POWER QUALITY IMPROVEMENT USING DVR AND DSTATCOM

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With Specialization in Power System Engineering)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work presented in this dissertation entitled **"Power Quality Improvement Using DVR and DSTATCOM"** submitted in partial fulfillment of the requirements for the award of the degree of **Master of Technology** with specialization in **Power System Engineering** in the **Department of Electrical Engineering**, Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out from July 2004 to June 2005 under the guidance of **Dr. R.N. Patel**, Lecturer and **Dr. E.Fernandez**, Assistant Professor , Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee.

I have not submitted the matter embodied in this report for the award of any other degree or diploma.

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CERTIFICATE

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

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ABSTRACT

A Power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure or a mis-operation of end user equipments. Power quality is certainly a major concern in the present era; it becomes especially important with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply. As customers increasingly use process and computer equipment that is highly sensitive to power system interruptions, utilities are being forced to serve these loads with transmission and distribution systems that are at or exceeding capacity. Voltage sags is one of the severe power quality problems, this report addresses all the different aspects related to voltage sag problem, such as: its types, consequences and mitigation.

At present, wide ranges of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications. Among these, the Dynamic Voltage Restorer (DVR) and Distribution Static Compensator (D-STATCOM) are most effective devices. A DVR injects a voltage in series with the system; D-STATCOM injects a current into the system to correct the voltage sag problem. Matlab Simulink/Power System Blockset (PSB) has been used in this work to perform the simulation and analysis of such controllers. The performance of both DVR and D-STATCOM is obtained for various voltage sags such as balanced, unbalanced voltage sags, and reactive power injection and consumption. Comprehensive results are presented to assess the performance of each device as a potential custom power solution.

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CHAPTER-1

INTRODUCTION

1.1 Introduction

The aims of the electric power system are to supply electrical energy to terminals of electrical equipment, and to maintain the voltage at the equipment terminals within certain limits. For decades research and education have been concentrated on the first aim. Quality of supply was rarely an issue. A change in attitude came about probably in the early 1980s. Starting in industrial and commercial power systems and spreading to the public supply, the power quality problems appeared.

Power quality (PQ) is an issue that is becoming increasingly important to electricity consumers at all levels of usage. Sensitive equipment and non-linear loads are now more commonplace in both the Industrial, commercial sectors and the domestic environment [1]. Because of this a heightened awareness of power quality is developing amongst electricity users. Occurrences affecting the electricity supply that were once considered acceptable by electricity companies and users are now often considered a problem to the users of everyday equipment. Some of the most common PQ disturbances include interruptions; voltage sags and swells; harmonic distortions and surges. These are depicted in Fig.1.1.

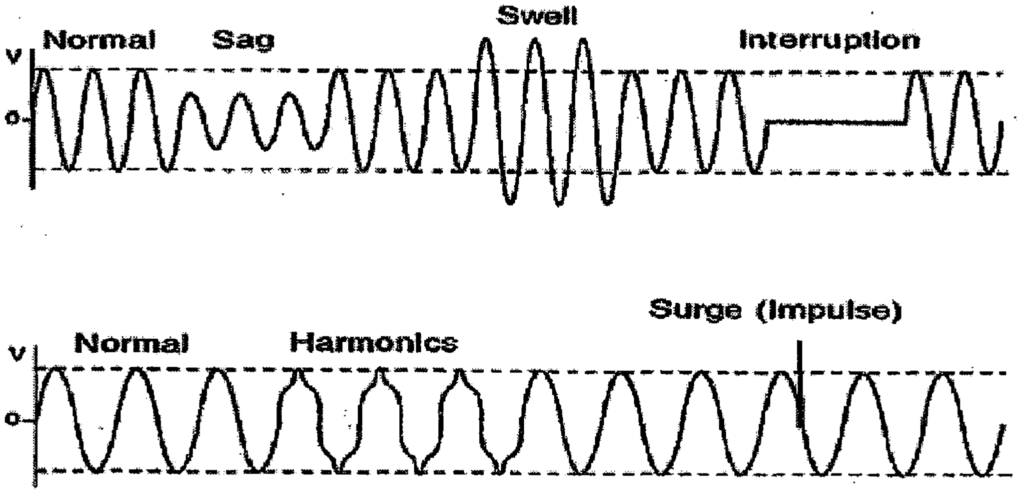


Fig.1.1 Common power quality disturbances

Modern semiconductor switching devices are being utilized more and more in a wide range of applications in distribution networks, particularly in domestic and industrial loads. Examples of such applications widely used are adjustable-speed motor drives, diode and thyristor rectifiers, uninterruptible power supplies (UPS), computers and their peripherals, consumer electronics appliances (TV sets for example), among others. Those power electronics devices offer economical and reliable solutions to better manage and control the use of electric energy. These devices, aggregated in thousands, have become the main polluters, the main distorters, of the modern power systems [2]. At the same time, microelectronics processors have found their way into many applications: from automated industrial assembly lines, to hospital diagnostics and measurement schemes. These applications are sensitive and vulnerable to power quality problems such as such as voltage sag, swell, asymmetry, flicker, fluctuation, and harmonics and so on. Those problems may create unfavorable influence on production processes and assemblies, reducing product quality, making the production processes interrupt, and thus causing huge economic losses. The losses caused by voltage problems surpass 20 billion U.S. dollars in the United States industry every year [1]. Therefore, scholars and experts all over the world had paid more and more attention to power quality problems and its solutions. Some of the reasons for the increased interest on power quality issues are listed below [2]:

- Equipment has become more sensitive to voltage disturbances.
- Equipment causes voltage disturbances.
- A growing need for standardization and performance criteria.
- Utilities want to deliver a good product.
- End-users have increased awareness of PQ issues and challenged the utilities to improve the quality of power delivered.
- The power quality can be improved using mitigation devices.

The aim therefore, in this work, is to identify the prominent concerns in this area and thereby to recommend measures that can enhance the quality of the power, keeping in mind their economic viability and technical repercussions.

1.2 Objective of the Work

The power quality can be degraded by the use of nonlinear and power electronically switched loads. The demand for better power quality is increasing with the extensive use of electronics equipment such as variable speed drives, robots, automated production lines, machine tools, programmable logic controllers, personal computers, etc. To improve the electric PQ, an appropriate mitigating action should be taken.

This work introduces customer power technology which is emerging area in mitigating power quality disturbances and improving power system reliability. Custom power devices like DVR and D-STATCOM are used to correct many types of PQ problems at distribution level. A DVR is a series device that generates an ac voltage and injects it in series with the supply voltage through an injection transformer to compensate the voltage sag. On the other hand, a D-STATCOM is a shunt device that generates an ac voltage, which in turn causes a current injection into the system through a shunt transformer to compensate the voltage sag. These two devices works on the voltage source converter (VSC) principle. For the operation VSC, switching pulses should be given to gates of IGBTs; this can be done in so many methods. In this work a new direct control scheme is implemented for obtaining required switching pulses.

This thesis emphasizes on the voltage sags such as balanced, unbalanced sags, and swells mitigation by custom power devices. Because, among all PQ problems, voltage sag is most prominent and frequently occurring problem. In this work two important custom power devices DVR and DSTATCOM are simulated using Matlab Simulink/Power System Blockset (PSB), and applied them on a 25kV distribution system for correction of voltage quality problems. Comprehensive results are presented and discussed. The response time of both DVR and D-STATCOM is very short and is limited by the power electronics devices. The response time is about 25 ms, and which is much less than some of the traditional methods of voltage correction such as tap-changing transformers.

1.3 Report Organization

The first chapter of this dissertation presents the introduction, objective of the work, report organization and literature review.

In chapter 2, various power quality disturbances, their sources and effects on the end user equipment are discussed. At the end possible mitigation techniques are presented.

Chapter 3 presents the voltage quality analysis. The PQ is more or less equal to voltage quality. In this chapter various voltage quality issues, characteristics and mitigation techniques are discussed.

In chapter 4, custom power technology is introduced. Custom power solutions to PQ problems like DVR and DSTATCOM their topologies and operating principles are presented in detail.

In chapter 5 simulations of custom power devices is presented. New control scheme for DVR and DSTATCOM i.e direct controller proposed. VSC with energy conversion principle is implemented.

Chapter 6, Presents the simulation results and discussions.

Chapter 7 concludes the present work done for this dissertation and forwards some suggestions for future considerations.

1.4 Literature Review

John and Collinsion [1] describe the commonly accepted definitions used in the field of power quality and discuss some of the most pertinent issues affecting end users, equipment manufacturers, and electricity suppliers relating to the field. This special feature contains a range of articles balanced to give the reader an overview of the current situation with representation from the electricity industry, monitoring equipment manufacturers, solution equipment manufacturers, specialist consultants and govt. research establishments.

Bollen [2] discusses in his paper entitled: “What is Power Quality?” about the terminology and various issues related to ‘power quality’ problems. The interest in power quality is explained in the contest of recent developments in power engineering like deregulation of electric industry, increased quality disturbances etc. The author points out that the voltage sags and harmonic distortion are the two major problems in the present context. For each of these two disturbances a number of other issues are briefly discussed in this work, some of which are characterization, origin, mitigation, and the need for future research.

Yaleinkaya et al. [3] describe voltage sags as a three-phase phenomenon. The principle cause of all voltage sags is a short-duration increase in current. The main contributions are motor starting, transformer energizing, and faults. The kind of sag experienced by the load depends on its connection. For a single-phase fault: star-connected load experiences a drop only in one phase. Delta-connected load will experience a drop in two phases, where the third phase is not affected. For a phase-phase fault, star-load has a volt drop in two phases; delta load has a large drop in one phase and a small drop in the other two phases. Statistical and stochastic methods for collecting data to calculate event magnitude and duration were also highlighted. Mitigation methods were also proposed.

Guasch et al. [4] analyze the effects caused by the unsymmetrical voltage sags in the induction machine supply system: current and torque peaks, and mechanical speed loss. These effects depend on many elements, such as the sag magnitude and duration, the type of sag (symmetrical or unsymmetrical), and the fault and recovery voltage instants. It is shown that the most severe transient occurs for specific instants. Extensive ranges of voltage drop have been analyzed (for different magnitude and duration and the most severe fault and recovery voltage instants), and machine sensitivity is graphically shown in CBEMA curves. These curves can be applied to protective relay coordination, especially for large machines. It is also shown that different unsymmetrical sags with the same positive-sequence voltage produce similar effects. These unsymmetrical sags can be grouped to express machine sensitivity in CBEMA curves, using the positive-sequence voltage for ordinates.

Arrillaga et al. [5] discuss in their paper entitled, "Power Quality Following Deregulation", about the two most important power quality issues related to the present power industry, which are: voltage sags and harmonic distortion, with a brief reference to interruptions. The paper summarizes the extent to which power quality issues will be affected by deregulation as well as the actions required to meet specified levels of quality throughout the power system. A review of power quality simulation techniques has been attempted and the special needs of power quality monitoring at points of energy interchange have been discussed. Emerging power quality state estimation techniques have also been described in this work.

Hingorani [6] has introduced the custom power concept. This concept has been proposed to ensure high quality of power supply in distribution networks using power electronic devices. The evolution power controllers for improvement in the distribution system, is discussed. Series and shunt custom power devices topologies and their operating principles are discussed. Some power quality problems and their effects also described in short.

Arnold [7] explains various power quality problems and the solutions to those problems with solid state switching devices such as: Static VAR Compensator, Static Compensator (STATCOM), Unified Power Flow Controller (UPFC), and Dynamic Voltage Restorer (DVR) in detail. The author also discusses the energy storage systems for voltage sag mitigation. Here author suggested that for the future developments of devices we must consider both of technical and economic aspects to existing problems and their solution techniques.

Woo et al. [8] presents the use of DSTATCOM in mitigating power quality problem, control algorithm, simulation and practical investigation. When a fault happens in a distribution network, sudden voltage sag will appear on adjacent loads. DSTATCOM installed on a sensitive load, restores the line voltage to its nominal value within the response time of a few milliseconds thus avoiding any power disruption to the load. Currently, most of the STATCOM design studies are based on the assumption of the balanced three-phase system. And almost all researches are based on the three-phase three-wire systems.

Awad and Svensson [9] assimilate the information regarding the Static Series Compensator (SSC) and discuss its design criteria. The operational principle and layout of a typical SSC are presented. Characteristics of the individual components contributing to the SSC configuration are described. Design criteria and rated power calculations are also formulated. This paper proposed two control strategies to improve the dynamic performance of the SSC. The first strategy is based on adding a negative sequence controller to the Double Vector Controller (DVC). The second strategy is based on increasing the switching frequency while using only the basic DVC.

Ghosh and Ledwich [10] have given the principle of operation of DVR. A DVR is usually built round a dc–ac power converter that is connected in series with a distribution line through three single phase transformers. The dc side of the converter is connected to a dc energy-storage device. The energy state of the device is regulated by taking power from the feeder. It has been proposed a series compensator for the correction of supply-side unbalance and voltage regulation. Here, it is demonstrated that this device can tightly regulate the voltage at the load terminal against imbalance or harmonic in the source side. The behavior of the device is studied through steady-state analysis, and limits to achievable performance are found.

Haque et al. [11-12] describe the techniques of correcting the supply voltage sag in a distribution system by two power electronics based devices called DVR and D-STATCOM. The steady state performance of both DVR and D-STATCOM is determined and compared for various values of voltage sag, system fault level and load level. The minimum apparent power injection required to correct a given voltage sag by these devices is also determined and compared. The maximum voltage sag that can be corrected without injecting any active power into the system is also determined.

Mienski et al. [13] has given the compensation of frequently time-variable loads by means of STATCOM controllers. An arc furnace is considered as a heavily distributing load. The STATCOM system was used to ensure good power quality at the point of common coupling. Simulation models of the load and two types of STATCOM controllers namely; 12-pulses and 24-pulses are discussed in detail. The simulation results demonstrate the compensation effectiveness.

Sannino et al. [14] presents an overview of power-electronic based devices for mitigation of power quality phenomena. The concept of custom power is highlighted. Both devices for mitigation of interruptions and voltage sags (sags) and devices for compensation of unbalance flicker and harmonics are treated. The attention is focused on medium-voltage applications. It is shown that custom power devices provide, in many cases, higher performance compared with traditional mitigation methods. However, the choice of the most suitable solution depends on the characteristics of the supply at the point of connection, the requirements of the load and economics.

Anaya-Lara [15] addresses the timely issue of modeling and analysis of custom power controllers. This new generation of power electronics-based equipment aimed at enhancing the reliability and quality of power flows in low-voltage distribution networks. Presented electromagnetic transient models of custom power controllers namely, distribution static compensator (D-STATCOM), dynamic voltage restorer (DVR), and solid-state transfer switch (SSTS), and applied them to the study of PQ. D-STATCOM was proven to have a rapid regulation response, minimize waveform distortion and keeping transient overshooting at minimum. DVR is able to provide excellent voltage regulation capabilities based on the rating of the dc storage device and the characteristics of the coupling transformer. These two factors determine the maximum value of sag mitigation that the DVR can provide.

Walmir et al. [16] analyze a dynamic study about the influences of ac generators (induction and synchronous machines) and distribution static synchronous compensator (DSTATCOM) devices on the dynamic behavior of distribution networks. The performance of a DSTATCOM as a voltage controller or a power factor controller is analyzed. The impacts of these controllers on the stability and protection system of distribution networks with distributed generators are determined. Computer simulation results show that a DSTATCOM voltage controller can improve the stability performance of induction generators significantly. On the other hand, a DSTATCOM power factor controller may adversely affect the stability performance of synchronous generators.

Sybille and Le-Huy [17] presents the features of the Power System Blockset and its applications in the simulation of power systems and power electronics systems. It explains the principle of operation of the PSB. The PSB is a graphic tool that allows building schematics and simulation of power systems in the Simulink environment. The Blockset uses the Simulink environment to represent common components and devices found in electrical power networks. It consists of a block library Diagrams can be assembled simply by using click and drag procedures into Simulink windows. The Power System Blockset uses the same drawing and interactive dialogue boxes to enter parameters as in standard Simulink blocks.

CHAPTER-2

POWER QUALITY ISSUES

2.1 What is Power Quality?

There is a lot of confusion on the meaning of the term 'power quality', different authors use different definitions. Power quality is the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment [2]. The International Electro-technical Commission (IEC), however, uses electromagnetic compatibility (EMC) to define quality of power: Electromagnetic compatibility is the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

There could be completely different definitions for power quality (PQ), depending on one's frame of reference. From many publications, power quality is the study or description of both voltage and current disturbances. Power quality can be seen as the combination of voltage quality and current quality. Generally, PQ is concerned with deviations of voltage and/or current from the ideal, and has nothing to do with deviations of the product of voltage and current (power) from any ideal shape. One should realize that there is no general consensus on the use of these definitions. A consistent set of definitions is given as follows [2]:

Voltage Quality is concerned with deviations of the voltage from the ideal. The ideal voltage is a single-frequency sine wave of constant amplitude and frequency.
Current Quality is the complementary term to voltage quality. It is concerned with the deviation of the current from the ideal. The ideal current is again a single-frequency sine wave of constant amplitude and frequency, with the additional requirement that the current sine wave is in phase with the voltage sine wave.
Power Quality is the combination of voltage quality and current quality.

Quality of Supply is a combination of voltage quality and the non-technical aspects of the interaction from the power network to its customers.

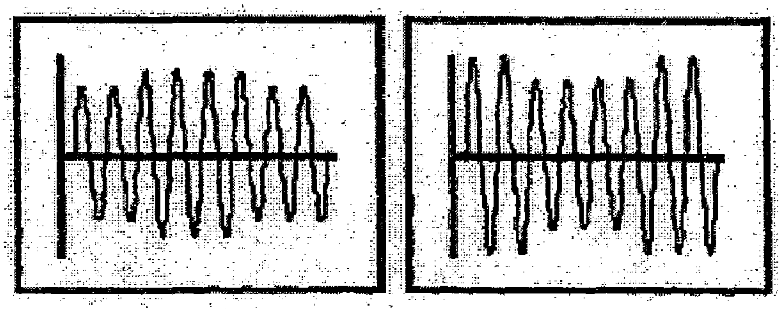
Quality of Consumption is the complementary term to quality of supply.

Variations are small deviations of voltage or current characteristics from its nominal or ideal value, e.g. the variation of voltage rms. value and frequency from their nominal values. Variations are disturbances that are measured at any moment in time.

Events are larger deviations that only occur occasionally, e.g. voltage interruptions or load switching currents.

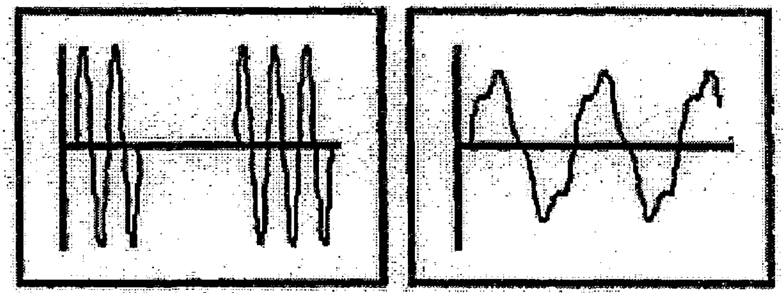
2.2 Types of Power Quality Problems: [1, 18]

Some of the power quality disturbances waveforms are shown in Fig.2.1 and IEEE standards for power quality problems are given in Appendix A.



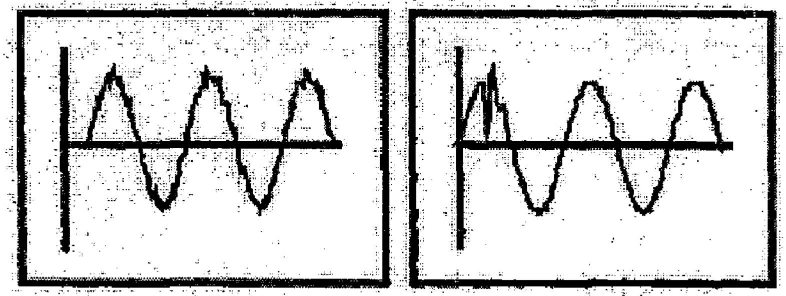
Voltage Swell

Voltage Sag



Interruptions

Harmonics



Noise

Transients

Fig.2.1 Some power quality disturbances

2.2.1 Transients These are sub cycle disturbances with a very fast voltage change. They typically have frequencies often to hundreds of kilohertz and sometimes megahertz. The voltage excursions range from hundreds to thousands of volts. Transients are also called spikes, impulses and surges. Two categories of transients are described in [18], impulsive transient and oscillatory transient. Examples of transients include lightning, electro-static discharge; load switching, line/ cable switching, capacitor bank or transformer energizing and ferro-resonance.

2.2.2 Long- Duration Voltage Variations

Long-duration variations encompass root-mean-square (rms) deviations at power frequencies for longer than 1 min. A voltage variation is considered to be long-duration when the limits are exceeded for greater than 1 min. These variations are categorized below:

Over voltage: An over voltage is an increase in the rms voltage greater than 110 percent at power frequency for duration longer than 1 min. Examples include load switching, incorrect tap settings on transformers, etc.

Under voltage: An under voltage is a decrease in the rms ac voltage to less than 90 percent at power frequency for duration longer than 1 min. Examples include load switching, capacitor bank switching off, overloaded circuits, etc.

Sustained interruptions: These come about when the supply voltage stays at zero longer than 1 min. They are often permanent and require human intervention to repair the system restoration. Examples include system faults, protection mal-trip, operator intervention, etc.

2.2.3 Short- Duration Voltage Variations

Short-duration variations encompass the voltage sags and short interruptions. Each type of variations can be designated as instantaneous, momentary, or temporary, depending on its duration these variations can be categorized as:

Interruptions: This occurs when the supply voltage or load current decreases to less than 0.1 pu for a time not exceeding 1 min. The voltage magnitude is always less than 10 percent of nominal. Examples include system faults, equipment failures, control malfunctions, etc.

***Sags (dips)*:** Sag is a decrease to between 0.1 and 0.9 pu in rms voltage or current at power frequency for durations from 0.5 cycle to 1 min. Examples include system faults, energization of heavy loads, starting of large motors, etc.

***Swells*:** A swell is an increase to between 1.1 and 1.8 pu in rms voltage or current at power frequency for durations from 0.5 cycle to 1 min. Swells are not as common as sags. Sometimes the term momentary over voltage is used as a synonym for the term swell. Examples include system faults, switching off heavy loads, energizing a large capacitor bank, etc.

2.2.4 Voltage and Current Imbalance

Unbalance, or three-phase unbalance, is the phenomenon in a three-phase system, in which the rms values of the voltages or the phase angles between consecutive phases are not equal. Examples include unbalanced load, large single-phase load, blown fuse in one phase of a three-phase capacitor bank, etc.

2.2.5 Voltage Fluctuation

The fast variation in voltage magnitude is called "voltage fluctuation", or "light flicker". Sometimes the term "voltage flicker" is also used. This voltage magnitude ranges from 0.9 to 1.1 pu of nominal. One example is an arc furnace.

2.2.6 Power Frequency Variations

Power frequency variations are defined as deviation of the power system fundamental frequency from its specified nominal value (eg. 50 or 60Hz). This frequency is directly related to the rotational speed of the generators supplying the system. There are slight variations in frequency as the dynamic balance between load and generation changes. The size of the frequency shift and its duration depends on the load characteristics and the response of the generation control system to load changes. Examples include faults on transmission system, disconnection of large load, disconnection of large generator, etc.

2.2.7 Waveform Distortion

Waveform distortion is defined as a steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation. Three types of waveform distortion are listed below:

***Harmonics*:** These are steady-state sinusoidal voltages or currents having frequencies that are integer multiples of the fundamental frequency. Harmonic distortion originates in the nonlinear characteristics of devices and loads on the power system. Examples include computers; fax machines, UPS systems, variable frequency drives (VFDs), etc.

***Inter harmonics*:** These are voltages and currents having frequency components which are not integer multiples of the fundamental frequency. Examples include static frequency converters, cyclo-converters, induction motors and arcing devices.

***Noise*:** This is unwanted electrical signals with broadband spectral content lower than 200 kHz superimposed on system voltage or current in phase conductors, or found on neutral conductors or signal lines. Examples include power electronics applications, control circuits, solid-state rectifiers, switching power supplies, etc.

2.3 Causes of Power Quality Variations

The main causes of poor power quality come from the customers themselves (internal), generated from one customer that may impact other customers (neighbors), and also from the utility. Neighbors here include those in separate buildings near the customer and separate businesses under the same roof such as a small business park. The types and causes of power quality variations are as follows [1, 18]:

Table 2.1 Internal Causes of Power Quality Variations

Types	Causes
Transient	Small lightning strikes at low voltage levels (e.g.500V) can disrupt or damage electronic equipment. Reactive loads turning on and off generate spikes. Poor connections in the wiring system lead to arcing-caused transients. Switching of power electronics devices.
Long-duration voltage variations	Over- and under-voltages are caused by load variations on the system. Overloaded circuits results in under voltages. Sustained interruptions are caused by lightning strikes.
Short-duration voltage variations	Sags and swells occur whenever there is a sudden change in the load current or voltage. Sags result when a load turns on suddenly (e.g. starting of large motors). Sags do not directly cause damage but initiate problems indirectly. Swells caused by the sudden turning off of loads can easily damage user equipment.

Waveform distortions	Current distortion affects the power system and distribution equipment. Overheating and failure in transformer and high neutral currents are some direct problems. Current harmonics may excite resonant frequencies in the system, which can cause extremely high harmonic voltages to damage equipment. Nonlinear loads (eg. Variable frequency drives, induction motors, power electronics components) cause voltage distortions, which can cause motor to overheat and vibrate excessively, resulting in damage to the shaft of motors. Components in computers may also be damaged. Electrical noise indirectly causes damage and loss of product Process control equipment and telecommunications are sensitive to such noise.
Wiring& grounding	Inappropriate or poor wiring and grounding can affect the operation and reliability of sensitive loads and local area networks.

Table 2.2 Neighboring Causes of Power Quality Variations

Types	Causes and effects
Transient	Transients are generated from the switching of loads. In situations where multiple, separate businesses share wiring or other parts of the power system, arcing-based transients are possible. Reactive loads, regardless of light or heavy motors, generate spikes.
Long / Short duration voltage variations	Changing currents interact with the system impedance. Loads in the neighbor's facility must be large and changing enough to affect the voltage feeding the customer's facility or office. If shared wiring is present, then even simple devices may cause similar concerns. Overloading may be the cause as well.
Waveform distortion	If a customer's neighbors draw large amount of distorted current, this current will subsequently distort the utility supply voltage, which is then fed back to the customer. Hence, loads within the customer's business are subjected to potential problems.

Table 2.3 Utility Causes of Power Quality Variations

Types	Causes
Transient	The most common causes of transients come from lightning surges. Other causes include capacitor bank energization, transformer energization, system faults
Long-duration voltage variations	These voltage variations are the result of load switching (eg. switching on/off a large load, or on/off a capacitor bank). Incorrect tap settings on transformers can also cause system over voltages. Overloaded circuits can result in under voltages as well.
Short-duration voltage variations	These variations are caused by fault conditions, energization of large loads that require high starting currents, or intermittent loose connections in power wiring. Delayed reclosing of protective devices may cause momentary or temporary interruptions.
Voltage and current imbalance	Primary source of voltage unbalance is unbalanced load (thus current unbalance). This is due to an uneven spread of single-phase, low voltage customers over the three phases, but more commonly due to a large single-phase load. Three-phase unbalance can also result because of capacitor bank anomalies, such as a blown fuse in one phase of a three-phase bank.
Power frequency variation	The frequency of the supply voltage is not constant. This frequency variation is due to unbalance between load and generation. Short circuits also contribute to this variation.
Waveform distortion	The amount of harmonic distortion originating from the power system is normally small. The increasing use of power electronics for control of power flow and voltage (flexible ac transmission systems or FACTS) carries the risk of increasing the amount of harmonic distortion originating in the power system. Harmonic current distortion requires over-rating of series components like transformers and cables Inter harmonics can excite unexpected resonance between transformer inductances and capacitor banks. More dangerous are sub-harmonic currents, which can lead to saturation of transformers and damage to synchronous generators and turbines.

2.4 Effects of Poor Power Quality

Many people think that poor power quality can only affect sensitive electronic components. In reality, disturbances such as harmonic distortion and voltage sags can also affect motor performance [4], overheating of transformers and data loss in computer. The entire system from transmission, to distribution, to utilization, has been subjected to damage and destruction from various PQ phenomena. Poor PQ will lead to damaged equipment and downtime for the affected equipment. This subsequently leads to repair and replacement costs. Loss of product means expensive rework, loss of productivity and higher overhead costs. Especially in this deregulated industry, the loss of customer confidence may result in financial losses.

Long transmission lines having high line impedance will cause substantial voltage drops in the presence of harmonics, resulting in unsatisfactory voltage regulation near the end of the line. Other power quality problems caused by dynamic load variations and interactions between the load and the network also affect the voltage waveforms supplied to utility customers.

2.5 Solution to Power Quality Problems

There are two approaches to the mitigation of power quality problems. The solution to the power quality can be done from customer side or from utility side [12]. 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 or counteracts the power system disturbances. Active power filters offer a flexible and versatile solution to voltage quality problems. Currently they are based on PWM converters and connect to low and medium voltage distribution system in shunt or in series [7]. Series active power filters must operate in conjunction with shunt passive filters in order to compensate load current harmonics. 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 bus having a reactive element such as a capacitor.

Active power filters can perform one or more of the functions required to compensate power systems and improving power quality. Their performance also depends on the power rating and the speed of response. 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:

1) Earthing practices:

A large number of reported power quality problems are caused by incorrect earthing practices. Verification of earthing arrangements, particularly when harmonics problems arc reported, should always he conducted early in a power quality investigation.

2) Transfer switches:

Transfer switches are used to transfer a load connection from one supply to another, allowing the choice of two supplies for the load (or sub network), should one supply suffer power disturbances then the other supply will be automatically switched in reducing the possibility of supply disruption to the load.

3) Static breakers:

The power electronic equivalent of a circuit breaker with a sub-cyclic response time is nothing but static circuit breaker. The static breaker will allow the isolation of faulted circuits in the shortest possible time frame; other nearby loads will therefore have improved power quality.

4) Active filters and SVCs:

The control of reactive power, and therefore harmonics, can be achieved by controlling a proportion of the power systems current through a reactive element. Conventionally this is achieved by switching inductors and capacitors in shunt with the power system, using thyristors. With the SVC the control of the current is achieved by controlling the output voltage magnitude of an inverter. SVCs are used to absorb or inject reactive currents to eliminate the harmonic distorting currents drawn by non-linear loads. Unified power flow controllers (UPFCs) are similar to SVCs but allow both series and shunt compensation.

5) Passive filters

Passive filters or power line filters are simple filters consisting of discrete capacitors and/or inductors. Normally designed to attenuate high frequencies (low-pass filters), fitted to equipment to remove higher order harmonic frequencies from the supply

6) Energy storage systems

All electrical energy storage systems have the same basic components, interface with power system, power conditioning system, charge/ discharge control and the energy storage medium itself. Each storage medium has different characteristics, energy density, charge/discharge time, effect of repeated cycling on performance and lice, cost, maintenance requirements etc. These characteristics help to make the decision of what storage medium is best suited to which application, each medium having merits that make it the most suitable in different circumstances. Energy storage systems available include:

- Superconducting magnetic energy storage.
- Flywheel energy storage.
- Battery/advanced battery energy storage.
- Capacitor or ultra-capacitor storage.

7) Ferro-resonant transformers

A constant voltage, or Ferro-resonant, transformer is normally a transformer with a 1: 1 turns ratio and with a core that is highly magnetized close to saturation under normal operation. The variation of primary voltage has a much-reduced effect on the secondary voltage; hence voltage sags do not significantly affect the output. The key power quality solution technologies centre on the development, in recent years, of higher-powered solid-state switching devices re becoming popular quality problems.

3.1 Introduction

Most commonly occurring power quality problems today are voltage sags and swells. As explained in previous chapter a voltage Sag is a decrease in rms voltage between 0.1 and 0.9 pu at power frequency for durations from 0.5 cycle to 1 min. And a voltage swell is increase in rms voltage between 1.1 and 1.8 pu at power frequency for durations from 0.5 cycle to 1 min. Despite a short duration, a small deviation from the nominal voltage can result in serious disturbances. Swells are not as common as sags for this reason voltage quality analysis deals with voltage sags. The majority of voltage sags are 4-10 cycles long and with a remaining voltage of 85-90% of the nominal voltage [3].

A three-phase voltage study of voltage sags, divide in to two main groups, balanced and unbalanced voltage sags. Balanced voltage sag has an equal magnitude in all phases and a phase shift of 120° between the voltages, as shown in Fig.3.1.

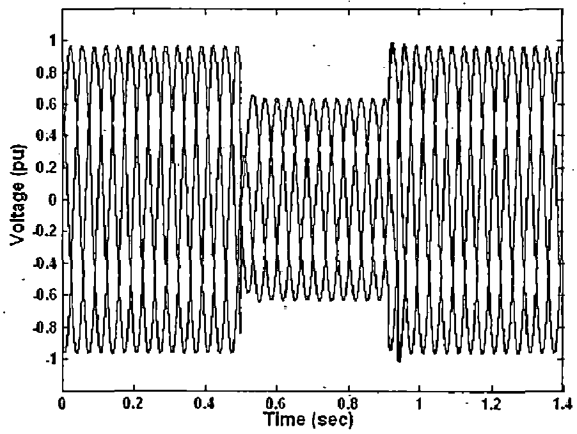


Fig.3.1 Balanced 3-phase voltage sag

Unbalanced voltage sags do not have the same magnitude in all phases or a phase shift of 120° between the phases. These types are more complicated and can be further divided into 6 subgroups. An example of unbalanced voltage sag caused by LLG fault is shown in Fig.3.2

In a system with large induction motors, voltage sag will not have a rectangular shape due to the behavior of the motors. It will also be prolonged because of the load behavior.

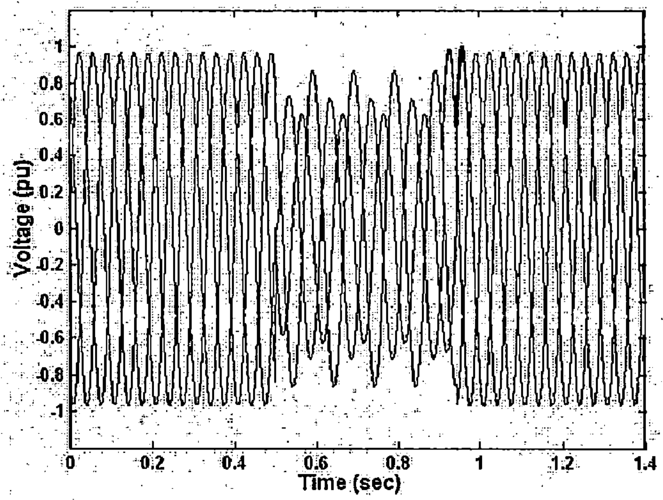


Fig.3.2 Unbalanced 3-phase voltage sag

3.2 Sources and Occurrence of Voltage Sags

The principal cause of all voltage sags is a short-duration increase in current. The main contributions are motor starting, transformer energizing, and faults (earth faults and short-circuit faults) [3]. Examples of voltage sags with different causes are shown in Fig.3.3 through 3.5. In these figures, the rms voltages are plotted instead of the voltages as a function of time. Fig.3.3 shows voltage sag due to motor starting: a rather small sudden drop in voltage, followed by a gradual recovery. As electrical motors are three-phase balanced loads, the voltage drops are the same in the three phases.

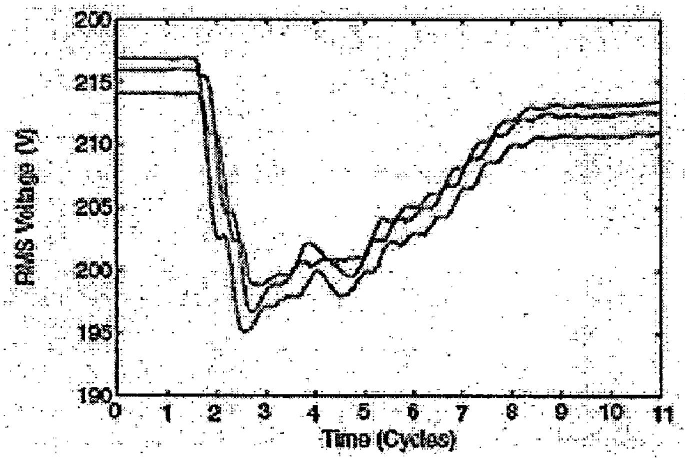


Fig.3.3 Voltage sag due to motor starting

The voltage sag shown in Fig.3.4 shows a sudden drop followed by a slow recovery. The drops are different in the three phases, however. This event is due to the energizing of a large transformer. The inrush current is different in the three phases and associated with large second and fourth harmonic distortion.

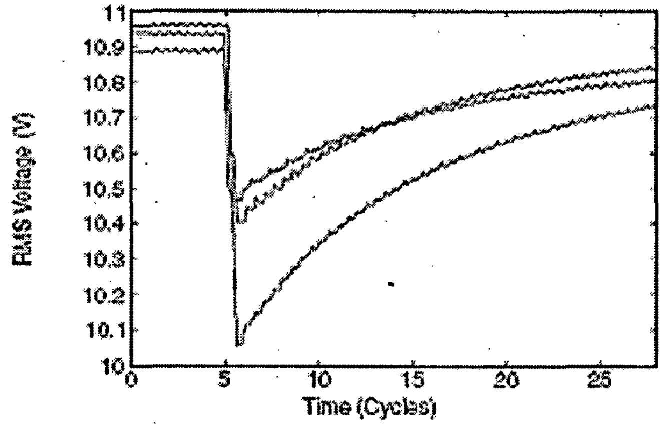


Fig.3.4 Voltage sag due to transformer energizing

The voltage sag shown in Fig.3.5 is due to a single-phase fault: the voltage drop is sharp in two phases and recovers sharply a few cycles later. Drop and recovery are associated with fault initiation and fault clearing, respectively. In this example, the voltage during the event is constant, and the voltage recovers immediately. This is not always the case. Some events show multiple stages due to developing faults or due to the breakers on both sides of a transmission line opening with some time delay.

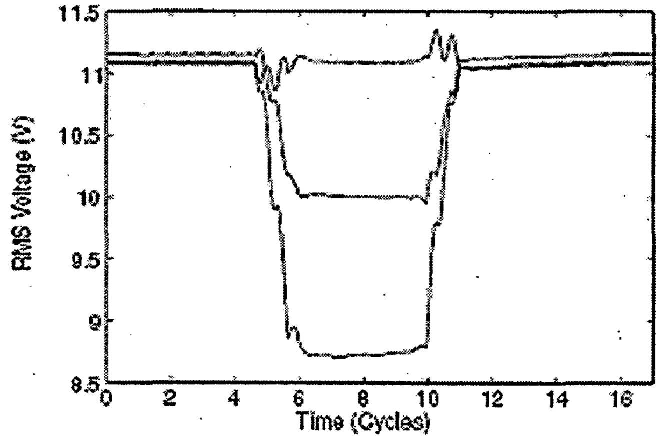


Fig.3.5 Voltage sag due to fault

3.3 Characterization of Voltage Sags

3.3.1 Sag Magnitude

The voltage magnitude during sag is commonly obtained by means of Root-Mean- Square (rms) method:

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_i^2} \tag{3.1}$$

Where N is the number of samples per cycle and v_i are the sampled voltages in time domain. Theoretically, the sag magnitude can also be calculated if the impedance of the power system network is known. Consider a simple radial circuit shown in Fig.3.6,

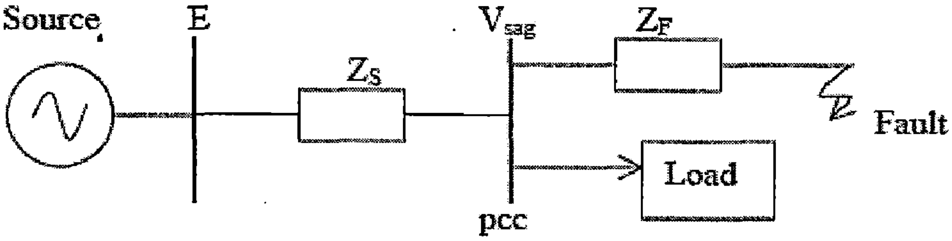


Fig.3.6 Simple radial circuit

By voltage divider rule, the voltage at the point of common coupling (pcc) during a fault on one of the feeder is given by:

$$V_{sag} = \frac{Z_F}{Z_S + Z_F}.E \tag{3.2}$$

Where E is the pre-fault voltage, Z_S is the source impedance as seen from the pcc, and Z_F is the impedance between the pcc and the fault.

When calculating voltage sag magnitude, the following should also be considered:

- The cross section of the transmission line or cable.
- The presence of a transformer between the fault and the pcc.

The above calculation is valid for radial systems. Nonetheless, it can also be extended for calculations in non-radial systems and meshed systems.

3.3.2 Sag Duration

The duration of voltage sag is determined by the fault-clearing time of the protective device. Usually, fault clearing in transmission systems are faster than in distribution systems. Typical fault-clearing time of various protective devices given below [18]:

Referring back to Fig.3.1, it could be seen easily that the duration of the sag due to a fault was around 500ms.

Table 3.1 Typical Clearing Times of Protective Devices

Type of Protective Device	Clearing Time in seconds	
	Typical Minimum	Typical Time Delay
Current-limiting fuse	<0.02	0.02 to 0.12
Expulsion Fuse	0.01	0.01 to 1.2
Electronic Recloser	0.06	0.02 to 0.6
Oil Circuit Breaker	0.1	0.02 to 1.2
Vacuum Breaker or SF_6	0.06	0.02 to 1.2

3.3.3 Three-Phase Unbalance

Most faults in power systems are single phase or two phases. Therefore we need to use the symmetrical components theory for the analysis of non-symmetrical faults. For all faults, the general equation is given by:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ V_F \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \quad (3.3)$$

Where V_F is the pre-fault voltage and the subscripts 0, 1, 2 represent zero, positive and negative sequence respectively.

Different types of faults lead to different types of voltage sags. Normally, voltage sag is characterized by a magnitude and duration. The magnitude and phase-angle jump of sags are directly related to the voltage in the faulted phase, or between faulted phases, at the point-of-common-coupling (pcc) between the load and the fault. For three-phase equipment, voltage sags come in seven basic types [3, 4]:

A balanced three-phase voltage sag will result in a type A. Since the voltage sag is balanced, the zero-sequence is zero, and a transformer will not affect the appearance of the voltage sag. This holds both for the phase-ground voltage and phase-to-phase-voltage. A phase-to-ground-fault will result in a type B. If there is a transformer that removes the zero-sequence between the fault location and the load, the voltage sag will be of type D. A phase-to-phase-fault results in a type C. The voltage sags of type E, F and G are due to a two-phase-to-ground-fault.

Voltage sag types due to three-phase, two-phase or l-g fault; phasor representation is shown in Fig.3.7, followed by phase voltage equations and listed in Table 3.2.

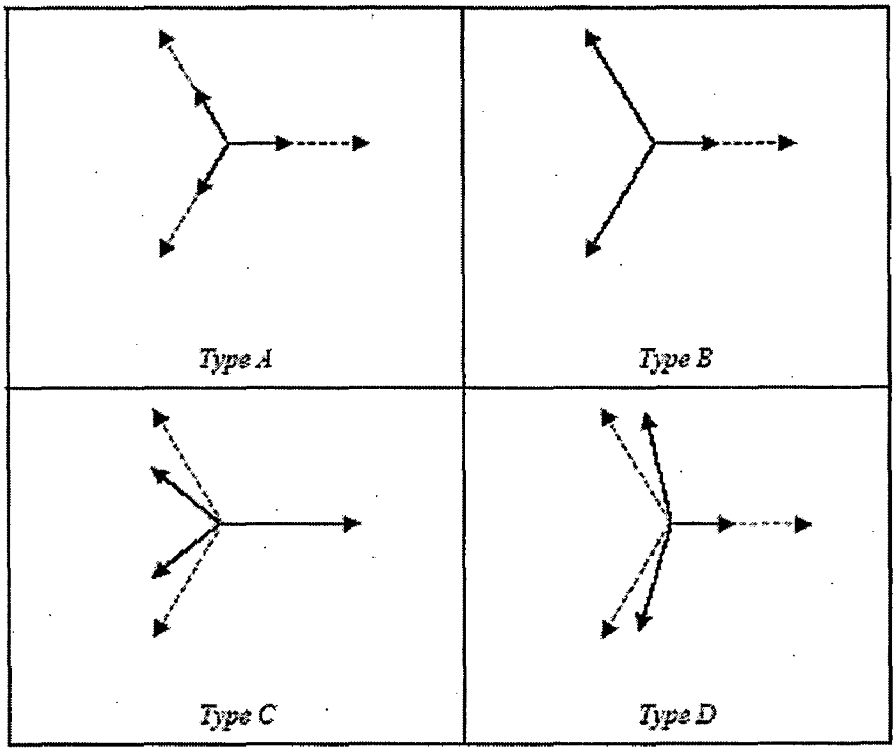


Fig.3.7 Four types of voltage sags due to 3ϕ or L-G fault

Type A	Type B
$\overline{V}_a = V$ $\overline{V}_b = -\frac{1}{2}V - \frac{\sqrt{3}}{2}jV$ $\overline{V}_c = -\frac{1}{2}V + \frac{\sqrt{3}}{2}jV$	$\overline{V}_a = V$ $\overline{V}_b = -\frac{1}{2} - \frac{\sqrt{3}}{2}j$ $\overline{V}_c = -\frac{1}{2} + \frac{\sqrt{3}}{2}j$
Type C	Type D
$\overline{V}_a = 1$ $\overline{V}_b = -\frac{1}{2} - \frac{\sqrt{3}}{2}jV$ $\overline{V}_c = -\frac{1}{2} + \frac{\sqrt{3}}{2}jV$	$\overline{V}_a = V$ $\overline{V}_b = -\frac{1}{2}V - \frac{\sqrt{3}}{2}j$ $\overline{V}_c = -\frac{1}{2}V + \frac{\sqrt{3}}{2}j$

Table 3.2 Different Types of Voltage Sags Due To 3ϕ, or L-G Fault

Sag type	Fault type
Type A	Three-phase
Type B	Single-phase-to-ground
Type C	Phase-to-phase
Type D	Phase-to-phase fault (experienced by a delta connected load), single-phase-to-ground (zero sequence-component removed)

Voltage sag types due to a two-phase-to-ground fault; phasor representation is shown in fig.3.7 followed by phase voltage equations, and listed in Table 3.3.

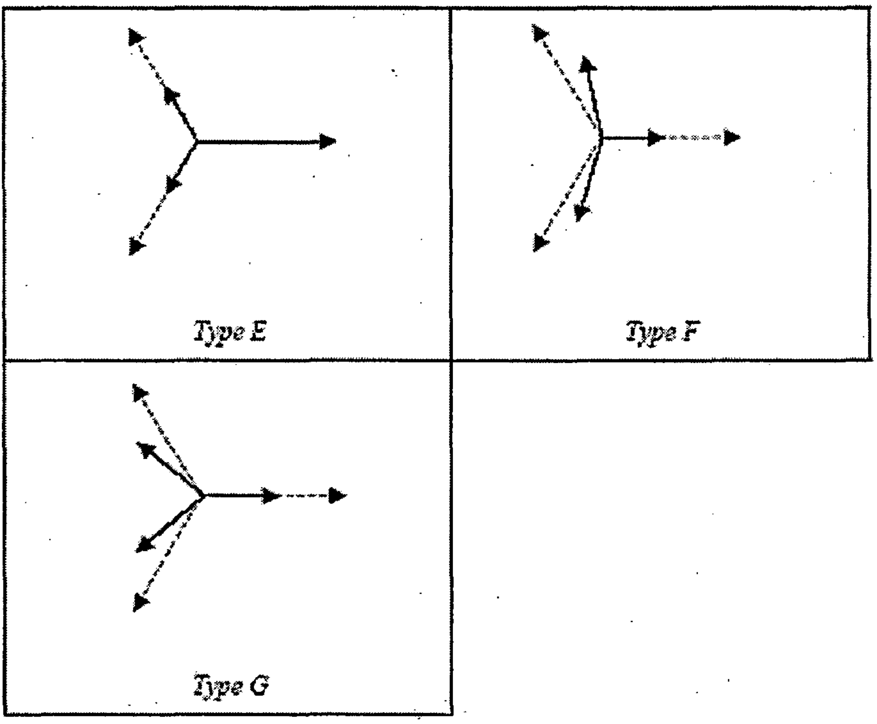


Fig.3.8 Three types of voltage sag due to L-L-G fault

Type E	Type F
$\overline{V}_a = 1$ $\overline{V}_b = -\frac{1}{2}V - \frac{\sqrt{3}}{2}jV$ $\overline{V}_c = -\frac{1}{2}V + \frac{\sqrt{3}}{2}jV$	$\overline{V}_a = V$ $\overline{V}_b = -\frac{1}{2}V - \frac{\sqrt{3}}{2}j\left(\frac{2}{3}+\frac{1}{3}V\right)V$ $\overline{V}_c = -\frac{1}{2}V + \frac{\sqrt{3}}{2}j\left(\frac{2}{3}+\frac{1}{3}V\right)V$
Type G $\overline{V}_a = \left(\frac{2}{3}+\frac{1}{3}V\right)$ $\overline{V}_b = -\frac{1}{2}\left(\frac{2}{3}+\frac{1}{3}V\right) - \frac{\sqrt{3}}{2}jV$ $\overline{V}_c = -\frac{1}{2}\left(\frac{2}{3}+\frac{1}{3}V\right) + \frac{\sqrt{3}}{2}jV$	

Table 3.3 Different Types of Voltage Sags Due To L-L-G-Fault

Sag type	Fault type
Type E	Two-phase-to-phase fault (experienced by a Wye connected load)
Type F	Two-phase-to-phase fault (experienced by a delta connected load)
Type G	Two-phase-to-phase fault (experienced by a load connected via a non- grounded transformer removing the zero-sequence the component)

5.3.4 Phase-Angle Jumps

Phase angle jumps are due to the difference in X/R ratio between the source and the feeder, and also due to the transformation of sags to lower voltage levels (effect of transformers) [5]. Fig.3.9 shows sag to 70% nominal and a phase-angle jump of +45^0 (i.e. the during-fault voltage leads the pre-fault voltage)

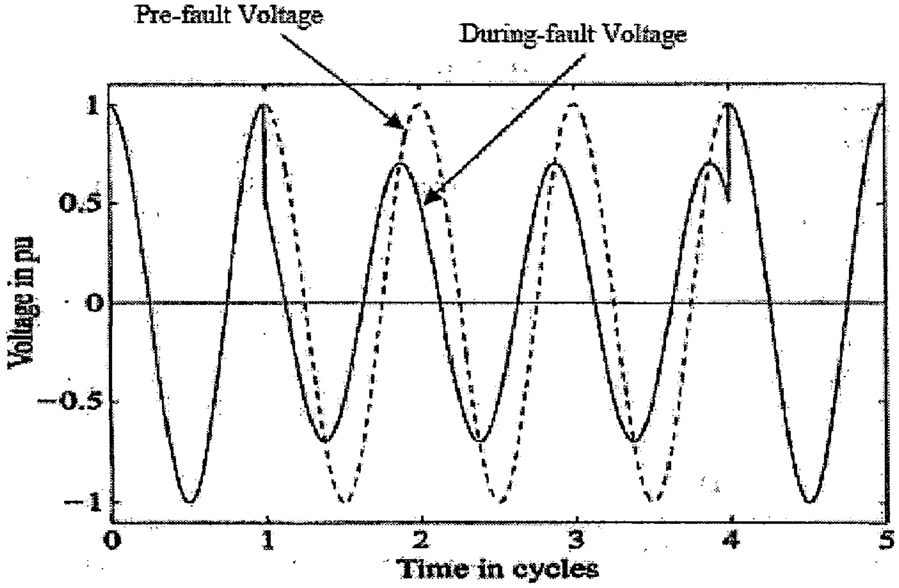


Fig.3.9 Sag with mag.70% nominal and a phase-angle jump of +45^0

From (3.2) considering pahse-angle jumps, the voltage at the pcc is:

$$\overline{V_{sag}} = \frac{\overline{Z_F}}{\overline{Z_S} + \overline{Z_F}}.E \tag{3.4}$$

where $\overline{Z_F} = R_F + jX_F$ is the complex impedance of the fault

$\overline{Z_S} = R_S + jX_S$ is the complex impedance of the source.

The phase-angle jump in the voltage $\overline{V_{sag}}$ is given by:

$$\nabla\phi = \arg(\overline{V_{sag}}) = \tan^{-1}\left(\frac{X_F}{R_F}\right) - \tan^{-1}\left(\frac{X_S + X_F}{R_S + R_F}\right) \tag{3.5}$$

As can be seen from (3.5), the phase-angle jump will be zero if $\frac{X_F}{R_F} = \frac{X_S}{R_S}$

3.4 Sensitivity of Equipment to Voltage Sags

Load susceptibility to rms voltage variations depends on the specific load type, control settings and applications. It is often very difficult to determine the likely cause of equipment malfunction from the characteristics of a given rms variation. An entire production process for example can be interrupted, if a single piece of equipment in the process fails due to a drop in voltage [6], even though the rms variation is within limit.

It has been reported that High Intensity Discharge lamps used for industrial illumination get extinguished at voltage sags of 20%. Even a sag magnitude of 90% could cause the variable frequency drives (VFDs) or programmable logic controllers (PLCs) on a large milling mill to "trip out", thereby causing lost production and costing company money.

According to [6] there are three main categories of sensitive equipment:

- Equipment sensitive to only the voltage during an rms variation (e.g. process controllers, motor drives controllers and undervoltage relays). This equipment is sensitive to the minimum voltage magnitude experienced during sag. The time during which this voltage is low is of less importance.
- Equipment sensitive to both the magnitude and duration of an rms variation (e.g. power electronics). The magnitude and duration that the rms voltage is below a specified threshold, at which the equipment trips are equally important.
- Equipment sensitive to characteristics other than magnitude and duration, such as transient oscillations and phase unbalance during the disturbance. The impacts of such characteristics on equipment are more difficult to generalize.

One has to realize that different categories of equipment and even different brands of equipment within a category are significantly different in terms of sensitivity to voltage sags. Hence, it is difficult to develop a single standard that defines the sensitivity of industrial process equipment. Some of the commonly adopted "standards" like the Computer Business Equipment Manufacturer Association (CBEMA) and Information Technology Industry Council (ITIC) curves are described below.

3.4.1 CBEMA Curve

The well-known "Computer Business Equipment Manufacturer Association (CBEMA) curve" shown in Fig.3.10, can be used to evaluate the voltage quality of a power system with respect to voltage interruptions, sags or under voltages and swells or over voltages. This curve was originally produced as a guideline to help CBEMA members in the design of the power supply for their computer and electronic equipment. By noting the changes of power supply voltage on the curve, it is possible to assess if the supply is reliable for operating electronic equipment [5], which is generally the most susceptive equipment in the power system.

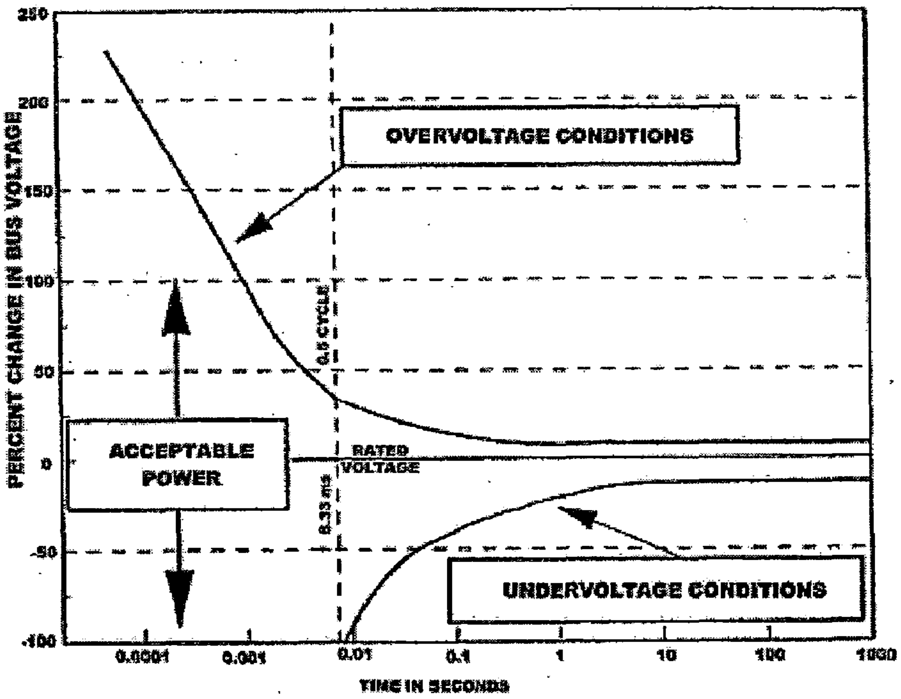


Fig.3.10 CBEMA Power acceptability curve

The curve shows the magnitude and duration of voltage variations on the power system. The region between the two sides of the curve is the tolerance envelope within which electronic equipment is expected to operate reliably. Rather than noting a point on the plot for every measured disturbance, the plot can be divided into small regions with certain range of magnitude and duration. The number of occurrences within each small region can be recorded to provide a reasonable indication of the quality of the system.

3.4.2 ITIC Curve

CBEMA has been renamed Information Technology Industry Council (ITIC), and a new curve, as shown in Fig.3.11 has been developed to replace CBEMA's. The main difference between them is that the ITIC version is piecewise and hence easier to digitize than the continuous CBEMA curve. The tolerance limits at different durations are very similar in both cases [5]. The boundary of the ITIC curve is defined by seven possible disturbance events.

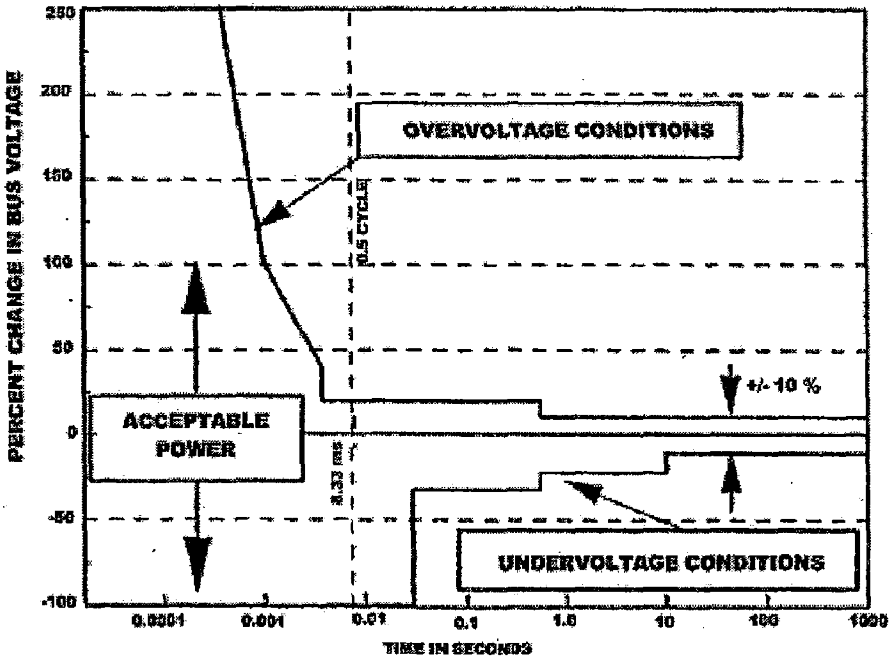


Fig.3.11 ITIC Power acceptability curve

Steady-state tolerances: This range describes an rms variation between ±10% from the nominal voltage, which is either very slowly varying or is constant. Any voltages in this range may be present for an indefinite period and are function of normal loadings and losses in the system.

Line voltage swell: This region describes an rms voltage rise of up to 120% of the rms nominal voltage, with duration of up to 0.5 s. This event may occur when large loads are removed from the system and when a single-phase fault occurs in the distribution part of the system.

Low-frequency decaying ring wave: This region describes a decaying ring wave transient, which typically results from the connection of power-factor-correction capacitors to a distribution system. The transient may have a frequency ranging from 200 Hz to 5 kHz, depending on the resonant frequency of the system. It is assumed to have completely decayed by the end of the half-cycle in which it occurs, and it occurs near the peak of the nominal voltage waveform. Its amplitude varies from 140% for 200-Hz ring waves to 200% for 5-kHz ring waves with a linear increase in amplitude with frequency.

High-frequency impulse and ring wave: This region describes the transients, which typically occur as a result of lightning strikes, and it is characterized by both peak value and duration (energy) rather than by rms value and duration.

Long duration voltage sags: down to 80% of nominal: These sags are the result of application of heavy loads, as well as fault conditions, at various points in the distribution system. They have a typical duration of up to 10 s.

Voltage sags down to 70% of nominal: These also result from heavy loads switching and system faults. Their typical duration is up to 0.5 s.

Dropout: This transient is typically the result of occurrence and subsequent clearing of faults in the distribution system. It includes both severe rms voltage sags and complete interruptions, followed by immediate re-application of the nominal voltage; a total interruption (i.e. zero voltage) should be tolerated by the equipment for up to 20 ms. Both the CBEMA and ITIC curves were specifically derived for use in the 60-Hz 120-V distribution voltage system.

3.5 Voltage Sag Mitigation Methods

In the previous sections we discussed voltage magnitude events (voltage sags, short interruptions, and long interruptions) in considerable detail: their origin, methods of characterization, and their effects on equipment. In this section we look at existing and future ways of mitigating voltage magnitude events. This can be done in a number of ways [7]:

1) Reducing the number of faults: There are several well-known methods for this, like tree-trimming, animal guards, and shielding wires. Replacing, overhead lines by underground cables, because fault rate on an underground cable is less than that of an overhead line. Increase the insulation level. This generally reduces the risk of short-circuit faults. Note that many short circuits are due to over voltages or due to a deterioration of the insulation. One has to keep in mind, however, that these measures may be very expensive and that its costs have to be weighted against the consequences of the equipment trips.

2) Faster fault clearing: Faster fault-clearing time does not reduce the number of events but only their severity. The ultimate reduction in fault-clearing time is achieved by using current-limiting fuses. Current-limiting fuses are able to clear a fault within one half-cycle, so that the duration of voltage sag will rarely exceed one cycle. The recently introduced static circuit breakers also gives a fault clearing time within one half-cycle; but it is obviously much more expensive than a current-limiting fuse. Much gain can be obtained in distribution networks, but at transmission level the fault-clearing time is already very short. Further improvement at transmission level would require the development of a new generation of circuit breakers and relays.

3) Improved network design and operation: The network can be changed such that a fault will not lead to severe sag at a certain location. Some examples of mitigation methods are: Installing a generator near the sensitive load. The generators will keep the voltage up during sag due to a remote fault. The reduction in voltage drop is equal to the percentage contribution of the generator station to the fault current. Feed the bus with the sensitive equipment from two or more substations. A voltage sag in one substation will be mitigated by the in-feed from the other substations. The more independent the substations are the more the mitigation effect. This has been a common practice in the design of industrial power systems, but not in the public supply. Also the use of very fast transfer switches can be seen as a network-based solution.

4) Mitigation equipment at the interface: The most commonly applied method of mitigation is the installation of additional equipment at the system-equipment interface. Recent developments point toward a continued interest in this way of mitigation. The popularity of mitigation equipment is explained by it being the only place where the customer has control over the situation. Some examples of mitigation equipment are:

- Uninterruptible power supplies (UPSs) are extremely popular for computers: personal computers, central servers, and process-control equipment.

- Motor-generator sets are often depicted as noisy and as needing much maintenance. But in industrial environments noisy equipment and maintenance on rotating machines are rather normal.
- Voltage source converters (VSCs) generate a sinusoidal voltage with the required magnitude and phase, by switching a dc voltage in a particular way over the three phases [8]. This voltage source can be used to mitigate voltage sags and interruptions.

5) Improved end-user equipment: Improvement of equipment immunity is probably the most effective solution against equipment trips due to voltage sags. But it is often not suitable as a short time solution. A customer often only finds out about equipment immunity after the equipment has been installed. For consumer electronics it is very hard for a customer to find out about immunity of the equipment as he is not in direct contact with the manufacturer. Some specific solutions toward improved equipment are:

- The immunity of consumer electronics, computers, and control equipment (i.e., single-phase low-power equipment) can be significantly improved by connecting more capacitance to the internal dc bus. This will increase the maximum sag duration, which can be tolerated.
- Single-phase low-power equipment can also be improved by using a more sophisticated dc/dc converter: one, which is able to operate over a wider range of input voltages. This will reduce the minimum voltage for which the equipment is able to operate properly.

For short interruptions, equipment immunity is very hard to achieve, for long interruptions it is impossible to achieve. The equipment should in so far be immune to interruptions that no damage is caused and no dangerous situation arises. This is especially important when considering a complete installation.

CHAPTER-4
CUSTOM POWER DEVICES

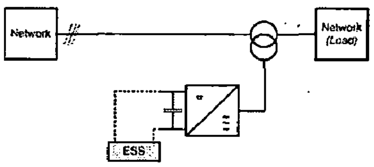
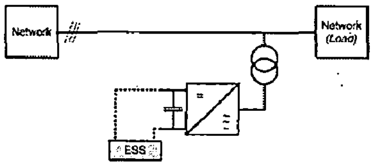
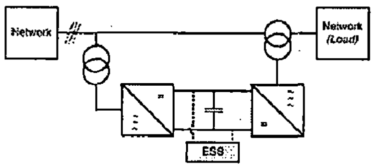
4.1 Introduction

The twin concepts of Flexible Alternating Current transmission Systems (FACTS) and Custom Power emerged from the Electric Power Research Institute (EPRI) in the late1980's. Ever since, both technologies have attracted great interest from equipment manufacturers, utilities and university research establishments. FACTS use the latest power electronic devices and methods to control electronically the high-voltage side of the network Custom Power focuses on low-voltage distribution, and it is a technology born in response to reports of 'poor power' quality and reliability of supply affecting factories, offices and homes. With Custom Power solutions in place, the end-user will see tighter voltage regulation, near-zero power interruptions, low harmonic voltages, and acceptance of rapidly fluctuating and other non-linear loads in the vicinity. The fruits of fully matured FACTS and Custom Power technologies are many and yet the issues to be resolved, at this point in time, are even greater. Once the incorporation of the new technology takes place in earnest, an increase in operational complexity is expected. The principle being to provide a "Total solution" strategy comprising more than one device coupled with software to achieve power control at the transmission level and signal conditioning at the distribution level.

Facts are primarily concerned with the control of power flow from generator to user. The use of fact devices helps increase in transmission capability by operating closer to the thermal limit. Because these devices effectively control the impedance of the lines, power can be directed along the desired paths reducing the 'strain' on certain networks during peak demand. Some of the FACTS devices are SVC, STATCOM and UPSC etc

Custom power, on the other hand, is dedicated to maintaining and improving the quality and reliability of distribution level power received and to protecting customers against disturbances generated by other users on the network [6]. The concept of custom power is to offer a 'total solution 'package to the customer, with in which will feature a number of integrated microprocessor controlled units 'tailored' to meeting the customers need. Custom power is concerned particularly with protecting critical and high security loads where an interruptible power supply is essential. The custom power devices technology centered on two particular power electronic devices; the Gate Turn Off (GTO) Thyristor and the Insulated Gate Bipolar Transistor (IGBT).The GTO switches are used to interrupt large voltage surges, voltage spikes and short circuit currents. Both are used as the switching element in the inverter units or voltage sourced generators, manufacturing voltage waveforms which can be injected into the line at any phase angle to either sustain or reduce the line voltage to the desired value. The pulse width and switching frequency determine the magnitude and phase of the input voltage [9, 10]. Some of the custom power devices are DVR, DSTATCOM and UPQC etc. Comparison between FACTS devices and custom power devices is summarized in Table 4.1.

Table 4.1 Equipment in Transmission and Distribution Networks

Name		Topology	Preferred Tasks	
Transmission	Distribution		Transmission	Distribution
SSSC (Static Synchronous Series Compensator)	DVR (Dynamic Voltage Restorer)		• power flow • transient stability • oscillation damping	• sag/swell compensation
STATCOM (Static Synchronous Compensator)	DSTATCOM (Distribution STATCOM)		• voltage control • oscillation damping • reactive power regulation	• sag/swell compensation • reactive power compensation • harmonic filter
UPFC (Unified Power Flow Controller)	UPQC (Unified Power Quality Controller)		• STATCOM and SSSC advantages	• under voltage / over voltage compensation • DSTATCOM and DVR advantages

Solid state technology is becoming more prominent in power transmission and distribution due to a variety of reasons GTO thyristors are:

- Self commutating devices
- Simple control schemes
- Real time operational capability
- No mechanical components
- Series operation for voltages and parallel operation for current capability.

The custom power devices themselves will be:

- Robust, versatile and compact, ideal for portable systems.
- Require a minimum of maintenance
- Compatible with condition monitoring systems
- Operationally efficient.

4.2 Custom Power Devices

Custom Power Devices classified into two types:

1) Network reconfiguring type.
2) Compensating type.

1) Network reconfiguring type:

These devices protect the source from the load,

1. Static Current Limiter (SCL)
2. Static Circuit Breaker (SCB)
3. Static Transfer Switches (STS)

2) Compensating type:

These devices protect the load from the source,

1. Distribution Static Compensator (DSTATCOM)
2. Dynamic Voltage Restorer (DVR)
3. Active Power Filter (APF)
4. Unified Power Quality Conditioner (UPQC)

Among these devices Dynamic Voltage Restorer (DVR), Distribution Static Compensator (DSTATCOM) and Active Power Filters (APF), contain voltage source converter (VSC) in them. VSC can solve many power quality problems very effectively.

4.2.1 Dynamic Voltage Restorer (DVR)

Dynamic Power's two principle Custom Power devices are the Dynamic Voltage Restorer (DVR) and the Distribution Static Compensator (DSTATCOM). They are complementary devices which provide simultaneous power control and power quality functions [11]. The DVR is best suited to protecting sensitive loads from incoming supply disturbances such as voltage sags. The DSTATCOM is ideal for protecting the distribution system from the effect of polluting loads, such as harmonics. Either device can be connected at any distribution voltage level to protect whole or large portions of a plant with a single solution. The DVR is a series voltage controller which consists of a voltage source converter in series with the supply voltage as shown in Fig.4.1.

At the heart of the DVR is a three phase voltage source inverter [9]: a solid state power electronics device which converts ac to dc and vice versa. By fast switching a dc source, the DVR is able to synthesize an ac waveform. The DVR constantly monitors incoming supply voltage and compares it with a reference voltage. In the event of a disturbance it injects three single-phase ac output voltages of compensatory amplitude, phase and harmonic content. This ensures that the voltage seen by the load is of the desired magnitude, preventing unnecessary process interruptions.

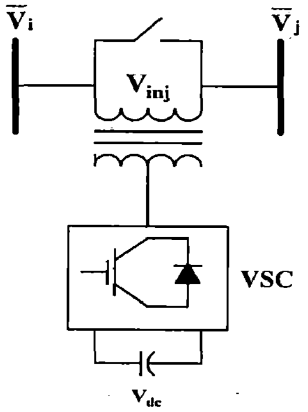


Fig.4.1 Configuration of DVR

The primary side of the DVR injection transformer is sized to carry the full line current. The primary voltage rating is the maximum voltage the DVR can inject into the line for a given application. The secondary voltage is controlled by three single phase bridge inverters, connected to a common dc link. The bridge outputs are filtered before being applied to the injection transformer and are independently controllable to allow each phase to be compensated separately.

Most voltage sags are asymmetric, or unbalanced. In such cases the DVR can draw energy from the high voltage phase(s) and transfer it to the low voltage phase(s). In the event of a more serious sag the DVR must exchange real power with the line and draws energy from an energy storage system [11]; normally a capacitor. Energy is exchanged between the dc link and storage capacitors by a dc to dc voltage conversion circuit. During normal line voltage conditions following the sag, the energy storage device is recharged from the ac system by the DVR. Reactive power exchanged between the DVR and the distribution system is internally generated by the DVR without any ac passive reactive components.

The DVR need not be fully rated to the load requirements. Installing a DVR capable of injecting an additional 50% rated voltage for a short period could effectively screen a load from the majority of sags, while the remainder would be sufficiently reduced in severity that plant equipment would be able to tolerate them [10]. For example, a 4MVA load capable of riding through sags of greater than 80% retained voltage could be protected by a 2MVA DVR from sags to as little as 30% retained voltage.

Principle of Operation [18]

Load voltage of the system is equal to sum of sag voltage and controller voltages,

$$\overline{V}_{load} = \overline{V}_{cont} + \overline{V}_{sag} \tag{4.1}$$

we assume that the voltage at the load terminals is 1pu along the positive real axis $\overline{V}_{load} = 1 + j0$ the load current is 1 pu in magnitude, with a lagging power factor

$$\overline{I}_{load} = \cos\phi - j\sin\phi \tag{4.2}$$

The voltage sag at the system side of the controller has a magnitude v and phase angle jump ψ

$$\overline{V}_{sag} = V\cos\Psi + jV\sin\Psi \tag{4.3}$$

The complex power taken by load is found from

$$P_{load} + jQ_{load} = \overline{V}_{load}\overline{I}^{*}{}_{load} = \cos\Phi + j\sin\Phi \tag{4.4}$$

The complex power taken from the system is

$$P_{sys} + jQ_{sys} = V\cos(\Phi + \Psi) + jV\sin(\Phi + \Psi) \tag{4.5}$$

The active power that needed to be generated by the controller is the difference between the active power taken from the system and the active part of the load:

$$P_{cont} = P_{load} - P_{sys} \tag{4.6}$$

This can be written as

$$P_{cont} = \left[1 - \frac{V\cos(\Phi + \Psi)}{\cos\Phi}\right] \times P_{load} \tag{4.7}$$

The active power requirement is linearly proportional to the drop in voltage. When phase-angle jumps are considered the relation is no longer linear and becomes depending on the power factor also. A series voltage controller does not function during an interruption. It needs a closed path for the load current, which is not always present during an interruption.

4.2.2 Distribution Static Compensator (DSTATCOM)

D-STATCOM or distribution STATCOM is a custom power device, used for mitigating voltage sags and compensating the reactive power. It is also capable of flicker and harmonics mitigation [12, 13]. The DSTATCOM mainly consists of DC voltage source behind self-commutated inverters using IGBT and coupling transformer. The IGBT inverter with a DC voltage source can be modeled as a variable voltage source. The distribution power system can also be modeled as a voltage source. Two voltage sources are connected by a reactor representing the leakage reactance of the transformer.

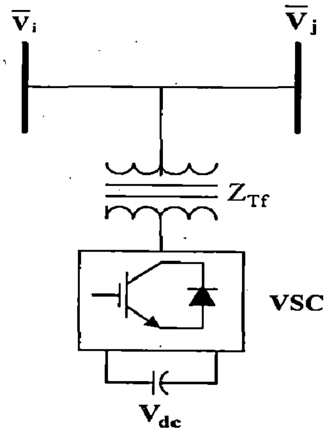


Fig.4.2 Configuration of DSTATCOM

A DSTATCOM is connected in shunt with the distribution feeder as shown in Fig.4.2. It generates a current injection, which is summed to the non-sinusoidal load current. Thus the phase currents taken from the grid will be nearly sine wave. If DSTATCOM does not contain any active power storage and thus only injects or draws reactive power. Limited voltage sag mitigation is possible with the injection of reactive power only, but active power needed if both magnitude and phase angle of the pre-event voltage need to be kept constant [13]. The device rating determines the maximum total current, which can be injected. In case an energy storage is connected to the DSTATCOM also its capacity needs to be rated. DSTATCOMs equipped with energy storage and additional high-speed switchgear is able to inject also active power and thus support the load even during an interruption on the grid side. The steady state model of analyzing the rms voltages and currents, fundamental frequency power and energy flows, applies to DSTATCOMs. Another type of power quality analysis can also be performed with devices developed for harmonics mitigation.

Principle of Operation [18]

Assume that the voltage without controller is

$$\overline{V}\mathrm{sag} = V\cos\psi + jV\sin\psi \tag{4.8}$$

The load voltage is again equal to 1pu $\overline{V} = 1 + j0$. The required change in voltage due to the injected current is the difference between the load voltage and the sag voltage

$$\Delta\overline{V} = 1 - V\cos\Psi - JV\sin\Psi \tag{4.9}$$

This change in voltage must obtained by injecting current equal to $\overline{I}_{cont} = P - jQ$, with P he active power and Q he reactive power injected by the controller. The active power will determine the requirements for energy storage. Let the impedance seen by the shunt controller be equal to $\overline{Z} = R + jX$. The effect of the injected current is change in voltage according to

$$\Delta\overline{V} = \overline{I}_{cont}\overline{Z} = (R + jX)(P - jQ) \tag{4.10}$$

The required voltage increase and the achieved increase have to be equal. This gives the following expression for the injected complex power.

$$P - jQ = \frac{1 - V\cos\Psi - jV\sin\Psi}{R + jX} \tag{4.11}$$

Splitting the complex power in a real and an imaginary part, gives expressions for active and reactive power

$$P = \frac{R(1 - V\cos\Psi) - VX\sin\Psi}{R^2 + X^2} \tag{4.12}$$

$$Q = \frac{RV\sin\Psi + X(1 - V\cos\Psi)}{R^2 + X^2} \tag{4.13}$$

The main limitation of the shunt controller is that source impedance becomes very small for faults at the same voltage level close to the load. Mitigating such sags through a shunt controller is impractical as it would require very large currents.

The main disadvantage of the shunt controller is its high active power demand. In case of a large load with a dedicated supply from a transmission net work shunt controller is feasible. Another disadvantage of the shunt controller is that it not only increases the voltage for the local load but for all loads in the system. The behavior of the shunt voltage controller during an interruption depends upon amount of load involved in the interruption [11]. If the controller is able to maintain the load during the interruption, synchronization problems can occur when the voltage comes back.

4.2.3 Active Power Filters (APF)

Passive filters have been most commonly used to limit the flow of harmonic currents in distribution systems. They are usually custom designed for the application. However, their performance is limited to a few harmonics, and they can introduce resonance in the power system. Among the different new technical options available to improve power quality, active power filters have proved to be an important and flexible alternative to compensate for current and voltage disturbances in power distribution systems. Fig.4.3 shows the connection of shunt active power filter.

The idea of active filters is relatively old, but their practical development was made possible with the new improvements in power electronics and microcomputer control strategies as well as with cost reduction in electronic components. Active power filters are becoming a viable alternative to passive filters and are gaining market share speedily as their cost becomes competitive with the passive variety. Through power electronics, the active filter introduces current or voltage components, which cancel the harmonic components of the nonlinear loads or supply lines, respectively. Different active power filters topologies have been introduced and many of them are already available in the market.

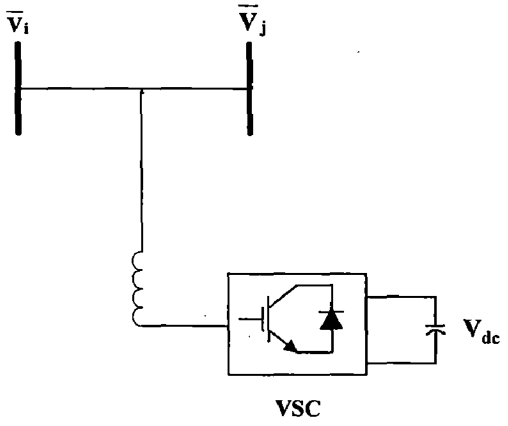


Fig.4.3 Configuration shunt APF

Active Power Filter Topologies:

The simplest method of harmonic filtering is with passive filters. They use reactive storage components, namely capacitors and inductors. Among the more commonly used passive filters are the shunt-tuned LC filters and the shunt low-pass LC filters. They have some advantages such as simplicity, reliability, efficiency, and cost. Among the main disadvantages are the resonances introduced into the ac supply; the filter effectiveness, which is a function of the overall system configuration; and the tuning and possible detuning issues. These drawbacks are overcome with the use of active power filters. Most of the active power filter topologies use voltage source converters, which have a voltage source at the dc bus, usually a capacitor, as an energy storage device Converts, a dc voltage into an ac voltage by appropriately gating the power semiconductor switches. Although a single pulse for each half cycle can be applied to synthesize an ac voltage, for most applications requiring dynamic performance, pulse width modulation (PWM) is the most commonly used today. PWM techniques applied to a voltage source inverter consist of chopping the dc bus voltage to produce an ac voltage of an arbitrary waveform. There are a large number of PWM techniques available to synthesize sinusoidal patterns or any arbitrary pattern. With PWM techniques, the ac output of the filter can be controlled as a current or voltage source device.

a) Shunt Active Filters

The shunt-connected active power filter, with a self-controlled dc bus, has a topology similar to that of a static compensator (STATCOM) used for reactive power compensation in power transmission systems. Shunt active power filters compensate load current harmonics by injecting equal-but opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase-shifted by 180°.

b) Series Active Filters

Series active power filters were introduced by the end of the 1980s and operate mainly as a voltage regulator and as a harmonic isolator between the nonlinear load and the utility system. The series-connected filter protects the consumer from an inadequate supply-voltage quality. This type of approach is especially recommended for compensation of voltage unbalances and voltage sags from the ac supply and for low-power applications and represents an economically attractive alternative to UPS, since no energy storage (battery) is necessary and the overall rating of the components is smaller. The series active filter injects a voltage component in series with the supply voltage and therefore can be regarded as a controlled voltage source, compensating voltage sags and swells on the load side. In many cases, series active filters work as hybrid topologies with passive LC filters. If passive LC filters are connected in parallel to the load, the series active power filter operates as a harmonic isolator, forcing the load current harmonics to circulate mainly through the passive filter rather than the power distribution system. The main advantage of this scheme is that the rated power of the series active filter is a small fraction of the load kVA rating, typically 5%. However, the apparent power rating of the series active power filter may increase in case of voltage compensation. Fig4.8 shows the connection of a series active power filter. Series filters can also be useful for fundamental voltage disturbances. The load voltage remains almost constant, and only small instabilities and oscillations are observed during initial and final edges of disturbance.

c) Series shunt active filter:

As the name suggests, the series-shunt active filter is a combination of the series active filter and the shunt active filter. And it does the work of both series and shunt active filters operation.

4.3 Voltage Source Converter (VSC)

A Voltage Source Converter (VSC) is a power electronic device, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. Voltage source converters are widely used in adjustable-speed drives, but can also be used to mitigate voltage sags. The VSC is used to either completely replace the voltage or to inject the 'missing voltage'. The 'missing voltage' is the difference between the nominal voltage and the actual. Basic configuration of VSC is shown in Fig.4.4.

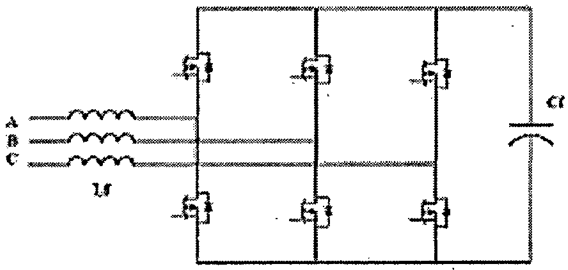


Fig.4.4 Configuration of VSC

The converter is normally based on some kind of energy storage, which will supply the converter with a DC voltage. The solid-state electronics in the converter is then switched to get the desired output voltage. Normally the VSC is not only used for voltage sag mitigation, but also for other power quality issues, e.g. flicker and harmonics.

4.4 Sinusoidal PWM Based Control

The VSC switching strategy is based on a sinusoidal PWM technique which offers simplicity and good response. Since custom power is a relatively low-power application, PWM methods offer a more flexible option than the fundamental frequency switching (FFS) methods favored in FACTS applications. Besides, high switching frequencies can be used to improve on the efficiency of the converter, without incurring significant switching losses.

In order to control the semiconductors of the PWM Inverter, a triangular reference signal along with a sinusoidal reference signal are used to determine the switching times for the semiconductors. These inputs are compared and will control the ON/OFF states of the semiconductors.

4.4.1 Sinusoidal Pulse Width Modulation (SPWM)

The sinusoidal PWM method is very popular for industrial inverters and is implemented in this thesis. Fig.4.5 explains the general principle of SPWM, where an isosceles triangular carrier wave of frequency f_c is compared with the fundamental f sinusoidal modulating wave [19], and the points of intersection determines the switching points of power devices shown in figure. For example, v_{ao} fabrication by switching upper and lower switches of half-bridge inverter. This method is known as the triangulation method. The notch and pulse widths of v_{ao} wave vary in a sinusoidal manner so that the average or fundamental component frequency is the same as f and its amplitude is proportional to the command modulating wave.

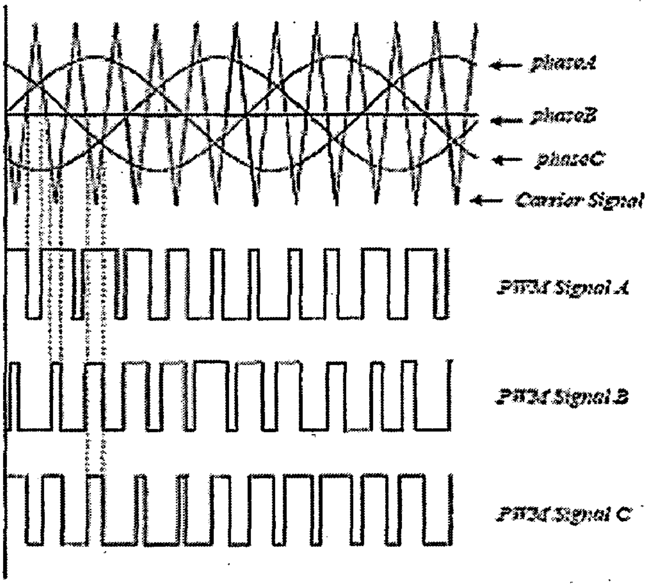


Fig.4.5 Three-phase SPWM with triangular carrier

The same carrier wave can be used for all three-phases. The typical wave shape of line and phase voltages for an isolated neutral load can be plotted graphically. The Fourier analysis of the v_{ao} wave is to be the following form:

$$v_{ao} = 0.5mV_{dc}\sin(\omega t+\phi)+high-frequency(M\omega_c \pm N\omega)terms \qquad (4.14)$$

where m = modulation index, ω = fundamental frequency in rad/sec and Φ = phase shift of output, depending on the position of the modulating wave. The modulation index is defined as:

$$m = \frac{V_P}{V_T} \tag{4.15}$$

where V_P = peak value of the modulating wave and V_T = peak value of the carrier wave. Ideally, m can be varied from 0 to 1 to give linear relation between the modulating and output wave. The inverter basically acts as a linear amplifier. Combining the above two equations 4.14 and 415 the amplifier gain u_f is given as

$$u_f = \frac{0.5mV_d}{V_P} = \frac{0.5V_d}{V_T} \tag{4.16}$$

At m = 1, the maximum value of fundamental peak voltage is $0.5V_d$, which is 78.55% of the peak voltage ($4V_d/2\pi$) of the square wave. In fact, the maximum value in the linear range can be increased to 90.7% of the square wave by mixing the appropriate values of the triplen harmonics with the modulating wave. This is carrier based PWM method where the switching frequency is fixed,

CHAPTER-5

SIMULATION OF DVR AND DSTATCOM

5.1 Introduction

In the previous chapter we have discussed about types of custom power devices, among them DVR and DSTATCOM are most effective devices to solve many power quality problems. Both devices have voltage source converter in them, and the operation of this voltage source converter is depends on the switching pulses of IGBT gates. Till today there are so many control schemes are proposed for the control of voltage source converter. In this work a direct voltage controller is simulated for control of switching pulses of DVR and DSTATCOM. Although a directly controlled converter is more difficult and expensive to implement than an indirectly controlled converter, which requires only measurement of the rms voltage at load point, the former presents superior dynamic performance with measurements of rms voltage and current at load point.

5.2 Simulation of DVR and DSTATCOM

In this work, the performance of VSC based power devices acting as a voltage controller is investigated. Moreover, it is assumed that the converter is directly controlled (i.e., both the angular position and the magnitude of the output voltage are controllable by appropriate on/off signals) for this it requires measurement of the rms voltage and current at the load point.

5.2.1 Dynamic Voltage Restorer (DVR)

In its most basic form, the DVR configuration consists of a VSC, a dc energy storage device and a coupling transformer connected in series with the ac system, and associated control circuits. Fig.5.1 shows the schematic representation of the DVR connected to a 25kV distribution system. Internal model of DVR is presented in Appendix-B. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages [14]. These voltages are in phase and coupled with the ac system through the series-coupling transformer. Suitable adjustment of the phase and magnitude of the DVR output voltages allows effective control of voltage restoration of distribution system.

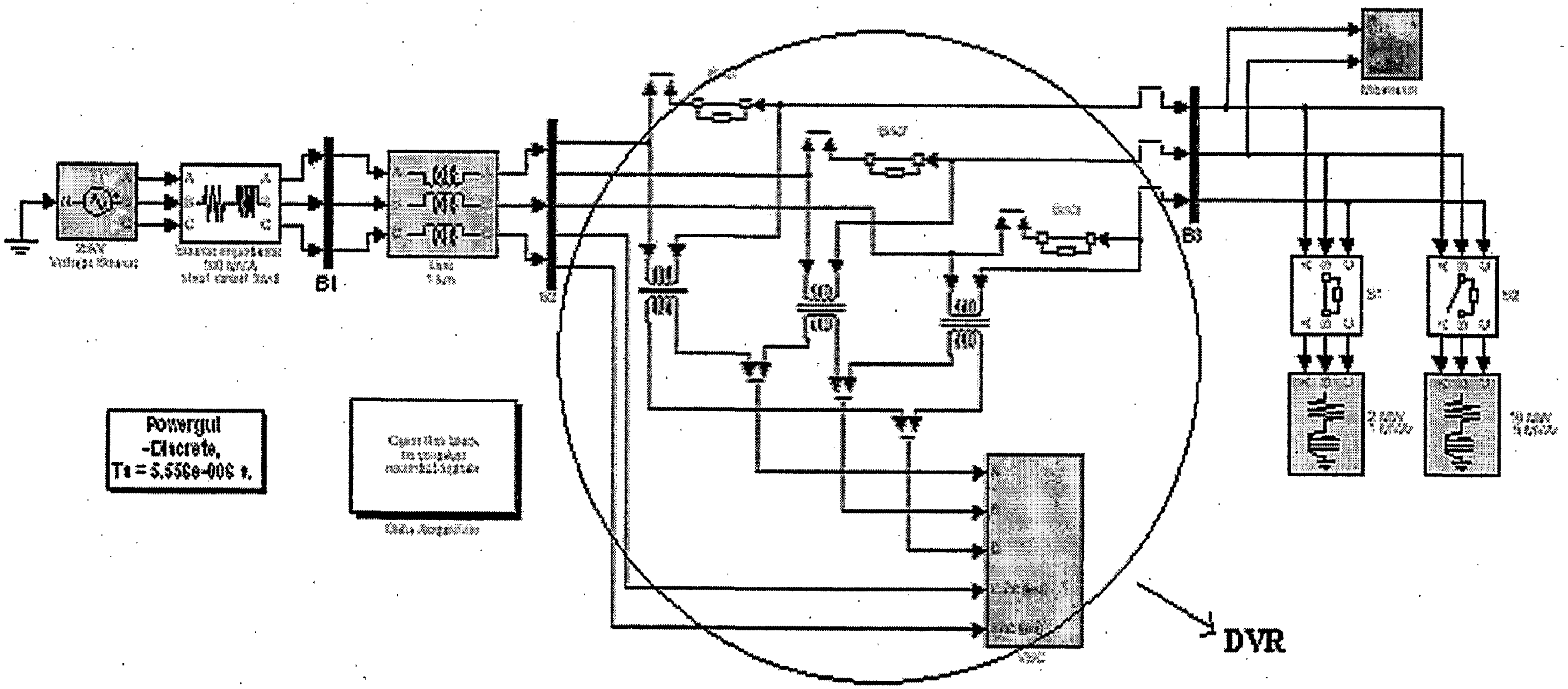


Fig.5.1 DVR connected to 25kVdistribution system

The design approach of the control system determines the priorities and functions developed in each case. In this thesis, the DVR is used to regulate voltage at the point of connection. The direct control is based on sinusoidal PWM and it requires the measurement of the rms voltage and current at the load point as explained in Section 5.3.

5.2.2 Distribution Static Compensator (D-STATCOM)

The DSTATCOM is commonly used for voltage sags mitigation and harmonic elimination at the point of connection. The DSTATCOM employs the same blocks as the DVR, but in this application the coupling transformer is connected in shunt with the ac system, as illustrated in Fig. 5.2. The VSC generates a three-phase ac output current which is controllable in phase and magnitude [14]. These currents are injected into the ac distribution system in order to maintain the load voltage at the desired voltage reference. Active and reactive power exchanges between the the VSC connected in shunt with the ac system provides a multifunctional topology which can be used for up to three quite distinct purposes [15]:

1) Voltage regulation and compensation of reactive power;
2) Correction of power factor;
3) Elimination of current harmonics.

The main features of the DSTATCOM control scheme implemented in this thesis are explained in Section 5.3. Internal model of DSTATCOM is presented in Appendix-B.

5.3 PWM Based Model of VSC

In the PWM based model, the switching elements–IGBTs/diodes, the PWM signal generator and the dc capacitor are explicitly represented. Considering the DSTATCOM and DVR as a voltage controller, the detailed model is shown in Fig.5.3. Such a model consists of a six-pulse voltage-source converter using IGBTs/diodes, a 10000-μF dc capacitor, a PWM signal generator with switching frequency equal to 3 kHz, a passive filter to eliminate harmonic components, and a voltage controller as that shown in Fig.5.4. The dc voltage (V_{dc}) is measured and sent to the controller as well as the three-phase terminal voltages (V_{ABC}) and the injected three-phase currents (I_{abc}). V_a, V_b and V_c are voltages at the converter output.

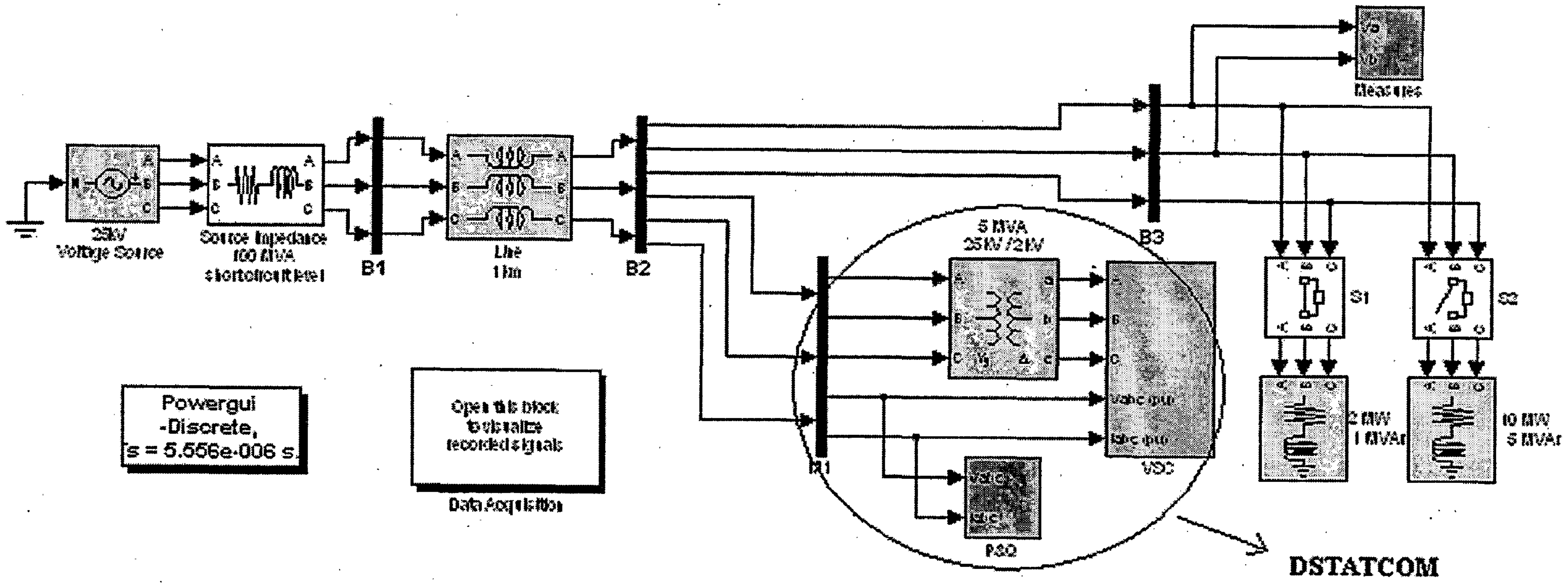


Fig.5.2 DSTATCOM connected to 25kVdistribution system

For the DSTATCOM when the simulation starts, the DC capacitor starts charging. This requires Id component corresponding to the active power absorbed by the capacitor. When the DC voltage reaches its reference value, the Id component drops to a value very close to zero and the Iq component stays at the 1 pu reference value. In the case of the DVR, a constant dc source is provided across the capacitor for charging the capacitor to dc voltage reference value.

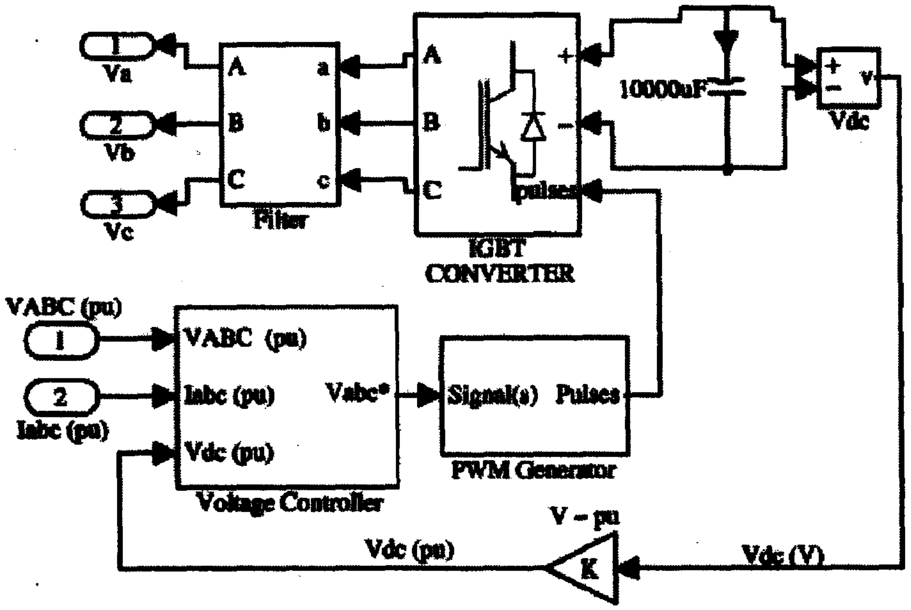


Fig. 5.3 PWM based model of VSC

5.4 Voltage Controller of DVR and DSTATCOM

This section describes the PWM-based control scheme with reference to the DVR. The control scheme for the DSTATCOM follows the same principle. The aim of the control scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected, under system disturbances.

The voltage controller analyzed in this work is exhibited in Fig.5.4, and its sim power systems implementation is presented in Appendix-B. Which employs the dq0 rotating reference frames because it offers higher accuracy than stationary frame based techniques [16]. In this figure, V_{ABC} are the three-phase terminal voltages, I_{abc} are the three-phase currents injected by the devices into the network, V_{rms} is the rms terminal voltage, Vdc is the dc voltage measured in the capacitor and the superscripts * indicate reference values. Such controller employs a PLL (Phase Locked Loop) to synchronize the three-phase voltages at the converter output with the zero crossings of the fundamental component of the phase-A terminal voltage. Therefore, the PLL provides the angle φ to the abc-to-dq0 (and dq0-to-abc) transformation. There are also four PI regulators. The first one is responsible for controlling the terminal voltage through the reactive power exchange with the ac network

This PI regulator provides the reactive current reference Iq*, which is limited between +1 pu capacitive and -1 pu inductive. This regulator has one droop characteristic, usually ±5%, which allows the terminal voltage to suffer only small variations. Another PI regulator is responsible for keeping constant the dc voltage through a small active power exchange with the ac network, compensating the active power losses in the transformer and inverter. This PI regulator provides the active current reference Id*.

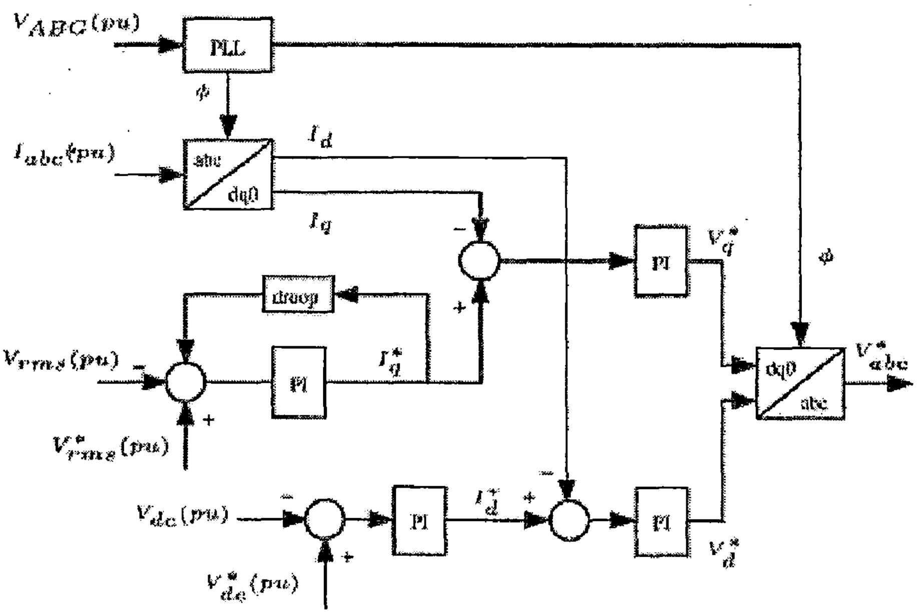


Fig. 5.4 Voltage controller of DVR and DSTATCOM

The other two PI regulators determine voltage reference Vd* and Vq*, which are sent to the PWM signal generator of the converter, after a dq0-to-abc transformation. Finally, Vabc* are the three-phase voltages desired at the converter output.

5.5 Energy Conversion Principle Model of VSC

In the energy conversion principle model of VSC; the converter, the PWM signal generator, and the filter are replaced by a set of three controllable ac voltage sources. Such sources are controlled by the signal V_{abc}^* obtained from the controller. However, the three-phase voltages at the converter output, in volts, are dependent on the dc link voltage [16] (i.e., Va= $KV_{dc}V_b^*$, and $V_c = KV_{dc}V_c^*$, where K depends on the kind of converter).

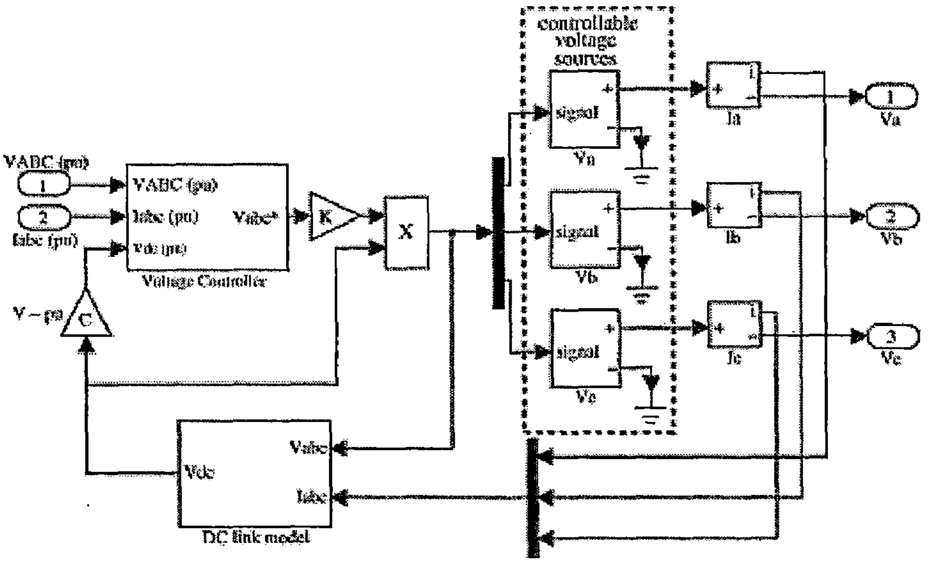


Fig.5.5 Energy conversion principle model of VSC

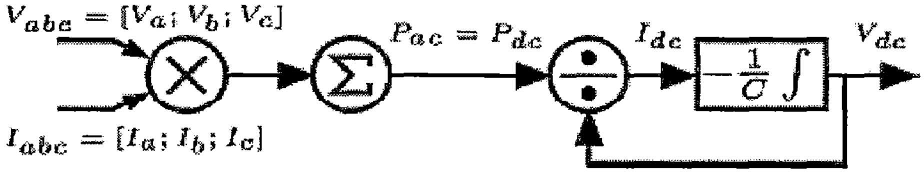


Fig.5.6 DC link model

Therefore, it is important that the dc link dynamic be correctly represented. This can be carried out by applying the energy conservation principle, which resides in the physical fact that, neglecting the converter losses, the instantaneous power at the ac output terminals must always be equal to the instantaneous power at the dc input terminal

Such principles can be expressed by

$$V_{dc}I_{dc} = V_aI_a + V_bI_b + V_cI_c \tag{5.1}$$

Where I_{dc} is the current in the dc link, Moreover, the relationship between V_{dc} and I_{dc} is given by (2), where C is the dc capacitance value. Equations (5.1) and (5.2) can be iteratively solved by means of an algebraic-differential loop, as schematically depicted in Fig.5.6

$$V_{dc} = -(\frac{1}{C}) \int I_{dc} dt \tag{5.2}$$

The implementation of the energy conversion principle model of VSC using Sim Power Systems is shown in Fig.5.5 where a voltage controller case is assumed. In this figure, there is a voltage controller as described in Fig.5.4, a set of three controllable ac voltage sources, and a dc link model as exhibited in Fig.5.6. Note that the three-phase currents and voltages injected to the network are measured and sent to the dc link model. Moreover, the reference voltage of the controller is multiplied by a constant K to take into account the relationship among the rms voltage, modulation index, and dc voltage of a six-pulse voltage-source converter.

CHAPTER-6

RESULTS AND DISCUSSION

6.1 Introduction

The test system is shown in Fig.6.1 is used for comparing the performance of DVR and DSTATCOM. Such a system is comprised of a 25-kV, 100-MVA, 60-Hz substation, represented by a Thevenin equivalent, feeding a distribution network through a transmission line. At load point a small load of 2MW, 1MVar and a large load 10MW, 5MVar are connected through switches S1 and S2 respectively. The simulation models of this system are presented in Appendix-B. Performance of the devices can be obtained by opening and closing these switches and varying the terminal voltage at bus 2.

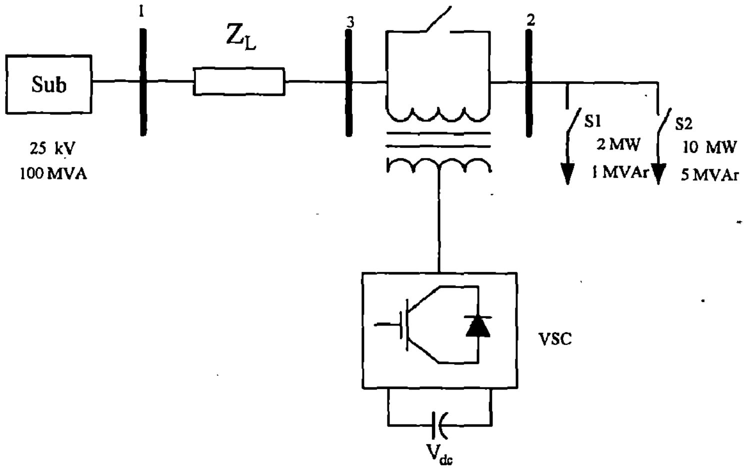


Fig.6.1 (a) Single-line diagram of the test system with DVR

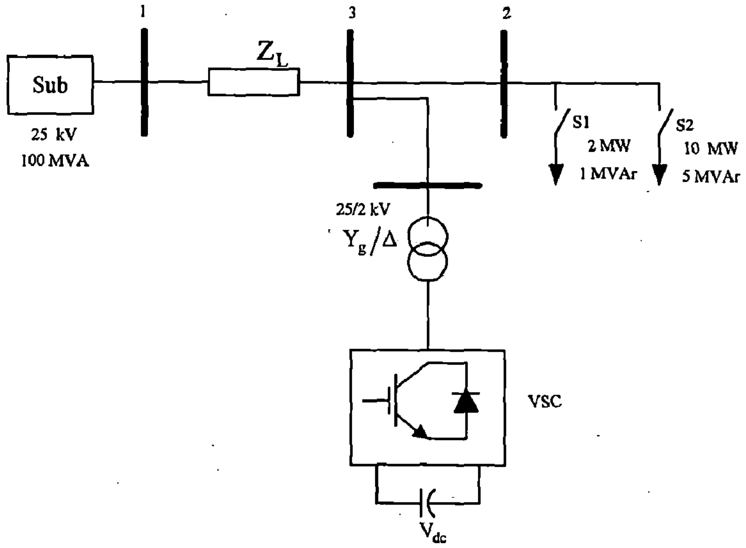


Fig.6.1 (b) Single-line diagram of the test system with DSTATCOM

6.2 Balanced Voltage Sag

The sequence of events simulated is explained as follows: Initially, there is a permanent load of 2MW, 1MVar connected at bus 2. Here bus 3 is taken for only connecting devices to the distribution system. At t=350ms, a large load is connected to the system by closing switch S2, and it is opened at 650ms. During this event, the terminal voltage of bus 2 decreases. The phase to phase and rms value of the terminal voltage of bus 2 for this event described is shown in Fig.6.2. Here the sag obtained is balanced sag and voltage decrease in each phase is equal in magnitude of 90% rated voltage. In the absence of the DVR and DSTATCOM, the terminal voltage varies considerably, but such variations are minimized in the presence of the DVR and DSTATCOM. Using the facilities available in MATLAB the DVR is simulated to be in operation only for the duration of the over loading, as it is expected to be the case in a practical situation. The results for both simulations are shown in Fig.6.3 and Fig.6.4 respectively.

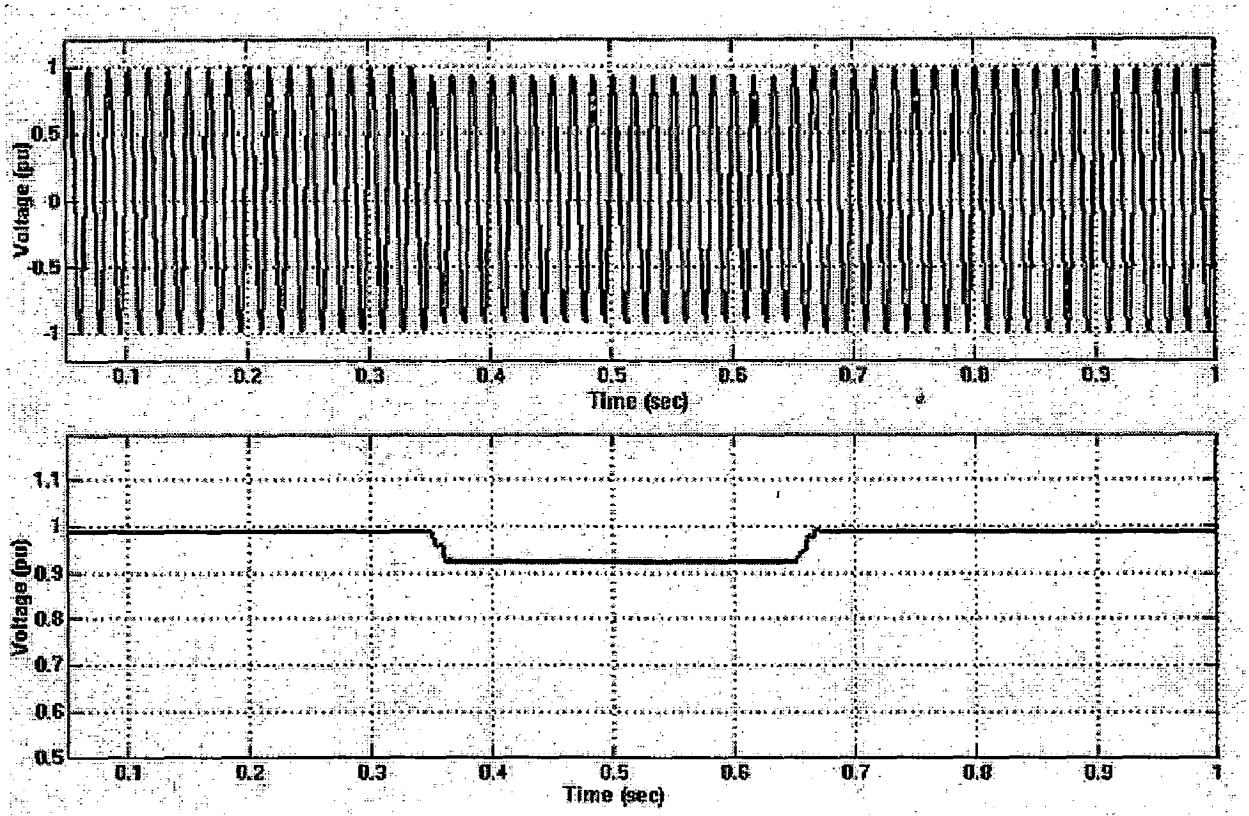


Fig.6.2 Phase-to-phase and rms voltages at bus 2 with out compensation

When the DVR is in operation the voltage sag is mitigated almost completely, and the rms voltage at the sensitive load point is maintained almost at 100%, as shown in Fig.6.3 (a). The PWM control scheme controls the magnitude and the phase of the injected voltages, restoring the rms voltage very effectively. Fig.6.3 (b) shows the waveforms of inverter voltage and current at ac side and capacitor voltage at dc side.

Similarly when the DSTATCOM is in operation the rms voltage at the sensitive load point is maintained at 100%, as shown in Fig.6.4 (a). The sag mitigation is performed with a smooth, and stable, DSTATCOM response. Fig.6.4 (b) shows the waveforms of inverter voltage and current at ac side and capacitor voltage at dc side. At the time of sag DSTATCOM injected current in to the system and restored the load voltage.

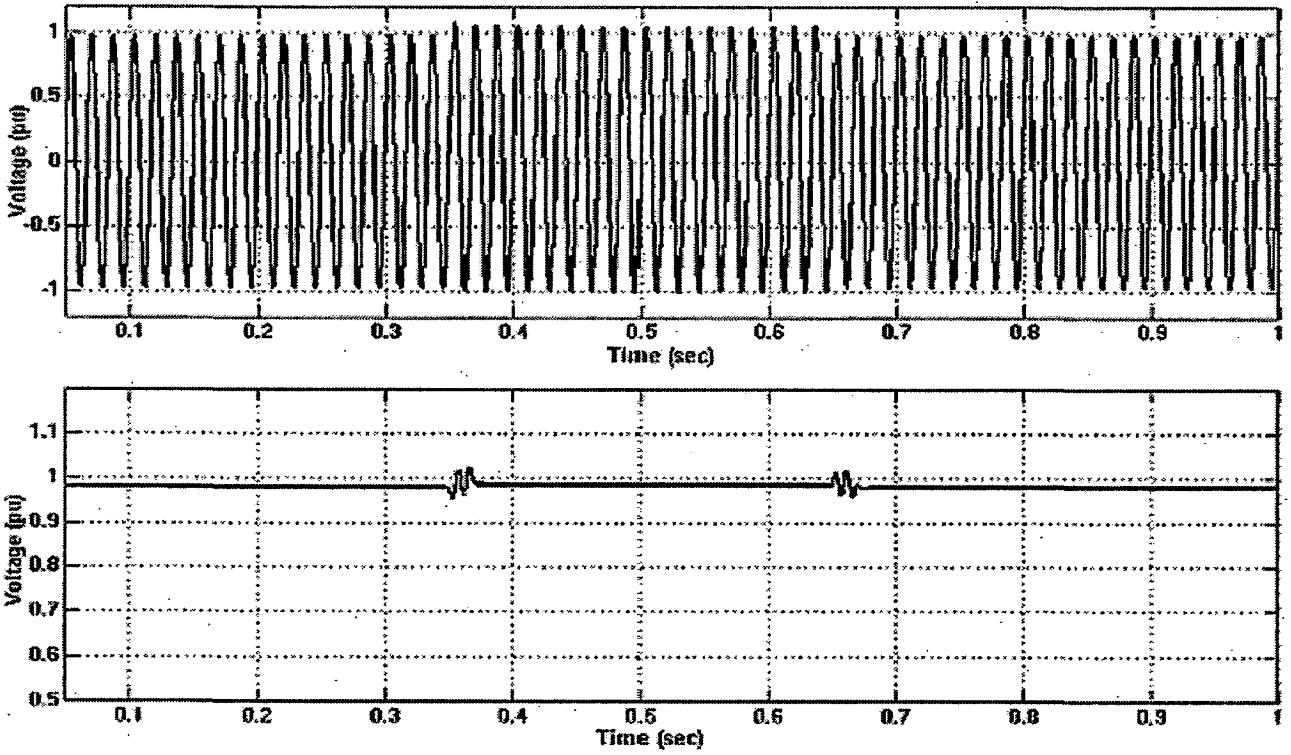


Fig.6.3 (a) Phase-to-phase and rms voltages at bus 2 with DVR

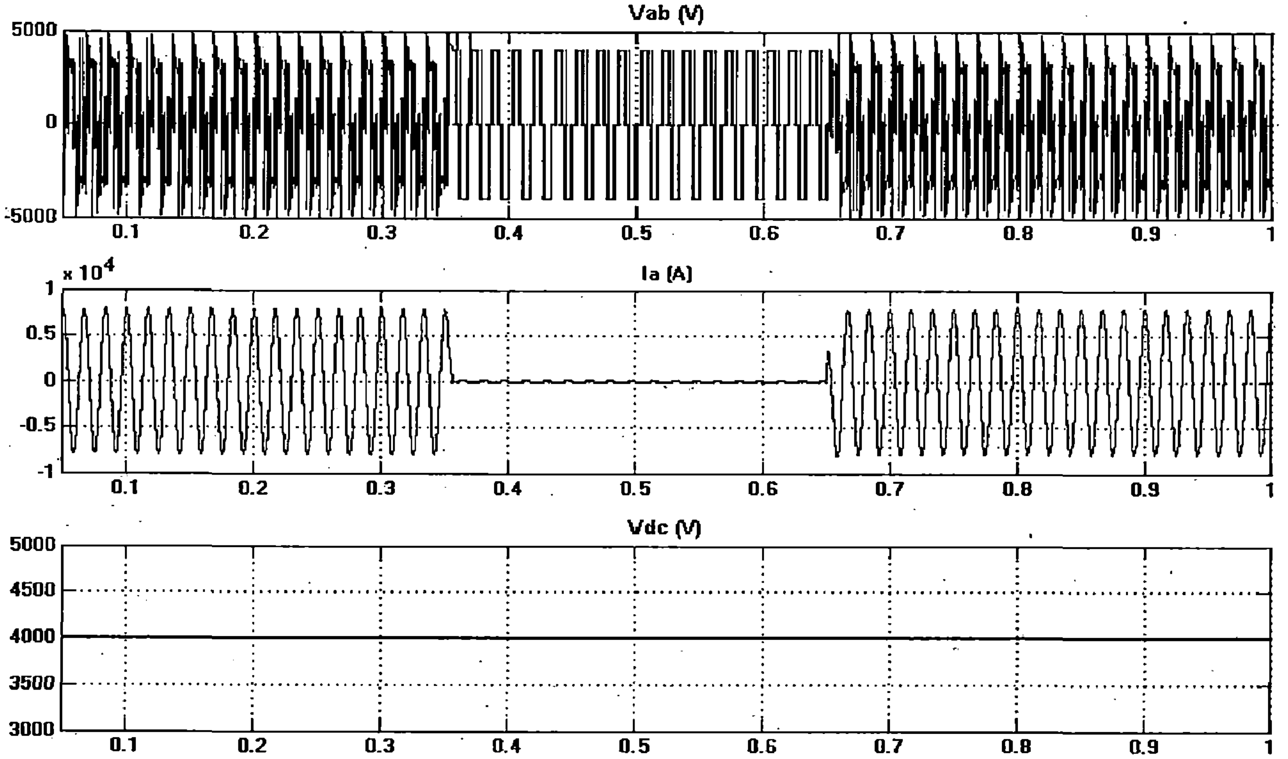


Fig.6.3 (b) Voltage and current waveforms of Inverter (DVR)

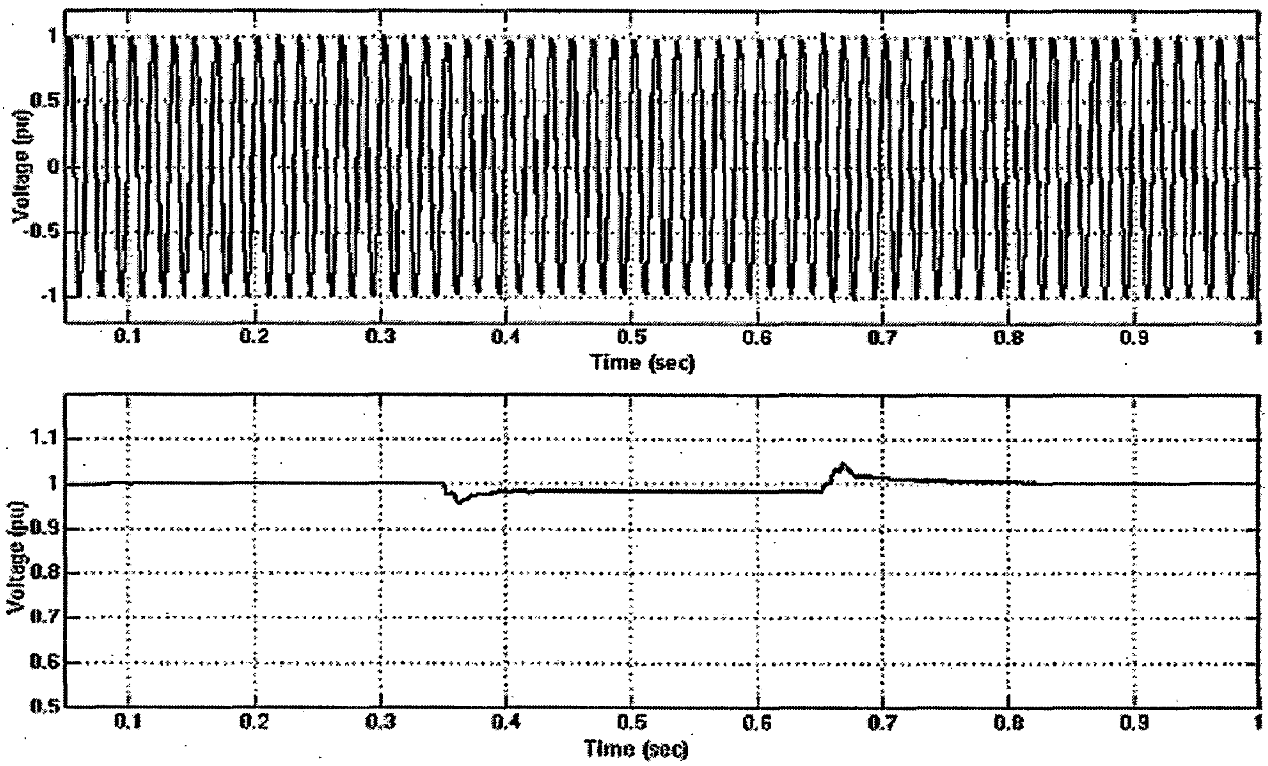


Fig.6.4 (a) Phase-to-phase and rms voltages at bus 2 with DSTATCOM

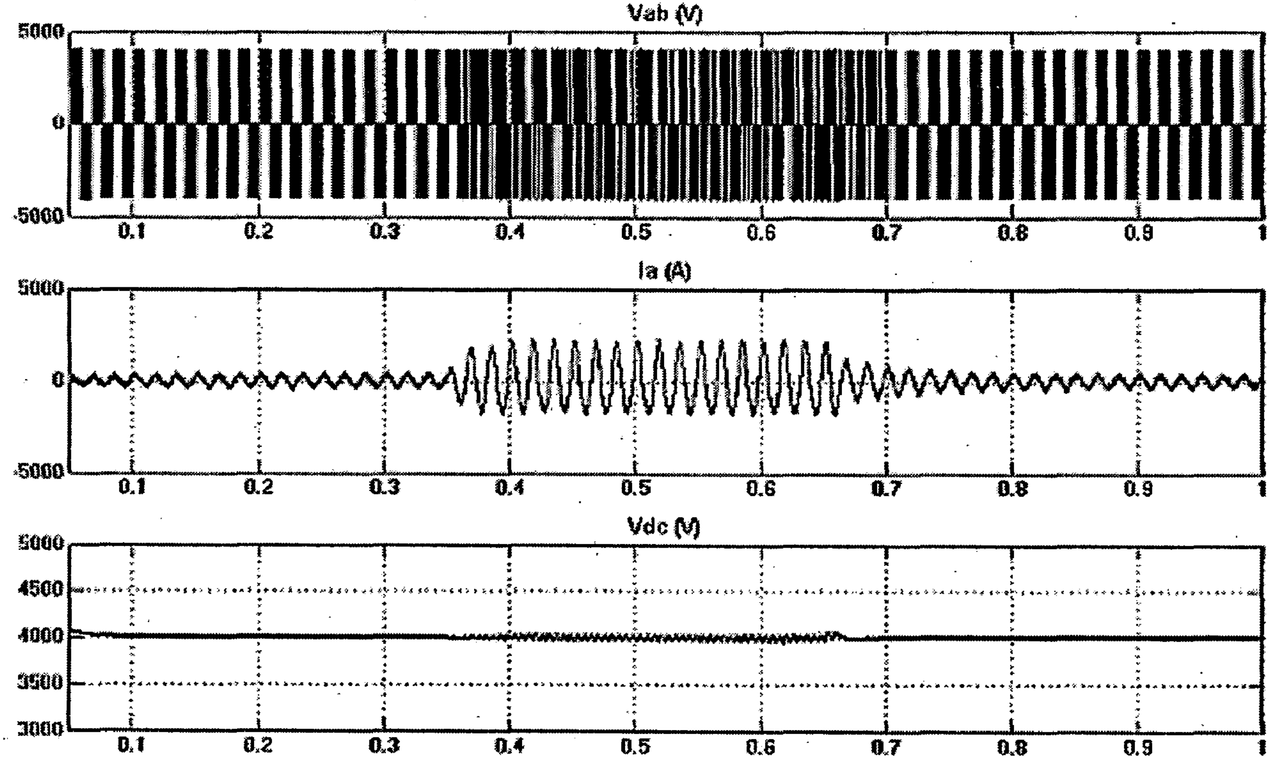


Fig.6.4 (b) Voltage and current waveforms of Inverter (DSTATCOM)

6.3 Unbalanced Voltage Sag

6.3.1 Double Line to Ground Fault

Simulation model for this system is presented in Appendix B. For obtaining the unbalanced voltage sags the sequence of events simulated is explained as follows: Initially, there is a permanent load of 2MW, 1MVar connected at bus 2. Between t=350ms, to 650ms a double line to ground fault is created in the line 1-2 between phase A and B. During this event, the terminal voltage of bus 2 decreases. The rms values of the terminal voltages of bus 2 for this event described is shown in Fig. 6.5. Here the sag obtained is unbalanced sag and voltage decrease in faulted two phases is equal in magnitude of 90% rated voltage, and healthy phase voltage is remains unchanged.

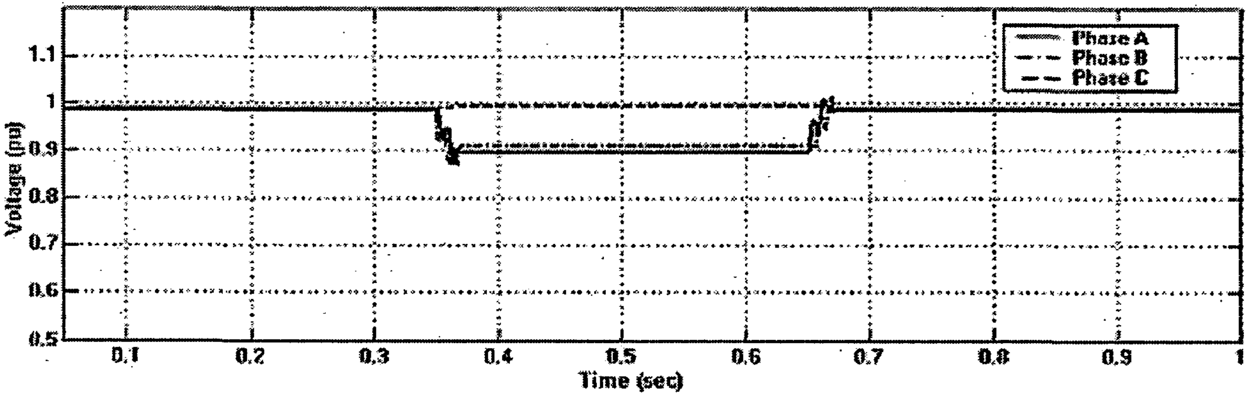


Fig.6.5 Rms voltages at bus 2 with out compensation

When the DVR is in operation the average rms voltage at the sensitive load point is maintained at 99% of rated as shown in Fig.6.6(b).Individual phase voltages are shown in Fig.6.6(a) The sag mitigation is performed with stable and rapid DVR response. Rms voltages of all three phases are almost mitigated completely.

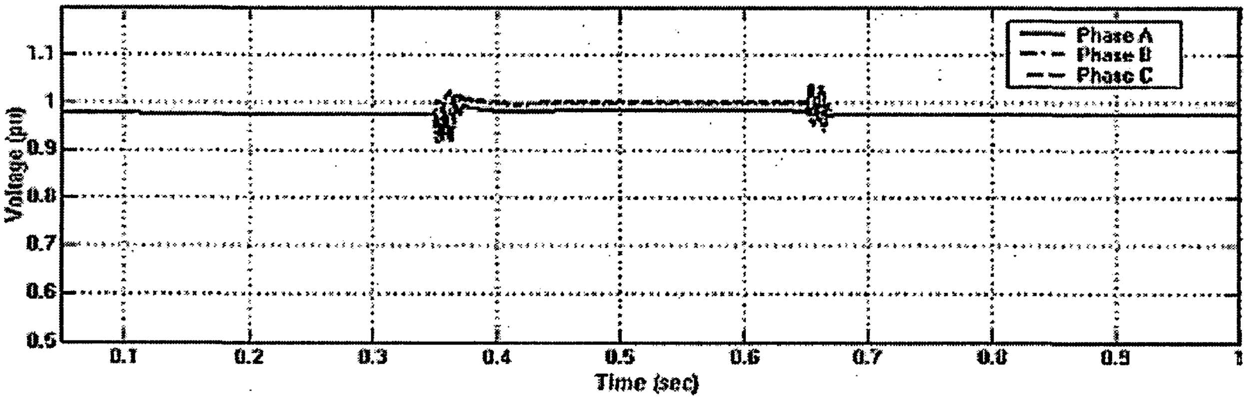


Fig.6.6 (a) Rms voltages at bus 2 with DVR

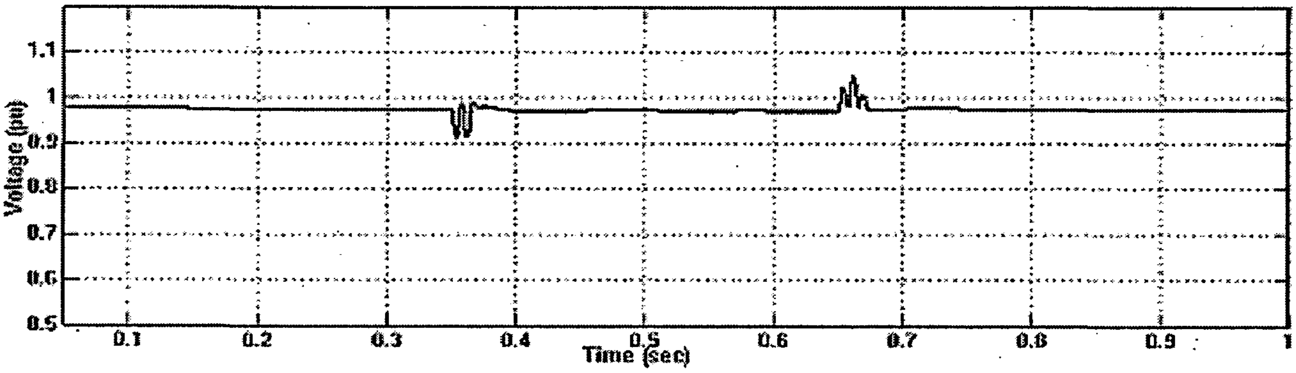


Fig.6.6 (b) Average of three phase voltages at bus 2 with DVR

But when the DSTATCOM is in operation the voltage sag is mitigated partially, but the average rms voltage of three phases at the sensitive load point is maintained at 99%, as shown in Fig.6.7. DSTATCOM has mitigated the high sag phase, voltage and partially (up to 95% rated) mitigated medium sag voltage phase.

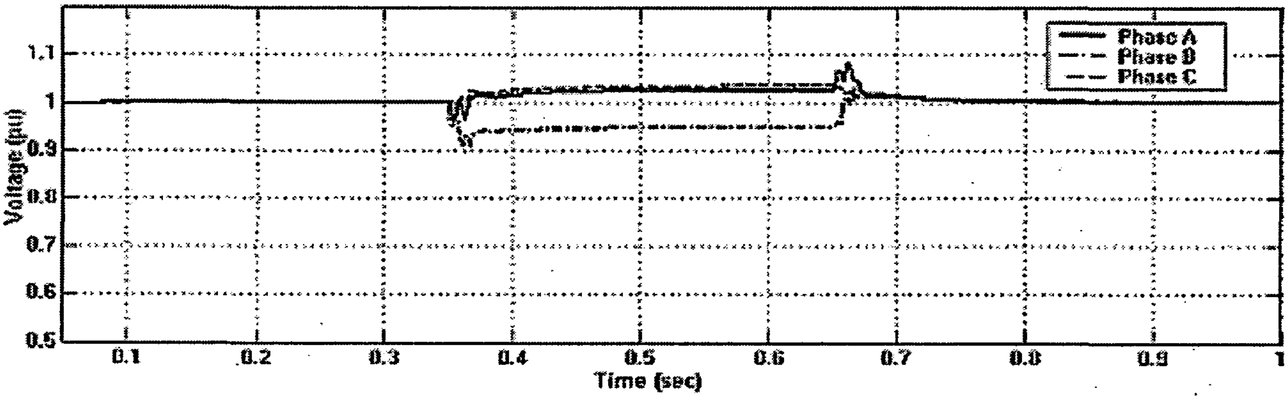


Fig.6.7 (a) Rms voltages at bus 2 with DSTATCOM

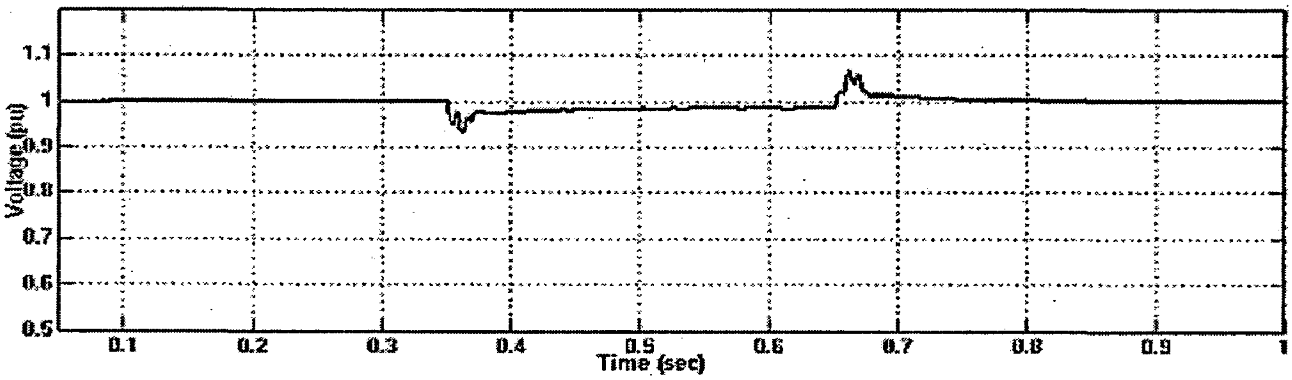


Fig.6.7 (b) Average of three phase voltages at bus 2 with DSTATCOM

6.3.1 Single Line to Ground Fault

Similar to the L-L-G fault, a single line to ground fault is created in the line 1-2. Fault in phase A between t=350ms, to 650ms is created. During this event, the terminal voltage of bus 2 decreases. The rms values of the terminal voltages of bus 2 for this event described is shown in Fig. 6.8. Here the sag obtained is unbalanced sag and voltage decrease in one faulted phase is equal in magnitude of 90% rated voltage, and two healthy phase voltages is remains unchanged.

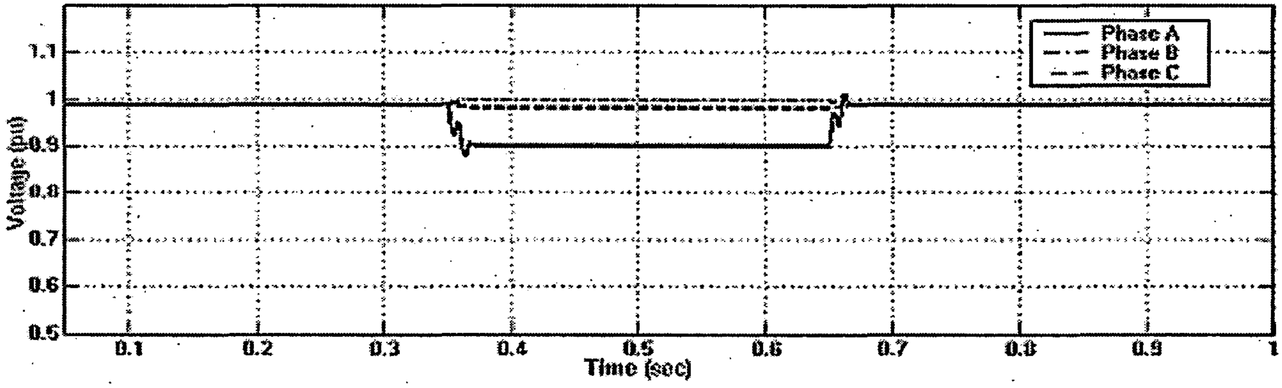


Fig.6.8 Rms voltage at bus 2 with out compensation

When the DVR is in operation the rms voltage at the sensitive load point is maintained at 102%, as shown in Fig.6.9. The aim of DVR is only restoration of voltage that's why it has injected excess voltage. Even though the voltages are some what higher than rated, the damage to equipment is less compared to sag of 90%.

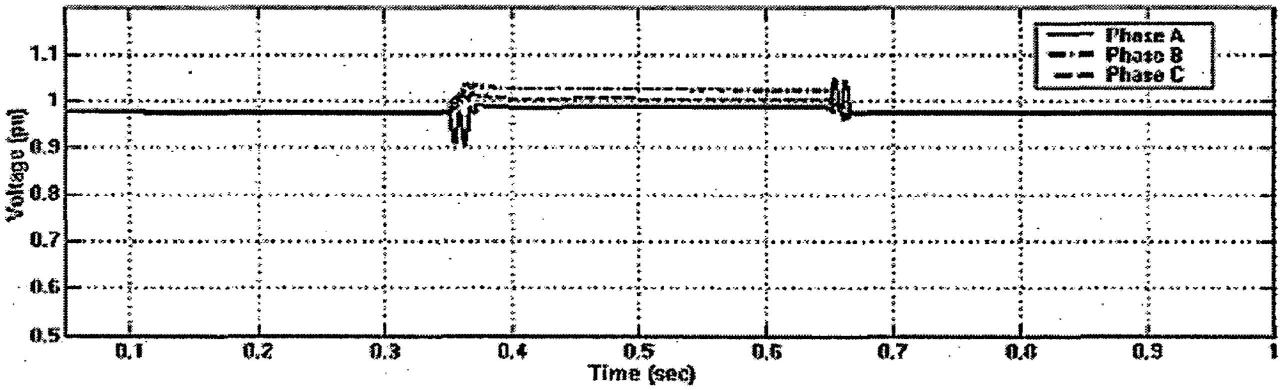


Fig.6.9 Rms voltage at bus 2 with DVR

Similar to L-L-G fault when, the DSTATCOM is in operation the voltage sag is mitigated partially, and the average rms voltage of three phases at the sensitive load point is maintained at 98%, as shown in Fig.6.10. DSTATCOM has mitigated the faulted phase voltage completely but, it has raised the voltage of one of the healthy phase to 1.05% of the rated voltage.

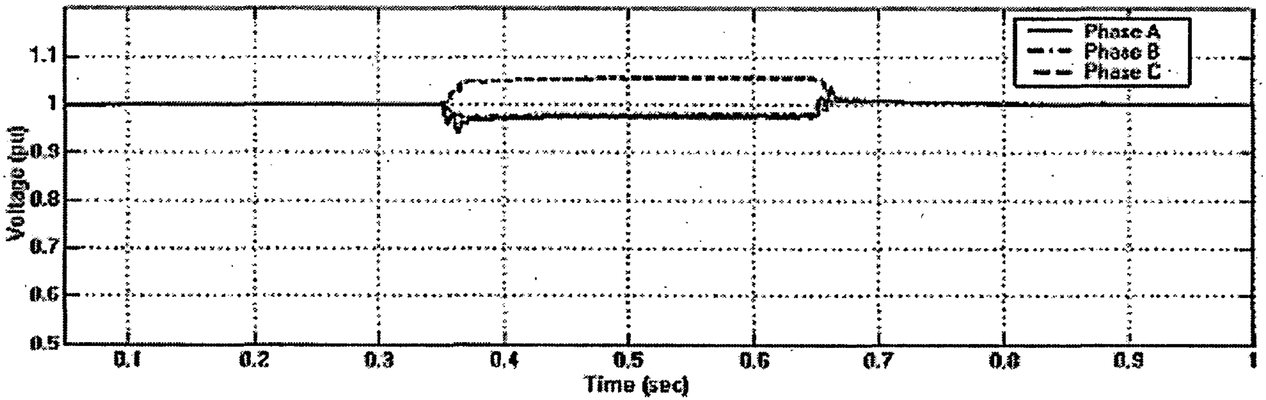


Fig.6.10 Rms voltage at bus 2 with DSTATCOM

6.4 Voltage Swell and Reactive Power Compensation

To verify the performance of the DSTATCOM, voltage swell and reactive power compensation capabilities two loads of 5MW, 2MVar and 10MW, 5MVar are connected at bus 2 and the substation voltage is also changed during the simulation. The sequence of events simulated as follows: Initially, there is no load connected at bus 2; at t = 200 ms the switch S1 is closed and at t = 500 ms the switch S2 is closed too; both switches remain closed until the end of the simulation. During these events, the terminal voltage of bus 2 decreases. At t = 800 ms the substation voltage is increased to 30 kV (1.20% of rated), consequently, the terminal voltage of bus 2 also rises, which is as shown in Fig.6.11 below.

PWM Based Model of DSTATCOM:

When the DSTATCOM is in operation the voltage sag is mitigated almost completely as shown in Fig.6.12. Load voltage is maintained within the limits (±5% of rated). However, it is indispensable to mention here that the results obtained using the DSTATCOM are very similar with actual results.

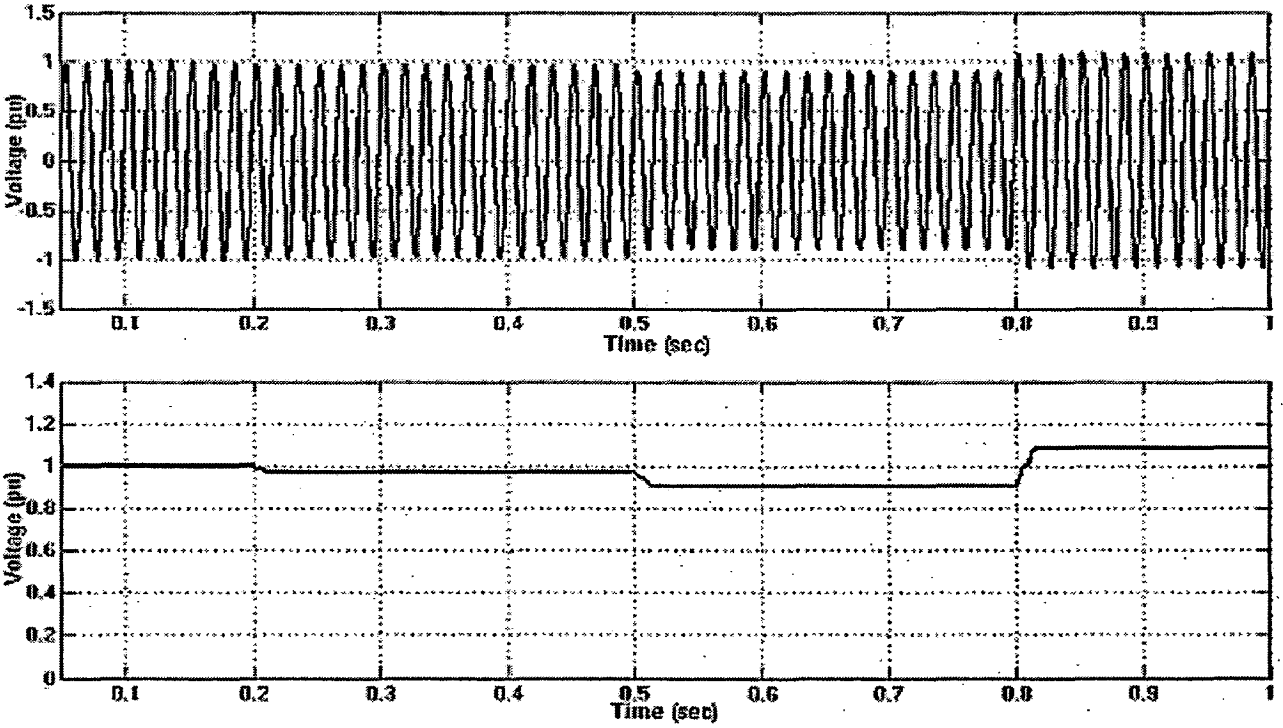


Fig.6.11 Rms voltage at bus 2 with out compensation

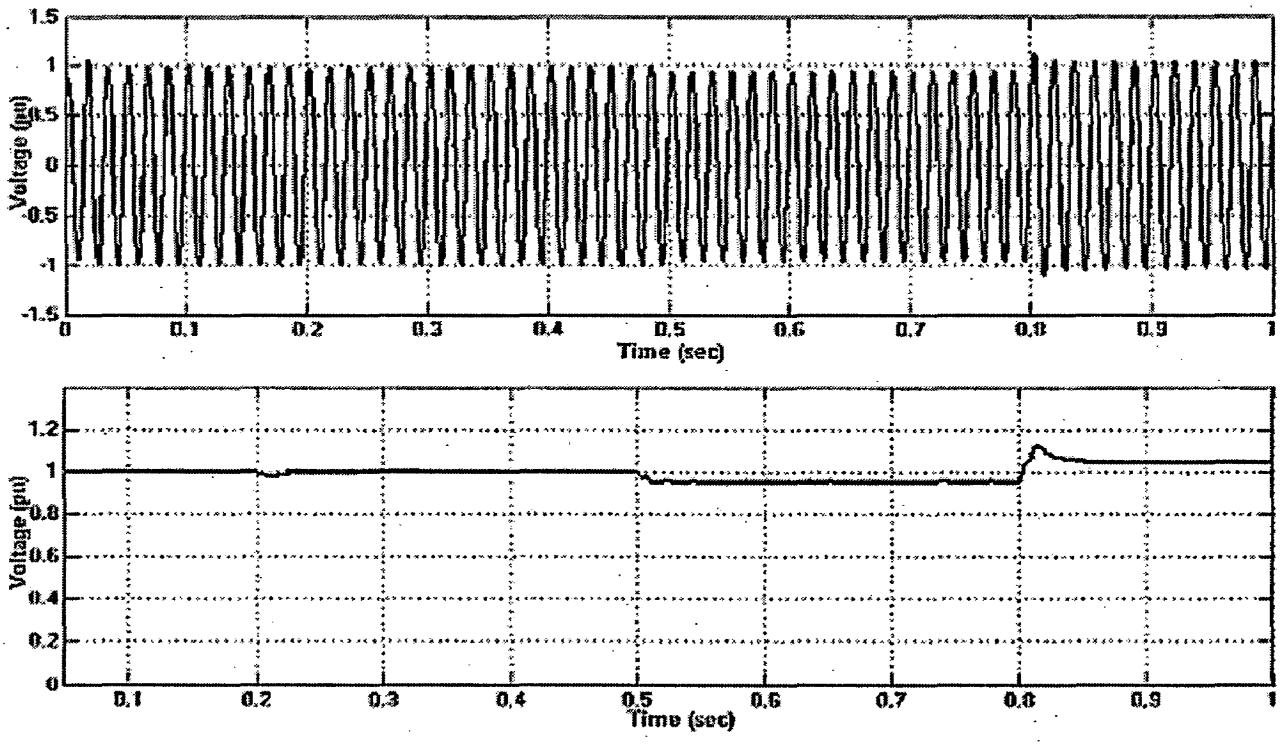


Fig.6.12 Rms voltage at bus 2 with PWM based DSTATCOM

Furthermore, the reactive and active power injected by the DSTATCOM into the network is shown in Fig.6.13. The reactive and active power consumption and compensation of DSTATCOM are varying according to swell and sag of the load voltage.

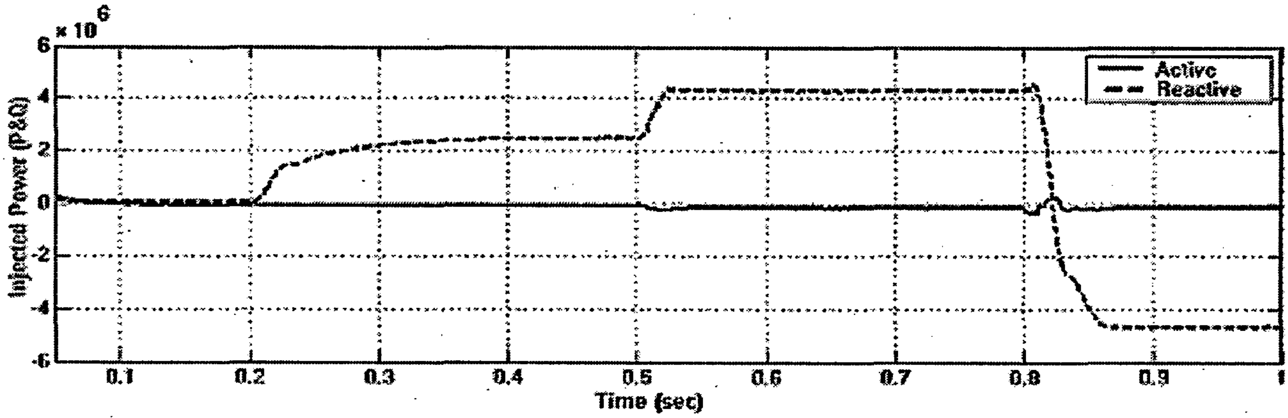


Fig.6.13 Active (P) and reactive (Q) power injected by DSTATCOM

Energy Conversion Principle Model of DSTATCOM

Voltage sag compensated by energy conversion principle model of DSTATCOM is as shown in Fig.6.14. Furthermore, Active & Reactive power consumption as well as compensation graphs obtained with energy conversion principle model are very similar to that of PWM based model case in previous section. Practically, there is no difference among the results obtained from these models and, therefore, the energy conversion principle model can represent very well the dynamic behavior of the DSTATCOM.

In the PWM based model case, the switching instant is determined by using interpolation. Thus, even if the switching instant occurs between two integration steps, it is accurately simulated. However, the integration step size should be chosen small enough to avoid that various switching occur between two integration steps. As the switching rate utilized for the PWM was 3000 Hz, considering a 60 Hz system, one switching may occur at each 5.556 microseconds (1/60/3000). Thus, the PWM based model requires an integration step of 5.556 microseconds to show a suitable accuracy. On the other hand, the integration step adopted for the energy conversion principle model was 50 times larger, i.e 277.78 microseconds (50/60/3000). Consequently, it is theoretically possible to obtain a speedup of 50 times.

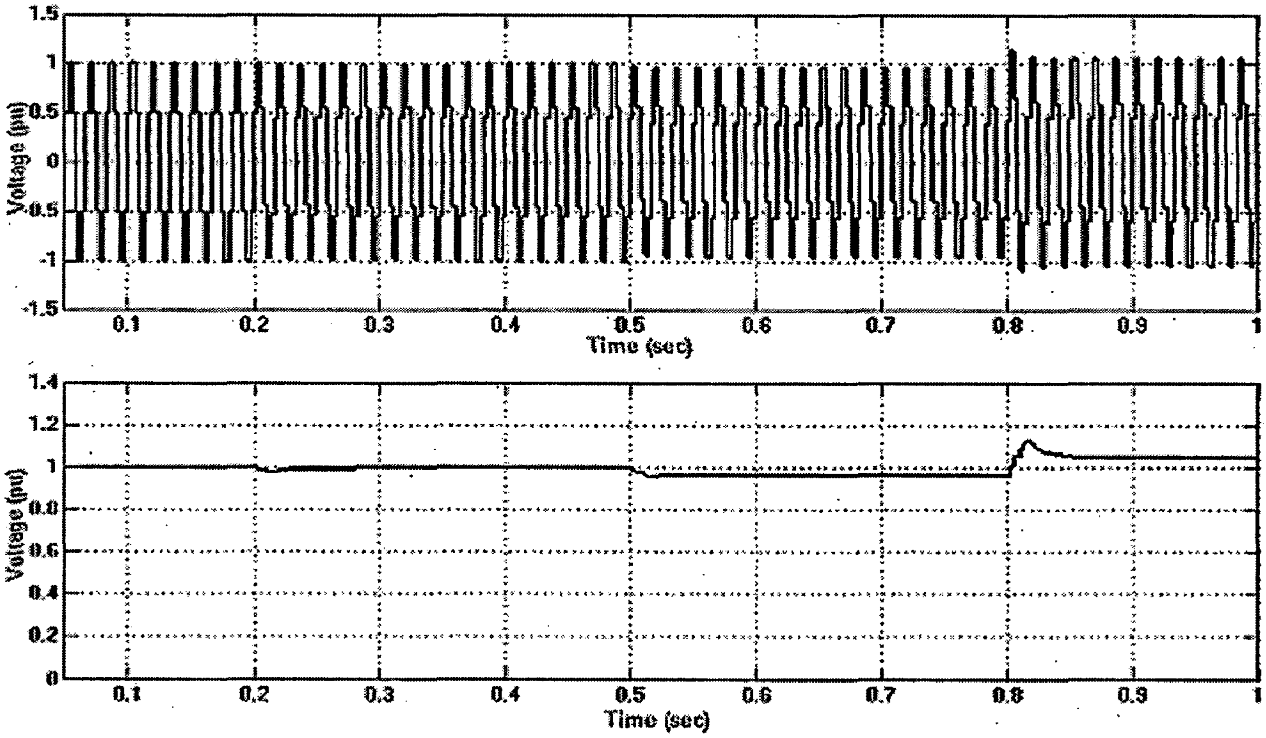


Fig.6.14 Rms voltage with energy conversion principle DSTATCOM

6.5 Sag Due To Induction Motor Starting

After observing DVR and DSTATCOM performance in mitigation of balanced and unbalanced voltage sags an attempt is made with DSTATCOM to mitigate sags due to induction motor. Synchronous motor is supplying voltage to an induction motor drive and a small load. The simulation model of this system is presented in the Appendix-B. When ever this motor starts other load experiences the sag. In this simulation synchronous generator is supplying a small load. At 300ms induction motor is started, small load experienced a sudden sag of 70% of rated voltage due to high starting current of induction motor, and after some time at 600ms it reached the rated voltage which can be seen from Fig.6.15. In the next simulation with DSTATCOM in operation sag has decreased very fastly and settled at rated voltage at 340ms, and sag depth also reduced considerably to 84% of rated voltage. The improvement of system voltage is shown in Fig.6.16.

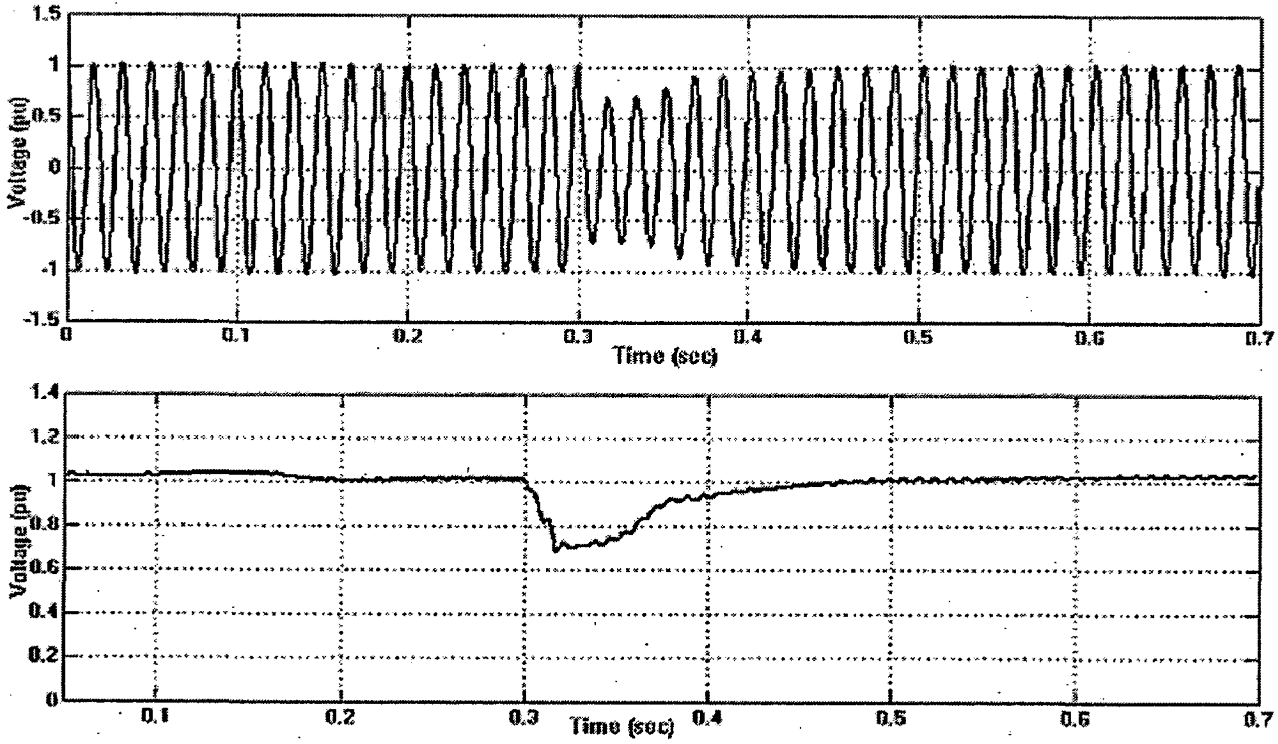


Fig.6.15 Rms voltage at bus 2 without compensation

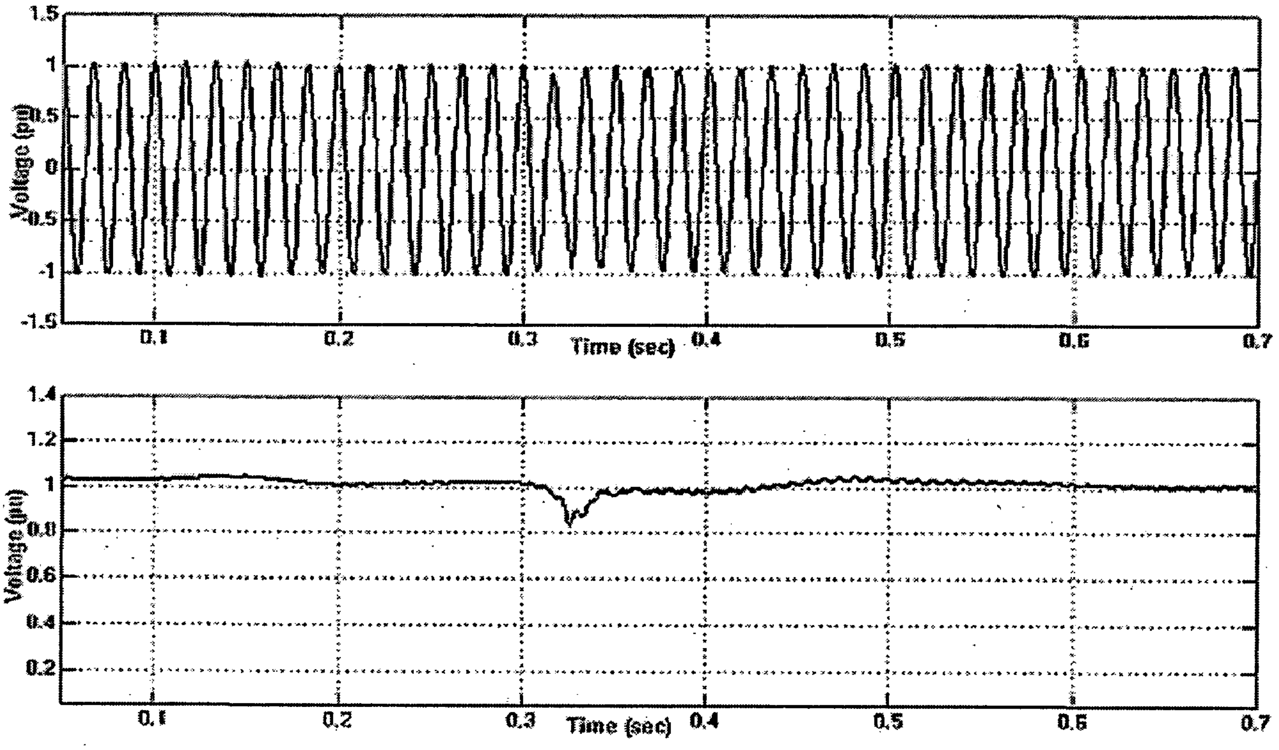


Fig.6.16 Rms voltage at bus 2 with DSTATCOM

CHAPTER-7

CONCLUSIONS AND FUTURE SCOPE

7.1 Conclusions

In this thesis attempt is made to find out various power quality problems. And among those problems most prominent and frequently occurring problem voltage sag is analyzed. Its sources, effects and mitigation methods are explained in detail. Mitigation of voltage sag problems is done in various methods. Among those custom power devices are the new trend of devices to solve more power quality problems such as sags swells and harmonics. In this work DVR and DSTATCOM devices are simulated using Matlab Simulink/ Power System Blockset (PSB). For generating switching pulses a new direct control is used for simulations. Results obtained were compared with results obtained in index journals. The fallowing conclusions were made.

1. A new PWM-based direct control scheme has been implemented to control the electronic valves in voltage source converter.
2. Both DVR and DSTATCOM have equal potential in mitigating balanced voltage sags, but DVR is superior in mitigation of unbalanced voltage sags.
3. A DSTATCOM can significantly mitigate voltage swell effect, and voltage sag effect due to induction motor starting, by absorbing and injecting reactive power through capacitor.
4. Energy conversion principle model is validated by comparing with PWM based model. Practically, there is no difference among the results obtained from those models.
5. This work presented a study about the behavior of custom power devices namely DVR and DSTATCOM to improve the voltage stability of distribution networks with overloading and faults. Simulation results show that these devices can increase the voltage stability limit.

7.2 Recommendations for Future Work

1. In this thesis, custom power device, simulations were made for DVR and DSTATCOM. Hence from these models it is possible to model UPQC (Unified Power Quality Conditioner), which is combination of both to carry out in the study of voltage sag and more other PQ disturbances.
2. Voltage sags and swells, analyzed in this thesis were concentrated on radial distribution system. Comparisons and analysis can be carried out in other systems. For example, ring system.
3. For obtaining smooth and accurate results, filtering scheme can be modified.
4. In this thesis performance of devices is obtained for only voltage quality problems, these devices can be applied to mitigate other power quality problems, such as harmonics and flickering due to arc furnace.

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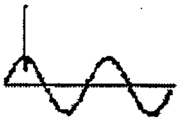
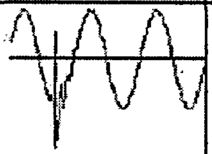
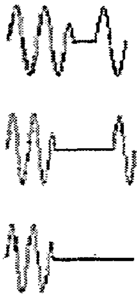
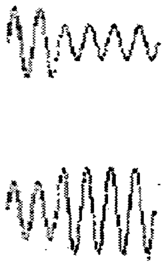
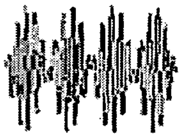
APPENDIX A

Table A1: Power Quality Standards

Categories	Typical Spectral Content	Typical Duration	Typical Voltage Magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 ns rise	<50ns	
1.1.2 Microsecond	1 us rise	50 ns - 1ms	
1.1.3 Millisecond	0.1 ms rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low Frequency	<5kHz	3 - 50ms	0-4pu
1.2.2 Medium Frequency	5-500 kHz	20 us	0-8pu
1.2.3 High Frequency	0.5 - 5MHz	5 us	0-4pu
2.0 Short - Duration Variations			
2.1 Instantaneous			
2.1.1 Sag		0.5 - 30 cycles	0.1 -0.9pu
2.1.2 Swell		0.5 - 30 cycles	1.1 -1.Spu
2.2 Momentary			
2.2.1 Interruption		0.5 cycles -3s	<0.1pu
2.2.2 Sag		30 cycles -3s	0.1 -0.9pu
2.2.3 Swell		30 cycles -3s	1.1 -1.4pu
2.3 Temporary			
2.3.1 Interruption		3 s—1 min	<0.1 pu
2.3.2 Sag		3 s—1 min	0.1-0.9pu
2.3.3 Swell		3 s—1 min	1.1- 1.2 pu
3.0 Long Duration Variations			
3.1 Interruption, Sustained		> 1 minute	0.0 pu
3.2 Under voltages		> 1 minute	0.8 - 0.9 pu
3.3 Over voltages		> 1 minute	1.1- 1.2 pu
4.0 Voltage Imbalance		Steady state	0.5-2%
5.0 Waveform Distortion			
5.1 DC Offset		Steady - state	0-0.1%
5.2 Harmonics	0 - 100th H	Steady - state	0-20%
5.3 Inter — harmonics	0-6KHz	Steady - state	0-2%
5.4 Notching		Steady - state	
5.5 Noise> 1 minute	Broad - band	Steady - state	0 - 1 %
6.0 Voltage Variations	<25Hz	Intermittent	0.1-7%
7.0 Power Frequency Variations		<10s	

Table A2: Summary of Power Quality Problems

Diagram of waveshape or RMS variation	Causes	Sources	Effects	Examples of protective devices
	Impulsive transients	■ Lightning ■ Electrostatic discharge ■ Load/Capacitor switching	-- Destroys computer components and regulators	■ Surge arresters ■ Filters ■ Isolation transformer
	Oscillatory Transients	■ Line/cable switching ■ Capacitor/Load switching	-- Destroys computer components and regulators	■ -- Surge arresters ■ Filters ■ Isolation transformer
 	Sags/Swells	■ Remote system fault	-- Motor stalling and overheating -- Computer failures -- ASDs shutting down	■ Ferroresonant transformers ■ Uninterruptible Power supply (UPS)
	Interruptions	■ System	-- Shutting	■ UPS

		protection breakers ■ Fuses	down of equipment	■ Backup generators
	Undervoltage / Overvoltage	■ Motor starting ■ Load variations	-- Shorten lives of motors and lightning filaments	■ Voltage regulators ■ Ferroresonant transformers
	Harmonic	■ Nonlinear loads ■ System resonance	-- Overheating transformers and motors -- Fuses blown -- Relay trip	■ Active or passive filters ■ Transformers with cancellation of zero sequence components
	Voltage flicker	■ Intermittent loads ■ Motor starting ■ Arc furnaces	-- Light flicker -- Irritation	-- Static VAR systems

APPENDIX B

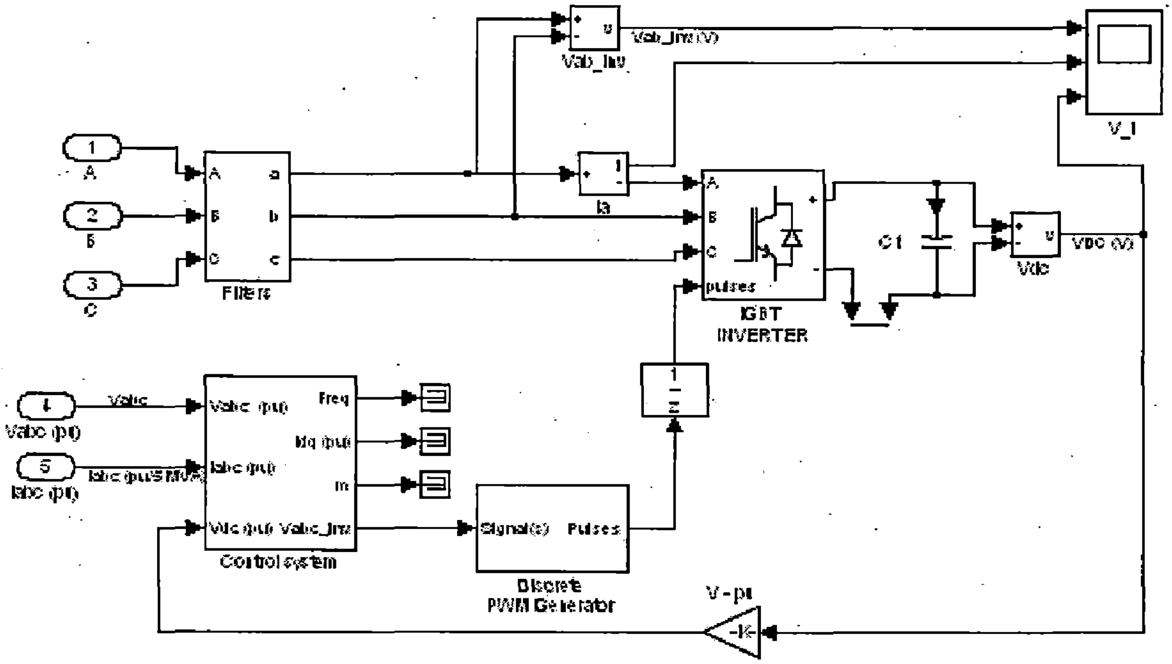


Fig.B1: Simulation model of VSC for DVR and DSTATCOM

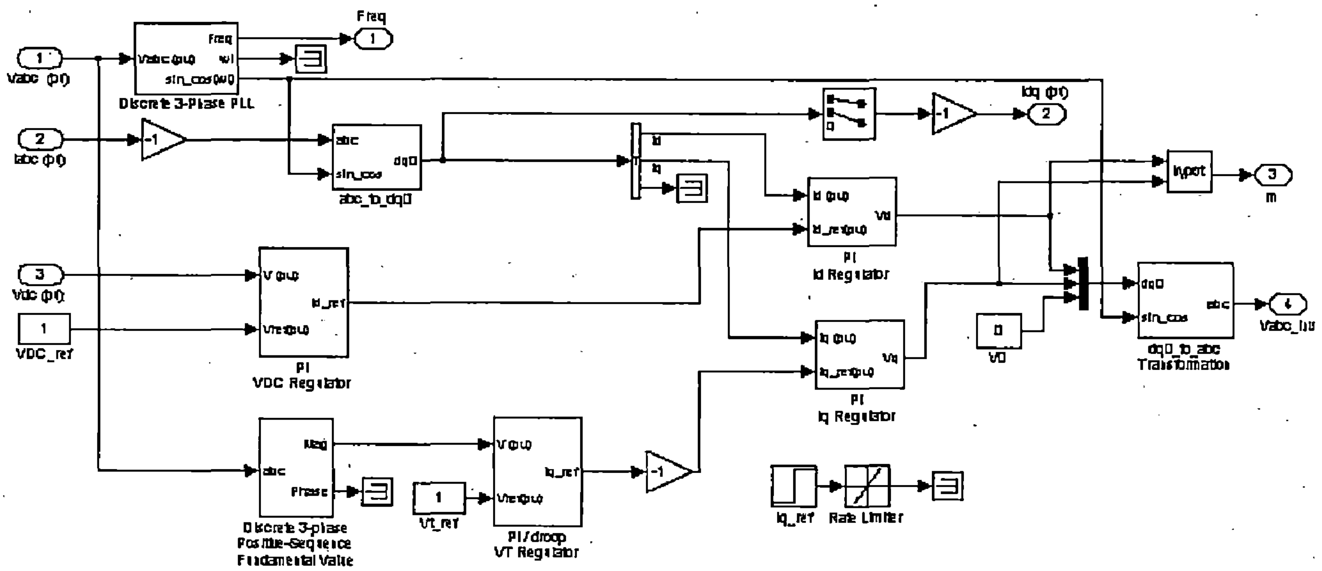


Fig.B2: Simulation model of controller for DVR and DSTATCOM

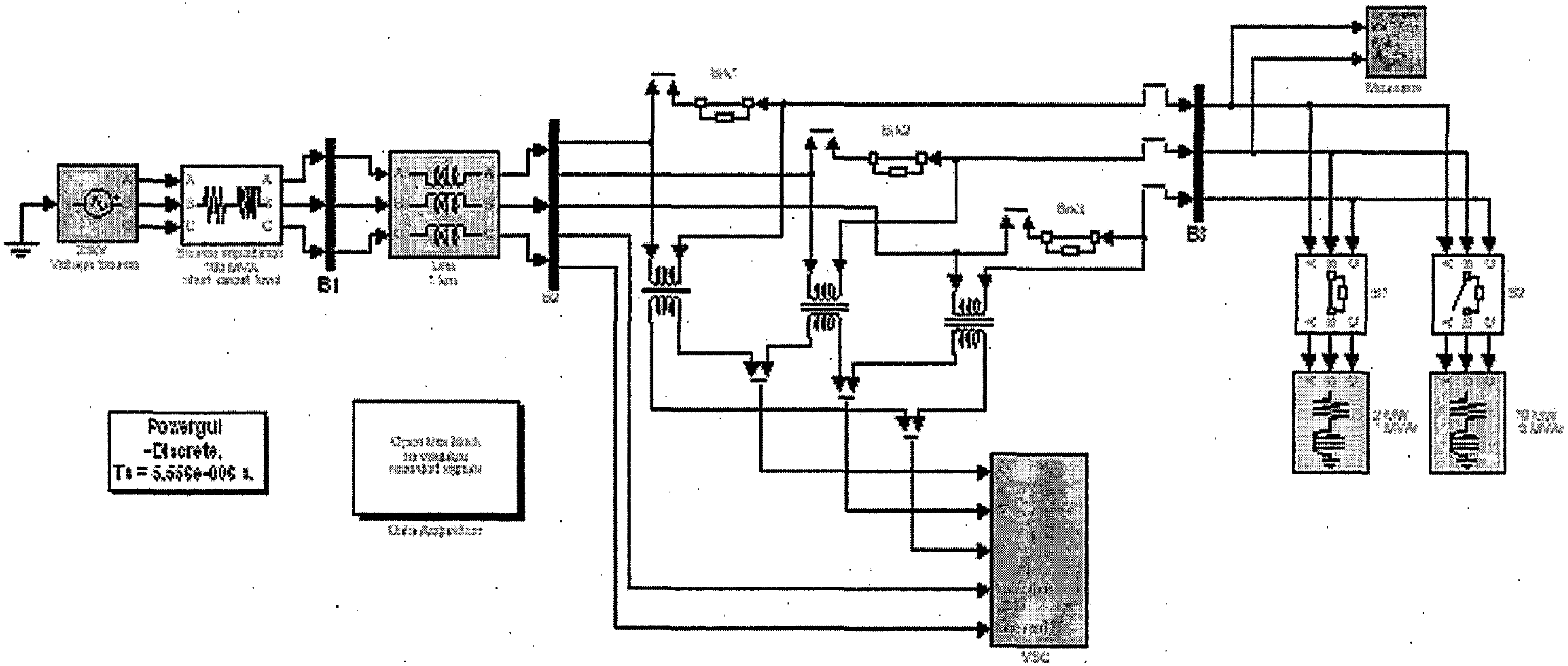


Fig.B3: Simulation model of DVR for balanced voltage sag study

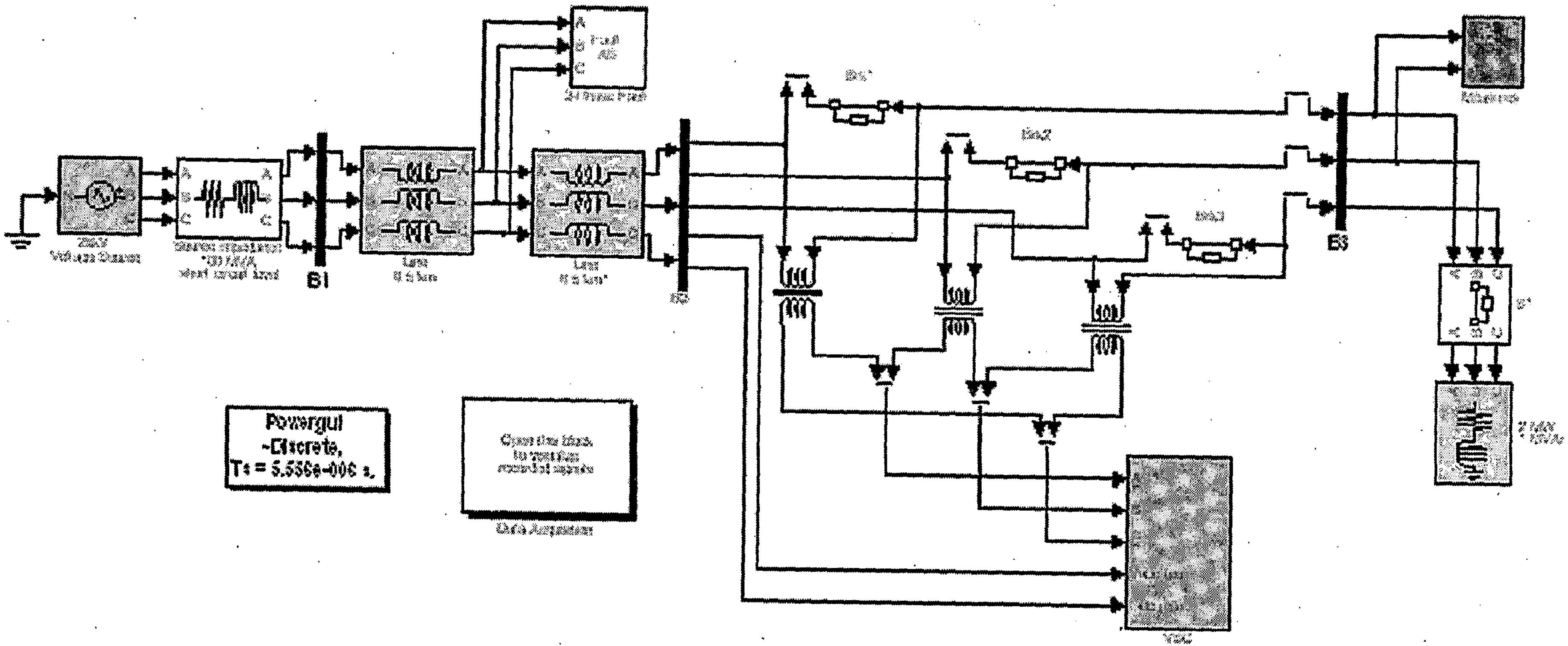


Fig.B4: Simulation model of DVR for un-balanced voltage sag study

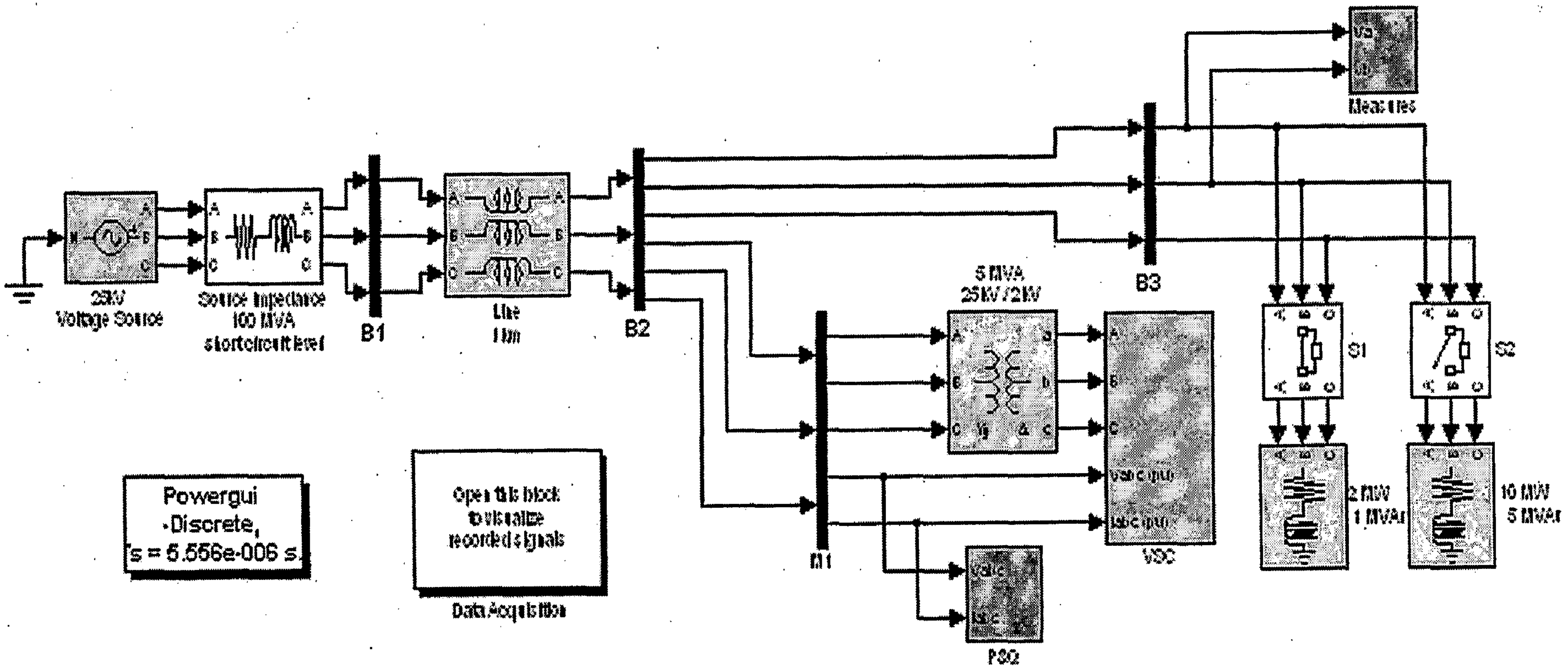


Fig.B5: Simulation model of DSTATCOM for balanced voltage sag study

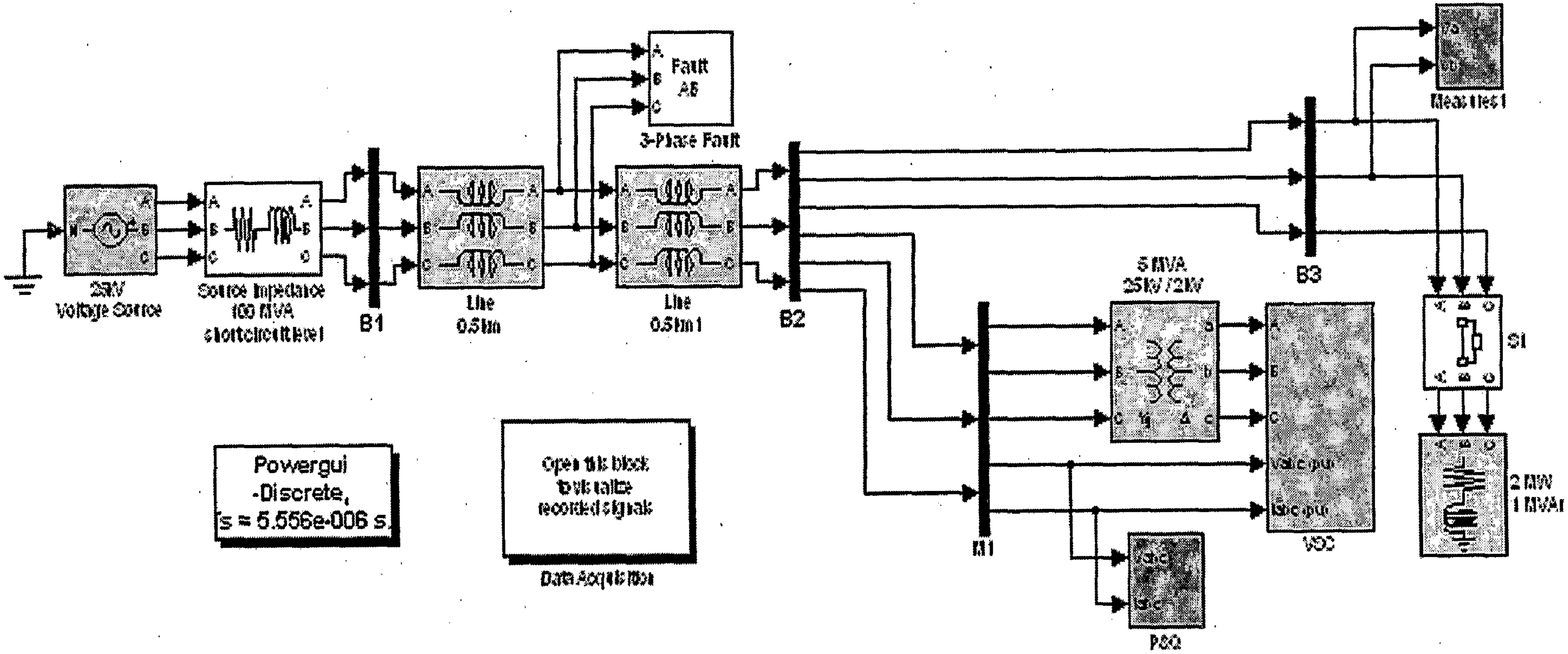


Fig.B6: Simulation model of DSTATCOM for un-balanced sag study

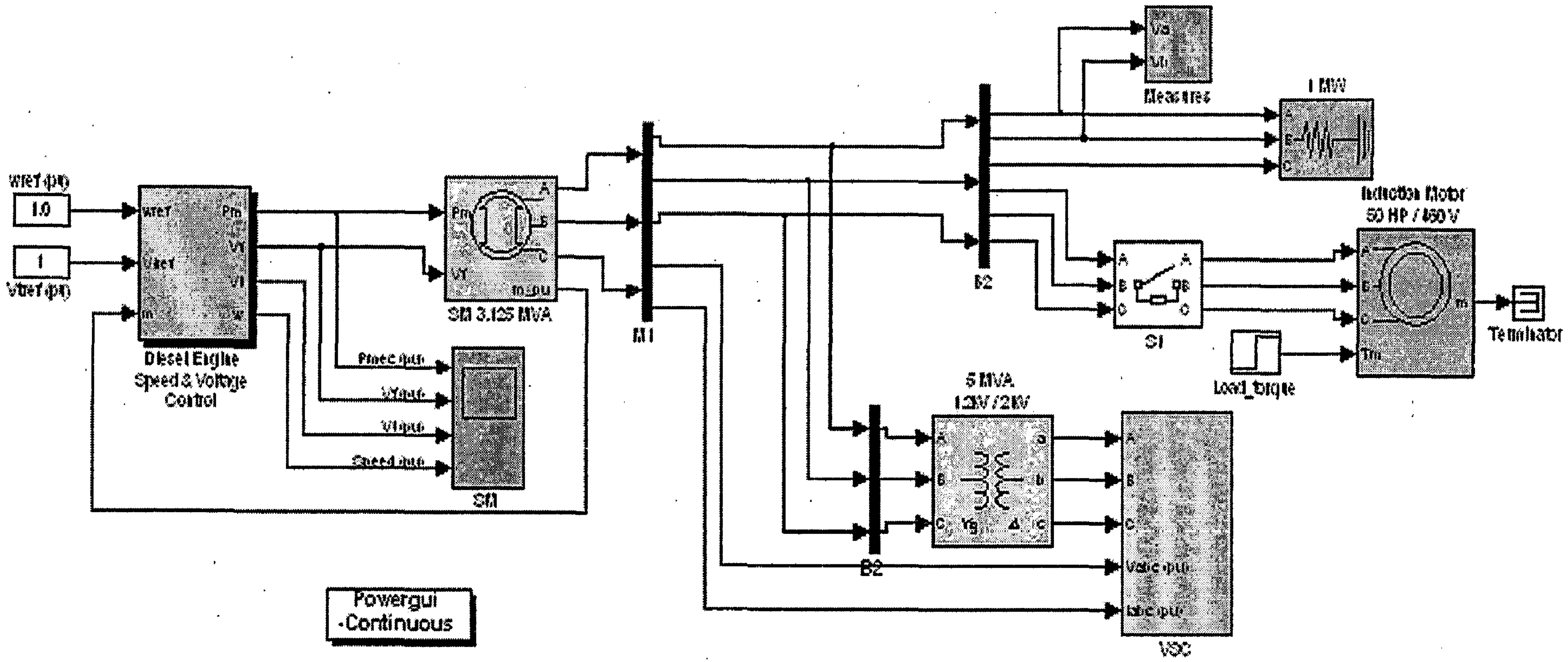


Fig.B7: Simulation model of DSTATCOM for induction motor sag study