INVESTIGATIONS ON THE ROLE OF DYNAMIC VOLTAGE RESTORER FOR POWER QUALITY IMPROVEMENT OF DISTRIBUTION NETWORKS

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

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in

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Thapar University, Patiala

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CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled, **"Investigations on the Role of Dynamic Voltage Restorer for Power Quality Improvement of Distribution Networks"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in *Power Systems & Electric Drives* submitted in Electrical and Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Mr. Parag Nijhawan, Assistant Professor, EIED and refers other researcher's work which are duly listed in the reference section.

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

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ABSTRACT

Modem power systems comprises of complex networks, where many generating stations and load centres are interconnected through long power transmission and distribution networks. Utility distribution networks, critical commercial operations and sensitive industrial loads all suffer from various types of outages and interruptions which can lead to significant financial loss, loss of production, idle work forces etc. Today due the changing trends and restructuring of power systems, the consumers are looking forward to the quality and reliability of power supply at the load centres.

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 use equipments. With shifting trend towards distributed and dispersed generation, the issue of power quality is taking new dimensions. The concept of custom power was introduced to distribution systems for improving the system performance. The aim therefore, in this work, is to identify the prominent concerns in the area and thereby to recommend measures that can enhance the quality of the power, keeping in mind their economic viability and technical consequences.

The Dynamic Voltage Restorer (DVR) is an effective custom power device for the enhancement of power quality due to its quick response, high reliability and nominal cost. A dynamic voltage restorer is used to compensate deep voltage sags, voltage unbalances and harmonics. It is efficiently capable of protecting sensitive loads against the voltage variations or disturbances. DVR is a forced commutated voltage source converter that injects a dynamically controlled voltage in series with the supply voltage through injection transformer or three single-phase transformers for correcting the load voltage.

The modeling and simulation of a DVR using Matlab Simulink has been presented. A control system based on dqo technique, which is a scaled error between source side of the DVR and its reference for sags/swell correction is used. The system based on this control technique is developed and the results have been analysed for the cases of static load and adjustable speed drive load. The simulation results show that the DVR performance is satisfactory in mitigating unbalanced voltages and faulted conditions in the system.

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LIST OF ABBREVIATIONS

AC	Alternate Current
APF	Active Power Filters
ASAI	Average Service Availability Index
ASIDI	Average System Interruption Frequency Index
ASIFI	Average System Interruption Frequency Index
ASVC	Advanced Static VAR Compensator
BESS	Battery Energy Storage Systems
CAIDI	Customer Average Interruption Duration Frequency Index
CBEMA	Computer Business Equipment Manufacturers Association
CMI	Customer Minutes of Interruption
CMO	Customer Minutes of Outage
DC	Direct Current
DFACTS	Distribution FACTS
DIN	Distortion Index
DSC	Distribution Series Capacitors
DSP	Digital Signal Processing
DSTATCOM	Distribution Static Synchronous Compensators
DVR	Dynamic Voltage Restorer
FACTS	Flexible AC Transmission Systems
FFT	Fast Fourier Transform
FOC	Field Orientated Control
FT	Fourier Transform
GTO	Gate Turn- Off Thyristors
HSMTS	High Speed Mechanical Transfer Switch
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IGBT	Insulated Gate Bipolar Transistors
IGCT	Integrated Gate Commutated Thyristors
IPQT	instantaneous p-q Theory
ITIC	Information Technology Industry Council
LSVI	Leading Series Voltage Injection
MAIFI	Momentary Average Interruption Frequency Index

MATLAB	Matrix Laboratory
MOSFET	Metal Oxide Semiconductor Field Effect Transistors
MOV	Metal-Oxide Varistors
MTBF	Mean Time between Failures
PCC	Point of Common Coupling
PLL	Phase Lock Loop
PQ	Power Quality
PWM	Pulse Width Modulation
SA	Surge Arresters
SAIDI	System Average Interruption Duration Frequency Index
SAIFI	System Average Interruption Frequency Index
$SAIRFI_X$	System Instantaneous Average RMS Variation Frequency Index
$SARFI_X$	System Average RMS Variation Frequency Index
SETC	Static Electronic Tap Changers
$SMARFI_X$	System Momentary Average RMS Variation Frequency Index
SMES	Super Conducting Magnetic Energy Systems
SPWM	Sinusoidal Pulse Width Modulation
SSCB	Solid State Circuit Breaker
SSCL	Solid State Current Limiter
SSF	Synchronous Stationary Frame
SSFCL	Solid State Fault Current Limiter
SSSC	Static Synchronous Series Compensator
SSTS	Solid State Transfer Switch
$STARFI_X$	System Temporary Average RMS Variation Frequency Index
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
SVPWM	Space Vector Pulse Width Modulation
THD	Total Harmonic Distortion
UPFC	Unified Power Flow Controller
UPQC	Unified Power Quality Conditioner
UPS	Uninterruptible Power Supplies
USSC	Unified Series-Shunt Controller
VSC	Voltage Source Converter
WT	Wavelet Transform

LIST OF SYMBOLS

δ	Phase Angle Jump
μF	Micro Farad
μs	Micro Second
/yr	per year
hr	hour
hr/yr	hour per year
Hz	Hertz
I	Current Flowing Through the Circuit
i_{Sq}	Torque Component
$kg.m^2$	Kilogram Meter Square
kHz	Kilo Hertz
kV	Kilo Volt
kVA	Kilo Volt Ampere
kVAR	Kilo Volt Ampere Reactive
m	Torque
mH	Mille Henry
MHz	Mega Hertz
ms	Mille Second
MV/LV	Medium Voltage/Low Voltage
MVA	Mega Volt Ampere
Nm	Newton Meter
ns	Nano Second
Ø	Power Factor Angle
P	Active Power
pf	Power Factor
P_L	Active Power of Load
P_{st}	Perception of Light Flicker in the Short Term
pu	Per Unit
Q	Reactive Power
Q_L	Reactive Power of Load
R	Resistance
S	Apparent Power

sec	Second
V	Volt
V	Voltage Applied to a Circuit
V_1	RMS Magnitude of the Fundamental Component
VA	Volt Ampere
V_{DVR}	Dynamically Controlled Voltage
$\mathrm{V}_{\mathrm{inj}}$	Injected Voltage
V_{L}	Desired Load Voltage Magnitude
V_L	Load Voltage Magnitude
$\mathrm{V}_{\mathrm{ref}}$	1 p.u. Voltage
$\mathrm{V}_{\mathrm{rms}}$	RMS Voltage
V_{s}	Source Voltage during Sags/Swells Condition
$V_{s\text{-}postsag}$	Post-Fault Source Voltage
$V_{s\text{-}presag}$	Pre-Fault Source Voltage
X_{L}	Inductive Reactance
Z	Total Impedance
θ_{inj}	Injected Supply Voltage
$\theta_{s\text{-}postsag}$	Post-Fault Phase of Supply Voltage
$\theta_{s\text{-}presag}$	Pre-Fault Phase of Supply Voltage
Ω	Ohm
λ	Failure Rate
ψ_R	Rotor Flux

CHAPTER 1
INTRODUCTION

1.1 Overview

In recent years, the nonlinear loads and complexity of control systems in industrial processes have triggered the power quality problems in the distribution network. The major aim of power quality enhancing techniques is to maintain a specified voltage magnitude at a desired frequency for sensitive loads irrespective of the faults or conditions in the power distribution network. This is possible only by ensuring an uninterrupted flow of power at proper voltage and frequency levels. As a result of this, the need of custom power devices is felt.

Custom Power devices are power electronics based systems used in low-voltage distribution side of the power system network rated 1 through 38 kV like Static series compensator (SSC) commercially known as Dynamic voltage restorer (DVR), High speed mechanical transfer switch (HSMTS), Advanced static VAR compensator (ASVC), Distribution STATCOM (D-STATCOM), Unified series-shunt controller (USSC) or Unified power quality conditioner (UPQC). Custom power technology is the possible solution to the modern power sector need. This technology emerged to enhance the reliability and quality of power supply affecting factories, offices and homes. Reliability is expanded to include power quality goals like no power interruptions, improved voltage regulation, low harmonic distortion, low flicker at load voltage and low phase unbalance. There are two categories of custom power devices – Network Configuring type and Compensating type. The former enhances the power quality by changing the configuration of power system network like solid state current limiter (SSCL), solid state circuit breaker (SSCB) and solid state transfer switch (SSTS). These devices use GTO or thyristors. The devices like DSTATCOM, DVR and UPQC are compensating type custom power devices. These devices have converters. As already discussed, there is wide range of custom power devices available but in this work, the main focus is kept only on Dynamic Voltage Restorer (DVR).

A Dynamic Voltage Restorer (DVR) is based on power electronic converter, placed in series with a sensitive load to protect critical loads from all supply-side disturbances other than outages. The DVR is a promising and effective device for power quality enhancement due to its quick response and high reliability.

1.2 Literature Review

With the deregulation of the electric power energy market, providing quality power [1-4] has become an important concern of both power suppliers and customers. Efforts have been made to improve the power quality. Aspects on power quality can be classified into three categories that is, voltage stability, continuity of supplying power, and voltage waveform. Based on this classification, several examples of power quality level definitions were presented by Toshifiimi Ise, et al. [5].

Comprehensive review of compensating type custom power devices, issues of power quality, survey of power quality problems, standards and indices proposed by different agencies and different approaches to improve power quality from time to time [6-8].

The dynamic voltage restorer (DVR) is a series custom power device intended to protect sensitive loads to improve the quality of power. The main purpose of a DVR is to protect sensitive loads from sags/swells and interruptions in the supply side. If the load is phase-shift sensitive, this protection must include compensation that guards from a sudden phase jump that accompanies a voltage sag. A huge number of publications have addressed the voltage sag compensation using DVR. The researchers have investigated all the topics associated to DVR including; the compensation strategy, the circuit topology, the components design, the control circuit, the filter design and the detection of the sag.

Afshin Lashkar Ara et. al. [9] described the power electronic devices and technical review in various power engineering levels. In addition, the power electronics-based equipment, which are called power conditioners are use to solve power quality problems. Power conditioners are also called Distribution FACTS (DFACTS) devices. [1] presents the comparison of the operating modes and applications of FACTS devices (such as STATCOM, SSSC, UPFC, DSTATCOM, DVR and UPQC) in transmission and distribution systems.

Kong Shuhong, et al. [10] investigated that most power quality problems in distribution systems are related to voltage sags. Its principle and control strategies are also presented.

S.V Ravi Kumar et. al. [11] presented that the power quality problems such as voltage dips, swells and interruptions, consequences, and mitigation techniques of custom power electronic devices DVR, D-STATCOM, and SSTS. The design and applications of DVR, D-STATCOM and SSTS for voltage sags, interruptions and swells alongwith the comprehensive results are presented.

Mahesh Singh et al. [12] demonstrated that power quality measures can be applied both at the user end and also at the utility level. The work identifies some important measures that can be applied at the utility level without much system upset. The models of custom power equipment, namely D-STATCOM and DVR are presented and applied to mitigate voltage dip which is very prominent as per utilities are concerned using a new PWM-based control scheme. It was observed that in case of DSTATCOM capacity for power compensation and voltage regulation depends mainly on the rating of the dc storage device.

Chellali Benachaiba et al. [13] presents an application of DVR for the improvement of voltage quality. Paisan Boonchiaml Promsak et al. [14] describes a technique of correcting the voltage drop or sag by a DVR. The expressions for the injected voltage magnitude and angle that minimize the active power injection are also derived.

M.H.J. Bollen [15] addresses the voltage, current and power ratings of DVR. The active power injection requirements are calculated for a DVR under various system and load conditions, for different fault types, for three-phase load and for single-phase load. It is shown that the power requirement depends on the sag magnitude and phase-angle jump as well as on the power factor of the load. For controllers with an energy reservoir the voltage-tolerance curve of the load-controller combination is obtained. For a combined shunt-series controller the current rating of the shunt controller is found. Finally the voltage rating of the series controller is assessed.

C.S. Chang et al. [16] has analyzed the performance of voltage sag mitigation devices such as the Dynamic Voltage Restorer (DVR) in highly simplified electrical environment consisting of simple line and load models. The negative influences of dynamic motor loads on the existing voltage disturbance, such as post-fault sags, additional during-fault phase-angle deviations, during-fault and post-fault voltage fluctuations have often been overlooked.

Mehmet Tümay et al. [17] has presented the study related to the modeling and simulation of a DVR with SPWM based controller has been developed by using MATLAB/SIMULINK. The load side connected converter topology has capability of mitigating the long duration voltage sags on the line. The dynamic performance capability of DVR increases the number of sensitive equipments to use in the system. Mojtaba Nemati, et al. [18] has demonstrated the role of different functional components of DVR as a compensator of voltage dips. M.Arun Bhaskar, et al. [19] presents the performance of a DVR in mitigating voltage sags and swells.

T.Devaraju, et al. [20] implemented a PWM-based control scheme for D-STATCOM and DVR. Rosli Omar et al. [21] presented the low voltage dynamic voltage restorer (DVR) based on application of space Vector Pulse Width Modulation (SVPWM) for three phases Voltage Source Converter (VSC) and it is the standard PWM techniques to utilize the DC-AC power conversion. Paisan Boonchiam and Nadarajah Mithulananthan [22] described the DVR, which is based on forced-commutated voltage source converter (VSC) has been proved suitable for the task of compensating voltage sags/swells.

JD Li, et al. [23] examined the effect of voltage phase shift on the loads and verified that both the static load and the induction motor load will exhibit drastic dynamic responses under this kind of phase shift, and analytical expressions indicate that load transients current responses are dependent of the magnitude of voltage phase shift and load parameters. The research work is an attempt, to obtain qualitative DVR and loads.

V.K. Ramachandaramurthy, et al. [24] determined the impact of system issues on the performance and power rating of dynamics voltage restorers. The supervisory control scheme is examined to determine algorithms to restore network voltage sag or swell to given set points. The influence of the choice of the supervisory control algorithm on the selection of protection scheme and the interaction between the protection scheme and the device power rating are also examined.

Marcio Magalhães de Oliveira [25] dealt with the application of compensators and switches based on power electronics in AC transmission and distribution systems. The objective of the studied devices/equipment was the power flow and voltage control in transmission systems and the mitigation of voltage sags and momentary interruptions to critical loads in distribution systems. J. Barros, et al. [26] presented the results of the monitoring of subharmonic voltages in a low-voltage distribution network using an IEC harmonic measurement instrument.

Rosli Omar, et al. [27-28] proposed a control system based on dqo technique which is a scaled error of the between source side of the DVR and its reference for sags/swell correction. K.Chandrasekaran, et al. [29] presented a generalized control algorithm for voltage disturbance extraction and mitigation. The suggested control algorithm employs the synchronous stationary frame (SSF) for sag detection and instantaneous p-q theory (IPQT) technique for harmonic extraction to effectively track and extract the most common voltage disturbances. M. Jazayeri and H. Abdollahzadeh [30] introduced LS estimation algorithm in the DVR control system. Chris Fitzer, et al. [31] proposed a new matrix method, which is able to compute the phase shift and voltage reduction of the supply voltage much quicker than the Fourier transform or a PLL. Aamir Hanif, et al. [32] demonstrated the DVR using the leading series voltage injection LSVI concept for mitigating voltage sag and swells as well as share power in a manner which suits a specific customer. In case of abundant availability of generated power from a distributed energy resource, maximum power can be shared, while in case of scarcity, minimum power sag mitigation can be managed.

Brice J. Quirl, et al. [33] examined the control of a DVR. Emphasis was put on DVR control strategies that eliminate propagation of voltage sags or phase shifts to the load. Two control methods were explored, the first method is described as pre-sag to in-phase compensation and the second method includes the compensation during the sag and after the sag has left the system.

Mahinda Vilathgamuwa, et al. [34] state that the existing open-loop control strategy used in the DVR to regulate load voltage can produce poorly damped response due to the presence of the switching harmonic filter in the restorer. Hyosung Kim, et al. [35] proposed a design criterion and a design example for the LC filter combination considering the control characteristics and the size of DVRs. The cutoff frequency of a LC output filter for Dynamic Voltage Restorers (DVR) limits the control bandwidth of a DVR system and the attenuation factor against the inverter switching ripples.

From the above review of research papers, it is quite clear that DVR has been proved suitable for compensating voltage sags/swells and has enormous amount of contribution in improving power quality. A large number of control schemes have been applied to maintain the voltage level at the rated value of sensitive loads. In this work, the dqo transformation control scheme is applied to the DVR. The proposed scheme of DVR is successfully tested for the power system network with (i) static load and (ii) adjustable speed drive load under different fault and unbalanced conditions.

1.3 Scope of Work

This dissertation proposes the Matlab Simulink model of dynamic voltage restorer which is used for the improvement of power quality at distribution level. The major objectives are summarized as follows:

- Study the model of DVR along with its controller.
- Investigating the performance of Dynamic Voltage Restorer (DVR) using dqo transformation control scheme for static load under different fault and unbalance conditions.
- Investigating the performance of Dynamic Voltage Restorer (DVR) using dqo transformation control scheme for ASD load under different fault and unbalance conditions.

1.4 Organization of Thesis

This thesis is compiled in six chapters as per the details given below:

The Chapter 1 highlights the brief introduction, summary of work carried out by various researchers. The scope of the work is also identified and the outline of the thesis is also given in this chapter.

The Chapter 2 explains the power quality and different kinds of power quality problems and the various solutions that can be implemented to improve the quality of power in distribution networks.

The Chapter 3 describes how the concept of custom power was introduced to improve the power quality and the brief introduction of different kinds of custom power devices.

The Chapter 4 discusses the dynamic voltage restorer in detail and outlines the control technique used in the simulation of dynamic voltage restorer.

The Chapter 5 presents the results pertaining to various cases and the comparison of results obtained for various methods.

The conclusions and the scope of further work are presented in Chapter 6.

CHAPTER 2
POWER QUALITY

2.1 Background

In earlier times, the biggest challenge faced was the generation of electricity and transmitting it to the larger area. With the passage of time, the electricity generation was not a big issue. Then, the main concern of consumers of electricity became the reliability of supply. In recent years, there has been an increased emphasis on, and concern for, the quality of power delivered to industries, commercial establishments, and residences. This is due in part to the preponderance of harmonic-creating systems in use. Adjustable-speed drives, switching power supplies, arc furnaces, electronic fluorescent lamp ballasts, and other harmonic-generating equipment all contribute to the harmonic burden the system must accommodate. In addition, utility switching and fault clearing produce disturbances that affects the quality of delivered power [2]. Power quality has assumed increasing importance in view of the widespread use of power electronic equipment.

2.2 Definition of Power Quality

Power quality is a term that means different things to different people. Institute of Electrical and Electronic Engineers (IEEE) Standard IEEE1100 defines power quality as “the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment” [3]. Power quality problems are associated with power systems with broad ranges of time frames such as long duration variations, short duration variations and other disturbances. All electrical devices are prone to failure or malfunction when exposed to one or more power quality problems.

2.3 Need of Power Quality

There is an increased concern of power quality due to the following reasons [4]:

1. Newer-generation load equipment, with microprocessor-based controls and power electronic devices, is more sensitive to power quality variations than was equipment used in the past.
2. The increasing emphasis on overall power system efficiency has resulted in continued growth in the application of devices such as high-efficiency, adjustable-speed motor drives

and shunt capacitors for power factor correction to reduce losses. This is resulting in increasing harmonic levels on power systems and has many people concerned about the future impact on system capabilities.

3. End users have an increased awareness of power quality issues. Utility customers are becoming better informed about such issues as interruptions, sags, and switching transients and are challenging the utilities to improve the quality of power delivered.

4. Many things are now interconnected in a network. Integrated processes mean that the failure of any component has much more important consequences.

2.4 Power Quality Problems

2.4.1 Classes of Power Quality Problems

The term power quality is applied to a wide variety of electromagnetic phenomena on the power system. The increasing application of electronic equipment and distributed generation has raised the interest in power quality in recent years, and this has been accompanied by the development of a special terminology to describe the phenomena. Figure 2.1 [5] describe the demarcation of the various power quality issues defined by IEEE Std. 1159-1995.

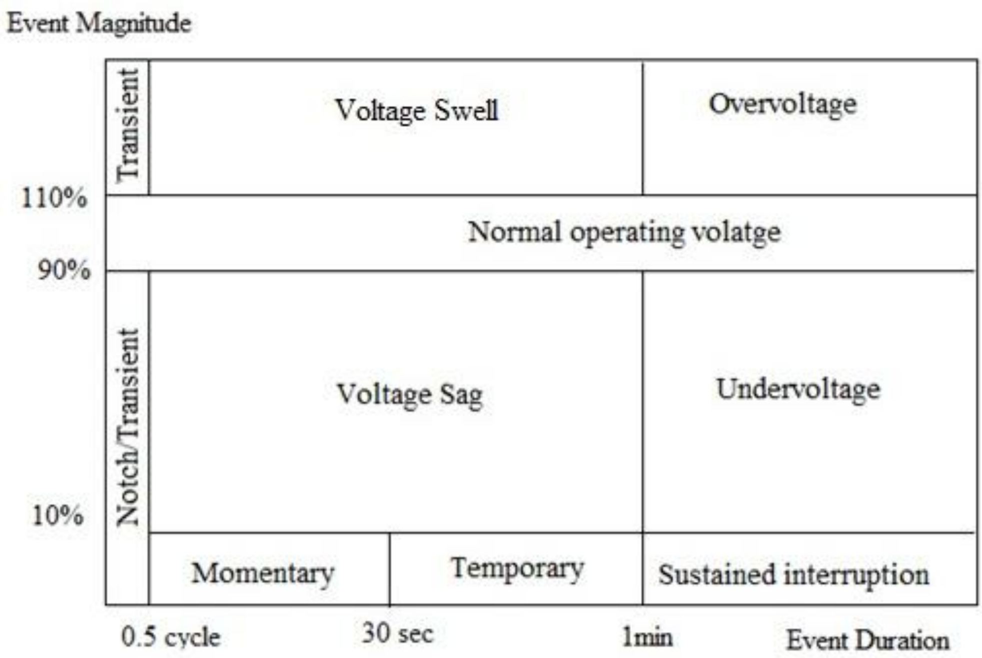


Figure 2.1: Definitions of Events by IEEE Std.1159-1995

Table 2.1 [4] shows the categorization of typical spectral content, duration, and magnitude which are appropriate for each category of electromagnetic phenomena. The categories and their descriptions are important in order to classify measurement results and to describe electromagnetic phenomena which can cause power quality problems.

Table 2.1: Categories and Characteristics of Power System Electromagnetic Phenomena

S.No	Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.	**Transients**			
	(i) Impulsive			
	Nanosecond Microsecond Millisecond	5-ns rise 1-μs rise 0.1-ms rise	<50 ns 50 ns–1 ms >1 ms	
	(ii) Oscillatory			
	Low frequency Medium frequency High frequency	<5 kHz 5–500 kHz 0.5–5 MHz	0.3–50 ms 20 μs 5 μs	0–4 pu 0–8 pu 0–4 pu
2.	**Short-duration variations**			
	(i) Instantaneous			
	Interruption Sag (dip) Swell		0.5–30 cycles 0.5–30 cycles 0.5–30 cycles	<0.1 pu 0.1–0.9 pu 1.1–1.8 pu
	(ii) Momentary			
	Interruption Sag (dip) Swell		30 cycles–3 s 30 cycles–3 s 30 cycles–3 s	<0.1 pu 0.1–0.9 pu 1.1–1.4 pu
	(iii) Temporary			
	Interruption Sag (dip) Swell		3 s–1 min 3 s–1 min 3 s–1 min	<0.1 pu 0.1–0.9 pu 1.1–1.2 pu
3.	**Long-duration variations**			
	(i) Interruption, sustained		>1 min	0.0 pu
	(ii) Undervoltages		>1 min	0.8–0.9 pu

	(iii) Overvoltages		>1 min	1.1–1.2 pu
4.	**Voltage unbalance**		Steady state	0.5–2%
5.	**Waveform distortion**			
	(i) DC offset		Steady state	0–0.1%
	(ii) Harmonics	0–100th harmonic	Steady state	0–20%
	(iii) Interharmonics	0–6 kHz	Steady state	0–2%
	(iv) Subharmonics		Steady state	
	(v) Notching		Steady state	
	(vi) Noise	Broadband	Steady state	0–1%
6.	**Voltage fluctuations**	<25 Hz	Intermittent	0.1–7% 0.2–2 P_{st}
7.	**Power frequency variations**		<10 s	

2.4.1.1 Short Duration Voltage Variation

Depending on the fault location and the system conditions, the fault can cause either temporary voltage drops (sags), voltage rises (swells), or a complete loss of voltage (interruptions). The duration of short voltage variations is less than 1minute. These variations are caused by fault conditions, the energization of large loads which require high starting currents, or intermittent loose connections in power wiring. [4].

(i) Voltage Sag: voltage sag (also called a "dip") is a brief decrease in the rms line voltage of 10 to 90 percent of the nominal line-voltage. The duration of a sag is 0.5 cycle to 1 minute. Common sources that contribute to voltage sags are the starting of large induction motors and utility faults.

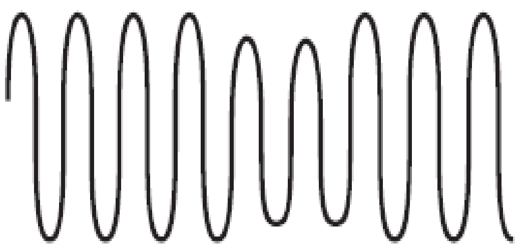


Figure 2.2: Voltage Sag

(ii) Voltage Swell: A swell is a brief increase in the rms line-voltage of 110 to 180 percent of the nominal line-voltage for duration of 0.5 cycle to 1 minute. The main sources of voltage swells are line faults and incorrect tap settings in tap changers in substations.

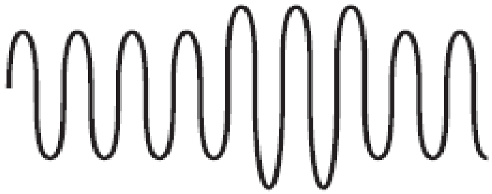


Figure 2.3: Voltage Swell

(iii) Interruption: An interruption is defined as a reduction in line-voltage or current to less than 10 percent of the nominal, not exceeding 60 seconds in length. Interruptions can occur due to power system faults, equipment failures, and control malfunctions.

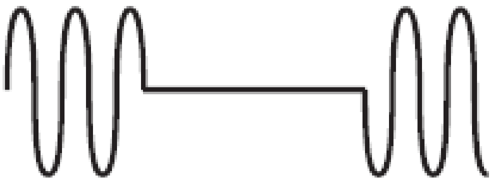


Figure 2.4: Interruption

2.4.1.2 Long-Duration Voltage Variation

Long-duration variations can be categorised as overvoltages, undervoltages or sustained interruptions.

(i) Overvoltage: An overvoltage is an increase in the rms ac voltage greater than 110 percent at the power frequency for duration longer than 1 min. Overvoltages are usually the result of load switching or incorrect tap settings on transformers.

(ii) Undervoltage: An undervoltage is decreases in the rms ac voltage to less than 90 percent at the power frequency for duration longer than 1 min. A load switching on or a capacitor bank switching off can cause an undervoltage until voltage regulation equipment on the system can restore the voltage back to within tolerance limits. Also overloaded circuits can result in undervoltage.

(iii) Sustained Interruptions: When the supply voltage has been zero for a period of time in excess of 1 min, the long-duration voltage variation is considered a sustained interruption.

2.4.1.3. Transients

(i) Impulsive Transient: An impulsive transient is a brief, unidirectional variation in voltage, current, or both on a power line. Lightning strikes, switching of inductive loads, or switching in the power distribution system are the most common causes of impulsive transients. The effects of transients can be mitigated by the use of transient voltage suppressors such as Zener diodes and MOVs (metal-oxide varistors).

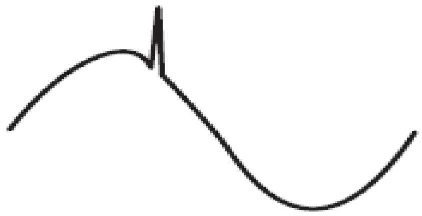


Figure 2.5: Impulsive Transients

(ii) Oscillatory Transient: An oscillatory transient is a brief, bidirectional variation in voltage, current, or both on a power line. These are caused due to the switching of power factor correction capacitors, or transformer ferroresonance.

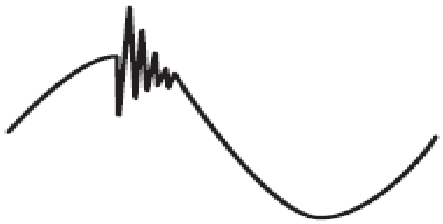


Figure 2.6: Oscillatory Transients

2.4.1.4. Voltage Fluctuations

Voltage fluctuations are relatively small (less than ± 5 percent) variations in the rms line voltage. Cycloconverters, arc furnaces, and other systems that draw current not in synchronization with the line frequency are the main contributors of these variations.

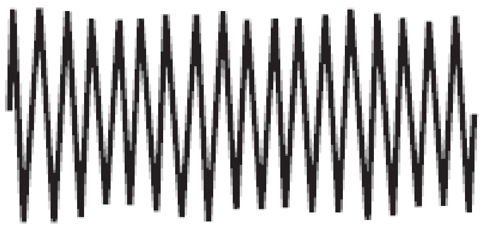


Figure 2.7: Voltage Fluctuations or Flicker

2.4.1.5. Voltage Imbalance

A voltage imbalance is a variation in the amplitudes of three-phase voltages, relative to one another. Voltage imbalance can be the result of different loads on the phases, resulting in different voltage drops through the phase-line impedances.

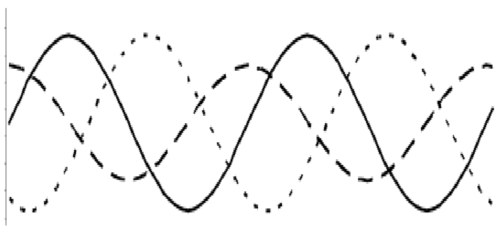


Figure 2.8: Voltage Imbalance

2.4.1.6. 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.

(i) DC offset: The presence of a dc voltage or current in an ac power system is termed dc offset.

(ii) Harmonics: Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate, termed as the fundamental frequency which is usually 50 or 60 Hz. Harmonic distortion originates in the nonlinear characteristics of devices and loads on the power system.

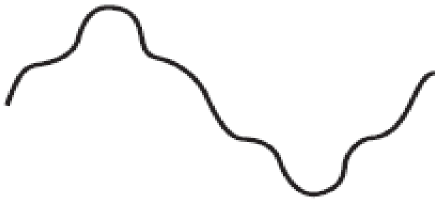


Figure 2.9: Harmonics

Harmonic distortion levels can be described by the calculating total harmonic distortion (THD) which measures the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. THD is represented as the square-root of the sum of the squares of each individual harmonic [18]. Voltage THD is

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

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

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

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

THD and DIN are interrelated by the following equations

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

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

(iii) Interharmonics: Voltages or currents having frequency components that are not integer multiples of the frequency at which the supply system is designed to operate (50 or 60 Hz) are called interharmonics. Interharmonics can appear as discrete frequencies or as a wideband spectrum. The main sources of interharmonic waveform distortion are static frequency converters, induction furnaces, cycloconverters and arcing devices. Power line carrier signals can also be considered as interharmonics.

(iv) Subharmonics: Subharmonics can be defined as frequency components in voltage and current waveforms less than the power system frequency. Cycloconverters, adjustable speed drives, arc furnaces, wind generators and other loads inject low frequency currents that produce subharmonic distortion in voltage supply [26].

(v) Notching: Notching is a periodic voltage disturbance caused by the normal operation of power electronic devices when current is commutated from one phase to another [4].

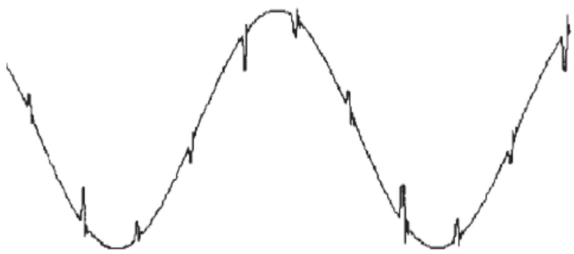


Figure 2.10: Notching

(vi) Noise: Noise is defined as unwanted electrical signals with broadband spectral content lower than 200 kHz superimposed upon the power system voltage or current in phase conductors, or found on neutral conductors or signal lines. Noise in power systems can be due to power electronic devices, control circuits, arcing equipment, loads with solid-state rectifiers, and switching power supplies.

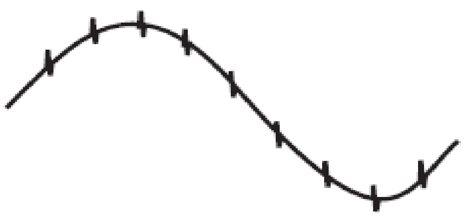


Figure 2.11: Noise Waveform

2.4.1.7 Power Frequency Variations

Power frequency variations are defined as the deviation of the power system fundamental frequency from its specified nominal value (e.g. 50 or 60 Hz). The power system frequency directly depends on the rotational speed of the generators supplying the system [4].

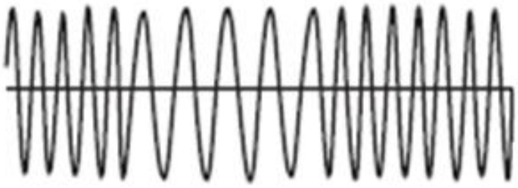


Figure 2.12: Power Frequency Variations

2.5 Distribution Reliability

Better reliability performance can be achieved with regular maintenance schedules, better design schemes which can include the use of expensive protection equipment (i.e. reclosures), and distribution automation such as sensors, monitors and advanced technologies for condition monitoring [7].

There are several ways to exactly define the reliability or the quality of the electric supply. The two main ways used to quantify the reliability of the electric supply are based on:

(i) Frequency – The rate of interruptions of the electric supply is often quantified in terms of the mean time between failures (MTBF). The failure rate is often denoted by λ in units of average failures per unit of time (λ = 1/MTBF).

(ii) Duration – An interruption of the electric supply can be quantified as the availability or as the unavailability. Availability can be specified in per unit or percent. Even though the unavailability is a unit-less quantity, it is usually referred to in units of time such as minutes per year. The unavailability is r λ, where r is denoted for the repair time and λ is the failure rate.

2.5.1 Customer-Based Indices

Utilities most commonly use two indices, SAIFI and SAIDI, to benchmark reliability. These characterize the frequency and duration of interruptions during the reporting period (usually years) (IEEE Std. 1366-2000) [9].

SAIFI, System average interruption frequency index

$$\text{SAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}} \ /\text{yr} \qquad (2.5)$$

Typically, a utility’s customers average between one and two sustained interruptions per year. SAIFI is also the average failure rate, which is often labelled λ. Another useful measure is the mean time between failure (MTBF), which is the reciprocal of the failure rate: MTBF in years = 1/ λ.

SAIDI, System average interruption duration frequency index

$$\text{SAIDI} = \frac{\text{Sum of all customer interruption durations}}{\text{Total number of customers served}} \quad \text{hr/yr} \qquad (2.6)$$

SAIDI quantifies the average total duration of interruptions. SAIDI is cited in units of hours or minutes per year. Other common names for SAIDI are CMI and CMO, standing for customer minutes of interruption and outage respectively.

Another related index is CAIDI:

CAIDI, Customer average interruption duration frequency index

$$\text{CAIDI} = \frac{SAIDI}{SAIFI} \quad \text{hr} \qquad (2.7)$$

$$\text{CAIDI} = \frac{\text{Sum of all customer interruption durations}}{\text{Total number of customer interruptions}} \quad \text{hr} \qquad (2.8)$$

CAIDI is the “apparent” repair time (from the customers’ perspective). It is generally much shorter than the actual repair time because utilities normally sectionalize circuits to reenergize as many customers as possible before fixing of the actual damage. Also used in many other industries, the availability is quantified as

ASAI, Average service availability index

$$\text{ASAI} = \frac{\text{Customer hours service availability}}{\text{Customer hours service demanded}} \quad \text{pu} \qquad (2.9)$$

We can find ASAI from SAIDI specified in hours as

$$\text{ASAI} = \frac{8760 - \text{SAIDI}}{8760} \quad \text{pu} \qquad (2.10)$$

(Use 8784 h/year for a leap year.)

MAIFI stands for Momentary average interruption frequency index. This index deals with momentary hour short duration interruptions. In general, the utilities do not treat the short duration interruptions as outages and hence momentary interruptions are not classified under SAIFI or CAIFI. The momentary index is computed as

$$\text{MAIFI} = \frac{\text{Number of Customer momentary interruptions}}{\text{Total number of Customers}} \quad /\text{yr} \qquad (2.11)$$

2.5.2 Load-Based Indices

To more fairly weight larger customers, load-based indices are available; the equivalent of SAIFI and SAIDI, but scaled by load, are ASIFI and ASIDI:

ASIFI, Average system interruption frequency index

ASIFI = $\frac{\text{Connected kVA interrupted}}{\text{Total connected kVA served}}$ /yr (2.12)

ASIDI, Average system interruption frequency index

ASIDI = $\frac{\text{Connected kVA interruption duration}}{\text{Total connected kVA served}}$ hr/yr (2.13)

Less than 8% of utilities track ASIFI and ASIDI mainly because they are hard to track as knowing load interrupted is more difficult than knowing number of customers interrupted. Utilities also feel that commercial and industrial customers have enough clout that their problems are given due attention [9].

2.5.3 Power Quality Indices

Reliability is the subset of power quality, and many reliability decisions affect other areas of power quality. Because of this, familiarity with basic power quality indices is necessary. Many sensitive loads cannot depict the difference between voltage sags and momentary interruptions. Thus all customer concerns are not reflected by the interruption-based reliability indices therefore the voltage sag indices are gaining wide importance.

$SARFI_X$, System average RMS Variation Frequency Index

$SARFI_X$ = $\frac{\text{Total Customer Sags Below x\%}}{\text{Total Number of Customers Served}}$ /yr (2.14)

$SARFI_X$ may not contain enough information to be useful index in all cases. Since the severity of voltage sags depends upon duration as well as magnitude. The approach to decompose $SARFI_X$ into instantaneous, momentary and temporary index is based on the duration of sag. Thus duration dependent sag indices are:

System Instantaneous Average RMS Variation Frequency Index:

$SAIRFI_X$ = $\frac{\text{Total Customer Sags Below x\% (0.5c}-\text{30c)}}{\text{Total Number of Customers Served}}$ /yr (2.15)

System Momentary Average RMS Variation Frequency Index:

$SMARFI_X$ = $\frac{\text{Total Customer Sags Below x\% (30c}-\text{3s)}}{\text{Total Number of Customers Served}}$ /yr (2.16)

System Temporary Average RMS Variation Frequency Index:

$STARFI_X$ = $\frac{\text{Total Customer Sags Below x\% (3s}-\text{60s)}}{\text{Total Number of Customers Served}}$ /yr (2.17)

2.6 Power Acceptability Curves

These curves quantify the acceptability of supply power as a function of duration versus magnitude of bus voltage disturbances [6]. In the 1970s, the Computer Business Equipment Manufacturers Association (CBEMA) developed the curve shown in figure 2.13 [2] to set limits to the withstanding capabilities of computers in terms of magnitude and duration of voltage disturbance. The horizontal axis of the curve represents the duration of the sag or swell, and the vertical axis represents the percent change in line voltage. CBEMA curve was developed utilizing historical data from mainframe computer operations, showing the range of acceptable power supply voltages for computer equipment.

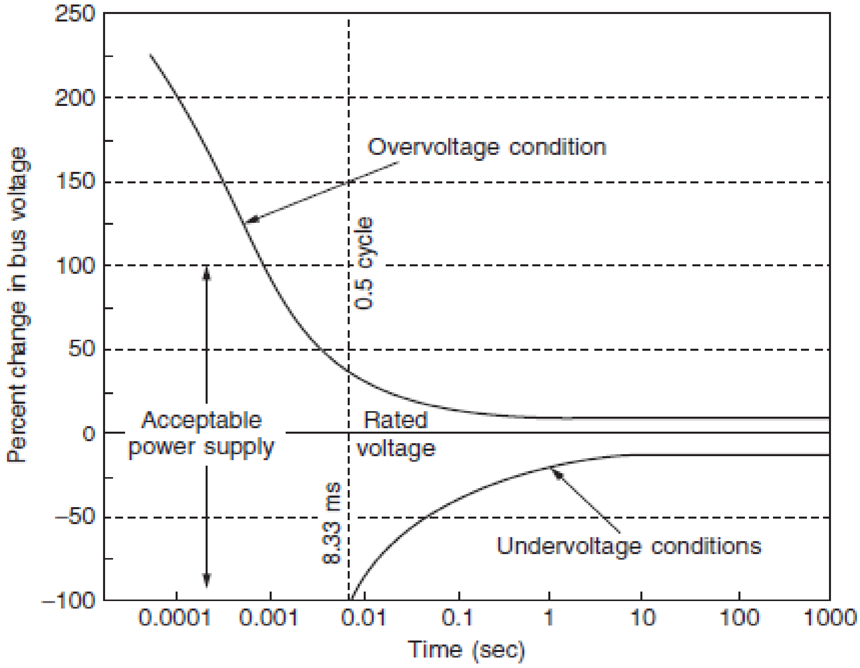


Figure 2.13: The CBEMA Curve

In the 1990s, the Information Technology Industry Council (ITIC) redesigned the CBEMA curve and developed the ITIC curve as shown in figure 2.14 [2] which describes the acceptable range in steps rather than smooth curve used in CBEMA.

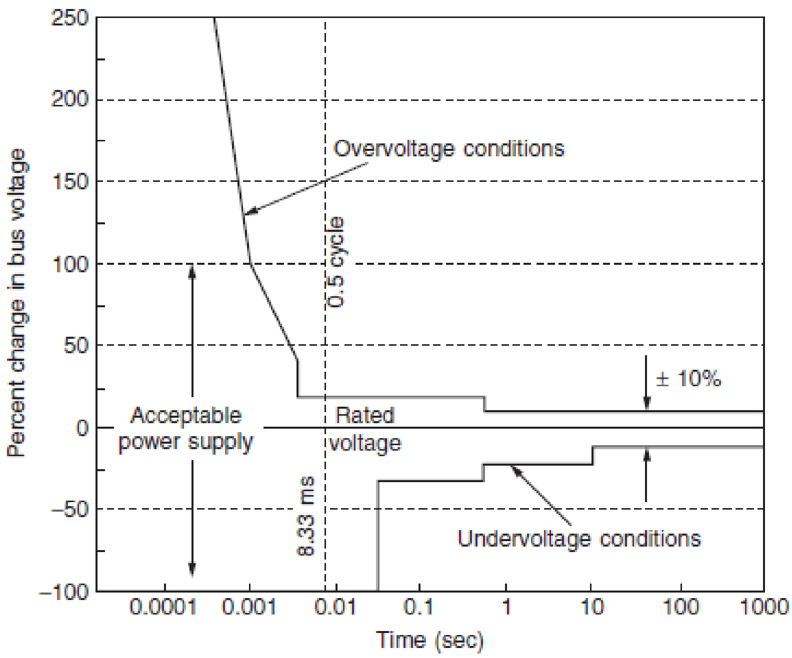


Figure 2.14: The ITIC Curve

2.7 Solutions to Power Quality Problems

The mitigation of power quality problems can be achieved in two ways. The solution to the power quality can be done from customer side or from utility side. First approach is called load conditioning and the other is line conditioning. Load conditioning ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion while the instalment of line conditioning systems suppresses or counteracts the power system disturbances. They are based on PWM converters and connect in shunt or in series to low and medium voltage distribution system. Series active power filters must operate in conjunction with shunt passive filters in order to compensate load current harmonics. Series active power filters operates as a controllable voltage source whereas shunt active power filters operate as a controllable current source. Both schemes are implemented preferable with voltage source PWM inverters, with a dc bus having a reactive element such as a capacitor. However, with shifting trend towards distributed and dispersed generation and with the restructuring of power sector, the line conditioning systems or utility side solutions will play a vital role in improving the inherent supply quality [12]. Some of the effective and economic measures can be identified as following:

(i) Lightening and Surge Arresters: Arresters are designed for lightening protection of transformers, but are certainly not sufficient for limiting voltage to protect sensitive electronic control circuits from voltage surges.

(ii) Thyristor Based Static Switches: The static switch is a device for switching a new element into the circuit when the voltage support is needed. It has a dynamic response time of about one cycle. It can be used in the alternate power line applications. To correct quickly for voltage spikes, sags or interruptions, the static switch can used to switch one or more of devices such as filter, capacitor, alternate power line, energy storage systems etc.

(iii) Energy Storage Systems: Storage systems can be used to protect sensitive production equipments from shutdowns caused by voltage sags or momentary interruptions. The energy is fed to the system to compensate for the energy that would be lost by the voltage sag or interruption. These are usually DC storage systems such as batteries, UPS, superconducting magnet energy storage (SMES), storage capacitors or even fly wheels driving DC generators. The output of these devices can be supplied to the system through an inverter on a momentary basis.

(iv) Electronic Tap Changing Transformer: A voltage-regulating transformer with an electronic load tap changer can be used with a single line from the utility. It can regulate the voltage drops up to 50% and requires a stiff system (short circuit power to load ratio of 10:1 or better). It can have the provision of coarse or smooth steps intended for occasional voltage variations.

(v) Harmonic Filters: Filters are used in some instances to effectively reduce or eliminate certain harmonics. If possible, it is always preferable to use a 12-pluse or higher transformer connection, rather than a filter. Usually, multiple filters are needed, each tuned to a separate harmonic. Each filter causes a parallel resonance as well as a series resonance, and each filter slightly changes the resonances of other filters.

CHAPTER 3
CUSTOM POWER

3.1 Introduction

For improving the system performance for distribution system and with the growing development of the power semiconductor technology, the concepts of custom power was introduced to distribution systems. The concept describes the value-added power that electric utilities will offer their customers in the future, focusing on the quality of power flow and reliability [25]. Due to this increasing demand and the rapid development of the high power semiconductor technology, the custom power solutions are taking place very fast.

3.2 Need of Custom Power

With the passage of time and technology, came a demand for greater dependability. The problem arises because of the changing trends. The increased use of automated equipment, like adjustable speed drives, programmable logic controllers, switching power supplies, arc furnaces, electronic fluorescent lamp ballasts, automated production lines are far more vulnerable to disturbances on the utility system than were the previous generation of electromechanical equipment and the previous less automated production and information systems.

Conventional protection equipments used in distribution systems are based on mechanical parts e.g. reclosures and breakers. Typical fault clearing times of these equipments vary from 3 to 30 cycles, depending on fault current magnitude and the type of over-current protection. Before the protection system actuates system has to withstand high fault currents and transient overvoltages at the opening of breakers thus components of the distribution system have to be over-dimensioned. In addition to that, such type of electrical stress results in the reduction of the life expectancy of the equipment. Remote faults in the system can cause a voltage reduction where a critical customer is connected. The resulting voltage sag can be significant, if the current magnitude is relatively large compared to the available fault current at that point (i.e. the short-circuit capacity/power).

Even though the power generation in most advanced country is fairly reliable, the distribution is not always so. It is however not only reliability that the consumers want these days, quality too is very important for them. With the deregulation of the electric power energy market, the awareness regarding the quality of power is increasing day by day among different categories of customers. Power quality is an issue that is becoming increasingly important to electricity consumers at all levels of usage.

Also, in the several processes such as semiconductor manufacturing or food processing plants, a batch of product can b ruined by a voltage dip of very short duration. Even short dips are sufficient to cause contactors on motor drives to drop out. There are also very sensitive loads such as hospitals, processing plants, air traffic control and numerous other data processing and service providers that require clean and uninterrupted power. Thus in the changed scenario in which customers increasingly demand power quality, the term power quality attains increased significance.

The factors mentioned point to the problems faced by the industry and awareness among the people about quality of power due to which it has increasingly become important to provide the consumers with the reliable as well as superior power quality. Thus the development of custom power has gained so much of widespread attention nowadays.

3.3 Custom Power Devices

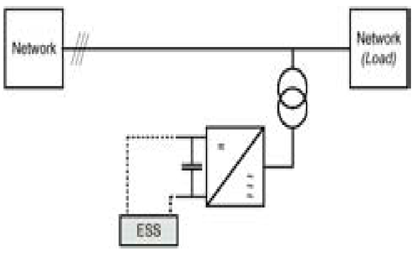
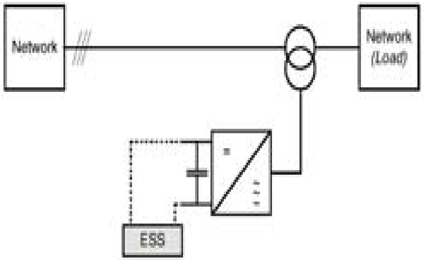
There are many types of Custom Power devices. Some of these devices include Active Power Filters (APF), Surge Arresters (SA). Battery Energy Storage Systems (BESS), Super conducting Magnetic Energy Systems (SMES), Static Electronic Tap Changers (SETC), Solid State Fault Current Limiter (SSFCL), Solid-State Transfer Switches (SSTS), Static Var Compensator (SVC), Distribution Series Capacitors (DSC), Dynamic Voltage Restorer (DVR), Distribution Static synchronous Compensators (DSTATCOM) and Uninterruptible Power Supplies (UPS) [13].

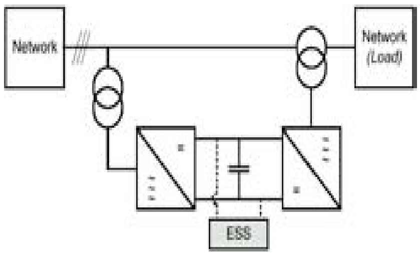
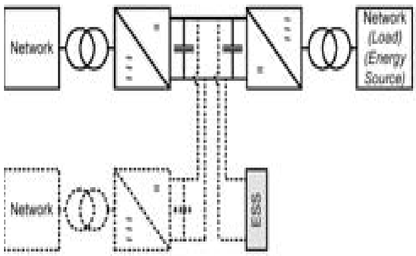
The classification of custom power devices can be done into two major categories, one is network configuring type and the other is compensating type. The network configuring type devices changes the configuration of the power system network for power quality enhancement. SSCL (Solid State Current Limiter), SSCB (Solid State Circuit Breaker) and SSTS (Solid State Transfer Switch) are the most representative in this category. SSCL is a GTO based device that inserts an inductor in series with a power system and limits the fault current and once the fault is cleared the inductor is removed from the circuit. SSCB acts as a protection device. It isolates the faulted circuit from the system. SSTS transfers rapidly the load from a faulted line to an alternative line to protect a sensitive load. Due to the use of GTO or thyristors in these devices, they are therefore called “solid state” devices.

The compensating type devices are used for active filtering; load balancing, power factor correction and voltage regulation. The family of compensating devices include DSTATCOM (Distribution Static compensator), DVR (Dynamic voltage restorer) and Unified power quality conditioner (UPQC). DSTATCOM is connected in shunt with the power system while DVR is a series connected device that injects a rapid series voltage to compensate the supply voltage. UPQC is the combination of DSTATCOM and DVR. It injects series voltage and shunt currents to the system [13, 24].

Table 3.1 shows the circuit topology and tasks performed by the FACTS equipments in distribution system. Though there are many different methods to mitigate voltage sags and swells, but the use of a custom power device is considered to be the most efficient method to serve for different purposes and to provide with different economical justifications. The term Custom Power pertains to the use of power electronics controllers in a distribution system to deal with various power quality problems. It makes sure that customers get pre-specified quality and reliability of power supply [8]. This pre-specified quality of power may includes a single or the combination of the specifications like no power interruptions, low phase unbalance, low harmonic distortion in load voltage, low flicker at the load voltage, acceptance of fluctuations, magnitude and duration of overvoltage and under voltages within specified limits and poor factor loads without significant effect on the terminal voltage.

Table 3.1: FACTS Equipment in Distribution System

Name	Topology	Preferred Tasks
DSTATCOM (Distribution STSTCOM)	 energy storage system	• Flicker compensation • Reactive power compensation • Harmonic filter
DVR (dynamic voltage restorer)		• Sag/swell compensation

UPQC (unified power quality controller)		• Undervoltage/overvoltage compensation • DSTATCOM and DVR advantages
Direct current transmission & HVDC Light system		• Coupling of remote loads or remote energy sources • Optimization of energy cost through coupling of bus bars or system parts

3.3.1 Distribution Statcom (DSTATCOM)

The coupling of DSTATCOM is three phase, in parallel to network and load. In order to compensate undesirable components of the load current the DSTATCOM injects currents into the point of common coupling. A DSTATCOM is utilized to eliminate the harmonics from the source currents and also balance them in addition to providing reactive power.

3.3.2 Dynamic Voltage Restorer (DVR)

DVR injects a voltage component in series with the supply voltage, thus compensating voltage sags and swells on the load side. Control response is on the order of 3msec, ensuring a secure voltage supply under transient network conditions. Voltage injection of arbitrary phase with respect to the load current implies active power transfer capability. This active power is transferred via the dc link, and is supplied either by a diode bridge connected to the ac network, a shunt connected PWM converter or by an energy storage device. It works as a harmonic isolator to prevent the harmonics in the source voltage reaching the load in addition to balancing the voltages and providing voltage regulation.

3.3.3 Unified Power Quality Controller (UPQC)

The best protect for sensitive loads from voltage sources with inadequate quality, is shunt-series connection power conditioner (UPQC) in which the shunt part supplies the required power of the series part in the condition of voltage sags. It consists of two PWM converters and a dc link capacitor. Shunt converters in spite of supplying the required active power by in series converters, they also can have applying DSTATCOM modes. Series converters inject a series voltage to the supply voltage and can posses the advantages of DVR.

Of all these custom power devices, our main focus will be on dynamic voltage restorer. DVR is considered as the active solution for voltage sag mitigation. In our work, we will be working on DVR which is used to restore load voltage to its rated value, thus enabling the consumer to continuously receive high quality power.

3.4 Superiority of DVR over Other Devices

Each of Custom Power devices has its own benefits and limitations. The most effective type of these devices is considered to be the Dynamic Voltage Restorer (DVR). There are numerous reasons why the DVR is preferred over the others. The SVC pre-dates the DVR, but the DVR is still preferred over SVC because the SVC has no ability to control active power flow. Another reason is that the DVR is less costly as compared to the UPS. Moreover UPS also requires a high level of maintenance because of leakages of batteries and has to be replaced as often as every five years. Also comparing the DVR with SMES device, the DVR has a higher energy capacity and lower costs. Furthermore, the DVR is smaller in size and costs less compared to the DSTATCOM. Based on these reasons, the DVR is widely considered as an effective custom power device in mitigating voltage sags and swells. In addition to voltage sags and swells compensation, DVR can also added other features such as harmonics and power factor correction [13]. Compared to the other devices, the DVR clearly provides the best economic solution for its size and capabilities.

CHAPTER 4

DYNAMIC VOLTAGE RESTORER

4.1 Introduction

Due to the fast variations in the source voltage, the performance of critical loads such as semiconductor fabrication plants, paper mills, food processing plants and automotive assembly plants can be affected. The most commonly occurring disturbances in the source voltages are the voltage sags or swell that can be due to disturbances arising in the transmission system, adjacent feeder faults or fuse or breaker operation. Voltage sags of even 10% reduction in magnitude, lasting for 5-10 cycles can result in costly damage in critical loads. They can arise due to symmetrical or unsymmetrical faults.

Uncompensated nonlinear loads in the distribution system can cause harmonic components in the supply voltages. To mitigate the problems caused by poor quality of power supply, series connected compensators known as Dynamic Voltage Restorer (DVR) are used [1].

A Dynamic Voltage Restorer is a series connected solid state device that injects voltage into the system in order to regulate the load side voltage. It is normally installed in a distribution system between the supply and the critical load feeder [26]. Its primary function is to rapidly recover the load-side voltage in the event of a disturbance in order to avoid any power disruption to that load. There are various circuit topologies and control schemes that can be used to implement a DVR. The DVR has also the capability to deal with line voltage harmonics compensation, reduction of transients in voltage and fault current limitations.

In order to mitigate voltage sag, DVR should be capable of generating and absorbing active and reactive power to/from the grid. To correct a given voltage sag, not only voltage but also active and/or reactive power injections are required. DVR is capable of generating the reactive power, but the injected active power must come from the energy storage part of DVR [14]. Thus minimization of active power injection is essential to increase the lift of the energy storage.

4.2 Basic Configuration of DVR

The general configuration of the DVR consists of

(i) Injection / Booster transformer

(ii) Harmonic filter

(iii) Voltage Source Converter (VSC)

(iv) Control and Protection system.

4.2.1 Injection / Booster Transformer

The Injection / Booster transformer is a specially designed transformer that attempts to limit the coupling of noise and transient energy from the primary side to the secondary side [35]. It connects the DVR to the distribution network via the HV-windings and transformers and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage. In addition, the Injection / Booster transformer serves the purpose of isolating the load from the system.

4.2.2 Harmonic Filter

The main task of harmonic filter is to keep the harmonic voltage content generated by the inverter within tolerable limits. These filters are placed at the high voltage side to avoid introductions in phase angle shift, which can disrupt the control algorithm [29].

4.2.3 Voltage Source Converter

A VSC is a power electronic system consisting of a storage device and switching devices, which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle. In the DVR application, the VSC is used to temporarily replace the supply voltage or to generate the part of the supply voltage which is missing. Numerous circuit topologies are available for the VSC but the widely used method is the two level or multilevel three-phase converter which shares a dc capacitor between all phases. The purpose of this capacitor is mainly to absorb harmonic ripple and hence it has a relatively small energy storage requirement, particularly when operating in balanced conditions.

- **Switching Devices**

There are four main types of switching devices: Gate Turn- Off thyristors (GTO), Insulated Gate Bipolar Transistors (IGBT), Integrated Gate Commutated Thyristors (IGCT) and Metal Oxide Semiconductor Field Effect Transistors (MOSFET). Each type of device has its own benefits and limitations. The IGCT is a recent compact device with enhanced performance and reliability that allows building VSC with very large power ratings. Because of the highly sophisticated converter design with IGCTs, the DVR can compensate dips which are beyond the capability of the past DVRs using conventional devices.

- **Storage Devices**

The purpose is to supply the necessary energy to the VSC via dc link for the generation of injected voltages. Batteries and Ultra capacitors are the most common types of energy storage devices. Batteries can be highly effective if a high voltage battery configuration is used. Certain ultra capacitors (unsymmetrical electrochemical) can hold charge over extended periods of time, so as to act like a battery. However, unlike batteries, these ultra capacitors have a short charge time and much longer lifetime. In fact, the capacity of the stored energy determines directly the duration of the sag which can be mitigated by the DVR.

4.2.4 Control and Protection System

The control mechanism of the general configuration typically consists of Digital Signal Processing (DSP) boards. The controls such as detection and correction are provided by the software on the DSP board. Filters are commonly used for these purposes. The most common types of filter algorithm are the Fourier Transform (FT) and the Wavelet Transform (WT) [19].

4.3 Location of DVR

The location of the DVR, in terms of the connection arrangement of upstream transformers (typically) and the type of protection it is to offer to potentially sensitive loads, is a major factor when determining the type of inverter control required. The DVR is located downstream of a delta-star distribution transformer, thus eliminating the need to control the zero sequence [31].

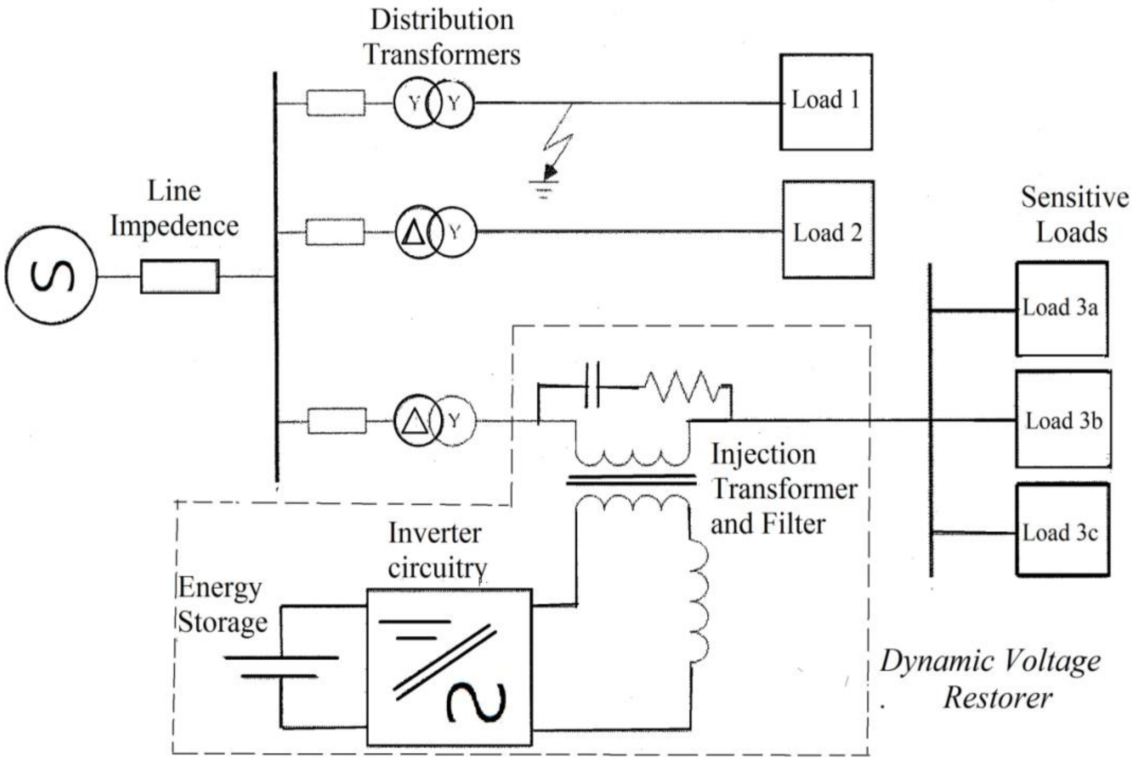


Figure 4.1: Typical Location of a DVR in a Power Network

4.4 Principle of Operation

The DVR is a custom power device that is connected in series with the distribution system as shown in figure 4.2. [28]. The DVR is forced commutated voltage source converter that injects a dynamically controlled voltage (V_{DVR}) in series to the bus voltage by means of a booster transformer. The momentary amplitudes of the three injected phase voltages caused by transient disturbances in the ac feeder will be compensated by an equivalent voltage generated by the converter and injected on the medium voltage level through the booster transformer.

The DVR works independently of the type of fault or any event that happens in the system, provided that the whole system remains connected to the supply grid, i.e. the line breaker does not trip. For most cases, a more economical design can be achieved by only compensating the positive and negative sequence components of the voltage disturbance seen at the input of the DVR. For a typical distribution bus configuration, because of infinite impedance the zero sequence part of a disturbance will not pass through the step down transformer.

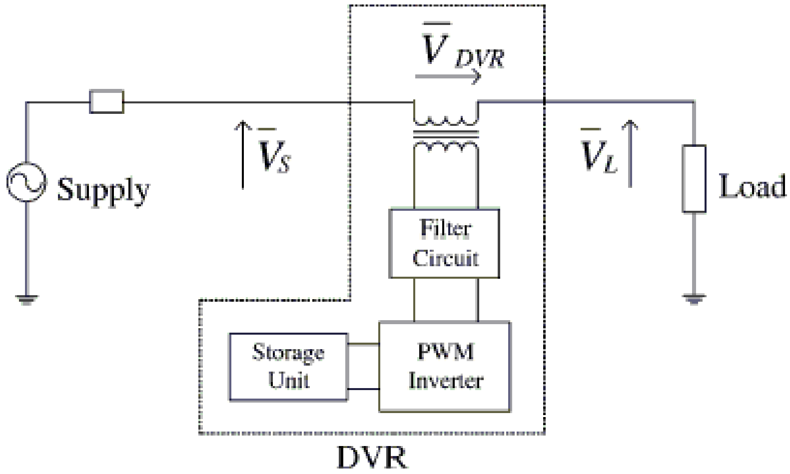


Figure 4.2: DVR Operation

Figure 4.3 [28] shows the equivalent circuit of the DVR, when the source voltage rises or drops, the DVR injects a series voltage V_{inj} through the injection/booster transformer so that the desired load voltage magnitude V_L can be maintained. The series injected voltage of the DVR can be written as

$$V_{inj} = V_L + V_s \quad (4.1)$$

Where

V_L is the desired load voltage magnitude

V_s is the source voltage during sags/swells condition

The load current I_L is given by,

$$I_L = ((P_L \pm J * Q_L) / V_L) \quad (4.2)$$

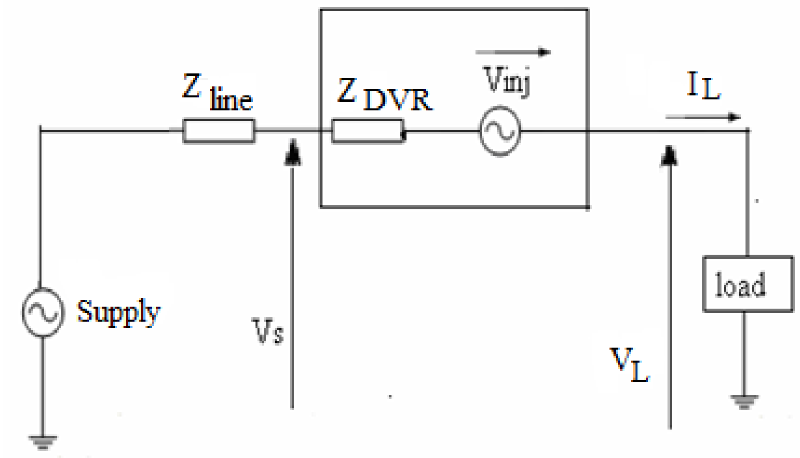


Figure 4.3: Equivalent Circuit of DVR

4.5 Operating Modes of DVR

Generally, the DVR is categorized into three-operation mode: protection mode, standby mode (during steady state) and injection mode (during sag).

4.5.1 Protection Mode

Due to short circuit on the load or large inrush currents, the DVR is protected from the over current in the load side. If the over current on the load side exceeds a permissible limit, the DVR will be isolated from the systems by using the bypass switches (S2 and S3 will open) and supplying another path for current (S1 will be closed).The bypass switches remove the DVR from system by supplying another path for current as shown in figure 4.4 [17].

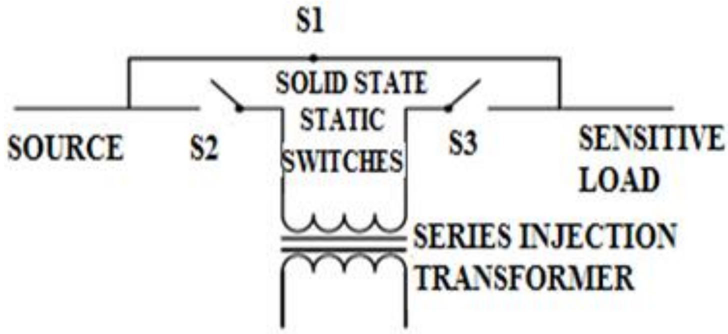


Figure 4.4: Protection Mode of DVR

4.5.2 Standby Mode (also termed as short circuit operation (SCO) mode)

In this mode the voltage injected has zero magnitude (V_{DVR}=0), the booster transformer's low voltage winding is shorted through the converter. The DVR will be most of the time in this mode. No switching of semiconductors occurs in this mode of operation. Therefore, only the comparatively low conduction losses of the semiconductors in this current loop contribute to the losses.

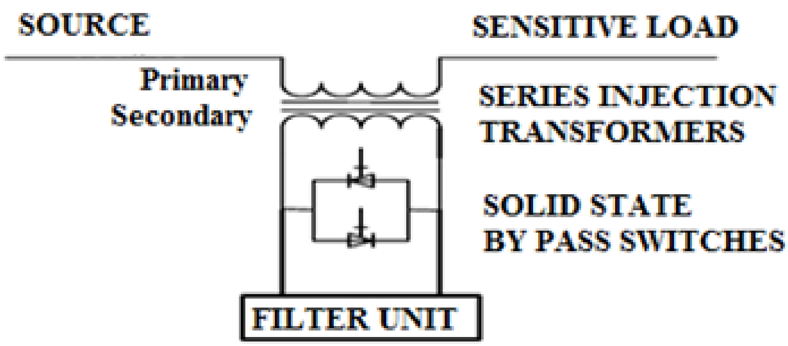


Figure 4.5: Standby Mode of DVR

4.5.3 Injection/Boost Mode

The DVR goes into injection mode as soon as the sag is detected. The DVR injects a required voltage of appropriate magnitude and phase to restore the pre fault load bus voltage (V_{DVR}>0). Three single-phase ac voltages are injected in series with required magnitude, phase and wave shape for compensation. The possibility of compensating voltage sag is determined from the types of voltage sags, load conditions and power rating of DVR. The DVR should ensure the unchanged load voltage with minimum energy dissipation for injection due to the high cost of capacitors.

4.6 Voltage Sag Compensation Methods

The voltage sag compensation can be achieved in three different methods which are in-phase, pre-fault and optimized energy depending on limiting factors like DVR power rating, various conditions of load and different types of voltage sag. The methods are analyzed as follows.

(a) In-Phase Compensation Method

The phasor diagram of in-phase compensation method is shown in figure 4.6. In this method DVR voltage is injected to the network in phase with the post-sag source voltage ($V_{S-postsag}$). Thus during compensation period, the phase angle of the compensated load voltage (V_L) is equal to the angle of post-fault network voltage. Consequently, if the occurred disturbance causes an angle jump (δ) in the network voltage, then compensated load voltage will experience the same value of phase angle jump.

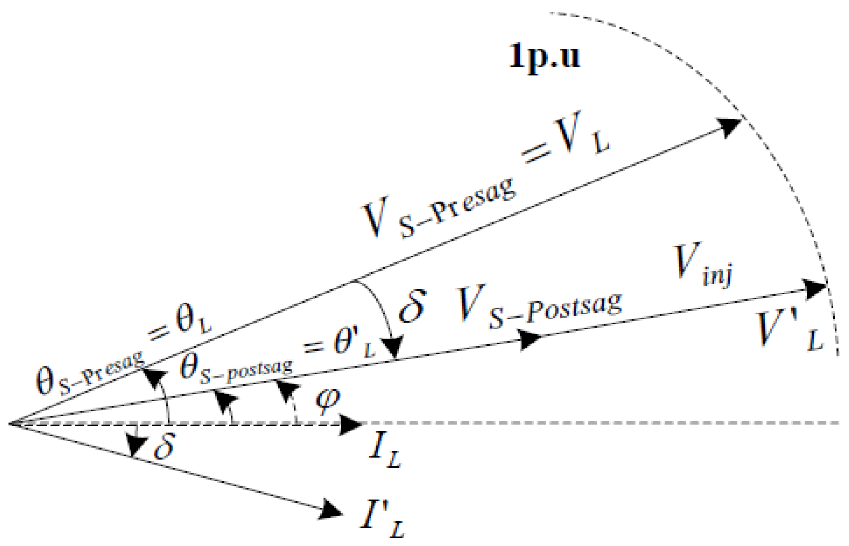


Figure 4.6: Phasor Diagram of In-Phase Compensation Method

Considering the phasor diagram represented in figure 4.6, amplitude and phase of the injection voltage in in-phase compensation strategy are calculated as follows:

$|V_{inj}| = 1- |V_{S\text{-}presag}|$ (4.3)

$\angle V_{inj} = \theta_{S\text{-}postsag} = \theta'_L$ (4.4)

Where $V_{S\text{-}presag}$ and $\theta_{S\text{-}postsag}$ are pre-fault source voltage and post-fault phase of supply voltage respectively. In comparison with other strategies the advantage of this method is that the amplitude of DVR injection voltage is minimum for certain voltage sag. This method is practically used in the application of in non-sensitive loads to phase angle jump [30].

(b) Optimized Energy Compensation Method

In this method, maximum reactive capacity of the DVR is used to compensate voltage sags. Therefore, DVR voltage is injected in such a way that during the compensation period the load current and post-sag supply voltage are kept in-phase. Phasor diagram of the voltage sag compensation with optimized energy strategy is illustrated in figure 4.7, by application of this method, shallow voltage sags could be improved only by injecting reactive power and there will be no concern about the energy storage capacity and duration of compensation. But its disadvantages are its inability of mitigating phase angle jump and higher amplitude of injection voltage as compared to other methods.

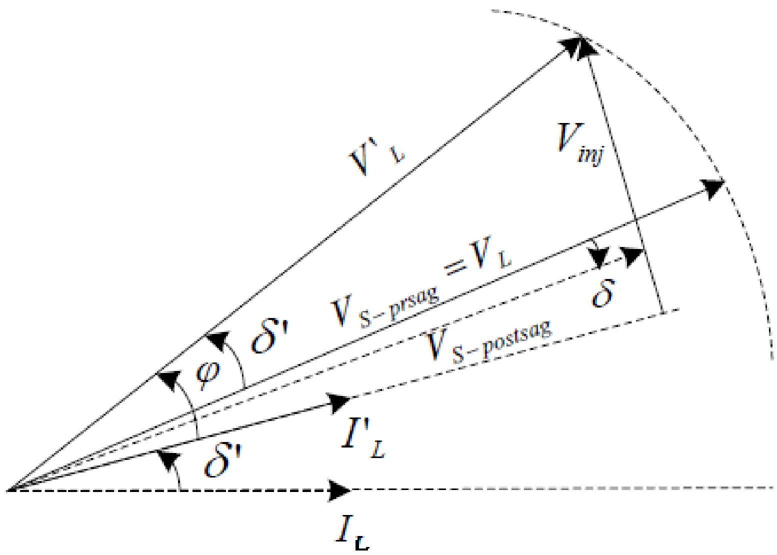


Figure 4.7: Phasor Diagram of Optimized Energy Compensation Method

(c) Pre-Fault Compensation Method

Mitigation of voltage sags in the both phase angle and amplitude sensitive loads would be solely achieved by pre-fault compensation method. Figure 4.8 describes the phasor diagram of this voltage sag compensation with pre-fault. In pre-fault compensation strategy amplitude and phase of the DVR voltage is injected in such a way that load voltage will be exactly restored to the presag values.

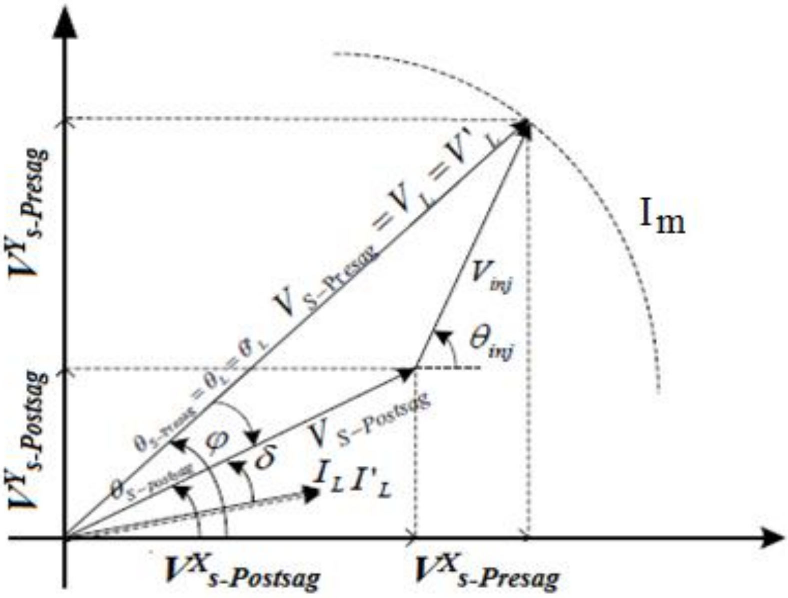


Figure 4.8: Phasor Diagram of Pre-Fault Compensation Method

As shown in figure 4.8, amplitude and phase angle of the DVR injection voltage in pre-fault method could be calculated as follows:

$$|V_{inj}| = \sqrt{1 + V_{S-Postsag}^2 - 2V_{S-Postsag}\,\mathrm{Cos}(\theta_{S-Postsag} - \theta_{S-Presag})}$$

$$\theta_{inj} = \tan^{-1}\left[\frac{\mathrm{Sin}(\theta_{S-Presag}) - V_{S-Postsag}\,\mathrm{Cos}(\theta_{S-Postsag})}{\mathrm{Sin}(\theta_{S-Presag}) - V_{S-Postsag}\,\mathrm{Cos}(\theta_{S-Postsag})}\right] \qquad (4.5)$$

In the pre-fault strategy, amplitude of the injection voltage is more than that of in-phase method thereby increases the energy storage capacity in DVR design. According to equation (4.5), calculation of the DVR injection voltage in the pre-fault compensation method will require estimating the amplitude and phase angle of source voltage (Vs) in each phase [30].

4.7 Control and Protection of DVR

The following functional requirements must be considered for the control and protection of a DVR designed to compensate voltage sags.

1. When the supply voltage is normal, the DVR operates in a standby mode thereby injecting zero voltage. However if the energy storage device (e.g. batteries) is to be charged, then the DVR can operate in a self-charging control mode.

2. The DVR needs to inject three single phase voltages in synchronism with the supply in a very short time during the event of voltage sag/swell. Each phase of the injected voltage can be controlled independently in magnitude and phase. The zero sequence voltage can be

eliminated in cases where it has no effect. The DVR draws active power from the energy source and supplies this along with the reactive power to the load.

3. If there is a fault on the downstream of the DVR, the converter is by passed temporarily using thyristor switches to protect the DVR against overcurrents. The threshold is determined by the current ratings of the DVR.

The overall design of DVR must consider the following parameters:

- Ratings of the load and power factor
- Voltage rating of the distribution line
- Maximum single phase sag (expressed in percentage)
- Maximum three phase sag (expressed in percentage)
- Duration of the voltage sag (in milliseconds)
- The voltage time area (for the energy requirements)
- Recovery time for the DC link voltage to 100%
- Over-current capability without going into bypass mode.

Typically, a DVR may be designed to protect a sensitive load against 35% of three phase voltage sag or 50% of the single phase sag [2]. The duration of the sag could be 200 ms. The DVR can compensate higher voltage sags lasting for shorter durations or allow longer durations (up to 500 ms) for smaller voltage sags. The response time could be as small as 1 ms.

4.8 Control Scheme

The basic functions of a controller in a DVR are the detection of voltage sag/swell in the system; computation of the correcting voltage, generation of trigger pulses to the sinusoidal PWM based DC-AC inverter, correction of any anomalies in the series voltage injection and termination of the trigger pulses when the event has passed. The controller may also be used to shift the DC-AC inverter into rectifier mode to charge the capacitors in the DC energy link in the absence of voltage sags/swells.

4.9 Control Using dqo Transformation

The dqo transformation or Park’s transformation is used to control of DVR. The advantage of using dqo method is that it gives the sag depth and phase shift information with start and end times. The quantities are expressed as the instantaneous space vectors. The voltage is firstly converted from abc reference frame to d-q-o reference. For simplicity zero phase sequence components is ignored. Figure 4.9 illustrates a flow chart of the feed forward dqo transformation for voltage sags/swells detection [29].

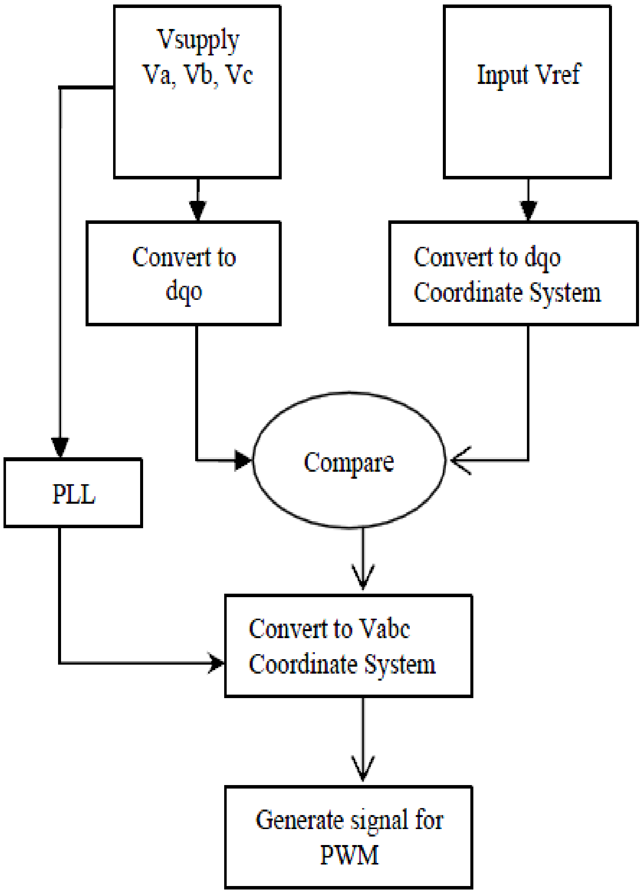


Figure 4.9: Flow Chart of the Feed Forward dqo Transformation for Voltage Sags/Swells Detection

The detection of unbalanced voltage is carried out in each of the three phases on the basis of comparison of a voltage reference and the measured terminal voltage (V_a, V_b, V_c). The voltage sag is detected when the supply drops below 90% of the reference value whereas voltage swells is detected when supply voltage increases up to 25% of the reference value. The error signal is used as a modulation signal that generates a commutation pattern for the power switches (IGBT's) constituting the voltage source converter. The commutation pattern is generated by means of the sinusoidal pulse width modulation technique (SPWM); where voltages are controlled through the modulation. The PLL circuit is used to generate a unit sinusoidal wave in phase with mains voltage. The control algorithm produces a three phase reference voltage to the series converter that tries to maintain the load voltage at its reference value.

Figure 4.10 [22] shows the basic control scheme and parameters that are measured for control purposes. At normal voltage level the DVR is controlled to reduce the losses in the DVR to a minimum. When voltage sags/swells are detected, the DVR should react as fast as possible and inject an ac voltage to the grid. It can be implemented using a feedback control technique based on the voltage reference and instantaneous values of supply and load voltage. The d-reference component is set to a rated voltage and the q-reference components are set to zero.

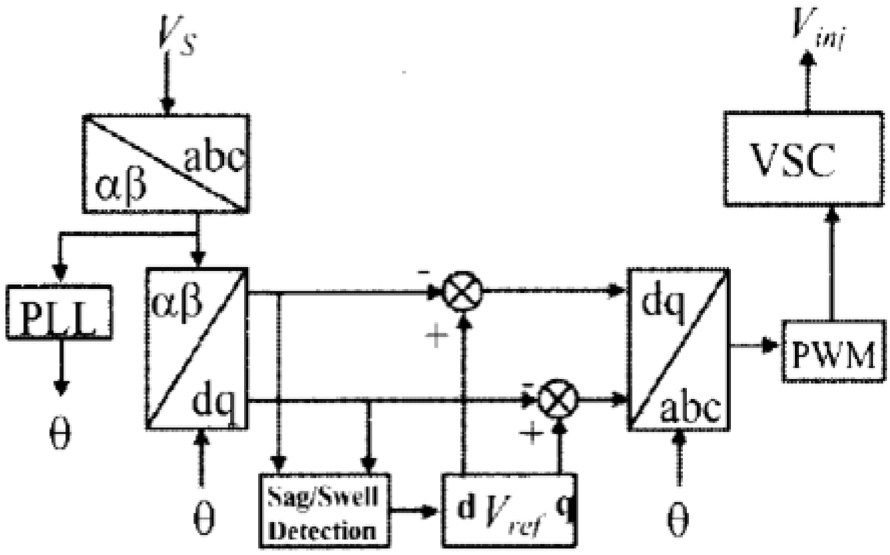


Figure 4.10: Control Structure of DVR

In Figure 4.10, the supply voltage is connected to a transformation block that converts stationary frame to αβ-frame. Output of transformation block is connected to a phase lock loop (PLL) and another transformation block that converts αβ- frame to rotating frame (dq), which detects the phase and changes the axis of the supply voltage. The voltage sag/swell detection block generates the reference load voltage whenever voltage sag/swell is detected. The injection voltage is also generated by difference between the reference load voltage and supply voltage and is applied to the VSC to produce the required voltage, with the help of pulse width modulation (PWM).

Equation (4.6) defines the transformation from three phase system a, b, c to dqo stationary frame. In this transformation, phase A is aligned to the d-axis that is in quadrature with the q-axis. The theta (θ) is defined by the angle between phase A to the d-axis [30].

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \begin{bmatrix} \mathrm{Cos}(\theta) & \mathrm{Cos}(\theta - \frac{2\pi}{3}) & 1 \\ -\mathrm{Sin}(\theta) & -\mathrm{Sin}(\theta - \frac{2\pi}{3}) & 1 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (4.6)$$

In the next chapter, the Simulink Models of the applications of DVR using dqo transformation to improve the quality of power are presented. The loads considered in these models are: Static RLC load and Field-oriented control Induction motor load which is an adjustable speed drive (ASD). The results and the corresponding conclusions are also compiled.

CHAPTER 5

SIMULATION AND RESULTS

In this work, the role of dynamic voltage restorer for power quality improvement of following distribution networks is carried out:

- Distribution network having static load
- Distribution network having adjustable speed drive load

The solution to the following power quality problems is explored in this work for each of the above said distribution networks:

- For the case of unbalanced supply
    - When supply voltage of one of the phase is increased
    - When line impedance value of one of the phase is changed
    - Single-phasing problem
- For the case of balanced three phase supply but having a fault in the system

5.1 In Case of Linear Static (RLC) Load

The Three-Phase Parallel RLC Load implements a three-phase balanced load as a parallel combination of RLC elements. The load exhibits constant impedance at the specified frequency. The active and reactive powers absorbed by the load are proportional to the square of the applied voltage.

The power triangle shown in Figure 5.1 [4] represents the apparent and reactive powers.

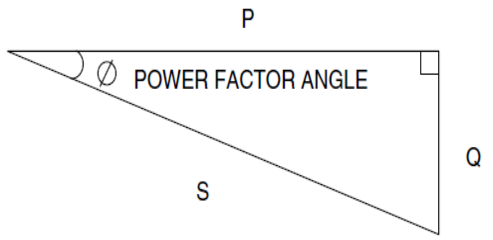


Figure 5.1: Power Triangle and Relationship among Active, Reactive and Apparent Power

The following relationships apply:

$S = \sqrt{P^2 + Q^2}$ (5.1)

$P = S \cos\varnothing$ (5.2)

$Q = S \sin\varnothing$ (5.3)

$Q/P = \tan Ø$ (5.4)

where S = apparent power (kVA), P = active power (kW), Q = reactive power (kVAR), and Ø is the power factor angle. V is the voltage applied to a circuit and I is the current. In an inductive circuit, the current lags the voltage by angle Ø, as shown in the figure, and Ø is called the power factor angle.

If X_L is the inductive reactance given by:

$X_L = 2\pi fL$ (5.5)

then total impedance (Z) is given by:

$Z = R + jX_L$ (5.6)

Where j is the imaginary operator = $\sqrt{-1}$

The power factor angle is calculated from the expression:

$\tan Ø = (X_L/R)$ or $Ø = \tan{-1}(X_L/R)$ (5.7)

5.1.1 Simulink Model of DVR using dqo Transformations Control with Unbalanced Supply and RLC Load

Figure 5.2 shows the configuration of the proposed DVR design using Matlab Simulink, where the outputs are connected to the utility supply via wye-open connected series transformer. With the occurrence of voltage disturbance, the inverter output can be steered in phase with the incoming ac source while the load is maintained constant with the help of dqo transformation based control scheme. The output of inverter is installed with capacitors and inductors for the filtering scheme.

The system parameters and constant values are listed in Table 5.1. It is assumed that the voltage magnitude of the load bus is maintained at 1 pu during the period of unbalanced voltage. The load has been assumed linear with power factor pf =0.85 lagging and its capacity of 5 KVA.

Table 5.1: System Parameters and Constant Values

Main Supply Voltage per phase	220 V
Line Impedance	L_s=0.6mH R_s=0.2Ω
DC Bus Voltage	170 V
Series transformer turns ratio	1:1
Filter Inductance	1mH
Filter Capacitance	1μF

Load Resistance	40 Ω
Load Inductance	60mH
Nominal Phase to Phase Voltage at Load	440V
Line Frequency	50 Hz
Carrier Frequency of PWM	1080 Hz

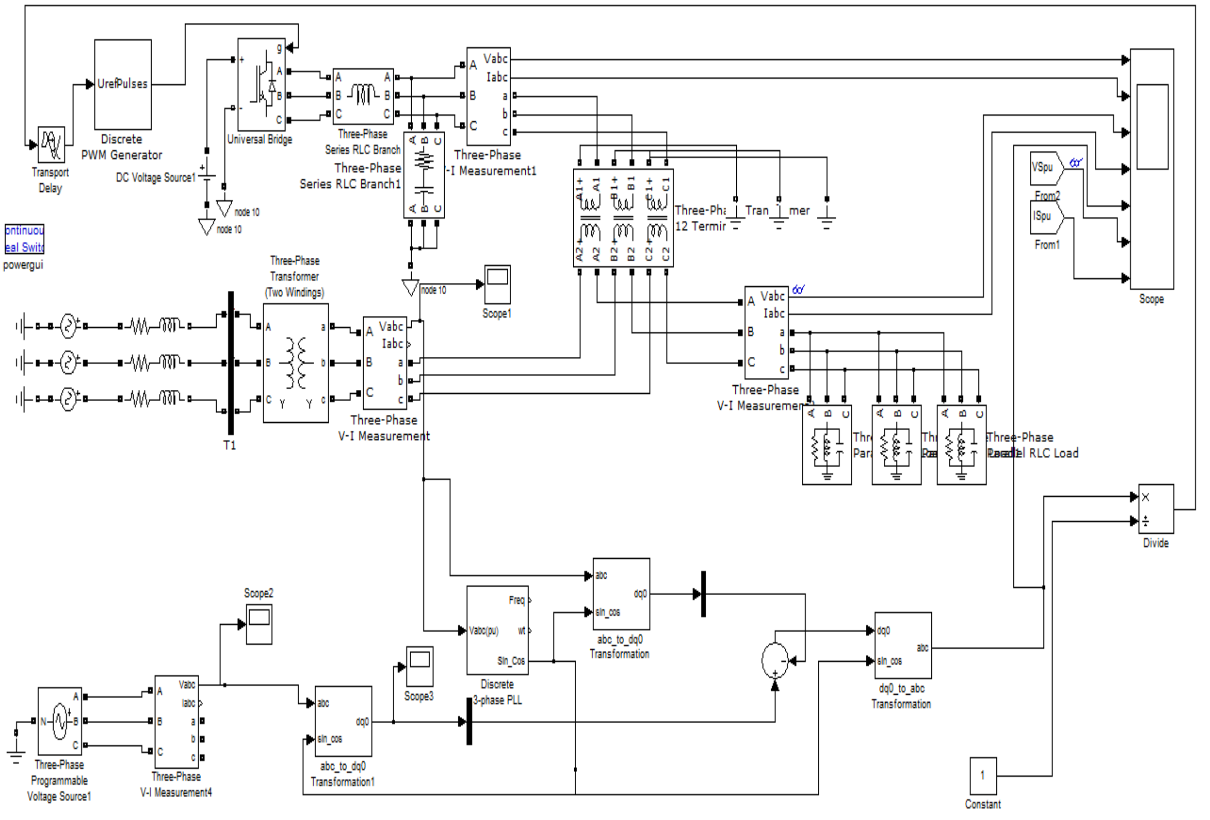
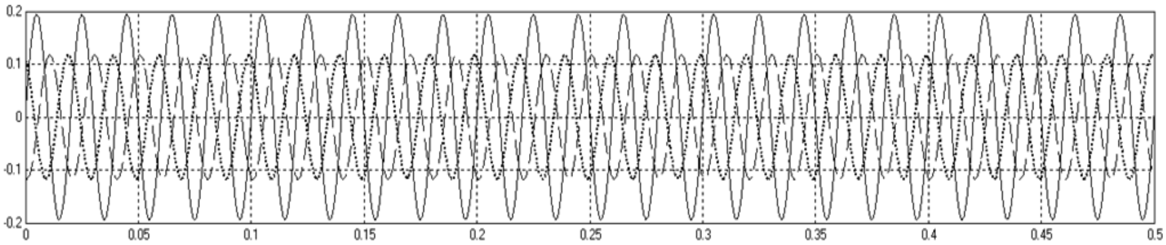


Figure 5.2: MATLAB Simulation Model of DVR using dqo Transformation Control with Unbalanced Supply and RLC Load

Case I: The case is of unbalancing of the voltage at the supply side. The supply voltage of one phase is increased by 20% and the efficiency of the DVR is observed through the waveform available at the load side. The DVR compensates the voltage thereby providing with balanced voltage at load. The results of simulation in figure 5.3 show the fast compensation capability of the DVR.



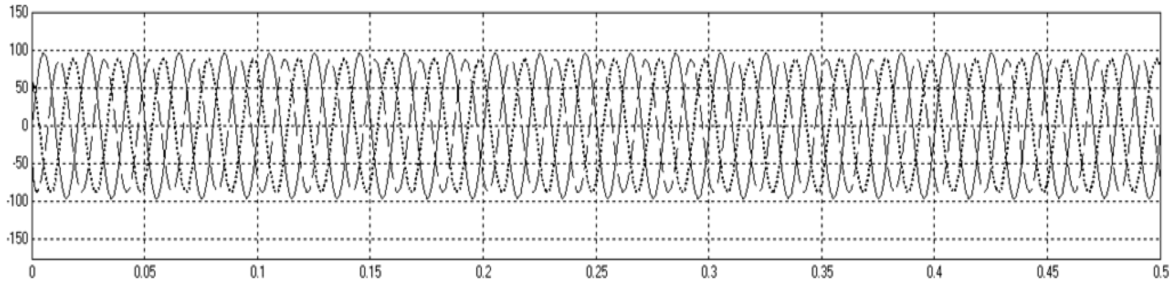


Figure 5.3: (a) Source Voltage (pu) (b) Load Voltage (pu)

Case II: In order to create unbalance in the supply voltage, the source resistance (R_s) of line impedance is altered from 0.2Ω to 0.02Ω. The results are as shown in figure 5.4. It can be seen that the load voltage is kept at nominal value with the help of DVR.

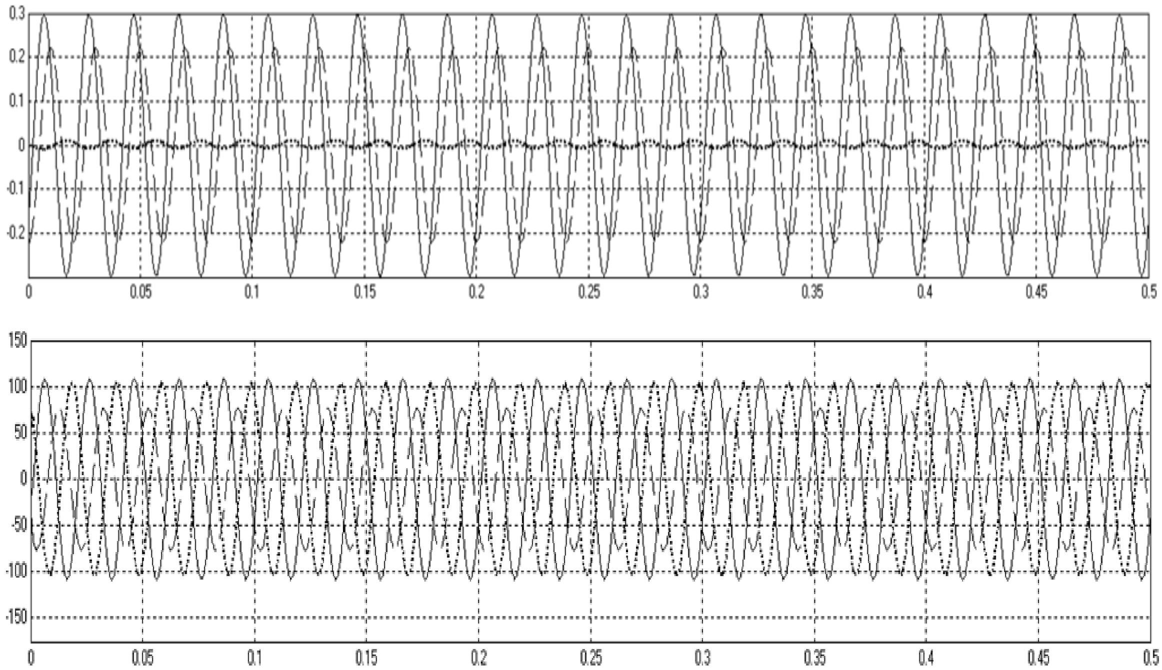
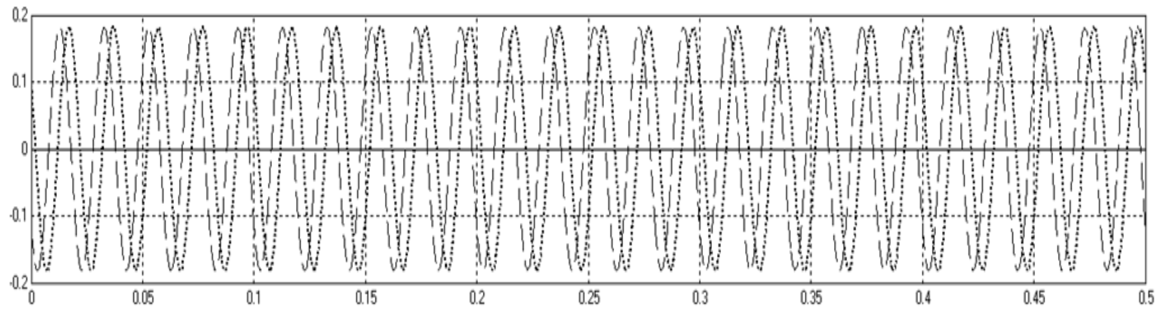


Figure 5.4: (a) Source Voltage (pu) (b) Load Voltage (pu)

Case III: It represents the case of single line to ground fault. This is an example of the severe fault in the system. From the waveform of figure 5.5, we observed that the DVR reacts quickly to inject the appropriate voltage component to correct the supply voltage to its best possible level.



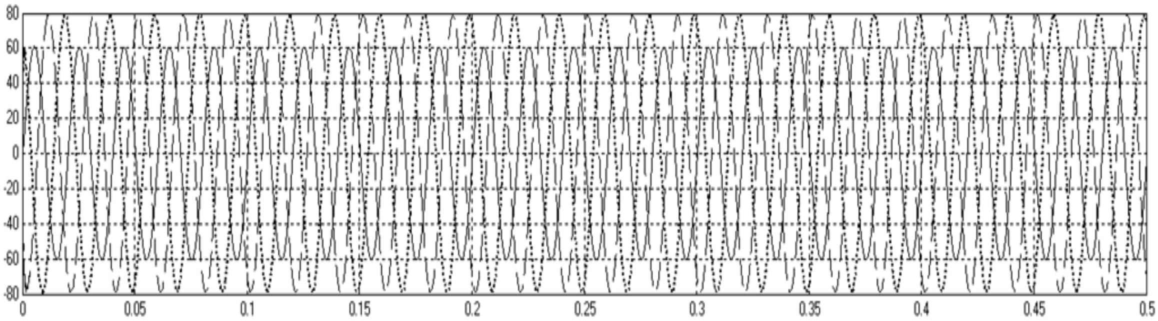


Figure 5.5: (a) Source Voltage (pu) (b) Load Voltage (pu)

5.1.2 Simulink Model of DVR using dqo Transformation Control with Balanced Supply and Static Load in a Faulted System

Detailed simulations of dynamic voltage restorer model using dqo transformation control are performed using Matlab Simulink. System performance is analyzed to achieve rated voltage at a given load with the help of DVR.

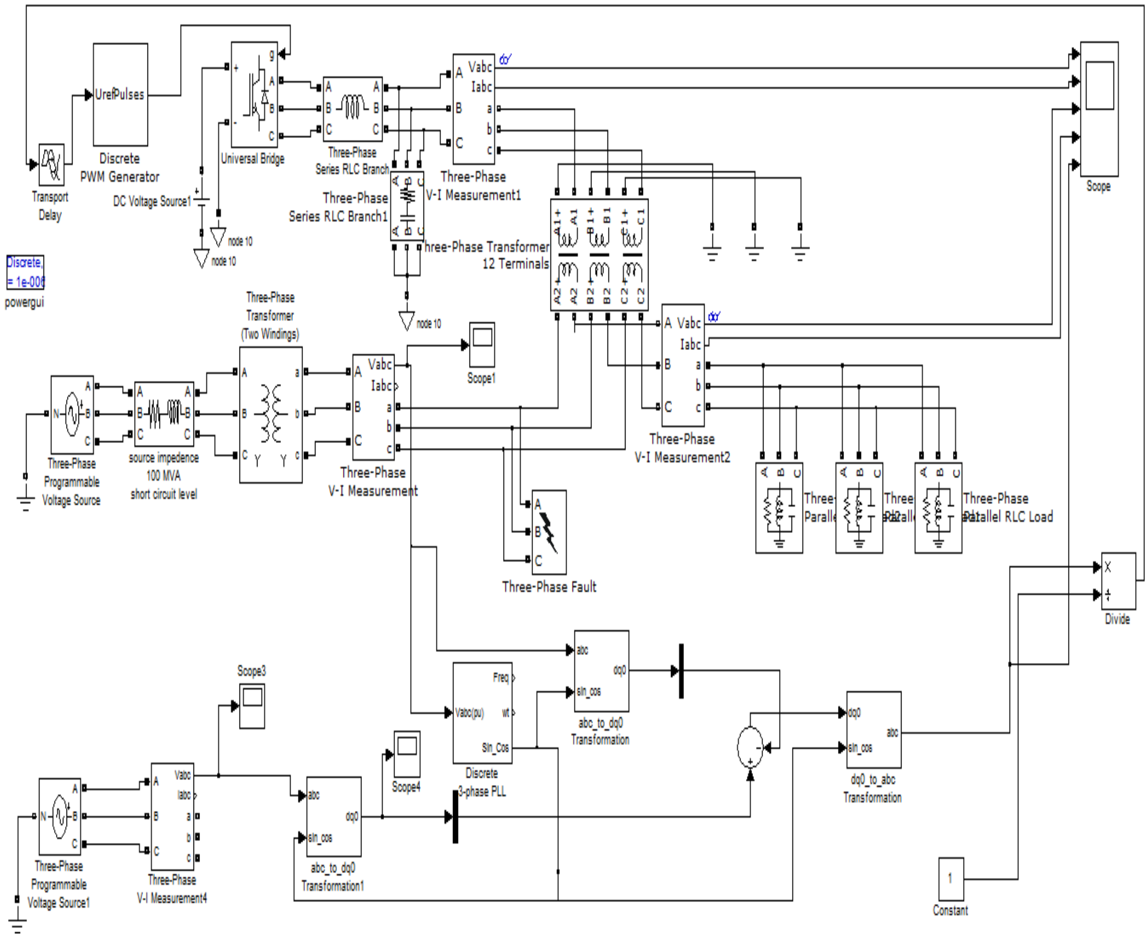


Figure 5.6: MATLAB Simulation Model of DVR using dqo Transformation Control with Balanced Supply and RLC Load in a Faulted System

A fault is created in one of the phase via a resistance of 0.01 Ω. Transition time for the fault is considered from 0.1 sec to 0.25 sec. The simulation results without and with DVR compensation technique are shown in Figure 5.7 on p.u basis.

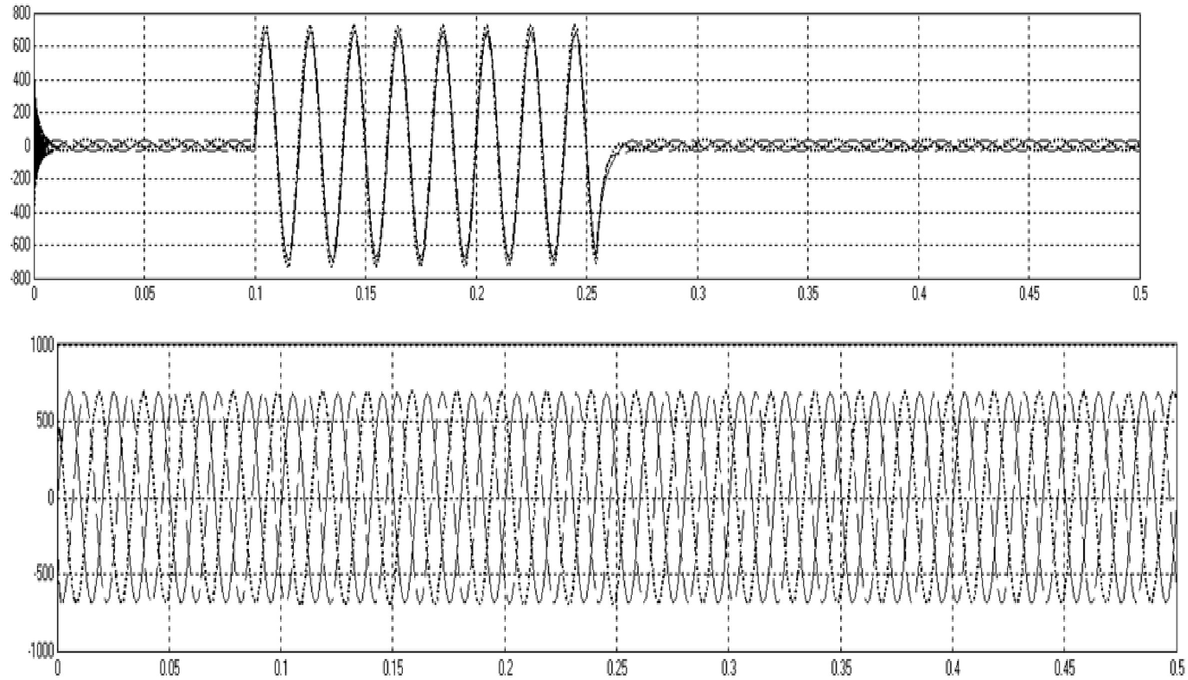


Figure 5.7: (a) Load Voltage without DVR (pu) (b) Load Voltage with DVR (pu)

5.2 In Case of Adjustable Speed Drive Load

Induction motors have been widely used in the industry comparing to other rotating machinery, because of the existence of the large inductances in the induction motors which could weaken their ride-through capability, they are thought to be particularly vulnerable to voltage dips. The transient of the induction motors consists of electromagnetic transients and electromechanical transients. Voltage sag phenomenon is usually associated with fault and its subsequent clearance for a few cycles of the mains frequency. Thus for such a short time, it is the electromagnetic transients of the DVR-motor system which are dominant. During voltage sag the electrical torque of the motor (proportional to the square of the RMS supply voltage) drops down. Over this period, it is also reasonable to assume that the motor mechanical speed is constant. Once the voltage sag is removed, rebuilding of the air gap flux will result in a large inrush current. This will slow down the voltage recovery momentarily, after which the motor will accelerate again until it reaches its presag speed. During the re-acceleration the motor will again absorb a large current. This postsag phenomenon can result in tripping of some sensitive devices that have survived the sag. In any case, the more complex sag profile complicates the compensation process [23,24].

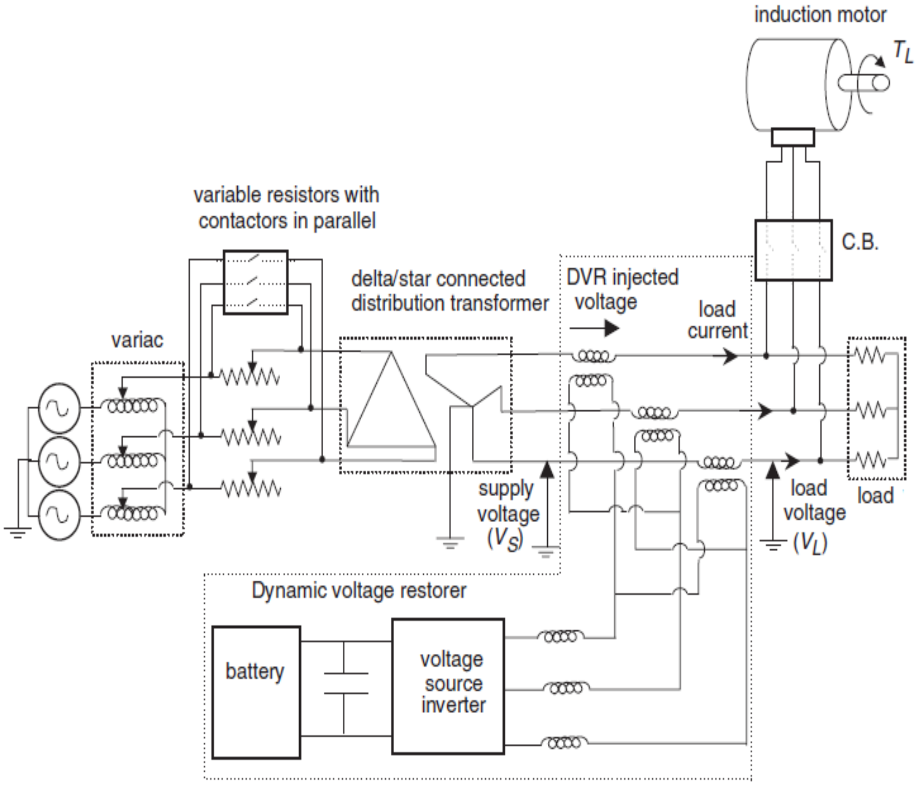


Figure 5.8: Experimental Set-up Using Induction Motor Load

Field-Oriented Control Induction Motor Drive: The Field Orientated Control (FOC) consists of controlling the stator currents represented by a vector. This control is based on projections which transform a three phase time and speed dependent system into a two co-ordinate (d and q co-ordinates) time invariant system. Field orientated controlled machines need two input references constants the first is the torque component (aligned with the q co-ordinate) and the other is flux component (aligned with d co-ordinate). The control structure handles instantaneous electrical quantities. This makes the control accurate in steady state as well as transient state operation and independent of the limited bandwidth mathematical model. The FOC thus solves the classic scheme problems, in the following ways:

- The ease of reaching constant reference (torque component and flux component of the stator current)
- The ease of applying direct torque control because in the (d,q) reference frame the expression of the torque is:

$$m \propto \psi_R \, i_{Sq} \tag{6.8}$$

By maintaining the fixed value of amplitude of the rotor flux (ψ_R) a linear relationship between torque and torque component (i_{Sq}) can be obtained. We can then control the torque by controlling the torque component of stator current vector.

5.2.1 Simulink Model of DVR using dqo Transformations Control with Unbalanced Supply and Field-Oriented Control Induction Motor Load

A whole view of the model is shown in figure 5.9. It is including a three source, an injection transformer, a typical load system, a filter circuit, an inverter unit. As for the filtering scheme, output of inverter is installed with capacitors and inductors. Once a voltage disturbance occurs, with the help of dqo transformation based control scheme, the inverter output can be controlled in phase with the ac source while the load is maintained constant.

Analysis of the influence of non linear loads on the mitigation ability of the DVR has been performed by simulation studies using Matlab Simulink. The motor parameters are listed in table 5.2.

Table 5.2: Motor Parameters Referred to the Stator

Motor Parameters	
Rated Power	2238VA
Rated Voltage	220Vrms
Frequency	50Hz
Combined rotor and load inertia	0.089 kg.m^2
Stator Resistance	0.435 Ω
Stator Reactance	2 mH
Rotor Resistance	0.816 Ω
Rotor Reactance	2 mH
Magnetizing inductance	69.31mH
Pair of Poles	2
Shaft mechanical Torque	2Nm

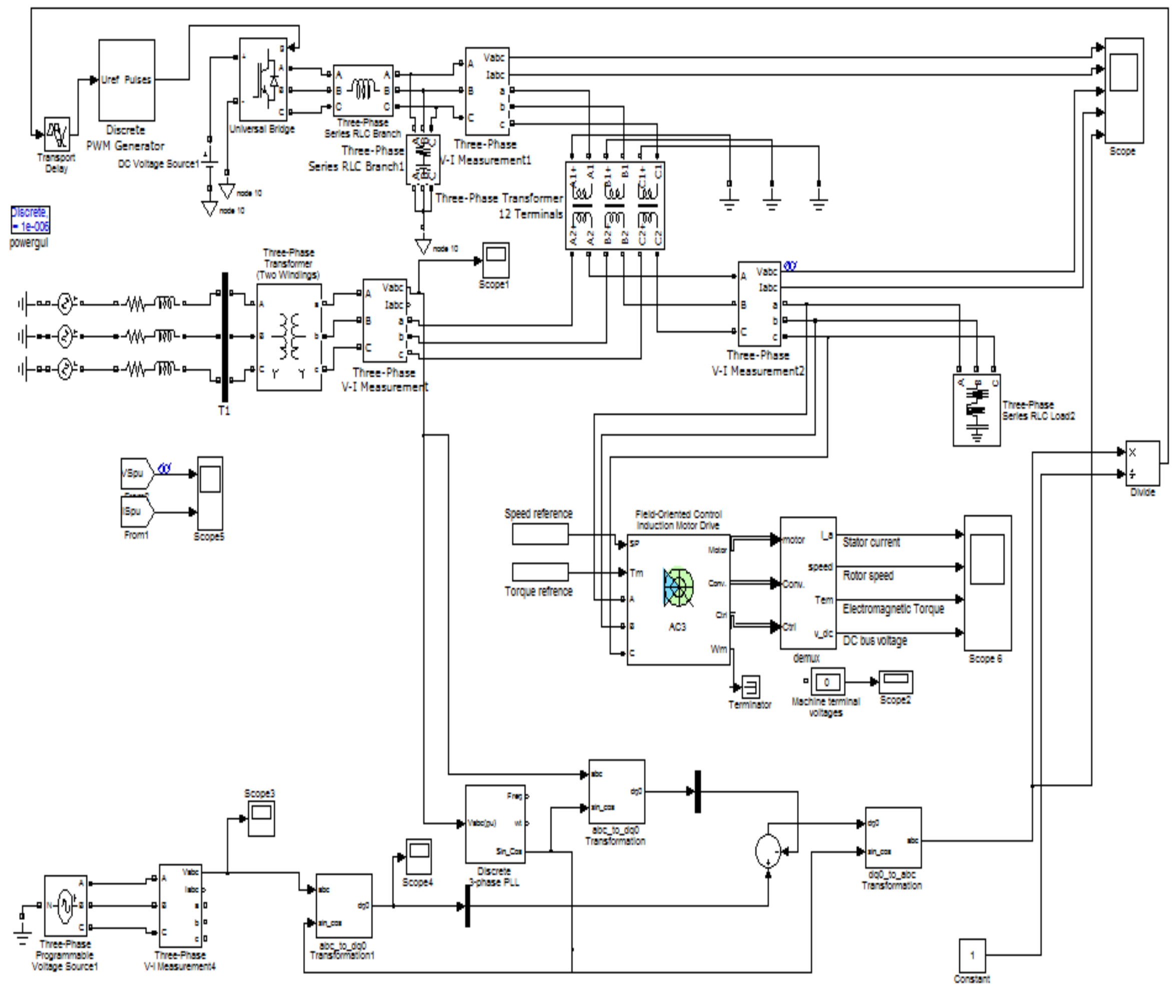
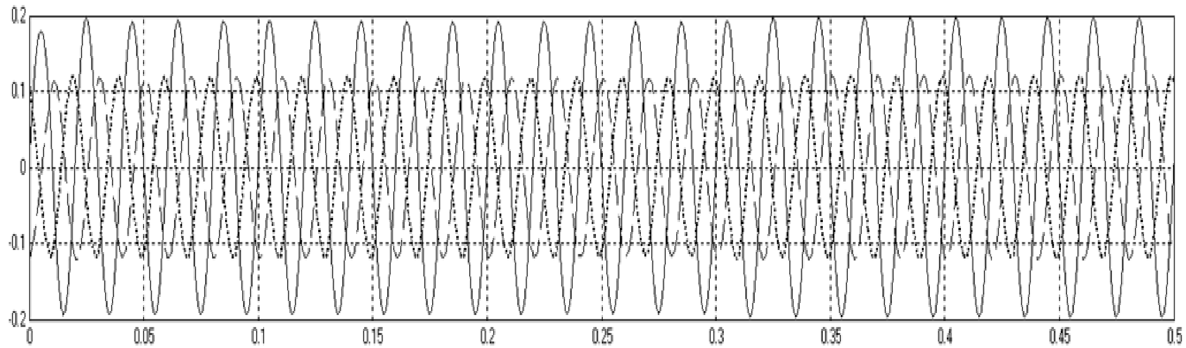


Figure 5.9: MATLAB Simulation Model of DVR using dqo Transformations with Unbalanced Supply and Field-Oriented Control Induction Motor Load

Case I: The supply voltage of one phase is increased by 20%. The results of simulation as shown in figure 5.10 clearly depict the effectiveness of DVR under unbalanced conditions. The comparison of FFT analysis shows the vast improvement in total harmonic distortion on the load side of the system which is connected to DVR than to a system without DVR.



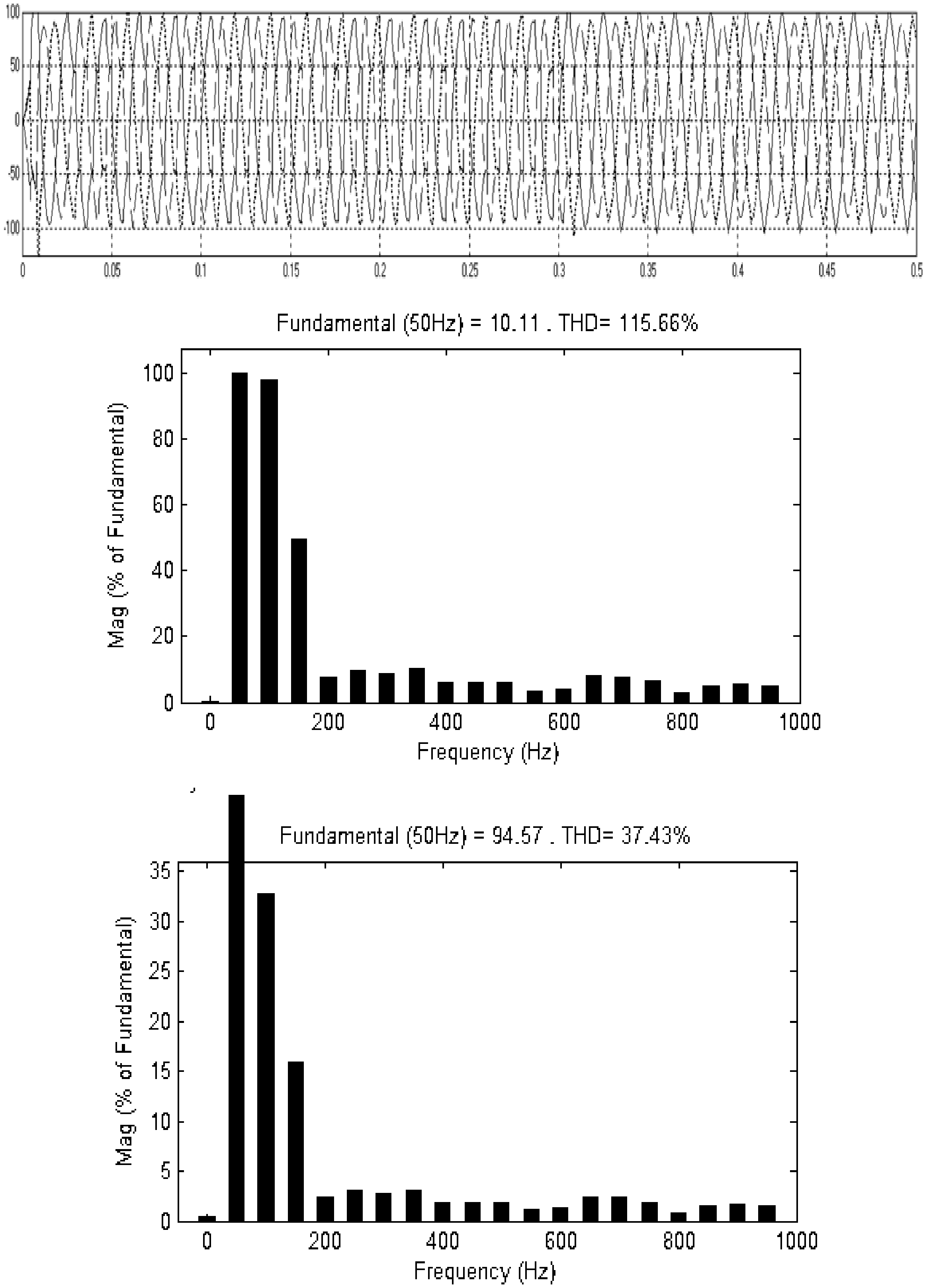
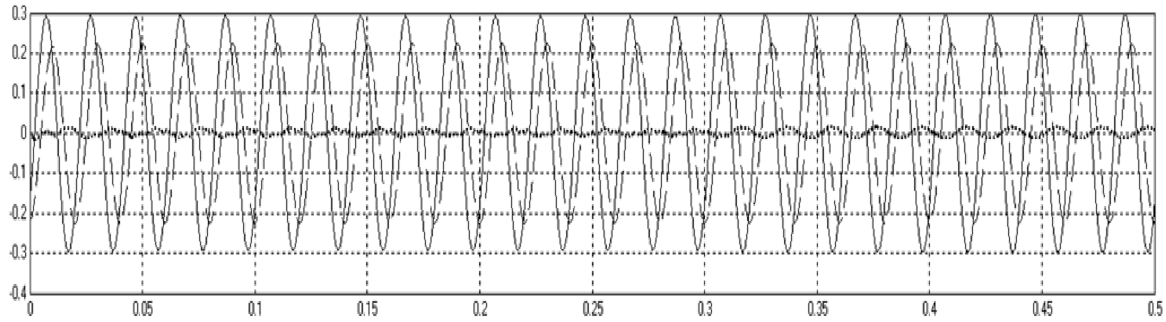
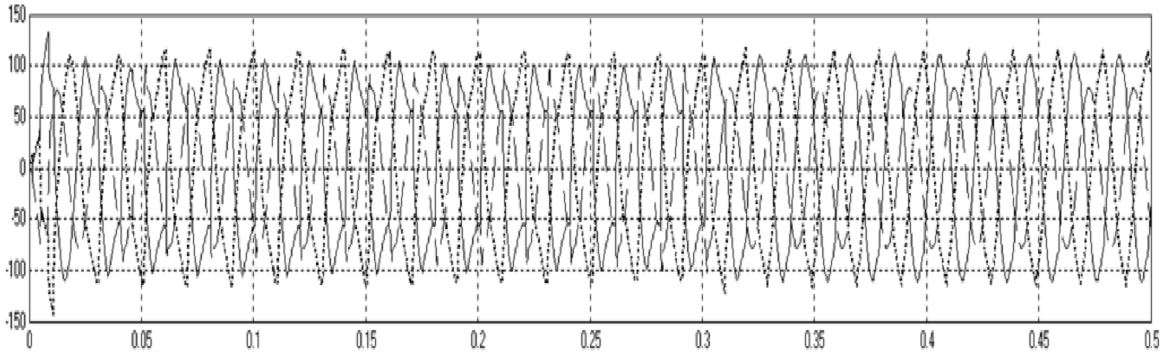
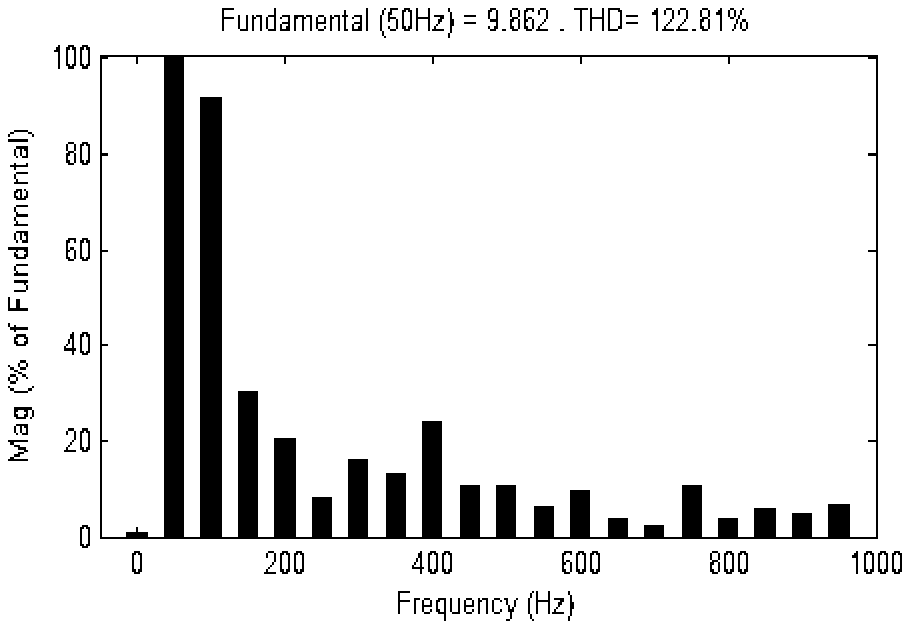


Figure 5.10 (a) Source Voltage (pu) (b) Load Voltage (pu) (c) Percentage of Total Harmonic Distortion on the Load of System without DVR (d) Percentage of Total Harmonic Distortion on the Load of System with DVR

Case II: The source resistance (R_s) of line impedance is altered from 0.2Ω to 0.02Ω in this case. The results of simulation are as shown in figure 5.11. The voltage at load is improved but due to an adjustable speed drive load the harmonic distortion in waveform can be seen at the load side. But by the use of dynamic voltage restorer, the total harmonic distortion level can be reduced. Thus DVR can serve the twin purpose that is compensating the voltage and reducing the level of harmonics at the load.







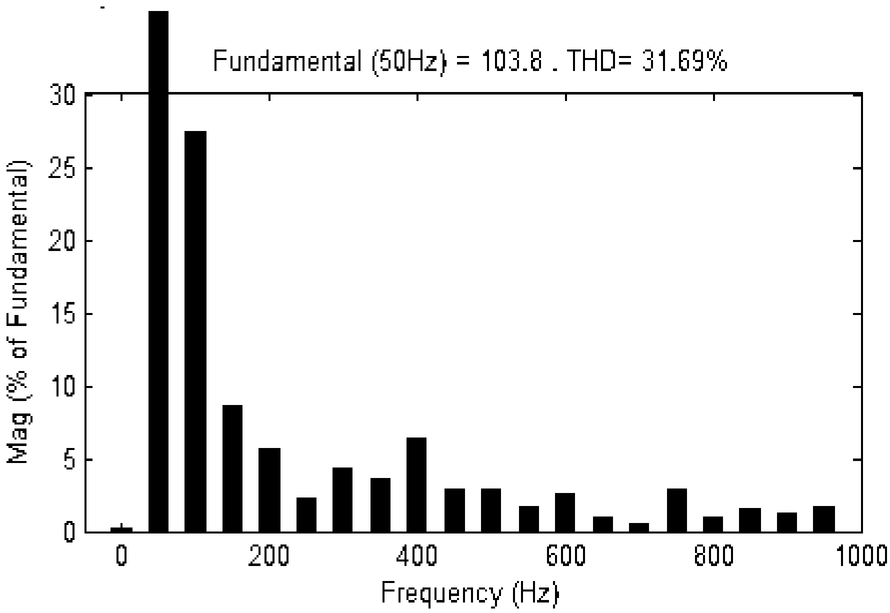
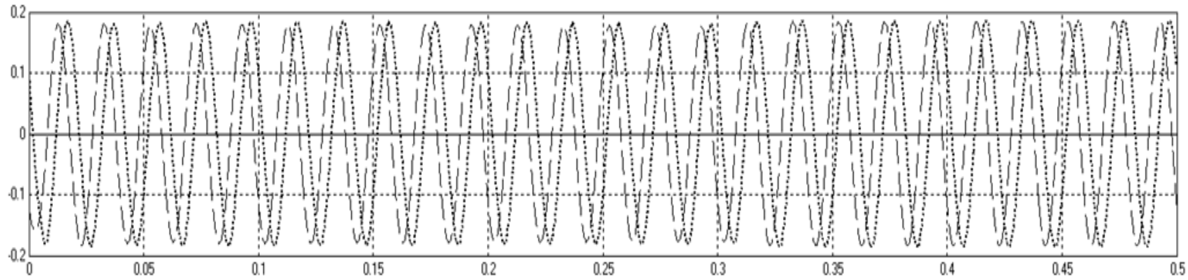
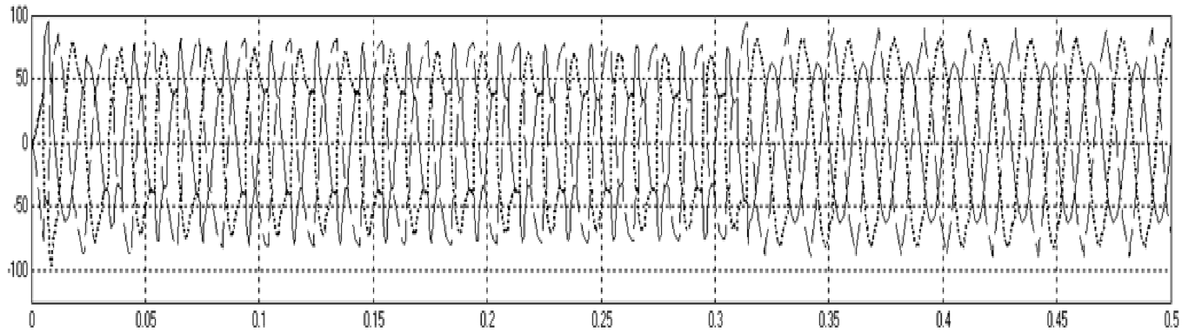


Figure 5.11: (a) Source Voltage (pu) (b) Load Voltage (pu) (c) Percentage of Total Harmonic Distortion on the Load of System without DVR (d) Percentage of Total Harmonic Distortion on the Load of System with DVR

Case III: It represents the single line to ground fault in the system which is balanced by DVR at the load side by recovering the missing cycles to some extent shown in figure 5.12. This case also represents the problem of single-phasing commonly encountered in power system network. The comparison of FFT analysis of the voltage waveform at the load side of the system with and without DVR illustrates the reduction in the level of total harmonic distortion.





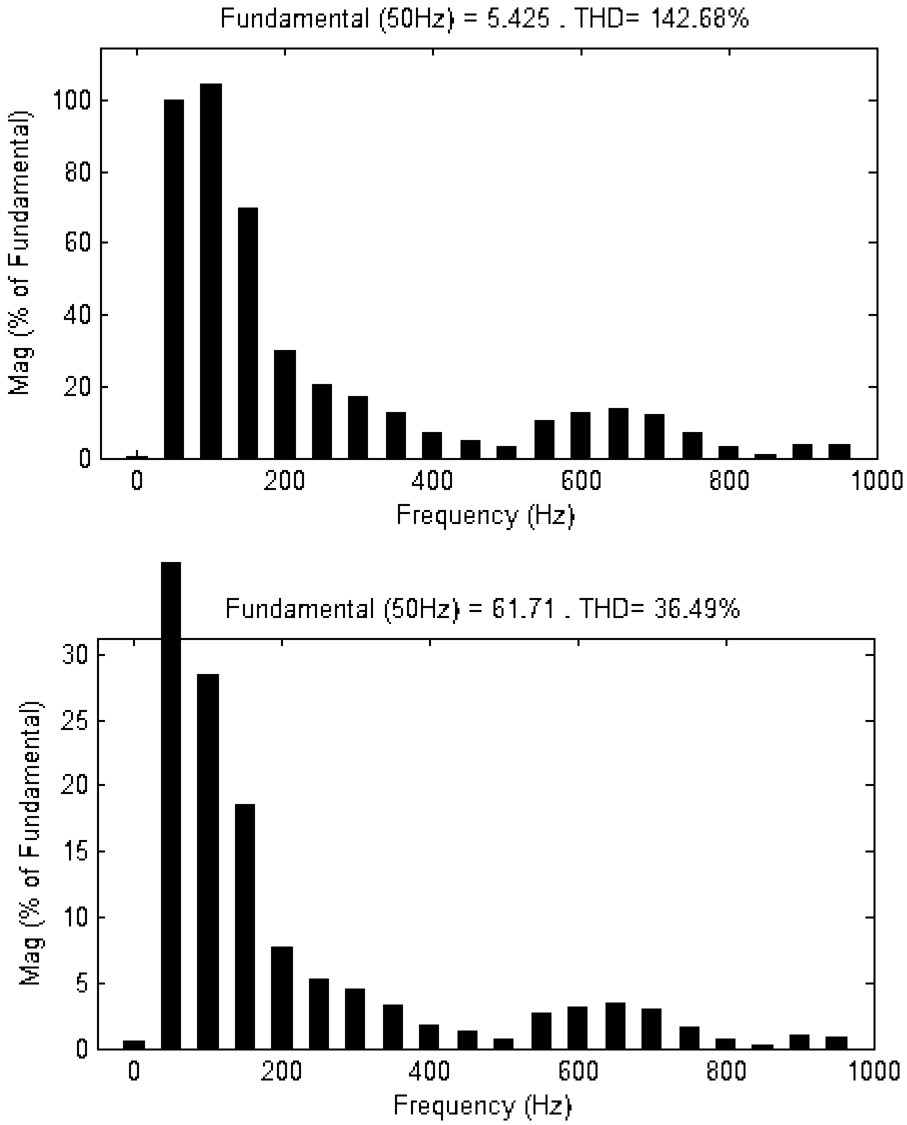


Figure 5.12: (a) Source Voltage (pu) (b) Load Voltage (pu) (c) Percentage of Total Harmonic Distortion on the Load of System without DVR (d) Percentage of Total Harmonic Distortion on the Load of System with DVR

5.2.2 Simulink Model of DVR using dqo Transformations Control with Balanced Supply and Field-Oriented Control Induction Motor Load In a Faulted System

A detailed system has been modelled by Matlab Simulink to study the efficiency of suggested control strategy using field orientation control induction motor load. In order to understand the performance of the DVR using the specific load along with control, a simple distribution network as shown in figure 5.13, is implemented.

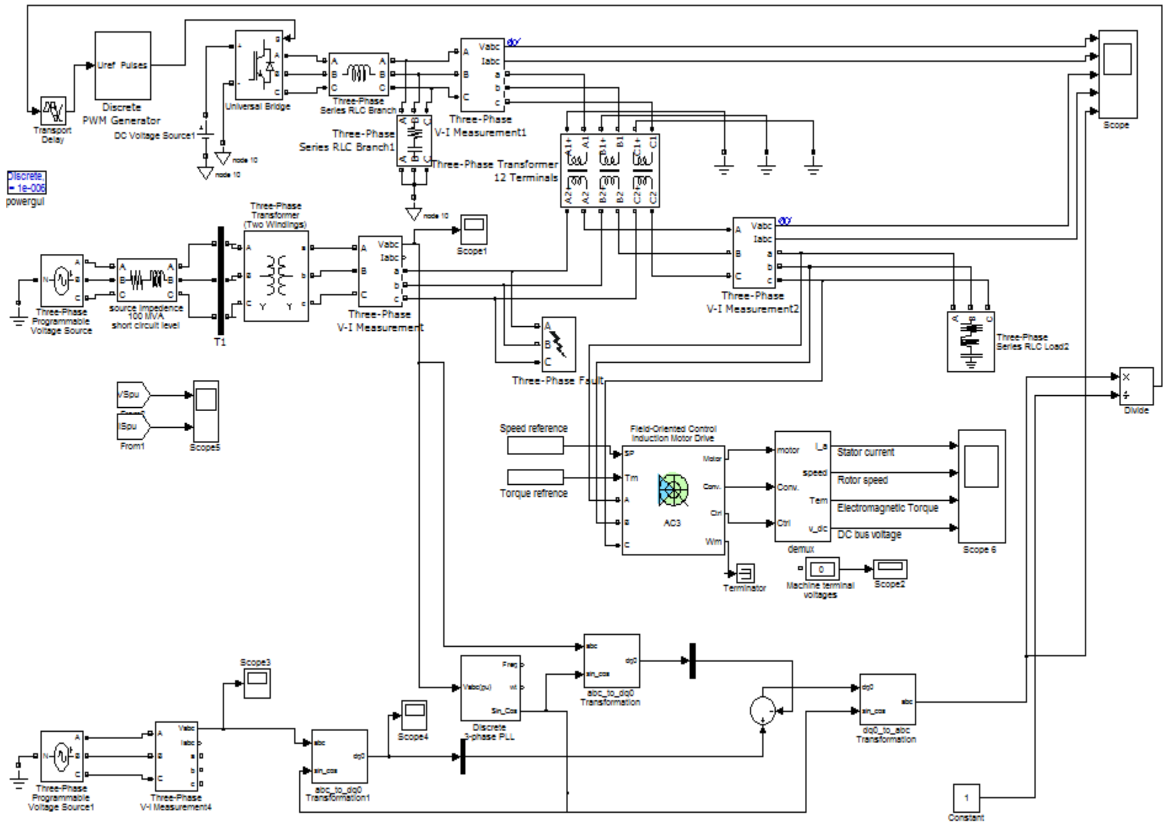
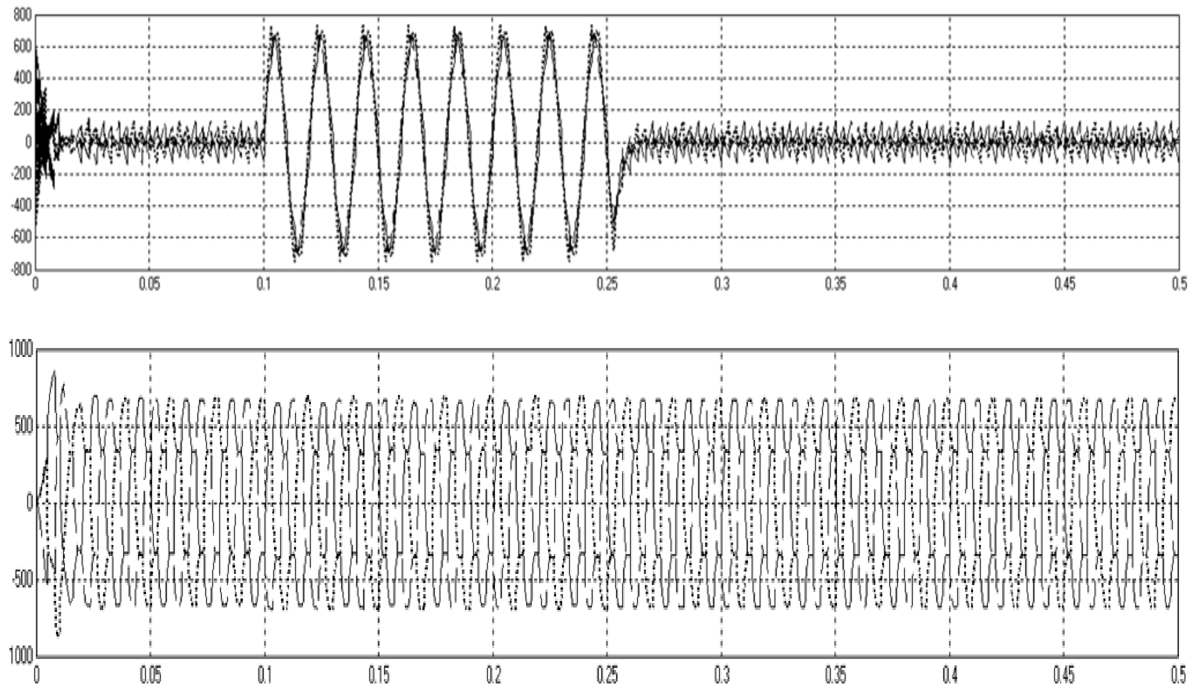


Figure 5.13: MATLAB Simulation Model of DVR using dqo Transformations with Balanced Supply and Field-Oriented Control Induction Motor Load in a Faulted System

The fault is created in one of the phase via a resistance of 0.01 Ω. Transition time for the fault is considered from 0.1 sec to 0.25 sec. The simulation results without and with DVR compensation technique are shown in Figure 5.14 on p.u basis



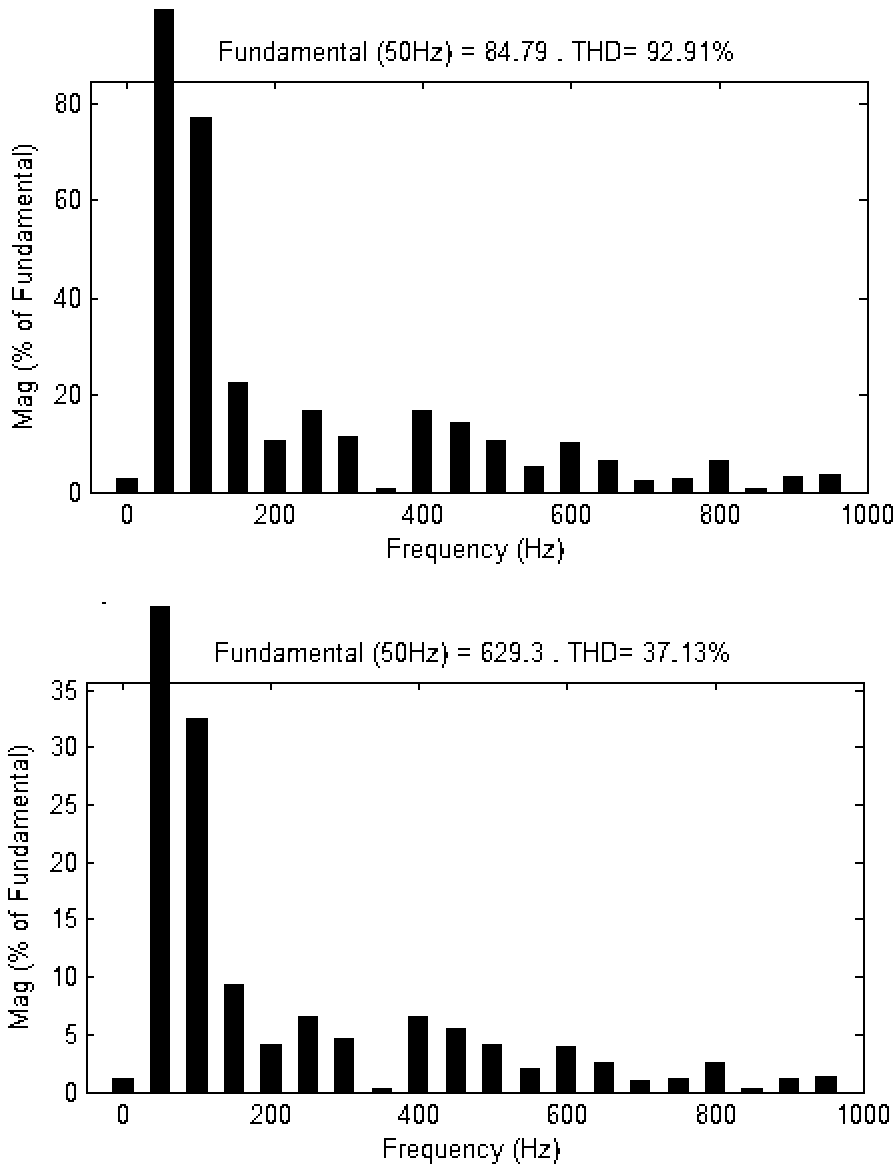


Figure 5.14: (a) Load Voltage without DVR (pu) (b) Load Voltage with DVR (pu) (c) Percentage of Total Harmonic Distortion on the Load of System without DVR (d) Percentage of Total Harmonic Distortion on the Load of System with DVR

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

In the research, the main objectives for the utilization of the studied equipment have been to mitigate unbalances in voltage and reducing the distortion level occurring in the cases of harmonic generating load in distribution networks and thus highly improving the power quality of the system. This research has studied the characterization of voltage unbalances and its impact with special attention on the mitigation techniques.

In order to protect critical loads from more severe faults in the distribution network, the series connected voltage-source converter known as Dynamic Voltage Restorer is more suitable and satisfactory. Being reliable and cost effective, it was adopted to be the optimal solution for the compensation of voltage. It has also been pointed out that the zero-sequence component of the voltage in impedance grounded systems must be eliminated to the control system.

The highly developed graphic facilities available in MATLAB/SIMULINK were used to carry out extensive simulation studies on dynamic voltage restorer. The control scheme used is dqo transformation control along with static (linear) load and adjustable speed drive (non-linear) load. Therefore, DVR is considered to be an efficient solution due to its relatively low cost, small size and fast dynamic response. The simulation results show the performance of a DVR in mitigating different faulty conditions. The DVR handles both balanced and unbalanced situations easily and injects the appropriate voltage component to correct rapidly any anomaly in the supply voltage to keep the load voltage balanced and constant at the nominal value. Also DVR is capable of reducing the level of THD in the case of networks which are connected to the harmonics generating load (like ASD).

6.2 Future Work

The completion of one research project opens the avenues for work in many other related areas. The presented work can be extended in following areas:

- The application of the model presented in this work may be extended to other Power Electronic loads used in a modern hi-tech industry.
- The regenerative power system network consisting of an active load (such as solar photovoltaic system or wind turbine system) with better power quality and lesser power disturbances using DVR can be explored.

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