POWER QUALITY IMPROVEMENT IN DISTRIBUTION NETWORKS USING OPEN UPQC

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CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled **"Investigations on the Role of open Unified Power Quality Controller for Power quality improvement of Distributions Networks"**, 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

In 20th century the expansion of power system and electronic devices has been grown at very fast rate. The most noticeable for electrical engineer is Power Quality in recent years. Power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure or a misoperation of end user equipment. With Power quality Problem utility distribution networks, industrial load, sensitive load etc are suffered. With the restructuring of power systems and with shifting trend towards distributed and dispersed generation, the issue of power quality is going to take new dimensions. To overcome the problem related to power quality Custom power devices are introduced.

A number of power quality solutions are provided by Custom power devices .At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components are emerging for custom power applications. Among these, The 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 UPQC is used to compensate deep voltage sags, voltage unbalances and harmonics. It is efficiently capable of protecting sensitive loads against the voltage variations or disturbances. 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

AC	Alternate Current
APF	Active Power Filters
BESS	Battery Energy Storage Systems
DC	Direct Current
DFACTS	Distribution FACTS
DSP	Digital Signal Processing
DSTATCOM	Distribution Static Synchronous Compensators
DTC	Direct Torque control
DVR	Dynamic Voltage Restorer
FACTS	Flexible AC Transmission Systems
FFT	Fast Fourier Transform
FOC	Field Orientated Control
FT	Fourier Transform
GTO	Gate Turn- Off Thyristors
HVDC	High Voltage Direct Current
IEC	International Electro technical Commission
IEEE	Institute of Electrical and Electronic Engineers
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 PWM (pulse width modulation)
SA	Surge Arresters
SMES	Super Conducting Magnetic Energy Systems
SPWM	Sinusoidal Pulse Width Modulation
SSCL	Solid State Current Limiter
SSFCL	Solid State Fault Current Limiter
SSSC	Static Synchronous Series Compensator
SSTS	Solid State Transfer Switch
SVC	Static Var Compensator
SVPWM	Space Vector Pulse Width Modulation
THD	Total Harmonic Distortion
UPFC	Unified Power Flow Controller
UPQC	Unified Power Quality Conditioner
UPS	Uninterruptible Power Supplies
USSC	Unified Series-Shunt Controller

LIST OF SYMBOLS

δ	Phase Angle Jump
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
kHz	Kilo Hertz
kV	Kilo Volt
kVA	Kilo Volt Ampere
kVAR	Kilo Volt Ampere Reactive
m	Torque
mH	Mille Henry
MHz	Mega Hertz
ms	Mille Second
MV/LV	Medium Voltage/Low Voltage
MVA	Mega Volt Ampere
Nm	Newton Meter
ns	Nano Second
Ø	Power Factor Angle
P	Active Power
pf	Power Factor
P_L	Active Power of Load
Pu	Per Unit
Q	Reactive Power
Q_L	Reactive Power of Load
R	Resistance
S	Apparent Power
V_L	Desired Load Voltage Magnitude
V_L	Load Voltage Magnitude
V_{ref}	1 p.u. Voltage
V_{rms}	RMS Voltage
V_s	Source Voltage during Sags/Swells Condition
X_L	Inductive Reactance
Z	Total Impedance
Ω	Ohm
λ	Failure Rate
V_{DVR}	Dynamically Controlled Voltage
V_{inj}	Injected Voltage
V	Volt

CHAPTER 1

INTRODUCTION

1.1 Overview

One of the main responsibilities of a utility system is to supply electric power in the form of sinusoidal and currents with appropriate magnitudes and frequency for the customers at the points of common coupling (PCC) .Although the generated voltage of synchronous machines in power plants are nearly sinusoidal ,some undesired conditions such as lightning and short circuit faults and non linear loads cause steady state error or transient voltages and current disturbances .For example ,electric arc furnaces cause voltage fluctuations, power electronic converters generate current harmonics and distort voltage waveforms, and short circuits faults result in voltage sags and swells [1-4]. On the other hand most customer loads such as computers, microcontrollers and hospital equipment are sensitive and unprotected to power quality disturbances and their proper operation depends on the quality of the voltage that is delivered to them.

This is possible only by ensuring an uninterrupted flow of power at proper voltage and frequency levels. As a result of this, the need of custom power devices. Custom power is a strategy, which is designed primarily to meet the requirements of industrial and commercial customer. The concept of custom power is to use power electronic or static controllers in the medium voltage distribution system aiming to supply reliable and high quality power to sensitive users . 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). But in this work, the main focus is kept only on OPEN Unified Power Quality Conditioner OPEN UPQC.

The open unified power quality conditioner (UPQC), composed of a power-electronic series main unit installed in the medium-voltage/low-voltage (LV) substation, along with several power-electronic shunt units connected close to the end users. The series and parallel units do not have a common dc link, so their control strategies are independent of each other.

1.2 Literature Survey

Power distribution systems should provide their customers with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency. However in power systems, especially the distribution systems, have many nonlinear loads, which significantly affect the quality of power supplies [1-4].

Power quality can be classified into three categories that is, voltage stability, continuity of supplying power, and voltage Based on this classification, several examples of power quality level definitions were presented by **Toshifiimi Ise** *et al.* [5].

Arindam Ghosh *et al.* [6] 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.

Juan W. Dixon *et al.* [7] 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.

H. Hingorani *et al.* [8] presented the term custom power means the use of power electronics controllers for distribution systems. The custom power increase 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.

T.Devaraju *et al.* [9] proposed that power quality problem is an occurrence manifested as a non standard voltage, current or frequency that results in a failure of equipments. Utility distribution networks, sensitive industrial loads, and critical commercial operations all suffer from various types of outages and service interruptions which can cost significant financial loss per incident based on process down-time, lost production, idle work forces, and other factors. In this electromagnetic transient studies are presented for the following two custom power controllers: the distribution static compensator (D-STATCOM), and the dynamic voltage restorer (DVR).

Olimpo Anaya-Lara *et al*. [10] demonstrated the timely issue of modelling and analysis of custom power controllers a new generation of power electronics-based equipment aimed at enhancing the reliability and quality of power flows in low-voltage distribution networks. Graphics-based models suitable for electromagnetic transient studies are presented for the following three custom power controllers: the distribution static compensator (D-STATCOM), the dynamic voltage restorer (DVR), and the solid-state transfer switch (SSTS).Comprehensive results are presented to assess the performance of each device as a potential custom power solution.

RVD Ram Rao *et al***.** [11] proposed the quality of power is effected 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.

Malabika Basu *et al.* [12] suggested that Unified Power Quality Conditioner (UPQC) is one of the major custom power solutions that is capable of mitigating the effect of supply voltage sag at the load end or the Point of Common Coupling (PCC). It also prevents load current harmonics from entering the utility and corrects the input power factor of the load. The control of series compensator is such that it injects voltage in quadrature advance to the supply current, so that no active power is consumed by the series compensator at steady state.

Gu Jianjun *et al.* [13] presented that the Unified power quality conditioner (UPQC), which aims at the integration of series-active and shunt-active power filters. The main purpose of a UPQC is to compensate for voltage imbalance, reactive power, negative-sequence current and harmonics.

Ke Dai *et al*. [14] presented a three-phase three-wire series-parallel compensated universal power quality conditioner based on two voltage-source converters controlled separately by two digital signal processors . Different from those popular active power filters, the series voltage-source converter is controlled as a fundamental sinusoidal current source in phase with the utility, while the parallel voltage-source converter is controlled as a fundamental sinusoidal voltage source with constant voltage and constant frequency. It is shown that the total harmonic distortion values of input current and output voltage are both less than 5% with almost unity input power factor, even in the case of distorted utility and feeding reactive and non-linear loads.

Jiangyuan Le *et al* .[15] presented 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.

Guozhu Chen *et al.* [16] proposed Unified Power Quality Conditioner (WQC) with One Cycle Control (OCC) to deal with most of the problems identified above as a whole. The proposed OCC-WQC consists of a serial three-phase three-leg and a parallel three-phase four-leg converter. The OCC-UPQC has the advantages of no reference calculation that results in simplicity, vector operation for reduced losses, modular approach with the flexibility **to** work in both three-wire or four-wire systems, in addition to the inherent features of fast transient response, high precision, constant switching frequency, etc.

Ahmed. M *et al.* [17] presented the term Power Quality is used to describe the electromagnetic phenomenon in variations of voltage and current in the power system. Currently, there are so many industries using a high technology for the manufacturing and requiring a high quality of power supply. Power quality disturbance and the technique used to improve the quality of delivered power such as Unified Power Quality Conditioner (UPQC).

Metin Kesler *et al.* [18] 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.

Hideaki Fujita *et al.* [19] presented the unified power quality conditioners (UPQCs) which aim at integration of series active filters and shunt active filters. The main purpose of a UPQC is to compensate for voltage flicker/imbalance, reactive power, negative sequence current, and harmonics. The UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems.

Arindam Ghosh *et al.* [20] discussed the operation and performance of a unified power quality conditioner (UPQC). A UPQC is a versatile device that can be used for various functions. The main aim of UPQC in such a way that it tightly regulates the bus voltage of critical loads against unbalance, harmonics, voltage sag/swell and other disturbances occurring in a distribution system.

M. Tarafdar Haque *et al.*[21] presented 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.

V.Khadkikar *et al.* [22] presented 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

A. Mokhtatpour *et al.* [23] 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. In UPQC control, Series Active Filter (SAF) is controlled by dqo approach for voltage sag, swell, interruption and harmonic compensation. Also, Parallel Active Filter (PAF) is controlled by composition of dqo and Fourier theories for current harmonic and reactive power compensation.

V. Khadkikar *et al*. [24] 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.

A.Kazemi *et al*. [25] presented a novel and easy to implement control strategy for unified power quality conditioner (UPQC). The control strategy of parallel active filter (PAF) is based on fourier transform theory, while the control circuit of series active filter (SAF) is based on positive sequence detection theory. Operating of PAF using this method compensates for reactive power and current harmonics, while operation of SAF compensates for imbalance, voltage harmonics and positive and zero sequence of utility voltages.

Luis F.C. Monteiro *et al*.[26] 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.

G. Siva Kumar *et al*. [27] presented 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

Morris Brenna *et al*. [28] presented the quality of supplied power is important to several customers. Power quality (PQ) is a service and many customers are ready to pay for it. A new device that can fulfill this role is the OPEN unified power quality conditioner

(UPQC), composed of a power-electronic series main unit installed in the medium-voltage/low-voltage (LV) substation, along with several power-electronic shunt units connected close to the end users. The series and parallel units do not have a common dc link, so their control strategies are independent of each other. This device can improvement in PQ, reducing the most common disturbances for all customers that are supplied by the mains (PQ) by using only the series unit. Therefore, this new simultaneously combine can improve the PQ and reduce the cost who needs high quality of power.

Sai Shankar *et al.* [29] presented the unified power quality conditioner (UPQC) is being used as a universal active power conditioning device to compensate both harmonics as well as reactive power. The UPQC has been modeled for both active and reactive power compensation using different control strategies. The behavior of UPQC has been analyzed with sudden switching of R-L loads, and R-C loads as well as occurrences of different shunt fault. The control scheme has been devised using PI controller in UPQC for real and reactive power control, and operation in case of switching and faults in transmission systems.

M. Vasudevan *et al.* [30] presented a detailed comparison between adaptive intelligent torque control strategies of induction motor, emphasizing advantages and disadvantages. Induction motors are characterized by complex, highly non-linear, time varying dynamics and hence can be considered as a challenging engineering problem. The advent of torque and flux control techniques have partially solved induction motor control problems, because they are sensitive to drive parameter variations and performance may deteriorate if conventional controllers are used. . In this the performance of the various sensor less intelligent Direct Torque Control (DTC) techniques of Induction motor such as neural network, fuzzy and genetic algorithm based torque controllers are evaluated. Adaptive intelligent techniques are used to achieve high performance decoupled flux and torque control.

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 along with its controller.

- Investigating the performance of open Unified Power Quality Controller (UPQC) using PI controller scheme for static load and dynamic load(direct torque control induction motor)

1.4 Organization of Thesis

The work present in the thesis has been summarized in six chapters as per the details given below:

The Chapter 1 briefs the overview, literature view and scope of work. It also contains the organisation of thesis.

The Chapter 2 shows the definitions of power quality and problems associated. It also contains solutions strategy.

The Chapter 3 discusses 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 on the introduction of open unified power quality conditioner in detail and the control technique used in the simulation of open unified power quality conditioner.

The Chapter 5 discuss test and result, parameter of the test system, Simulink model of the test system with static and dynamic load.

The Chapter 6 contains the conclusion and future scope.

CHAPTER 2

POWER QUALITY

2.1 Definition of Power Quality

According to definition of power quality given in IEEE standard, “Power quality is the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment.”

Power quality can also be defined as a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance or life expectancy [5].

Power distribution systems should provide their customers with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency. However, in power systems, especially the distribution systems, have many nonlinear loads, which significantly affect the quality of power supplies. As a result of the nonlinear loads, the pure sinusoidal waveform is lost. This ends up producing many power quality problems.

Sources of Poor Power Quality Are Listed As Follows:

L-G fault, Non- linear load, Arching devices, Lightning Strike, Starting of large motors, Sensitive equipment, Environmental related damages, Office equipments, Transformation energization [6].

2.2 Need of Power Quality

There is an increased concern of power quality due to the following reasons

1. New-generation load equipment, with microprocessor-based controls and power electronic devices, are more sensitive to power quality variations than the equipment used in past [7].
2. The increasing emphasis on overall power system efficiency has resulted in continued growth in the application of devices such as high-efficiency, adjustable-speed motor drives like DTC (direct torque control) induction motor drive and shunt capacitor for power factor correction to reduce losses. This results the increasing harmonic level on power systems and has many people concerned about the future impact on system capabilities.
3. End users are increasing awareness of power quality issues. Utility customers are becoming better informed about such issues as interruptions, sags, and switching transients and are challenging the utilities to improve the quality of power delivered.

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

2.3 Power Quality Problems

2.3.1 Voltage Sag: Voltage Sag is the most severe problem in the power quality. Voltage sag is the decreasing in voltage between 10% and 90% of nominal voltage for half cycle to one minute. The external causes of sag come from the utility transmission and distribution network. The Sags comes from the utility have a variety of cause like lightning, animal and human activity, and normal and abnormal utility equipment operation. The Sags generated on the transmission or distribution system can travel hundreds of miles thereby affecting thousands of customers during a single event.

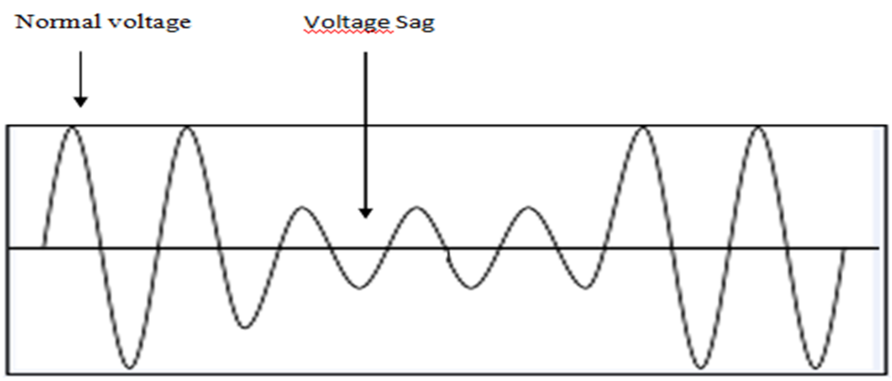


Figure 2.1: Voltage sag

2.3.2 Voltage Swell: Swell is the opposite of sag. An increasing in voltage above 110% of nominal for half cycle to one minute. Although swells occur infrequently when compared to sags, they may cause equipment malfunction. Swells may be caused by shutting off loads or switching capacitor banks on.

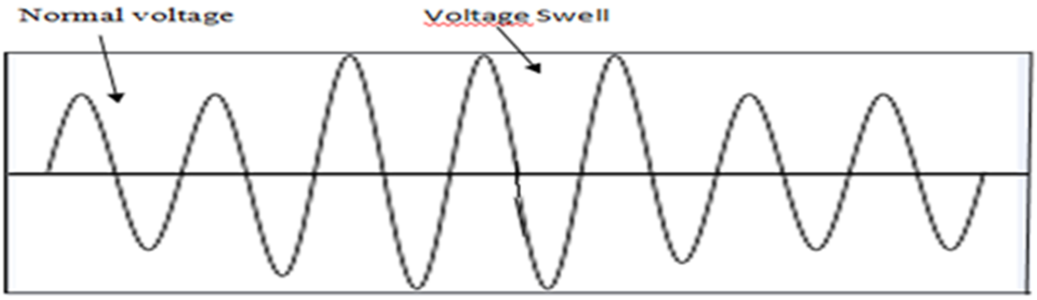


Figure 2.2: Voltage swell

2.3.3 Interruption: When a voltage drops below 10% of its nominal value it is called an interruption or a blackout. Interruptions have three classifications: momentary (lasting 30 cycles to 3 seconds), temporary (lasting 3 seconds to 1 minute) and sustained (lasting more than 1 minute). Although interruptions are the most severe form of power problem, they are also the least likely to occur.

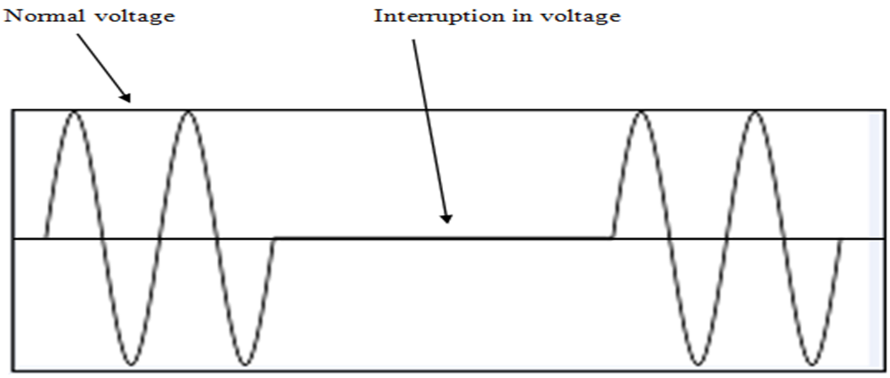


Figure 2.3: Interruption

2.3.4 Over voltage: An over voltage 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 due to load switching or incorrect tap settings on transformers.

2.3.5 Under voltage: Under voltage is a decrease in voltage below 90% of its nominal value for more than one minute. Under voltage is sometimes known as "brownout" although this term is not officially defined. Brownout is often used when the utility intentionally reduces system voltage to accommodate high demand . The reasons of under voltage can range from none to daily equipment malfunction or premature equipment failure. Besides the malfunction of equipment, chronic under voltage can cause excess wear on certain devices like motors as they will tend to run overly hot if the voltage is low.

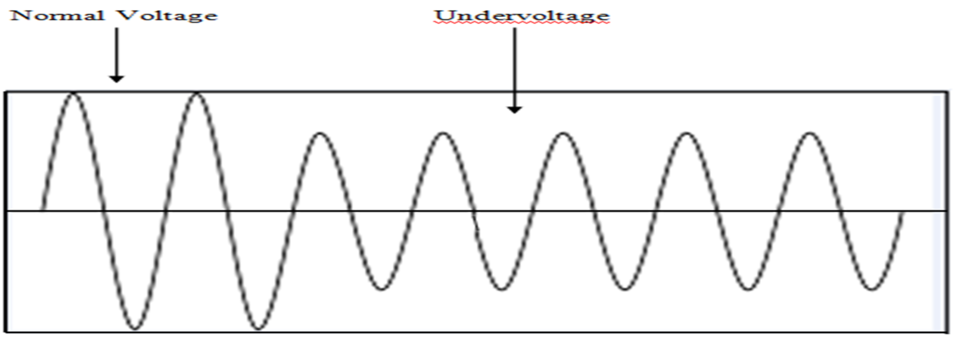


Figure 2.4: Undervoltage

2.3.6 Electrical Noise Noise is a high frequency distortion of voltage waveform. It will caused by disturbances on the utility system or by equipment such as welders, switchgear and transmitters, noise are frequently not noticeable . Frequent or high levels of noise can cause equipment malfunction, overheating and premature wear.

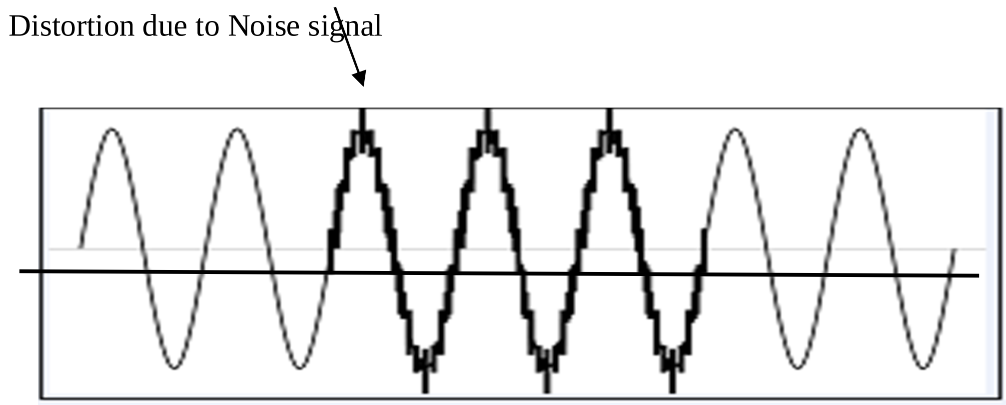


Figure 2.5: Electrical Noise Waveform

2.3.7 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.

2.3.8 Transients

(i) Impulsive Transient: An impulsive transient is a 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 reduced by the use of transient voltage suppressors such as Zener diodes.

Figure 2.6 Impulsive Transients

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

Figure 2.7: Oscillatory Transients

2.3.9 Harmonics: Harmonics are periodic sinusoidal distortions of the supply voltage or load current caused due to non-linear loads. Harmonics are measured in integer multiples of the fundamental supply frequency. In commercial facilities, computers, lighting, and electronic office equipment generate harmonic distortion. In industrial facilities, adjustable-speed drives and other power electronic loads can generate significant amounts of harmonics.

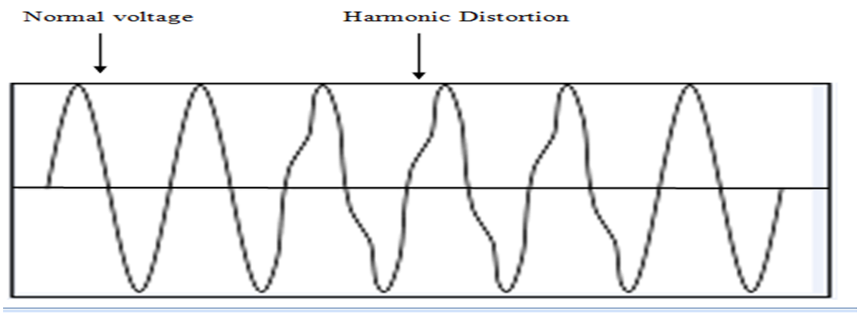


Figure 2.8: Harmonics

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 [18]. 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:

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

THD and DIN are interrelated by the following equations

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

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

2.3.10 Voltage Fluctuations A waveform exhibit voltage flicker if its waveform amplitude is modulated at frequencies less than 25 Hz, which the human eye can detect as a variation in the lamp intensity of a standard bulb. Voltage flicker is caused by an arcing condition on the power system. Flicker problems can be corrected with the installation of filters, static VAR systems, or distribution static compensators. Voltage flickering happens due to the arc furnace, arc lamps and arc welding machines. It causes strain on eyes. Even the life span of the equipment is reduced.

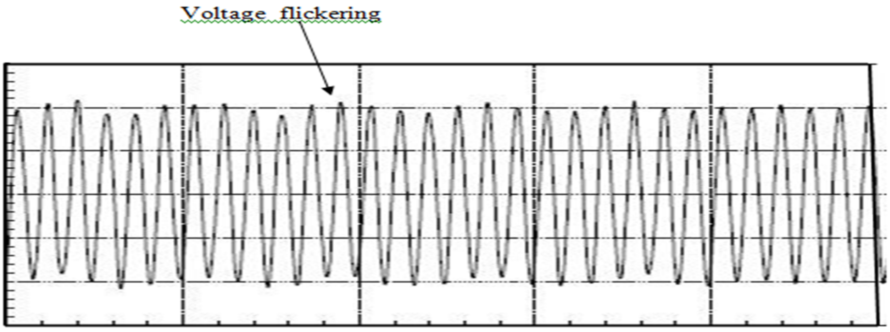


Figure 2.9: Voltage Fluctuations or Flicker

2.4 Solutions to Power Quality Problems

The mitigation of power quality problems can be achieved in two ways. The solution to the power quality can be done from customer side or from utility side. First method is called load conditioning and the other method is line conditioning. Load conditioning ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion while the instalment of line conditioning systems suppresses or counteracts the power system disturbances. They are depend on PWM converters and connected in shunt or in series to low and medium voltage distribution system. Series active power filters must operate in conjunction with shunt passive filters in order to compensate the load current harmonics. Series active power filters operates as a controllable voltage source whereas shunt active power filters operate as a controllable current source.

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

(ii) Thyristor Based Static Switches: The static switch is a device for switching a new element into the circuit when the voltage support is needed. It has dynamic response time of about one cycle. It may be used in the alternate power line applications. To correct quickly for voltage spikes, sags or interruptions, the static switch may 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 may be used to protect sensitive production equipments from shutdowns due to voltage sags or momentary interruptions. The energy is fed to system for compensate for the energy that will lost by the voltage sag or interruption. These are usually DC storage systems such as batteries, UPS, superconducting magnet energy storage (SMES), storage capacitors or even fly wheels driving DC generators. The output of these devices can be supplied to the system through an inverter on a momentary basis.

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

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

CHAPTER 3

CUSTOM POWER

3.1 Custom power

The concept of custom power was introduced by N.G.Hingorani [8]. The term custom power means the use of power electronics controllers for distribution systems. The custom power increase 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.

Custom power is a strategy, which is designed primarily to meet the requirements of industrial and commercial customer. The concept of custom power is to use of power electronic or static controllers in the medium voltage distribution system aiming to supply reliable and high quality power to sensitive users. Power electronic valves are the basis of those custom power devices such as the static transfer switch, active filters and converter-based devices. Converter based power electronics devices can be divided into two groups: shunt connected and series-connected devices. The shunt connected devices is known as the D-STATCOM and the series device is known as the Static Series Compensator (SSC), commercially known as DVR.

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.
• Magnitude and duration of over voltages within specified limits.
• Low harmonic voltage.
• Low phase unbalance.

3.2 Need of Custom Power

The increased use of automated equipment like adjustable speed drives, programmable logic controllers, switching power supplies, arc furnaces , 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. Although not only reliability that the consumers want these days, the quality of power is too important for them. With the deregulation of the electric power energy market, the awareness regarding the quality of power has been increasing day by day among different categories of customers. Power quality is an issue that is becoming increasingly important to electricity consumers at all levels of usage.

3.3 Types of Custom Power Devices

There are many types of Custom Power devices. Some of these devices are Active Power Filters (APF), Surge Arresters (SA). Battery Energy Storage Systems (BESS), Solid State Fault Current Limiter (SSFCL), Solid-State Transfer Switches (SSTS), Static VAR Compensator (SVC), Dynamic Voltage Restorer (DVR), Distribution Static synchronous Compensators (DSTATCOM) and Uninterruptible Power Supplies (UPS), Unified power quality conditioner (UPQC)

Custom power devices can be classified into two major categories [9]. One is network configuring type and the other is compensating type. The network reconfiguration devices are used for current limiting, current breaking and current transferring devices. There are mainly two devices are used for network reconfiguration:

(a) SSCL (Solid State Current Limiter)

(b) SSTS (Solid State Transfer Switch)

Devices used for compensation are:

(a) Active Power Filters (APF)

(b) Distribution Static Compensator (DSTATCOM)

(c) Dynamic Voltage Restorer (DVR)

(d) Unified Power Quality Conditioner (UPQC)

3.3.1 Solid State Current Limiter

The most common used solution for limitation of the fault currents is to use a transformer with a split secondary winding and current limiting reactors. Figure 3.1 shows the basic configuration of Solid State Current Limiter.

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

Parallel fault current limiters [10] 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.

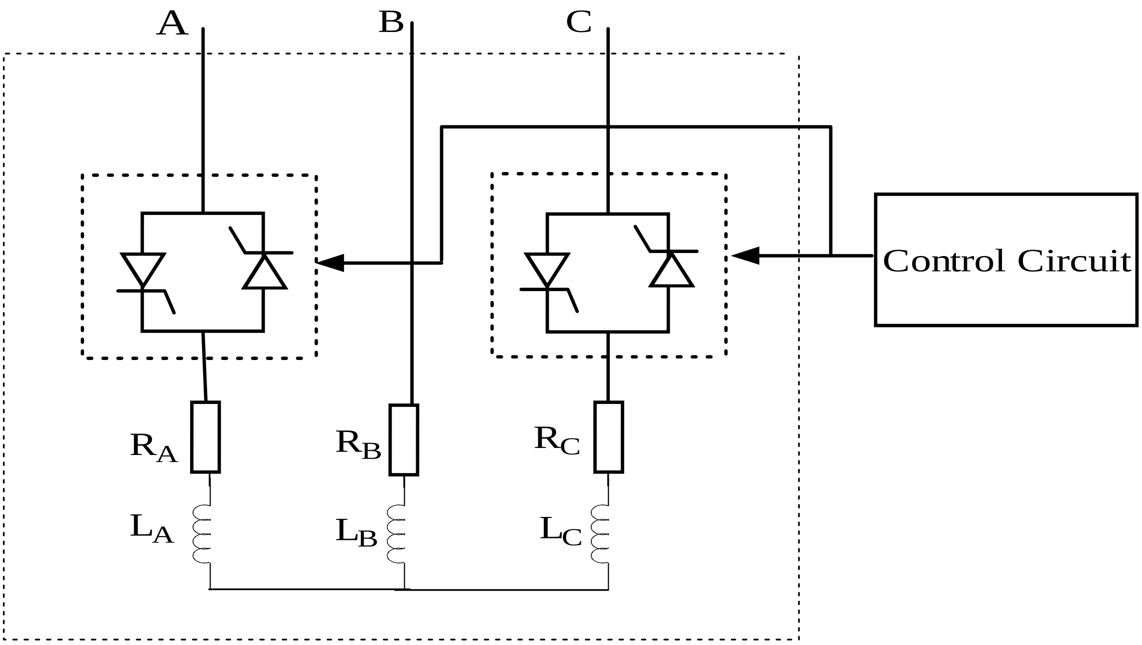


Figure 3.1: Solid State Current Limiter

3.3.2 Solid State Transfer Switch

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

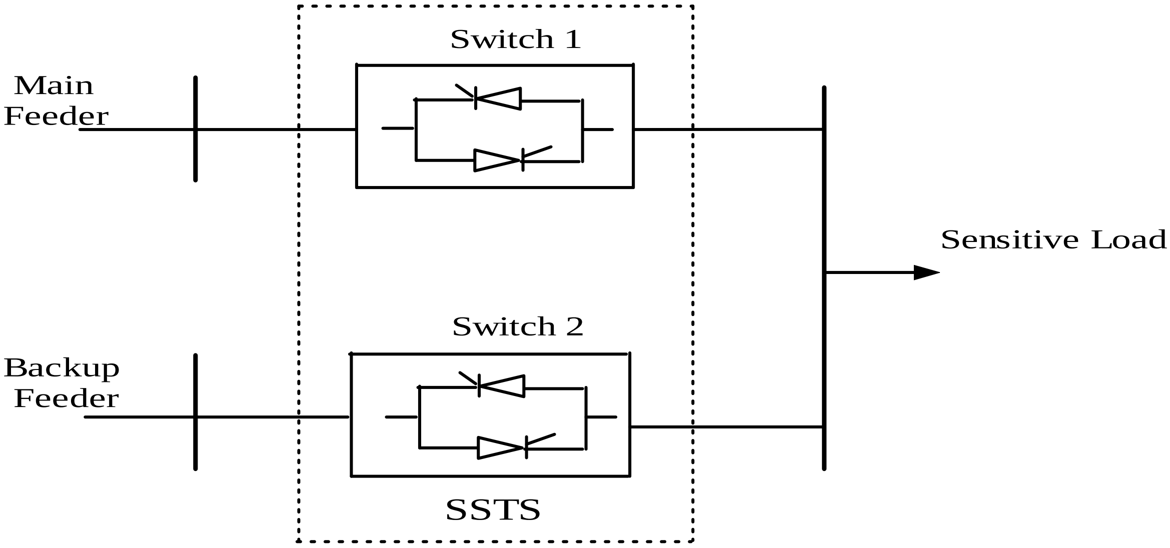


Figure 3.2: Solid State Transfer Switch

The SSTS is having 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 comprises of two three-phase solid-state switches, one for the main feeder and one for the backup feeder. These switches have an arrangement of back-to-back connected thyristors, as shown in Fig. 3.2

Each time a fault condition is detected in the main feeder, the control system interchange 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 it is within a prespecified range or not. 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.

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. The application of passive tuned filters provides new system resonances which are dependent on specific system conditions.

Passive filter ratings having a coordination 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 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. Currently these 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

3.3.3.1 Shunt Active Power Filter

The aim of the shunt active power filters is to cancel load harmonics fed to the supply. These filters works as a current sources which is connected in parallel with the nonlinear load, generating the harmonic currents the load requires. With an appropriated control strategy, it is also possible to correct power factor and unbalanced loads.

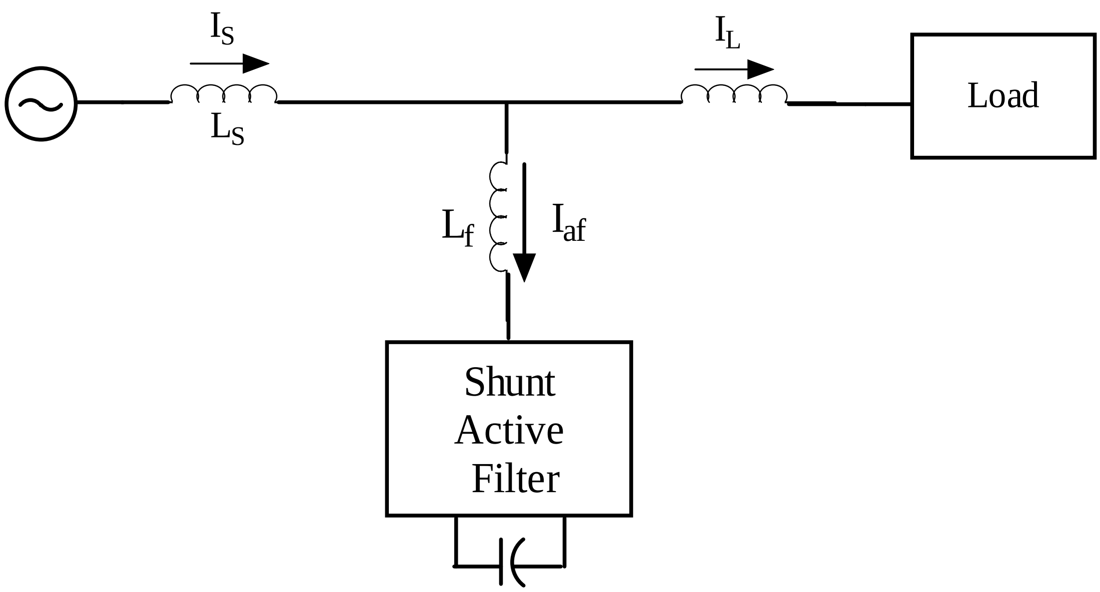


Figure 3.3: Block Diagram of shunt Active Filter

Shunt active power filters compensate the current harmonics by injecting equal-but in opposite harmonic compensating current. Figure 3.3 shows the block diagram of shunt active filter.

3.3.3.2 Series Active Power Filters

Series active power filters compensate current system distortion caused by non-linear loads by providing a high impedance path to the current harmonics which forces the high frequency currents to flow through the LC passive filter connected in parallel to the load. The high impedance imposed by the series active power filter is produced by generating a voltage of the same frequency so that current harmonics components can be eliminated.

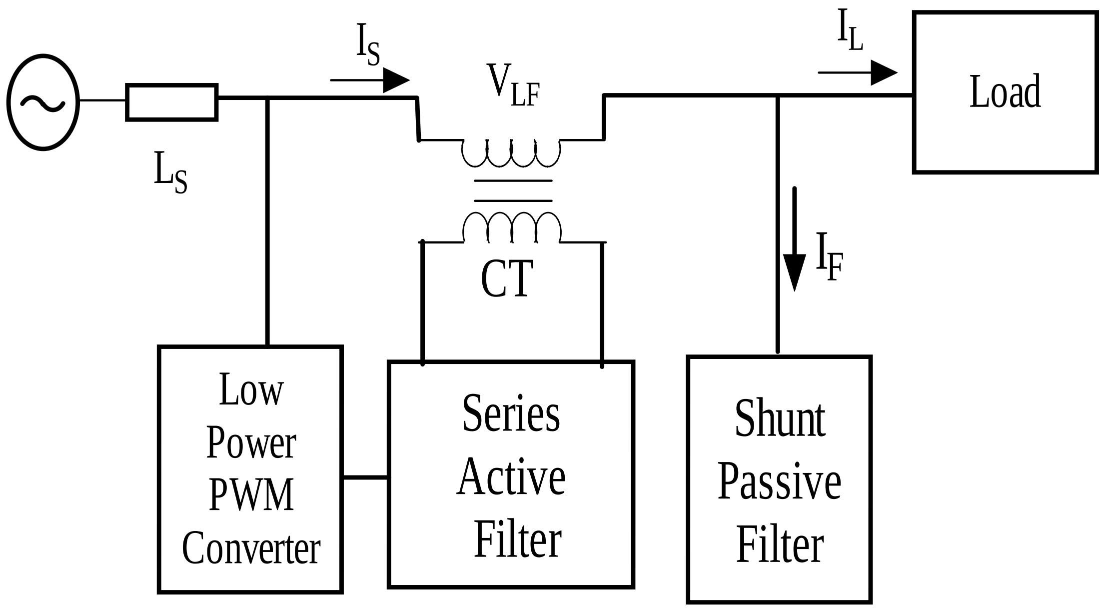


Figure 3.4 : Block Diagram Of Series Active Power Filter

The main advantage of series filters over parallel ones is that they are ideal for eliminating voltage-waveform harmonics, and for balancing three-phase voltages.

3.4 Distribution Statcom (DSTATCOM)

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

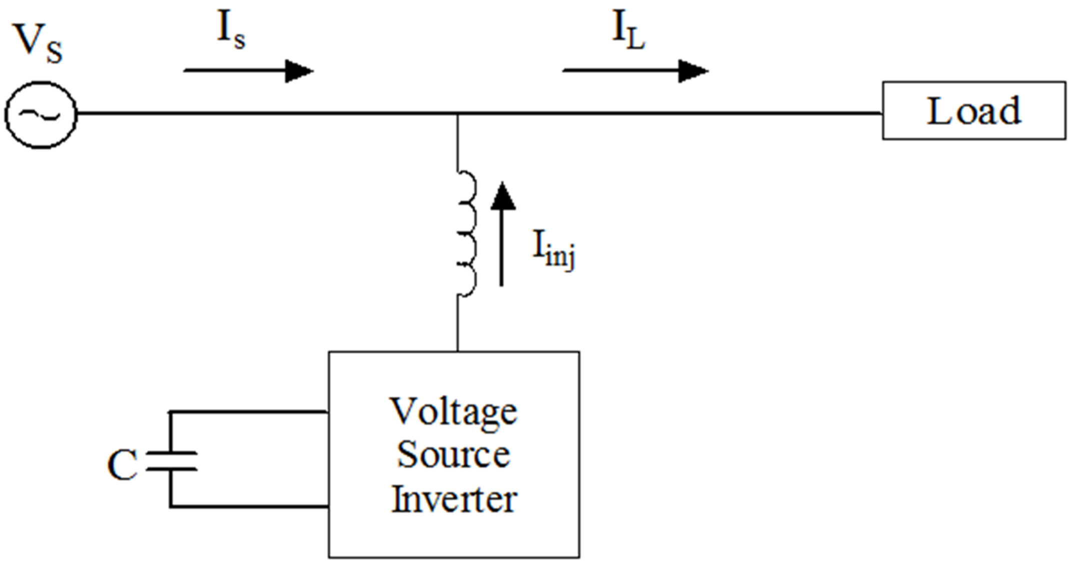


Figure 3.5: Single Phase DSTATCOM

3.5 Dynamic Voltage Restorer (DVR)

DVR injects a voltage component which is connected in series with the supply voltage, thus compensating the voltage sags and swells on the load side. Control response is of the order of 3msec, ensuring a secure voltage supply under transient conditions. The main function of a DVR is the protection of sensitive loads from voltage sags/swells coming from the network. The DVR is located on the basis of sensitive loads. If a fault occurs on other lines, DVR inserts series voltage V_{dvr} and compensates load voltage to pre fault value. The momentary amplitudes of the three injected phase voltages are controlled in such a way to eliminate any detrimental effects of a bus fault to the load voltage V_l.

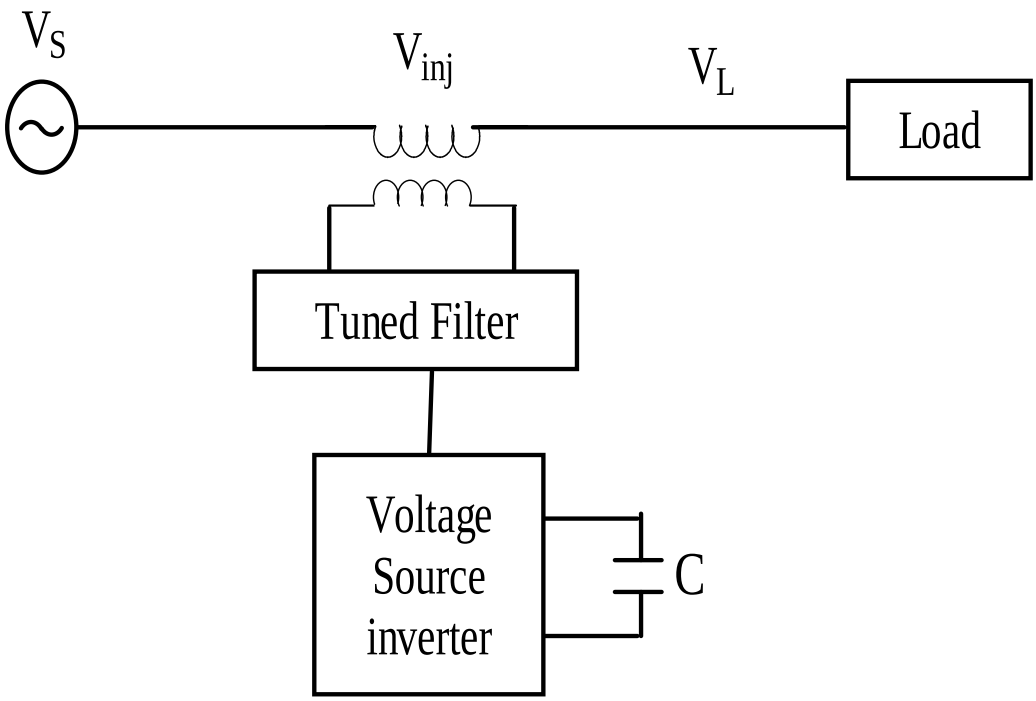


Figure 3.6: Single phase DVR

3.6 Unified Power Quality Controller (UPQC)

Poor power quality in a system may be due to different factors such as voltage sag, voltage swell, over correction of power factor and unacceptable levels of harmonics in the current and voltage. Modern solution for poor power quality is to take advantage of advanced power electronics technology. Recent research efforts have been made towards utilizing a device called unified power quality conditioner (UPQC) to solve almost all power quality problems [11]. The basic configuration of UPQC is shown in fig. 3.7.

The main purpose of a UPQC is to compensate for supply voltage flicker/imbalance, reactive power and harmonics. In other words, the UPQC has the ability of improving power quality at the point of installation on power distribution systems or industrial power systems. The UPQC, therefore one of the most powerful solutions to large capacity loads sensitive to voltage flicker/imbalance [12].

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

- It reduces the harmonics in the supply current, so that it can 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 required [13].
- 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 which is taken from the same dc link, thus no additional dc link voltage support is required for the series compensator [14].

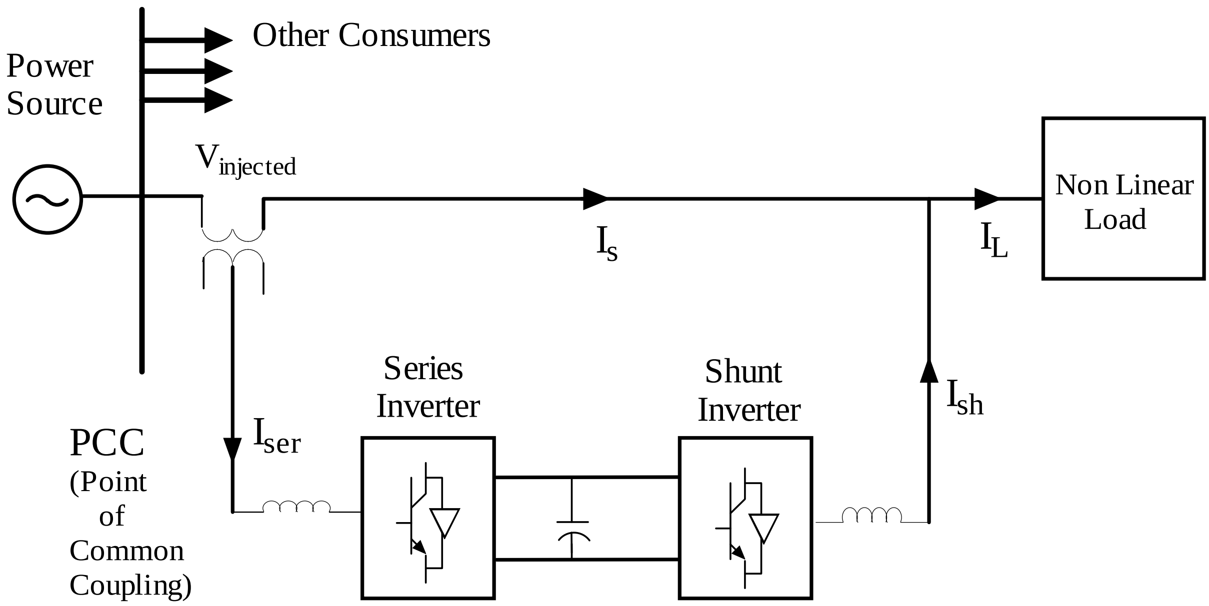


Figure 3.7: Unified Power Quality Conditioner

There are three principle components to the custom power concept:

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

- The Distribution Static Compensator (D-STATCOM), it gives continuously variable shunt compensation by current injection for eliminating voltage fluctuations and obtaining the 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.

- Solid State Transfer Switch (SSTS), it protects circuits from electrical disturbances by transferring load from a faulted line (main source) to a healthy line (back up source). SSTS is not operate in the same way as a conventional circuit breaker. It interrupts fault currents by monitoring both steady current and rate of change of current and only interrupts when the onset of a fault is detected.

3.7 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 [15]. 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.

Based on these reasons, the UPQC is widely considered as an effective custom power device in mitigating voltage sags and swells. In addition to voltage sags and swell compensation, UPQC can also added other features such as harmonics and power factor correction [16].

CHAPTER 4

OPEN UNIFIED POWER QUALITY CONDITIONER

4.1 Introduction

The quality of the power is having disability by several reasons. This degradation of the quality of the power is seen e.g. as supply interruptions, transient over voltages, dips, harmonics and voltage unbalance [17]. The use of non-linear and unbalanced loads such as direct torque control induction motor drive in distribution systems is increasing drastically, due to which the currents in the network become unbalanced and distorted .The THD (total harmonic distortion) basically depends on type of load for example adjustable speed drive DTC (direct torque control) induction motor when used produce a waveform which is not a pure sine wave and includes harmonic distortion which is supplied to the motor. The harmonics are multiples of a fundamental frequency with a current component and the current component will create 5 to 8 percent extra heat in the motor. As it is a solid state electronic load it will also cause distortion to be induced on the input electrical power supply. This can severely distort the electrical power supply within the facility and if not properly protected, can hinder the operation of other devices various solutions are available to compensate for these disturbances [18].

One solution involves increasing the short circuit level of the distribution network, i.e., revamping all the LV distribution cables or raising the power of the MV/LV substation transformer, thus increasing the power quality for all end users. In this way, an incoming disturbance from a load (i.e., harmonics) or from a fault in a line is reduced at the point of common coupling (PCC). Therefore, this solution effectively reduces the depth of the voltage variations, but does not protect the loads against transients and short interruptions. A second solution that can compensate any kind of disturbance, including interruptions, is installation of on-line, off-line, line interactive and hybrid UPS systems [19]. In all of these cases, only the end users that decide to install them are protected, while all of the other costumers do not receive any improvement in PQ. Often, these solutions cannot be adopted by the local utility companies or by the end users, because they are too expensive relative to the increase in power quality that they produce. However, many cheaper solutions are available. In particular, several electronic devices have been developed, studied and proposed to the international scientific community with the goal of improving supplied power quality. Different connection topologies (series or shunt types) are used to realize these devices. The series devices are connected upstream of the protected lines, while the shunt devices are connected in parallel to the sensitive loads. In general, both types of conditioning devices increase the power quality level at the loads. The unified power quality conditioner (UPQC) compensator seems to be a particularly provide power conditioner device [20]. This is constituted of a series and a shunt unit, with a common dc link through which power can be exchanged. Its function is to improve the quality levels of the current absorbed at the mains and the load supply voltage . However, these devices do not allow local distributors to guarantee different quality demand levels to the final customers, because they improve power quality for all the supplied end users. The installation investments are also quite high relative to the power quality level obtained. A solution that has similar performances and advantages, but also makes cost reduction possible, is the proposed Open UPQC [28]. The basic diagram of UPQC is shown in figure 4.1.

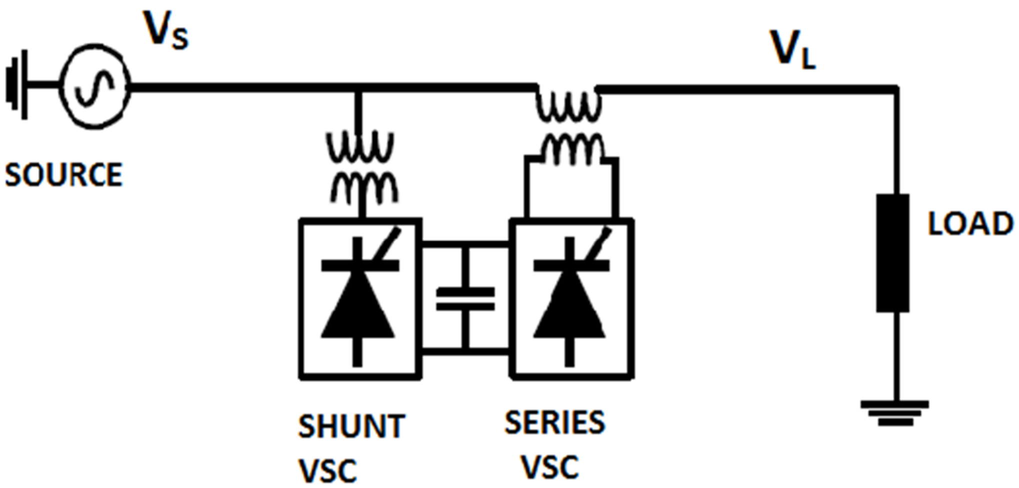


Figure 4.1: Block diagram of UPQC

4.2 Basic configuration of UPQC

The main components of a OPEN 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 the voltage-source converter connected which in series with the AC line and acts as a voltage source to mitigate the voltage distortions. It eliminates supply voltage fluctuations 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 are generated by the comparison of a fundamental voltage reference signal with a high-frequency triangular waveform [21].

4.2.2 Shunt converter: It is the voltage-source converter connected in shunt with the same AC line and acts as a current source to cancel current distortions to compensate reactive current of the load and to improve the power factor. It also performs the DC-link voltage regulation, results the significant reduction of the DC capacitor rating. The output current of the shunt converter is adjusted -by controlling the status of semiconductor switches such 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/ Yo 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

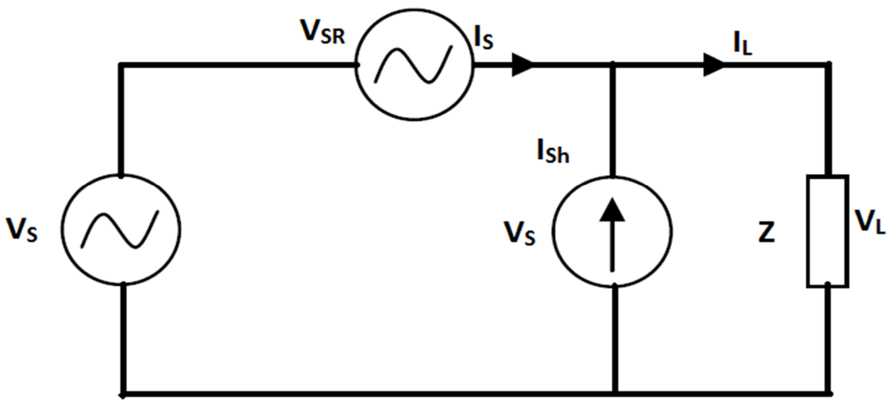


Figure 4.2: equivalent circuit for UPQC

In this circuit,

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 [22].

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,

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

$$= I_{1p} \sin(\omega t - \theta_{1P}) \cos \varphi_{1P} \quad (4.5)$$

4.4 UPQC Configuration

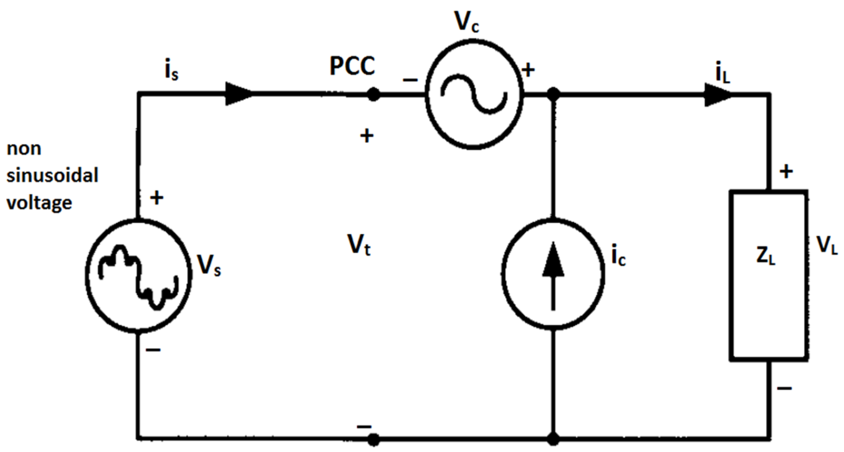


Figure 4.3: The right shunt UPQC compensation configuration

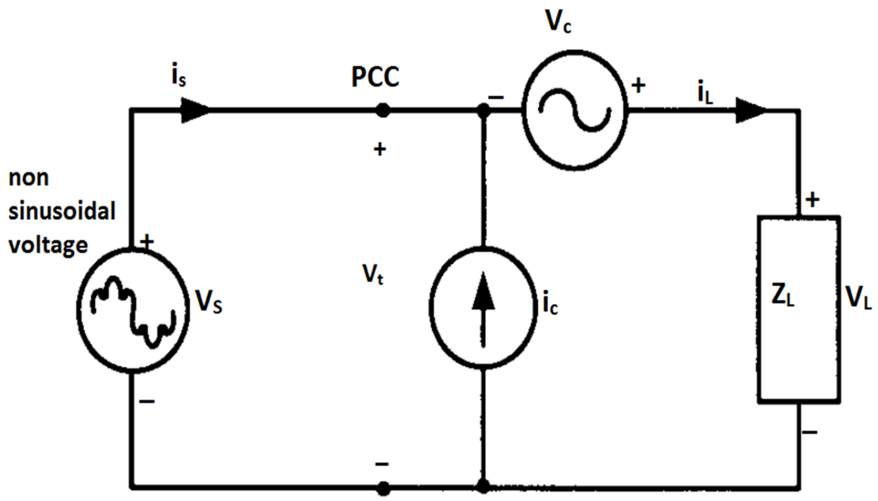


Figure 4.4: The left shunt compensation configuration

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

- Right-shunt UPQC (figure 4.3), where the shunt compensator (i_c) ia placed at the right side of the series compensator (V_c).
- Left –shunt UPQC (figure 4.4), where the shunt compensator (i_c) is placed at the left side of $V_{c.}$

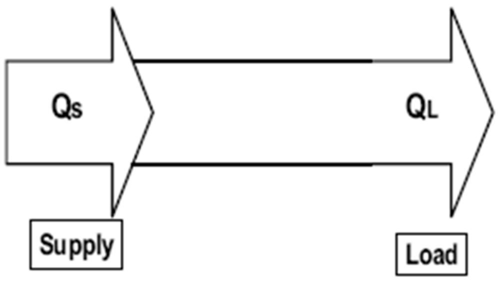
These two structures have similar features; however the overall characteristics of the right shunt UPQC are superior (e.g. operation at zero) power injection/absorption mode, achieving unity power factor at load terminals, and full reactive power compensation).

4.5 Steady – State Power Flow Analysis

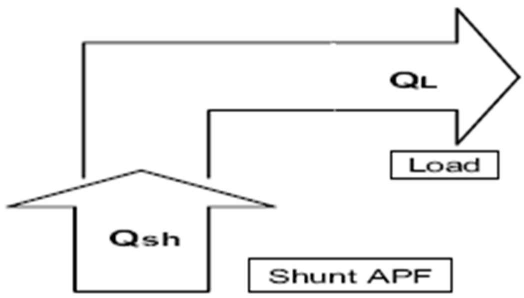
The powers due to harmonic quantities are negligible as compared to the power at fundamental component, therefore, the harmonic power is neglected and the steady state operating analysis is done on the basis of fundamental frequency component only. The UPQC is controlled in such a way that the voltage 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 [23].

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



(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.

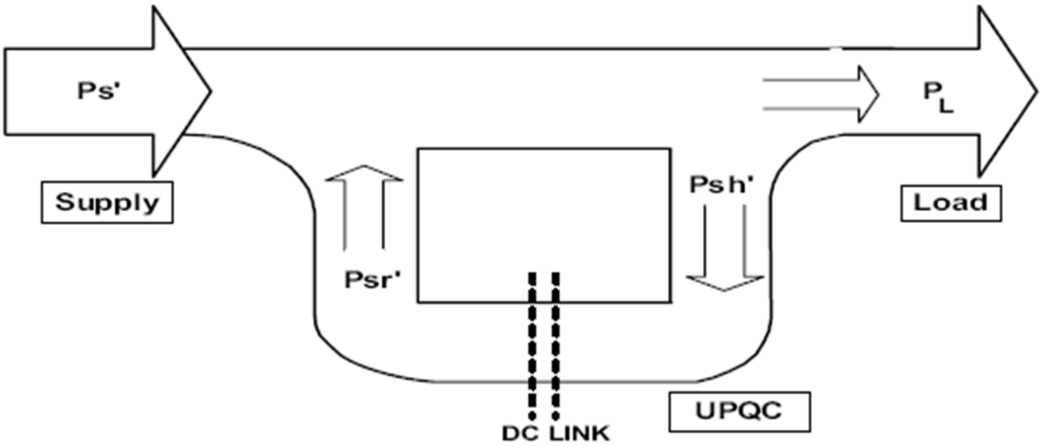


Figure 4.6: Active Power Flow during Voltage Sag Condition

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. PL

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.

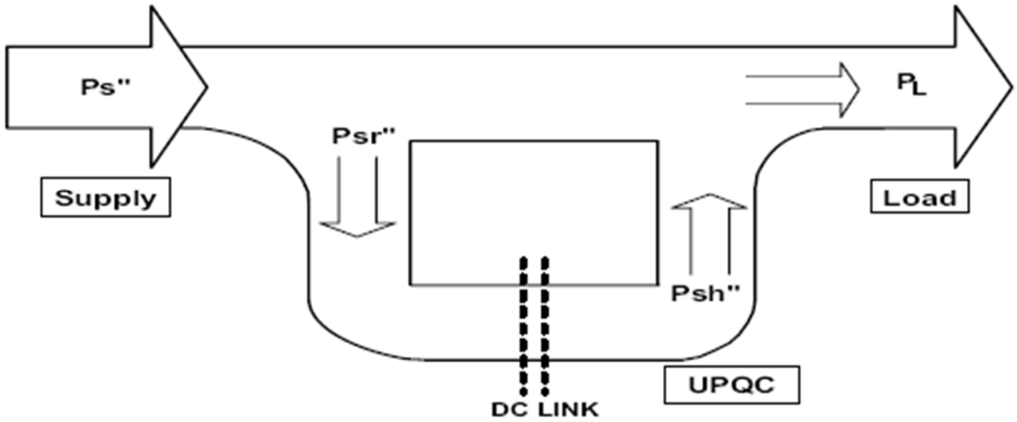


Figure 4.7: Active Power Flow during Voltage Swell Condition

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.

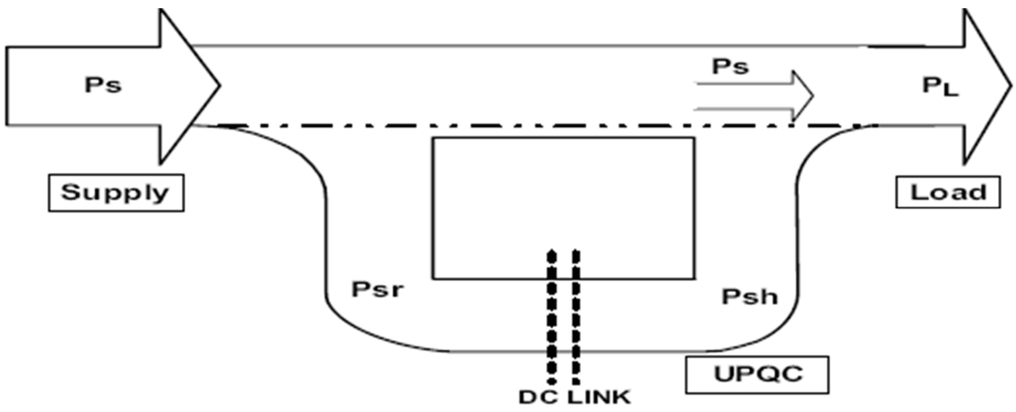


Figure 4.8: Active Power Flow during Normal Working Condition

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.

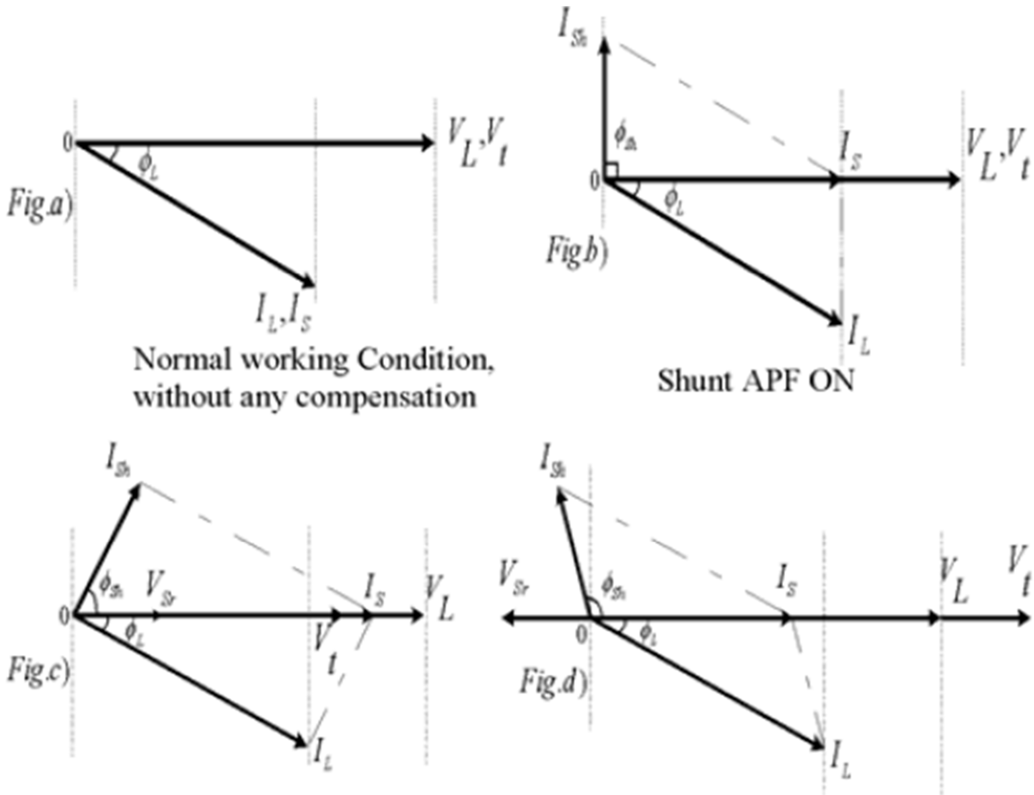


Figure 4.9 a) – d): Phasor Representation of all Possible Conditions

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 is to balanced sinusoids through the shunt compensator [24].
- 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 Open Unified Power Quality Conditioner

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 [28] .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 a multi functioning device 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 factor [25]. The OPEN unified power quality conditioner (UPQC), composed of a power-electronic series main unit installed in the medium-voltage/low-voltage (LV) substation, along with several power-electronic shunt units connected close to the end users. The series and parallel units do not have a common dc link, so their control strategies are independent of each other. This device can achieve general improvement in PQ, reducing the most common disturbances for all customers that are supplied by the mains (PQ) by using only the series unit. Therefore, this new simultaneously combines can improve the PQ and reduce the cost who needs high quality of power. Most end user disturbances are characterized by short duration and small amplitude, though they can still cause interruptions in production processes. Most voltage sags have small depth and short durations. More than 95% of voltage sags can be compensated by injecting a voltage of up to 60% of the nominal voltage. This information is primarily used to evaluate a suitable size for the OPEN UPQC [26]. The series unit of the OPEN UPQC, sized to supply 60% of the LV network power and equipped with a small storage system, can compensate for most of the voltage disturbances. Each shunt unit is sized in relation to the supplied load power, and can protect its sensitive load against interruptions. The shunt unit's function is similar to that of the UPS output stage but is less expensive because it is having only one conversion stage and involves less power loss. The series unit consists of a coupling transformer (TR), with the primary circuit connected in series with the mains line and a secondary one supplying the reversible ac/dc power converter. The output stage of the pulse width modulation (PWM) voltage controlled converter contains passive RC shunt filters, to compensate for the harmonic currents.

4.8 Different Modes of OPEN UPQC

• ***Compensator*:** When the PCC voltage is within its operation limits, the SS are closed, therefore the series unit works as a three phase voltage generator and the shunt units work as current generators

• ***Back-up***: When the PCC voltage is outside of its operation limits, the SS are open, decoupling the network and the load-compensator system. Each sensitive load is supplied by its shunt unit, which acts as a sinusoidal voltage generator, using the energy stored in the storage system as an energy source.

4.9 Control Philosophy

A controller is required to control the working of UPQC whenever any fault there for this purpose PI controller is used [29].

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}.

4.10 PI Controller

A PI-Lead controller is a proportional gain which is 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.

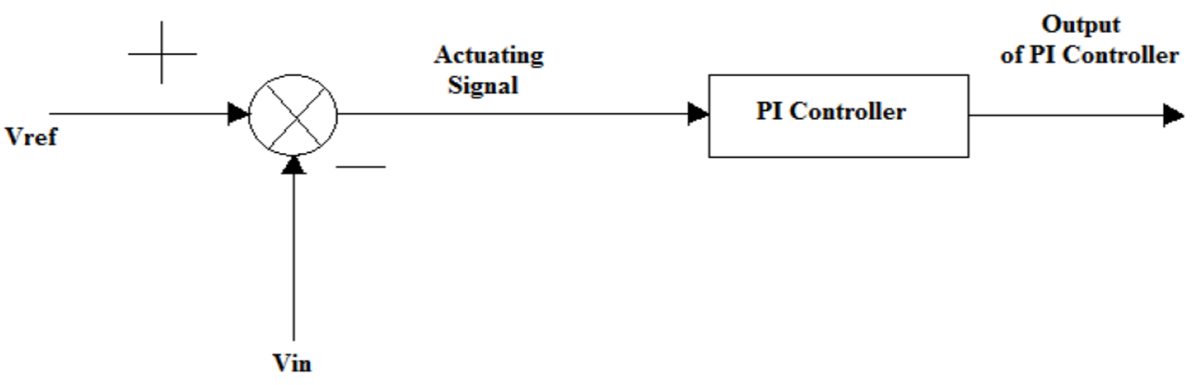


Figure 4.10: PI controller

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 will 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

- Fast action
- Eliminate the offset

Disadvantage

- Oscillatory or unstable with integral control
- One more parameter to tune

CHAPTER 5

SIMULATION AND RESULTS

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

- Distribution network having non linear load
- Distribution network having DTC (direct torque control)

5.1 Non Linear Load:

A load is considered to be non-linear if its impedance changes with the applied voltage. The changing impedance means that the current drawn by the non-linear load will not be sinusoidal even when it is connected to a sinusoidal voltage. These non-sinusoidal currents contain harmonic currents that interact with the impedance of the power distribution system to create voltage distortion that can affect both the distribution system equipment and the loads connected to it.

In the past, non-linear loads were primarily found in heavy industrial applications such as arc furnaces, heavy rectifiers for electrolytic refining, etc. The harmonics they generated were typically localized and often addressed by knowledgeable experts.

Times have changed. Harmonic problems are now common in not only industrial area but in commercial buildings as well. This is due primarily to new power conversion technologies, such as the Switch-mode Power Supply (SMPS), which can be found in virtually every power electronic device (computers, servers, monitors, printers, photocopiers, telecom systems, broadcasting equipment, banking machines, etc.). The SMPS is an excellent power supply, but it is also a highly non-linear load.

Parameters of Test System:

Simulation model of UPQC using PI controller and non linear load drive as load is shown in Figure 5.1. System parameters of test system are listed in Table

Table 5.1 System Parameters for Non Linear 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=100 for series control Kp=1000,Ki=1000 for first shunt control, K_P=0.5,K_i=100 for second shunt control Sample time=50 µs
4	RL load	Active power = 1kW Inductive Reactive Power=400 VAR
5	Non linear load	Snubber resistance R_s =$1e^5$, Snubber capacitance C_s=100,Ron =$1e^{-3}$
6	Transformer1	Y/Δ/Δ 13/115/115Kv
7	Transformer2	Δ/Y 115/11KV

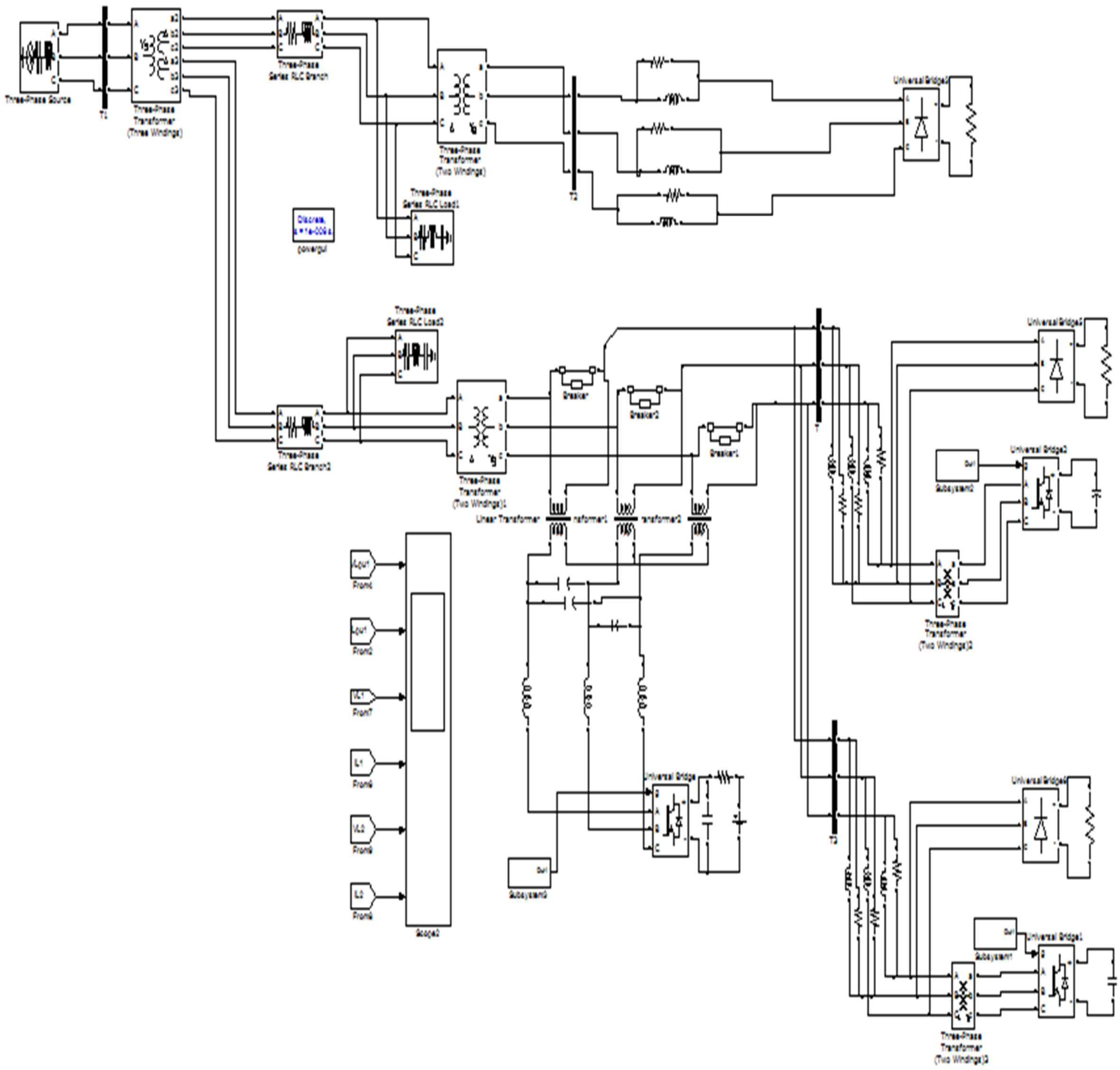


Figure 5.1: MATLAB Simulation Model of open UPQC using PI Control with non linear Load

Simulation And Results

An ideal three-phase sinusoidal supply voltage is applied to the non-linear load (static load) injecting current and voltage harmonics into the system. Figure 5.2 (a) shows load 1 voltage in three-phase before compensation. Figure 5.3 (b) shows THD level for uncompensated load voltage. Figure 5.4 (c) shows load 1 voltage in three-phase after compensation. Figure 5.5(d) shows THD level for compensated load voltage. Figure 5.6 (a) shows load 1 current in three-phase before compensation. Figure 5.7 (b) shows THD level for uncompensated load current. Figure 5.8 (c) shows load 1 current in three-phase after compensation. Figure 5.9(d) shows THD level for compensated load current Figure 5.10 (a)shows load 2 voltage in three-phase after compensation. Figure 5.11(b) shows THD level for compensated load voltage. Figure 5.12 (a) shows load 2 current in three-phase after compensation. Figure 5.13 (b) shows THD level for compensated load current. The Total Harmonic Distortion (THD) for load 1 voltage which was 8.60% in Figure 5.2 (b) before compensation is effectively reduces to 5.18 % in Figure 5.4 (d) after compensation using PI controller. Shunt inverter is able to reduce the harmonics entering into the system. The Total Harmonic Distortion (THD) for load 1 current which was 10.87% in Figure 5.7 (b) before compensation and effectively reduces to 4.80 % in Figure 5.9 (d) after compensation using PI controller. The Total Harmonic Distortion (THD) for load 2 voltage which was 8.60% in Figure 5.3(b) before compensation is effectively reduces to 5.18 % in Figure 5.11(b) after compensation using PI controller. The Total Harmonic Distortion (THD) for load 2 current which was 10.87% in Figure(5.7b) before compensation and effectively reduces to 5.40 % in Figure (5.13b) after compensation using PI controller. The voltage compensation is small because system consist of transformers which are already doing compensation for voltage.

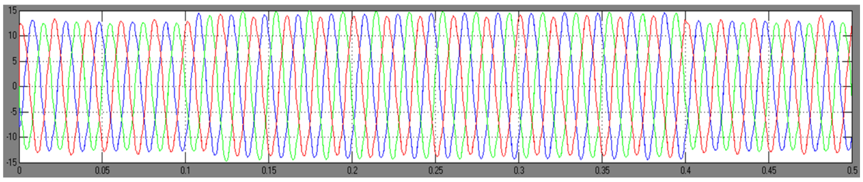


Figure 5.2(a): Load 1, voltage waveform without open UPQC

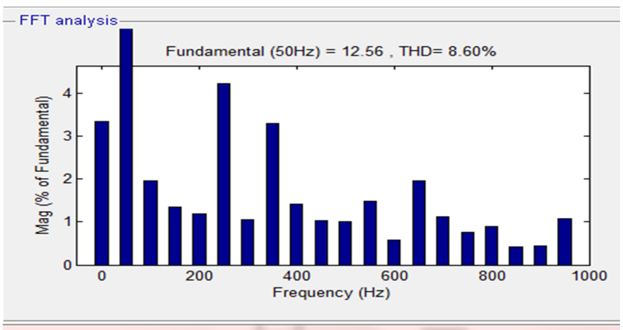


Figure 5.3(b): Load 1, Total harmonic distortion without open UPQC for voltage

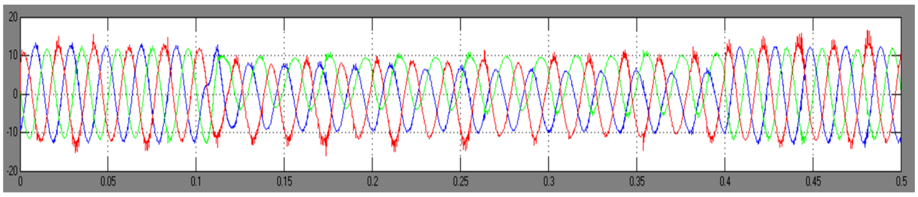


Figure 5.4(c): Load 1, Voltage waveform with open UPQC

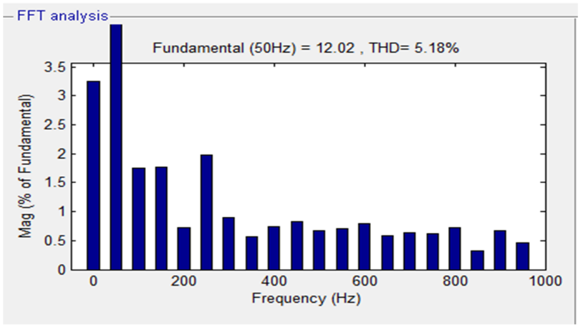


Figure 5.5(d): Load 1, Total harmonic distortion with open UPQC for voltage

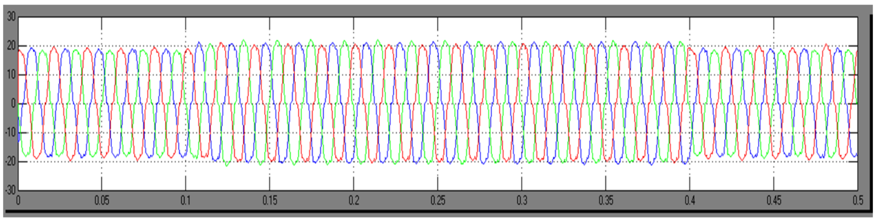


Figure 5.6(a): Load 1, current waveform without open UPQC

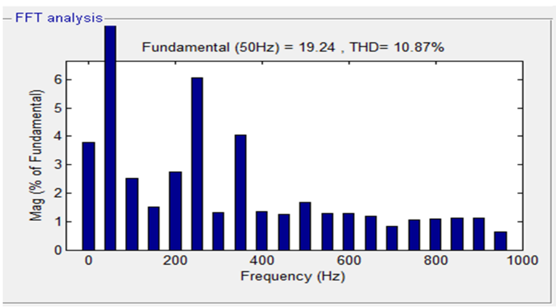


Figure 5.7(b): Load 1, Total harmonic distortion without open UPQC for current

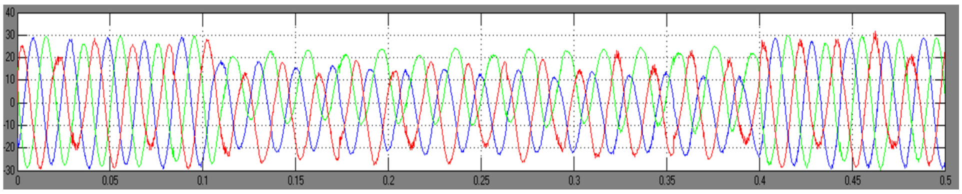


Figure 5.8(c) : Load 1, current waveform with open UPQC

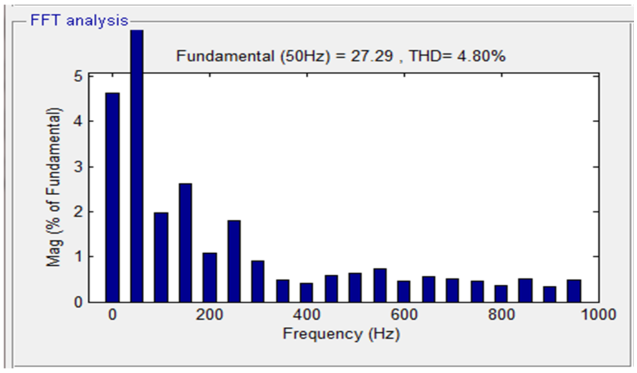


Figure 5.9(d): Load 1, Total harmonic distortion with open UPQC for current

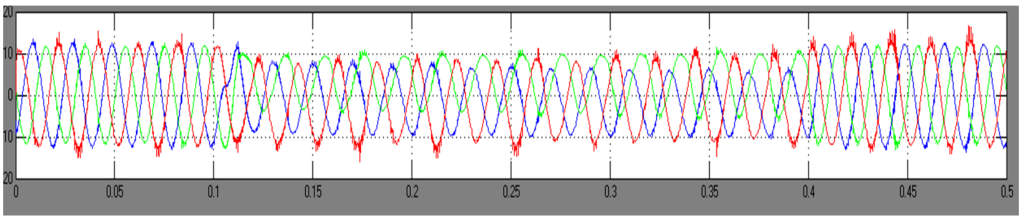


Figure 5.10(a): Load 2, voltage waveform with open UPQC

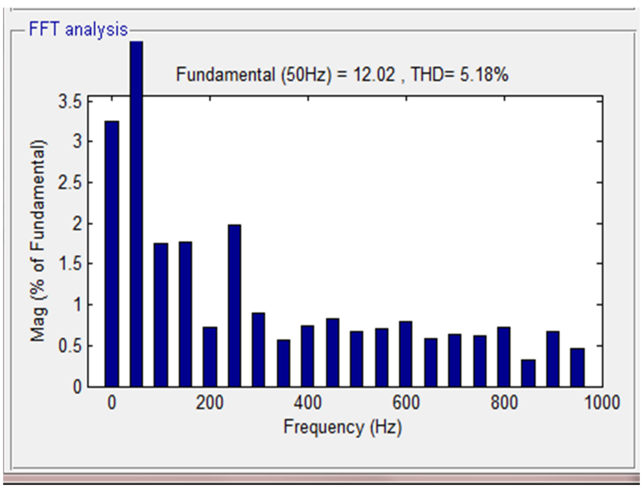


Figure 5.11(b): Load 2, Total harmonic distortion with open UPQC for voltage

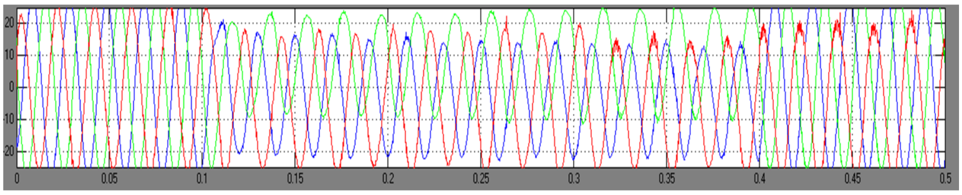


Figure 5.12(a): Load 2, current waveform with open UPQC

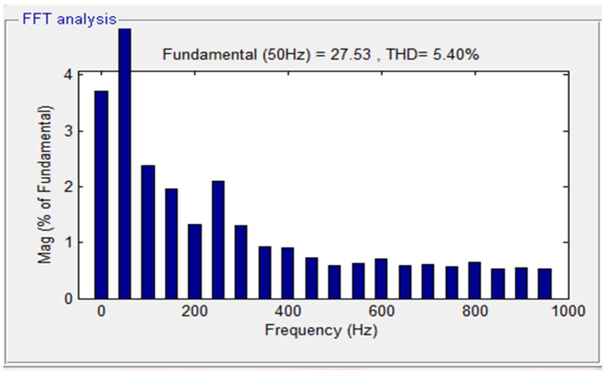


Figure 5.13(b): Load 2, Total harmonic distortion with open UPQC for current

5.2 Adjustable Speed Drive Load

Adjustable Speed Drives (ASD) have become very popular variable speed control devices used in industrial, commercial and some residential applications. These devices have been available for about 20 years and have a wide range of applications ranging from single motor driven pumps, fans and compressors, to highly sophisticated multi-drive machine.

Advantages of ASD

- Energy Savings
- Improved Process Control
- Reduced Voltage Starting
- Lower System Maintenance
- Bypass Capability
- Multi-motor Control

Disadvantages of ASD

- Initial Cost

- Motor Heating at low speeds
- Maintenance
- Output Harmonics

5.2.1 DTC (Direct Torque Control) Induction Motor Drive

Induction motor drives controlled by Field Oriented control (FOC) has used in high performance industrial applications, has achieved a quick torque response, and has been applied in various industrial applications instead of dc motors .It provides independent control of the torque and flux by decoupling the stator current into two orthogonal components FOC, however, is very sensitive to flux, which is mainly affected by parameter variations [28]. During the last decade a new control method called DTC (Direct Torque Control) has been developed for electrical machines. In this method, Stator voltage vectors is selected according to the differences between the reference and actual torque and stator flux linkage. The DTC method is characterised by its simple implementation and a fast dynamic response. There are different types of control strategies used for DTC (Direct Torque Control) like Neural Network, Genetic Algorithm (Binary Representation), Genetic Algorithm (Floating point Representation), Fuzzy Logic[30].

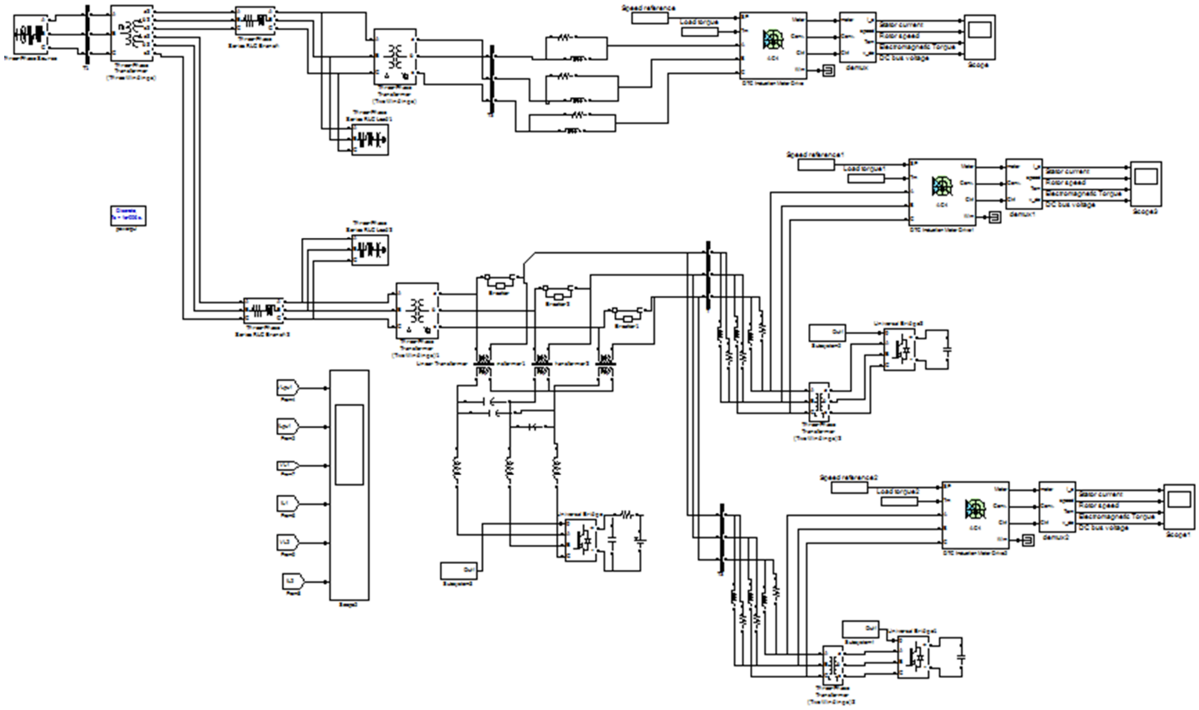
Parameters of Test System:

Simulation model of UPQC using PI control and Direct torque control induction motor drive as load is shown in Fig.5.2. System parameters of test system are listed in Table

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=100 for series control K_p=1000,K_i=1000 for first shunt control,K_p=0.5,K_i=100 for second shunt control Sample time=50 µs
4	RL load	Active power = 1kW Inductive Reactive Power=400 VAR
5	Motor load	Voltage Vrms=220V Frequency 50hz
6	Transformer1	Y/Δ/Δ 13/115/115kV
7	Transformer2	Δ/Y 115/11kV

Table 5.2 System Parameters for DTC (direct torque control) induction motor


Speed reference
Load torque
Stator current
Rotor speed
Electromagnetic Torque
DC bus voltage
Scope
Speed reference1
Load torque1
Speed reference2
Load torque2
Scope1

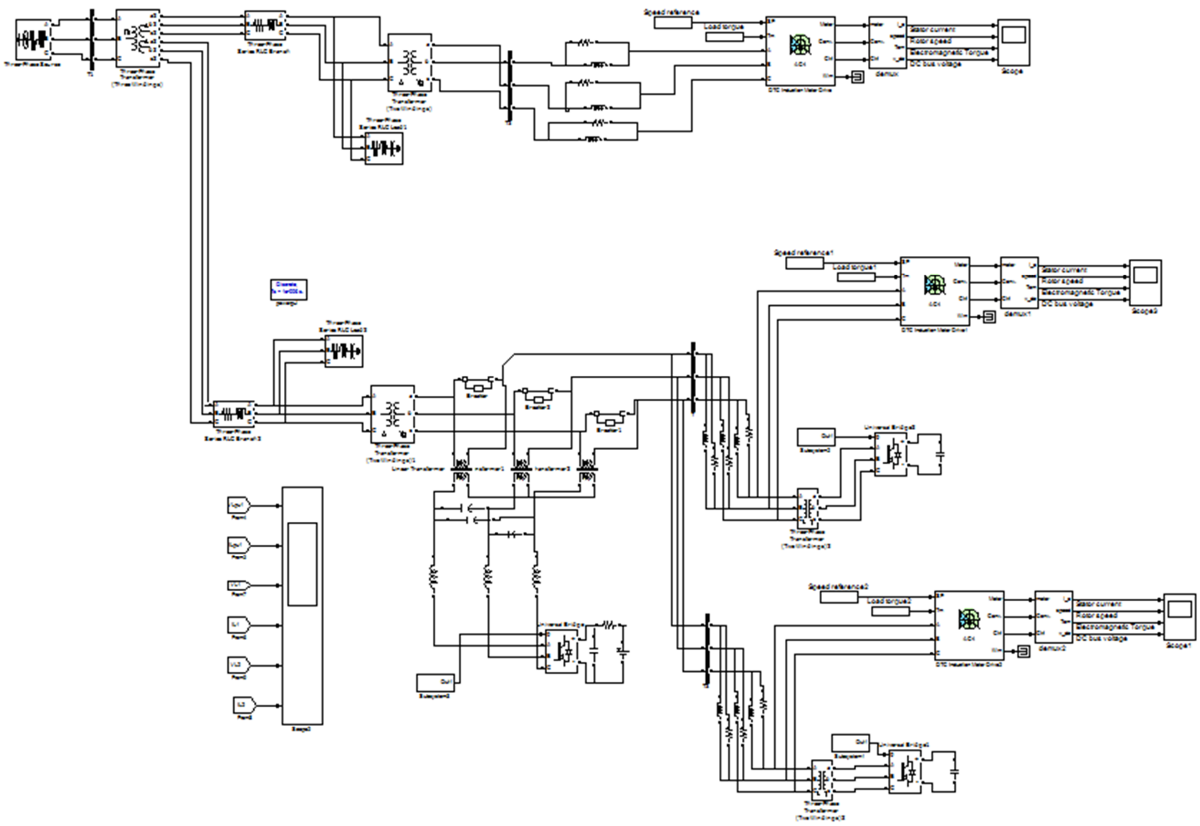


Figure 5.14: Simulation model of OPEN UPQC using DTC induction motor drive as load

Simulation and Results

An ideal three-phase sinusoidal supply voltage is applied to the non-linear load (Direct torque control Induction motor drive) injecting current and voltage harmonics into the system. Figure 5.15(a) shows load 1 voltage in three-phase before compensation. Figure 5.16(b) shows THD level for uncompensated load voltage. Figure 5.17 (c) shows load 1 voltage in three-phase after compensation. Figure 5.18(d) shows THD level for compensated load voltage. Figure 5.19 (a) shows load 1 current in three-phase before compensation. Figure 5.20 (b) shows THD level for uncompensated load current. Figure 5.2(c) shows load 1 current in three-phase after compensation. Figure 5.22(d) shows THD level for compensated load current Figure 5.23(a)shows load 2 voltage in three-phase after compensation. Figure 5.24 (b) shows THD level for compensated load voltage. Figure 5.25(a) shows load 2 current in three-phase after compensation. Figure 5.26(b) shows THD level for compensated load current. The Total Harmonic Distortion (THD) for load 1 voltage which was 10.99% in Figure 5.16(b) before compensation is effectively reduces to 7.04 % in Figure 5.18 (d) after compensation using PI controller. Shunt inverter is able to reduce the harmonics entering into the system. The Total Harmonic Distortion (THD) for load 1 current which was 24.94% in Figure 5.20 (b) before compensation and effectively reduces to 5.69 % in Figure5.22(d) after compensation using PI controller. The Total Harmonic Distortion (THD) for load 2 voltage which was 10.99% in Figure 5.16 (b) before compensation is effectively reduces to 7.04 % Fig. 5.24 (b) after compensation using PI controller. The Total Harmonic Distortion (THD) for load 2 current which was 24.94% in Figure 5.20 (b) before compensation and effectively reduces to 4.74 % in Figure 5.26 (b) after compensation using PI controller. The voltage compensation is small because system consist of transformers which are already doing compensation for voltage.

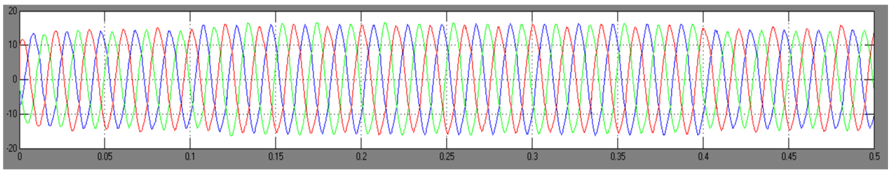


Figure 5.15(a): Load 1, voltage waveform without open UPQC

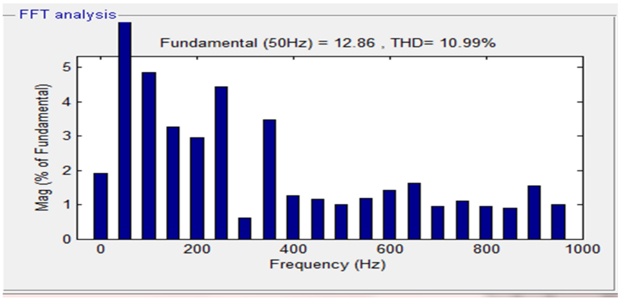


Figure 5.16(b) Load 1, Total harmonic distortion without open UPQC for voltage

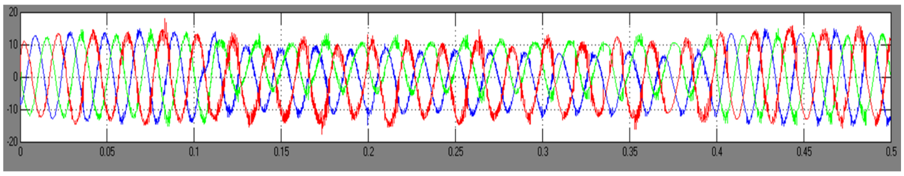


Figure 5. 17(c): Load 1, voltage waveform with open UPQC

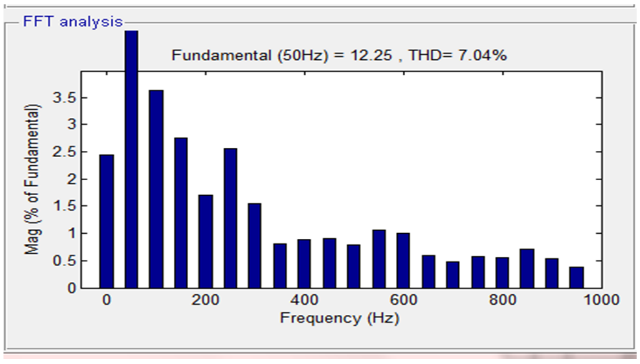


Figure 5.18(d) Load 1, Total harmonic distortion with open UPQC for voltage

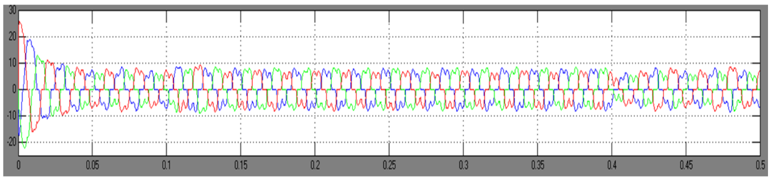


Figure 5.19:(a) Load 1, current waveform without open UPQC

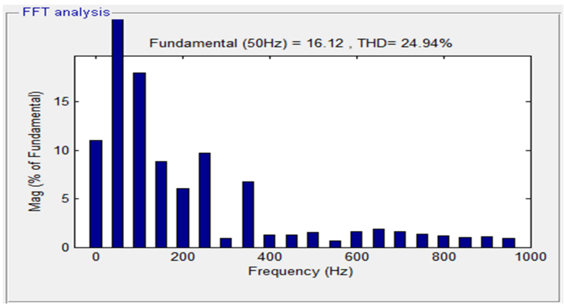


Figure 5.20(b): Load 1, Total harmonic distortion without open UPQC for current

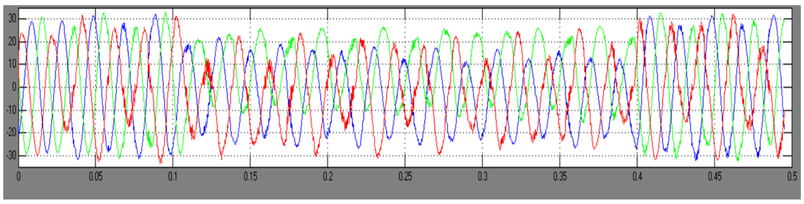


Figure 5.21(c): Load 1, current waveform with open UPQC

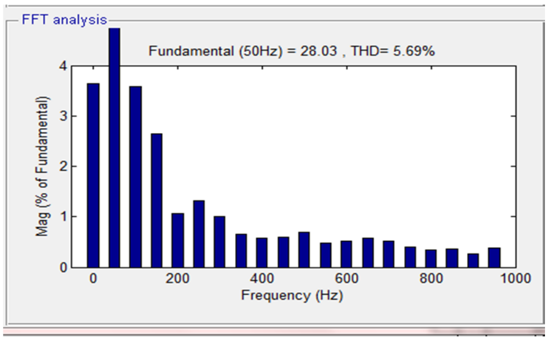


Figure 5.22(d): Load 1, Total harmonic distortion with open UPQC for current

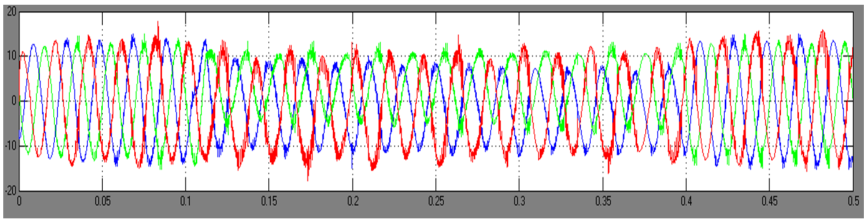


Figure 5.23(a) :Load 2, voltage waveform with open UPQC

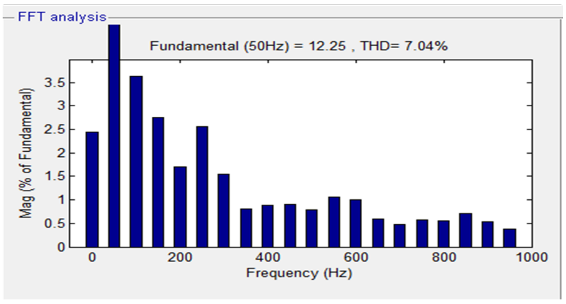


Figure 5.24(b): Load 2, Total harmonic distortion with open UPQC for voltage

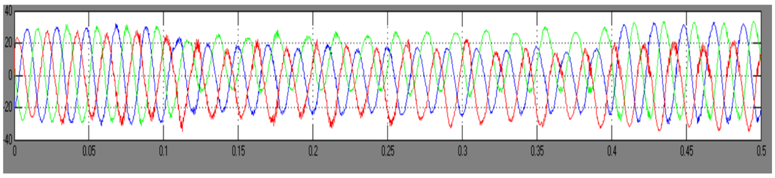


Figure 5.25(a): Load 2, current waveform with open UPQC

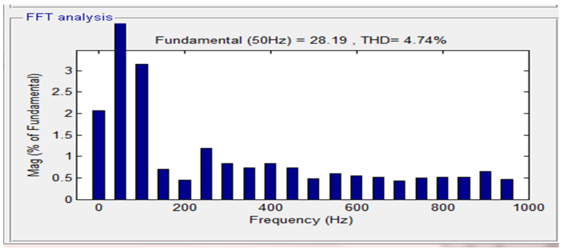


Figure 5.26(b): Load 2, Total harmonic distortion with open UPQC for current

CHAPTER 6

6.1 Conclusion

In the research, the main objectives for the utilization of the studied equipment have been to mitigate reducing the distortion level occurring in the cases of harmonics generating load in distribution networks and thus 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 series connected voltage-source converter known as Dynamic Voltage Restorer and shunt connected Dstatcom is suitable and satisfactory. Being reliable and cost effective, it was adopted to be the optimal solution for the compensation of voltage and current .

The highly developed graphic facilities available in MATLAB/SIMULINK were used to carry out extensive simulation studies on open unified power quality conditioner . The control scheme used is pi control along with static (linear) load and adjustable speed drive (non-linear) load. Therefore, UPQC is considered to be an efficient solution . Open UPQC is capable of reducing the level of THD in the case of networks which are connected to the harmonics generating load (like ASD).

6.2 Future Work

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

- The application of the model show in this work may be extended to other Power Electronic loads used in a modern hi-tech industry.
- Other advanced controllers like fuzzy controller , adaptive fuzzy controller, parallel active filter based on p-q theory, series active filter using instantaneous theory can be used with OPEN UPQC to increase the effectiveness of UPQC in distribution.

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