INVESTIGATION ON THE ROLE OF UPQC FOR POWER QUALITY IMPROVEMENT OF DISTRIBUTION NETWORK WITH FOC INDUCTION MOTOR

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

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Power Systems & Electric Drives

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CERTIFICATE

I hereby certify that the work which is being presented in this Report entitle **"Investigation on the Role of UPQC for Power quality improvement of Distributions Network with FOC Induction Motor"**, in partial fulfilment 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

Modern power system 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 Unified power quality conditioner (UPQC) is an effective custom power device for the enhancement of power quality due to its quick response, high reliability and nominal cost. A Unified power quality conditioner is used to compensate distortion, unbalanced voltage and current conditions. It is efficiently capable of protecting sensitive loads against the voltage variations or disturbances. UPQC employs two converters that are connected to a common DC link with an energy storage capacitor. The main components of UPQC are shunt and series converters ,DC capacitors low pass and high pass filters and series and shunt transformers

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LIST OF ABBREVIATIONS

LG	Single Line to Ground
LLG	Double Line to Ground
LLL	Three Phase Fault
IEEE	Institute of Electrical and Electronic Engineers
DVR	Dynamic Voltage Restorer
DSTATCOM	Distribution Static Synchronous Compensators
AC	Alternate Current
FACTS	Flexible AC Transmission Systems
ASD	Adjustable Speed Drive
FOC	Field Orientated Control
APF	Active Power Filters
BESS	Battery Energy Storage Systems
DC	Direct Current
DFACTS	Distribution FACTS
DIN	Distortion Index
PI	Proportional Integral
SVPWM	Space Vector Pulse Width Modulation
PWM	Pulse Width Modulation
FFT	Fast Fourier Transform
FOC	Field Orientated Control
FT	Fourier Transform
GTO	Gate Turn- Off Thyristor
HVDC	High Voltage Direct Current
IEC	International Electro technical Commission
IGBT	Insulated Gate Bipolar Transistors
IPQT	instantaneous p-q Theory
ITIC	Information Technology Industry Council
LSVI	Leading Series Voltage Injection
MATLAB	Matrix Laboratory
MOSFET	Metal Oxide Semiconductor Field Effect Transistors
PCC	Point of Common Coupling
PLL	Phase Lock Loop
PQ	Power Quality
SA	Surge Arresters
SMES	Super Conducting Magnetic Energy Systems
SPWM	Sinusoidal Pulse Width Modulation
SSCB	Solid State Circuit Breaker
UPS	Uninterruptible Power Supplies
SSSC	Static Synchronous Series Compensator
SSTS	Solid State Transfer Switch
SVC	Static Var Compensator
UPFC	Unified Power Flow Controller
UPQC	Unified Power Quality Conditioner
THD	Total Harmonic Distortion

LIST OF SYMBOLS

kHz	Kilo Hertz
kV	Kilo Volt
kVA	Kilo Volt Ampere
kVAR	Kilo Volt Ampere Reactive
P	Active Power
S	Apparent Power
pf	Power Factor
P_L	Active Power of Load
pu	Per Unit
Q	Reactive Power
Q_L	Reactive Power of Load
X_L	Inductive Reactance
Z	Total Impedance
Ω	Ohm
µF	Micro Farad
µs	Micro Second
hr	hour
hr/yr	hour per year
Hz	Hertz
I	Current Flowing Through the Circuit
kg.m^2	Kilogram Meter Square
m	Torque
mH	Mille Henry
MHz	Mega Hertz
ms	Mille Second
MVA	Mega Volt Ampere
Nm	Newton Meter
ns	Nano Second
Ø	Power Factor Angle
R	Resistance
L	Inductance
C	Capacitance
V_L	Load Voltage Magnitude
Vref	1 p.u. Voltage
Vrms	RMS Voltage
V_{inj}	Injected Voltage
VA	Volt Ampere
Vs	Source Voltage
V	Volt

CHAPTER 1

INTRODUCTION

1.1 Overview

In recent years, Power engineers are increasingly concerned over the quality of the electrical power. In modern industries, load equipment uses electronic controllers which are sensitive to poor voltage quality and will shut down if the supply voltage is depressed and may mal-operate in other ways if harmonic Distortion of the supply voltage is excessive. Most of this modern load equipment uses electronic switching devices which can contribute to poor network voltage quality. The competition in electrical energy supply has created greater commercial awareness of the issues of power quality while equipment is readily available to measure the quality of the voltage waveform and so quantify the problem.

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

Many efforts have been taken by utilities to fulfill consumer requirement, some consumers require a higher level of power quality than the level provided by modern electric networks. This implies that some measures must be taken so that higher levels of Power Quality can be obtained.

The FACTS devices and Custom power devices are introduced to electrical system to improve the power quality of the electrical power. DVR, DSTATCOM, ACTIVE FILTERs, UPQC etc are some of the devices used to improve the power quality of the voltage and current. With the help of these devices we are capable to reduce the problems related to power quality.

Although all devices can improve the power quality but in this the focus is on UPQC.UPQC is a power electronic device consisting of both DVR and D-STATCOM, former is connected in series and latter is connected in parallel to protect the sensitive load from all disturbances.

1.2 Literature survey

To provide quality power [1-4] has become today's most concerned area for both power suppliers and customers due to the deregulation of the electric power energy market, . 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.

The concept of custom power was introduced by **N.G.Hingorani** [5]. The term custom power means the use of power electronics controllers for distribution systems. The custom power increases the quality and reliability of the power that is delivered to the customers. Customers are increasingly demanding quality in the power supplied by the electric company.

Juan W. Dixon et al. [6] presented a series active power filter working as a sinusoidal current source, which is in phase with the mains voltage. The amplitude of the fundamental current in the series filter is controlled with the help of error signal generated between the load voltage and a pre established reference. The control provides the effective correction of power factor, harmonic distortion, and load voltage regulation**.**

Yash Pal et al. [7] describes different types of custom power devices such as Dynamic voltage restorer (DVR) and Distribution Static compensator (DSTATCOM), Unified power quality conditioner are their.DVR and DSTATCOM each one provide part of the compensation capabilities required. 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 [8-10].

Mojtaba Nemati, *et al*. [11] has demonstrated the role of different functional components of DVR as a compensator of voltage dips.

J. Barros, *et al.* [12] presented the results of the monitoring of sub harmonic voltages in a low-voltage distribution network using an IEC harmonic measurement instrument.

Mahesh Singh *et al.* [13] 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.* [14] presents an application of DVR for the improvement of voltage quality.

R.N.Bhargavi, *et al.* [15] presents causes of a poor power quality are harmonic currents, poor power factor, supply voltage variations, etc. Voltage sag, swell, momentary interruption, under voltages, over voltages, noise and harmonics are the most common power quality disturbances. A new connection for a unified power quality conditioner (UPQC) to improve the power quality of two feeders in a distribution system is proposed. This paper illustrates how UPQC can improve the power quality by mitigating all these PQ disturbances.

K. Palanisamy *et al.* [16] presents a novel control strategy for the case of 3-phase 3-wire Unified Power-Quality Conditioner (UPQC) based on the concepts of instantaneous active and reactive Power theory. The UPQCs is presented as one of the major custom power solutions capable of mitigating the effect of supply voltage sags / swells, distortion, unbalance voltage at the point of common coupling (PCC) as well as load harmonics, unbalance load and reactive power requirement of load. Using this control strategy harmonic detection, reactive power compensation, voltage sag and swell have been simulated and the results are analyzed.

G. Siva Kumar *et al.* [17] presents a device that can be used to enhance power quality i.e. unified power quality conditioner (UPQC).The UPQC is a versatile device which could function as series active filter and shunt active filter. It can fulfill different objectives like, maintaining a balanced sinusoidal (harmonic free) nominal voltage at the load bus, eliminating harmonics in the source currents, load balancing and power factor correction.

V. Khadkikar *et al.* [18] describes that UPQC can work in zero active power consumption mode, active power absorption mode and active power delivering mode. The series active power filter (APF) part of UPQC works in active power delivering mode and absorption mode during voltage sag and swell condition, respectively. The shunt APF part of UPQC during these conditions helps series APF by maintaining dc link voltage at constant level.

V. Khadkikar, *et al.* [19] presents a single-phase unified power quality conditioner (UPQC) so that power quality problems can be solved in single-phase systems. It is found that the UPQC in single-phase system effectively compensates the important power quality issues, such as the load reactive power, load current harmonics, voltage harmonics, voltage sag, voltage swell and voltage flicker. Under distorted source voltage having total harmonics distortion (THD) of 14.1%

with a non-linear load producing a distorted current (THD of 30.98%), the UPQC simultaneously compensates these harmonics resulting sinusoidal source current (THD of 3.77%) and load voltage (THD of 2.54%).

M. Faridi & H. Maeiiat, *et al*. [20] presents the effect of a static synchronous series compensator (SSSC) device in controlling active and reactive powers as well as damping power system oscillations in transient mode. The SSSC equipped with a source of energy in the DC link can supply or absorb the reactive and active power to or from the line. It is obtained that for selected bus-2 in two machine power system the efficiency of this compensator as one of the FACTS devices member in controlling power flows, achieving the desired value for active and reactive powers, and damping oscillations appropriately.

B. Singh, *et al.* [21] presents the solid-state controllers that are widely used to convert AC power for feeding number of electrical loads such as adjustable speed drives, furnaces, power supplies etc. Some of these controllers behave as nonlinear loads because they draw non sinusoidal current from the AC mains. Filter technology for improving power quality of such loads has matured to a reasonable level. Hybrid filters are considered one of best options for improving power quality for a number of considerations. A comprehensive review of The hybrid filters configurations are given: their control approaches, state of art, design considerations, selection criteria, potential applications, latest trends, future developments and their comparative features.

V. Khadkikar, *et al*. [22] focuses on the application of active power conditioners to tackle power quality problems has become a matured subject. The paper is based on a unified approach for load and source compensation using Unified Power Quality Conditioner (UPQC). Performance of this UPQC has been evaluated with a typical industrial load with realistic parameters supplied by a polluted distribution network. The system performance for current harmonics, voltage harmonics, voltage sag and voltage swell has been evaluated.

Ahmed M. & A. Haidar, *et al*. [23] discussed that most power quality disturbances can come from the facility itself, such as large loads turning on simultaneously, improper wiring and grounding practices, the start-up of large motors and electronic equipments that can be both a source and victim of power quality phenomena. The paper is focused mainly on power quality disturbance and the technique used to improve the quality of delivered power such as Unified Power Quality Conditioner (UPQC). A comprehensive analysis was performed on the parameters that affect the performance of UPQC Based on the results of analysis, it is confirmed that UPQC is an effective technique for quick improvement of power quality.

M. Tarafdar Haque, *et al.* [24] presents a novel and easy to implement control strategy for unified power (UPQC). This control strategy is usable in three-phase three wire quality conditioner utilities. The control strategy of parallel active filter (PAF) is based on combination of extended p-q theory and instantaneous symmetrical components theory while the control circuit of series active filter (SAF) is based on instantaneous symmetrical components theory. The problem of generating three phase imbalance reference currents of extended p-q theory is solved. Operation using this method compensates for reactive power, current harmonics and imbalance currents while operation of SAF compensates for voltage imbalance and voltage harmonics.

Jiangyuan Le, *et al.* [25] presents a nonlinear control strategy for unified power quality conditioner (UPQC) with better stability and dynamic performance in comparison with PI control and classical decoupled strategy. The analysis is based on the rotating reference frame, and the nonlinear property of UPQC mode is partly dealt through the exact linearization via feedback. The operation of control circuit has been explained using MATLAB software and simulation. The validity of control strategy is studied through simulation results.

Sai Shankar, *et al*. [26] presents an issue that is becoming increasingly important to electricity consumers at all levels of usage. Due to nonlinear characteristics of power electronic devices two important limitations are there i.e. they generate harmonics and draw lagging current from the utility. The unified power quality conditioner (UPQC) is used to compensate both harmonics as well as reactive power. Modeling is done for both active and reactive power compensation using different control strategies. The behavior of UPQC is analyzed with sudden switching of R-L loads, and R-C loads as well as occurrences of different shunt faults.

A. Mokhtatpour, *et al.* [27] proposed a new control approach for power quality compensation using Unified Power Quality Conditioner (UPQC). This approach has capability of power flow control as well as power quality compensation, too. In the UPQC control, Series Active Filter (SAF) is controlled by dq0 approach for voltage sag, swell, unbalance, interruption and harmonic compensation. Parallel Active Filter (PAF) is controlled by composition of dqo and Fourier theories for current harmonic and reactive power compensation.

Metin Kesler, *et al.* [28] suggested a new control method to compensate the power quality problems through a three-phase unified power quality conditioner (UPQC) under non-ideal mains voltage and unbalanced load conditions. The performance of proposed control system was analyzed. The proposed UPQC system can improve the power quality at the point of common coupling (PCC) on power distribution system under non-ideal mains voltage and unbalanced load conditions.

Luis F.C. Monteiro, *et al.* [29] presents a three-phase three-wire system in which unified power quality conditioner is used and for control purpose a dual control strategy is used for series active filter. The work presented a control strategy for shunt-active filter that guarantees sinusoidal, balanced and minimized source currents even under unbalanced and / or distorted system voltages. Then, this control strategy was extended to develop a dual control strategy for series-active filter. The paper develops the integration principles of shunt current compensation and series voltages compensation, both based on instantaneous active and non-active powers, directly calculated from a-b-c phase voltages and line currents.

RVD Ram Rao *et al***.** [30] proposed the quality of power is affected by many factors like harmonic contamination due to non-linear loads, such as large thyristor power converters, rectifiers, voltage and current flickering due to arc in arc furnaces, sag and swell due to the switching of the loads etc. One of the many solutions is the use of a combined system of shunt and active series filters like unified power quality conditioner (UPQC) This device is a combination of shunt active filter together with a series active filter in a back to- back configuration, to simultaneously compensate the supply voltage and the load current or to mitigate any type of voltage and current fluctuations and power factor correction in a power distribution network.

Subramanium, *et al.* [31] presents the steady-state operating characteristics of Unified Active Power Filters (UAPF's). The UAPF is an integration of series and shunt active filters and has a unique approach towards the control of the series active filter for reactive power compensation. The principle characteristics of UAPF's are presented by way of analyzing steady-state operating conditions and identifying different modes of operation. Simulation results are provided to verify the analysis. The analytical results are useful for the selection of kVA ratings and optimal operating conditions of active filter components.

V.Khadkikar, *et al.* [32] presents the steady state analysis of unified power quality conditioner (UPQC). The mathematical analysis is based on active and reactive power flow through the shunt and series APF, wherein series APF can absorb or deliver the active power whereas the reactive power requirement is totally handle by shunt APF alone during all conditions.

The derived relationship between source current and % of sag/swell variation shows shunt APF plays an important role in maintaining the overall power balance in the entire network. The digital simulation is carried out to verify the analysis done. . This analysis can be very useful for selection of device ratings for both shunt and series APFs.

1.3 Scope of Work

This dissertation proposes the MATLAB SIMULINK model of unified power quality conditioner which is used for the improvement of power quality at distribution level. The major objectives are summarized as follows:

- Study the model of UPQC.
- Investigating the performance of Unified Power Quality Conditioner (UPQC) using the proportional integral control for field oriented control induction motor.
- Investigating the performance of Unified Power Quality Conditioner (UPQC) using the proportional integral for ASD load under different fault.

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 unified power quality conditioner in detail and outlines the control technique used in the simulation of Unified power quality conditioner.

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

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

CHAPTER 2

POWER QUALITY

2.1 Definition of Power Quality

Power quality has different meanings 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” [1]. There is a broad range of power quality problems associated with power systems based on time 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.

The main reasons for concern with power quality (PQ) are as following:

- End user devices become more sensitive to PQ due to many microprocessor based controls.
- Large computer systems in many businesses facilities.
- Power electronics equipment used for enhancing system stability, operation and efficiency. These are major sources of bad Power Quality.
- Continuous development of high performance equipment: Such equipment is more susceptible to power disturbances.

The users always demand higher power quality. Some basic criterions for power quality are constant rms value, constant frequency, symmetrical three-phases, pure sinusoidal wave shape and limited THD.

2.2 Responsibilities of the suppliers and users of electrical power

The realization of quality electrical power is the responsibility of the suppliers and users of electricity. Suppliers are in the business of selling electricity to widely varying client. The need of one user is usually not the same as the needs of other users. Most electrical equipment is designed to operate within a voltage of ±5% of nominal with marginal decrease in performance. For the most part, utilities are committed to adhering to these limits. At locations remote from substations supplying power from small generating stations, voltages outside of the ±5% limit are occasionally seen. Such variation could have a negative impact on loads such as motors and fluorescent lighting. The overall effects of voltage outside the nominal are not that significant unless the voltage approaches the limits of ±10% of nominal. Also, in urban areas, the utility frequencies are rarely outside ±0.1 Hz of the nominal frequency. This is well within the operating tolerance of most sensitive.

TABLE 2.1 Immunity and Power Quality Indices

Index	Description	Examples
		Equipment Immunity Indices
I	High immunity	Motors, transformers, incandescent lighting, heating loads, electromechanical relays
II	Moderate immunity	Electronic ballasts, solid-state relays, programmable logic controllers, adjustable speed drives
III	Low immunity	Signal, communication and data processing equipment, electronic medical equipment
		Power Quality Indices
I	Low power quality problems	Service entrance switchboard, lighting power distribution panel
II	Moderate power quality problems	HVAC power panels
III	High power quality problems	Panels supplying adjustable speed drives, elevators, large motors

2.3 Sources of Poor Power Quality

Sources of poor Power Quality are listed as follows [2]:

- Adjustable –speed drives
- Switching Power supplies
- Arc furnaces
- Electronic Fluorescent lamp ballasts
- Lightning Strike
- L-G fault
- Non- linear load
- Starting of large motors
- Power electronic devices

2.4 Need of Power Quality

There is an increased concern of power quality due to the following reasons [3]:

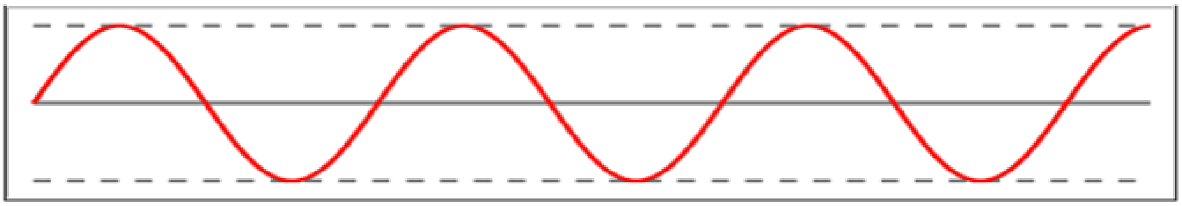
1. New-generation loads that uses microprocessor and microcontroller based controls and power electronic devices, are more sensitive to power quality variations than that equipments used in the past.
2. The demand for increased overall power system efficiency resulted in continued growth of devices such as high-efficiency adjustable-speed motor drives and shunt capacitors for power factor correction to reduce losses. This is resulting in increasing harmonic level 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. Most of the networks are interconnected these days. Integrated processes mean that the failure of any component has much more important consequences.

2.5 Classification of Power Quality Problems

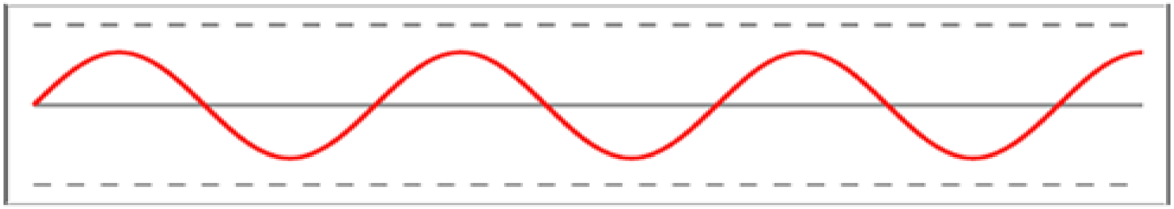
2.5.1. Short Duration Voltage Variation

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. [3].

(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.



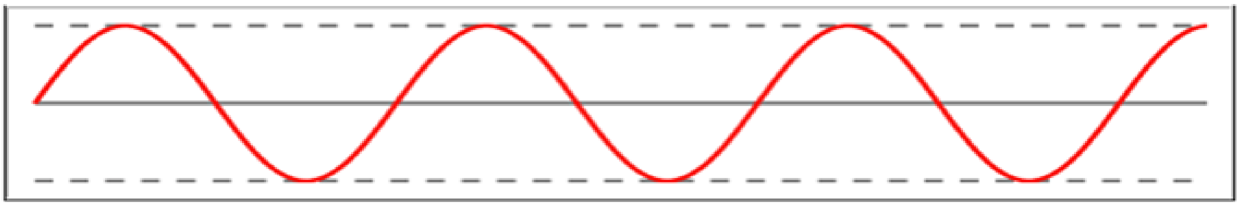
Normal waveform



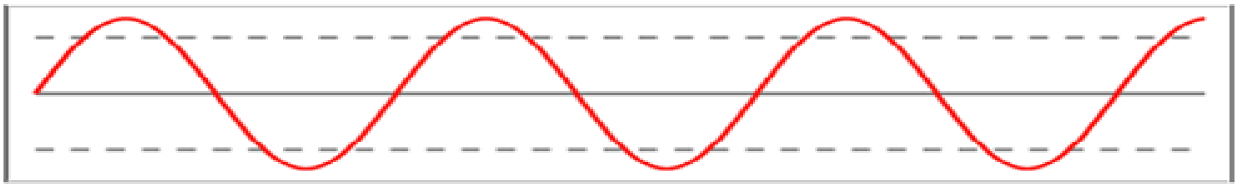
Sag

Figure 2.1: 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.



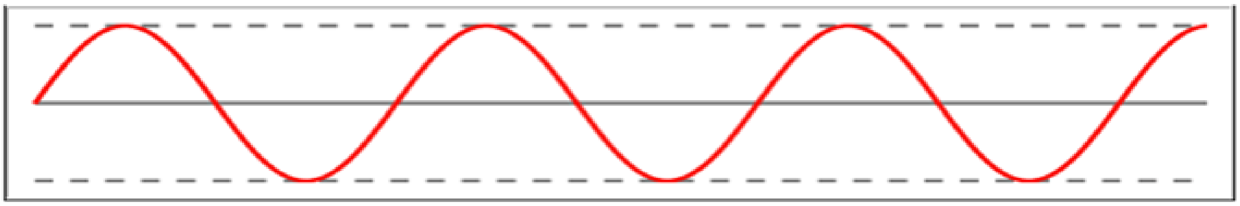
Normal waveform



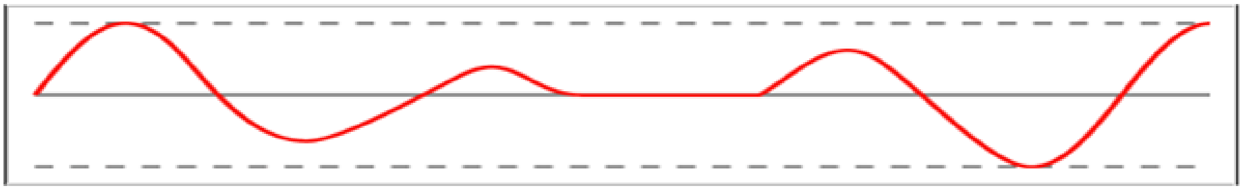
Swell

Figure 2.2: 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.



Normal waveform



Interruption

Figure 2.3: Interruption

2.5.2. Long-Duration Voltage Variation

Long-duration variations can be categorized as over voltages, under voltages 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. Over voltages are usually the results of load switching or incorrect tap settings on transformers.

(ii) Under voltage: An under voltage 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 under voltage until voltage regulation equipment on the system can restore the voltage back to within tolerance limits. Also overloaded circuits can result in under voltage.

(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.

2.5.3. 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.

Figure 2.4: 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.

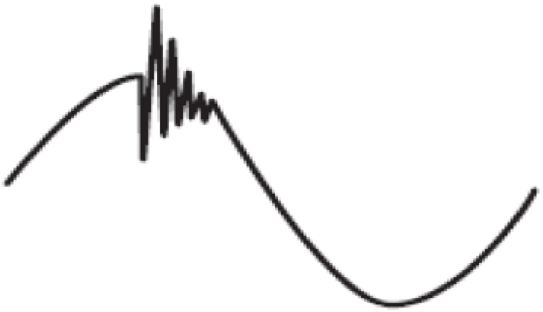


Figure 2.5: Oscillatory Transients

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

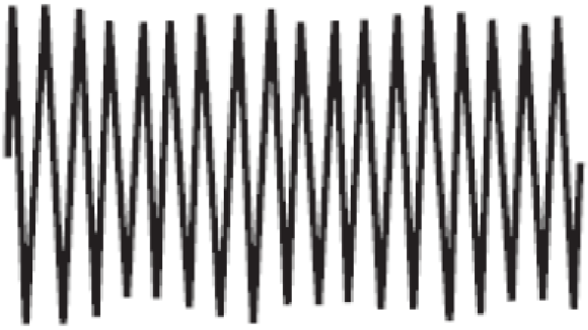


Figure 2.6: Voltage Fluctuations or Flicker

2.5.5 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.

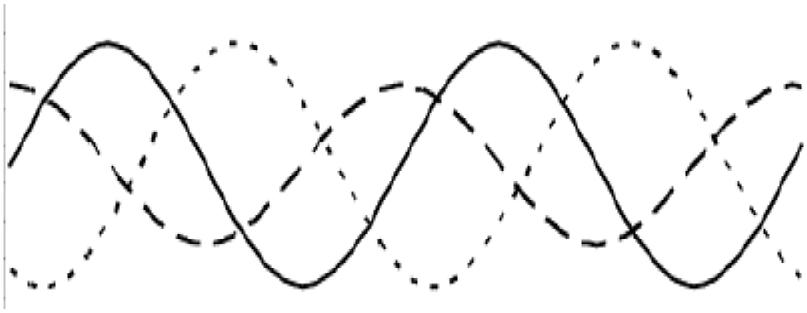


Figure 2.7: Voltage imbalance

2.5.6 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.

2.5.7 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, and that is known as the fundamental frequency which is usually 50 or 60 Hz. The harmonic distortion originates in the nonlinear characteristics of devices and also on loads connected to the power system.

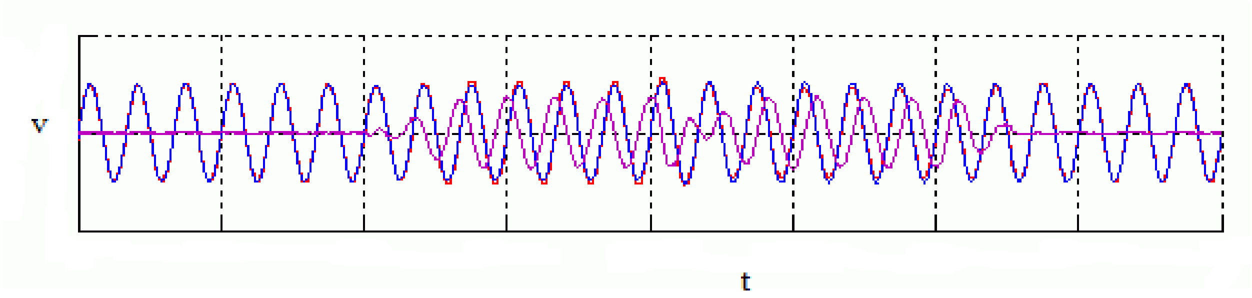


Figure 2.8: Harmonics

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 [28]. Voltage THD is

$$V_{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V1} \tag{2.1}$$

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

$$\mathrm{DIN} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{\sqrt{\sum_{n=1}^{\infty} V_n^2}} \tag{2.2}$$

THD and DIN are interrelated by the following equations

$$\mathrm{DIN} = \frac{THD}{\sqrt{1+THD^2}} \tag{2.3}$$

$$\mathrm{THD} = \frac{DIN}{\sqrt{1-DIN^2}} \tag{2.4}$$

(i) 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 [11].

(ii)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.

2.5.8 Electrical Noise

Noise is a high frequency distortion of the voltage waveform. Caused by disturbances on the utility system or by equipment such as welders, switchgear and transmitters, noise can frequently go unnoticed. Frequent or high levels of noise can cause equipment malfunction, overheating and premature wear.

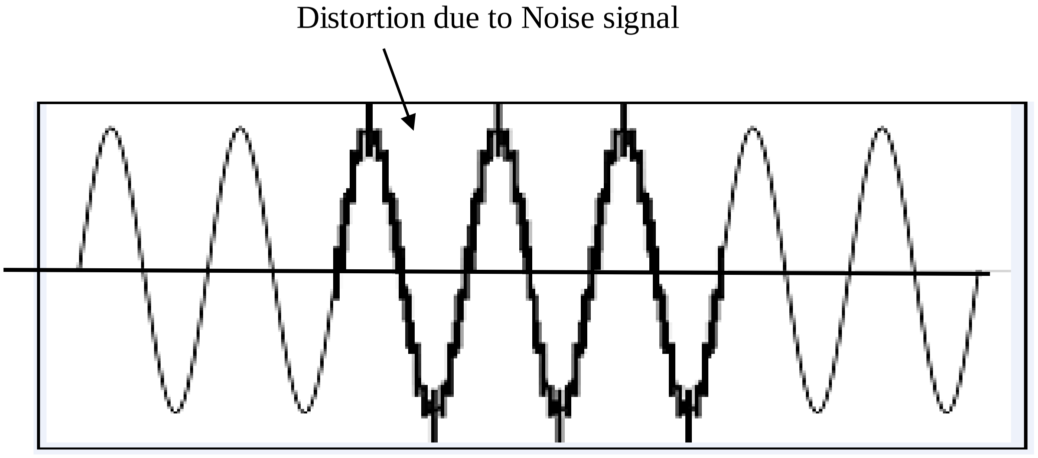


Figure 2.9: Electrical Noise Waveform

2.5.9 Notching: Notching is a disturbance of opposite polarity to the normal voltage waveform (which is subtracted from the normal waveform) lasting for less than one-half cycle. Notching is usually caused by malfunctioning of electronic switches or power conditioners. While it is generally not a major problem, notching can cause equipment, especially electronics, to operate improperly [3].

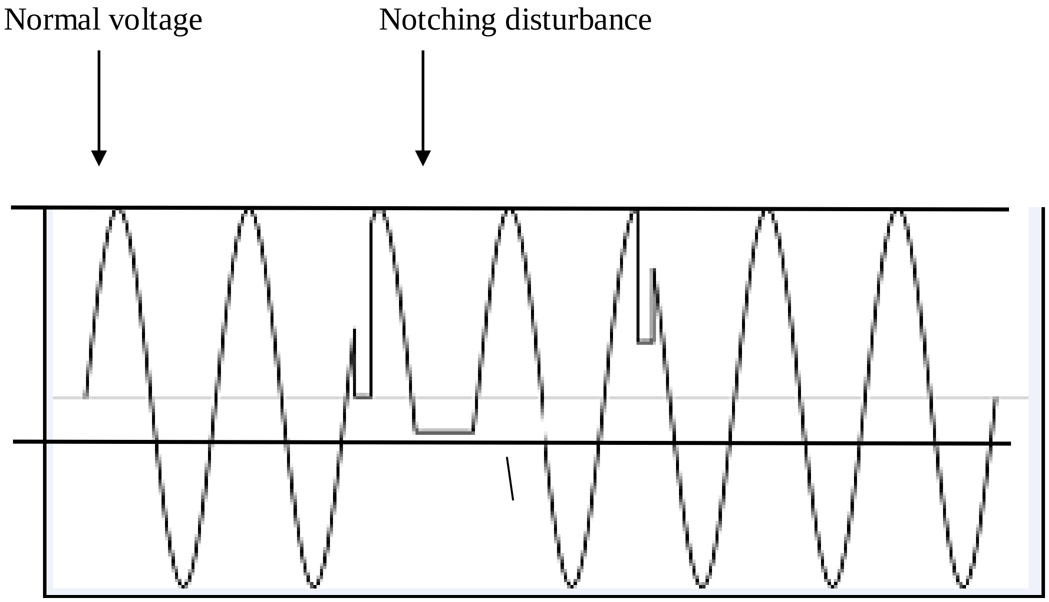


Figure 2.10: Notching Waveform

2.6 Solutions to Power Quality Problems: The mitigation of power quality problems can be achieved in two ways. It can be done from either customer side or utility side. First approach used is load conditioning and the other is line conditioning. Load conditioning ensures that the equipment is less sensitive to power disturbances. They are based on PWM converters and connected in shunt or in series to low and medium voltage distribution system. Series active power filters 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 of these schemes are implemented preferable with voltage source PWM inverters, with a dc bus having a reactive element such as a capacitor. However, 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. 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 not sufficient for limiting voltage fluctuations to protect sensitive electronic control circuits.

(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 be 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 equipments from shutdowns caused by voltage sags or momentary interruptions. Energy is fed to the system to compensate for the energy that would be lost by the voltage sag or interruption. The systems used 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 where effective reduction or elimination of certain harmonics is required. If possible, it is always preferable to use a 12-pulse 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

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 [32]. Due to this increasing demand and the rapid development of the high power semiconductor technology, the custom power solutions are taking place rapidly. In a custom power system customer receives specified power quality from a utility or a service provider or at-the-fence equipment installed by the customer in coordination with the utility, which includes an acceptable combination of the following features:

- No (or rare) power interruptions
- Magnitude and duration of voltage reductions within specified limits.
- Low harmonic voltage.
- Low phase unbalance.

This can be done on the basis of an individual, large customer, industry or a supply for a high tech community on a wide area basis.

3.2 Need of Custom Power

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 than were the previous generation equipment and less automated production and information systems.

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 customers. Power quality is an issue that is becoming increasingly important to electricity consumers at all levels of usage.

In the several processes such as semiconductor manufacturing or food processing plants, a batch of product can be 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 other loads which are very sensitive such as hospitals, processing plants, air traffic control and numerous other data processing and service providers that require clean and uninterrupted power. Thus in this scenario in which customers increasingly demand power quality, the term power quality attains increased significance.

The factors mentioned point out the problems faced by the industry and awareness of consumers 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) , Unified power quality conditioner(UPQC)[22].

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.

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 [16,19].

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. The term Custom Power pertains to the use of power electronic 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 that 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.

3.3.1. Solid State Current Limiter

The most widely used solution for limitation of the fault currents is to use a transformer with a split secondary winding (or a three windings transformer) and current limiting reactors [30]. The basic configuration of Solid State Current Limiter is shown in Figure 3.1.

However, the usage of fault current limiting reactors with powerful motor loads has a negative impact on the stability of motors, for example when short-term voltage sags occur. It would be worthwhile to directly control transients, resulting from faults, at primary circuits, thus alleviating effects of the faults.

Series fault current limiters used to limit the fault current by disconnecting solid-state switch and increasing the impedance. However, such scheme has a disadvantage: the system should be operating in continuous mode, and malfunction of the static switch could lead to interruption of power supply for the customer.

Parallel fault current limiters [12] are activated only at the moment of fault and have the following functions:

- limit the peak fault current
- decrease the motors feeding into the fault
- shunt the consumer switches while disconnecting

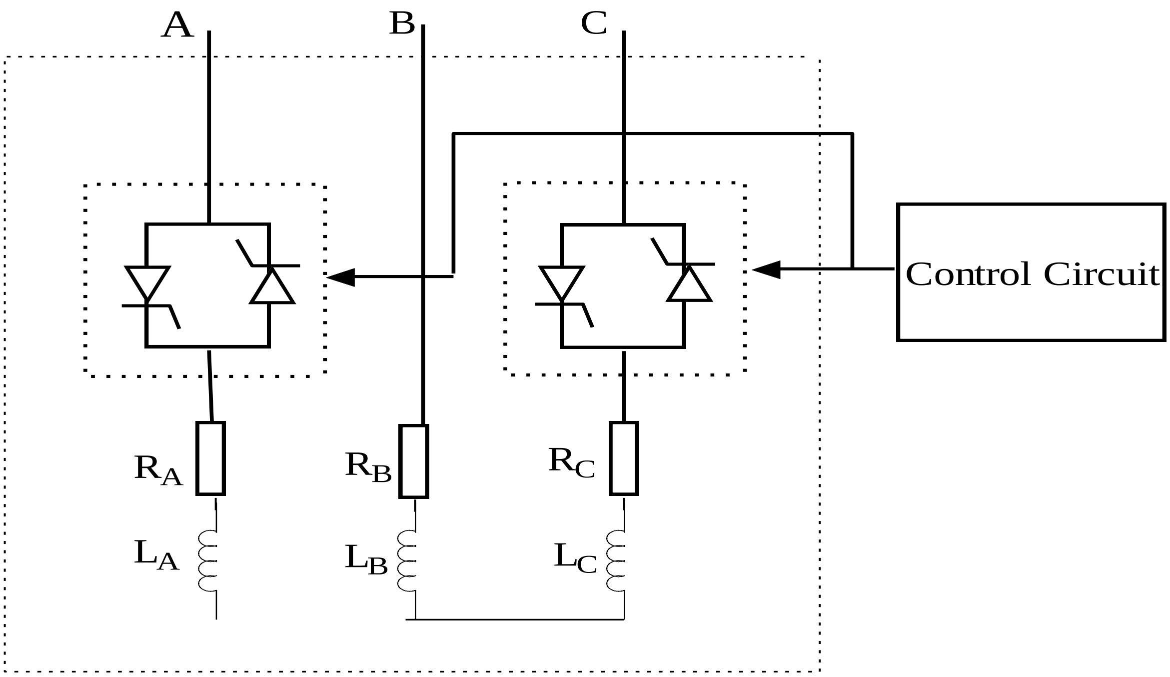


Figure 3.1: Solid State Current Limiter

3.3.2. Solid State Transfer Switch

The SSTS can be used very effectively to protect sensitive loads against voltage sags, swells and other electrical disturbances.

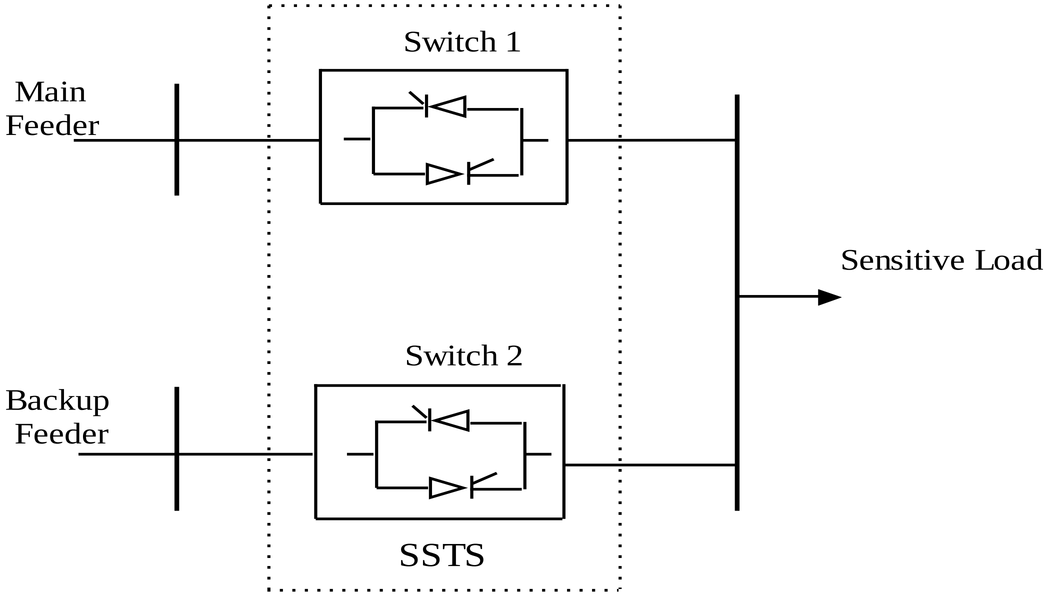


Figure 3.2: Solid State Transfer Switch

The SSTS provides continuous high-quality power supply to sensitive loads by transferring, within a time scale of milliseconds, the load from a faulted bus to a healthy one. The basic configuration of this device consists of two three-phase solid-state switches, one for the main feeder another for the backup feeder. These switches have an arrangement of back-to-back connected thyristors, as illustrated in the schematic diagram of Fig. 3.2.

Each time a fault condition is detected in the main feeder, the control system swaps the firing signals to the thyristors in both switches, i.e., Switch 1 in the main feeder is deactivated and Switch 2 in the backup feeder is activated. The control system measures the peak value of the voltage waveform at every half cycle and checks whether or not it is within a prespecified range. If it is outside limits, an abnormal condition is detected and the firing signals to the thyristors are changed to transfer the load to the healthy feeder.

The success of the SSTS is mainly due to its rather low cost compared with other solutions. A requirement is that a secondary in-feed, independent from the main source (e.g. a feeder to another substation), must be available. Therefore, this solution is particularly attractive for installations that already have mechanical transfer systems, where upgrading to a static system does not require major changes in the layout of the distribution system. Formerly available only for low voltages, SSTS systems are now advertised for higher voltages and load ratings, which make them suitable for high-power industrial applications. Transfer-time estimation of a SSTS is not a straightforward process due to its dependence on commutation between the thyristor switches in each phase. The commutation is determined by the system parameters and the component characteristics. To offer ride-through capability, the load must be transferred within the shortest possible time.

3.3.3 Active Power Filters

The increasing use of power electronics based loads (adjustable speed drives, switch mode power supplies, etc.) to improve system efficiency and controllability is increasing the concern for harmonic distortion levels in end use facilities and on the overall power system. The application of passive tuned filters creates new system resonances which are dependent on specific system conditions.

Passive filters often need to be significantly overrated to account for possible harmonic absorption from the power system. Passive filter ratings must coordinate with reactive power requirements of the loads and it is often difficult to design the filters to avoid leading power factor operation for some load conditions.

A flexible and versatile solution to voltage/current quality problems is offered by active power filters. Active filters have the advantage of being able to compensate for harmonics without fundamental frequency reactive power concerns [12]. Currently they are based on PWM converters and connect to low and medium voltage distribution system in shunt or in series. Series active power filters must operate in conjunction with shunt passive filters in order to compensate load current harmonics. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source. Both schemes are implemented preferable with voltage source PWM inverters, with a dc bus having a reactive element such as a capacitor. Active power filters can perform one or more of the functions required to compensate power systems and improving power quality. The rating of the active power can be less than a conquerable passive filter for the same nonlinear load and the active filter will not introduce system resonances that can move a harmonic problem from one frequency to another.

3.3.4 Distribution Statcom (DSTATCOM)

The purpose of the DSTATCOM is to cancel load harmonics fed to the supply. The coupling of DSTATCOM is three phase, in parallel to network and load. It work as current sources, connected in parallel with the nonlinear load, generating the harmonic currents the load requires also balance them in addition to providing reactive power.[6]. In order to compensate undesirable components of the load current the DSTATCOM injects currents into the point of common coupling. With an appropriated control strategy, it is also possible to correct power factor and unbalanced loads. This principle is applicable to any type of load considered a harmonic source.

Its advantage is that it of carries only the compensation current plus a small amount of active fundamental current supplied to compensate for system losses. Shunt Active Power Filter in current control mode is also called as DSTATCOM.

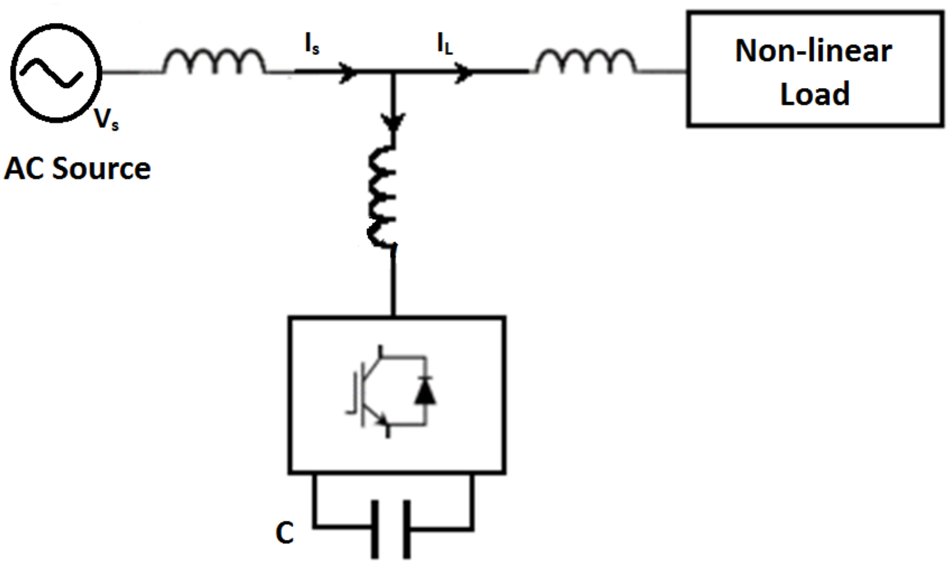


Figure 3.3: Disribution STATCOM

3.3.5 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.

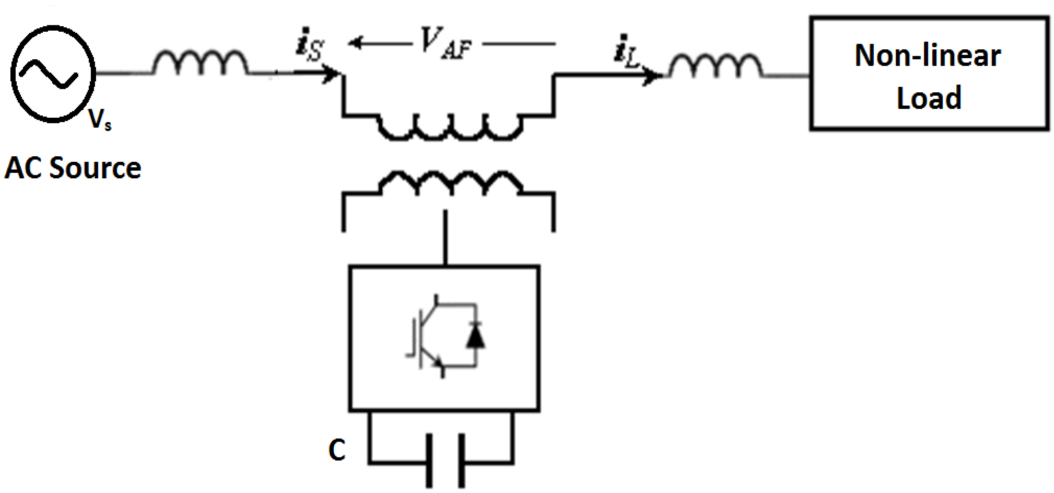


Figure 3.4: Dynamic voltage restorer

3.3.6

Unified Power Quality Conditioner (UPQC)

The best protection for sensitive loads from sources with inadequate quality, is shunt-series connection i.e. unified power quality conditioner (UPQC) .Recent research efforts have been made towards utilizing unified power quality conditioner (UPQC) to solve almost all power quality problems for example voltage sag, voltage swell, voltage outage and over correction of power factor and unacceptable levels of harmonics in the current and voltage The basic configuration of UPQC is shown in fig.3.5

The main purpose of a UPQC is to compensate for supply voltage flicker/imbalance, reactive power, negative-sequence current, and harmonics [14]. In other words, the UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems. The UPQC, therefore, is expected as one of the most powerful solutions to large capacity sensitive loads to voltage flicker/imbalance.

Unified Power Quality Conditioner (UPQC) for non-linear and a voltage sensitive load has following facilities:

- It eliminates the harmonics in the supply current, thus improves utility current quality for nonlinear loads.
- UPQC provides the VAR requirement of the load, so that the supply voltage and current are always in phase, therefore, no additional power factor correction equipment is necessary.
- UPQC maintains load end voltage at the rated value even in the presence of supply voltage sag.
- The voltage injected by UPQC to maintain the load end voltage at the desired value is taken from the same dc link, thus no additional dc link voltage support is required for the series compensator.

The UPQC consists of two three phase inverters connected in cascade in such a manner that Inverter I is connected in series with the supply voltage through a transformer inverter II is connected in parallel with the load. The main purpose of the shunt compensator is to compensate for the reactive power demanded by the load, to eliminate the harmonics and to regulate the common dc link voltage. The series compensator is operated in PWM voltage controlled mode. It injects voltage in quadrature advance to the supply voltage (current) such that the load end voltage is always maintained at the desired value. The two inverters operate in a coordinated manner.

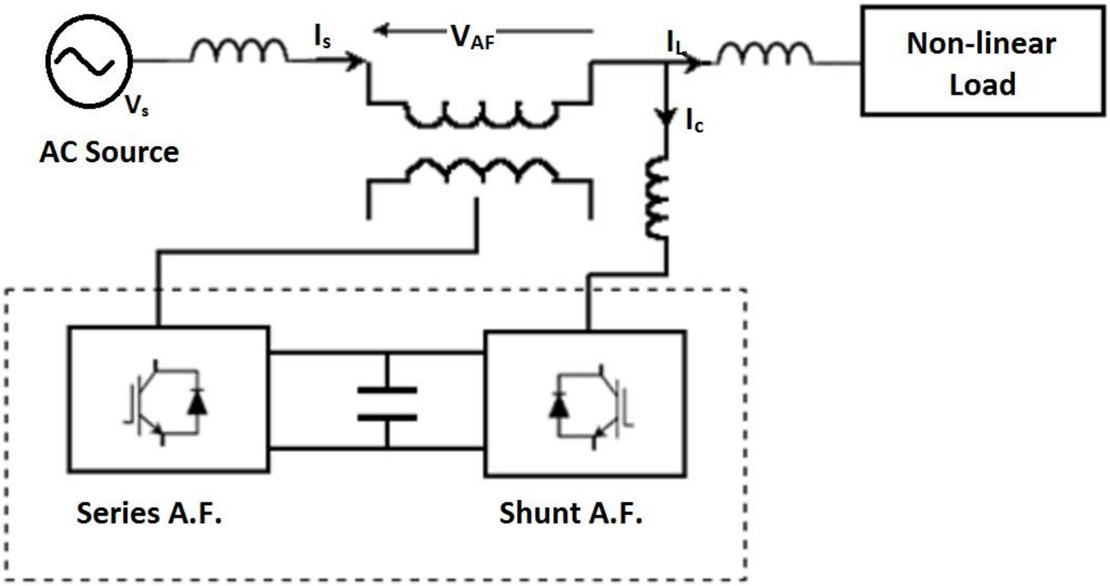


Figure 3.5: Unified power quality conditioner

There are three principle elements to the custom power concept; these are:

- The Dynamic Voltage Restorer (DVR), it provides series compensation by voltage injection for power system sag and swell.

- The Distribution Static Compensator (D-STATCOM), it provides continuously variable shunt compensation by current injection for eliminating voltage fluctuations and obtaining correct power factor in three-phase systems. An ideal application of it is to prevent disturbing loads from polluting the rest of the distribution system.

- Unified Power Quality Conditioner (UPQC), it provide series and shunt compensation i.e. inject voltage in sag and swell condition and inject current for elimination of voltage fluctuations ,correct power factor, avoid pollution to rest of the distribution system.

The proper selection of necessary custom power strategies in addition to accurate system modeling and appropriate protection devices will increase the power quality.

3.4 Superiority of UPQC over Other Devices

Each of Custom Power devices has its own benefits and limitations. The UPQC is expected to be one of the most powerful solutions to large capacity loads sensitive to supply voltage and load current disturbances /imbalance. The most effective type of these devices is considered to be the Unified Power Quality Conditioner (UPQC). There are numerous reasons why the UPQC is preferred over the others. UPQC is much flexible than any single inverter based device. It can simultaneously correct for the unbalance and distortion in the source voltage and load current where as all other devices either correct current or voltage distortion. Therefore the purpose of two devices is served by UPQC only.

CHAPTER 4

UNIFIED POWER QUALITY CONDITIONER

4.1 Introduction

The Unified Power Quality Conditioner is a custom power device that is employed in the distribution system to mitigate the disturbances that affect the performance of sensitive and/or critical load [1]. It is a type of hybrid APF and is the only versatile device which can mitigate several power quality problems related with voltage and current simultaneously therefore is multi functioning devices that compensate various voltage disturbances of the power supply, to correct voltage fluctuations and to prevent harmonic load current from entering the power system. Fig. 1 shows the system configuration of a single-phase UPQC. Unified Power Quality Conditioner (UPQC) consists of two IGBT based Voltage source converters (VSC), one shunt and one series cascaded by a common DC bus. The shunt converter is connected in parallel to the load. It provides VAR support to the load and supply harmonic currents. Whenever the supply voltage undergoes sag then series converter injects suitable voltage with supply [2]. Thus UPQC improves the power quality by preventing load current harmonics and by correcting the input power factor.

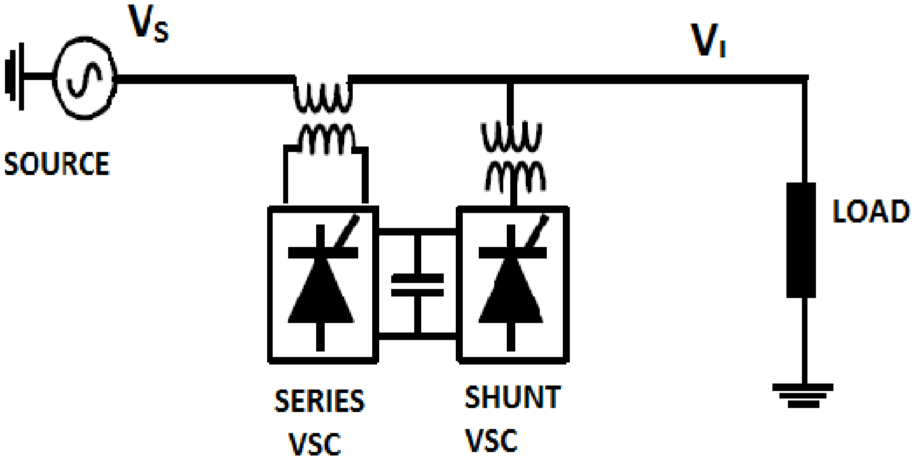


Figure 4.1: Block diagram of UPQC

4.2 Basic configuration of UPQC

The main components of a UPQC are series and shunt power converters, DC capacitors, low-pass and high-pass passive filters, and series and shunt transformers:

4.2.1 Series converter It is a voltage-source converter connected in series with the AC line and acts as a voltage source to mitigate voltage distortions. It is used to eliminate supply voltage flickers or imbalance from the load terminal voltage and forces the shunt branch to absorb current harmonics generated by the nonlinear load. Control of the series converter output voltage is usually performed using sinusoidal pulse-width modulation (SPWM). The gate pulses required for converter are generated by the comparison of a fundamental voltage reference signal with a high-frequency triangular waveform.

4.2.2 Shunt converter It is a voltage-source converter connected in shunt with the same AC line and acts as a current source to cancel current distortions, compensate reactive current of the load, and improve the power factor. It also performs the DC-link voltage regulation, resulting in a significant reduction of the DC capacitor rating. The output current of the shunt converter is adjusted using a dynamic hysteresis band by controlling the status of semiconductor switches so that output current follows the reference signal and remains in a predetermined hysteresis band.

4.2.3 Midpoint-to-ground DC capacitor bank It is divided into two groups, which are connected in series. The neutrals of the secondary transformers are directly connected to the DC link midpoint. As the connection of both three-phase transformers is Y/Y_o, the zero-sequence voltage appears in the primary winding of the series-connected transformer in order to compensate for the zero-sequence voltage of the supply system. No zero-sequence current flows in the primary side of both transformers. It ensures the system current to be balanced even when the voltage disturbance occurs.

4.2.4 Low-pass filter It is used to attenuate high frequency components at the output of the series converter that are generated by high-frequency switching.

4.2.5 High-pass filter It is installed at the output of shunt converter to absorb current switching ripples.

4.2.6 Series and shunt transformers These are implemented to inject the compensation voltages and currents, and for the purpose of electrical isolation of UPQC converters. The UPQC is capable of steady-state and dynamic series and/or shunt active and reactive power compensations at fundamental and harmonic frequencies. However, the UPQC is only concerned about the quality of the load voltage and the line current at the point of its installation, and it does not improve the power quality of the entire system.

4.3 Equivalent circuit

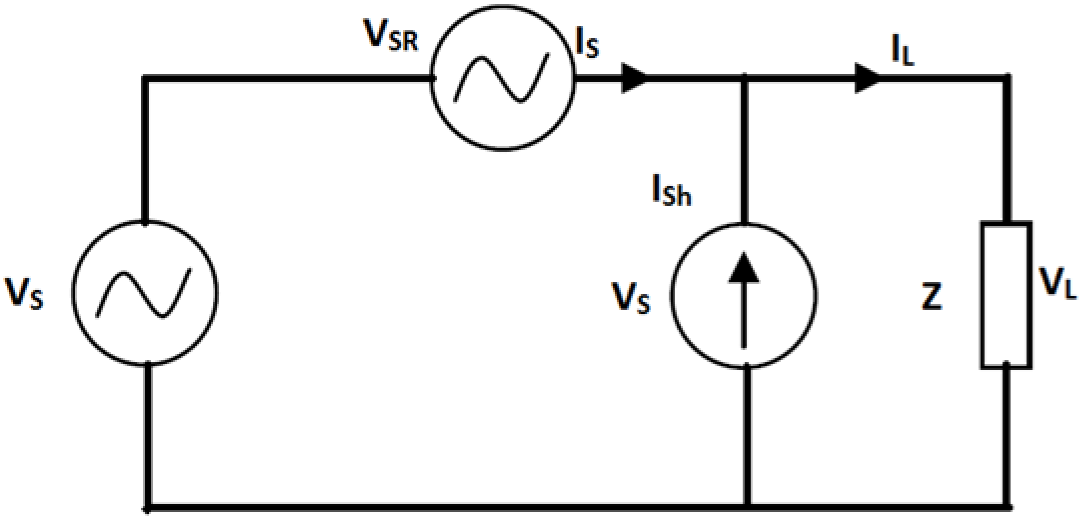


Figure 4.2: equivalent circuit for UPQC

In this circuit, [27]

V_S represents the voltage at power supply

V_{SR} is the series-APF for voltage compensation,

V_L represents the load voltage and

I_{Sh} is the shunt-APF for current and V_{SR} compensation.

Due to the voltage Distortion, the system may contain negative phase sequence and harmonic components.

In general, the source voltage in Figure 2 can be expressed as:

$$V_s + V_{sr} = V_L \tag{4.1}$$

To obtain a balance sinusoidal load voltage with fixed amplitude V, the output voltages of the series-APF should be given by;

$$V_{sr} = (V - V_{1p}) \sin(\omega t + \theta_{1P}) - V_{Ln}(t) - \sum_{K=2}^{\infty} V_K(t) \tag{4.2}$$

where,

V_{1P}: positive sequence voltage amplitude fundamental frequency

θ_{1P}: initial phase of voltage for positive sequence

V_{1n}: negative sequence component

The shunt-APF acts as a controlled current source and its output components should include harmonic, reactive and negative-sequence components in order to compensate these quantities in the load current, when the output current of shunt APF i_{sh} is kept to be equal to the component of the load as given in the following equation:

$$i_L = I_{1p} \cos(\omega t + \theta_{1P}) \sin \varphi_{1P} + i_{Ln} + \sum_{K=2}^{\infty} i_{LK} \quad (4.3)$$

$$\phi_{1P} = \varphi_{1P} - \theta_{1P} \quad (4.4)$$

where,

φ_{1P}: initial phase of current for positive sequence

As seen from the above equations that the harmonic, reactive and negative sequence current is not flowing into the power source. Therefore, the terminal source current is harmonic-free sinusoid and has the same phase angle as the phase voltage at the load terminal

$$i_S = i_L - i_{Sh}$$

$$= I_{1p} \sin(\omega t - \theta_{1P}) \cos \varphi_{1P} \quad (4.55)$$

4.4 UPQC Configurations

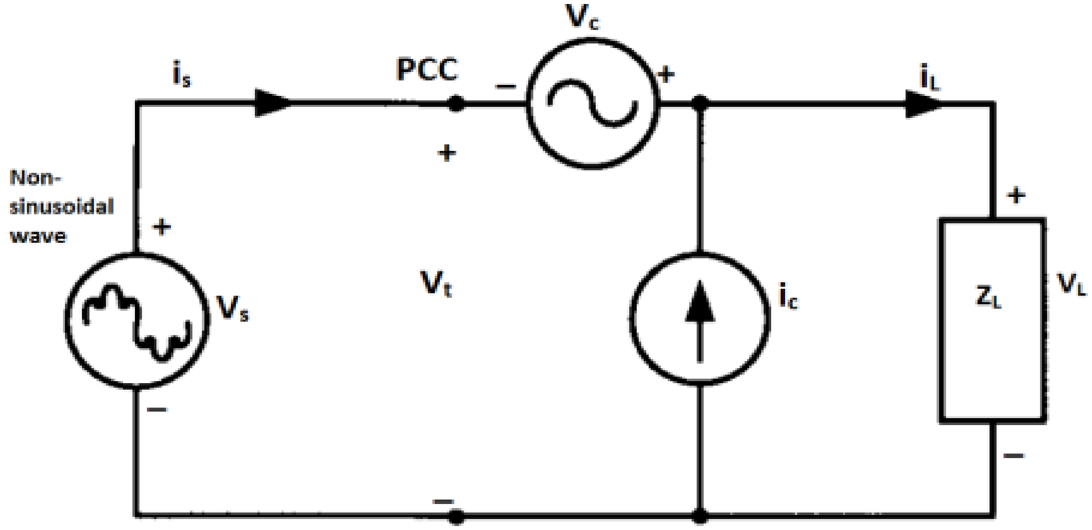


Figure 4.3: Right shunt UPQC compensation configuration

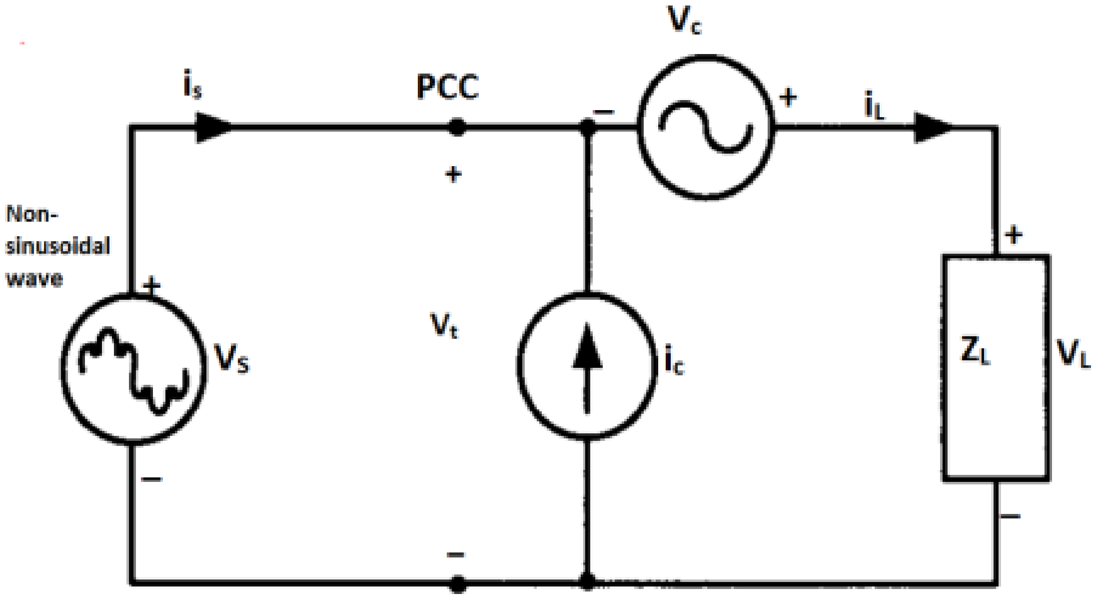


Figure 4.4 Left shunt UPQC compensation configuration

There are two possible ways of connecting the unit to the terminal voltage (V_t) at PCC:

- Right-shunt UPQC (figure4.3), where the shunt compensator (i_c) i_a placed at the right side of the series compensator (V_c).
- Left-shunt UPQC (figure4.4), where the shunt compensator (i_c) is placed at the left side of the series compensator (V_c).

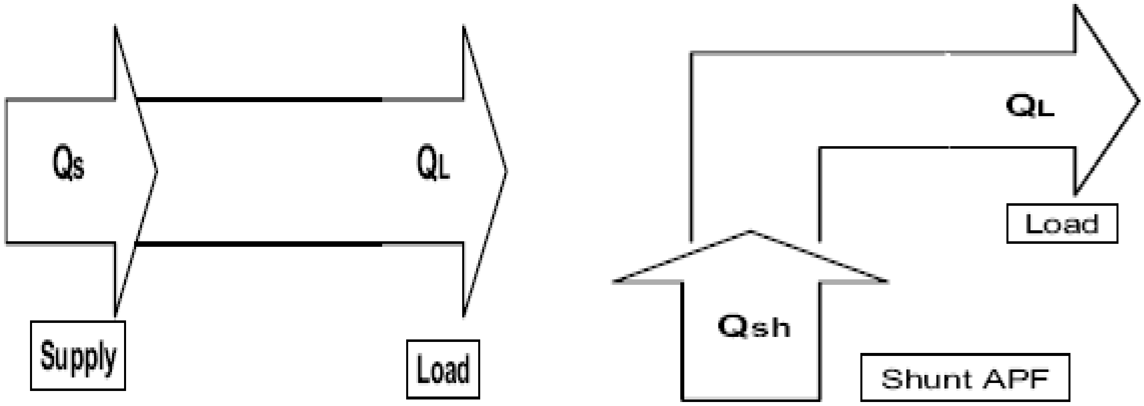
These two structures have similar features; however the overall characteristics of the right shunt UPQC are superior (e.g. operation at zero) power injection/absorption mode, achieving unity power factor at load terminals, and full reactive power compensation) [1].

4.5 Steady – State Power Flow Analysis

The powers due to harmonic quantities are negligible as compared to the power at fundamental component, therefore, the harmonic power is neglected and the steady state operating analysis is done on the basis of fundamental frequency component only. The UPQC is controlled in such a way that the voltage at load bus is always sinusoidal and at desired magnitude. Therefore the voltage injected by series APF must be equal to the difference between the supply voltage and the ideal load voltage. Thus the series APF acts as controlled voltage source. The function of shunt APF is to maintain the dc link voltage at constant level. In addition to this the shunt APF provides the VAR required by the load, such that the input power factor will be unity and only fundamental active power will be supplied by the source. [16]

Case I

The reactive power flow during the normal working condition when UPQC is not connected in the circuit is shown in the Fig. 4.5 a. In this condition the reactive power required by the load is completely supplied by the source only. When the UPQC is connected in the network and the shunt APF is put into the operation, the reactive power required by the load is now provided by the shunt APF alone; such that no reactive power burden is put on the mains. So as long as the shunt APF is ON, it is handling all the reactive power even during voltage sag, voltage swell and voltage harmonic compensation. The series APF does not take any active part in supplying the load reactive power demand. The reactive power flow during the entire operation of UPQC is shown in the Fig. 4.5 (b)[18].



(a) No UPQC **(b) Shunt APF ON**

Figure 4.5: a) – b) Reactive Power Flow

$v_s =$ source voltage

$v_t =$ terminal voltage at PCC load

$v_l =$ load voltage

$i_s =$ source current

$i_l =$ load current

v_{sr} = voltage injected by series APF

$i_{sr} =$ current injected by shunt APF

k = fluctuation of source voltage

Case II

If $k < 0$, i.e . $v_t < v_l$, P_{sr} will be positive, means series APF supplies the active power to the load. This condition is possible during the utility voltage sag condition. I_s will be more than the normal rated current. Thus we can say that the required active power is taken from the utility itself by taking more current so as to maintain the power balance in the network and to keep the dc link voltage at desired level [18].

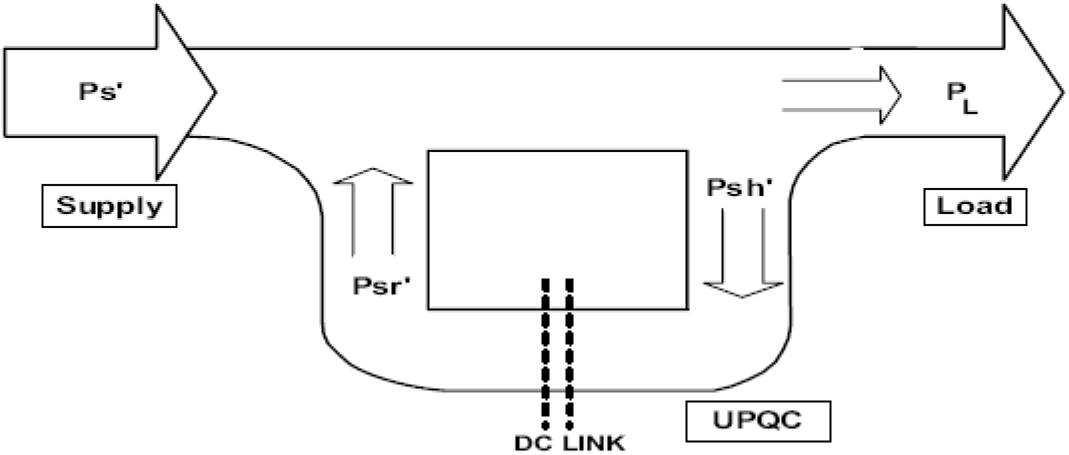


Figure 4.6: Active Power Flow during Voltage Sag Condition

P_s'= Power Supplied by the source to the load during voltage sag condition

P_{sr}'= Power Injected by Series APF in such way that sum P_{sr}'+P_s' will be the required load power during normal working condition i.e. P_L

P_{sh}'= Power absorbed by shunt APF during voltage sag condition

$P_{sr}' = P_{sh}'$

This active power flows from the source to shunt APF, from shunt APF to series APF via dc link and finally from series APF to the load. Thus the load would get the desired power even during voltage sag condition. Therefore in such cases the active power absorbed by shunt APF from the source is equal to the active power supplied by the series APF to the load. The overall active power flow is shown in Fig. 4.6.

Case III

If $k > 0$, i.e. $v_t > v_l$, P_{sr} will be negative, this means series APF is absorbing the extra real power from the source. This is possible during the voltage swell condition. i_s will be less than the normal rated current. Since v_s is increased, the dc link voltage can increase. To maintain the dc link voltage at constant level the shunt APF controller reduces the current drawn from the supply. In other words we can say that the UPQC feeds back the extra power to the supply system. The overall active power flow is shown in Fig. 4.7 [31]

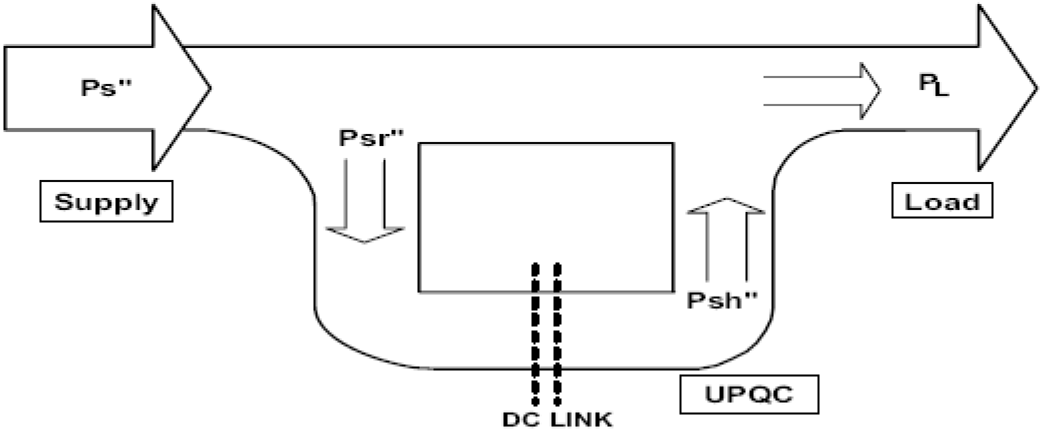


Figure 4.7: Active Power Flow during Voltage Swell Condition

P_s"= Power Supplied by the source to the load during voltage swell condition

P_{sr}"= Power Injected by Series APF in such way that sum Ps"-Psr" will be the required load power during normal working condition

P_{sh}"= Power delivered by shunt APF during voltage sag condition

P_{sr}"=P_{sh}"

Case IV

If $k = 0$, i.e. $v_t = v_l$, then there will not be any real power exchange though UPQC. This is the normal operating condition. The overall active power flow is shown in Fig. 4.8.

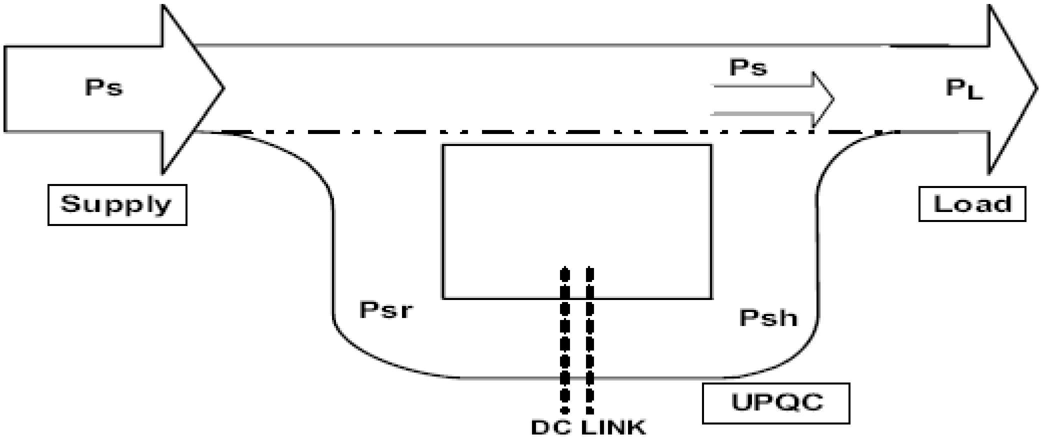
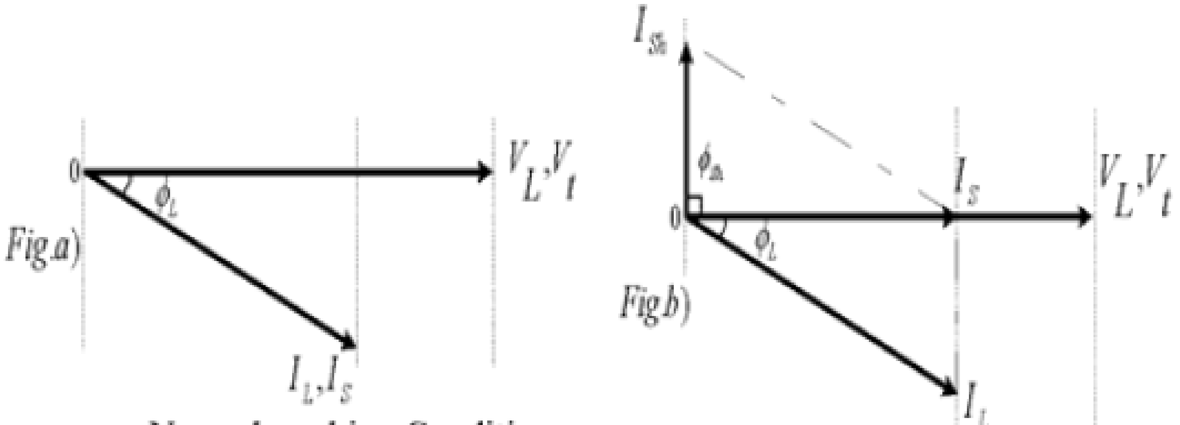


Figure 4.8: Active Power Flow during Normal Working Condition

The phasor representations of the above discussed conditions are shown in the Fig. 4.9 (a) – (d). Phasor 4.9(a) represents the normal working condition, considering load voltage v_l as a reference phasor. ϕ_l is lagging power factor angle of the load. During this condition i_s will be exactly equal to the i_l since no compensation is provided. When shunt APF is put into the operation, it supplies the required load VARs by injecting the leading current such that the source current will be in phase with the terminal voltage. The phasor representing this is shown in Fig. 4.9 (b). The phasor representations during voltage sag and voltage swell condition on the system are shown in the Fig. 4.9 (c) and Fig. 4.9 (d) respectively. The deviation of shunt compensating current phasor from quadrature relationship with terminal voltage suggests that there is some active power flowing through the shunt APF during these conditions [31].



Normal working Condition, without any compensation

Shunt APF ON

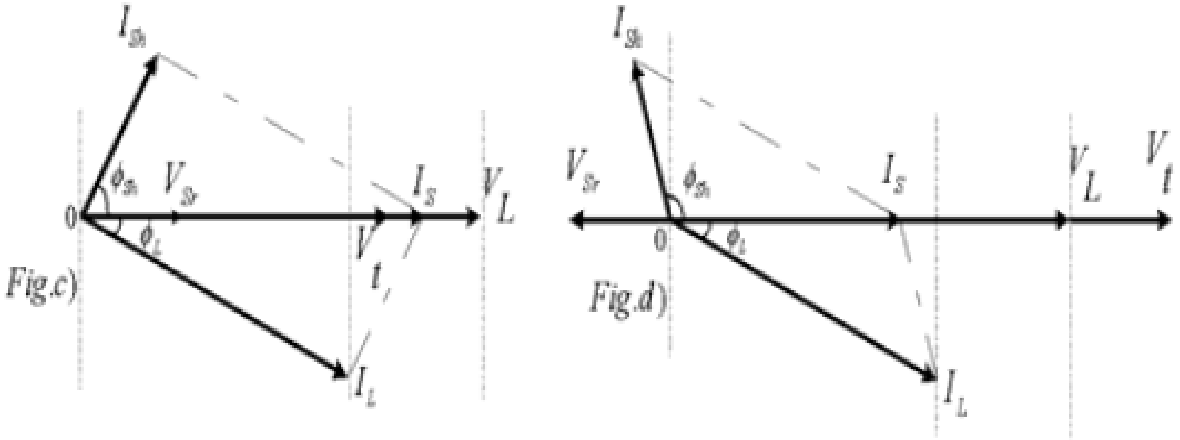


Figure 4.9 a) – d): Phasor Representation of all Possible Conditions

In normal operating condition, the shunt APF provides the load VAR, whereas, series APF handles no active or reactive power, so in this case the rating of series APF should be be small fraction of load rating. The shunt APF rating mainly depends on the compensating current provided by it, which depends on the load power factor or load VAR requirement. Lower the load power factor or higher the load VAR demand, higher would be the shunt APF rating. For the series APF rating depends on two factors; source current i_s and factor k. The current i_s increases during voltage sag condition whereas decreases during voltage swell condition. Therefore the rating of series APF is considerably affected by the % of sag need to be compensated. Since during voltage sag condition the increased source current flows through shunt APF, increasing the shunt APF rating too. Moreover, the shunt APF rating further affected during voltage sag / swell compensation, since it has to maintain the dc link voltage at constant level, which is done by taking requisite amount of active power from the source. A compromise can be made while considering shunt and series APF device ratings, which directly affects the sag/swell compensation capability of UPQC.

4.6 Functions performed by UPQC

- convert the feeder (system) current into balanced sinusoids through the shunt compensator.
- convert the load voltage VL to balanced sinusoids through the series compensator.
- ensure zero real power injection (and/or absorption) by the compensators.
- supply reactive power to the load (Q compensation).

4.7 Control Philosophy

A controller is required to control the working of UPQC whenever any fault there for this purpose pi controller is used.

For DVR control load voltage is sensed and passed through a sequence analyzer. The magnitude of the actual voltage is compared with reference voltage (V_{ref}).Pulse width modulation (PWM) control system is applied for inverter switching so as to generate a three phase sinusoidal voltage at the load terminals. Chopping frequency is in the range of a few KHz. The IGBT inverter is controlled with PI controller in order to maintain 1p.u. voltage at the load terminals. PI controller input is an actuating signal which is the difference between the V_{ref} and V_{in}.

For STATCOM control load current is sensed and passed through a sequence analyzer. The magnitude of the actual current is compared with reference current (I_{ref}).Pulse width modulation (PWM) control system is applied for inverter switching so as to generate a three phase sinusoidal current at the load terminals. Chopping frequency is in the range of a few kHz. The IGBT inverter is controlled with PI controller in order to maintain 1p.u. current at the load terminals. PI controller input is an actuating signal which is the difference between the I_{ref} and I_{in}.

4.8 Introduction to PI controller

A PI-Lead controller is a proportional gain in parallel with an integrator; both in series with a lead controller. The proportional gain provides fast error response. The integrator drives the system to a steady-state error. PI controller is one of the most widely sought after controller in industry as it is the simplest to design. [26]

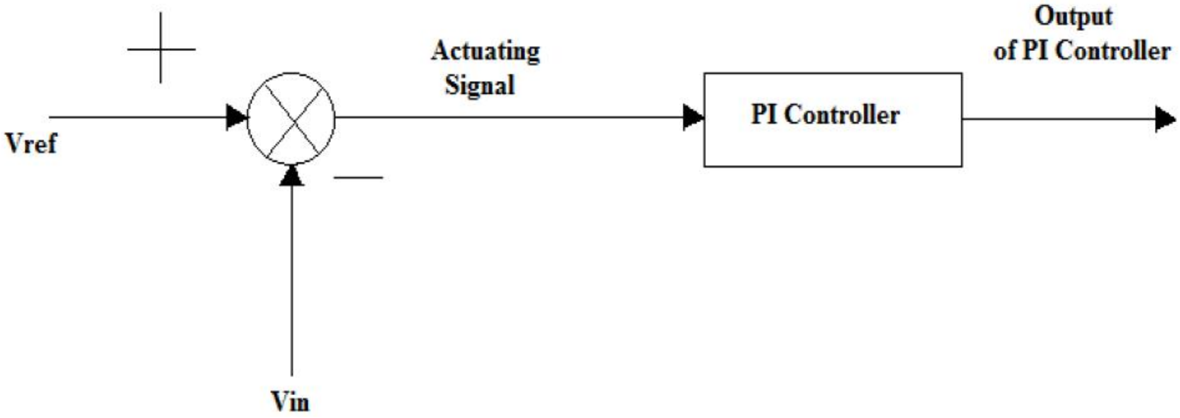


Figure 4.10: PI controller

The overview of PI controller is given below:

Proportional (Gain)

'P' is Proportional control in which the output varies based on how far you are from your target. The error is multiplied by a negative (for reverse action) proportional constant P, and added to the current output. P represents the band over which a controller's output is proportional to the error of the system. E.g. for a heater, a controller with a proportional band of 10 deg C and a set point of 100 deg C would have an output of 100% up to 90 deg C, 50% at 95 Deg C and 10% at 99 deg C. If the temperature overshoots the set point value, the heating power would be cut back further. Proportional only control can provide a stable process temperature but there will always be an error between the required set point and the actual process temperature.

Integral (Reset)

'I' is an Integral control in which the output varies based on how long it's taking you to get to your target. The error is integrated (averaged) over a period of time, and then multiplied by a constant 'I', and added to the current control output. 'I' represent the steady state error of the system and will remove set point / measured value errors. For many applications Proportional + Integral control will be satisfactory with good stability and at the desired set point.

Advantages and Disadvantages

To eliminate the offset, should be adjusted and reach a constant value when error becomes zero.

- The integral mode will change the bias value until the error becomes zero eliminate offset
- The action is not immediate until the integral becomes significant. Also, the integral mode tends the system to be more oscillatory, even unstable.

Advantages are Fast action, eliminate the offset.

Disadvantage are Oscillatory or unstable with integral control, one more parameter to tune.

4.9 Single Line Diagram of the UPQC Test System

It was observed from the literature Survey that, the field of power quality and custom power devices plays an important role in power system. UPQC is one of the custom power device used in distribution system for the improvement of power quality. Different type of controller namely fuzzy, hysteresis, PI, and PID are reported in literature to compensate various PQ problems. In this work, PI controller is used for controlling the UPQC.

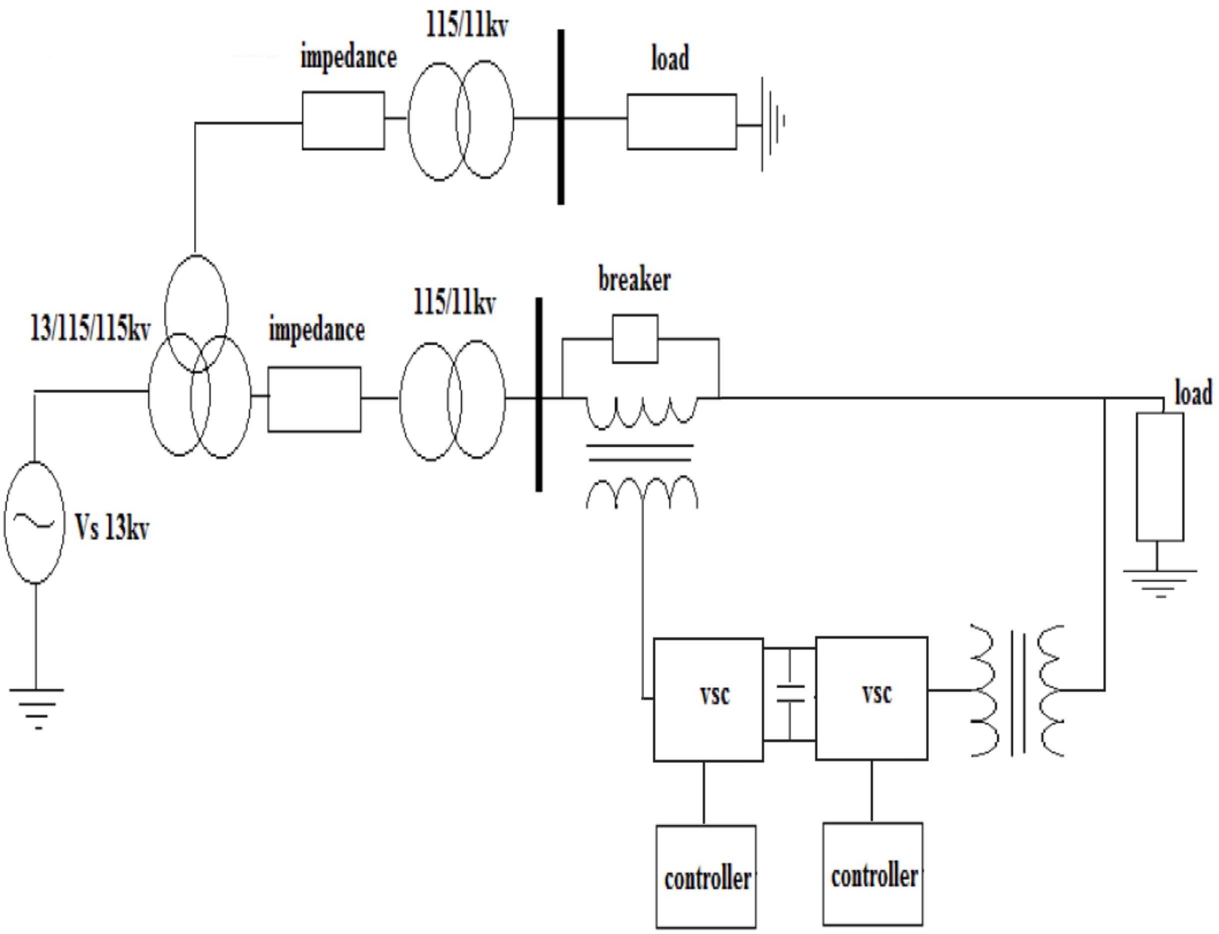


Figure 4.11: Circuit Model of UPQC Test System

In this system, the generating unit is of 13kV, 50 Hz. Test System employed to carry out the simulations concerning the UPQC Actuation. The output from generating unit is fed to the primary of the three winding transformer. Further two parallel feeders of 11kV each are drawn. In one of the feeders UPQC is connected and other feeder is kept as it is. For this system ASD load is considered and different fault conditions LL, LLG and LLLG are tested on this system. PI controller is used for the control section.

CHAPTER 5

SIMULATION AND RESULTS

In this work, the role of Unified power quality conditioner for power quality improvement of following distribution networks is carried out:

- Distribution network having adjustable speed drive load i.e. field oriented induction motor.
- Distribution network having field oriented control induction motor as load during fault conditions.

5.1 Introduction to Induction motor as an Adjustable speed drive

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 pre sag speed. During the re-acceleration the motor will again absorb a large current. This post sag 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 [13,14].

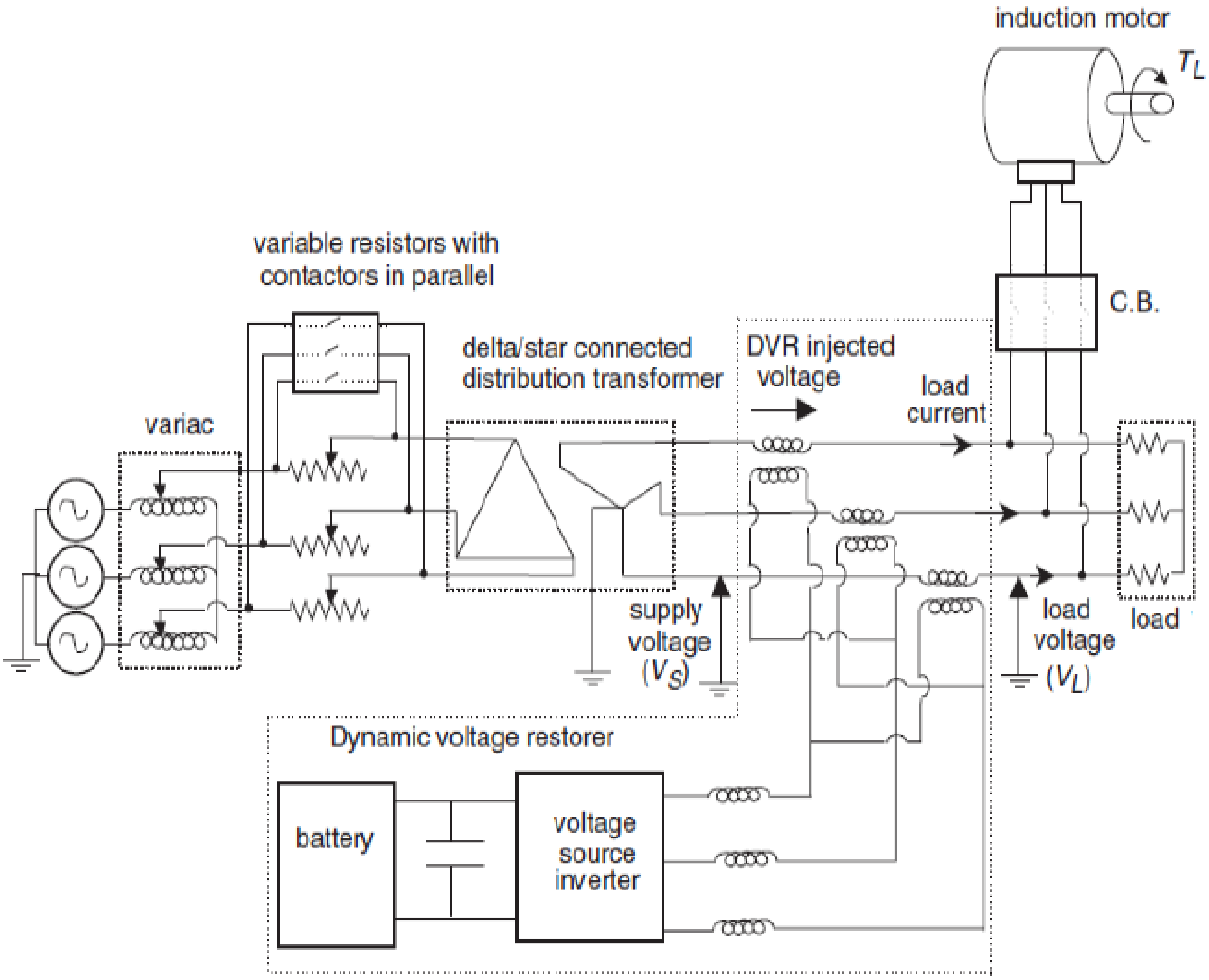


Figure 5.1: Experimental Set-up Using Induction Motor Load

5.2 When Field-Oriented Control Induction Motor Drive is used as load

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:

$$m \propto \Psi_R \, i_{sq} \tag{5.1}$$

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 Parameters of test system for field oriented control induction motor load

Simulation model of UPQC using pi controller and field oriented control induction motor as load is shown in Fig.5.2. System parameters of test system are listed in Table 1.

Table 5.1: System Parameters for field oriented control induction motor load

S. No.	System Quantities	Standards
1	Source	3-phase, 13kV, 50Hz
2	Inverter parameters	IGBT based, 3-arm, 6-Pulse, Carrier Frequency=1080 Hz, Sample Time=5 μs
3	PI controller	K_P=0.5, K_i=1000 for series control K_p=0.5, K_i=1000 for shunt control, Sample time=50 μs
4	RL load	Active power = 1kW, Inductive Reactive Power=400 VAR
5	Motor load	Voltage V_{rms}=11kV, Frequency 50 Hz
6	Transformer1	Y/Δ/Δ 13/115/115kV
7	Transformer2	Δ/Y 115/11kV

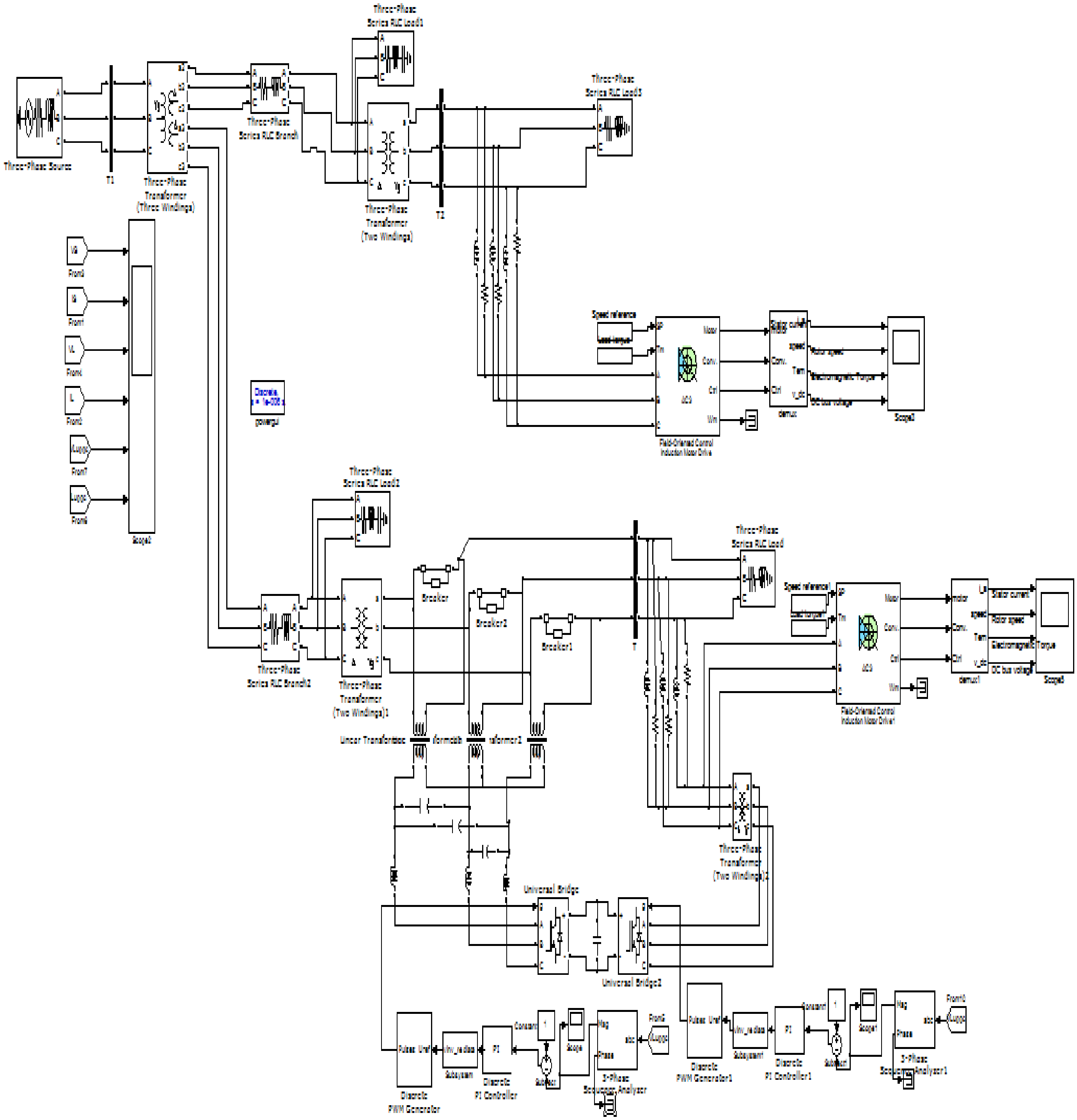


Figure 5.2: MATLAB Simulink model of UPQC using field oriented control induction motor drive

5.2.2 Results when Field oriented control induction motor drive is used as load

An ideal three-phase sinusoidal supply voltage is applied to the non-linear load (Field oriented control Induction motor drive) injecting current and voltage harmonics into the system. Figure 5.3(a) shows load current in three-phase before compensation Figure 5.3(b) shows THD level for uncompensated load current. Figure 5.4(a) shows the load current for compensated system Figure 5.4(b) shows THD level for compensated load current. Figure5.5(a) shows load voltage in three-phase before compensation Figure 5.5(b) shows THD level for uncompensated load voltage. Figure 5.7(a) shows the load voltage for compensated system Figure 5.6(b) shows THD level for compensated load voltage.

The Total Harmonic Distortion (THD) for load current which was 23.14% in Figure5.3(b) before compensation and effectively reduces to 4.87 % in Fig. 5.4(b) after compensation using PI controller. Shunt inverter is able to reduce the harmonics entering into the system. The Total Harmonic Distortion (THD) for load voltage which was 13.58% in Fig.5.5(b) before compensation and effectively reduces to 7.85 % in Fig.5.6(b) after compensation using PI controller. The voltage compensation is small because system consists of transformers which are already doing compensation for voltage.

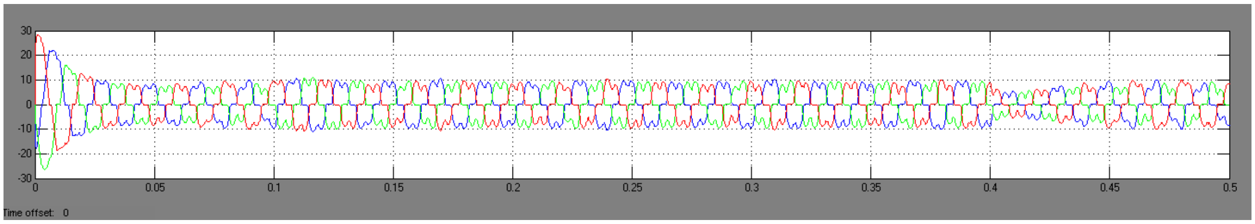


Figure 5.3(a) Current waveform without UPQC

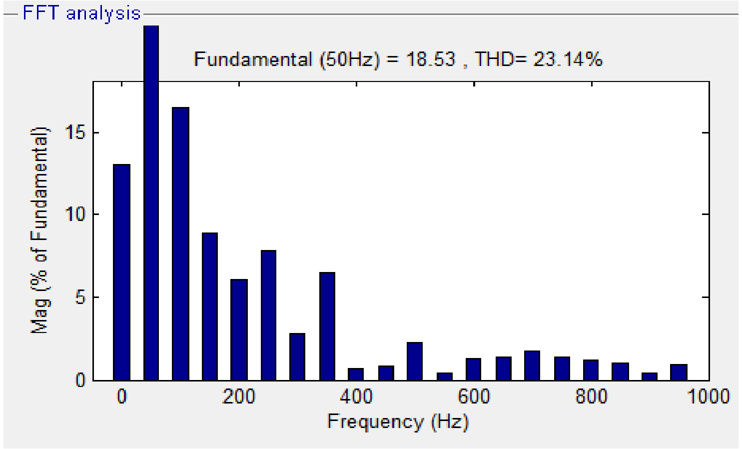


Figure 5.3(b) Total harmonic distortion without UPQC for current

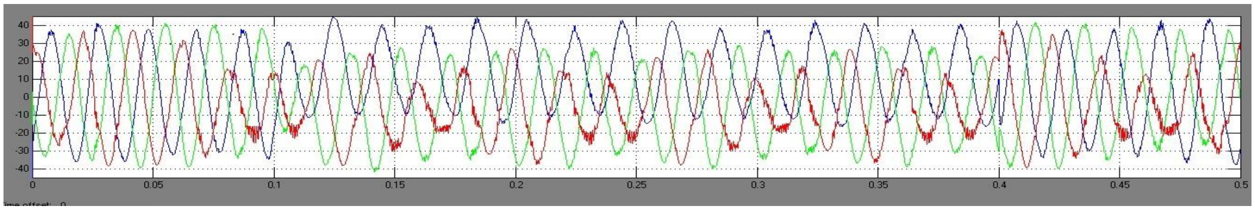


Figure 5.4(a) Current waveform with UPQC

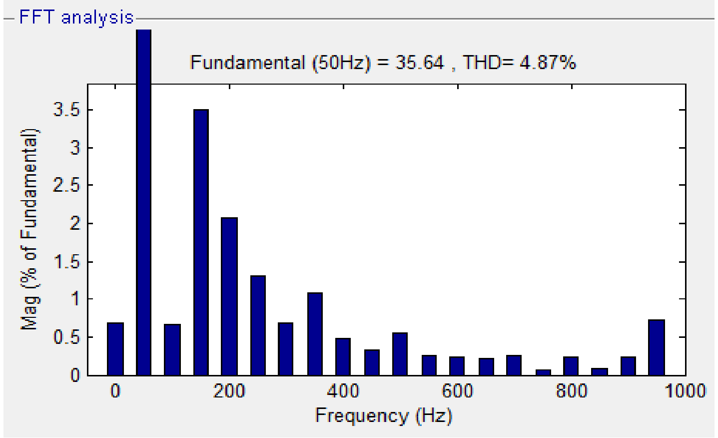


Figure 5.4(b) Total harmonic distortion with UPQC for current

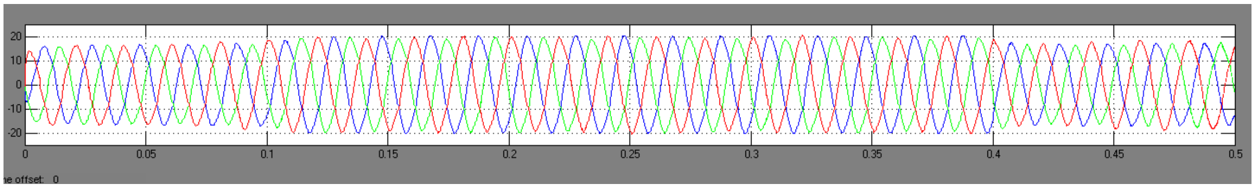


Figure 5.5(a) Voltage waveform without UPQC

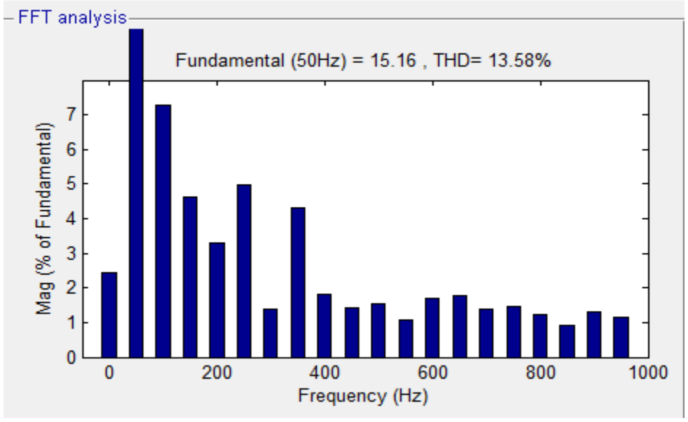


Figure 5.5(b) Total harmonic distortion without UPQC for voltage

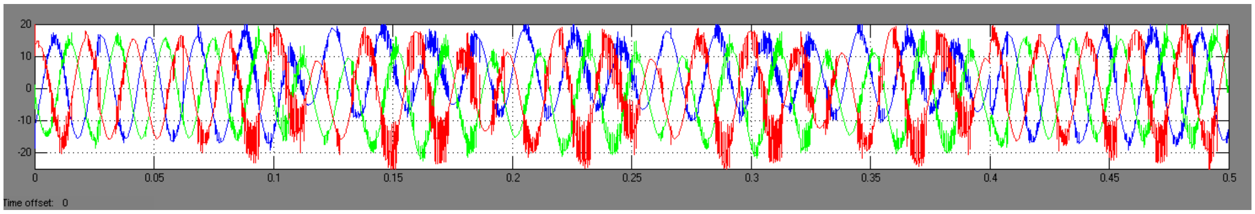


Figure 5.6(a) Voltage waveform with UPQC

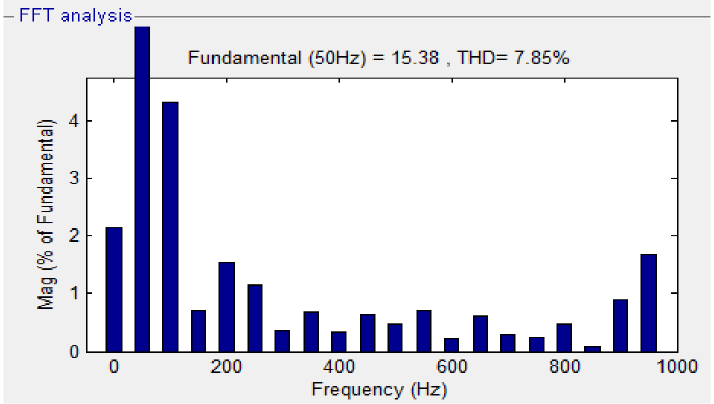


Figure 5.6(b) Total harmonic distortion with UPQC for voltage

5.3 Results under Different Fault Conditions

Three different fault conditions are considered for the test system as shown in Figure-5.7. Test System consist of Adjustable speed drive that is field oriented control induction motor and the controller used is a proportional integral controller. The faults that occur in the system are tested. It may be LG fault which mostly occur or LLG and LLLG fault which occur rarely in the system. The three different fault conditions are single line to ground, double line to ground and three phase line to ground fault. The results for each fault condition are given one by one.

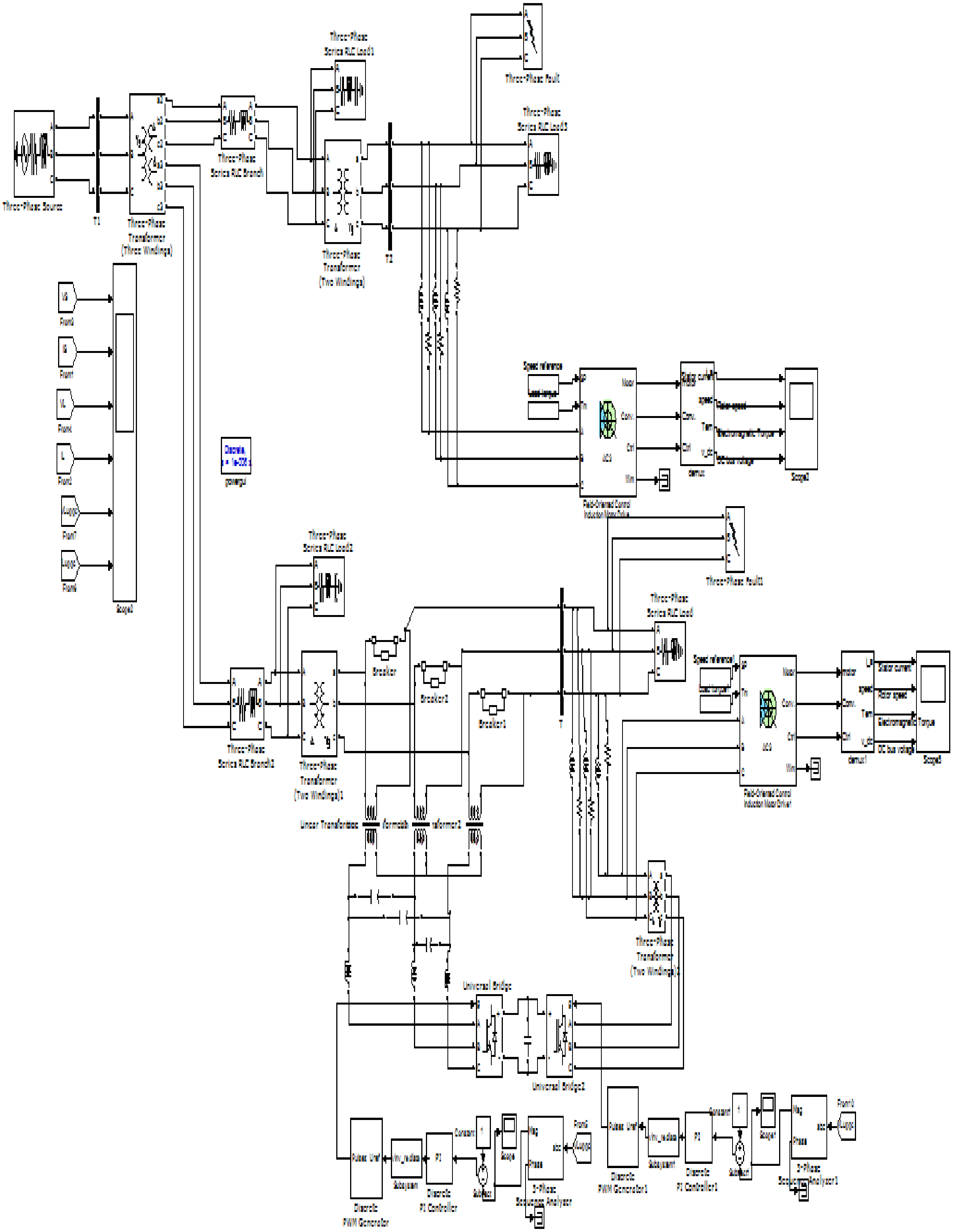


Figure 5.7: MATLAB Simulink model of UPQC using field oriented control induction motor drive during fault conditions

5.3.1 Single Line to Ground Fault Condition

In first case a single line to ground fault is considered for both the feeders. Here the fault resistance is 0.001 ohm and the ground resistance is 0.001 ohm. The fault is created for the duration of 0.05s to 0.15s. The output waveform for the load voltage without compensation is shown in Figure-5.8 (a) and with compensation is shown in Figure-5.8 (b). The output waveform for the load current without compensation is shown in Figure-5.9 (a) and compensation is shown in Figure-5.9 (b).

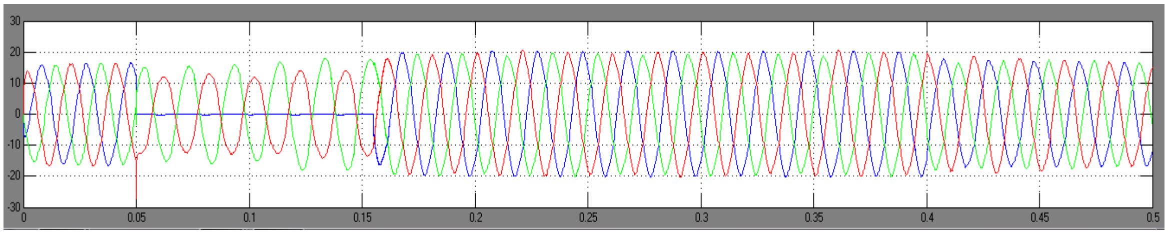


Figure 5.8(a) Voltage waveform without UPQC during LG fault

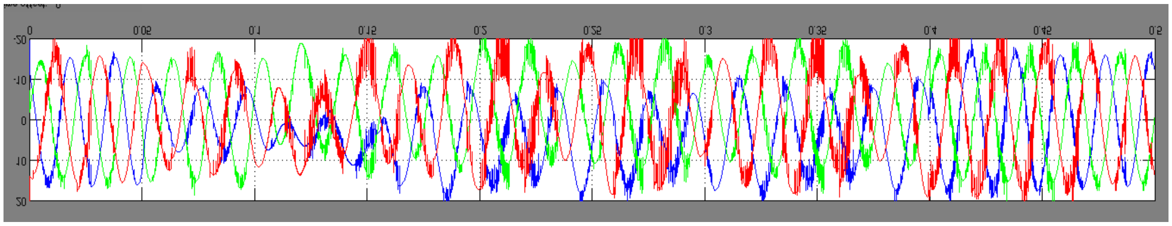


Figure 5.8(b) Voltage waveform with UPQC during LG fault

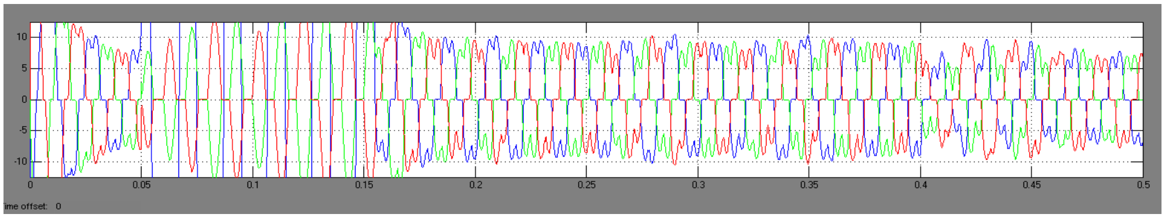


Figure 5.9(a) Current waveform without UPQC during LG fault

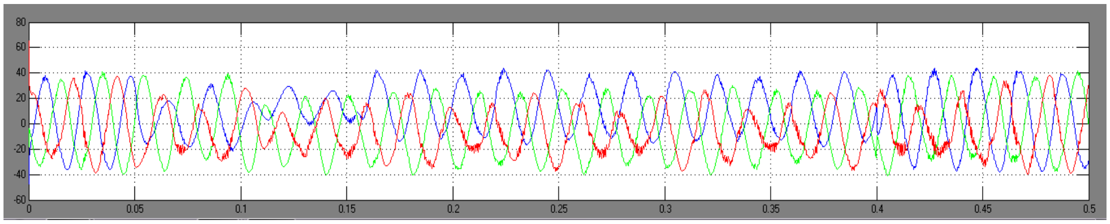


Figure 5.9(b) Current waveform with UPQC during LG fault

Here it is clear from the output wave shapes that the voltage in the phase where fault is created is decreasing and current in the phase where fault is created is increasing during the fault duration in the uncompensated feeder. So, here the unbalancing in the system where UPQC is connected is reduced clearly.

5.3.2 Double Line to Ground Fault Condition

In second case a double line to ground fault is considered for both the feeders. Here the fault resistance is 0.001 ohm and the ground resistance is 0.001 ohm. The fault is created for the duration of 0.05s to 0.15s. The output waveform for the load voltage without compensation is shown in Figure-5.10 (a) and with compensation is shown in Figure-5.10 (b). The output waveform for the load current without compensation is shown in Figure-5.11 (a) and compensation is shown in Figure-5.11 (b).

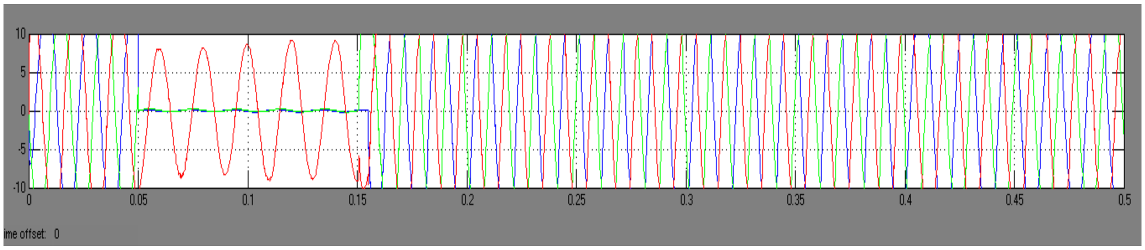


Figure 5.10(a) Voltage waveform without UPQC during LLG fault

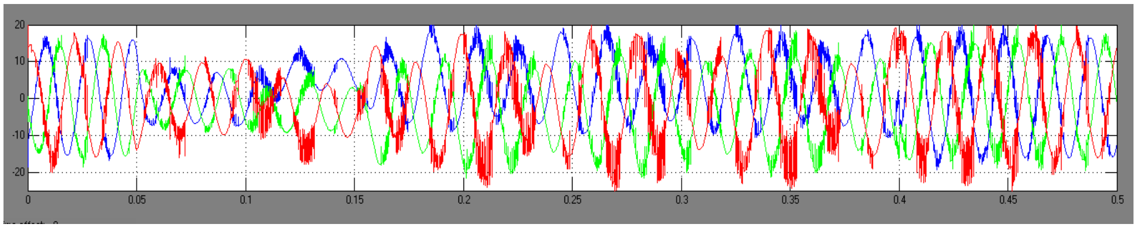


Figure 5.10(b) Voltage waveform with UPQC during LLG fault

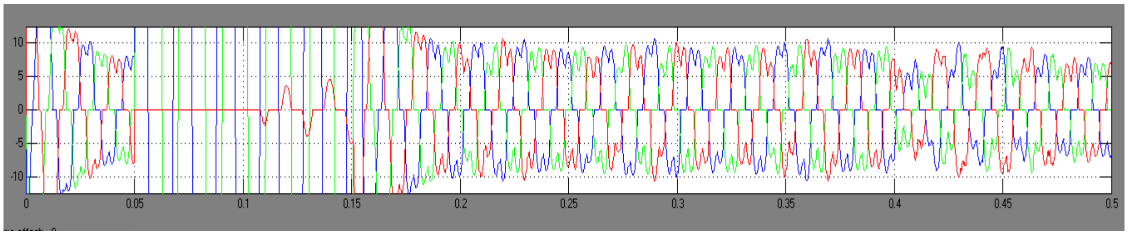


Figure 5.11(a) Current waveform without UPQC during LLG fault

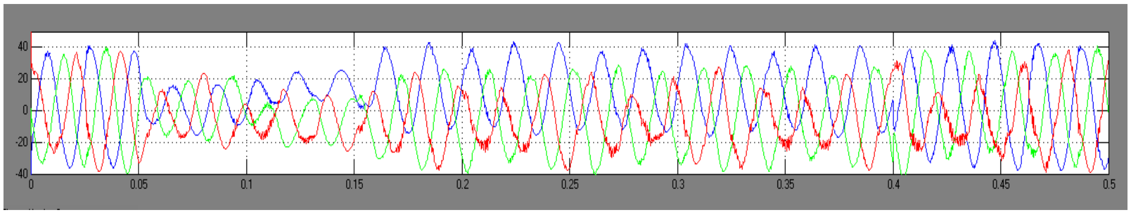


Figure 5.11(b) Current waveform with UPQC during LLG fault

Here it is clear from the output wave shapes that the voltage in the phase where fault is created is decreasing and current in the phase where fault is created is increasing during the fault duration in the uncompensated feeder. So, here the unbalancing in the system where UPQC is connected is reduced clearly.

5.3.3 Three Phase Line to Ground Fault Condition

In third case a three phase line to ground fault is considered for both the feeders. Here the fault resistance is 0.001 ohm and the ground resistance is 0.001 ohm. The fault is created for the duration of 0.05s to 0.15s. The output waveform for the load voltage without compensation is shown in Figure-5.12 (a) and with compensation is shown in Figure-5.12 (b). The output waveform for the load current without compensation is shown in Figure-5.13 (a) and compensation is shown in Figure-5.13 (b).

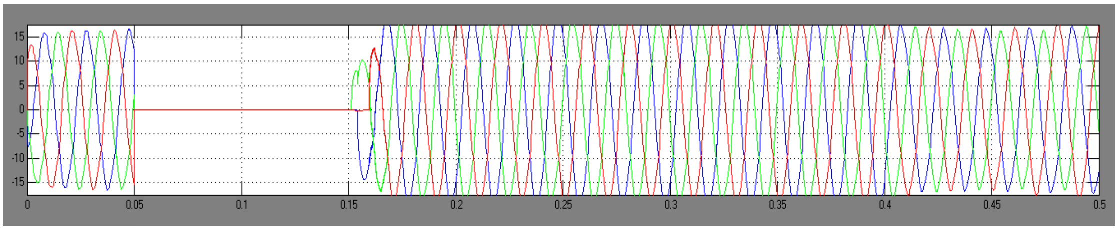


Figure 5.12(a) Voltage waveform without UPQC during LLLG fault

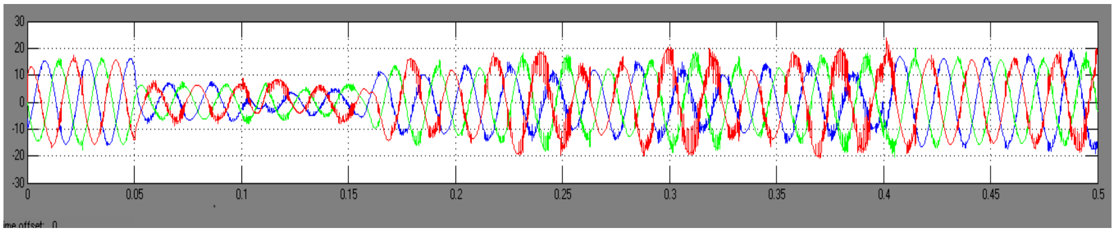


Figure 5.12(b) Voltage waveform with UPQC during LLLG fault

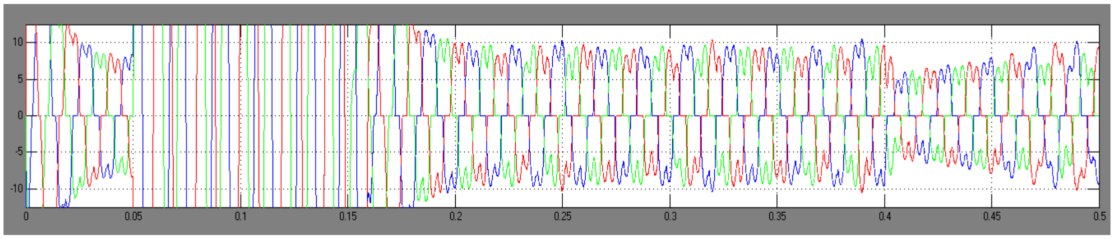


Figure 5.13(a) Current waveform without UPQC during LLLG fault

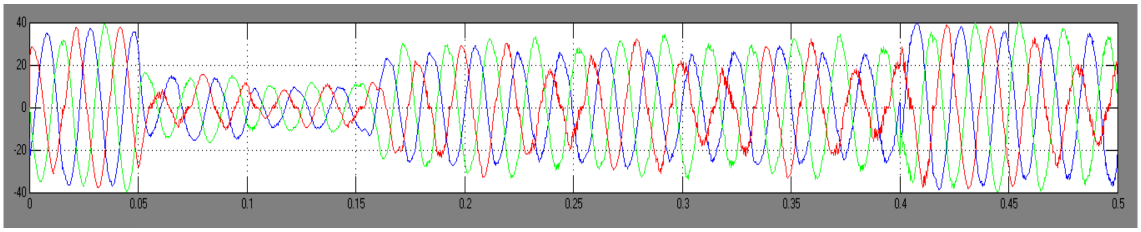


Figure 5.13(b) Current waveform with UPQC during LLLG fault

Here it is clear from the output wave shapes that the voltage in the phase where fault is created is decreasing and current in the phase where fault is created is increasing during the fault duration in the uncompensated feeder. So, here the unbalancing in the system where UPQC is connected is reduced clearly.

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 reducing the distortion level occurring in the cases of harmonics generating loads in distribution networks and highly improving the power quality of the system.

In order to protect critical loads from more voltage harmonics and current harmonics in the distribution network, the UPQC i.e., series connected voltage-source converter known as Dynamic Voltage Restorer and shunt connected voltage-source converter known as Dstatcom is suitable and satisfactory. Due to its reliability it was adopted as the optimal solution for the compensation of voltage and current.

The MATLAB/SIMULINK were used to carry out extensive simulation studies on unified power quality conditioner and for the controlling purpose the proportional integral controller is used and adjustable speed drive is used as a load . Therefore, UPQC is considered to be an efficient solution. Unified power quality conditioner is capable of reducing the level of THD in the case of networks which are connected to the harmonics generating load (like ASD). All type of faults (single line to ground, double line to ground, three phase line to ground fault are also compensated using UPQC.

6.2 Future Work

The presented work can be extended in other following related areas:

- The load in the test system can be replaced by some other load example turbine load, electric furnace.
- The more advanced controllers such as fuzzy controller, artificial neutral network, instantaneous power theory can also be used with UPQC to make the system more effective.
- Effectiveness of multi-level UPQC can be investigated.

[1] C. Sankaran, “Power Quality”, CRC Press LLC, 2002.

[2] Alexander Kusko and Marc T.Thompson, “Power Quality in Electrical Systems”, McGraw-Hill, 2007.

[3] Roger C. Dugan, Mark F. McGranaghan, Surya Santoso and H.Wayne Beaty, “Electrical Power Systems Quality”, The McGraw-Hill, Second Edition, 2004.

[4] K. R. Padiyar, “Facts Controllers in Power Transmission and Distribution”, New Age International Publishers, 2007.

[5] H. Hingorani, “Introducing Custom Power” IEEE Spectrum, Vol.32, Issue: 6, Page(s): 41-48, June 1995.

[6] Juan W. Dixon, Gustavo Venegas and Luis A. Moran, “A Series Active Power Filter Based on a Sinusoidal Current-Controlled Voltage-Source Inverter” IEEE Transactions on Industrial Electronics, Vol. 44, Issue: 5, Page(s): 612 - 620, October 1997.

[7] Yash Pal, A. Swarup, and Bhim Singh, “A Review of Compensating Type Custom Power Devices for Power Quality Improvement” 2008 Joint International Conference on Power System Technology (POWERCON) and IEEE Power India Conference New Delhi, India Page(s): 1 - 8, October 2008.

[8] Arindam Ghosh and Gerard ledwhich, “Power Quality Enhancement Using Custom Power Devices”, Kluwer Academic Publishers, 2002.

[9] Angelo Baggini, “Handbook of Power Quality”, John Wiley & Sons Ltd, 2008.

[10] T. A. Short, “Distribution Reliability and Power Quality”, Taylor & Francis Group, CRC Press, 2006, June 2009.

[11] Mojtaba Nemati, Hesam Addin Yousefian and Rouhollah Afshari, “Recognize the Role of DVR in Power Systems”, International Journal of Recent Trends in Engineering, Vol. 2, Page(s): 13 - 15, November 2009.

[12] J. Barros, M. de Apraiz, and R. I. Diego, “Measurement of Subharmonics In Power Voltages”, Power Tech, IEEE Lausanne, Page(s): 1736 – 1740, 2007.

[13] Mahesh Singh and Vaibhav Tiwari, “Modeling analysis and solution of Power Quality Problems”, http://eeeic.org/proc/papers/50.pdf.

[14] Chellali Benachaiba and Brahim Ferdi, “Voltage Quality Improvement Using DVR”, Electrical Power Quality and Utilisation, Journal Vol. XIV, No. 1, 2008.

[15] R.N.Bhargavi, “Power Quality Improvement Using Interline Unified Power Quality Conditioner”, 10th International Conference on Environment and Electrical Engineering (EEEIC), Page(s): 1 - 5, 2011.

[16] K. Palanisamy, J Sukumar Mishra, I. Jacob Raglend and D. P. Kothari, “Instantaneous Power Theory Based Unified Power Quality Conditioner (UPQC)”, 25th Annual IEEE Conference on Applied Power Electronics Conference and Exposition (APEC), Page(s): 374 – 379, 2010.

[17] G. Siva Kumar, P. Harsha Vardhana and B. Kalyan Kumar, “Minimization of VA Loading of Unified Power Quality Conditioner (UPQC)”, Conference on POWERENG 2009 Lisbon, Portugal, Page(s): 552 - 557, 2009.

[18] V. Khadkikar , A. Chandra, A.O. Barry and T.D Nguyen, “Conceptual Study of Unified Power Quality Conditioner (UPQC),” IEEE International Symposium on Industrial Electronics, Vol. 2, Page(s): 1088 –1093, 2006.

[19] V. Khadkikar , A. Chandra, A.O. Barry and T.D. Nguyen, “Power quality enhancement utilising single-phase unified power quality conditioner: digital signal processor-based experimental validation” Conference on Power Electronics, Vol. 4, Page(s): 323 –331, 2011.

[20] M. Faridi, H. Maeiiat, M. Karimi, P. Farhadi and H. Mosleh, “Power System Stability Enhancement Using Static Synchronous Series Compensator (SSSC)” Conference on Computer Research and Development (ICCRD) Vol. 3, Page(s): 387 – 391, 2011.

[21] B. Singh, V. Verma, A. Chandra and K. Al-Haddad, “Hybrid Filters for Power Quality Improvement”, IEE Proceedings- Generation, Transmission and Distribution”, Vol.152, Page(s): 365 - 375, 2005.

[22] V. Khadkikar , A. Chandra, A.O. Barry and T.D.Nguyen, "Application of UPQC to Protect a Sensitive Load on a Polluted Distribution Network", IEEE PES General Meeting, 2006.

[23] Ahmed M. A. Haidar, Chellali Benachaiba, Faisal A. F. Ibrahim and Kamarul Hawari, “Parameters Evaluation of Unified Power Quality Conditioner”, IEEE International Conference on Electro/Information Technology (EIT), page(s):1 - 6, 2011.

[24] M. Tarafdar Haque, and S.H. Hosseini, "A Novel Strategy for Unified Power Quality Conditioner (UPQC)", Conference on Proceedings of Power Electronics Specialists, Vol. 1, Page(s): 94 - 98, June 2002.

[25] Jiangyuan Le, Yunxiang Xie, Zhang Zhi and Cheng Lin, “A Nonlinear control strategy for UPQC”, International Conference on Electrical Machines and Systems, Page(s): 2067 - 2070, 2008.

[26] Sai Shankar, Ashwani Kumar and W. Gao, “Operation of Unified Power Quality Conditioner under Different Situations”, IEEE Power and Energy Society General Meeting, Page(s): 1 - 10, 2011.

[27] A. Mokhtatpour and H.A. Shayanfar “Power Quality Compensation as Well as Power Flow Control Using of Unified Power Quality Conditioner”, Asia- Pacific Power and Energy Engineering Conference (APPEEC), Page(s): 1 - 4, 2011.

[28] Metin Kesler and Engin Ozdemir “A Novel Control Method for Unified Power Quality Conditioner (UPQC) Under Non-Ideal Mains Voltage and Unbalanced Load Conditions”, 25th Annual IEEE Applied Power Electronics Conference and Exposition (APEC), Page(s): 374 – 379, 2010.

[29] Luis F.C. Monteiro, Mauricio Aredes and Joao A. Moor Neto “A Control Strategy for Unified Power Quality Conditioner”, IEEE International Symposium on Industrial Electronics, vol. 1, Page(s): 391 - 396, 2003.

[30] R.V.D. Rama Rao, Subhransu and Sekhar Dash, “Power Quality Enhancement by Unified Power Quality Conditioner Using ANN with Hysteresis Control” International Journal of Computer Applications (0975 – 8887) Vol. 6, Page(s): 9-15, Sep. 2010.

[31] Subramanian Muthu and Jonathan M. S. Kim “Steady-State Operating Characteristics of Unified Active Power Filters”, twelfth annual Applied Power Electronics Conference and Exposition, 1997, APEC '97 Vol. 1, Page(s): 199 - 205 vol.1, Feb 1997.

[32] V. Khadkikar, A. Chandra, A. O. Barry and T. D. Nguyen “Analysis of Power Flow in UPQC during Voltage Sag and Swell Conditions for Selection of Device Ratings”, Canadian Conference on Electrical and Computer Engineering, Montreal, Page(s): 867 -872, May 2006.