutions will play a major role in improving the inherent supply quality; some of the effective and economic measures can be identified as following:

2.4.1 THYRISTOR BASED STATIC SWITCHES:

The static switch is a versatile device for switching a novel element into the circuit when the voltage support is desired. It has a dynamic response time of about one cycle. To correct rapidly for voltage spikes, sags or interruptions, such static switch can used to switch one or more of devices such as capacitor, filter, alternate power line, energy storage systems etc. The static switch can be used in the alternate power line applications.

2.4.2 ENERGY STORAGE SYSTEMS:

Storage systems can be used to protect sensitive production equipments from shutdown which is caused by voltage sag or temporary interruptions. These are generally DC storage systems such as UPS, batteries, superconducting magnet energy storage (SMES), storage capacitors or even fly wheels driving DC generators are used. The output of these devices can be supplied to the system through an inverter on a momentary basis by a fast performing electronic switch like GTO or IGBT etc. Sufficient energy is fed to the system to compensate for the energy that would be lost by the fault conditions like voltage sag or interruption.

However there are many different methods to mitigate voltage sags and swells, but the use of a custom Power device is considered to be the most efficient method. Flexible AC Transmission Systems (FACTS) for transmission systems, the term custom power pertains to the use of power electronics controllers in a distribution system, particularly, to deal with a variety of power quality problems. Just as FACTS improves the power transfer capabilities and stability limits, custom power makes sure customers get pre-specified quality and reliability of supply. [3], [5].

There are many types of Custom Power devices like Active Power Filters (APF), Battery Energy Storage Systems (BESS), Distribution static synchronous compensators (DSTATCOM), Dynamic Voltage Restorer (DVR), Surge Arresters (SA), Super conducting Magnetic Energy Systems (SMES), Static Electronic Tap Changers (SETC), Solid-State Transfer Switches (SSTS), Solid State Fault Current Limiter (SSFCL), and unified power quality conditioner (UPQC).

CHAPTER 3

CUSTOM POWER DEVICES

3.1 INTRODUCTION

Initially for the improvement of power quality or reliability of the system FACTS devices like static synchronous compensator (STATCOM), static synchronous series compensator (SSSC), interline power flow controller (IPFC), and unified power flow controller (UPFC) etc are introduced. These FACTS devices are designed for the transmission system. But now a day as more attention is on the distribution system for the improvement of power quality, these devices are modified and known as custom power devices. The term "custom power" describes the value-added power that electric utilities will offer to their customers. The value addition involves the application of high power electronic controllers to distribution systems, at the supply end of industrial, commercial consumers.

The main custom power devices which are used in distribution system for power quality improvement are distribution static synchronous compensator (DSTATCOM), dynamic voltage Restorer (DVR), active filter (AF), unified power quality conditioner (UPQC) etc. N.G Hingorani [5] was the first to propose FACTS controllers for improving PQ. He termed them as Custom Power Devices (CPD). These are based on VSC and are of 3 types given below.

1. Shunt connected Distribution STATCOM (DSTATCOM)
2. Series connected Dynamic Voltage Restorer (DVR)
3. Combined shunt and series, Unified Power Quality Conditioner (UPQC).

The DVR is similar to SSSC while UPQC is similar to UPFC. In spite of the similarities, the control techniques are quite different for improving PQ. A major difference involves the injection of harmonic currents and voltages to separate the source from the load. A DVR can work as a harmonic isolator to prevent the harmonics in the source voltage reaching the load in addition to balancing the voltages and providing voltage regulation. A UPQC can be considered as the combination of DSTATCOM and DVR. A DSTATCOM is utilized to eliminate the harmonics from the source currents and also balance them in addition to providing reactive power compensation to improve power factor or regulate the load bus voltage.

Several power providers have installed custom power devices for mitigating power quality problems. In particular, three major power quality devices (PQDs)—an advanced static VAR compensator, a dynamic voltage restorer, and a high-speed transfer switch are used these days. Over the past ten years, advanced power electronic devices have been the center of various research studies, installation projects, and development technologies.

By custom power devices, we refer to power electronic static controllers used for power quality development on distribution systems rated 1 through 38 kV. This interest in the usage of power quality devices (PQDs) arises from the need of mounting power quality levels to meet the everyday growing sensitivity of consumer needs and expectations [4]. Power quality levels, if not achieved, can cause costly downtimes and customer dissatisfaction. According to contingency planning research company's annual study [5], downtime caused by power disturbances results in major financial losses. In order to face these new needs, advanced power electronic devices have developed over the last years. Their performance has been demonstrated at medium distribution levels, and most are available as commercial products [6], [7].

3.2 NEED OF CUSTOM POWER DEVICES

Power quality is one of major concerns in the present era. Distribution system locates the end of power system and is connected to the customer directly, so the reliability of power supply mainly depends on distribution system. It has become important, especially, with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply. Power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure of end use equipments. The electrical distribution network failures account for about 90% of the average customer interruptions. As the customer's demand for the reliability of power supply is increasing day by day, so the reliability of the distribution system has to be increased. One of the major problems dealt here is the power sag. Power distribution systems, ideally, should provide their customers with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency. However, in practice, power systems, especially the distribution system, have numerous nonlinear loads, which significantly affect the quality of power supplies. As a result of the nonlinear loads, the purity of the waveform of supplies is lost. This ends up producing many power quality problems. While power disturbances occur on all electrical systems, the sensitivity of today's sophisticated electronic devices makes them more disposed to the quality of power supply. For some sensitive devices, a temporary disturbance can cause scrambled data, interrupted communications, a frozen mouse, system crashes and equipment failure etc. A power voltage spike can damage valuable components.

To solve this problem, custom power devices are used. One of those devices is the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. Its appeal includes lower cost, smaller size, and its fast dynamic response to the disturbance.

3.3 CONFIGURATIONS

The compensating type custom power devices can be classified on the basis of different topologies and the number of phases. For power quality improvement the voltage source inverter (VSI) bridge structure is generally used for the development of custom power devices, while the use of current source inverter (CSI) is less reported. The topology can be shunt (DSTATCOM), series (DVR), or a combination of both (UPQC).

3.3.1 CONVERTER BASED CLASSIFICATION

For the development of compensating type custom power devices the VSI is used usually, because of self-supporting dc voltage bus with a large dc capacitor, while the use of CSI is less reported. The current source inverter topology finds it application for the development of active filters, DSTATCOM and UPQC. The voltage source inverter topology is popular because it can be expandable to multilevel, multi-step and chain converters to enhance the performance with lower switching frequency and increased power handling capacity. In addition to this, this topology can exchange a considerable amount of real power with energy storage devices in place of the dc capacitor.

3.3.2 TOPOLOGY BASED CLASSIFICATION

Compensating type custom power devices can be classified based on the topology used as shunt (DSTATCOM), series (DVR) and combination of both series and shunt (UPQC). DSTATCOM is most widely used for power factor correction, to eliminate current based distortion and load balancing, when connected at the load terminals. DVR can perform voltage regulation when connected to a distribution bus.

1. DSTATCOM

A DSTATCOM is a custom power device which is utilized to eliminate the harmonics from the source currents and also balance them in addition to providing reactive power compensation to improve power factor or regulate the load bus voltage.

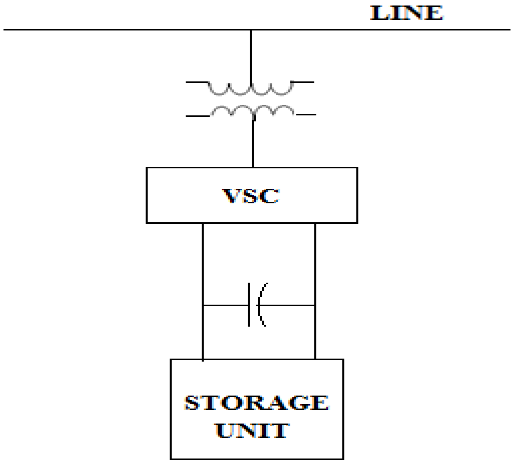

Figure-3.1 Distribution Shunt connected STATCOM

2. DVR (DYNAMIC VOLTAGE RESTORER)

A DVR is a custom power device which can work as a harmonic isolator to prevent the harmonics in the source voltage reaching the load in addition to balancing the voltages and providing voltage regulation.

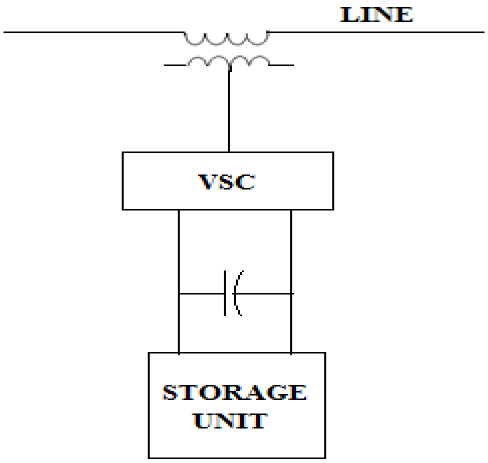

Figure-3.2 Series connected dynamic voltage restorer

3. UPQC(Unified Power Quality Conditioner)

A UPQC is also a custom power device which can be considered as the combination of DSTATCOM and DVR.

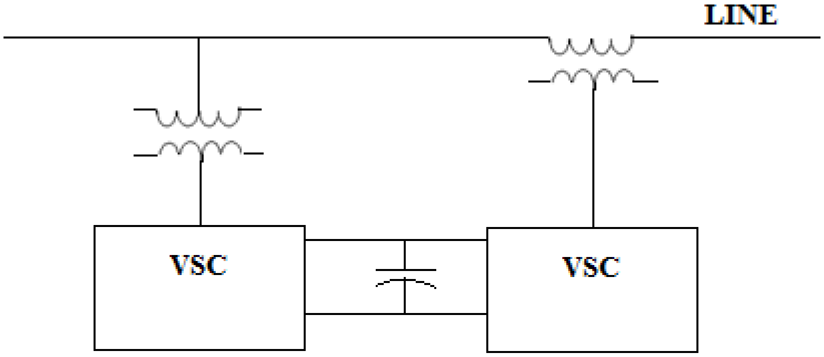

Figure-3.3 Unified power quality Conditioner

3.3.3 SUPPLY SYSTEM BASED CLASSIFICATION

This classification of compensating devices is based on the supply and/or the load system having single-phase (two wire) and three-phase (three-wire or four-wire) systems. There are many nonlinear loads, such as domestic appliances, connected to single-phase supply systems. Some three-phase nonlinear loads are without neutral, such as ASD's, fed from three-wire supply systems. There are many nonlinear single-phase loads distributed on four-wire three-phase supply systems, such as computers, commercial lighting, etc. Hence, compensating devices may also be classified accordingly as two-wire, three wire, and four-wire types [11].

3.4 BENEFITS WITH THE APPLICATION OF CUSTOM POWER DEVICES.

The custom power devices such as DVR, DSTATCOM, UPQC, etc are used to increase the reliability of the distribution system by providing voltage support at critical buses in the system (with series connected controllers) and regulate power flow in critical lines (with shunt connected controllers like DSTATCOM. Both voltage and power flow are controlled by the combined series and shunt controller which is known as UPQC. As we know that the power electronic control is quite fast and this enables regulation both under steady state and dynamic conditions as compared to other controllers when the system is subjected to disturbances. The benefits due to custom power devices are listed below.

1. The power flow in critical lines can be improved as the operating margins can be reduced by fast controllability.
2. The power carrying capacity of lines can be increased to values up to the thermal limits by imposed by current carrying capacity of the conductors).
3. The transient stability limit is improved thereby improving dynamic security of the system and reducing the incidence of blackouts caused by cascading outages.
4. They contribute to best possible system operation by improving voltage profile and reducing power losses.
5. The steady state or small signal stability region can be increased by providing auxiliary stabilizing controllers to damp low frequency oscillations.
6. FACTS controllers such as TCSC can counter the problem of Sub synchronous Resonance (SSR) experienced with fixed series capacitors connected in lines evacuating power from thermal power stations (with turbo generators).
7. The problem of voltage fluctuations and in particular, dynamic over voltages can be overcome by these controllers [3],[4].
8. The problem of starting voltage dip in case of industrial loads like induction motor can also be reduced by these devices.

CHAPTER 4

DYNAMIC VOLTAGE RESTORER

4.1 INTRODUCTION

Among the power quality problems like sag, swell, harmonic etc, voltage sag is the most severe disturbances in the distribution system. To overcome these problems the concept of custom power devices is introduced lately. One of those devices is the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks.

DVR is a recently proposed series connected solid state device that injects voltage into the system in order to regulate the load side voltage. It is generally installed in a distribution system between the supply and the critical load feeder at the point of common coupling (PCC). Other than voltage sags and swells compensation, DVR can also added other features like line voltage harmonics compensation, reduction of transients in voltage and fault current limitations.

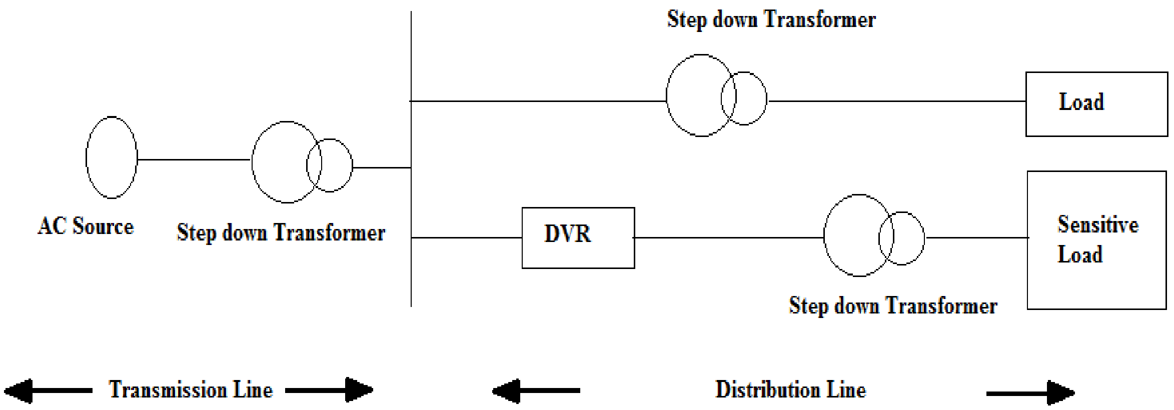

Figure-4.1 Location of DVR

4.2 PRINCIPLE OF DVR OPERATION

A DVR is a solid state power electronics switching device consisting of either GTO or IGBT, a capacitor bank as an energy storage device and injection transformers. It is linked in series between a distribution system and a load that shown in Figure 4.2. The basic idea of the DVR is to inject a controlled voltage generated by a forced commuted converter in a series to the bus voltage by means of an injecting transformer. A DC to AC inverter regulates this voltage by sinusoidal PWM technique. All through normal operating condition, the DVR injects only a small voltage to compensate for the voltage drop of the injection transformer and device losses. However, when voltage sag occurs in the distribution system, the DVR control system calculates and synthesizes the voltage required to preserve output voltage to the load by injecting a controlled voltage with a certain magnitude and phase angle into the distribution system to the critical load [18].

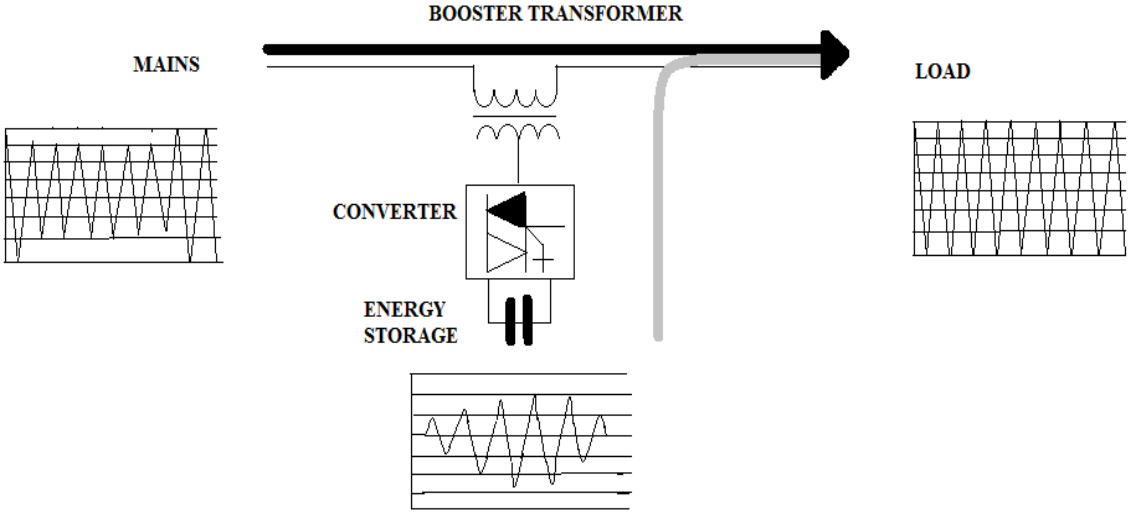

Figure-4.2 Principle of DVR system

Note that the DVR capable of generating or absorbing reactive power but the active power injection of the device must be provided by an external energy source or energy storage system. The response time of DVD is very short and is limited by the power electronics devices and the voltage sag detection time. The predictable response time is about 25 milliseconds, and which is much less than some of the traditional methods of voltage correction such as tap-changing transformers [17].

4.3 BASIC ARRANGEMENT OF DVR

The DVR mainly consists of the following components:

i. An Injection transformer

ii. DC charging unit

iii. Storage Devices

iv. A Voltage Source Converter (VSC)

v. Harmonic filter

vi. A Control and Protection system

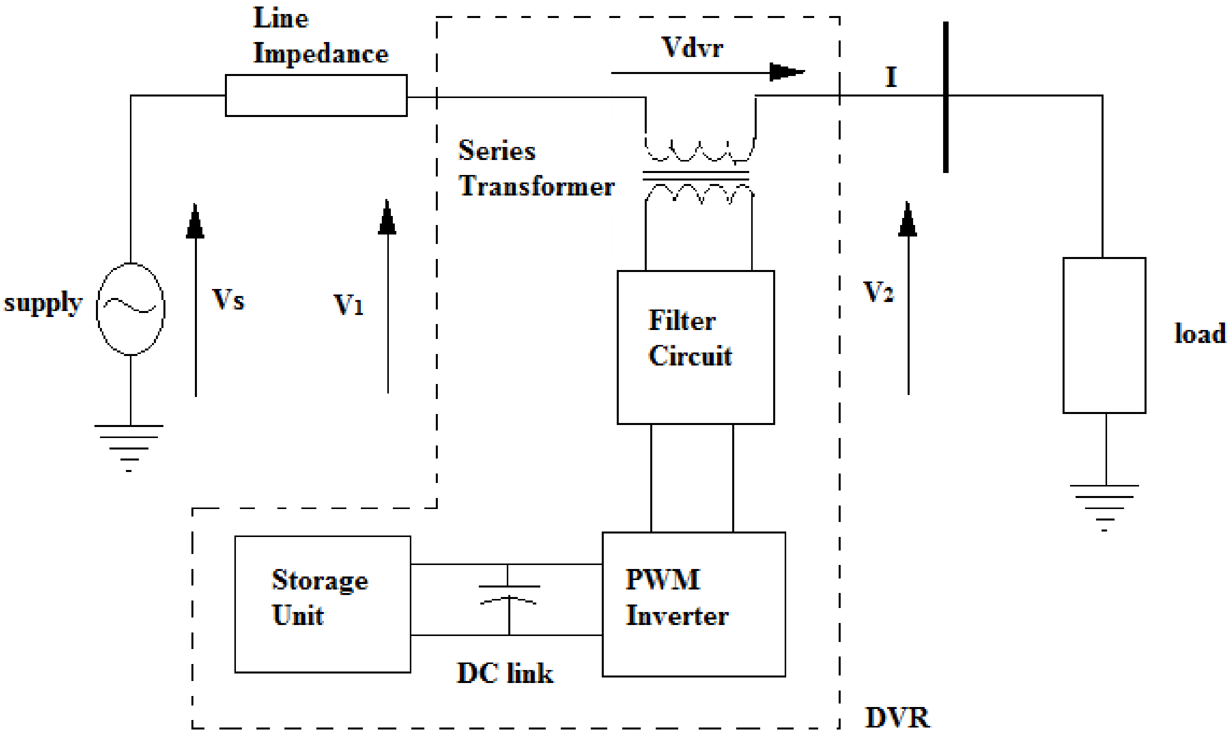

Figure-4.3 Schematic diagram of DVR

4.3.1 INJECTION TRANSFORMER

Three single phase transformers are connected in series with the distribution feeder to couple the VSC (at the lower voltage level) to the higher distribution voltage level. It links the DVR system to the distribution network via the HV-windings and transforms and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage. In addition, the Injection transformer also serves the purpose of isolating the load from the DVR system (VSC and control mechanism).

4.3.2 DC CHARGING UNIT

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

4.3.3 VOLTAGE SOURCE CONVERTER

A VSC is a power electronic system consists of a storage device and switching devices, which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle. It could be a 3 phase - 3 wire VSC or 3 phase - 4 wire VSC. Either a conventional two level converter or a three level converter is used. For DVR application, the VSC is used to momentarily replace the supply voltage or to generate the part of the supply voltage which is absent. There are four main types of switching devices: Metal Oxide Semiconductor Field Effect Transistors (MOSFET), Gate Turn-Off thyristors (GTO), Insulated Gate Bipolar Transistors (IGBT), and Integrated Gate Commutated thyristors (IGCT). Each type has its own benefits and drawbacks. The IGCT is a recent compact device with enhanced performance and consistency that allows building VSC with very large power ratings. The function of storage devices is to supply the required energy to the VSC via a dc link for the generation of injected voltages. The different kinds of energy storage devices are Superconductive magnetic energy storage (SMES), batteries and capacitance.

4.3.4 HARMONIC FILTER

As DVR consist of power electronic devices, the possibility of generation self harmonics is there so harmonic filter is also become a part of DVR. The main task of harmonic filter is to keep the harmonic voltage content generated by the VSC to the acceptable level.

4.3.5 CONTROL AND PROTECTION

A controller is also used for the proper operation of the DVR system. Load voltage is sensed and passed through a sequence analyzer. The magnitude of load voltage is compared with reference voltage. Pulse width modulated (PWM) control technique is applied for inverter switching so as to generate a three phase 50 Hz sinusoidal voltage at the load terminals[20]. Chopping frequency is set aside in the range of a few KHz. PI controller is used with the IGBT inverter to maintain 1 p.u. voltage at the load terminals. The controller used in the test models shown in chapter 5 is PI controller. Controller input is an actuating signal which is the difference between the V_{ref} (reference voltage) and V_{in} (actual voltage). An advantage of a proportional plus integral controller is that its integral term causes the steady-state error to be zero for a step input [19]. Output from the controller block is in the form of an angle δ that is used to establish an additional phase-lag/lead in the three-phase voltages.

All protective functions of the DVR should be implemented in the software. Differential current protection of the transformer, or short circuit current on the customer load side are only two examples of protection functions possibility [20].

4.4 EQUATIONS RELATED TO DVR

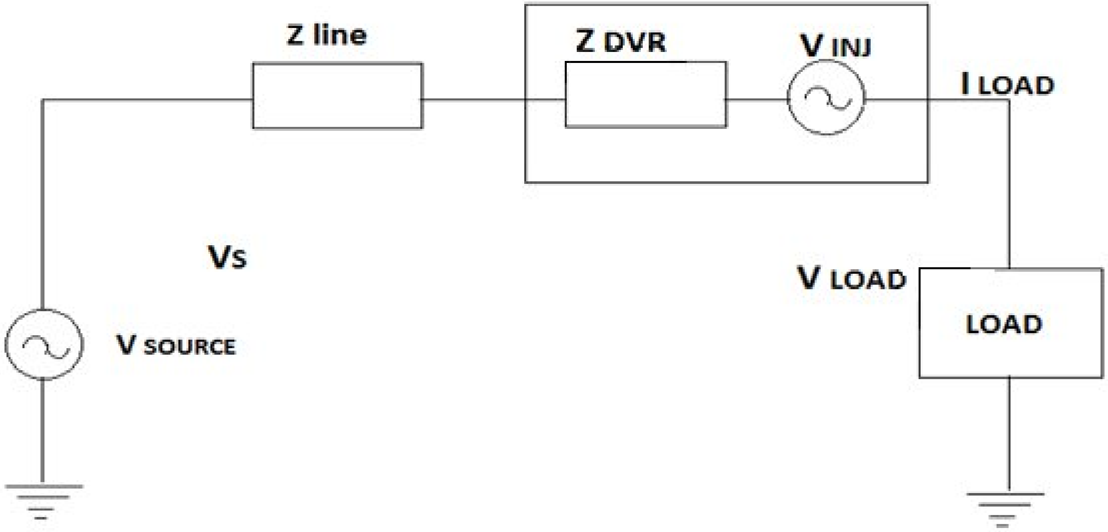

Figure-4.4 Equivalent circuit diagram of DVR

Here the impedance Z_{LINE} depends on the fault level of the load. When the system voltage (V_{SOURCE}) drops or reduced from any specific value, the DVR injects a series voltage i.e. V_{DVR} through the injection transformer such that the desired load voltage V_{LOAD} can be maintained. Now the injected voltage of the DVR can be written as

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

Where

V_{LOAD} = desired load voltage

Z_{LINE} = Line impedance

I_{LOAD} = Load current

V_{SOURCE} = system voltage during any fault condition

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

The load current I_L is given by,

$$I_L = \frac{[P_L + jQ_L]}{V}$$

When V_L is considered as a reference equation can be rewritten as,

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

$\propto$, β, δ are angles of V_{DVR}, Z_{TH}, V_{TH} respectively and θ is Load power angle

$$\theta = \tan^{-1}\theta\frac{Q_L}{P_L}$$

The complex power injection of the DVR can be written as,

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

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

4.5 OPERATING MODES OF DVR

The DVR is designed to inject a dynamically controlled voltage i.e. $V_{DVR,}$ which is generated by a forced commutated converter. This voltage is injected in series to the bus voltage by means of an injection transformer. The momentary amplitudes of the three injected phase voltages are controlled such as to remove any harmful effects of a bus fault to the load voltage V_L. This means that any differential voltages caused by transient disturbances in the ac feeder will be compensated by a equivalent voltage generated by the converter and injected on the medium voltage level through the injection transformer. The DVR has three modes of operation which are: protection mode, standby mode, injection/boost mode [16].

In protection mode, if the current on the load side exceeds a tolerable limit due to any fault or short circuit on the load, DVR will isolate from the system. In standby mode the voltage winding of the injection transformer is short circuited through converter.

In the Injection/Boost mode the DVR is injecting a compensating voltage through the injection transformer due to the detection of a disturbance in the supply voltage.

4.6 VOLTAGE INJECTION METHODS OF DVR

The voltage injection or compensation methods by means of a DVR mainly depend upon the limiting factors such as; DVR power ratings, different conditions of load, and different types of voltage sag [15].

There are different methods of DVR voltage injection which are
i. Pre-sag compensation method
ii. In-phase compensation method
iii. In-phase advanced compensation method

4.6.1 PRE SAG COMPENSATION

The supply voltage is always tracked and the load voltage is compensated to the pre-sag condition. This scheme results in undisturbed load voltage, but normally requires higher rating of the DVR. Before a sag occur, $V_S = V_L = Vo$. Here V_S is supply voltage, V_L is load voltage and V_O is pre sag voltage. The voltage sag results in drop in the magnitude of the supply voltage to V_{S1}. The phase angle of the supply also may shift (see Figure-4.5). The DVR injects a voltage

V_{C1} such that the load voltage ($V_L = V_{S1} + V_{C1}$) remains at Vo i.e. pre sag voltage (both in magnitude and phase). It is claimed that some loads are sensitive to phase jumps and it is essential to compensate for both the phase jumps and the voltage sags.

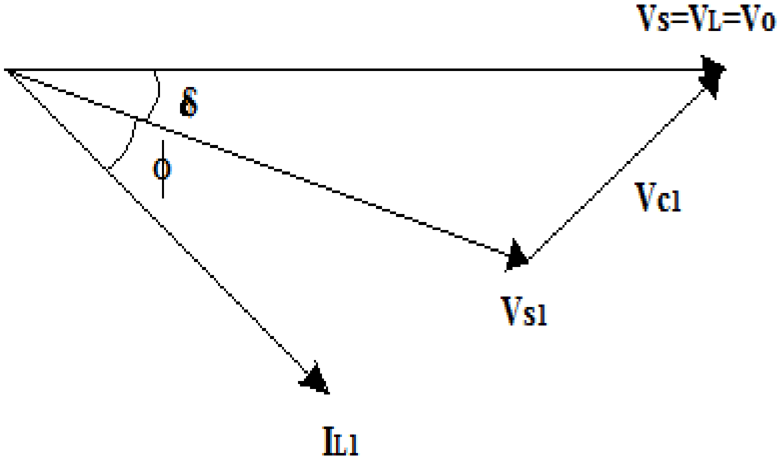

Figure-4.5 Phasor diagram showing injected voltage by DVR

4.6.2 IN PHASE COMPENSATION

The voltage which is injected by the DVR is always in phase with the supply voltage in spite of the load current and the pre-sag voltage (Vo). This control strategy results in the minimum value of the injected voltage (magnitude). However, the phase of the load voltage is disturbed. For loads which are not sensitive to the phase jumps, this control strategy results in optimum utilization of the voltage rating of the DVR. The power requirements for the DVR are not zero for this approach.

4.6.3 IN PHASE ADVANCED COMPENSATION

In this method the real power which is injected by the DVR is reduced by reducing the power angle between the voltage during sag condition and load current. The minimization of injected energy is achieved by making the active power component zero by having the injection voltage phasor perpendicular to the load current phasor. In this technique the values of load current and voltage are fixed in the system so only the phase of the voltage during sag is changed. This technique is only appropriate for a limited range of sag because this technique uses only reactive power and unfortunately, but al1 the sags cannot be mitigated without real power.

4.6.4 MINIMUM ENERGY INJECTION

In this injection method the injected voltage is in quadrature with load current. The power requirements of DVR are zero if the injected voltage by DVR is in quadrature with load current, neglecting losses. Minimum energy compensation strategy which considers the voltage limitation could control the active power exchange between DVR and the external system. The compensation capability of DVR could be maintained by the strategy not only when the injection voltage is under the voltage limitation but also when the injection voltage is above the voltage limitation. Both magnitude and phase control can be achieved by small or minimum energy injection.

CHAPTER 5

DVR TEST MODELS

5.1 DYNAMIC VOLTAGE RESTORER WITH PI CONTROLLER

5.1.1 INTRODUCTION

A dynamic voltage restorer (DVR) is a custom power device used to correct the voltage sag by injecting voltage as well power into the system. The mitigation capacity of DVR is generally influenced by the maximum load; power factor and maximum voltage dip to be compensated. The DVR is to transfer the voltage which is required for the compensation from DC side of the inverter to the injected transformer after filter**.** The compensation capacity of a particular DVR depends on the maximum voltage injection capability and the active power that can be supplied by the DVR. When DVR's voltage disturbance occurs, active power or energy should be injected from DVR to the distribution system. A DC system, which is linked to the inverter input, contains a large capacitor for storage energy. It provides reactive power to the load during faulty conditions. When the energy is drawn from the energy storage capacitors, the capacitor terminal voltage reduces. Therefore, there is a minimum voltage required below which the inverter of the DVR cannot generate the require voltage thus, size and rating of capacitor is very important for DVR power circuit. The DC capacitor value for a three phase system can be derived. The most important advantage of these capacitors is the potential to supply high current pulses repetitively for hundreds of thousands of cycles. Selection of capacitor rating is discussed on the basis of RMS value of a capacitor current, rated voltage of a capacitor and VA rating of the capacitor [18].

5.2 CONTROL PHILOSOPHY

A controller is required to control or to operate DVR during the fault conditions only. Load voltage is sensed and passed through a sequence analyzer. The magnitude of the actual voltage is compared with reference voltage (V_{ref}). Pulse width modulated (PWM) control system is applied for inverter switching so as to generate a three phase 50 Hz sinusoidal voltage at the load terminals. Chopping frequency is in the range of a few KHz. The IGBT inverter is controlled with PI controller in order to maintain 1p.u voltage at the load terminals. An advantage of a proportional plus integral controller is that its integral term causes the steady-state error to be zero for a step input. PI controller input is an actuating signal which is the difference between the V_{ref} and V_{in}. Output of the controller block is of the form of an angle δ, which introduces additional phase-lag/lead in the three-phase voltages. [20] The output of error detector is V_{ref} - V_{in}. Where V_{ref} equal to 1 p.u. voltage and V_{in} voltage in p.u. at the load terminals The controller output when compared at PWM signal generator results in the desired firing sequence.

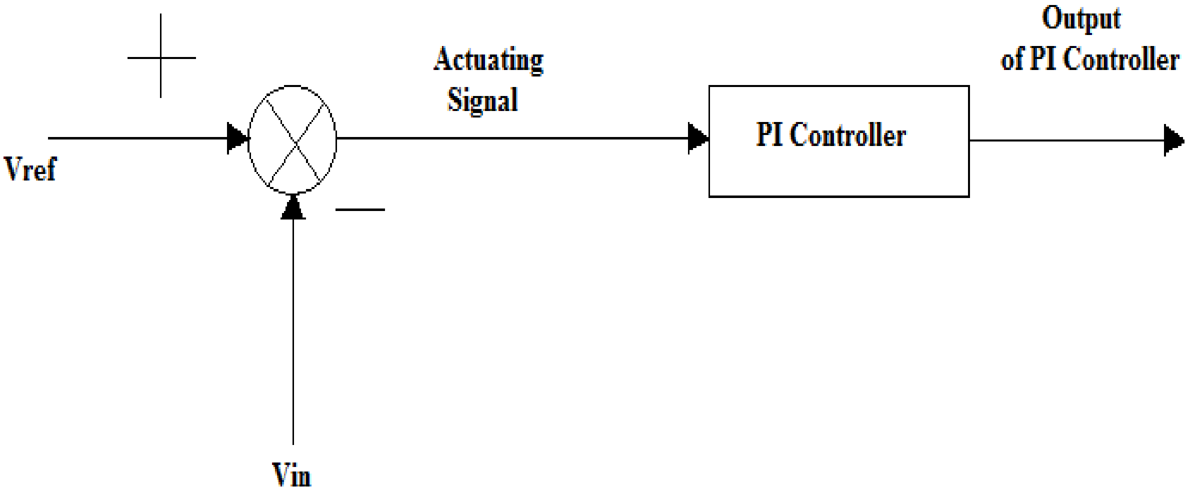

Figure-5.1 Schematic of a typical PI Controller

5.3 PARAMETERS OF DVR TEST SYSTEM

The test system employed to take out the simulations regarding the DVR actuation. This system is composed by a 13 KV, 50 Hz generation system, represented by a Thevenin's equivalent, feeding two transmission lines through a three winding transformer connected in Y/Δ/Δ 13/115/115 kV. Such transmission lines feed two distribution networks through two transformers connected in Δ/Y, 115/11 kV.

Table-5.1: System Parameters

Sr. No	System Quantities	Standards
1	Source	3-phase, 13kV, 50Hz
2	Inverter parameters	IGBT based,3 arms ,6Pulse, Carrier Frequency=1080 Hz , Sample Time= 5 µs
3	PI controller	Kp=0.5,Ki=30, Sample time=50 µs
4	RL load	Active power = 1KW ,Inductive Reactive Power=500 VAR
5	Motor load	Voltage V_{rms}=460V, Frequency 50Hz
6	Three winding Transformer	Y/Δ/Δ 13/115/115kv
7	Two winding Transformer	Δ/Y 115/11kv

5.3.1 SINGLE LINE DIAGRAM OF THE DVR TEST SYSTEM

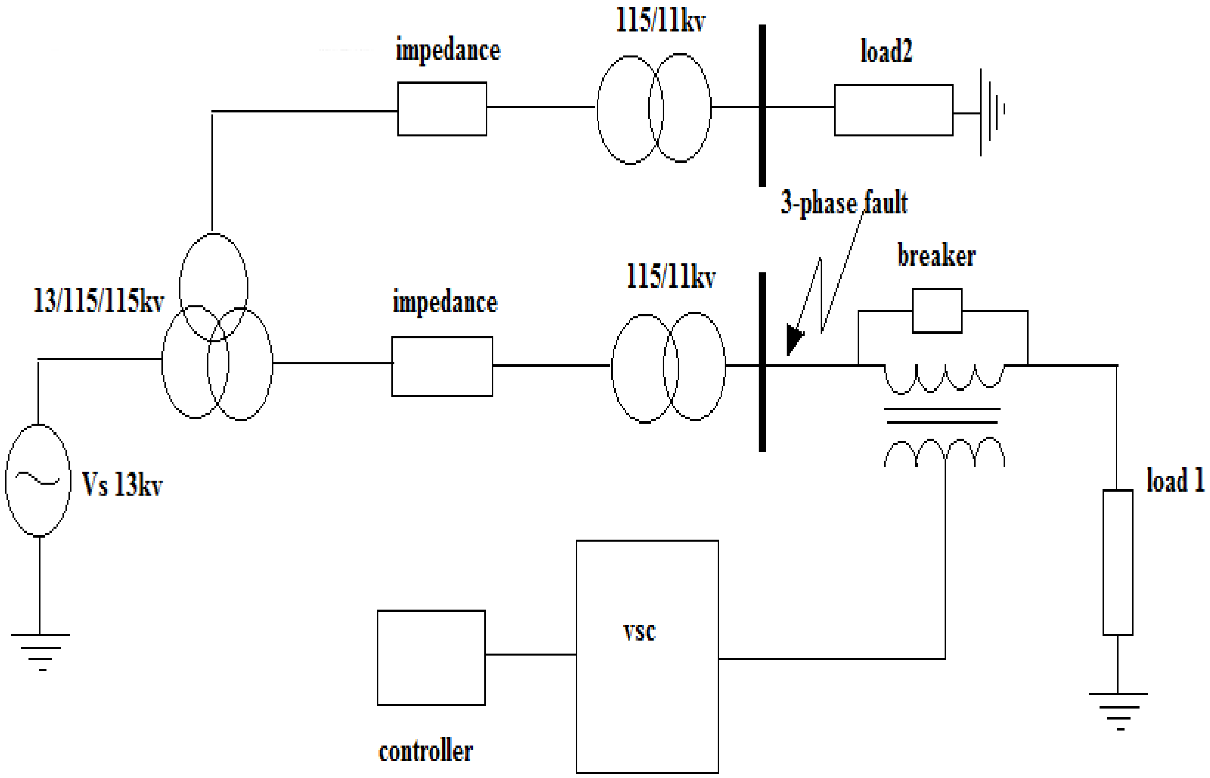

Fig.5.2 Circuit Model of DVR Test System

In this test system we have a generating unit of 13kv, 50 Hz. The test system employed to carry out the simulations concerning the DVR actuation. The output from generating unit is fed to the primary of the three winding transformer. Further two parallel feeders of 11kv each are drawn. In one of the feeder DVR is connected in series and other feeder is kept as it is. For this system two different loads are considered one by one with different fault conditions. The two loads are linear load and induction motor load. PI controller is used for the control section.

5.4 SIMULINK MODEL OF THE TEST SYSTEM WITH LINEAR LOAD

In this simulink model we have a system in which two parallel feeders are shown. In both the feeders further loads are also connected in parallel. In one feeder DVR is connected in series with line and the other feeder is kept as it is. PI controller is used for the control purpose. Here DVR system is connected to the distribution system using a booster transformer.

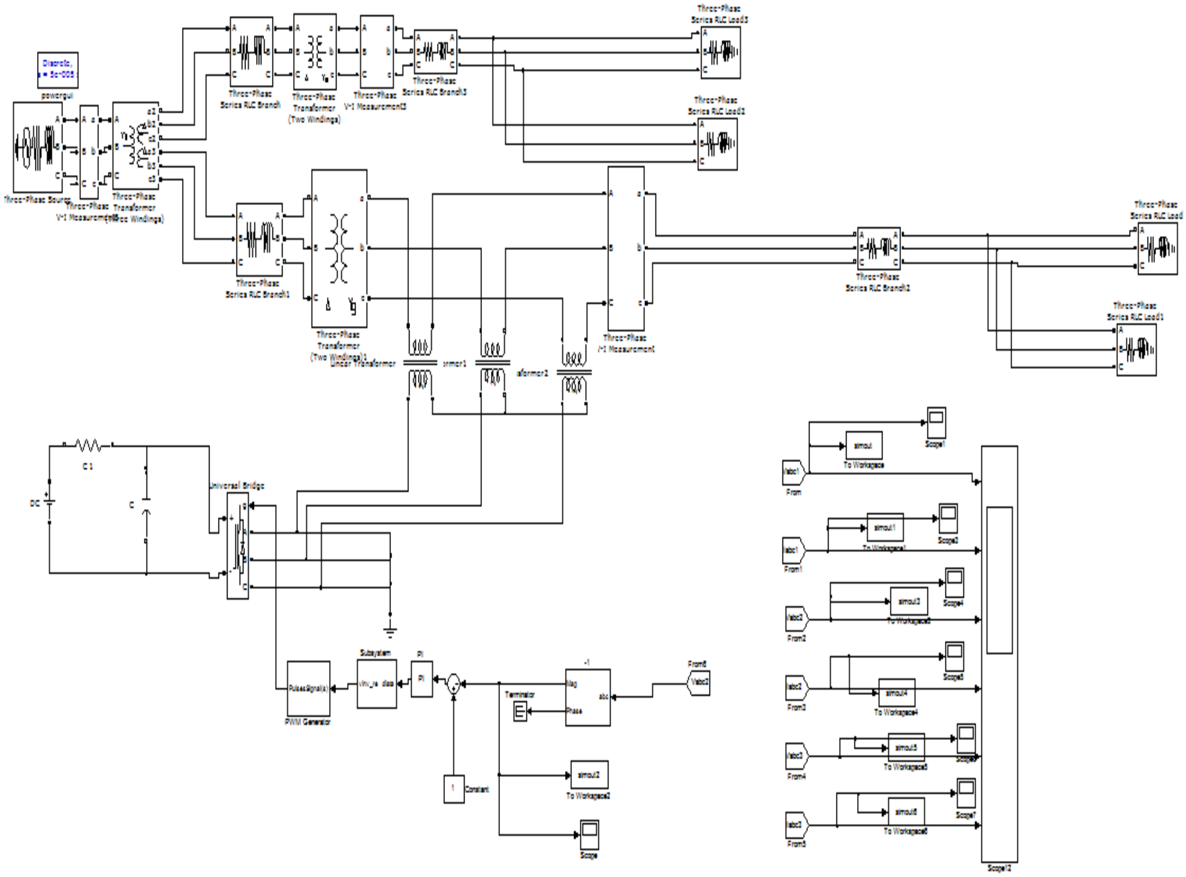

Figure-5.3 simulink model

Result for the above system in which no fault is created is given below. The output voltage for both the conditions with DVR and without DVR is same. The first two wave shapes in figure-5.4 represent input voltage and current with respect to time. The next two wave shapes are for load voltage and load current where DVR is connected. The last two wave shapes represents uncompensated load voltage and load current.

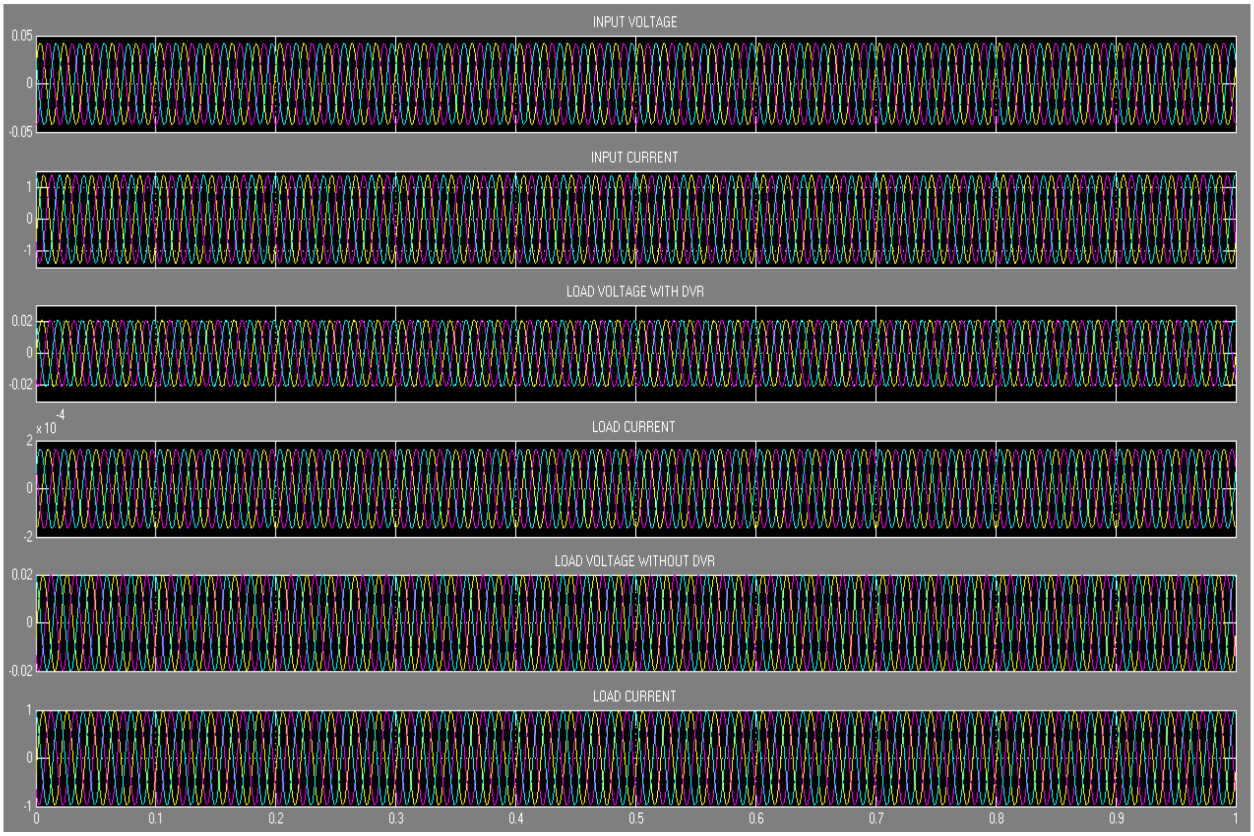

Figure-5.4 output for a normal system

5.4.1 SIMULINK MODEL OF THE PROPOSED SYSTEM WITH SINGLE PHASE GROUND FAULT CONDITION.

In this model a single phase line to ground fault is created in both the feeders. Here the fault resistance is 0.66 ohms and the ground resistance is 0.001 ohms. The fault time is 0.4s to 0.6s. The result of the load voltage in both feeders (with DVR and without DVR) for the above system is given below.

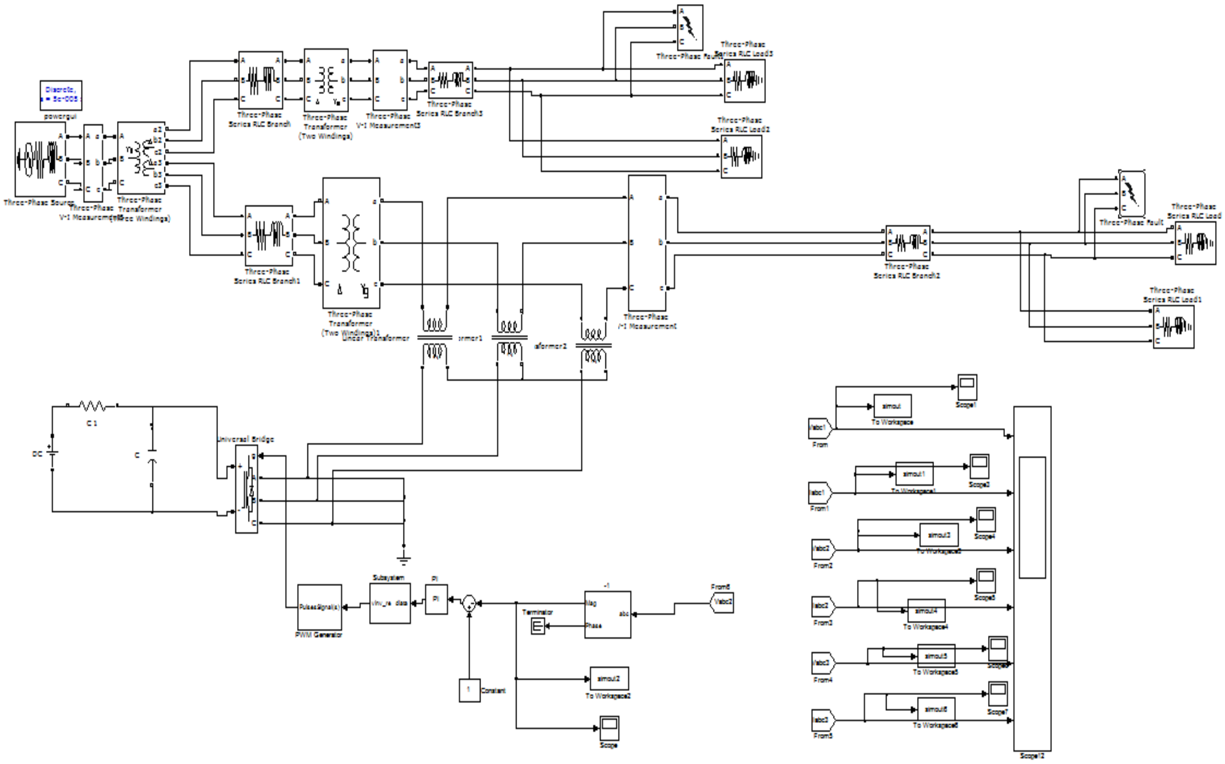

Figure-5.5: Simulink Model with single line to ground fault

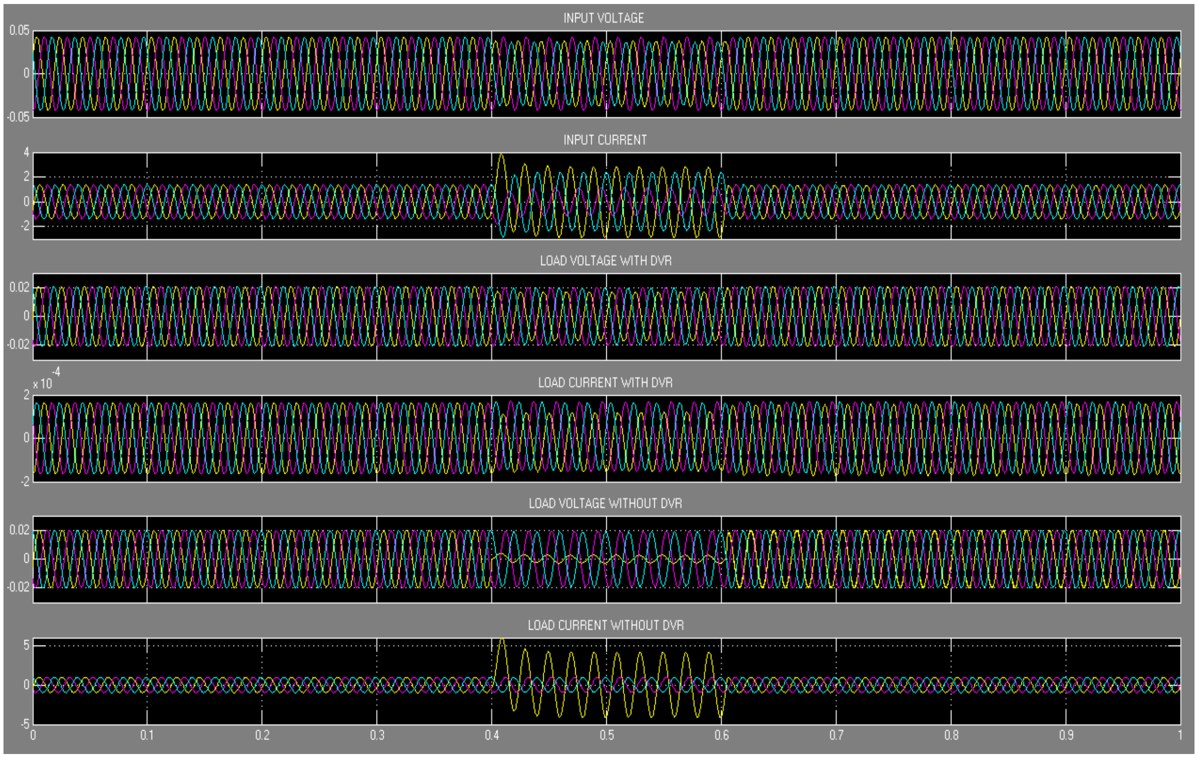

Figure-5.6: Output results for single line to ground

Now here, the wave shapes of both the load voltages i.e. without DVR and with DVR are compared.

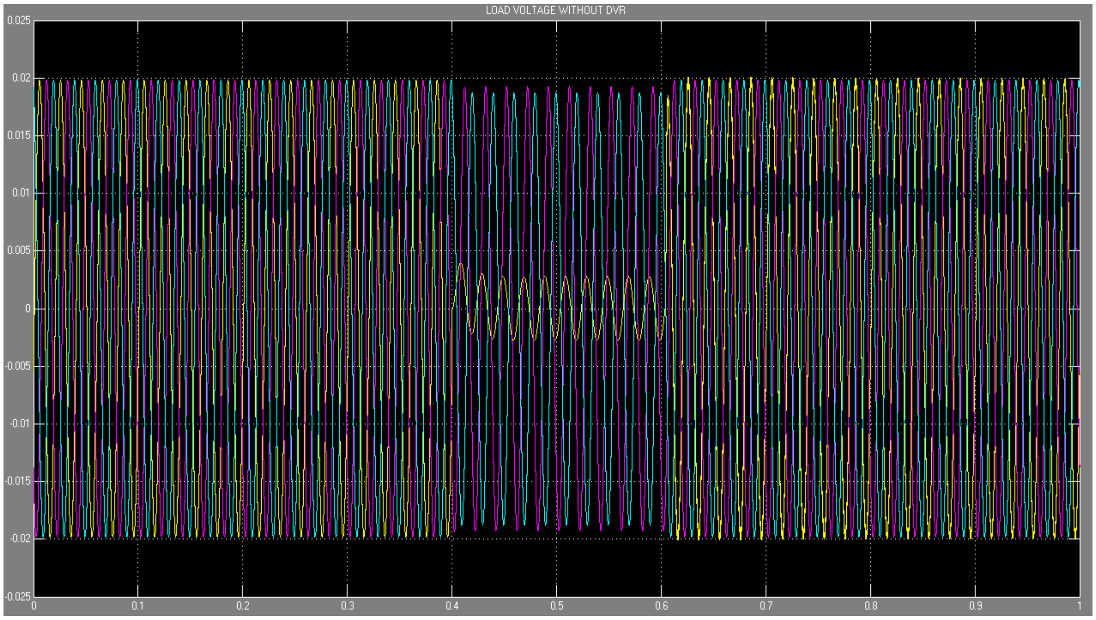

Figure-5.7: Load voltage without DVR

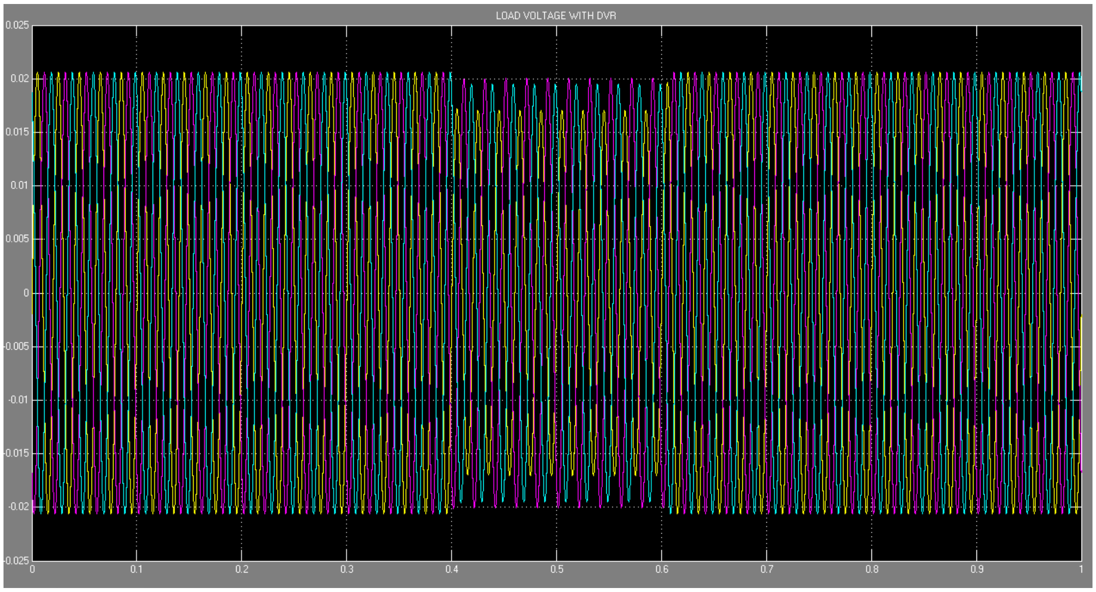

Figure-5.8: Load voltage with DVR

It is clear from the above wave shapes of the load voltages that the amount of unbalance in load voltage in that feeder where DVR is connected is compensated to large extent for single line to ground fault in the distribution network.

5.4.2 SIMULINK RESULTS OF PROPOSED SYSTEM WITH DOUBLE LINE TO GROUND FAULT CONDITION.

In this model a double line to ground fault is created in both the feeders. Here the fault resistance is 0.66 ohms and the ground resistance is 0.001 ohms. The fault time is 0.4s to 0.6s. The results of the load voltage in both feeders (with DVR and without DVR) for the above system are given below.

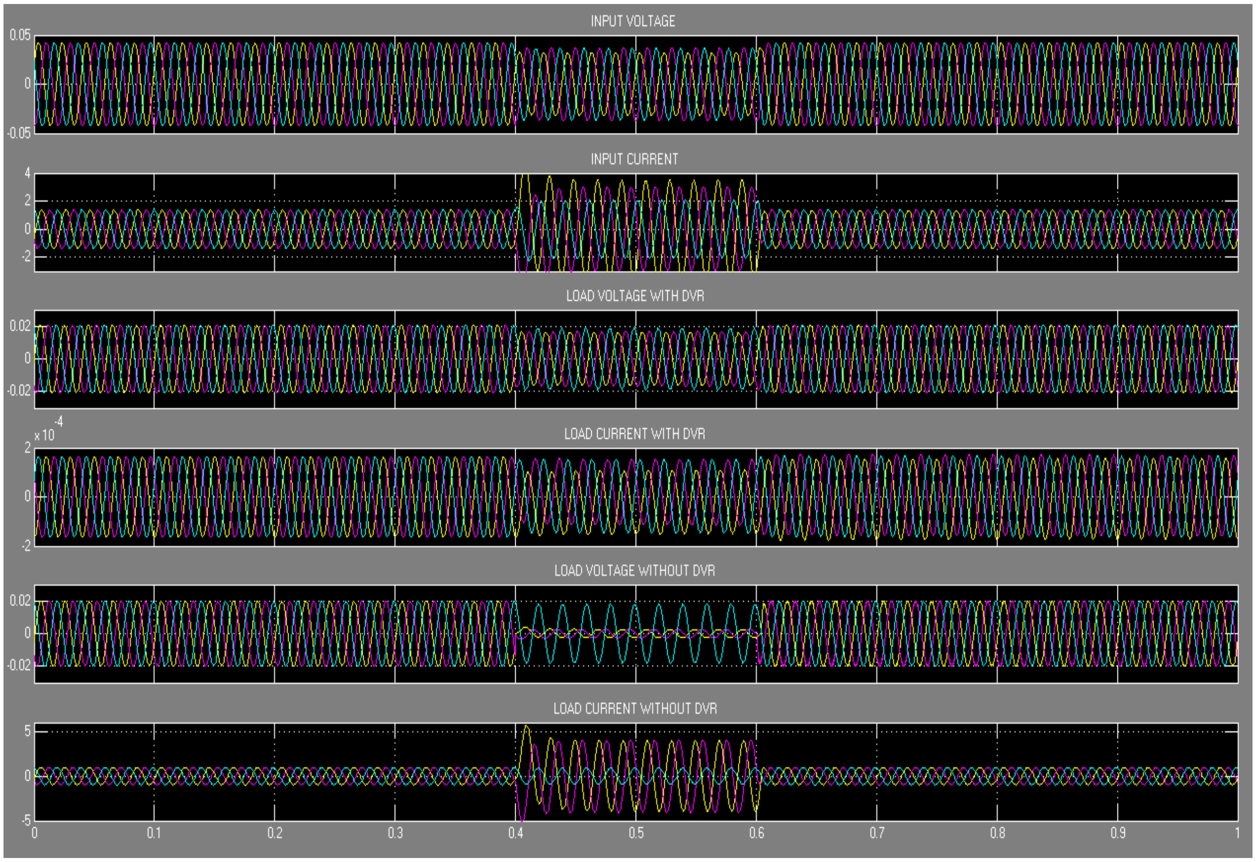

Figure-5.9: Output result for double line to ground fault condition

Now from the above result we can easily compare the wave shape of load voltage of both the feeders. The wave shape that the amount of unbalance in load voltage in that feeder where DVR is connected is compensated to large extent for double line to ground fault in the distribution network. The wave shapes for both the load voltages (with and without DVR) are given below.

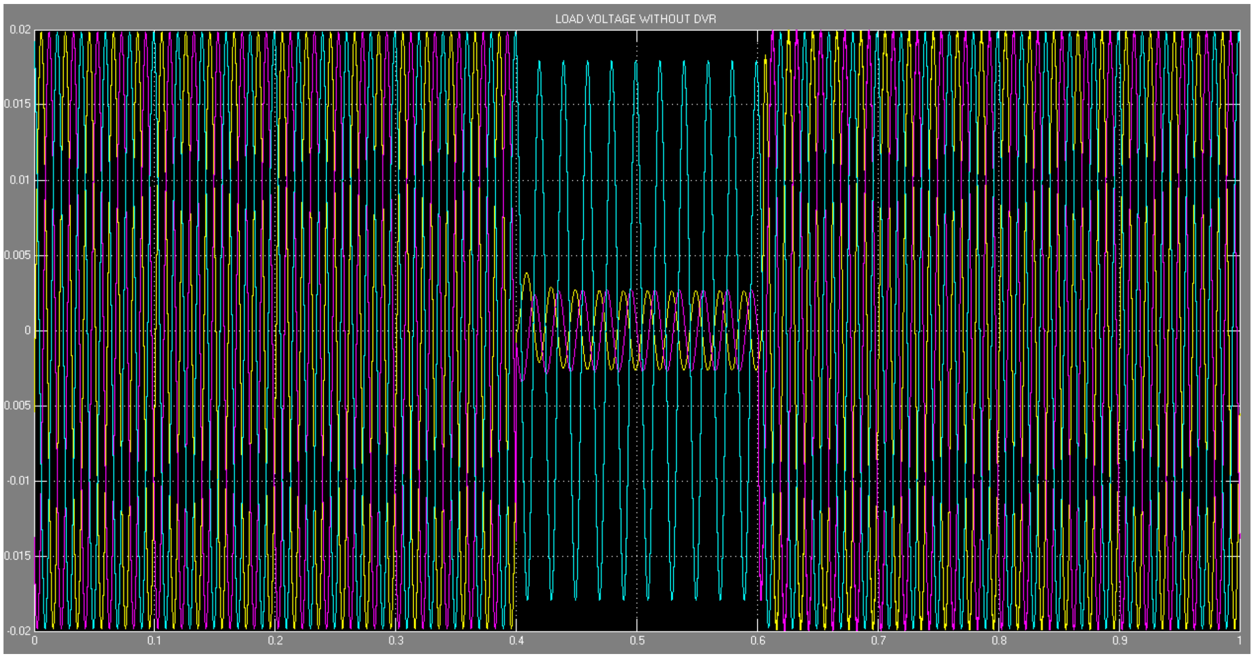

Figure-5.10: Load voltage without DVR

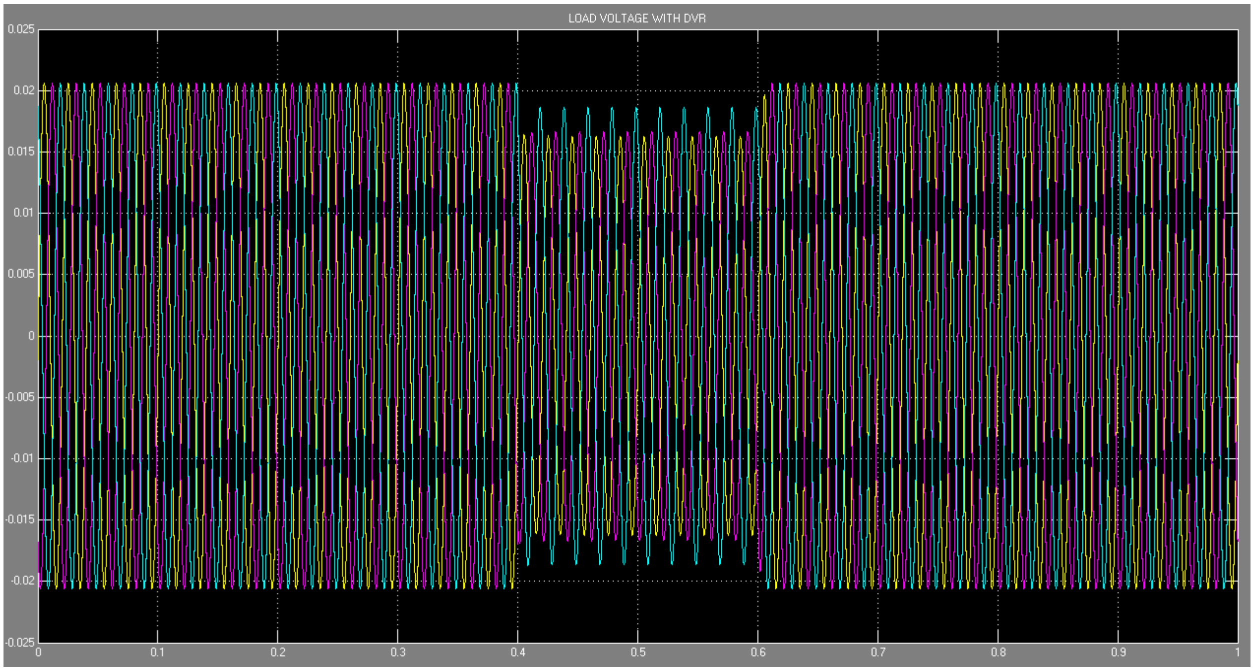

Figure-5.11: Load voltage with DVR

It is clear from the above wave shapes of the load voltages that the amount of unbalance in load voltage in that feeder where DVR is connected is compensated to large extent for double line to ground fault condition.

5.4.3 SIMULINK RESULTS OF PROPOSED SYSTEM WITH CONDITION OF VOLTAGE SAG

In this system voltage dip is introduce in the system in both the feeders for the duration of 0.4s to 0.6s using three phase to ground fault with fault resistance is 0.66 ohms and the ground resistance is 0.001 ohms. The output results for the above system are shown below.

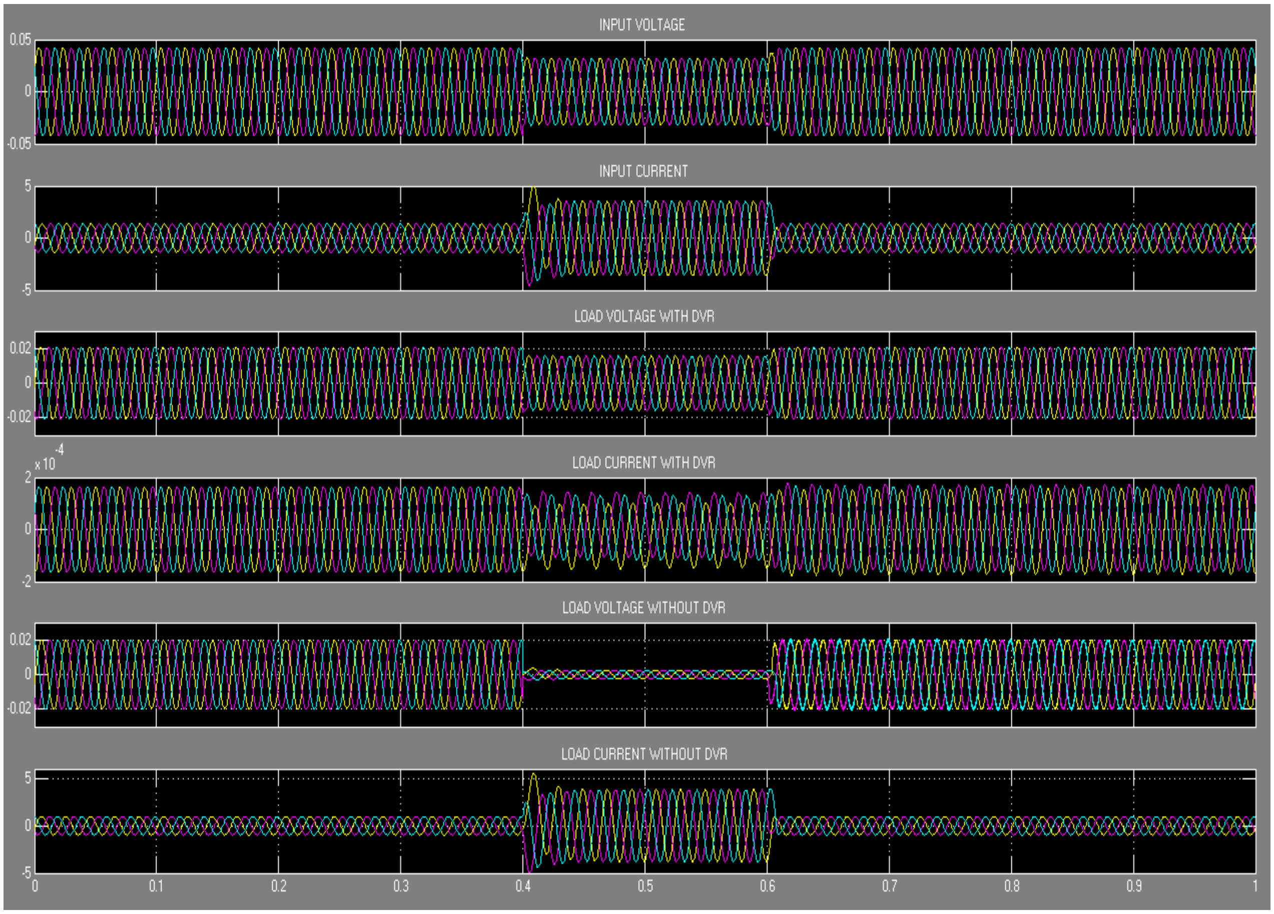

Figure-5.12: Output result for voltage sag condition

Here the load voltage wave shapes for both the feeders are compared. The wave shapes for load voltages only are given below.

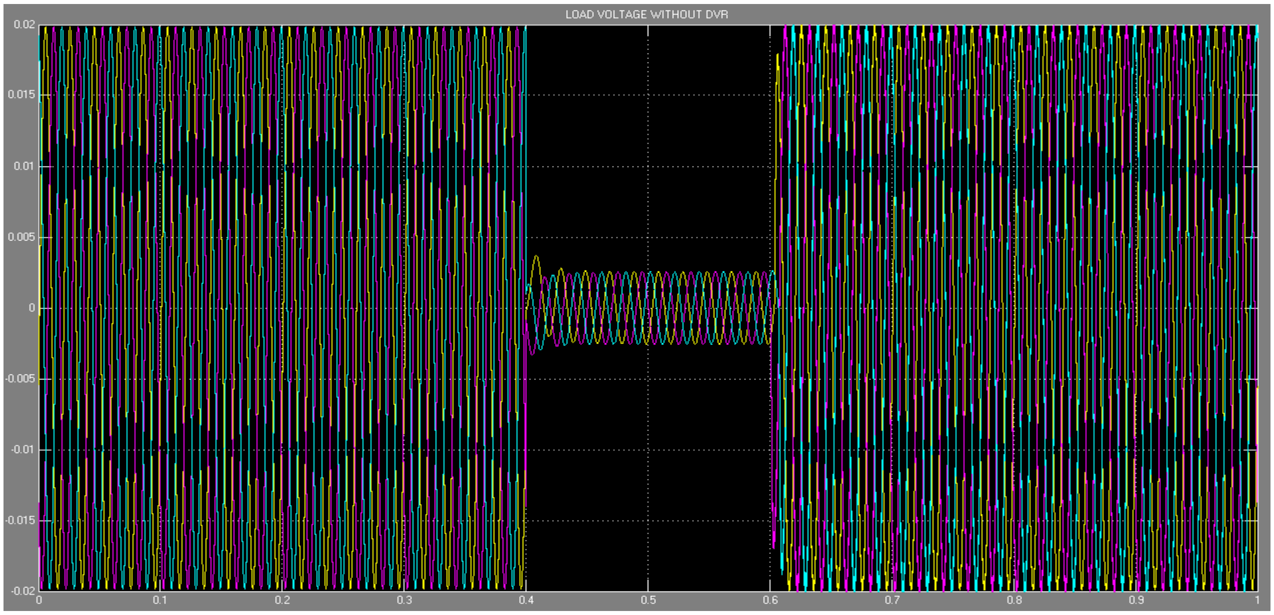

Figure-5.13: Load voltage without DVR

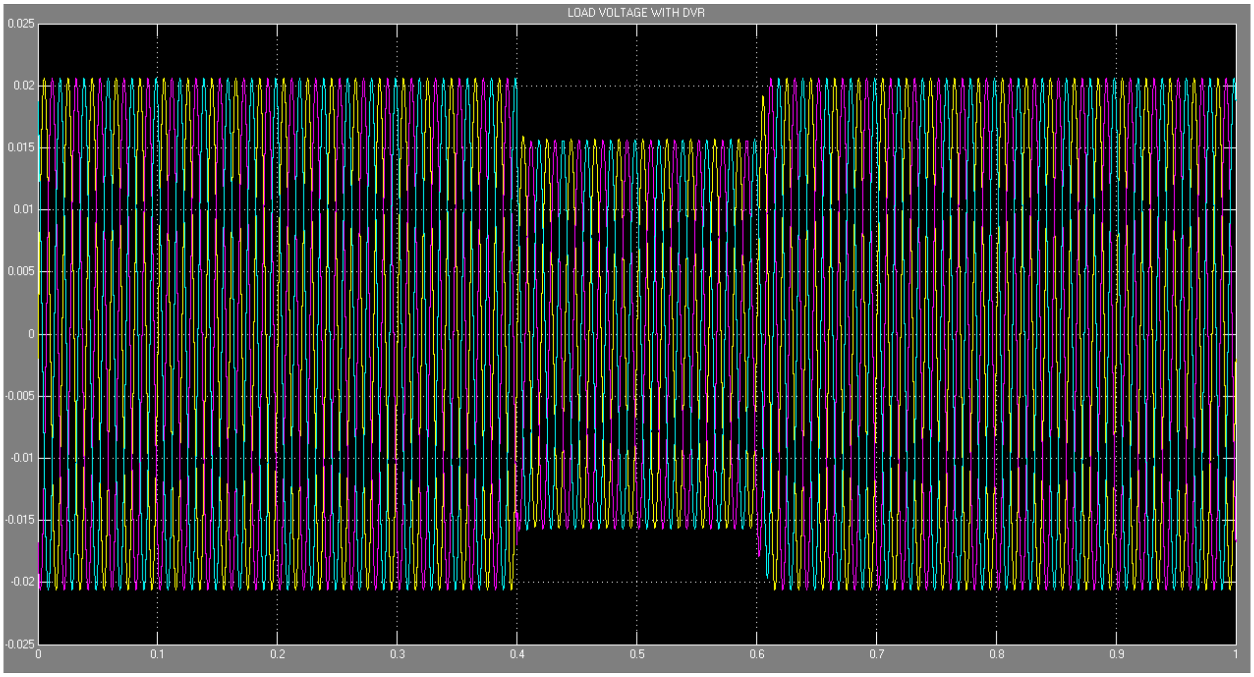

Figure-5.14: Load voltage with DVR

It is clear from the above wave shapes of the load voltages that the voltage in that feeder where DVR is connected is compensated to large extent for voltage dip condition. So here the amount of unbalance in load voltage in that feeder where DVR is connected is reduced.

5.5 SIMULINK MODEL OF THE TEST SYSTEM WITH INDUCTION MOTOR AS LOAD.

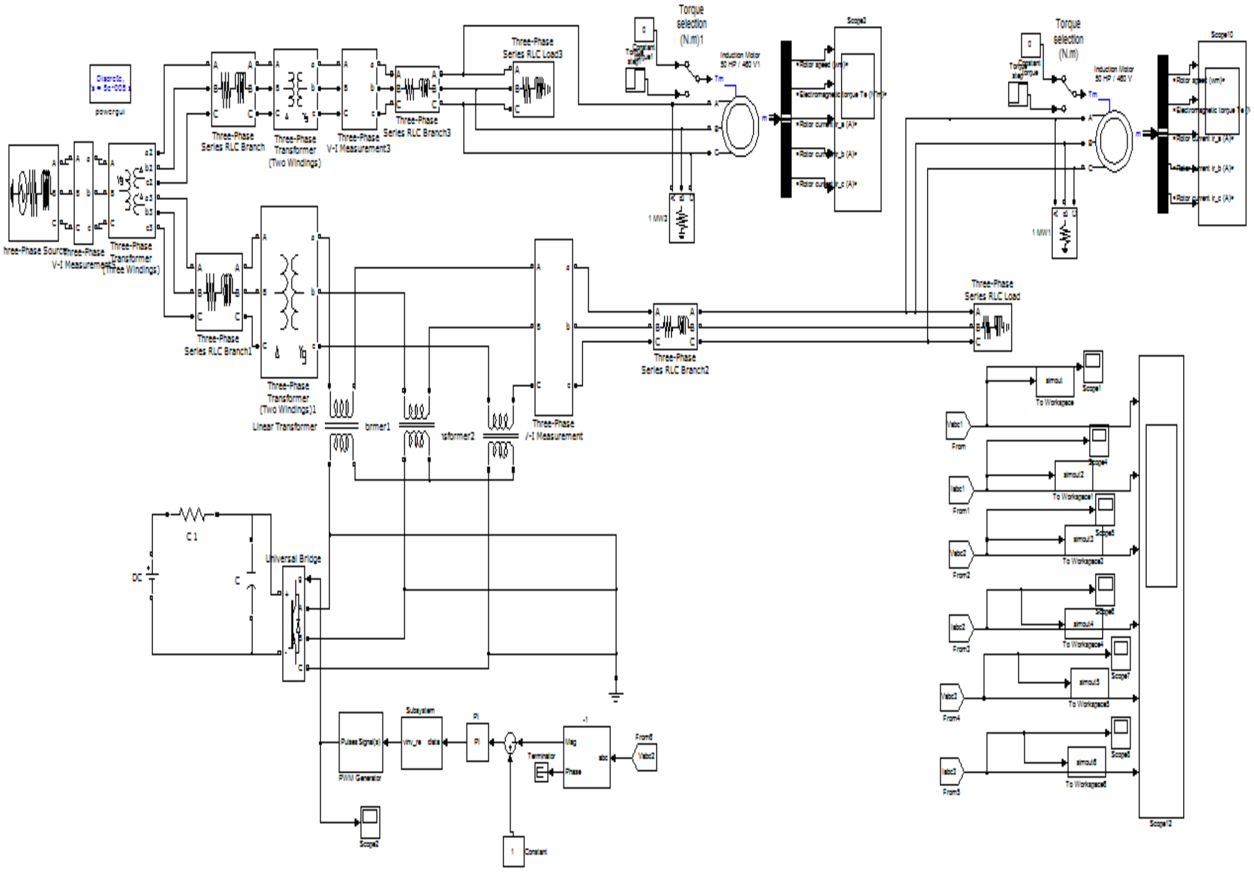

Figure-5.15: Simulink model with motor load

The simulink model with the induction motor load is also investigated. The parameters for the motor load is given in the system parameters Table-5.1. Different fault conditions are considered for this load. There is inherent problem of starting dip in case of induction motor and effectiveness of DVR to reduce this problem of induction motor is investigated in this work. In addition, the different fault conditions like single phase to ground fault, voltage sag condition are created in the proposed SIMULINK model and effectiveness of DVR for the same is investigated. Results for all these conditions are presented in the next section.

5.5.1 SIMULINK RESULTS OF PROPOSED SYSTEM WITH THE CONDITION OF STARTING VOLTAGE DIP FOR INDUCTION MOTOR.

In this case, only the starting voltage dip in case of induction motor is considered. The results for this case are given below.

The first two wave shapes in Figure-5.16 represents input voltage and current respectively, with respect to time. The next two wave shapes are for load voltage and load current where DVR is connected. The last two wave shapes represents uncompensated load voltage and load current.

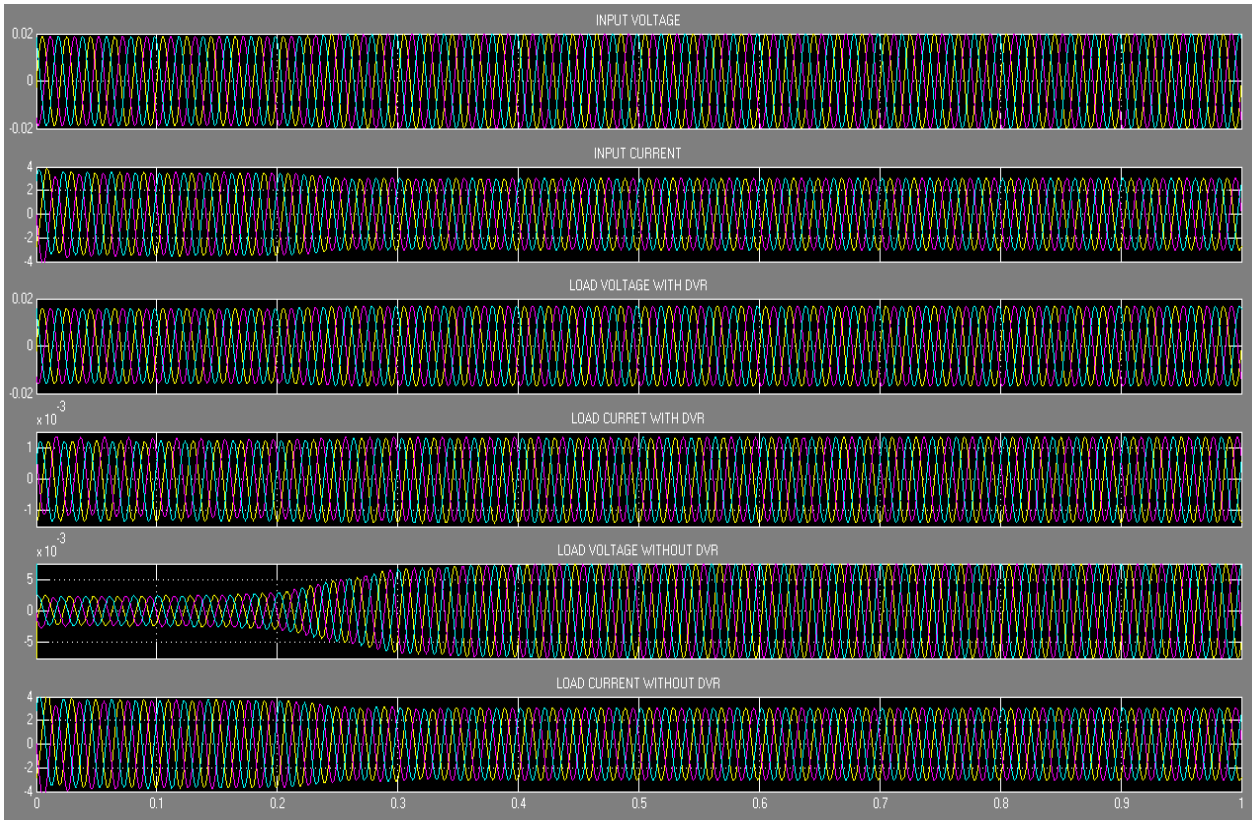

Figure-5.16: Output result for the starting voltage dip condition

In this result starting dip in case of an induction motor is taken only, without any fault condition. The wave shapes of the load voltages for both the feeders are compared. The wave shapes for load voltages are shown below.

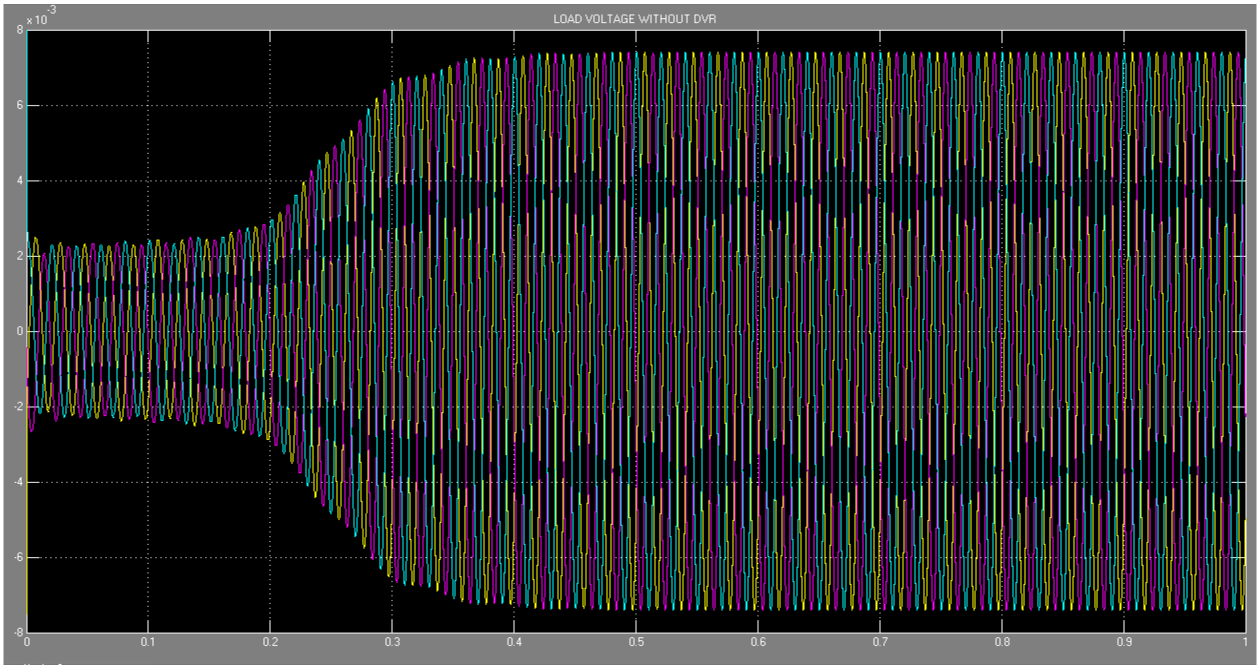

Figure-5.17: Load voltage without DVR

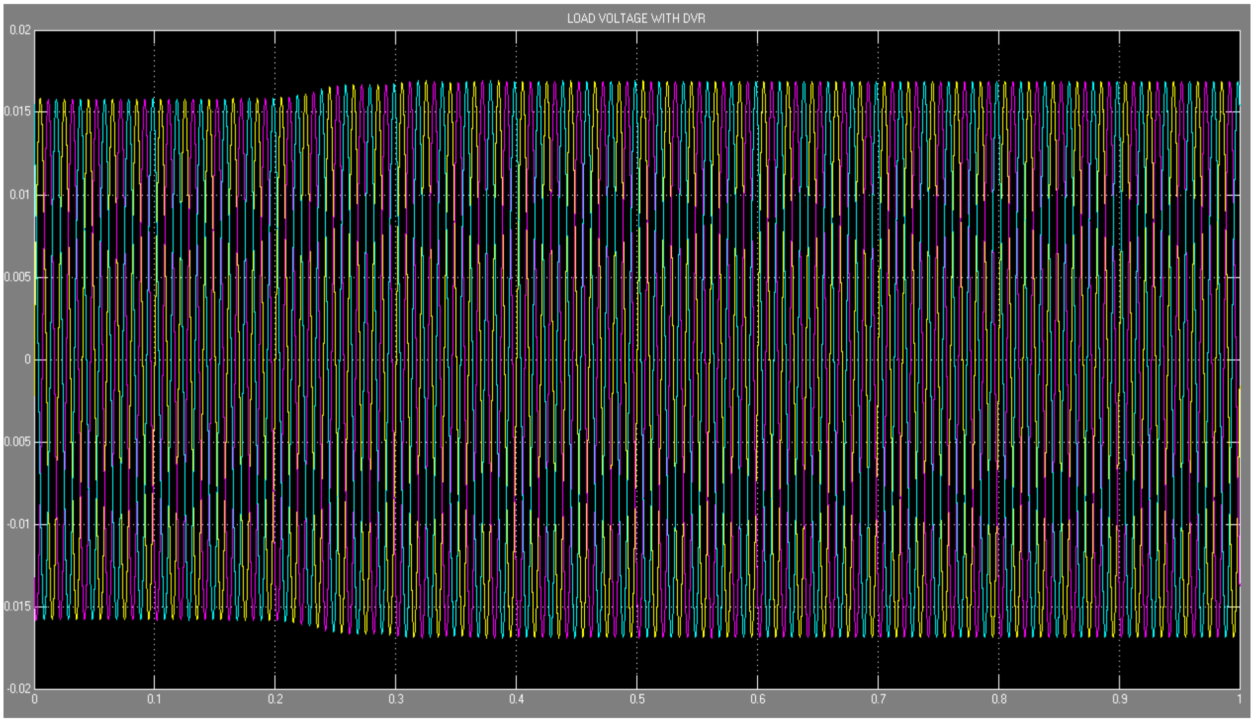

Figure-5.18: Load voltage with DVR

It is clear from the above wave shapes of the load voltages that the voltage in that feeder where DVR is connected is compensated for starting dip condition and the amount of unbalance in load voltage is reduced for induction motor load.

5.5.2 SIMULINK RESULTS OF PROPOSED SYSTEM WITH THE CONDITION OF STARTING VOLTAGE DIP AND SINGLE PHASE TO GROUND FAULT FOR INDUCTION MOTOR LOAD.

In the same model with induction motor as load a single phase line to ground fault is created in both the feeders. Here the fault resistance is 0.66 ohms and the ground resistance is 0.001 ohms. The fault time is 0.4s to 0.5s. The result of the load voltage in both feeders (with DVR and without DVR) for the above system is given below.

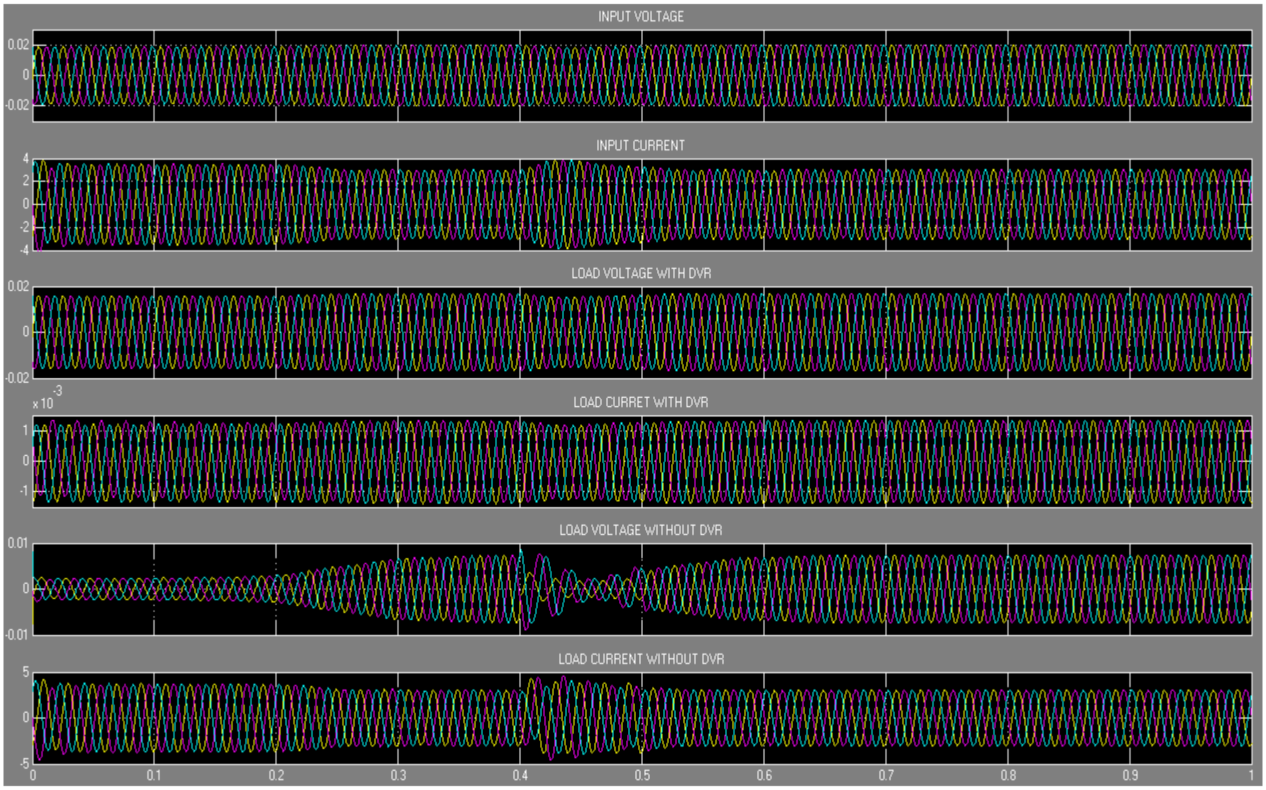

Figure-5.19: Output result for single phase to ground fault condition with motor load.

The wave shapes of the load voltages for both the feeders are easily compared. It is clear from the above results that for the condition of single line to ground fault, the load voltage is compensated to a large extent in the feeder where DVR is connected in series with the line. The wave shapes for load voltages are shown below.

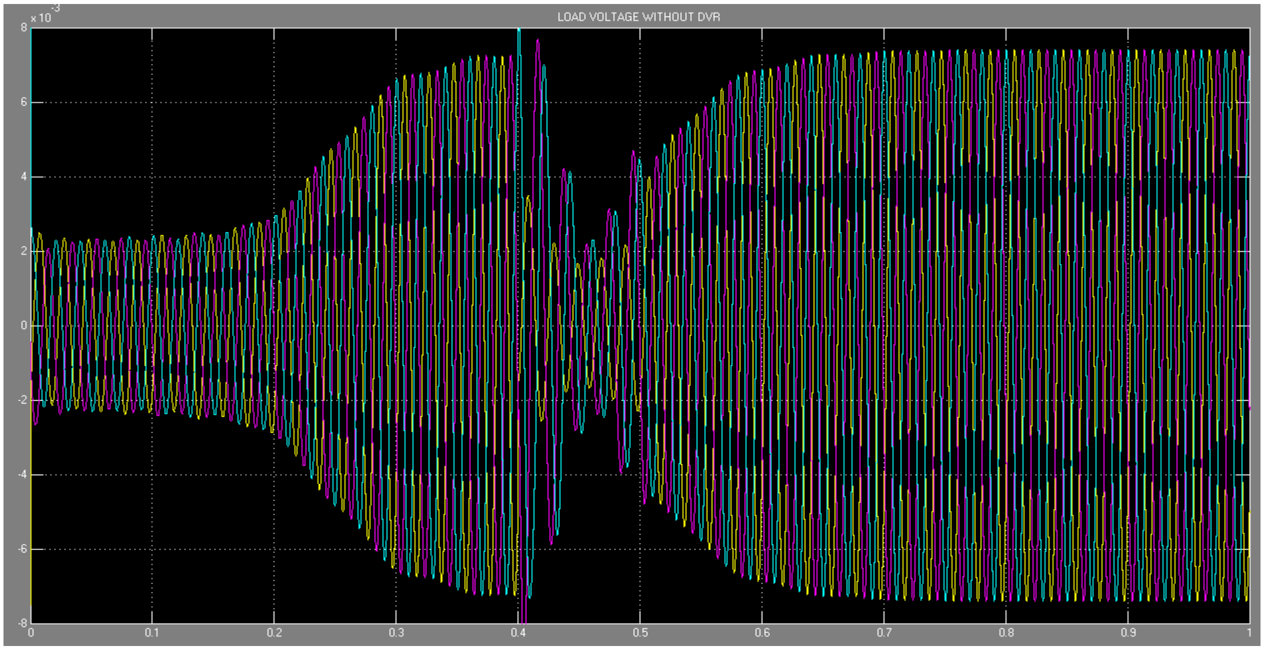

Figure-5.20: Load voltage without DVR for motor load

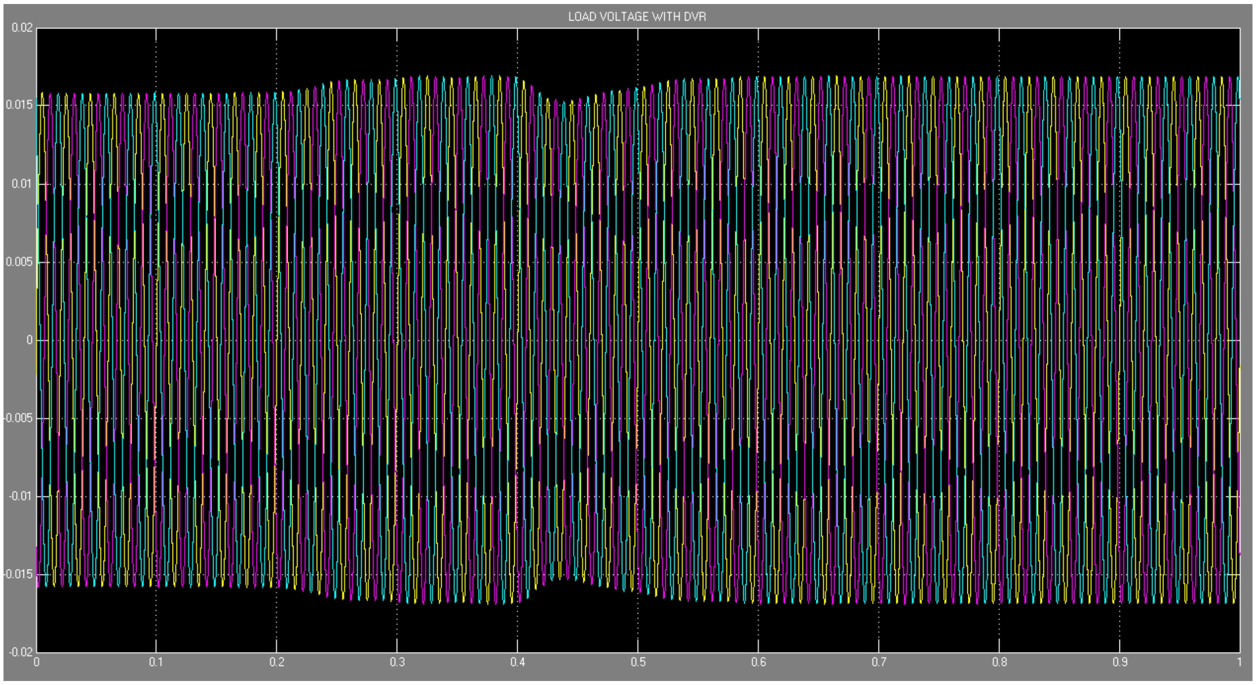

Figure-5.21: Load voltage with DVR for motor load

Now if we compare both the load voltages, the voltage in the feeder where DVR is connected is compensated and the amount of unbalance is also reduced.

5.5.3 SIMULINK RESULTS OF PROPOSED SYSTEM WITH THE CONDITION OF VOLTAGE SAG.

In this system in spite of the starting dip of an induction motor an extra dip is introduce in the system in both the feeders for the duration of 0.4s to 0.5s. The output results for the above system are shown below in Figure-5.22.

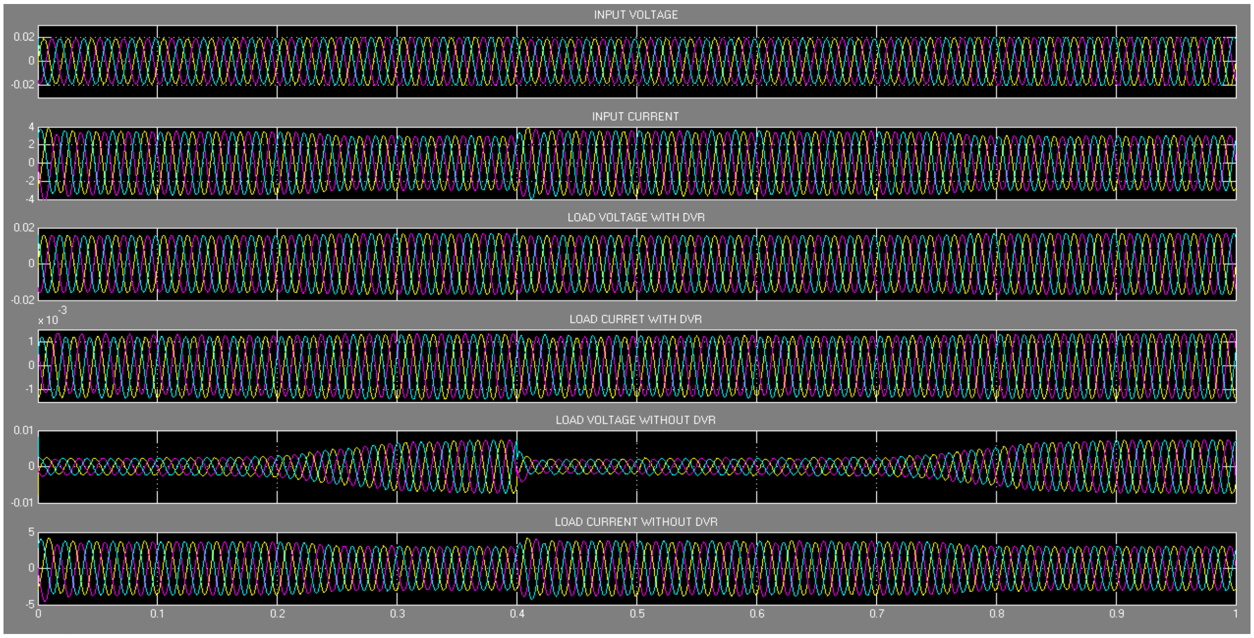

Figure-5.22: Output result with voltage sag condition for motor load

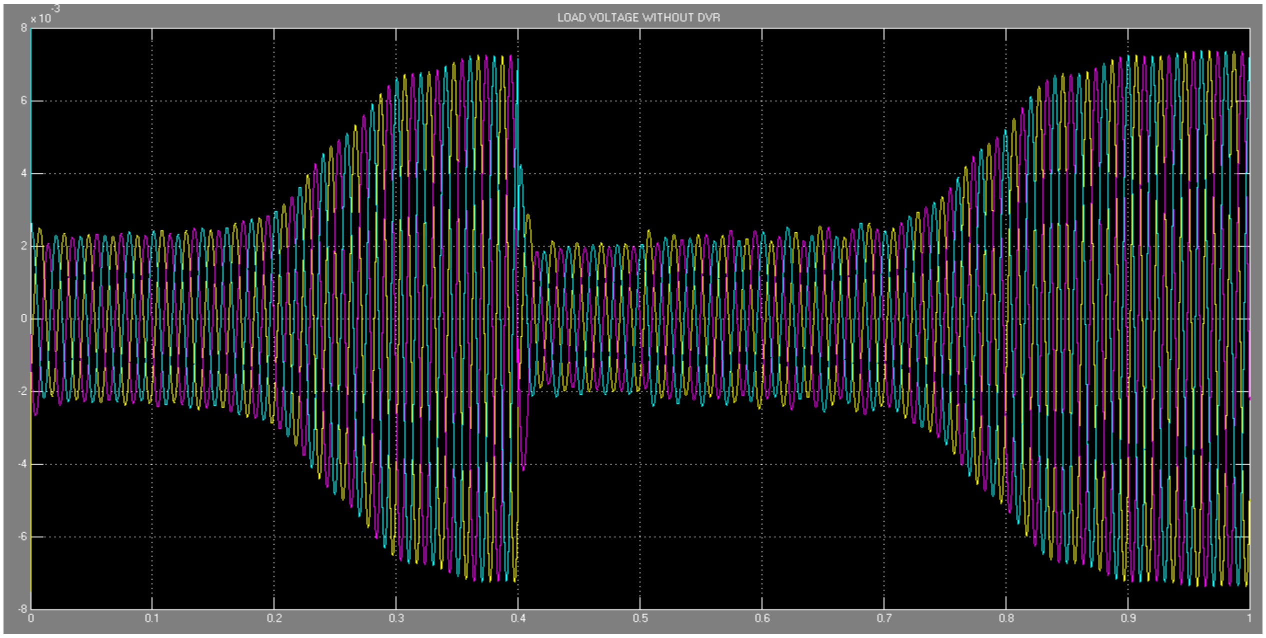

Figure-5.23: Load voltage without DVR for motor load

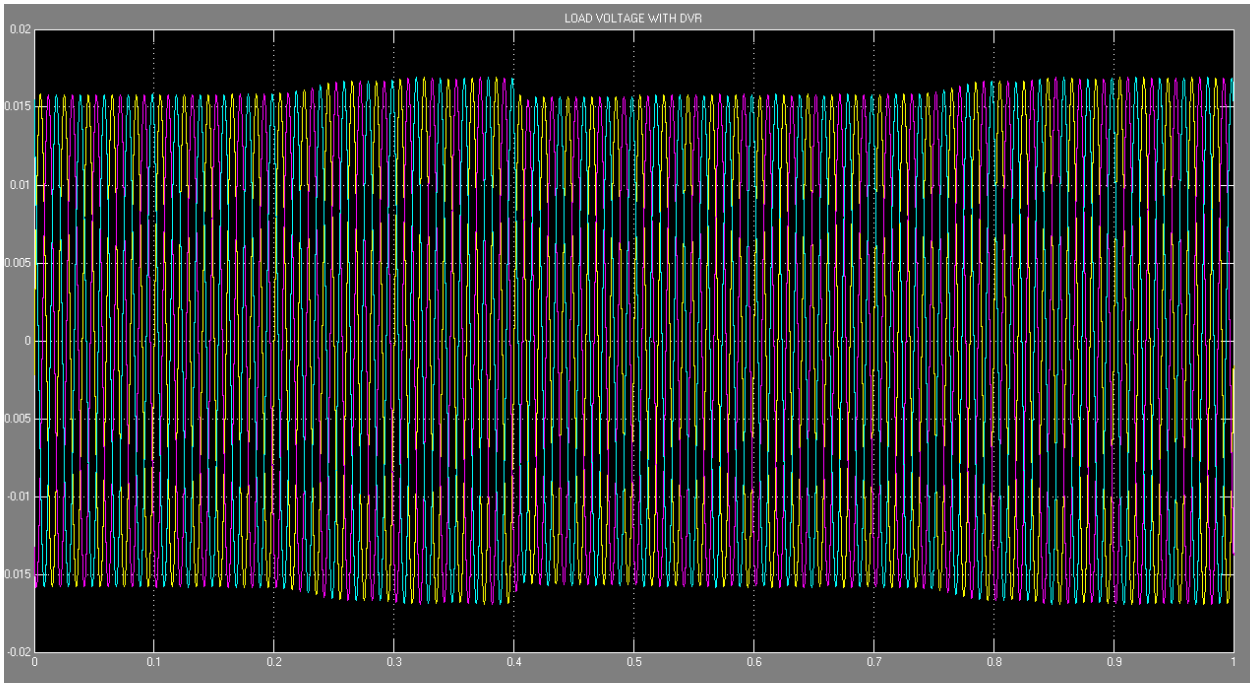

Figure-5.24: Load voltage with DVR for motor load

Now, from the above wave shapes of the load voltages that the voltage in that feeder where DVR is connected is compensated to large extent for voltage dip condition for induction motor load. Further this can also be shown through the THD (total harmonic distortion) graph that the harmonic are reduced to great extent for the system with DVR. The THD for system without DVR is about 29.67% and for the system with DVR the valve of THD is around 1.5%.

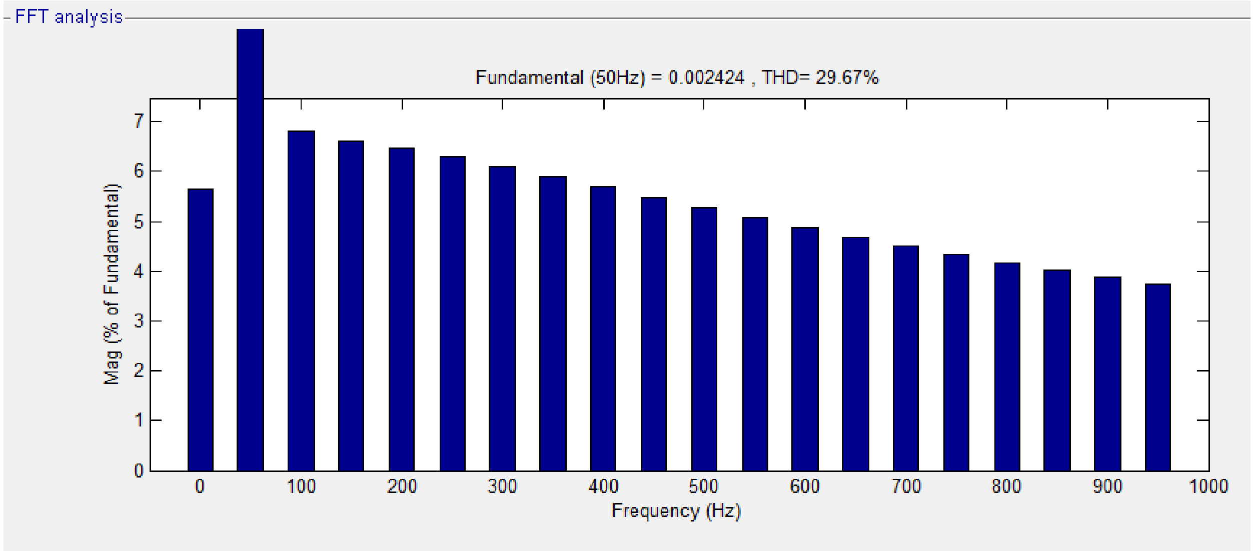

Figure-5.25: THD for load voltage (without DVR)

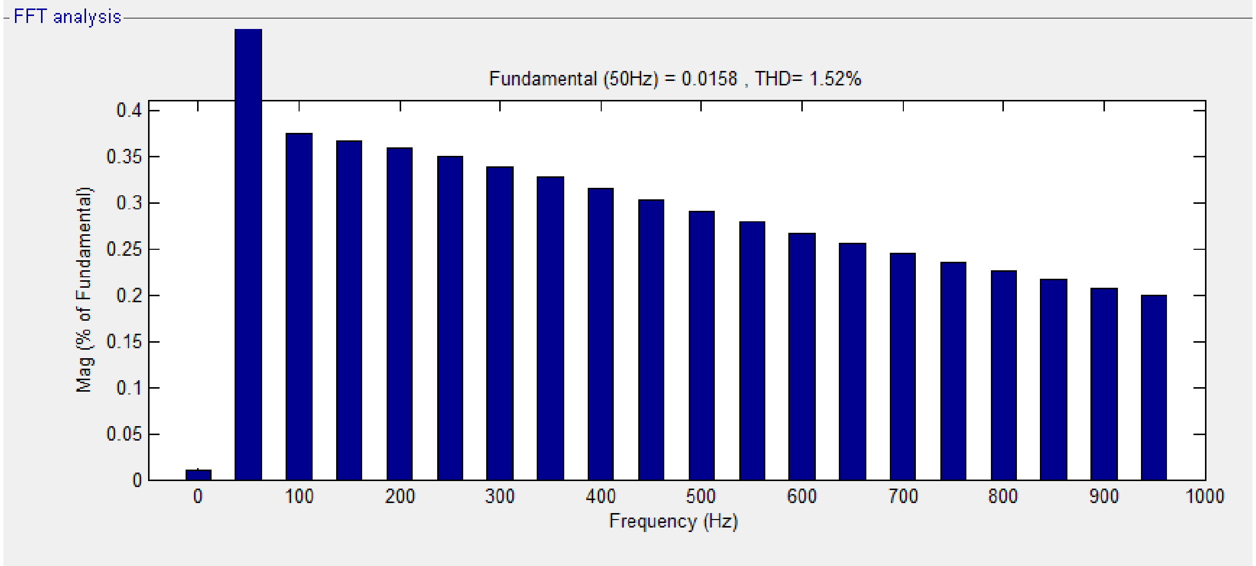

Figure-5.25: THD for load voltage (with DVR)

So it is also clear from the THD graphs that the amount of unbalance in load voltage in that feeder where DVR is connected is reduced to large extent, as the value of THD is reduced for the system, where DVR is connected.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE OF WORK

6.1 CONCLUSION

In this work, a fast and cost effective Dynamic Voltage Restorer (DVR) is proposed for mitigating the problem of voltage sag or dip and other fault conditions in industrial distribution systems, specially consisting of the induction motor load. A controller which is based on feed foreword technique is used which utilizes the error signal which is the difference between the reference voltage and actual measured load voltage to trigger the switches of an inverter using a Pulse Width Modulation (PWM) scheme. Here, investigations were carried out for various cases of load at 11kv feeder. It is clear from the results that the power quality of the system with induction motor as load is increased in the sense that the THD and the amount of unbalance in load voltage are decreased with the application of DVR. The effectiveness of DVR using PI controller is established both for linear static load and induction motor load.

6.2 FUTURE SCOPE

The following points are recommended for future extension of work:

- Other types of controllers like fuzzy controller and adaptive PI fuzzy controller can be employed in the DVR compensation scheme.
- Investigation of the effectiveness of multi-level DVR can be investigated.
- The effectiveness of DVR can be established for active loads like PV source and Wind turbine.

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