

**INVESTIGATIONS ON THE EFFECTIVENESS OF UPQC IN  
DISTRIBUTION NETWORKS WITH DTC DRIVE AS LOAD**

*Thesis submitted in partial fulfilment of the requirements for the award  
of degree of*

**MASTER OF ENGINEERING  
IN  
POWER SYSTEMS & ELECTRIC DRIVES**



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## CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled "INVESTIGATIONS OF THE EFFECTIVENESS OF UPQC IN DISTRIBUTION NETWORKS WITH DTC DRIVE AS LOAD" in partial fulfilment of requirement for the award of the master degree in POWER SYSTEM AND ELECTRIC DRIVES engineering submitted in the ELECTRICAL AND INSTRUMENTATION ENGINEERING department, Thapar University, Patiala is an authentic record of my own work carried out under the guidance of **Mr. PARAG NIJHAWAN**, (Assistant Professor EIED, Thapar University).

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

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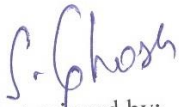
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This is to certify that the above statement made by the candidate is correct & true to the best of my knowledge & belief.


  
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## **ABSTRACT**

Power quality problem is a presence of nonstandard voltage, current or frequency that results in a failure 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 taking new dimensions. The concept of custom power was introduced to distribution systems for improving the system performance. Unified Power Quality Conditioner (UPQC) is a custom power device which can compensate for both voltage and current at distribution level and controls the reactive power flow at the same time. It protects the consumer at the load end from supply voltage sag, and provides unity power factor condition at the utility for different values of load power factor.

In this thesis work UPQC is realized using MATLAB/SIMULINK. The model is tested for varying load conditions under normal and faulted conditions. Comparison of voltage and current level in different operating condition is done along with the comparison of Total Harmonic Distortion (THD) level with and without UPQC compensation is presented. UPQC is realized using IGBT based PWM-VSI inverter having a DC bus capacitor. A dqo transformation based PWM current controller is used to derive gating pulses for the IGBT switch. It is seen that UPQC is effective in compensating current, harmonics, reactive power and improving the power quality of the distribution system.

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## LIST OF ABBREVIATIONS

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BESS	Battery Energy Storage System
DSTATCOM	Distribution Static Compensator
DTC	Direct Torque Control
DVR	Dynamic Voltage Restorer
ESS	Energy Storage System
FACTS	Flexible AC Transmission Systems
FFT	Fast Fourier Transform
GTO	Gate Turn-Off Thyristor
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
MOSFET	Metal-Oxide Semi-conductor Field effect Transistor
PI	Proportional Integral
PLL	Phase Locked Loop
PQ	Power Quality
PWM	Pulse Width Modulation
SA	Surge Arrester
SMESS	Super Magnetic Energy Storage System
SVC	Static VAR Compensator
THD	Total Harmonic Distortion
UPQC	Unified Power Quality Conditioner
VSC	Voltage Source Converter

## INTRODUCTION

---

### 1.1 Overview

Delivering sinusoidal voltage and current at receiving end of the power system network with proper magnitude and frequency is very important. Power quality problems [1] such as voltage sag, voltage swell, flickering; transients etc. are undesirable and need to be solved out. Although the power generated at the synchronous generator is almost sinusoidal but due to some problems such as lightening, faults or non-linear loads cause it to differ from what is actually needed. For example, electric arc furnace is a highly inductive load hence it always introduce harmonics in the circuit, also electric arc welding shops near premises.

Electricity supply plays an important role in the economic development and technology advancement throughout the world. The quality and reliability of power supplies relates closely to the economic growth of a country. The main task of the utility system is to provide the power to load with proper sinusoidal wave of the voltage and current, with fixed frequency (50Hz in case of India) and magnitude with less total harmonic distortion (THD) as possible according to IEEE 519-1992 standard (THD should be less than 5%). Our power system contains many non-linear loads like electric arc furnaces, power electronic convertors etc. which introduce current and voltage harmonics. Also the loads like computers, micro-controllers are sensitive loads; their proper functioning depends upon the quality of power supplied. However, power quality [1] disturbances such as sags, swells, flicker, harmonics, voltage imbalance etc., create a lot of problems in achieving a reliable and quality power supply. To mitigate these problems, power electronics based FACTS devices [2,16] are used in distribution systems.

Custom power devices are power electronic based devices rated 1 to 38 kV employed in distribution network to improve power quality [1] and enhance reliability of power supply. The FACTS based application of power electronic devices can also be effective for the power distribution systems to enhance the quality and the reliability of power delivered to the consumers. These devices are often called as custom power devices [3]. There are many types of custom power devices such as active power filters (APF), dynamic voltage restorer (DVR), super conducting magnetic energy system (SMES), solid state transfer switches (SSTS), static VAR compensator (SVC), surge arrestors, static electronic tap changers (SETC),

distribution static synchronous compensator (DSTATCOM), distribution series capacitor (DSC), uninterruptible power supply (UPS) and unified power quality conditioner (UPQC). The device considered in this work is UPQC, it contains a series and shunt compensator, series compensator maintains voltage quality and magnitude, while shunt provides VAR compensation. In the following report UPQC is presented. The case study showing the working and performance of the UPQC is also presented. As it contains both series and shunt compensator devices, connected in cascade manner through a DC capacitor link, both the devices are fired by gating signals. The gate pulses are generated by control technique used. UPQC performs the following functions [4].

- a) It maintains the load end side voltage to 1 p.u in case of sudden fault and voltage sag.
- b) It eliminates the harmonics in the current.
- c) It provides the VAR to load so that the current and voltage lies in phase. So that there is no requirement of the power factor correcting device.

The voltage to be boosted in case of sag is always in quadrature advance to the supply voltage. The quadrature injection of voltage requires additional capacity of series compensator and puts limitation on the range of sag mitigation. However, this scheme leads to a reduced VA rating of the shunt compensator as active power consumption by the series compensator is minimized. Additionally, the series compensator shares a part of VAR of the load. In this paper, the effectiveness of UPQC is investigated for distribution network with nonlinear load (DTC drive) under normal and faulted conditions. The SIMULINK model and results obtained are shown for the purpose of validation.

## 1.2 Literature Survey

To provide quality power 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.

**R. C. Dugan** *et al.* [1] have discussed basic power quality problems and methods to counter/suppress these problems.

**N. G. Hingorani** *et al.* [2] have presented 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.

**R. Omar** *et al.* [3] have presented the low voltage dynamic voltage restorer (DVR) based on application of space Vector Pulse Width Modulation (SVPWM) for three phases Voltage Source Converter (VSC) and it is the standard PWM techniques to utilize the DC-AC power conversion. A control technique based on SVPWM is also proposed for dynamic voltage restorer.

**M. Tarafdar Haque** *et al.* [4] have 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.

**M. Basu** *et al.* [5] have presented a PC based new hybrid control technique, which was tested for the laboratory prototype. The advantage of the prototype is that SERC can also share the VAR compensating burden.

**J. W. Dixon** *et al.* [6] have 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.

**O. A. Lara** *et al.* [7] have demonstrated the timely issue of modeling 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.

**S. Shankar** *et al.* [8] have 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.

**V. K. Ramachandramurthy** *et al.* [9] have presented a dynamic voltage restorer (DVR) based on the voltage space vector PWM (VSPWM) algorithm. In which phase jump compensation is achieved using a software phase-locked loop (SPLL). A battery charging control technique using the DVR itself was also described.

**M. G. Molina** *et al.* [10] have presented a dynamic performance of distribution static compensator (DSTATCOM) coupled with an energy storage system for improving power quality in distribution system. The presented work was analyzed as voltage controller, a power factor controller and an active power controller. The work was done with the theory of instantaneous reactive power theory.

**N. G. Hingorani** *et al.* [11] have presented a book in 2000 based on technology on power electronics to understand the better way of FACTS devices. A practical approach for power electronic devices is presented for electrical engineers to understand the application and instrument maintenance.

**F. Shahnia** *et al.* [12] have presented the application of series (DVR) and parallel (DSTATCOM) custom power devices are investigated to mitigate these problems. Load flow analysis was first carried out to investigate the effects of PVs on network voltage profile.

**K. Chatterjee** *et al.* [13] have presented a novel control method for a reactive volt-ampere compensator and harmonic suppressor system was proposed. It operates without sensing the reactive volt-ampere demand and nonlinearities present in the load. The compensation technique was operated in cycle by cycle in reference current control mode to achieve the instantaneous compensation.

**D. L. Brooks** *et al.* [14] have presented an example case that illustrates the use of power quality measurement estimation by an electric utility for a customer power quality study. Methods for estimating power quality measurement data and the associated quality indices from existing filed measurement and simulation were discussed.

**B. Singh** *et al.* [15] have presented a comprehensive review of active power filter configurations, control strategies, selection of components, other related economic and technical considerations and their selection for specific application.

**A. Ghosh** *et al.* [16] have presented 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.

**S. Khalid** *et al.* [17] have presented the power quality problems related to international standard. The effect of power quality problem in different apparatuses and methods for its correction was studied.

**K. R. Padiyar** [18] has presented the details of the facts controller devices. The problems related to the power system were discussed and their remedies were given in this book.

**A. Kusko** *et al.* [19] have presented the latest engineering techniques for providing power quality to all customers, and includes vital information on manufacturing, data processing, and healthcare facilities based on an IEEE Professional Education.

**N. Mohan** *et al.* [20] have presented power electronics fundamentals for applications and design in the power range of 500 kW or less also a variety of practical and emerging power electronic converters made feasible by the new generation of power semiconductor devices.

**V. Khadkikar** [21] has presented comprehensive review on the unified power quality conditioner (UPQC) to enhance the electric power quality at distribution levels. It was noticed that several researchers have used different names for the UPQC based on the unique function, task, application, or topology under consideration.

### **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 in distribution network. The major objectives are summarized as follows:

- 1) To study the model of UPQC.
- 2) To investigating the performance of Unified Power Quality Conditioner (UPQC) in distribution network with DTC drive under normal and faulted conditions.

## **1.4 Organization of Thesis**

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

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

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

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

The Chapter 4 discusses the 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 highlights the conclusions and future scope of work.

# POWER QUALITY

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### 2.1 Definition

According to the IEEE standard, power quality is defined as the “concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment.” Power distribution system should provide their customer with uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude of level and frequency. However, in power system, especially in distribution system, have many nonlinear loads, the pure sinusoidal waveform is lost. This creates power quality problems [1]. Some of the sources of power quality problems are: L-G fault, double-line to ground fault, arcing devices, lightning strike, starting of large motors, sensitive equipment, environmental related damage, transformer energization [16].

### 2.2 Need of Power Quality

Need of Power Quality there is an increased concern of power quality due to the following reasons [14]:

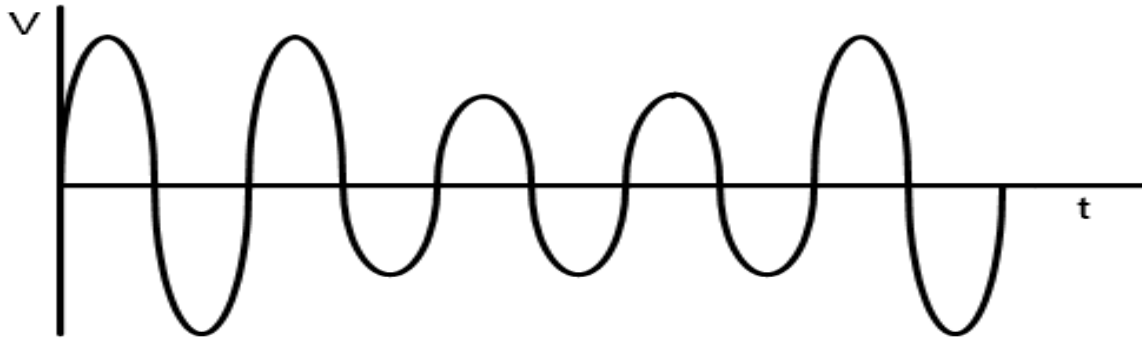
- 1) Microprocessor and microcontroller based system controls and power electronic devices, are more sensitive loads.
- 2) Harmonic levels are increased due to the increased demand of high efficiency devices like adjustable speed motor drives, shunt capacitors for power factor correction instruments.
- 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.

### 2.3 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 as shown in figure 2.1. The external causes of sag come from the utility transmission and

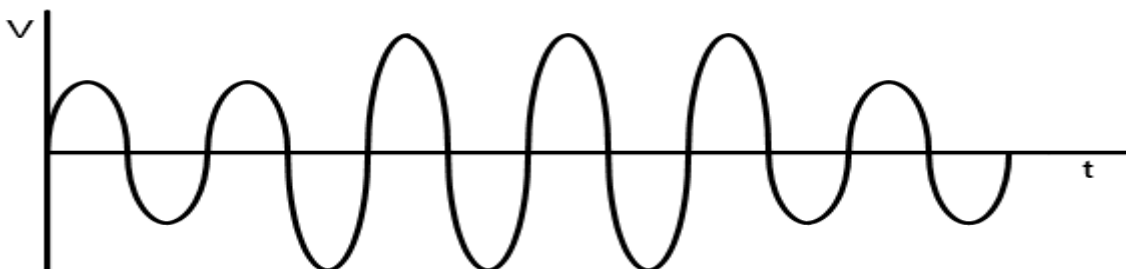
distribution network. The Sags comes from the utility have a variety of cause like lightning, animal and human activity, and normal and abnormal utility equipment operation. The Sags generated on the transmission or distribution system can travel hundreds of miles thereby affecting thousands of customers during a single event.



**Figure 2.1: Voltage Sag**

### 2.3.2 Voltage Swell

Voltage swell is opposite to voltage sag. It is the 10% increase in the value of applied voltage for half a cycle to one min as shown in figure 2.2. It is often caused due to switching off of loads and switching on of capacitor bank.



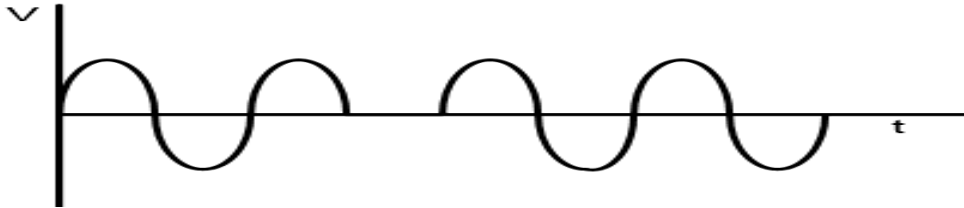
**Figure 2.2: Voltage Swell**

### 2.3.3 Interruption

When voltage level drops below its 10% value of its original value, then it are termed as black out or interruption as shown in figure 2.3. They are the worst type of error and also most little likely to occur. They are of three types (a) momentary interruption (last for 30 seconds). (b) Temporally (last for 1min). (C) sustained interruption (last for more than one min.).

### 2.3.4 Over-Voltages

Over voltage is the increase in the rms value more than 110% of the ac voltage at the power frequency for a duration more than 1 min. they happens due to the switching of loads and incorrect tap changing of transformer.



**Figure 2.3: Voltage Interruption**

### 2.3.5 Under-Voltage

Under voltage is a decrease in voltage rms value less than 90% of the power frequency voltage for more than 1 min duration. It is also known as Brownout, when utility does it intentionally.

### 2.3.6 Electrical Noise

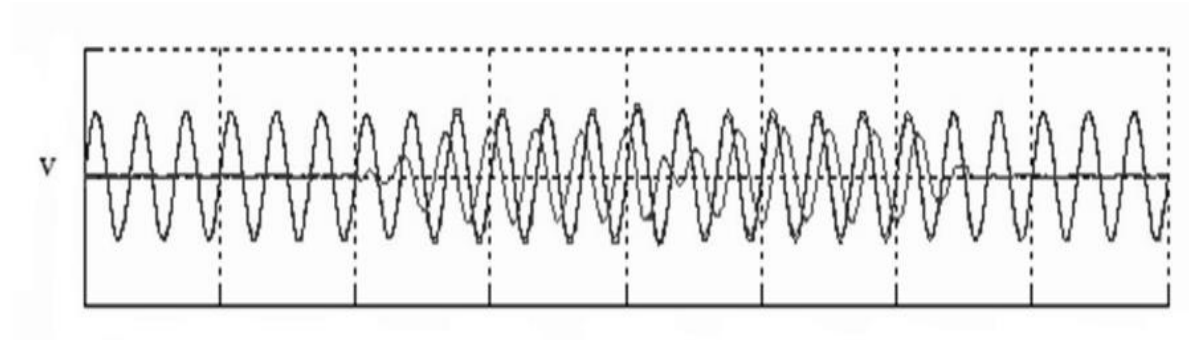
Noise is responsible for high frequency distortion of voltage waveform. It is caused by disturbance in the utility system or by equipment such as welder, switchgear and transmitter.

### 2.3.7 Transients

Transients results in deflection of original wave form from its wave shape. These are two types (a) Impulsive transients (b) oscillatory transients. Impulsive transients are the in which wave deforms at only on the upper side (unidirectional). Lightning strikes, switching of inductive load are the main causes of them. Oscillatory transients are the bidirectional variations of the wave. These are caused due to the power factor correcting capacitors in the system.

### 2.3.8 Harmonics

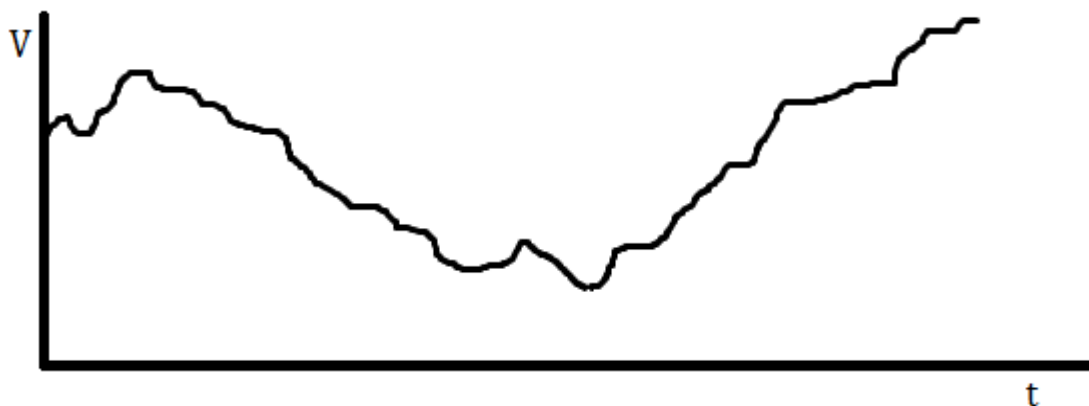
Harmonics are the periodic sinusoidal distortion of the supply voltages or load current due to non-linear loads as shown in figure 2.4. Harmonics are measured in integer multiple of fundamental frequency.



**Figure 2.4: Showing Voltage Harmonics**

### 2.3.9 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.

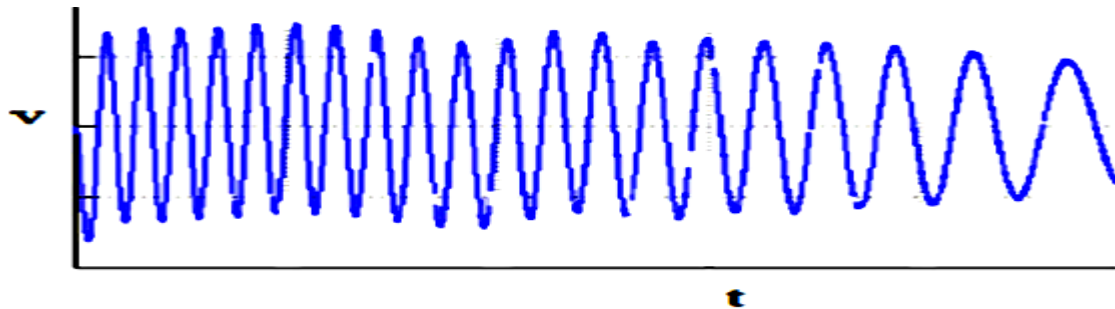


**Figure 2.5: Voltage Fluctuations**

### 2.3.10 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.

- **DC offset:** The presence of a dc voltage or current in an AC power system is termed dc offset. Due to the DC offset the actual wave form is either shifted above or below the main axis of the symmetry. The peak value of



**Figure 2.6: DC Offset in Voltage**

## 2.4 Causes of Poor Power Quality

Sources of poor Power Quality are listed as follows [15]:

- 1) Adjustable–speed drives.
- 2) Switching Power supplies.
- 3) Arc furnaces.
- 4) Electronic Fluorescent lamp ballasts.
- 5) Lightning Strike.
- 6) L-G fault.
- 7) Non- linear load.
- 8) Starting of large motors.
- 9) Power electronic devices.

## 2.5 Solutions to Power Quality Problems

Power quality can be improved by two ways either from the customer side or from the utility side. There are two methods of namely: **Load conditioning** ensures that the equipment is less sensitive to the disturbances, allowing operation under significant voltage distortion. While the installment of the **line conditioning** systems suppress or counteracts the power system disturbances.

- (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 use 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 equipment's 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. 12-pluse or higher transformer connection can also be used for same purpose. 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.

**CUSTOM POWER DEVICES**

---

**3.1 Introduction**

The concept of custom power was introduced by N. G. Hingorani [2]. 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.

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.

A recent survey of Power Quality experts indicates that 50% of all Power Quality problems [1] are related to grounding, ground bonds, and neutral to ground voltages, ground loops, ground current or other ground associated issues. Electrically operated or connected equipment is affected by Power Quality [17-21]. Determining the exact problems requires sophisticated electronic test equipment. The following symptoms are indicators of Power Quality problems:

- Piece of equipment misoperates at the same time of day.
- Circuit breakers trip without being overloaded.
- Equipment fails during a thunderstorm.

**3.2 Power Quality Standards**

Power quality is a worldwide issue, and keeping related standards current is a never-ending task. It typically takes years to push changes through the process. Most of the ongoing

work by the IEEE in harmonic standards development has shifted to modifying Standard 519-1992.

**A) IEEE 519 IEEE 519-1992**

Recommended Practices and Requirements for Harmonic Control in Electric Power Systems, established limits on harmonic currents and voltages at the point of common coupling (PCC) or point of metering [18]. The limits of IEEE 519 are intended to: 1) Assure that the electric utility can deliver relatively clean power to all of its customers; 2) Assure that the electric utility can protect its electrical equipment from overheating, loss of life from excessive harmonic currents, and excessive voltage stress due to excessive harmonic voltage. Each point from IEEE 519 lists the limits for harmonic distortion at the point of common coupling (PCC) or metering point with the utility. The voltage distortion limits are 3% for individual harmonics and 5% THD. All of the harmonic limits in IEEE 519 are based on a customer load mix and location on the power system. The limits are not applied to particular equipment, although, with a high amount of nonlinear loads, it is likely that some harmonic suppression may be necessary.

**B) IEEE 519 Standard for Current Harmonics**

- 1) **General Distribution Systems [120V- 69 kV]:** Below current distortion limits are for odd harmonics. Even harmonics are limited to 25% of the odd harmonic limits. For all power generation equipment, distortion limits are those with  $I_{SC} / I_L < 20$ .  $I_{SC}$  is the maximum short circuit current at the point of coupling "PCC".  $I_L$  is the maximum fundamental frequency 15-or 30- minutes load current at PCC. TDD is the Total Demand Distortion (=THD normalized by  $I_L$ ).
- 2) **General Sub-transmission Systems [69 kV-161 kV]:** The current harmonic distortion limits apply to limits of harmonics that loads should draw from the utility at the PCC. Note that the harmonic limits differ based on the  $I_{SC} / I_L$  rating, where  $I_{SC}$  is the maximum short- circuit current at the PCC, and the maximum demand load current at the PCC.

**C) IEEE Standard for Voltage Harmonics**

IEEE-519 - Voltage Distortion Limits the voltage harmonic distortion limits apply to the quality of the power. For instance, for systems of less than 69 kV, IEEE 519 requires limits of 3 percent harmonic distortion for an individual frequency component and 5 percent for total harmonic distortion.

**Table 1: Voltage Distortion Limits for Harmonics**

<b>BUS VOLTAGE (kV)</b>	<b>INDIVIDUAL (%)</b>	<b>THD (%)</b>
V < 69	3.0	5.0
69 < V < 161	1.5	2.5
V > 161	1.0	1.5

### 3.3 Need and Classification of Custom Devices

The first sign of a power-quality problem is a distortion in the voltage waveform of the power source from a sine wave, or in the amplitude from an established reference level, or a complete interruption. The disturbance can be caused by harmonics in the current or by events in the main voltage supply system. The disturbance can go for a fraction of a cycle (milliseconds) to great durations (seconds to hours) in the voltage supplied by the source. The aim for method for correction is to make the power source meet an international standard. Power-quality problems can basically start at four levels of the system that delivers electric power, first one, includes Power plants and the entire area transmission system. The second one are Transmission lines, major substations whereas third one includes distribution substations, primary, and secondary power lines, and distribution transformers and last and fourth one includes service equipment and building wiring. In addition, the problems can be caused by the equipment supplied with electric power for example, power-electronic converters. Redundancy at all levels of the electric-power system reduces the incidence and duration of line-voltage disturbances. The classification of custom power devices can be done into two major categories, one is network configuring type and the other is compensating type.

- **Network Configuring 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.
- **Compensating Type:** Compensating type devices includes DVR, DSTATCOM, and UPQC etc. they are either held in series or shunt to compensate for the electrical quantity like voltage or current respectively or both.

### 3.3.1 Solid State Current Limiter

Transformer with split secondary is used to limit the current due to fault. Figure 3.1 shows the basic configuration of the 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.

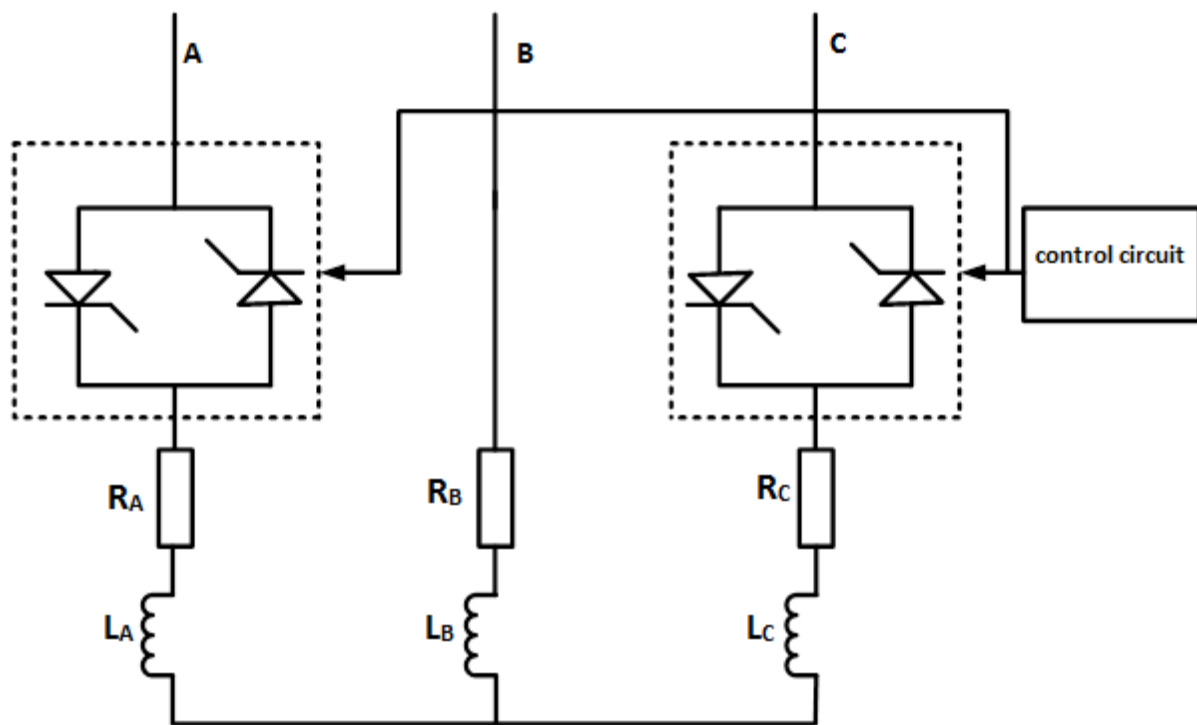
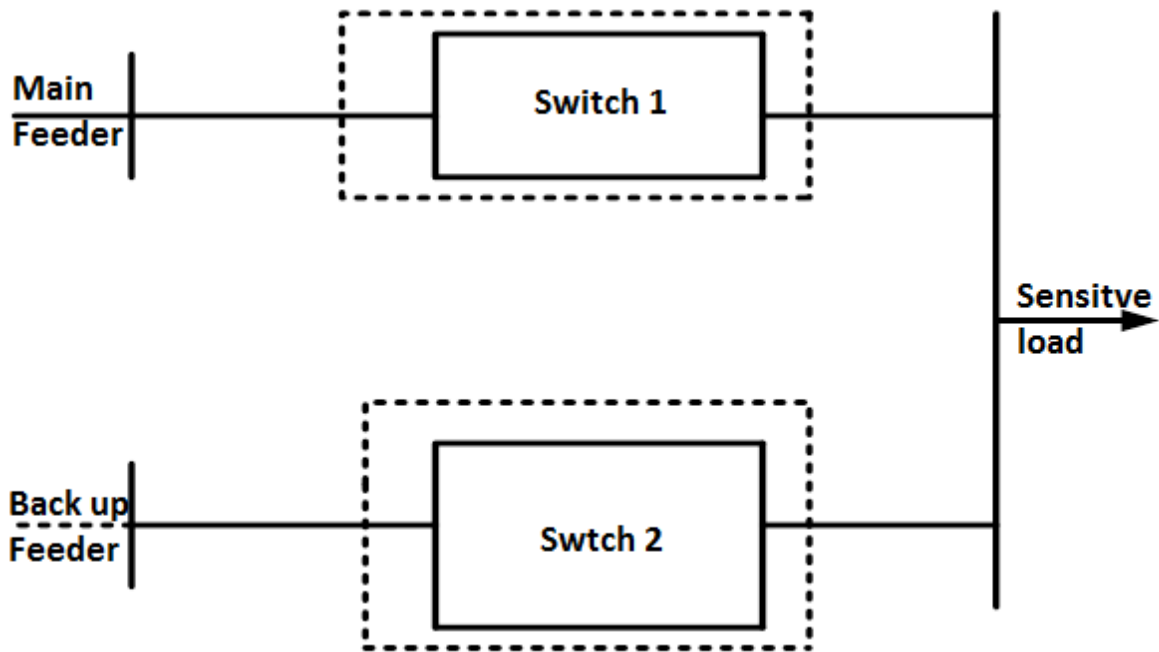


Figure 3.1: Solid State Current Limiter

### 3.3.2 Solid State Transfer Switch

Sensitive load can be protected against the voltage swell and voltage sag by SSTS. It contains two way switches which connect the sensitive load from the supply. The switch intern contains the antiparallel combination of SCR. Whenever fault condition is detected in main feeder the firing sequence is transferred to the backup feeder, now the load is supplied from the backup feeder until the fault is cleared and healthy condition restored. 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. Basic configuration of SSTS is shown in figure 3.2.



**Figure 3.2: Solid State Transfer Switch**

### 3.3.3 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 control technique is used can be of any type. Whenever there is any change in the voltage the compensating voltage is inserted into the line as a series voltage. And hence maintain the load voltage as the desired value.

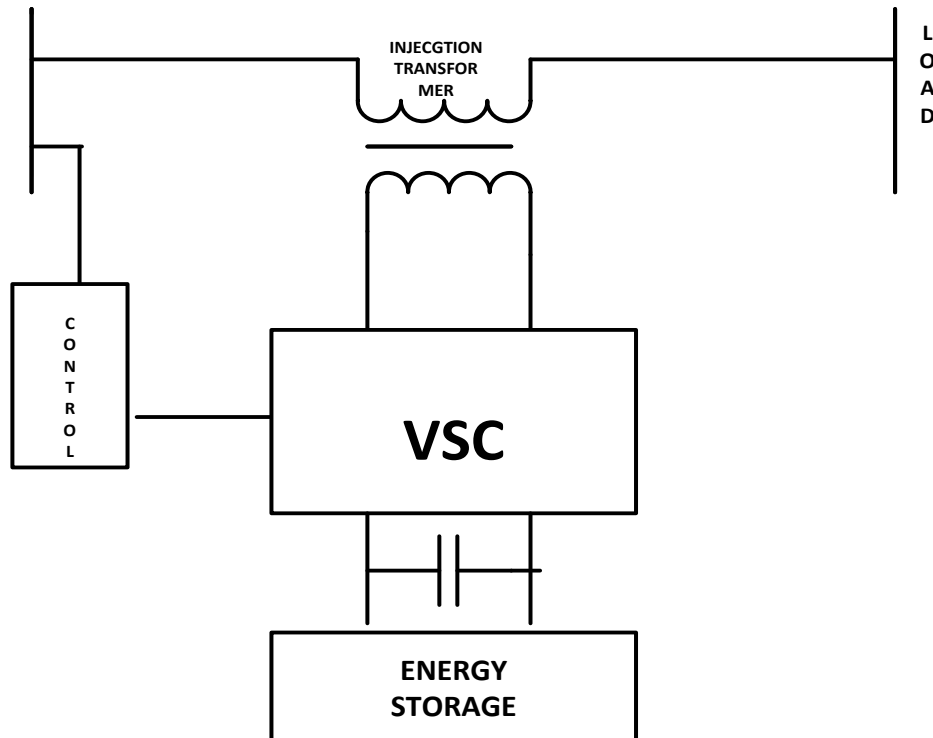
#### 3.3.3.1 Basic Configuration of DVR

The main component of DVR is a series convertor, DC capacitors, low pass filters, high pass passive filters and series transformers.

#### 3.3.3.2 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).



**Figure 3.3: Dynamic Voltage Restorer [9]**

### 3.3.3.3 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 are  $Y / Y_0$  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.

### 3.3.3.4 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.

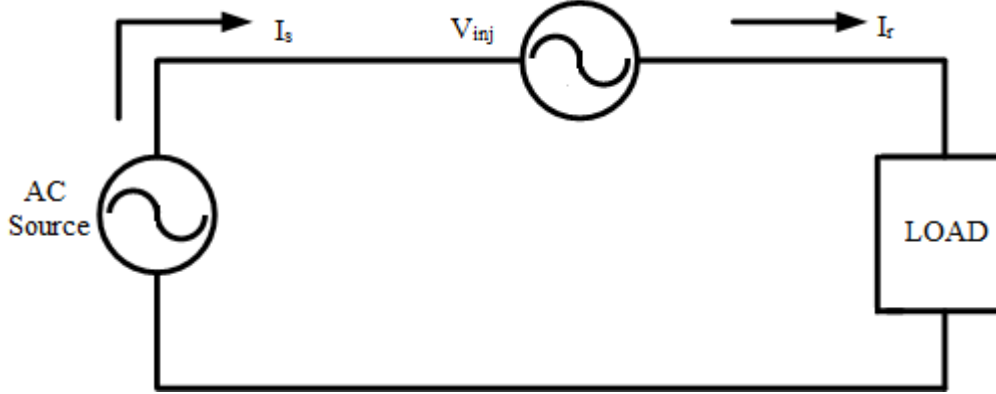
### 3.3.3.5 Series Transformer

These transformers are used to inject the series compensated voltage into the line.

Due to the voltage Distortion, the system may contain negative phase sequence and harmonic components. In general the source voltage in Fig 3.2 can be expressed as:

$$V_s + V_{dvr} = V_L \quad \dots (3.1)$$

Where,  $V_L$  = Voltage across the load.



**Figure 3.4: Equivalent Model of DVR [3]**

Where,

$V_s$  = Sending end voltage

$V_{dvr}$  = Injected voltage by DVR.

$I_s$  = Sending end current.

$I_r$  = Receiving end current.

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

$$V_{dvr} = (V + V_p) \sin(\omega t + \alpha_p) - V_n(t) - \sum_{k=2}^{\infty} V_k(t) \quad \dots (3.2)$$

$V_p$  = Positive sequence voltage amplitude fundamental frequency.

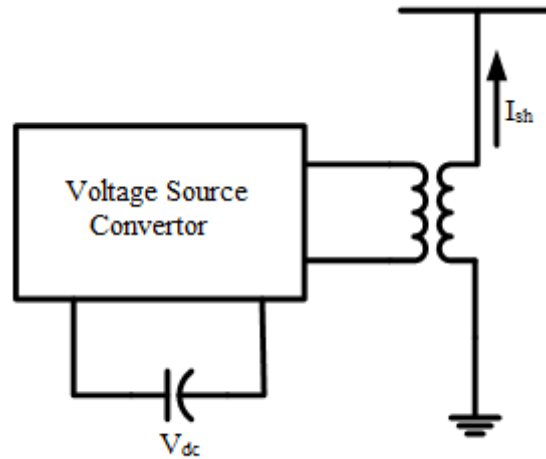
$\alpha_p$  = Initial phase of voltage for positive sequence.

$V_n$  = Negative sequence component.

### 3.3.4 Distribution Static Compensator (DSTATCOM)

DSTATCOM works as same as the DVR but, it compensates the current flowing in the power system. DSTATCOM is a shunt device which the capability to inject or absorb both active and reactive current. The reactive power output of a DSTATCOM is proportional to the system voltage rather than the square of system voltage, as in a capacitor. This makes DSTATCOM more suitable rather than using capacitors. Though storing energy is a problem

for long term basis, considering real power compensation for voltage control is not an ideal case. So most of the operation considered is steady state only and the power exchange in such a condition is reactive. To realize such a model it can be said that a DSTATCOM consist of a small DC capacitor and a voltage source convertor.



**Figure 3.5: Block Diagram of DSTATCOM [10]**

### 3.3.4.1 Configuration of DSTATCOM

The basic configuration of the DSTATCOM is VSC (voltage source convertor), coupling transformer, DC capacitor bank, high pass filter.

### 3.3.4.2 Shunt Convertor

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.

### 3.3.4.3 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/  $Y_0$  the zero-sequence voltage appears in the primary winding of the series-connected transformer in order to compensate for the zero-both

transformers. It ensures the system current to be balanced even when the voltage disturbance occurs.

### 3.3.4.4 High-Pass Filter

It is installed at the output of shunt converter to absorb current switching ripples.

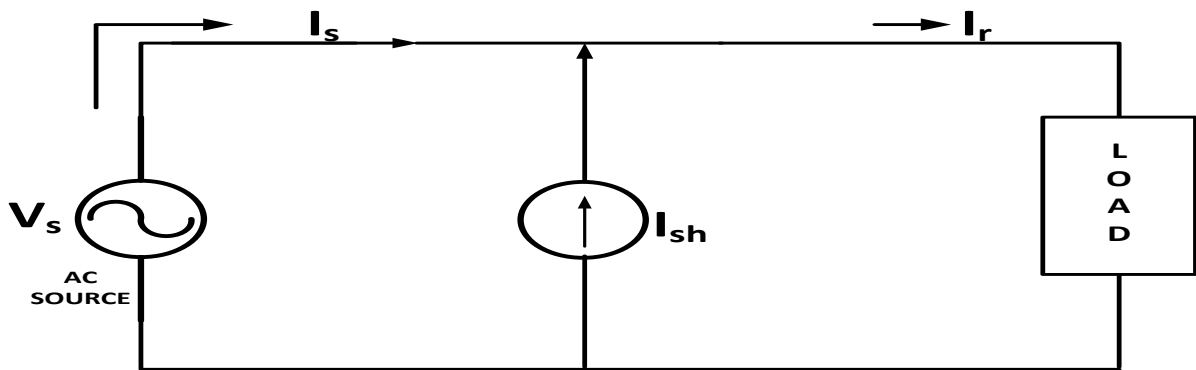


Figure 3.6: Equivalent model of DSTATCOM [10]

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:

$$I_L = I_p \cos(\omega t + \phi_p) \sin(\phi_p) + I_L + \sum_{K=2}^{\infty} I_L \quad \dots (3.3)$$

Where,

$I_L$  = Load current.

$\phi_p$  = 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,

$$I_S = I_L - I_{sh} \quad \dots (3.4)$$

### 3.3.5 Unified Power Quality Conditioner (UPQC)

UPQC is a combination of both DVR and DSTATCOM; it has both series and shunt compensation. The composition and working is same as that of DVR and DSTATCOM. The Details of UPQC have been discussed in chapter 4.

**UNIFIED POWER QUALITY CONDITIONER**

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**4.1 Introduction**

Electricity supply plays an important role in the economic development and technology advancement throughout the world. The quality and reliability of power supplies relates closely to the economic growth of a country. The main task of the utility system is to provide the power to load with proper sinusoidal wave of the voltage and current, with fixed frequency (50Hz in case of India) and magnitude with less total harmonic distortion (THD) as possible according to IEEE 519-1992 standard (THD should be less than 5%). Our power system contains many non-linear loads like electric arc furnaces, power electronic convertors etc. which introduce current and voltage harmonics. Also the loads like computers, micro-controllers are sensitive loads; their proper functioning depends upon the quality of power supplied. However, power quality disturbances such as sags, swells, flicker, harmonics, voltage imbalance etc., create a lot of problems in achieving a reliable and quality power supply. To mitigate these problems, power electronics based FACTS devices [2,16] are used in distribution systems.

The FACTS based application of power electronic devices can also be effective for the power distribution systems to enhance the quality and the reliability of power delivered to the consumers. These devices are often called as custom power devices [3]. Distribution Static Compensator (DSTATCOM), Dynamic Voltage Regulator (DVR) and Unified Power Quality Conditioner (UPQC) are some of the custom power devices used at distribution level. In this paper, the concentration is only on UPQC.

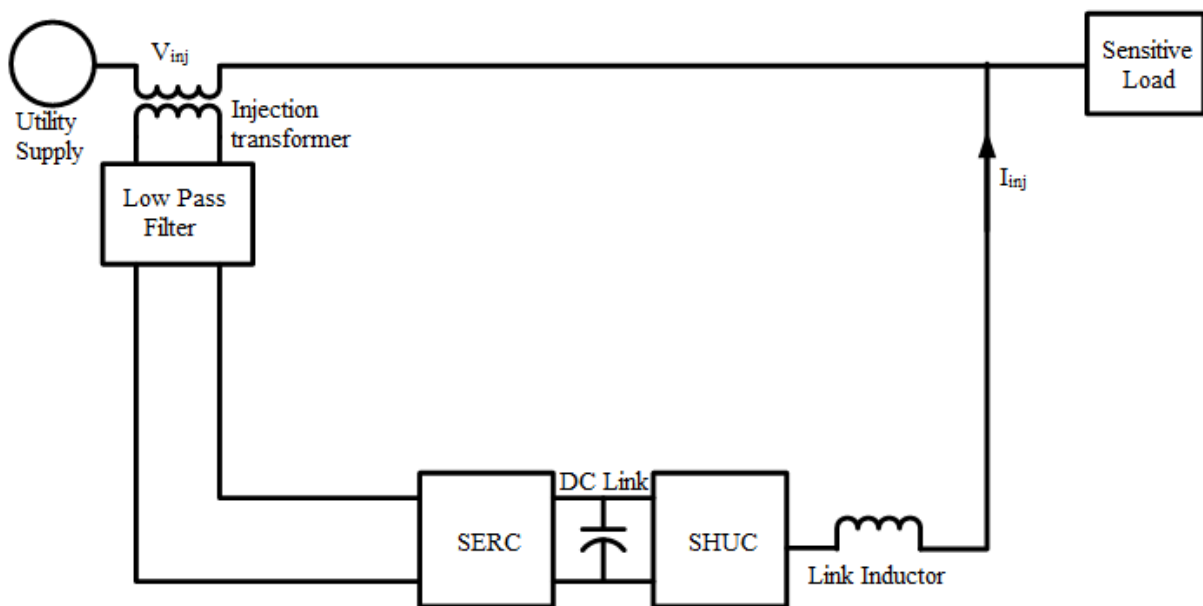
Load compensation using UPQC maintains both voltage and current to sinusoidal at source. As it contains both series and shunt compensator devices, connected in cascade manner through a DC capacitor link, both the devices are fired by gating signals. The gate pulses are generated by control technique used. UPQC performs the following functions [4].

- a) It maintains the load end side voltage to 1 p.u in case of sudden fault and voltage sag.
- b) It eliminates the harmonics in the current.
- c) It provides the VAR to load so that the current and voltage lies in phase. So that there is no requirement of the power factor correcting device.

The voltage to be boosted in case of sag is always in quadrature advance to the supply voltage. The quadrature injection of voltage requires additional capacity of series compensator and puts limitation on the range of sag mitigation. However, this scheme leads to a reduced VA rating of the shunt compensator as active power consumption by the series compensator is minimized. Additionally, the series compensator shares a part of VAR of the load. In this paper, the effectiveness of UPQC is investigated for distribution network with nonlinear load (DTC drive) under normal and faulted conditions. The SIMULINK model and results obtained are shown for the purpose of validation.

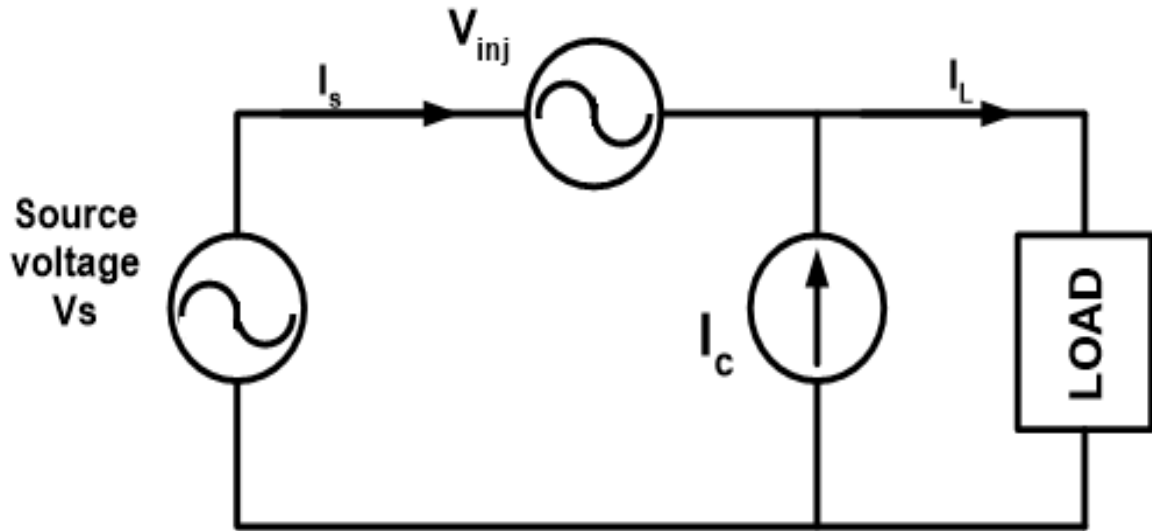
#### 4.2 Configuration of UPQC

The UPQC, whose block diagram is shown in figure1 [5], can be modeled as a combination of ideal controlled voltage source and ideal current source. The equivalent circuit is shown in the figure 2. The ideal controlled voltage source is connected in series in the circuit and current source is connected in shunt of the circuit so that the circuit works same as that of the UPQC.



**Figure 4.1: Block Diagram of UPQC**

The voltage injected in the series by ideal controlled voltage source is always injected in quadrature of the source voltage so that to increase the level of voltage in case of sag. At the time of fault the voltage level at the point of common coupling (PCC) reduces by large amount so it is feasible to consider the quadrature injection of the voltage. This can be shown by the equations given below where voltage source ( $V_s$ ) is taken as reference.



**Figure 4.2 Equivalent Circuit of UPQC**

$$V_L \angle \theta = V_S \angle 0^\circ + V_{inj} \angle \gamma \quad \dots (4.1)$$

Where  $V_L$  is the load voltage and  $V_{inj}$  is the voltage injected by the series compensator of UPQC (SERC). The specific control strategy maintains the angle of injection  $\gamma$  as 90 advances to the supply voltage to minimize the power requirement of the SERC. The current on the other hand is injected in shunt as said earlier. As the current in the whole circuit is same the distortion in the current transferred to the source current so the compensation of DSTATCOM is more important to avoid the penalty, the injection of current can be shown by the equation given by.

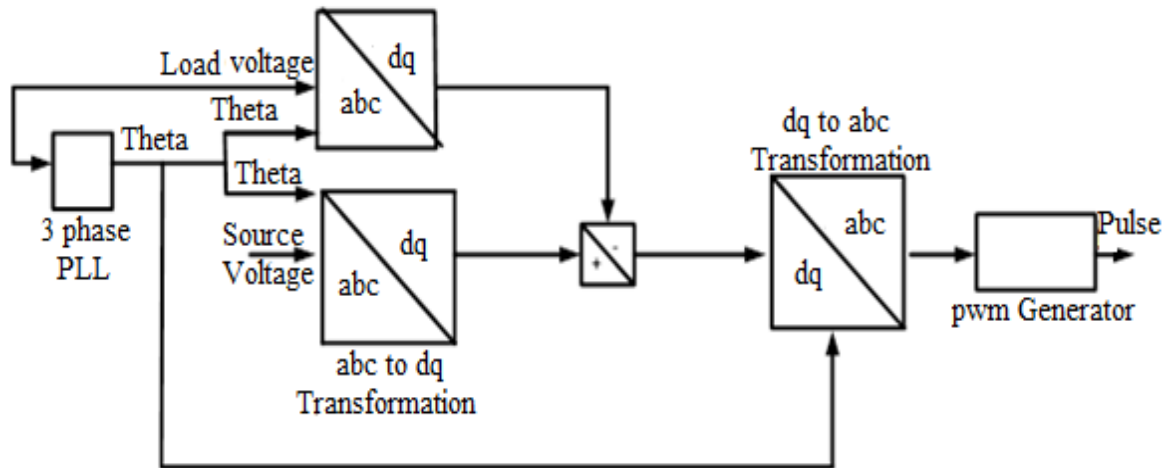
$$I_L(\theta - \phi) = I_S \angle 0^\circ + I_C \angle \beta \quad \dots (4.2)$$

The angle  $\phi$  represents the lagging angle of  $I_L$  with  $V_L$  and angle  $\theta$  is the angle of advancement of the  $V_L$  due to the  $V_{inj}$  with ( $\beta = 90 \pm \theta$ ).

### 4.3 Control Strategy

Synchronous Reference Frame theory [6,8] is used here for controlling of UPQC. The synchronous reference frame theory is based on the transformation of quantity in synchronously rotating d-q frame. In this paper, d-q frame theory is used to control both SERC and SHUC. Figure 4.3 shows the control strategy of SERC, in which voltage from the load and source is converted to its equivalent d-q components, by using the angles from the three phases PLL. The angles for the calculation are generated by using load voltage. After converting the respective voltages of load and source, d-q load voltage is subtracted from the

respective d-q component of source voltage. The resultant voltage is then transferred back to the 3 phase component using reverse transformation. The resultant abc component is the fed to the Pulse With Modulation generator (PWM) through transport delay, where 6 pulses is generated for the bridge convertor.



**Figure 4.3: Control Strategy for SERC [7]**

The d-q transformation is given by is given by

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \sqrt{3/2} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - 120^\circ) & \cos(\omega t + 120^\circ) \\ -\sin(\omega t) & -\sin(\omega t - 120^\circ) & -\sin(\omega t + 120^\circ) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \dots (4.3)$$

Where,

$V_d$ = direct axis component of source or load voltage.

$V_q$ = quadrature axis component of source or load voltage.

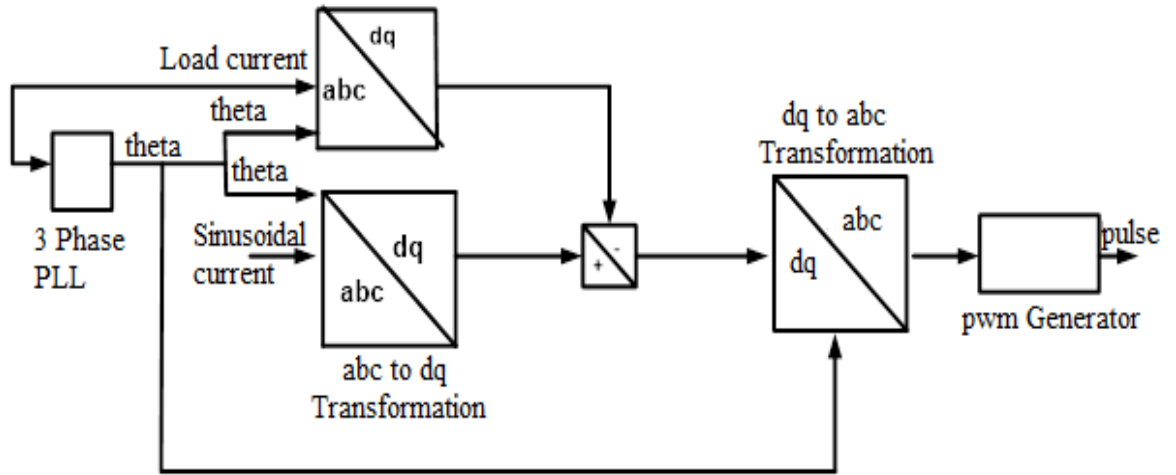
$V_0$ = zero axis component of source or load voltage.

The same formula can be used for current transformation.

Inverse parks transformation for the generation of reference signal can be made by taking inverse of the middle matrix.

Figure 4.4 shows the control strategy for SHUC. It is same as that for SERC, the difference lies in the fact that input in place of control voltage source voltage is the sinusoidal current wave having magnitude of 1 p.u controlled by the angles drawn from the PLL (phase locked loop). The PLL has input of load current. The synchronization of reference current or voltage is done with load side quantities so that the generated reference signal for the PWM generator must be in phase with the load side quantities, otherwise the compensation is not

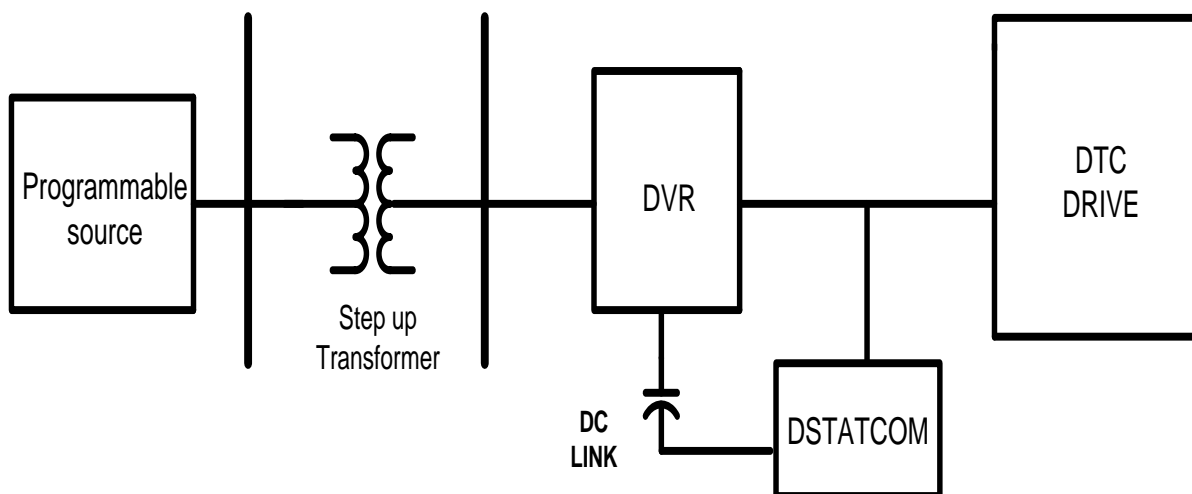
the desired as intended. Same formula can use for current transformation as given in equation 4.3.



**Figure 4.4: Control Strategy for SHUC**

#### 4.4 Test System

In this work, three-phase three-wire model of power system is investigated. A sensitive DTC drive load of 440V and 2238VA is chosen for the purpose of investigation. The effectiveness of UPQC in this test system is investigated under normal and faulted conditions. The load is fed from the utility of 200V and 50 Hz as a source. A step up transformer of 250 MVA is used to step up the utility voltage of 200V to 440V. A cascade connection of two groups of six semiconductor devices is placed in between the transformer and the load. Each group of six semiconductor device works as a convertor, one of which is connected in series with the existing power system and other is connected in shunt of the system. Thus the devices are able to compensate for series as well as shunt compensation.



**Figure 4.5: Block Diagram of Simulation Model of UPQC**

The series compensator of UPQC is connected through a filter so that to remove the harmonics from the injected voltage and shunt compensator of is connected through an inductor in order to remove the distortions in the injected current. The two compensators of UPQC works as Dynamic Voltage Restorer (DVR) and Distribution Static Compensator (DSTATCOM), the series compensator works as DVR and the shunt compensator works as DSTATCOM. The DVR and DSTATCOM are connected to the line with the help of coupling transformer as shown above in figure 4.5.

SIMULINK MODEL AND RESULTS

5.1 Parameters of Test System

System test parameters for UPQC are listed below:

Table 2: Test System Parameters

Source voltage	200 V
Source resistance	0.1 Ω
Source inductance	0.5 mH
Transformer	Nominal power 250 MVA, 50 Hz, star-star, 200 V/440 V, $\left(\frac{r_1}{r_2}, \frac{l_1}{l_2}\right) =$ (0.002/0.002,0.08/0.08) p.u.
DTC drive load	2238 VA, 440 V, 50 Hz

5.2 Simulink Model and Results

The SIMULINK model of test system is shown in figure 5.1. The system is tested for three different conditions. The results for the same are shown below.

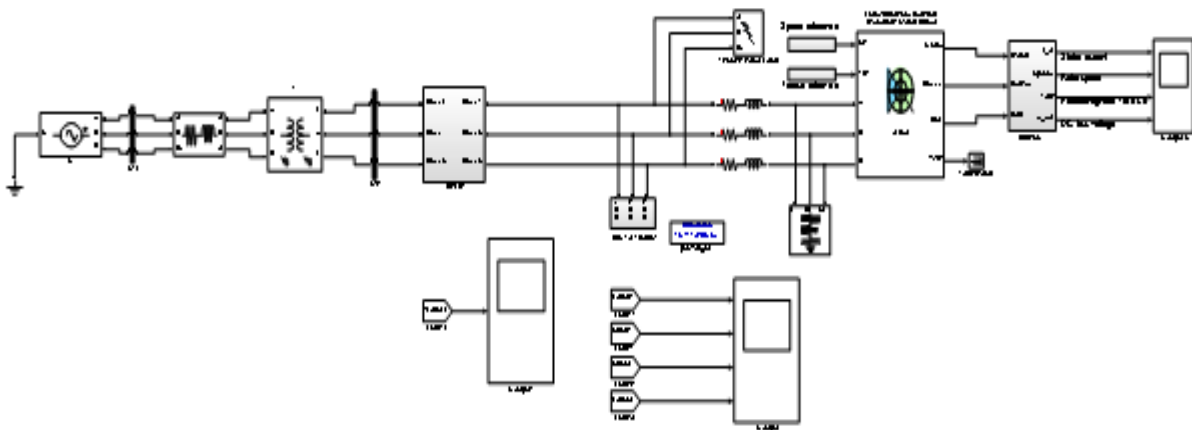
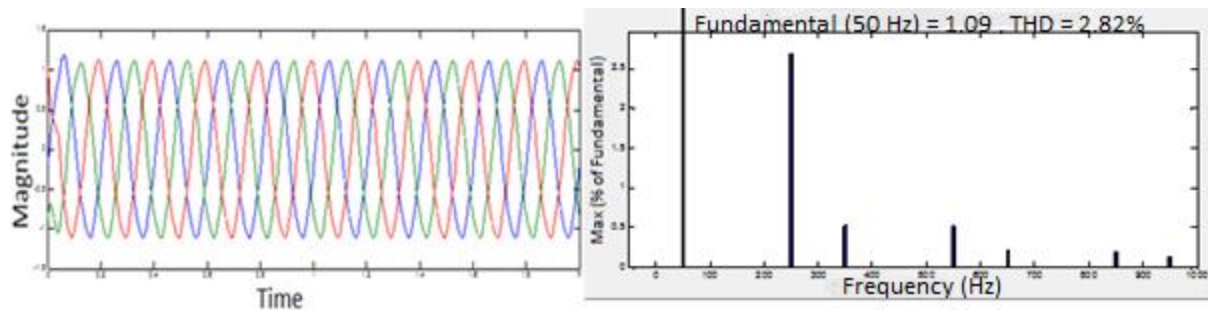


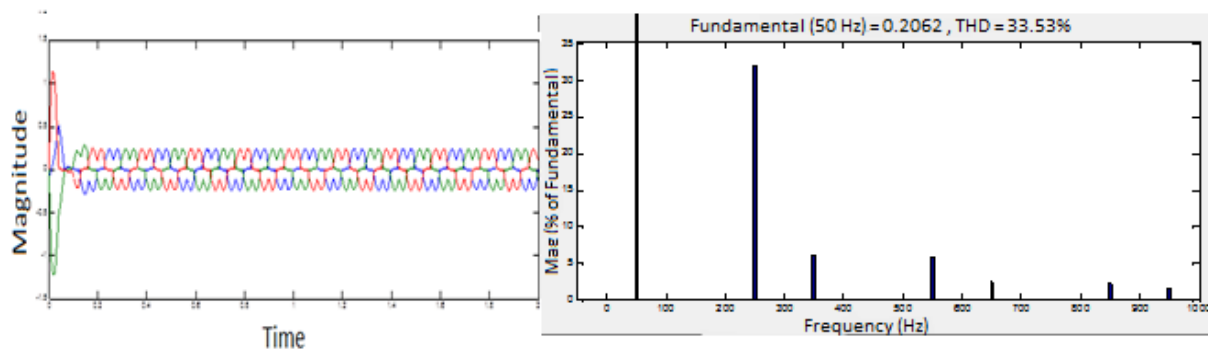
Figure 5.1: Simulink Model for UPQC

Case 1: Results Under Normal Operating Conditions- Simulink diagram for the dynamic load is shown in figure 5.1. The Induction motor drive is used for the purpose. It is a highly

sensitive and non-linear load. The figure 5.2 and 5.3 shows the voltage and current waveform for load during no compensation and their Fast Fourier Transform (FFT) analysis. It can be seen that the voltage harmonic level is low under tolerance; the harmonic level is 2.82% and the magnitude is 1.09p.u and the harmonic level of current is 33.53% and the magnitude level is 0.206p.u.

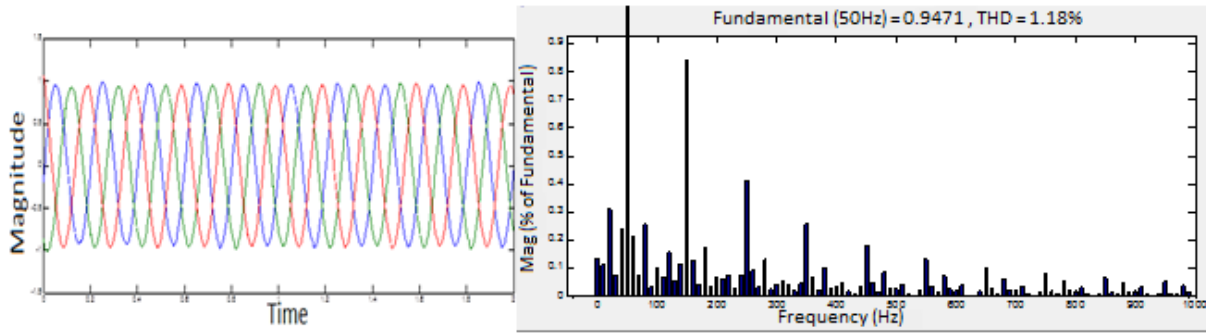


**Figure 5.2: Load Voltage without Compensation**

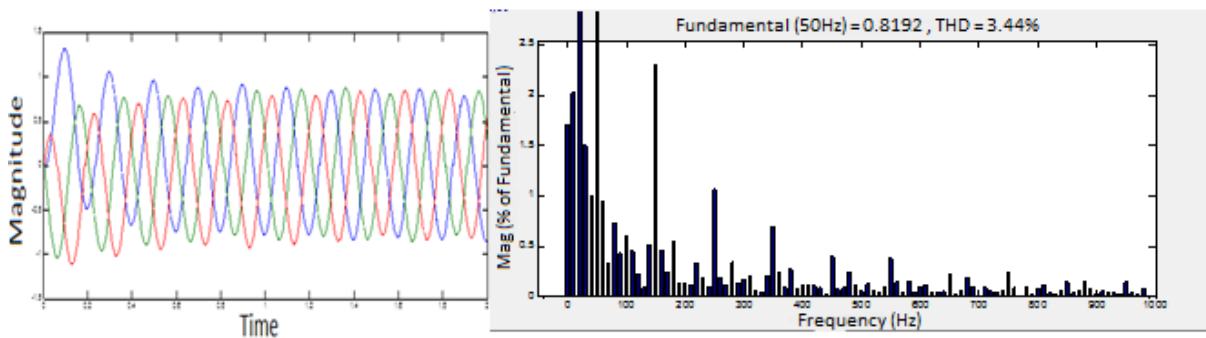


**Figure 5.3: Load Current without Compensation**

Figure 5.4 and figure 5.5 shows the waveforms of voltage and current during compensation and their respective FFT analysis. It can be seen that the harmonic distortion of load voltage is reduced to 1.8% and that of current is reduced to 3.44%. The magnitude is also limited to 0.9471p.u and 0.8192p.u of voltage and current respectively. Hence increase in the current magnitude increases the active power transfer to load.

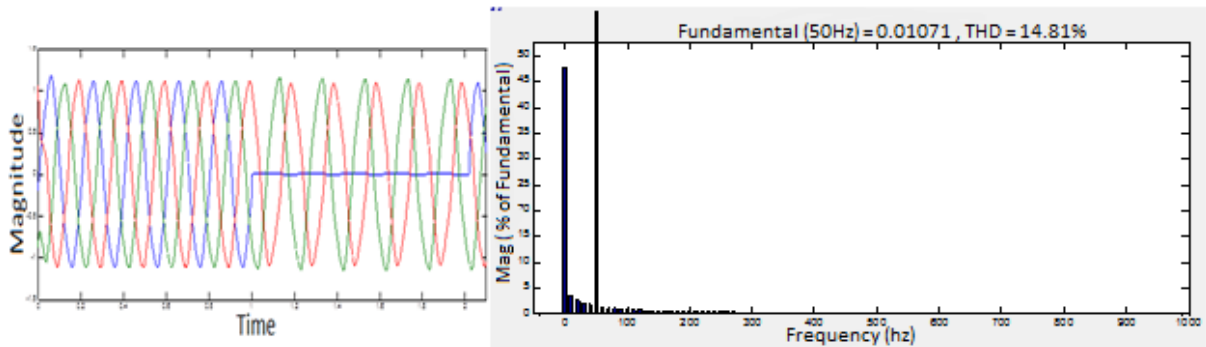


**Figure 5.4: Load Voltage with UPQC Compensation**

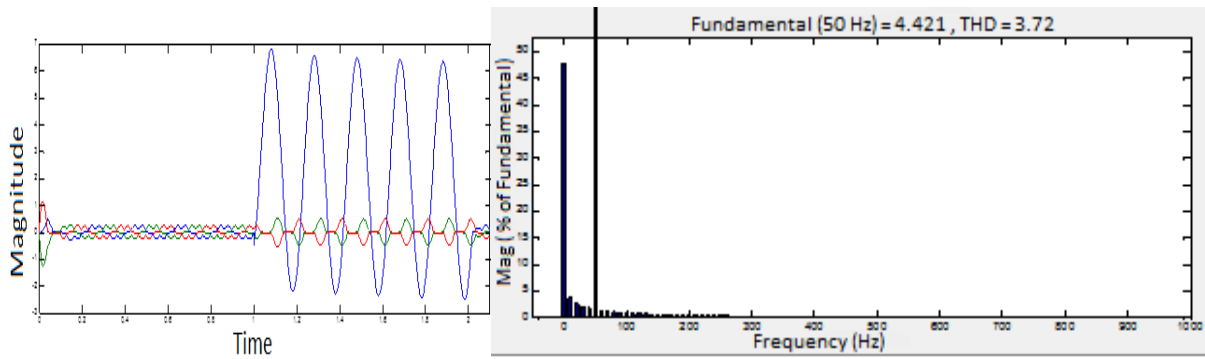


**Figure 5.5: Load Current with UPQC Compensation**

**Case 2: Results for Single Line to Ground Fault-** In this case a single line to ground fault is introduced in the circuit near the load. The fault transition time is chosen between 1-2 second. It can be seen that voltage level during the transition time is reduced considerably and the current level is increased. FFT analysis is done during the transition time only. The voltage and current magnitude at that time was 0.0107p.u and 4.421p.u respectively. Harmonic distortions for voltage and currents were 14.81% and 3.72% respectively. Figure 5.6, 5.7 shows the results for the same.

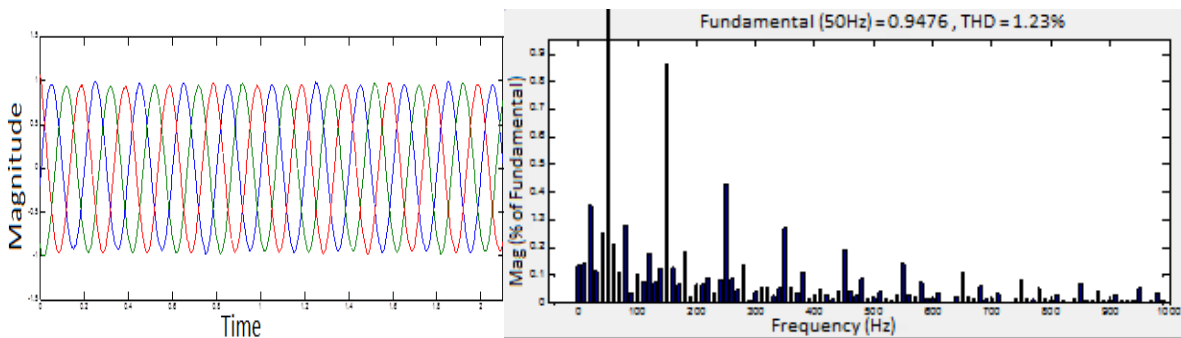


**Figure 5.6: Load Voltage Waveform During Single Line to Ground**

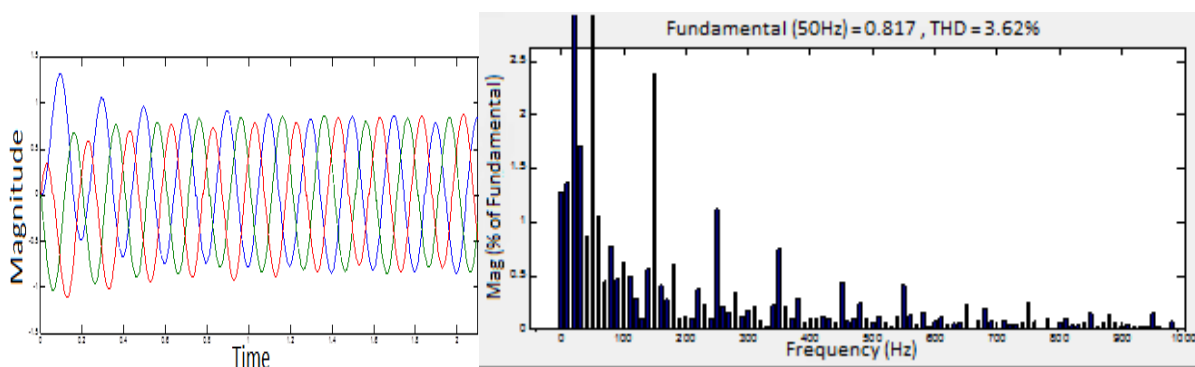


**Figure 5.7: Load Current Waveform during Single Line to Ground**

Figure 5.8 and 5.9 shows wave forms and FFT analysis during UPQC compensation. It is seen that that voltage and current levels are maintained at permissible limits and the harmonic distortion is considerably reduced below 5%. The levels of voltage and current are maintained at 0.9476p.u and 0.817p.u respectively. The harmonic distortions were 1.23% and 3.62% respectively.



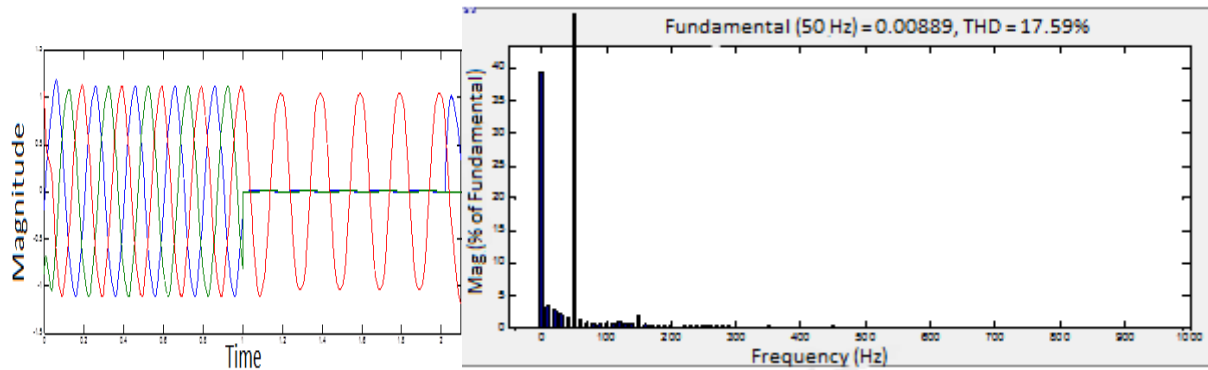
**Figure 5.8: Load Voltage Waveform with UPQC Compensation**



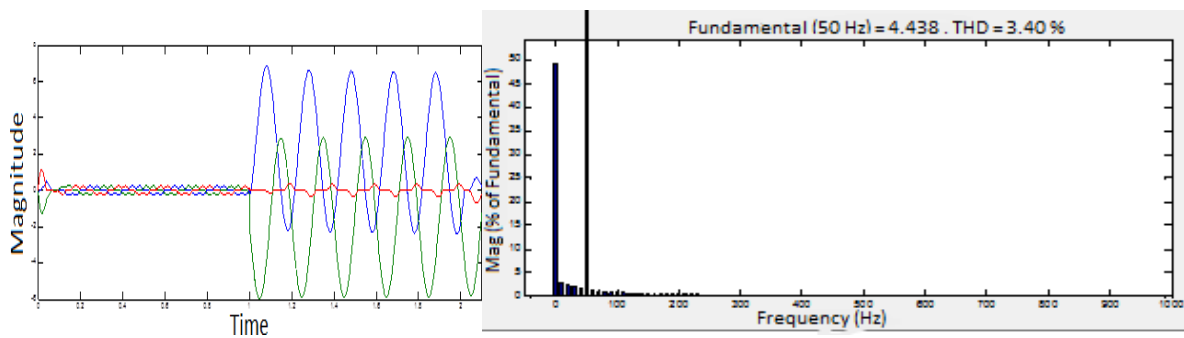
**Figure 5.9: Load Current Waveform with UPQC compensation**

**Case 3: Results for Double Line to Ground Fault-** In this case a double line to ground fault is introduced in the circuit near the load. The fault transition time is chosen between 1-2 second. It can be seen that voltage level during the transition time is reduced considerably

and the current level is increased. FFT analysis is done during the transition time only. The voltage and current magnitude at that time was 0.00889p.u and 4.438p.u respectively. Harmonic distortions for voltage and currents were 17.59% and 3.40% respectively. Figure 5.10, 5.11 shows the results for the same.

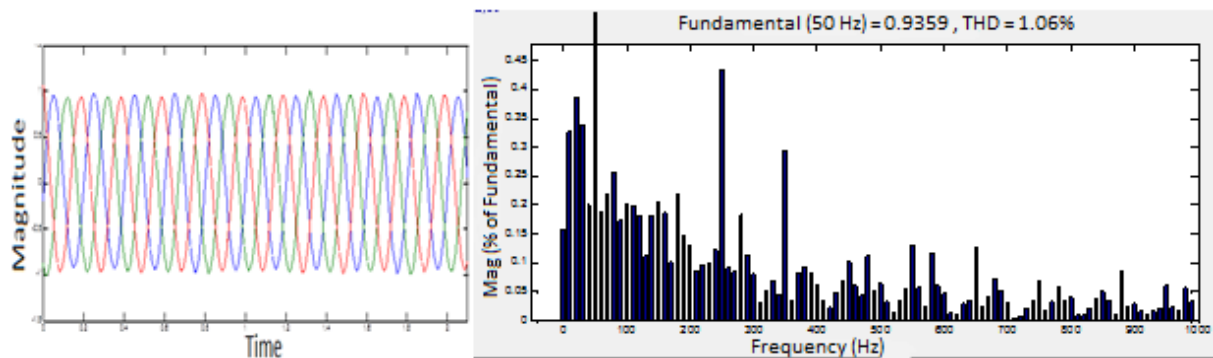


**Figure 5.10: Load Voltage during Double Line to Ground Fault**

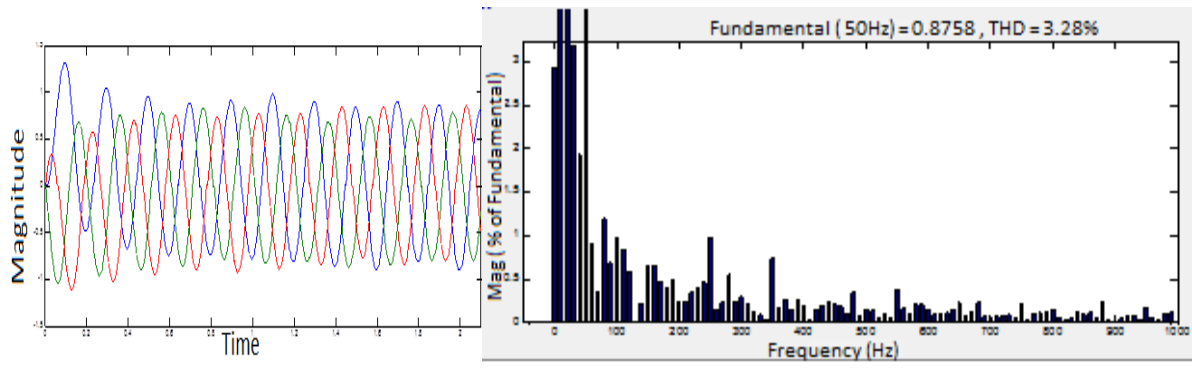


**Figure 5.11: Load Current during Double Line to Ground Fault**

Figure 5.12 and 5.13 shows wave forms and FFT analysis during UPQC compensation. It is seen that that voltage and current levels are maintained at permissible limits and the harmonic distortion is considerably reduced below 5%. The levels of voltage and current are maintained at 0.9359p.u and 0.8758p.u respectively. The harmonic distortions were 1.06% and 3.28% respectively.



**Figure 5.12 Load Voltage during UPQC Compensation**



**Figure 5.13: Load Current during UPQC Compensation**

### CONCLUSIONS AND FUTURE SCOPE OF WORK

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#### 6.1 Conclusions

Following conclusions can be made from the successful operation of UPQC with DTC drive under normal and faulted condition:

- a) The UPQC considered in this thesis is a multi-function power conditioner which can be used to compensate for various voltage disturbance of the power supply, to correct any voltage fluctuation and to prevent the harmonic load current from entering the power system.
- b) Simulink model of UPQC is tested under various varying load condition and single line to ground fault condition. It is seen that UPQC is capable of maintaining voltage and current in in permissible limit of 1p.u and distortion level under 5% of standard.
- c) The effectiveness of UPQC in suppressing the distortions is demonstrated under varying faulted levels. Hence, it is concluded that the proposed d-q theory based UPQC is effective even under faulted conditions.
- d) UPQC has four quadrant operations so it supplies the required reactive power to the load thus maintaining the power factor of the load. It is concluded that UPQC has a huge scope in improving power quality in distribution systems

#### 6.2 Future Scope of Work

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

- 1) Load in the test system can be replaced by some other type of loads like turbine load, arc furnace etc.
- 2) The more advanced controllers such as fuzzy controller, artificial neural network, Instantaneous power theory can also be used with UPQC to make the system more effective.
- 3) Effectiveness of multi-level UPQC can be investigated.

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## **PUBLICATION**

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