PERFORMANCE INVESTIGATION OF UNIFIED POWER QUALITY CONDITIONER (UPQC)

A DISSERTATION

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by

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CANDIDATE'S DECLARATION

I hereby declare that the work presented in this dissertation with title, "**Performance Investigation of Unified Power Quality Conditioner (UPQC)**", towards the fulfilment of the requirements for award of the degree of **Master of Technology** in **Electrical Engineering with specialization in "Electric Drives and Power Electronics"** submitted to the Department of **Electrical Engineering, Indian Institute of Technology, Roorkee, India** is an authentic record of my own work carried out during a period of July 2015 to May 2016 under the supervision of **Dr. Avik Bhattacharya**, Assistant Professor, Department of Electrical Engineering, Indian Institute of Technology, Roorkee.

The matter presented in this dissertation has not been submitted by me for the award of any other degree of this or any other institute.

Date:

Place: (**AMAL THOMAS)**

CERTIFICATE

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

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ABSTRACT

Power Quality (PQ) is used to describe the electrical phenomenon manifested in terms of variations in current, voltage and/or frequency that produce undesirable effects in the power system. The growing interest in the utilization of renewable energy resources for electric power generation is making the electric power distribution network more susceptible to power quality problems. Efficiency and cost are the major concerns in the transmission and distribution systems. In the last several years, there has been considerable interest in the development, use and application of active filters because of the increasing concern over power quality, at both distribution and consumer levels. Also there has been a need to control current & voltage harmonics, reactive power and voltage levels at different transmission levels.

This work aims at giving a brief outlook into the field of active filters, mainly, Unified Power Quality Conditioners (UPQC) in a three phase three wire system. The circuit configurations, basic working principle, the control scheme used, compensation techniques used for the generation of reference currents and reference voltages has been studied in detail. Also, this thesis discusses a reduced DC-link voltage rated Unified Power Quality Conditioner (UPQC) which eliminates current and voltage harmonics in a distribution network thereby improving the quality of power. Series capacitors have been introduced in cascade with the coupling inductors on the shunt filter side of the UPQC. This topology helps in reducing the voltage rating of DC-link capacitor without compromising on the harmonic mitigation and thus acts as a cost effective solution in the distribution side. A simulation study of the traditional and new topology of UPQC have been made in a three phase three wire system and is compared with the conventional topology of UPQC. Simulation has been implemented in MATLAB/Simulink and the results obtained prove the robustness of the new topology.

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Chapter 1: INTRODUCTION

1.1 Overview

In the past few years, the contribution of power electronics based electrical equipment in the industries and household devices has been increased significantly. Semi-conductor switches such as thyristors, MOSFETs etc. are being used to control electrical power in various loads mainly adjustable speed drives (ASD), electric arc furnaces, computer supplies etc. These kind of non-linear loads make the voltage and current being supplied non-sinusoidal. Even diode bridge rectifiers rated at low power produce a considerable amount of harmonic currents. The introduction of harmonics to the electric grid affects the other electrical appliances connected to the grid as well. The presence of non-linear loads results in poor efficiency and low power factor. In three-phase systems, these non-linear loads can also create unbalance and result in the absorption of large neutral currents. Thus, there is a need to control the harmonic pollution caused by the non-linear loads which employ power electronic loads and it is the duty of power electronic engineers to control or eliminate the problem. Here comes the significance of Power Quality.

1.2 Power Quality

The issue of Power Quality can be defined as "any occurrence manifested in terms of voltage, current, or frequency deviations that results in damage, failure, or mal-operation of end-use equipment." Flickering of lamps, heating up of equipment, communication interference are few of the problems that can be used to identify the power quality issues in a system. Various elements in the power system that are disturbed by harmonics include speed drives, transformers, induction motors, transmission line, capacitors and communication systems.

The mitigation of power quality problems can be dealt in mainly two aspects. Load conditioning is the first approach, in which the equipment is made to operate in a way that it less sensitive to voltage and current distortion. The second solution is the use of power-conditioning systems and filters that eliminate or counteract the power disruption.

1.3 Objective of Work

This work includes the simulation of unified power quality conditioner (UPQC) in MATLAB/Simulink, which is used for the improvement of power quality at distribution level. The major objectives of this work are as follows:

a) To develop and analyse various active power filter topologies mainly UPQC.
b) To assess the control scheme used in UPQC for reference current generation to eliminate harmonic issues at distribution level.
c) To develop a low DC link voltage rated UPQC and analyse its performance.

1.4 Organization of Thesis

This thesis is prepared and presented in five chapters. Contents of the different chapters are as given below:

The Chapter 1 presents the concise introduction, objective of the work. This chapter also includes the scope of the work and a general layout of the thesis report is also portrayed.

The Chapter 2 defines the concept of power quality, issues related to it and the study of various filters that are in use to bring out improvement in power quality in the three phase system.

The Chapter 3 mentions the literature review and brings light on the research works being carried out in the field of active filters, mainly UPQC.

The Chapter 4 highlights the basics of UPQC, the topologies and classification of UPQC based on various parameters and their details.

The Chapter 5 presents the control scheme used in the shunt and series part of filters and also discusses the controller used for the generation of firing pulses.

The Chapter 6 discusses a modified topology of UPQC which has a DC link capacitor with reduced voltage rating.

The Chapter 7 contains the simulation studies, Simulink blocks and various results obtained.

The Chapter 8 includes the conclusions and further works.

Chapter 2: POWER QUALITY

2.1 Power Quality

The Power Quality issue is defined as “any occurrence manifested in terms of voltage, current, or frequency deviations that results in damage, failure, or mal-operation of end-use equipment.” The Power Quality (PQ) problem can be detected from one of the following several symptoms depending on the type of issue involved. Flickering of lamps, heating up of equipment, communication interference are few of the problems that can be used to identify the power quality issues in a system. Various elements in the power system that are disturbed by harmonics include transformers, motors, transmission line cables, communication systems and capacitors.

The mitigation of power quality problems can be dealt with in mainly two aspects. Load conditioning is the first approach, in which the equipment is made to operate in a way that it less sensitive to voltage and current distortion. The second solution is the use of power-conditioning systems and filters that eliminate or counteract the power disruption.

2.2 Problems related with Power Quality

Short Duration Voltage Variation

These are the variations that are created due to faults in power systems, turning ON of high capacity loads etc. that occur for a duration of less than a minute. Various short duration variations are discussed below:

(a) Voltage Swell: An increase in the RMS line-voltage of about 110 to 180 percentage of the base value. The typical time period of voltage swell is a half cycle to less than a minute. Switching off of huge capacity loads and capacitor bank energisation are the main reason for voltage swell.

(b) Voltage Sag: A decrease in the RMS line voltage of about 10 to 90 percent of the base value of line-voltage. Its duration generally varies from a half cycle to less than a minute. Starting of large kVAR requiring induction motors causes sag.

(c) Interruption: A sudden decrease in the value of voltage or current in the system of less than 10% of the nominal value is called as interruption.

Interruptions occur for a very small duration of less than one minute. Faults/defects in the electrical systems, poor control systems and defects in the electrical equipment are the reasons for this disturbances.

Long-Duration Voltage Variation

Long-duration variations can be categorized as over voltages, under voltages or sustained interruptions.

(i) Overvoltage: An increase in the RMS ac voltage greater than 110 percentage at the power frequency is termed as overvoltage. It occurs for duration larger than 1 minute. Over voltages are usually the results of load switching or incorrect tap settings on transformers.

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

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

Transients

Transients are of types - Impulsive and Oscillatory.

(i) Oscillatory Transient: A short duration variation that occurs in both directions in the current or voltage signals in an electrical system. These are caused because of the energisation of capacitor banks.

(ii) Impulsive Transient: A short variation in voltage or current only in a single direction caused due to thunder and lightning is called impulsive transients. Zener diodes are used to overcome the adverse effects of impulsive transients.

Voltage Unbalance

A voltage unbalance is the case of differences in the value of voltages, relative to one another in a multi-phase system. Voltage imbalance can be the result of unequal load distribution on the phases. This creates different voltage drops across the line impedances.

Waveform Distortion

The steady-state deviation of the voltage and current signals from an ideal power frequency sine wave which is characterized by the spectral content of the deviation. DC offset, Notching, Harmonics, Interharmonics, Noise are the various kinds of waveform distortion.

2.3 Solutions for Power Quality Problems

An increase in the power quality problems results in low efficiency and poor power factor of the system. It creates troubles and adverse effects to the other loads connected and disturbs the communication systems due to interference. With the growth of power electronics, the effect of this nonlinearity has become sizeable over the past few years. Thus, there is a need to put a control on the problems associated with the usage of these non-linear loads. As a primary solution, passive filters consisting of LC tuned filters were employed to suppress the harmonics and capacitor banks were connected to improve the Power Factor (PF) of the supply system. But these passive filters have many disadvantages of big size, fixed compensation and can also incite resonance in the system by interacting with the line and source inductance.

The concept of custom devices for the betterment of power quality and ensuring reliability of supply was introduced by Hingorani [5]. This is now popular as the Flexible AC Transmission System (FACTS) technology. Following that, H Akagi developed the active power filter technology, which is now a fully flourished one in providing compensation for various power quality problems. Moreover, the growing interests on renewable energy systems like wind and solar, demands the use of active filters to obtain the energy green and clean.

The active power filters is now a powerful alternative over the passive filters for harmonic and reactive power compensation in the power system. The active filters are generally classified based on topology as series filter, shunt filter, hybrid filter which contains both active and passive filters and unified power quality conditioner (UPQC). The UPQC is a universal power quality improvement device which combines the advantages of both the shunt and series active filters. The series APF is connected through a series transformer with the ac line and shunt active power filter is added in shunt with the same ac line. These two are connected across the same DC-link capacitor. It combines the functions of both series & shunt filters.

Chapter 3: LITERATURE SURVEY

Today power quality [1-3] has come out to be the most important factor for both power suppliers and customers due to the deregulation of the electrical industry. A lot of works are being made to improve the power quality at all levels of the power system. The acceptable values of harmonics in different systems are mentioned in IEEE 519 standard [4]. As a primary solution, passive filters [2-3] consisting of LC tuned filters were in use to suppress the harmonics and capacitor banks turned out to be a solution to improve the power factor (PF) of the supply system. But these passive filters have many disadvantages of big size, fixed compensation and can also incite resonance in the system by interacting with the line and source inductance.

The concept of FACTS devices and custom power devices and was introduced by N.G.Hingorani [5]. Power electronic based devices are the key elements of these FACTS power devices [6]. The active filter technology is now mature for providing compensation for harmonics, reactive power, and/or neutral current in ac networks [7-10]. Active power filters were successfully developed as a solution to adverse effects created current and voltage harmonics, voltage flicker, and voltage unbalance in three-phase systems.

Bhim Singh et al. [7] presented a detailed review on the on active filters and the significant works in this field till date have been discussed. Various research works on UPQC based on topology, control strategy etc. is presented in a well-structured format.

Akagi et al. [8] proposed the best control theory based on instantaneous reactive power in three-phase circuits which is applicable at steady state and transients. They also explained the physical meaning of instantaneous real and reactive powers and the methods for reference current and voltage generations for the control strategy are also discussed. Edson H. Watanabe et al. presented a detailed analysis of the instantaneous reactive power theory in systems with non-linear loads.

H Akagi [11] also proposed the idea of a universal power line conditioner, which later came out to be popular as Unified Power Quality Conditioner (UPQC) and presents the harmonic compensation by combining the shunt and series active filters.

Vinod Khadkikar [10] presents a wide overview on the UPQC for power quality enhancement at distribution side. It provides a comprehensive review in this area and is one of the best review works. It discusses the works on various configurations of UPQC based on supply system, topology, compensation principles, control schemes etc.

Bhattacharya A[11] proposed a transformer less reduced switch hybrid active power filter that can be used at the distribution side and presents the robustness of the proposed system with simulation and hardware results.

Juan W. Dixon et al.[13] presented an active filter connected in series but functioning as a pure sinusoidal current source, in phase with the supply voltage. A closed loop control based on the error obtained from the load voltage and a set value is used to control the current in the series active filter. This control provided a solution to lower power factor.

M. A. Chaudhari et al. [14] presented a simplified control algorithm of a three-phase Series Active Power Filter as Power Quality Conditioner. SAPF compensates supply voltage unbalance and harmonics in such a way that they do not reach the load end resulting in low THD at the load voltage.

Chellali Benachaiba et al. described DVR principles and voltage restoration methods at the point of common coupling (PCC) and analysed different voltage injection method.

Bhim Singh et al. [18] suggested the use of dynamic voltage restorer (DVR) based on a simple control technique that can be used for the elimination of power quality problems in the load voltage. Synchronous reference frame theory is used for the reference voltage generation.

V.Khadkikar et al. [23] proposed a simple but powerful control strategy for Unified Power Quality Conditioner (UPQC), based on unit vector template generation for the elimination of voltage harmonics present in the utility voltage. This simple technique can be applied as an alternative to instantaneous pq theory based control for easy implementation.

The steady state power flow analysis of unified power quality conditioner (UPQC) is analysed in [18]. UPQC with dc side using split capacitor topology is used in (Ardes et al., 1998). Voltage source converter based active filters are preferred for both shunt and series sides as discussed in (Hosseni et al., 2009). The series converters are generally composed of six bridge VSI (Leon et al., 2009) and rarely composed of three single-phase H bridge voltage source inverters (Ghosh et al., 2004b). Shunt converters are generally composed of six bridge voltage source inverters for three-phase (Forghani et al., 2007).

A comparative study of conventional UPQC with open UPQC is done and the performance analysis of open UPQC is studied in detail by Pramod Agarwal et al [8]. Current source inverter based shunt active filters employing inductor on the dc link have also been studied by the same author.

An extensive research has been carried out in the control area of active filters. A large no of control techniques based on sinusoidal template vector algorithm (Djeghloud et al., 2008), artificial neural network based (Kinhal et al., 2011), space vector based control (D. Wuest et al.) and PI controller method (Basu et al., 2008), fuzzy control (Singh et al., 1998) have been done. Z. Radulovic and A. Sabanovic, developed an active filter based on sliding mode control.

Chapter 4: UNIFIED POWER QUALITY CONDITIONER

4.1 Introduction

Unified Power Quality Conditioner (UPQC) is a universal active power conditioner that is used to eliminate various current & voltage related disturbances of the power supply, to compensate reactive power, and to suppress harmonics in the supply system. UPQC has shunt and series compensation capabilities for (voltage and current) harmonics, reactive power, voltage disturbances (including sag, swell, flicker etc.), and power-flow control. UPQC consists of two voltage-source inverters sharing a common dc link. One inverter acts as a controlled harmonic voltage source, injecting harmonics in phase opposition and is connected in series with the network. The other inverter acts as a controlled harmonic, injecting current harmonics in phase opposition and is connected in parallel with the line. Thus, it is basically a combination of series APF and shunt APF. The shunt APF converter compensates for current harmonics, reactive power and also performs the voltage regulation of the DC link capacitor. Voltage related issues are taken care of by series filter.

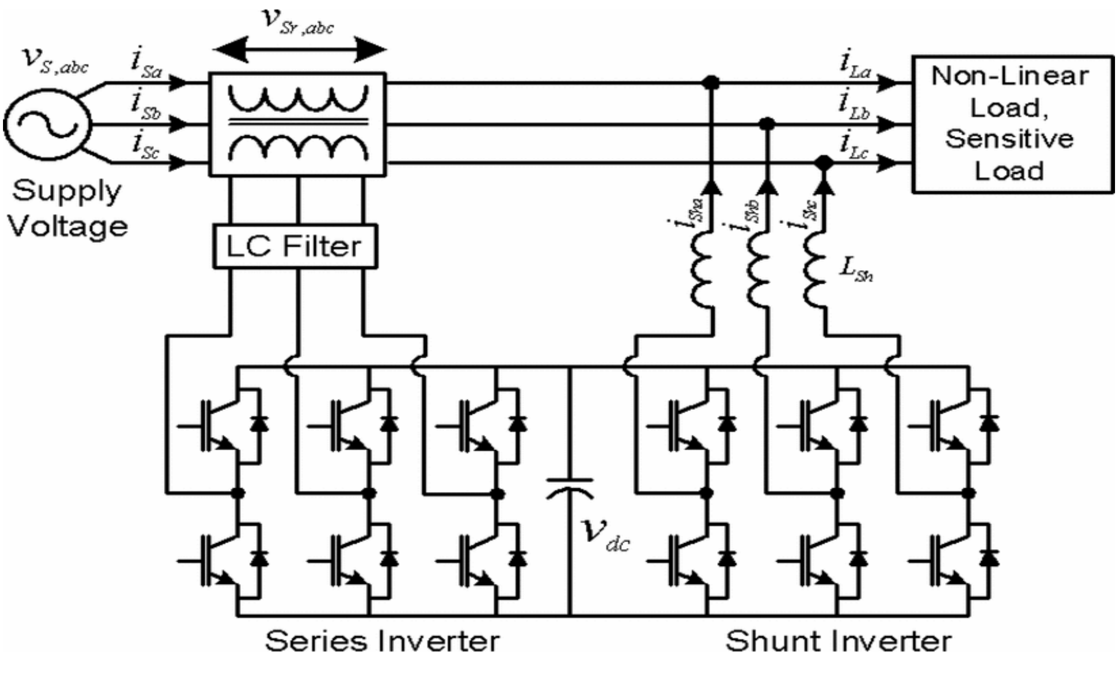

Fig 4.1 Power circuit of UPQC

4.2 Basic Configuration of UPQC

Fig. 3.1 shows system configuration of a three-phase UPQC. The fundamental components of UPQC are as follows:

- Series Inverter
- Shunt Inverter
- DC link capacitor
- Series injection transformer
- Coupling inductor

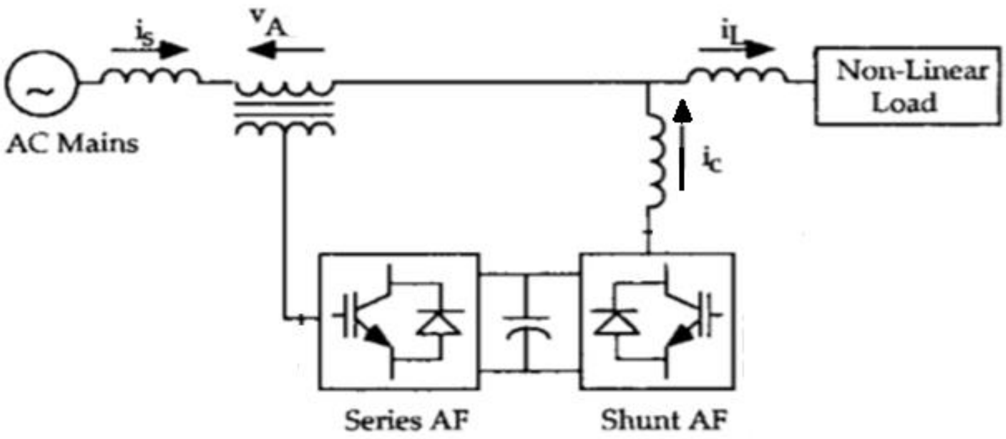

Fig 4.2 Schematic Diagram of UPQC

The detailed explanation of the main components of UPQC is discussed below:

4.3 Series inverter

It is generally a voltage-source inverter (VSC) (It can also be a current source inverter) connected in series with the AC line through a series transformer. It acts as a controlled voltage source to mitigate voltage related PQ problems. It eliminates harmonics present in the supply voltage, flickers and voltage imbalances. It can be related to the Dynamic Voltage Restorer used in power systems used for solving voltage related issues.

4.4 Shunt inverter

It is also a voltage-source inverter (VSC) connected in parallel at the point of common coupling (PCC). It acts as a harmonic current source that can effectively eliminate current harmonics and can supply the reactive power demand of the load. It also maintains the constant voltage across the DC link capacitor. It can be compared with the FACTs device, STATCOM which is used for reactive power injection in transmission side as they both have the same topology consisting of voltage source converters. Shunt active power filters injects equal but out of phase harmonic components at PCC so that the addition of it will result ina sinusoidal current at the source side. The current waveforms at different points of the system is as shown below:

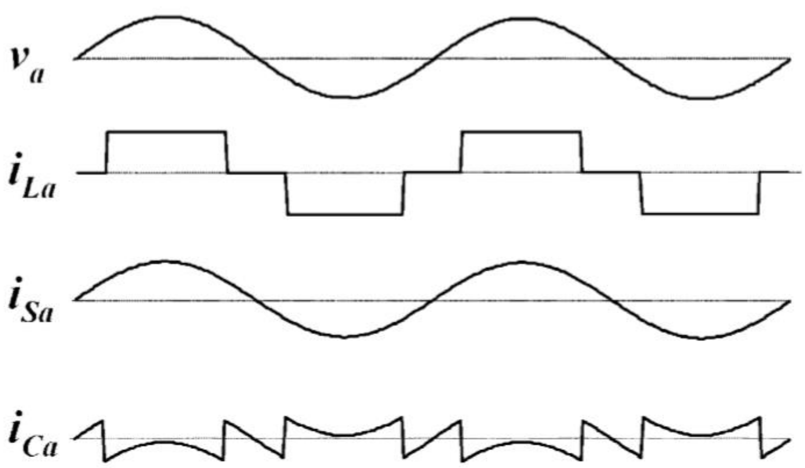

Fig 4.3 Voltage and current waveforms associated with shunt active filter

V_a: Supply voltage waveform

I_{sa}: Supply current waveform

I_{la}: Load current waveform

I_{Ca}: Filter current

$$I_{Ca} = I_{la} - I_{sa} \quad (1)$$

4.5 DC link capacitor

The two VSIs are connected to each other through a DC capacitor in a back to back fashion. The voltage across this capacitor provides the self-supporting DC voltage for proper operation of both the inverters. With proper control, the DC link voltage acts as a source of active as well as reactive power and thus eliminates the need of external DC source like battery. The DC side capacitor serves two main purposes: (i) it maintains a DC voltage with small ripple in steady state, and (ii) serves as an energy storage element to supply real power difference between load and source during the transient period. In the steady state, the real power supplied by the source should be equal to the real power demand of the load plus a small power to compensate the losses in the active filter. Thus, the DC capacitor voltage can be maintained at a reference value. However, when the load condition changes the real power balance between the mains and the load will be disturbed. This real power difference is to be compensated by the DC capacitor. This changes the DC capacitor voltage away from the reference voltage. In order to keep satisfactory operation or the active filter, the peak value of the reference current must be adjusted to proportionally change the real power drawn from the source. This real power charged/discharged by the capacitor compensates the real power consumed by the load.

Design of the DC side capacitor is based on the principle of instantaneous power flow on the DC and AC side of the converter. The fluctuation due to the load change cannot be taken as a method for capacitor design. However, unlike the voltage ripple caused by the load unbalance that the ripple must be suppressed by enlarging the capacitor value, the voltage control section will regulate this fluctuation caused by the load change. The selection of Cdc can be governed by reducing the voltage ripple.

$$C_{dc} = \frac{\Pi * I_{flrated}}{\sqrt{3}\omega V_{dc,p-p(\max)}} \qquad (2)$$

where I $_{flrated}$ is the rated current of filter, ω is the angular frequency and $V_{dc,\,p-p(\max)}$ is the peak to peak voltage ripple.

4.6 Series transformer

The necessary voltage generated by the series inverter to maintain a pure sinusoidal load voltage and at the desired value is injected in to the line through these series transformers. A suitable turns ratio is designed for the proper functioning of series inverter. Series transformer rating selection decides the compensation for voltage sag and swell.

4.7 Coupling Inductor

The smoothening/interfacing inductors, as the name suggests are used to interface the filter with the distribution system. The voltage source inverter in the active power filter injects the compensating current into the system through this coupling inductor. It effectively reduces the switching ripples associated with the turning on of active filters in the system. The filter inductor L_c is also used to filter the ripples of the converter current.

Inductor design can be done by considering the switching ripple into account. The switching ripple (I_{sw}) of the compensation current is determined by the available driving voltage across the interfacing inductor, the size of the interfacing inductor and switching frequency. The value of interfacing inductor is given as:

$$L_{f,\min} = \frac{V_{Cf}}{2*(\Delta I_{sw,p-p})*f_{sw,\max}} \quad (3)$$

4.8 Classification of UPQC

The UPQC can be categorised based on various parameters. The main constraints that attribute to these classifications are: 1) topology used; 2) supply system used; and 3) shunt and series inverters locations.

1) Classification Based on the Converter Topology:

   Based on the element used at the DC side of the inverter, UPQC can be categorised as current source and voltage source. UPQC can be developed on a current source inverter (CSI) that shares a common energy storage inductor (L_{dc}) to form the dc link. A voltage blocking diode has to be connected in series with the switching device (IGBT) in this topology. This topology of UPQC is not so popular because of various disadvantages of large cost of the inductor and increased losses. Also, it cannot be used in active filters using multilevel inverter. The second topology is the most widely used and popular converter topology for UPQC. It consists of PWM Voltage Source Inverter (VSI) that shares a common DC link capacitor (C_{dc}). Most of the research works on UPQC are based on this VSI-based topology. It can be employed in multilevel inverter configurations as well.

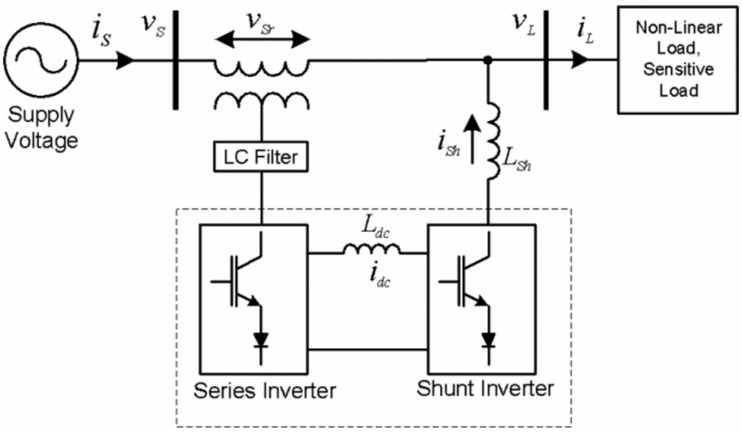

Fig 4.4 Current Source UPQC

2) Classification Based on the Supply System: Based on the equipment connected on the power system, system can be broadly divided into single-phase and three-phase, supplied by single-phase and three-phase (three-wire or four-wire). To mitigate the power quality problems in these systems, different UPQC configurations are possible and are classified based on the type of the supply system. For a single-phase system, the load reactive current and current harmonics are the major issues. In the case of three-phase three-wire (3P3W) system, unbalance also comes into consideration apart from reactive and harmonics current. A three-phase four-wire (3P4W) system requires neutral current compensation in addition to the above mentioned.

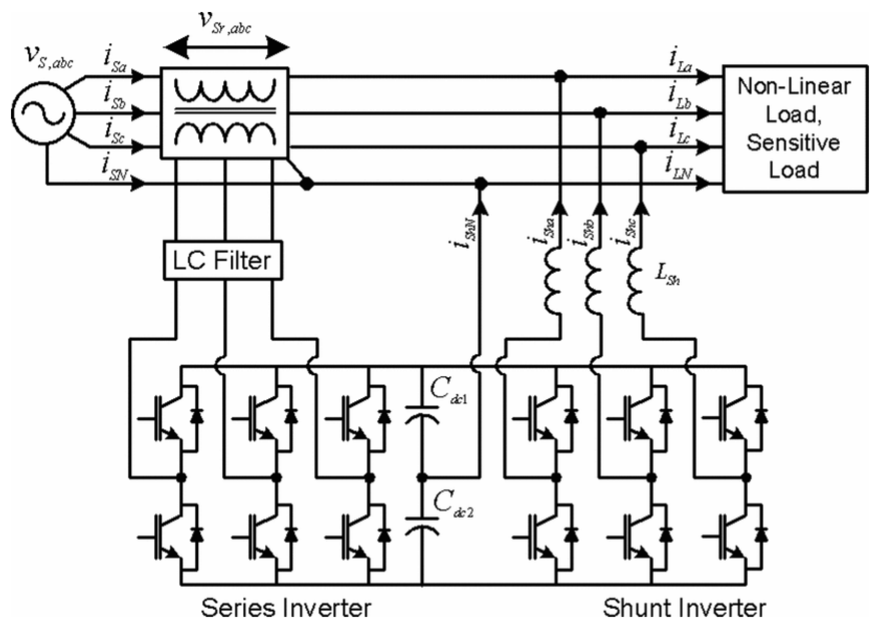

Fig 4.5 Four Wire UPQC system

3) Classification Based on the UPQC Configuration:

   a. Left Shunt and Right Shunt UPQC (UPQC-L and UPQC-R): It is based on the location of shunt and series filters in the system.
   b. Interline UPQC (UPQC-I): In this the UPQC is connected between different feeders/lines based on different substations.
   c. Multi converter UPQC (UPQC-MC): An additional voltage source converter is employed to maintain the DC side voltage.
   d. Modular UPQC (UPQC-MD): This configuration is realized by using several H-bridge modules connected in series and avoids the requirement of series injection transformer.
   e. Multilevel UPQC (UPQC-ML): Voltage source inverters employed in this configuration employs multi-level circuits for better operation.

Chapter 5: CONTROL SCHEME USED

5.1 Introduction

The Control strategy is the main attraction of the Active Filter design and is implemented mainly in three steps.

Step 1: Signal Sensing:

In this stage, the required signals for the closed loop control (mainly voltage & current) are sensed using potential and current transformers, Hall-effect sensors to get information regarding the parameters to be controlled. Mainly, instantaneous voltage and current signals are sensed in this stage. The typical signals that are sensed in APFs are ac terminal voltages, load currents, load voltages, dc link voltage of the capacitor, source currents etc. Potential Transformer and Hall-Effect sensors are used for sensing the voltage signals. Current signals are sensed using Current Transformers, Hall-effect current sensors etc.

Step 2: Development of compensating signals by reference signal generation

This stage plays the crucial role in the control of an active filter. There are two techniques for the generation of compensation signals and are based on frequency-domain or time-domain techniques. Fast Fourier Transform based analysis of the source voltage and current signals is carried out to generate the reference signals in frequency based approach. The fundamental and harmonic components are separated out and compensating signals are produced so as to eliminate the harmonic components. Time domain based approach employs instantaneous evaluation of compensating commands. Control methods of the AF's in the time domain are based on instantaneous derivation of compensating commands in the form of either voltage or current signals from distorted and harmonic-polluted voltage or current signals. There are a large number of control methods in the time domain, which are known as instantaneous p–q theory, synchronous detection method, synchronous d–q reference frame method, sliding mode controller etc.

Step 3: Firing Pulses Generation:

The third stage of control contains the generation of firing pulses for the switching devices employed in the inverters of the active filters. Pulses are generated based on the error created reference signals with the actual signals. Pulse width modulated control, mainly sinusoidal PWM technique, sliding mode control, state space control, model predictive control, hysteresis etc., can be used to create the required pulses for the effective control of active filters.

5.2 Unit Vector Template Generation (UVTG) Technique:.

The control scheme used here for reference current and voltage signal generation is Unit Vector Template (UVT) technique. This simple technique which uses the extraction of unit sinusoidal signals from the source side is be applicable for both shunt and series filter.

5.2.1 Control Strategy of Series VSI

The control strategy for the series APF is shown in Fig.5. The distorted source voltages (v_a, v_b, v_c) are sensed and processed through the phase locked loop (PLL) block to obtain unit magnitude reference signals (U_{abc}) in synchronism with the fundamental frequency. The unit vector templates are generated by creating proper phase delay. Reference load voltage signals (v_{abc}^{ref}) are obtained by multiplying the peak amplitude of fundamental input voltage (v_{lm}^{ref}) with unit vector templates.

$$v_{abc}^{ref} = U_{abc} * v_{lm}^{ref} \qquad (4)$$

To generate injected voltages, the sensed supply voltage signals are compared with the reference signals and the error signals obtained are fed to the hysteresis controller. The output of the hysteresis controller provides the necessary firing pulses for switches of the VSI of the series APF.

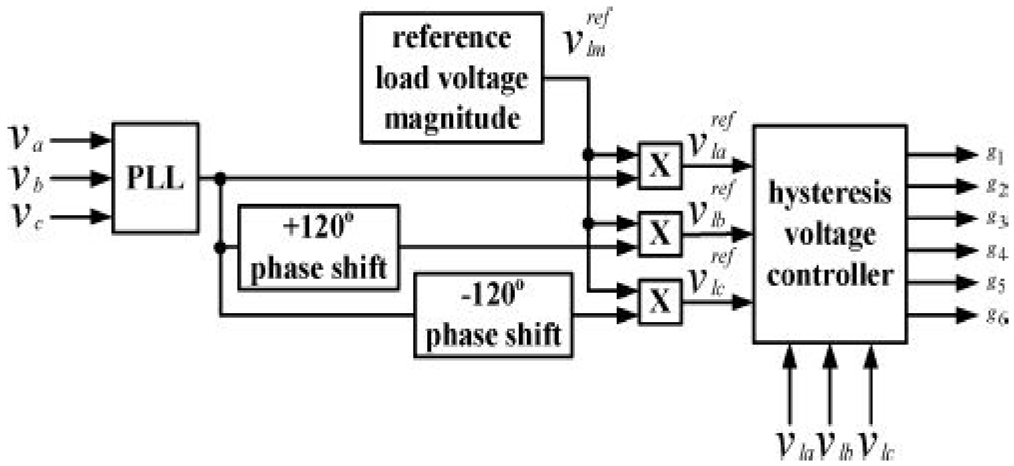

Fig 5.1 Control Scheme based on UVT technique for Series Filter

5.2.2 Control Strategy of Shunt VSI

The shunt APF performs mainly two functions. It eliminates the current harmonics and also maintains the constant voltage across the DC-link capacitor. The DC-link voltage is sensed and compared with a set value and the error is fed to a PI controller to maintain the voltage level constant. The PI controller produces an output signal which is the peak value of the source current (I_m^{ref}) is then multiplied with unit vector templates obtained using UVT technique giving the three phase reference currents (I_{sabc}^{ref}). Sensed source currents (I_{sabc}) are compared with the reference current signals and required firing pulses for the VSI in shunt APF are produced by the hysteresis controller is as shown in Fig 5.2.

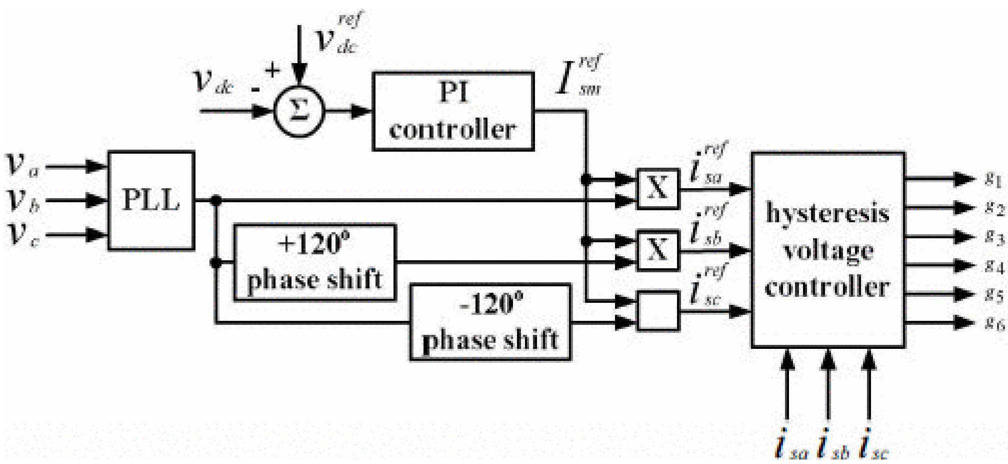

Fig 5.2 Control Scheme based on UVT technique for Shunt filter

5.3 Hysteresis Controller

This control technique used for the gate pulse generation for inverters in the active filters is the most robust control and widely use done. It is based on the comparison of actual currents and reference currents and the error signal produced is fed to a Schmitt trigger with a proper hysteresis band. The control using a hysteresis controller is shown in Figure 5.3. There are bands above and under the reference current. When the error touches the upper band, the current is forced to decrease and when the error reaches the lower band, the current is forced to increase.

The switching logic is formulated as follows:

- If I_f< (Iref − hb) upper switch is OFF and lower switch is ON.
- If I_f> (Iref + hb) upper switch is ON and lower switch is OFF.

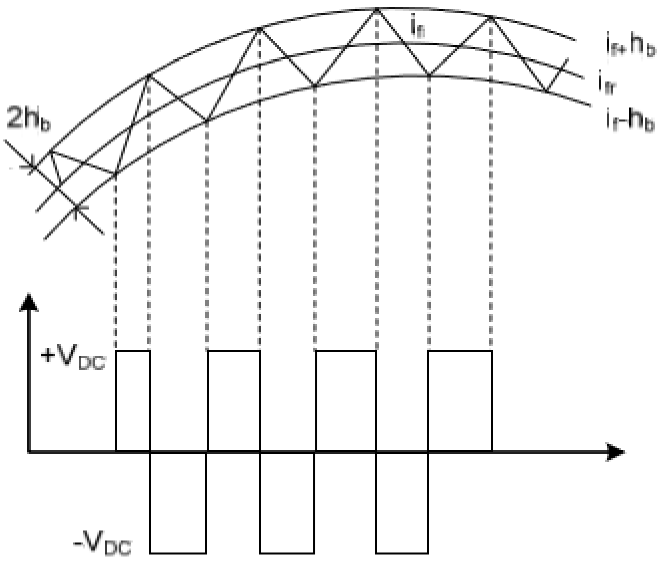

Figure 5.3 Hysteresis band control schematic

Similarly, for generating switching pulses in a series inverter, the actual voltages are compared with the reference voltages and the error signal is fed to a Schmitt trigger. Though a constant switching frequency cannot be obtained in hysteresis controller, it has greater advantages like easy implementation, highly robust, good stability and faster response.

5.4 Conclusions

In this chapter unified power quality conditioner (UPQC) has been discussed in details. UPQC consists of both series active power filter and shunt active power filter has the capability to compensate the current and voltage related disturbances simultaneously. Detailed discussion of operating principle and control scheme for UPQC has been carried out. A simple hysteresis voltage control with the principle for extraction of unit vector template is proposed to control the series APF. Control scheme based on the instantaneous reactive power theory for the shunt APF is presented and hysteresis current controller model is also shown. The Simulink model of series APF, shunt APF, UPQC and results thereof are shown in the next chapter.

Chapter 6: A REDUCED VOLTAGE RATED UPQC

6.1 Introduction

The voltage rating of the DC link capacitor highly influences the performance of active filters. The voltage level requirement for this DC link capacitor is different for a shunt and a series filter. The DC link voltage requirement for the shunt active filter is a higher value than the peak value of the line voltages. The dc-link voltage has to be maintained at a higher value in a shunt filter in order to inject the compensating currents from the filter into the system. Also, for reactive power compensation, the magnitude of reference dc-bus capacitor voltage should be higher than the peak voltage at the point of common coupling (PCC). And in case of a series filter, the DC link voltage required is equal to the peak value of line to line voltage of the system. The shunt active filter provides a path for real power flow to aid the operation of the series compensator and to maintain constant average voltage across the DC storage capacitor. Series and shunt parts require different levels of voltage at their DC sides. Thus in the case of UPQC, common DC link voltage level is selected in favour of shunt filter for proper compensation of both shunt and series filters.

This higher value of DC link voltage causes several disadvantages. They are as discussed below:

1. The series filter is over rated compared to shunt active filter.
2. The switching devices used in the VSI of series filter are rated for a larger value of voltage and current which is not necessary. This causes the system to be bulky.
3. Size as well as cost of the filter is increased.

6.2 UPQC with reduced rating

In order to reduce the dc-link voltage storage capacity, few attempts were made in literature. H Akagi [19] proposed a hybrid filter which includes the study of a shunt active filter with reduced voltage rating. It consists of a passive filter in series with the active filter and was successful to reduce the DC side voltage.

This chapter studies the extension of this idea to UPQC. Since, UPQC contains both shunt and series filter, this idea of a hybrid filter on the shunt side can be applied to it as well. A series capacitor is added in series with the interfacing inductor on the shunt side. The combination of this series capacitor (C_F) along with the inductor can be considered as a passive filter tuned for specific harmonics. This extra capacitor (C_F) has the following three main features:

1. It effectively reduces the voltage rating on DC link capacitor by absorbing the fundamental component of the source voltage.
2. Its series combination with the coupling inductor can act as a tuned LC filter to eliminate specific harmonics produced by the uncontrolled rectifier load.
3. It can also compensate a part of the reactive power required by the load.

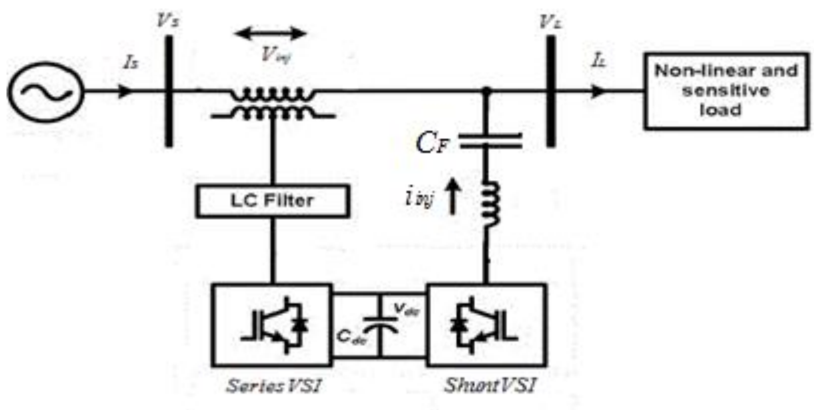

Fig.6.1. Outline of Modified UPQC with series capacitor

6.3 Design of parameters:

The main parameters to be estimated and designed in a traditional UPQC are the values of coupling inductance on both the sides of filter, DC link capacitance (C_{dc}), capacitor voltage (V_{dc}) and switching frequency(f_{sw}). The design considerations for coupling inductance and DC side capacitance and its voltage can be found in [6-9]. The same can be applied in case of UPQC.

The combination of inductance and series capacitance in the shunt filter side can be considered as a passive filter which can eliminate a pair of lower order harmonics. If the line and filter resistances are neglected, the amount of 5th harmonic current flowing through the filter may be expressed as [8-9]:

$$\frac{I_{h5}}{I_1} = \frac{25\alpha\beta_5}{25 - k^2 + 25\alpha} \quad (5)$$

Where, I_{h5} and I_1 are the 5th harmonic component of filter current and fundamental component of the load current respectively. Here the filter is optimally tuned for kth order harmonics and α and β_5 are expressed as:

$$\alpha = \frac{L_s}{L} \quad \beta_5 = \frac{I_5}{I_1}$$

where, L_s is the source inductance. The same concept can be applied to tune the filter for other harmonics as well. The reactive power associated with the passive filter is given as:

$$Q_c = 3\omega C_F V_{CF}^2 \quad (6)$$

where, V_{CF} is the voltage across the series capacitance C_F.

6.4 State Space Analysis of Modified UPQC

Fig 6.2. illustrates the equivalent circuit diagram of the modified UPQC. The harmonic polluted supply voltage (V_s) is represented as the addition of fundamental (V_f) and harmonics (V_h). A constant current source (I_L) having a load voltage (V_L) across it is used to denote the non-linear load used. R_1 and L_1 represent the line impedance. A DC voltage source u_1V_{dc} represents the series VSI with L_{se} and C_{se} as the low-pass filter and R_{se} corresponds to the series filter losses. C_a represents the series capacitance connected in series with the coupling inductance. In a similar fashion the shunt active filter of the UPQC is represented by u_2V_{dc} with L_{sh} as the coupling inductance, C_{sh} as the low-pass filter and R_{sh} as the losses of the shunt VSI. u_1V_{dc} and u_2V_{dc} represent the switched voltages appearing across the DC side of the inverters in the UPQC. V_{inj} and i_{inj} denotes the harmonic voltage and currents injected by the UPQC.

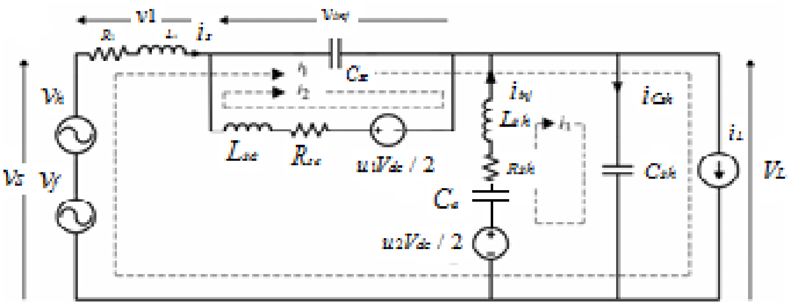

Fig 6.2 Equivalent circuit diagram of the modified UPQC

The model considered here is a linear, time invariant one for easy analysis. Basic Kirchhoff's voltage and current equations are applied to obtain the state space matrices. The state space model for normal UPQC can be written as:

$$\dot{X} = AX + B_1\begin{pmatrix} V_S \\ I_L \end{pmatrix} + B_2U \tag{7}$$

$$Y = CX + D_1\begin{pmatrix} V_S \\ I_L \end{pmatrix} + D_2U \tag{8}$$

$$X = \begin{pmatrix} i_s \\ i_{se} \\ i_{inj} \\ v_{inj} \\ v_{csh} \\ v_{ca} \end{pmatrix} \quad A = \begin{pmatrix} \frac{-R_1}{L_1} & 0 & 0 & 0 & \frac{-1}{L_1} & \frac{-1}{L_1} \\ 0 & \frac{-R_{se}}{L_{se}} & 0 & \frac{-1}{L_{se}} & 0 & 0 \\ 0 & 0 & \frac{-R_{sh}}{L_{sh}} & 0 & \frac{-1}{L_{sh}} & \frac{-1}{L_{sh}} \\ \frac{-1}{C_{se}} & \frac{-1}{C_{se}} & 0 & 0 & 0 & 0 \\ \frac{-1}{C_{sh}} & 0 & \frac{-1}{C_{sh}} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{C_a} & 0 & 0 & 0 \end{pmatrix} \quad B_1 = \begin{pmatrix} \frac{1}{L_1} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{-1}{C_{sh}} \\ 0 & 0 \end{pmatrix}$$

$$B_2 = \begin{pmatrix} 0 & 0 \\ \frac{V_{dc}}{L_{se}} & 0 \\ 0 & \frac{V_{dc}}{L_{sh}} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \qquad Y = \begin{pmatrix} V_{csh} = V_L \\ i_s \end{pmatrix}$$

$$C = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad D_1 = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \quad D_2 = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$$

6.5 Stability Analysis

The transfer function of the system under study has been obtained from the state space equations. Nyquist plots have been plotted for this MIMO system. The system has been found to be stable from the Nyquist plots satisfying the Nyquist criteria for stability. Fig. 6.3 shows the Nyquist plots corresponding to the system under study.

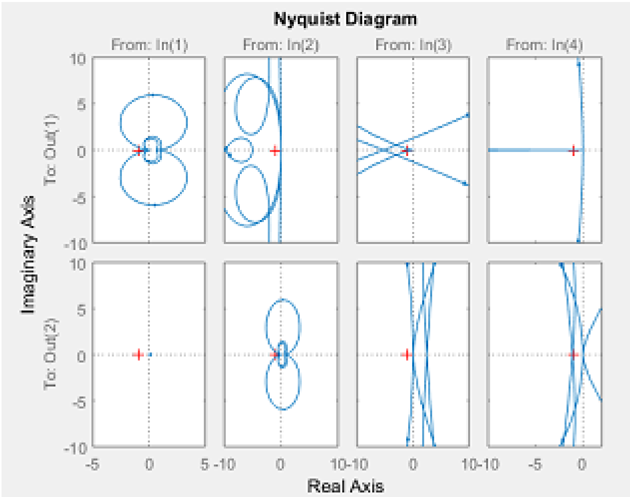

Fig 6.3 Nyquist plot

6.6 Summary

Thus a reduced DC-link voltage rated Unified Power Quality Conditioner (UPQC) which eliminates current and voltage harmonics in a distribution network thereby improving the quality of power has been discussed in this chapter. Series capacitors have been introduced in cascade with the coupling inductors on the shunt filter side of the UPQC. The proposed topology helps in reducing the voltage rating of DC-link capacitor without compromising on the harmonic mitigation and thus acts as a cost effective solution in the distribution side. Unit Vector Template (UVT) generation technique, as discussed in the previous chapter, is used as the control scheme for this topology also. A simulation study of the new topology has been made in a three phase three wire system and is compared with the conventional topology of UPQC. The results are presented in the coming chapter.

Chapter 7: SIMULATION STUDY & RESULTS

7.1 Introduction

This chapter discusses the simulation results of shunt active power filter (APF), series active power (APF) filter and the unified power quality conditioner to evaluate the proposed control strategy. The simulation models have been developed in MATLAB/SIMULINK environment. The models have been operated for non-linear load. The nonlinear load is realised in the system by employing a three phase diode bridge rectifier with RL load. Additionally, the simulation result under distorted voltage condition is also presented. First the simulation analysis of shunt APF is presented then that of series APF is presented and finally the simulation results for UPQC is presented.

7.2 Simulation of Shunt Active Filter

In this section the simulation results of shunt APF are shown. The developed model of a shunt APF developed in MATLAB/SIMULINK environment are shown in Fig.7.1. The non-linear load used here is a diode bridge rectifier with R-L load. (R = 30 Ω and L = 10 mH). Due to the non-linear load connected to the system, harmonics are produced in load current waveform as shown in Fig 7.2. At 0.8 sec, shunt APF is put in operation for compensating current harmonics. As soon as the shunt APF is turned ON, the feedback PI controller acts immediately forcing the DC link voltage (Fig 7.8) to settle down at reference value, here 700V. The DC link capacitor is initially charged at 700V to avoid shunt inverter to draw very high current while starting. At the same time, the shunt APF also starts compensating the current harmonics generated by non-linear load. The shunt APF injects a current (Fig 7.5) in such a way that the source current becomes sinusoidal. The improved source current profile can be noticed from Fig 7.6.

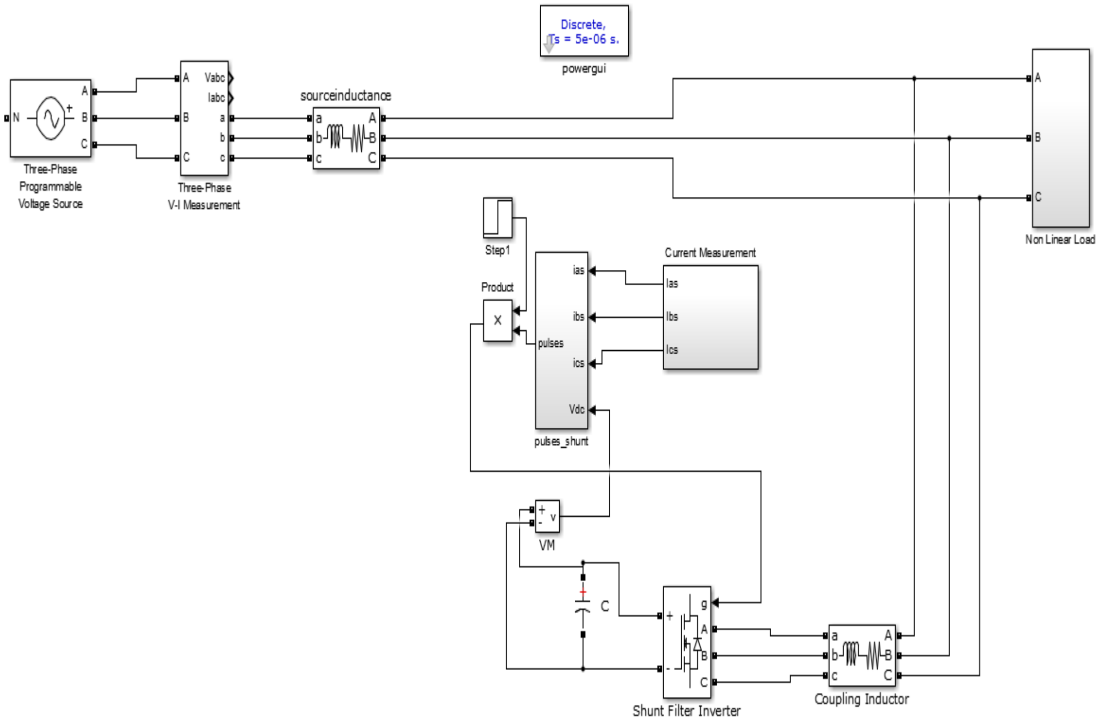

Fig 7.1 Simulink Model of Shunt active filter

The FFT analysis and total harmonic distortion of the uncompensated system (when shunt filter is OFF) is shown in Fig 7.2 and Fig 7.3. THD was found to be 20.37% with dominant 5^{th} and 7^{th} harmonics.

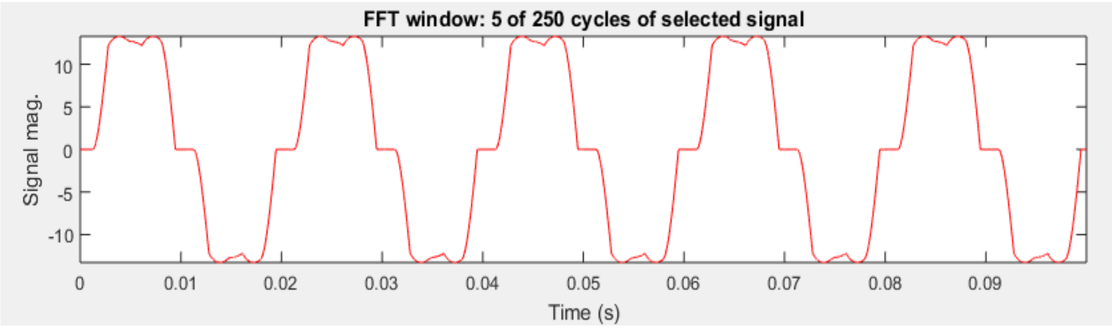

Fig 7.2 FFT window of uncompensated system

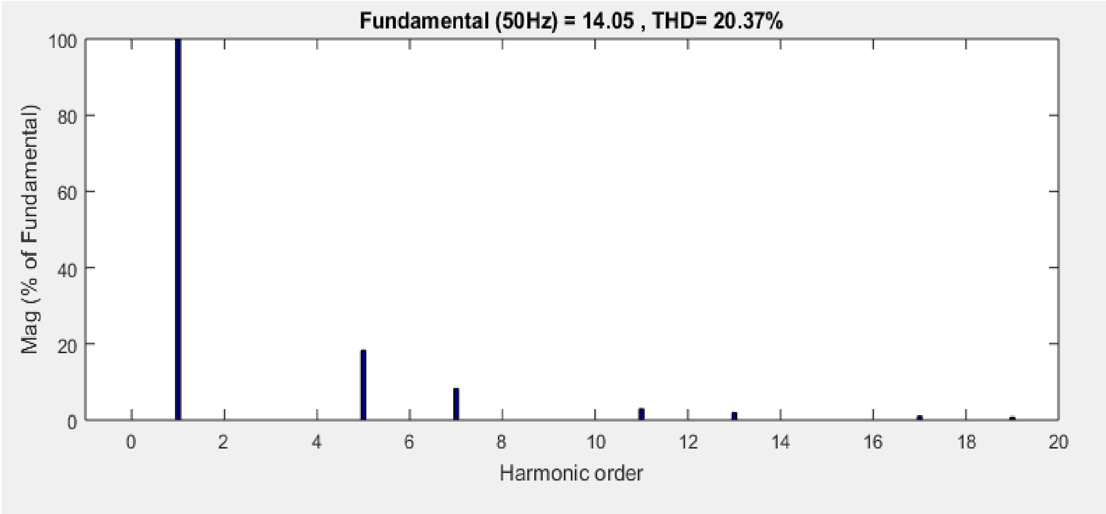

Fig 7.3 Harmonic analysis of Source current when shunt filter switched OFF

In the Simulink model, shunt filter is switched ON at t = 0.4s and the source current waveform before and after shunt filter is switched ON can be found in Fig 7.4. The current injected by shunt active filter into the system is shown in Fig 7.5. The source current is made sinusoidal and the THD is reduced to 0.88%. The FFT analysis and harmonic analysis of compensated source current is shown in Fig 7.6 and Fig 7.7. The DC link capacitor voltage waveform is shown in Fig 7.8.

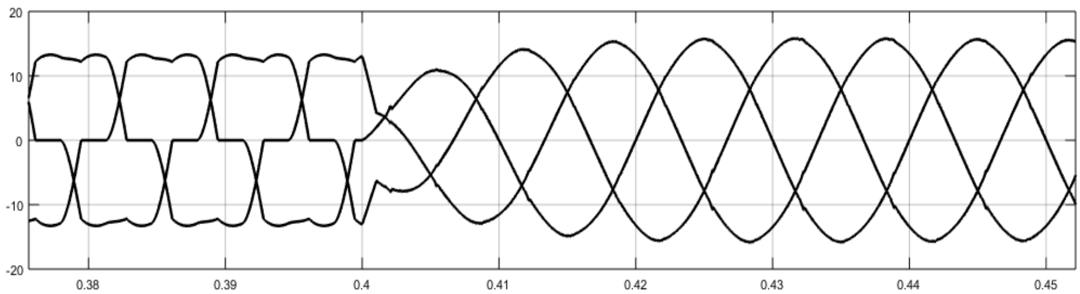

Fig 7.4 Source current before & after compensation. Shunt filter switched ON at 0.4s

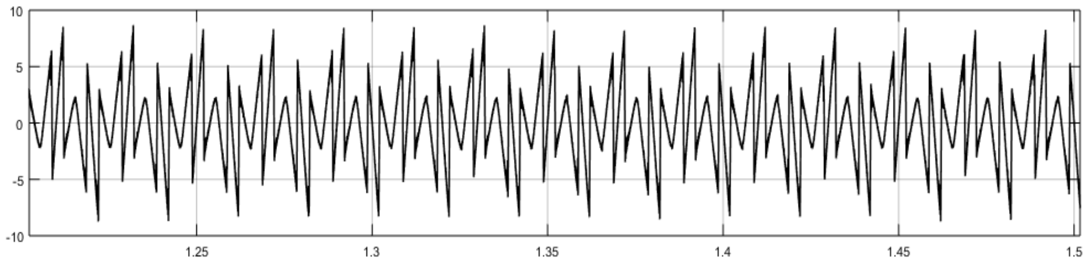

Fig 7.5 Injected current by Shunt active filter into the system

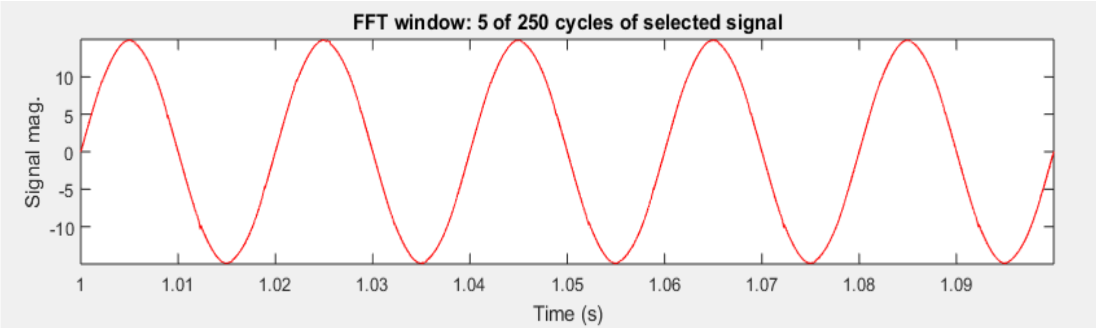

Fig 7.6 FFT window of compensated source current

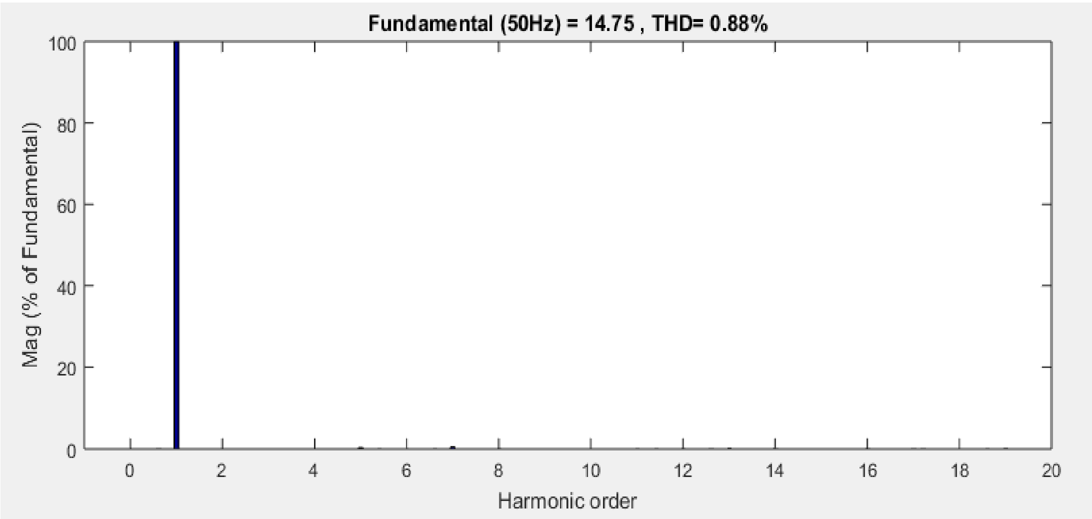

Fig 7.7 Harmonic analysis of Source current when shunt filter is ON

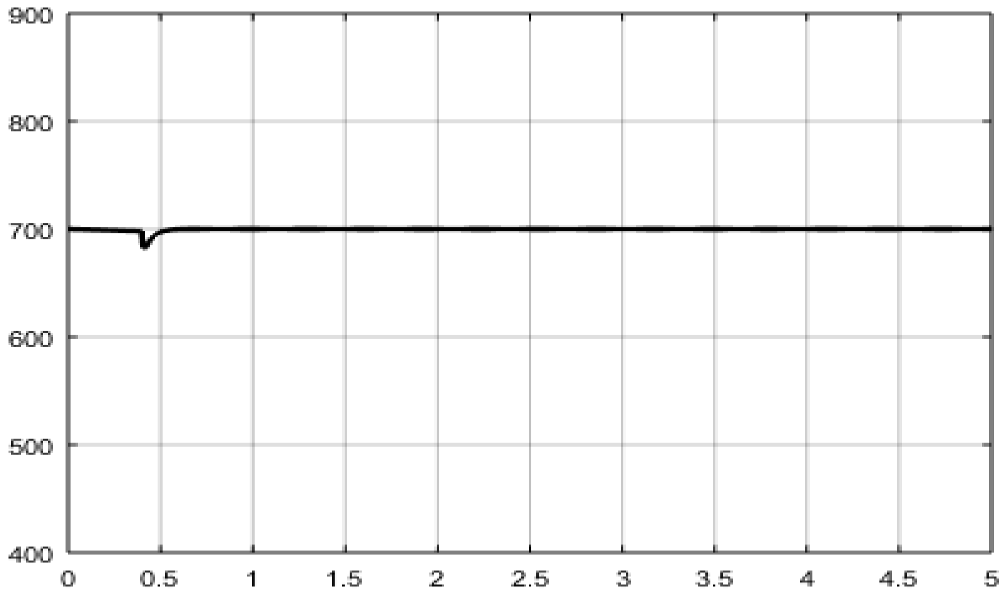

Fig 7.8 DC link voltage with a reference value of 700V

7.3 Simulation of Series Active Filter

To study the harmonic compensating capability of series active filter, the distortion in utility voltages is introduced deliberately by injecting a 5th order voltage harmonic into the 3ph source voltage. The series APF injects a 5th harmonic voltage which is out of phase through a series transformer. The DC side of the Voltage source inverter contains a DC battery. Since series filter cannot compensate for the current harmonics, a 3ph RL load is used. The Simulink model of series filter is shown in Fig 7.9.

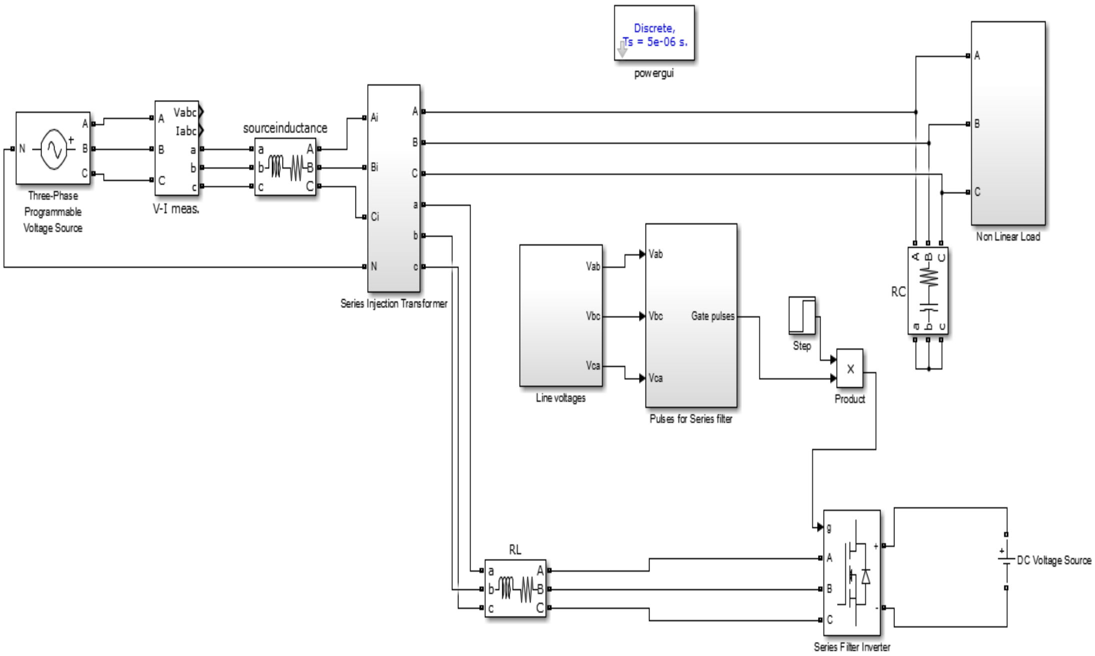

Fig 7.9 Simulink model of Series Filter

The voltage waveform, FFT analysis and harmonic analysis of the system before switching ON the series filter is shown. The total harmonic distortion was found to be 12.47%.

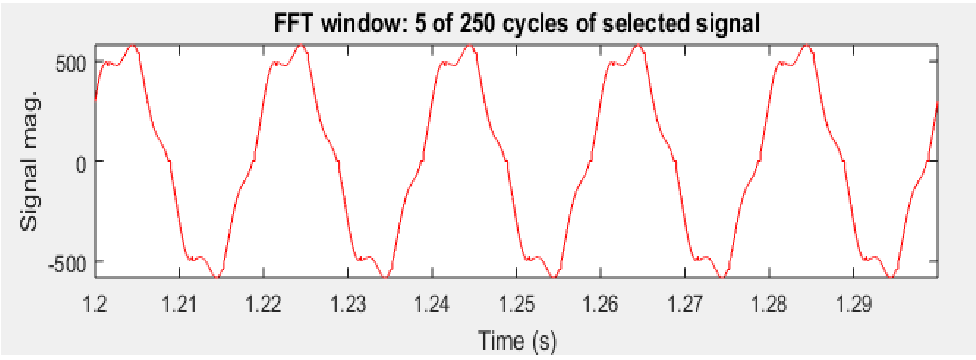

Fig 7.10 FFT window of polluted source voltage

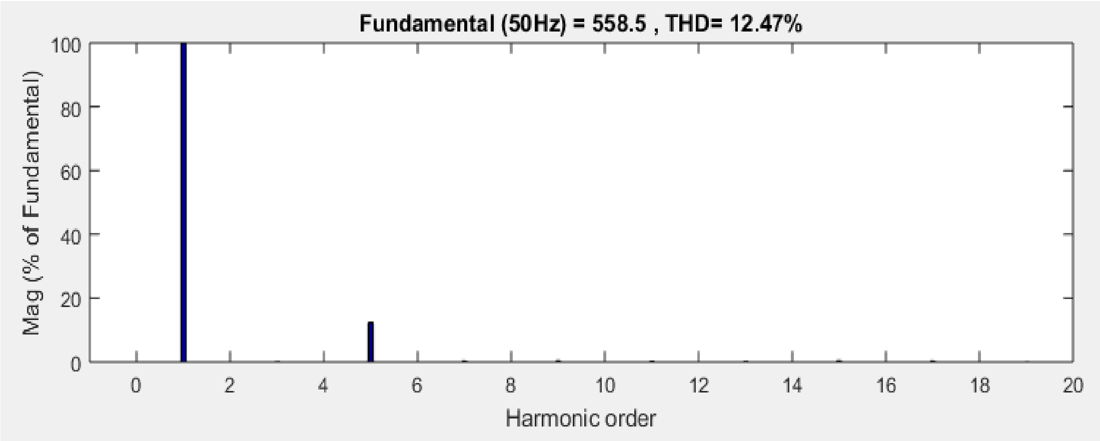

Fig 7.11 Harmonic analysis of distorted source voltage

The series filter is switched ON at t = 1.2s and the distorted source voltage is made sinusoidal. Total Harmonic Distortion is reduced to 1.16%. The source voltage waveform before and after compensation, its FFT and the harmonic analysis are as shown below.

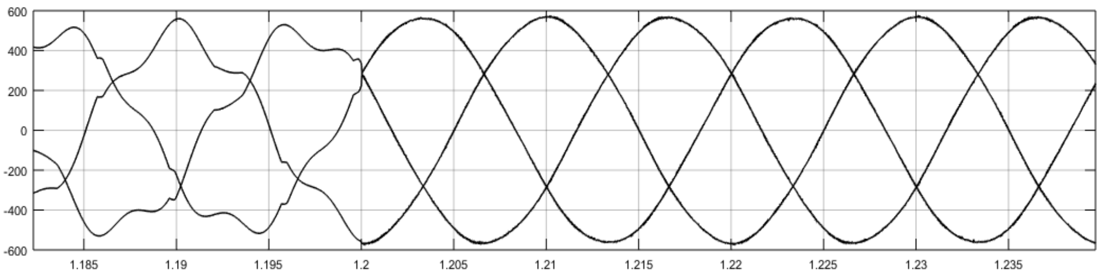

Fig 7.12 Source voltage waveform with Series filter switched ON at t = 1.2s

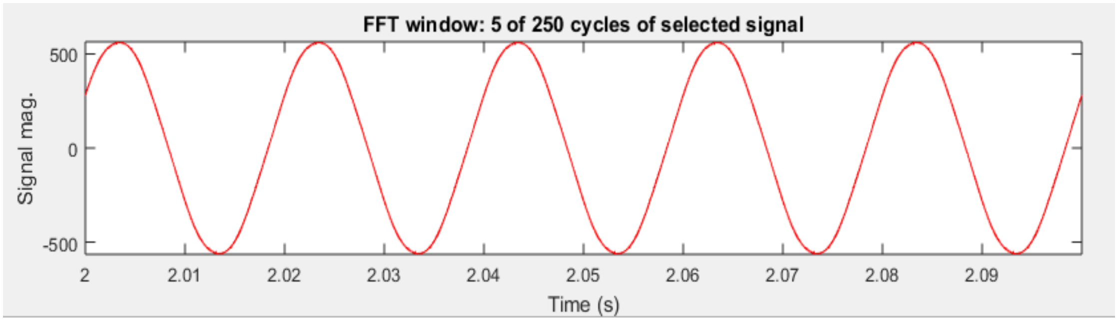

Fig 7.13 FFT window of Source voltage after compensation

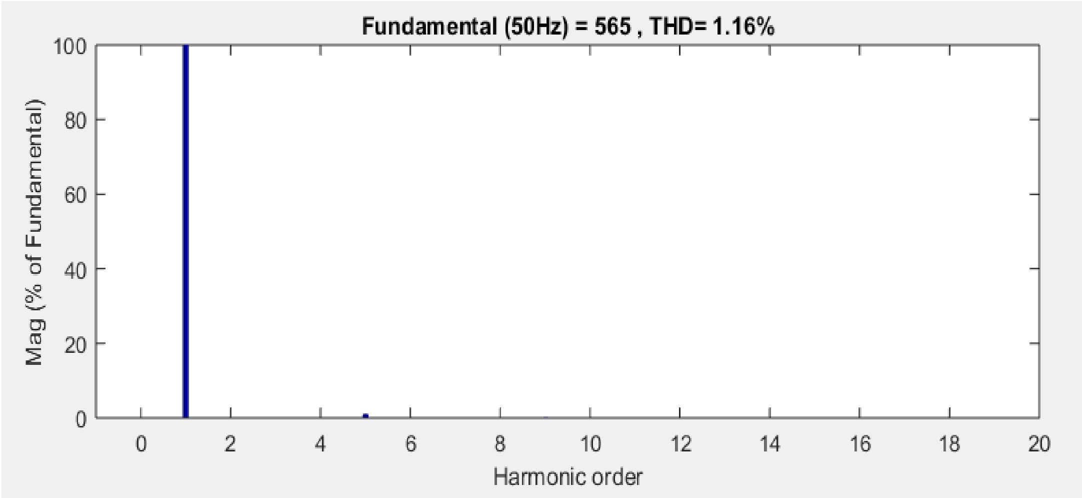

Fig 7.14 Harmonic analysis of Source voltage after compensation

7.4 Simulation of UPQC

In this section the simulation analysis of UPQC is described. In this the two filters (shunt active power filter and series active power filter) are combined on a common DC link to form the unified power quality conditioner. The developed model of UPQC in MATLAB/SIMULINK environment is shown in Fig 7.15. The control circuits for this model have already been discussed in the previous chapter. The shunt active power filter compensates current disturbances and also maintains the dc link voltage to reference value. While series active power filter compensates voltage harmonic problems for maintaining required load voltage. The harmonic analysis of the system under study has already been discussed under the simulation study of shunt and series filters. A non-linear load of 3ph diode bridge rectifier with R-L load has been used. DC link capacitor is same as that used in the shunt filter part. The voltage and current THD of the system before turning ON the UPQC is 20.37% and 12.47% respectively. The DC link capacitor is initially charged to 700V to avoid shunt filter drawing very high initial currents for charging. The shunt filter is switched ON at t = 0.8s and the series filter is switched ON at t = 1.2s. Simulink model, simulation results, FFT analysis and harmonic analysis are discussed below.

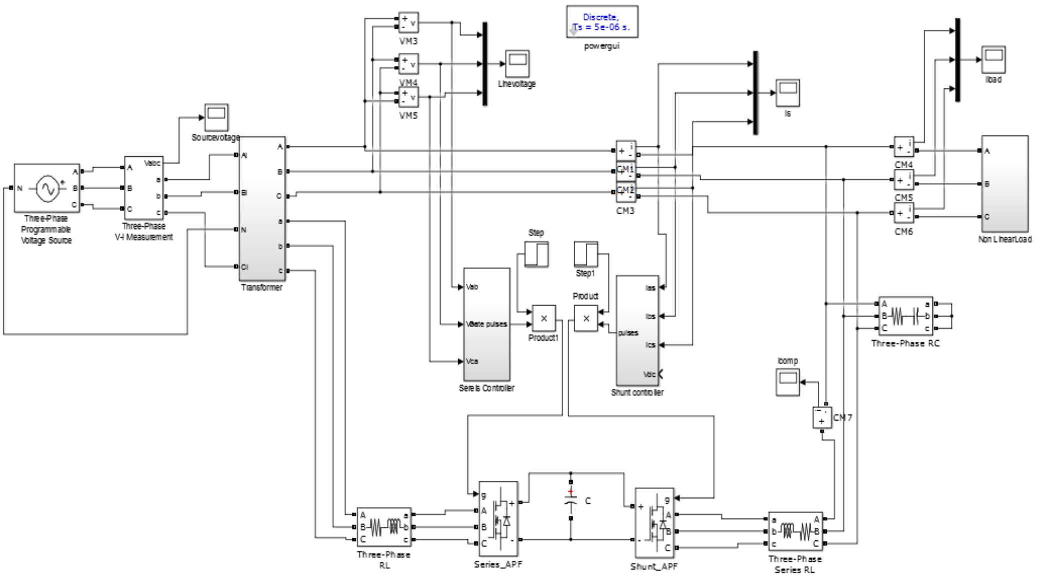

Fig 7.15 Simulink model of UPQC

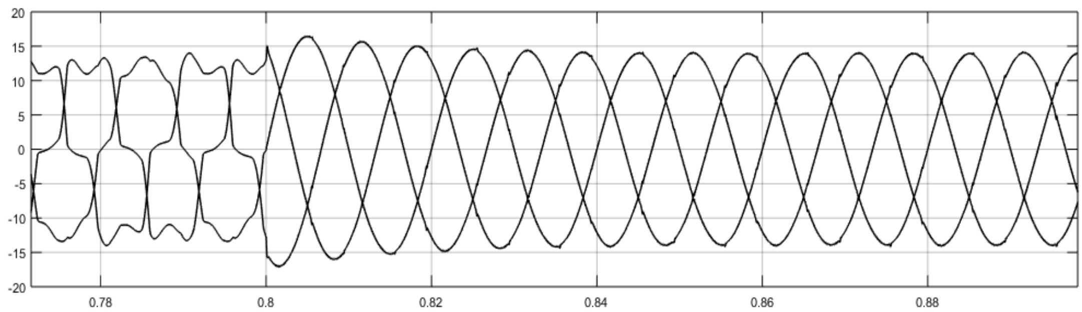

Fig 7.16 Source current waveform with shunt filter of UPQC switched ON at t = 0.8s

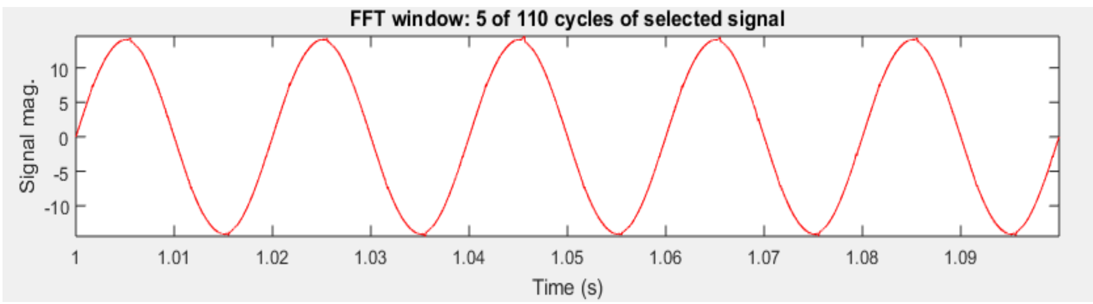

Fig 7.17 FFT window of source current in UPQC

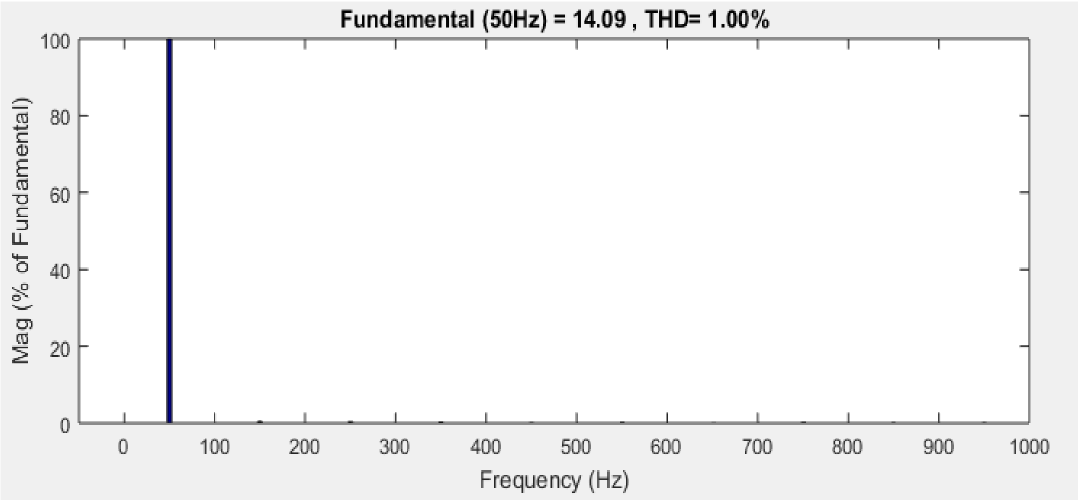

Fig 7.18 Harmonic analysis of Source current waveform in UPQC

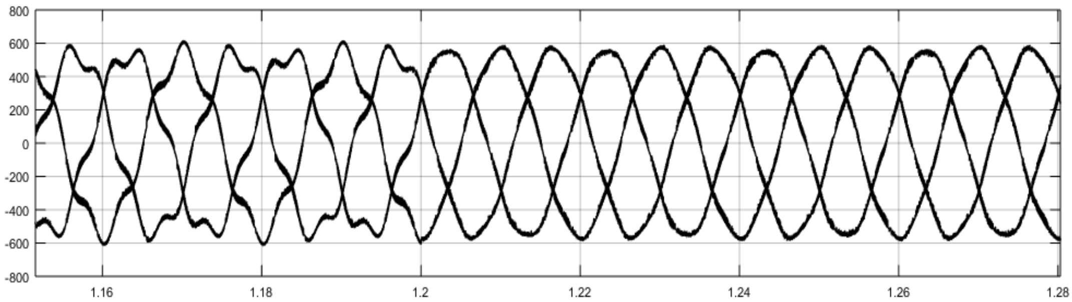

Fig 7.19 Source voltage waveform when Series filter of UPQC switched ON at t = 1.2s

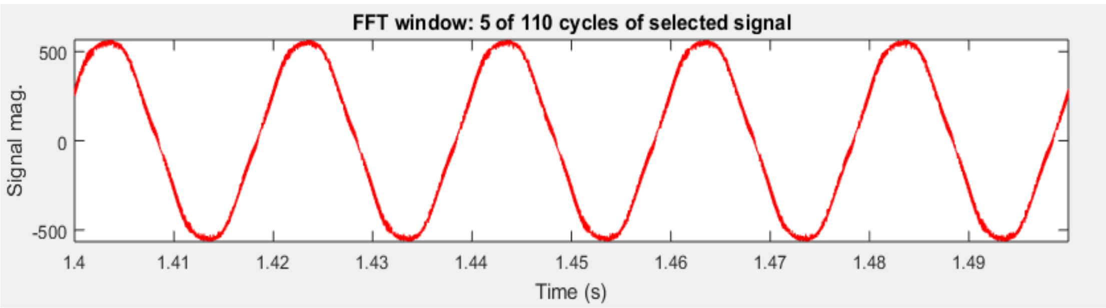

Fig 7.20 FFT window of Source voltage waveform in UPQC

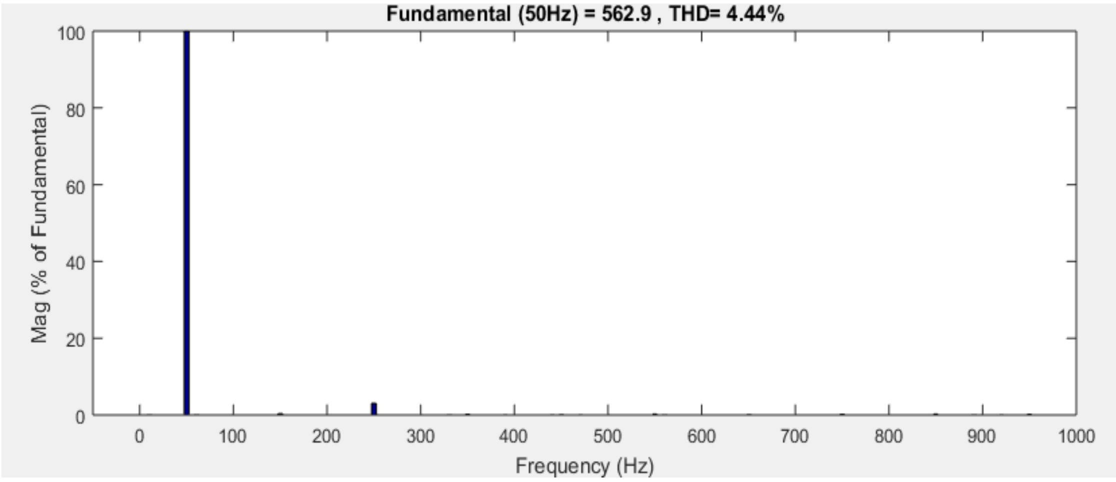

Fig 7.21 Harmonic analysis of source voltage waveform in UPQC

7.5 Simulation of UPQC with reduced voltage rating

The Simulink model of the modified UPQC with reduced voltage rating is as shown in Fig 7.22. Simulations are also carried out for the modified UPQC under the same load conditions. The DC link voltage rating of capacitor in this topology is reduced to 420V from a value of 700V. Capacitor is initially charged to 430V. Series capacitor, with a value of 56.25µF is added in the shunt side in cascade with the coupling inductance, whose value is 5mH. This combination of LC filter is tuned to eliminate 5th and 7th harmonic harmonics.

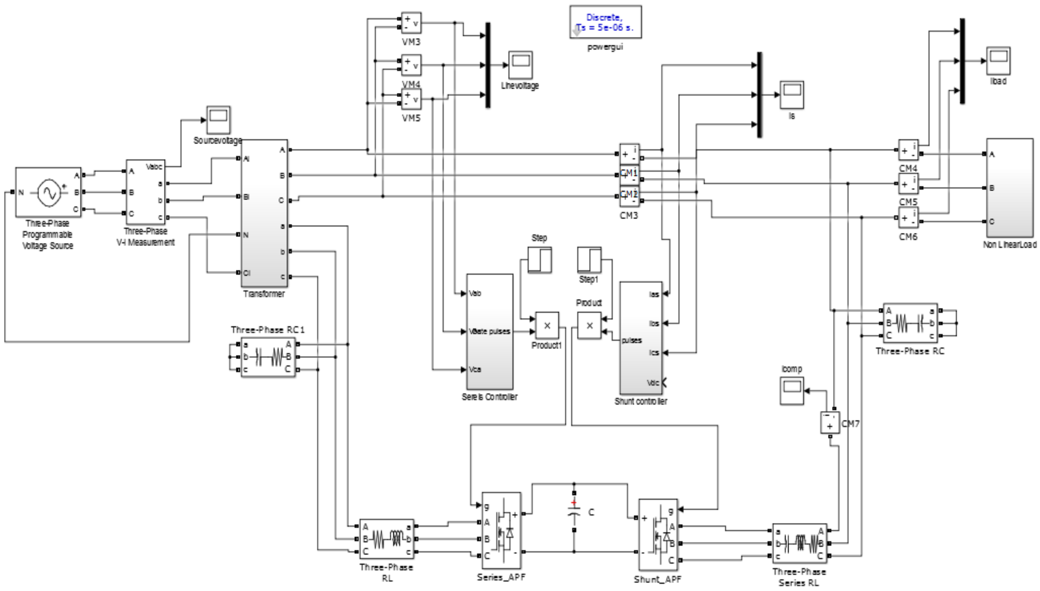

Fig 7.22 Simulink Model of UPQC with reduced voltage rating

Harmonics are successfully mitigated as per IEEE 519 Standard. Fig 7.21 shows the source current waveform before and after compensation when the shunt filter is switched ON at t=1.2s. Source current THD is reduced to 1.54%. Fig 7.22 shows the source voltage waveform when the series filter is switched ON at t=0.5s. Source voltage THD is reduced to 4.8%.

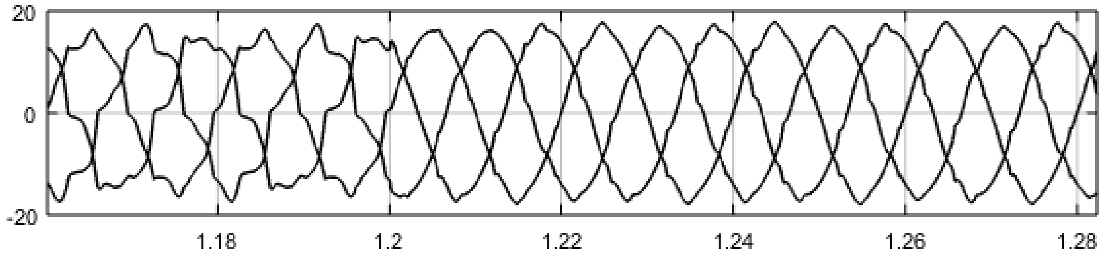

Fig 7.23 Source current in modified UPQC with shunt filter switched ON at t= 1.2s

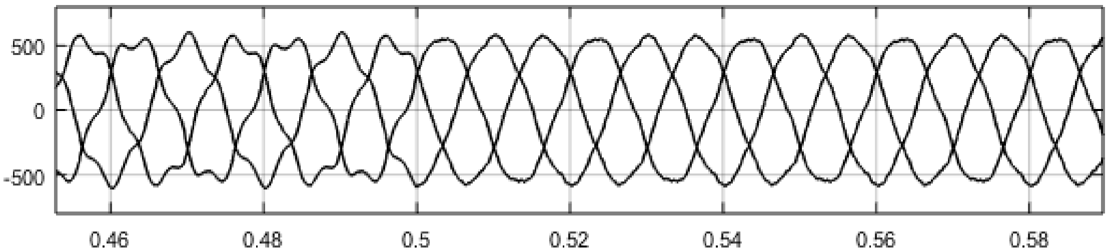

Fig 7.24 Source voltage in modified UPQC with series filter switched ON at t= 0.5s

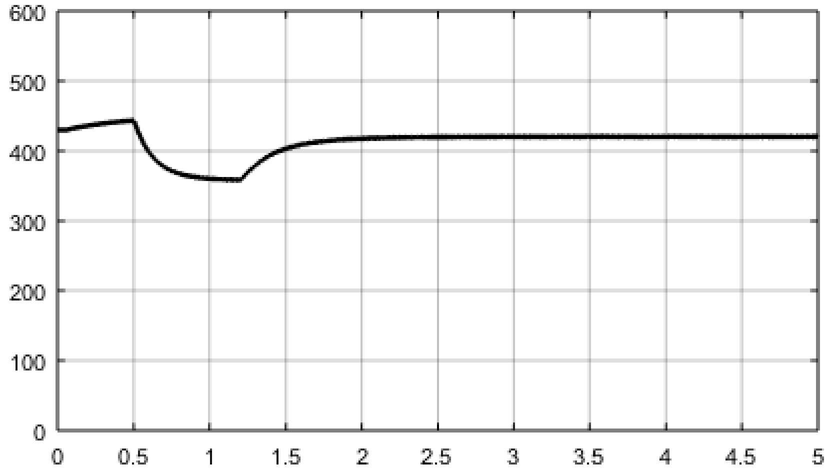

Fig 7.25 DC link capacitor voltage sustained at 420V

7.6 Summary

A comparative study of the results obtained for conventional and modified UPQC can be made from the table shown below.

Sl. No.	Parameter	Normal UPQC	Modified UPQC
1.	DC link voltage	700V	420V
2.	Current THD	1%	1.54%
3.	Voltage THD	4.44%	4.93%

As seen from the table, the voltage and current THD levels are effectively reduced by both the topologies as per IEEE standards. The modified topology is successful in reducing the voltage rating of the DC capacitor without compromising the harmonic compensation. Thus, it can be used as a cost effective solution at the distribution side where the major issues are harmonic compensation of voltage & currents.

Chapter 8: HARDWARE PROTOTYPE DEVELOPMENT

8.1 Introduction

This chapter discusses about the prototype development of a 3 phase 3 wire UPQC. Since UPQC consists of shunt and series active filters, a prototype is to be developed for shunt filter alone first and then for series filter and then combine them both to develop the UPQC. A non-linear load of diode rectifier with R-L load is used. A current controlled Voltage Source Inverter is used as shunt active power filter and voltage controlled Voltage Source Inverter is used as series power filter. Thus, two three phase voltage source inverters have been used as inverters for harmonic filtering. Control of both the inverters is to be done using DSP controller for generation of pulses. For the purpose of generating the pulses and validating the results, mainly 4 signals are to be sensed.

1. Source voltage
2. Source current
3. DC link voltage across the capacitor
4. Voltage at PCC

The prototype development for UPQC requires the following circuits:

1. MOSFET driver circuit
2. Protection circuit of MOSFET
3. Power supply
4. Voltage sensor circuit
5. Current sensor circuit
6. Three phase diode rectifier
7. Power circuit development for shunt and series active filters

8.2 Power circuit development for Active filters

The power circuit of 3P 3W UPQC consists of two three phase two level voltage source inverters connected back to back having a common DC link capacitance. 3 leg two level inverters are to be organised in three leg bridge configuration by using 12 MOSFETs. Both inverters are connected through a common DC link and inverters are to be connected to the grid using coupling inductors.

8.2 Development of MOSFET Driver circuit

MOSFET IRFP 460 is used as the switching device in the inverter circuit because of the high switching frequency and low cost. For protection, snubber circuits and metal oxide varistors (MOV) are used. Also heat sinks are mounted on each MOSFET for protection from excessive heat.

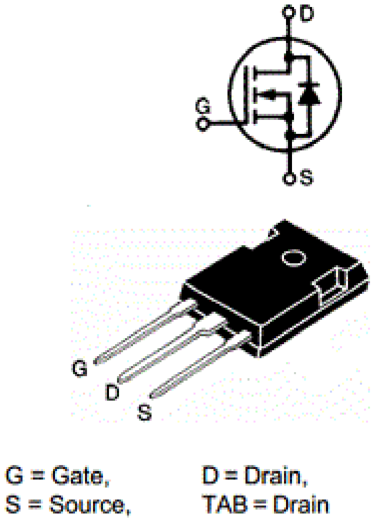

Fig 8.1 MOSFET IRFP 460

8.2.1 Driver circuit with MCT2E optocoupler

The detailed MOSFET driver circuit diagram is given in Fig 8.2. When the gate pulse is given to the base of the input transistor, input transistor goes into saturation state and current starts flowing through LED of optocoupler. The photo transistor of the optocoupler turns ON and thus no base drive goes to the output transistor and hence output transistor remains in cut off state making Gate to Source voltage at 12V. 12V is generated by using a diode bridge rectifier and regulator 7812 IC. This 12V is connected to the collector of output transistor by using a pull up resistor. Whenever input pulse is low, input transistor remains in cut off state making photo transistor in cut off state. Hence output transistor gets base drive and goes into saturation state with nearly 0.2V collector to emitter voltage hence 0.2V gate to source voltage of MOSFET. Thus optocoupler provides required isolation.

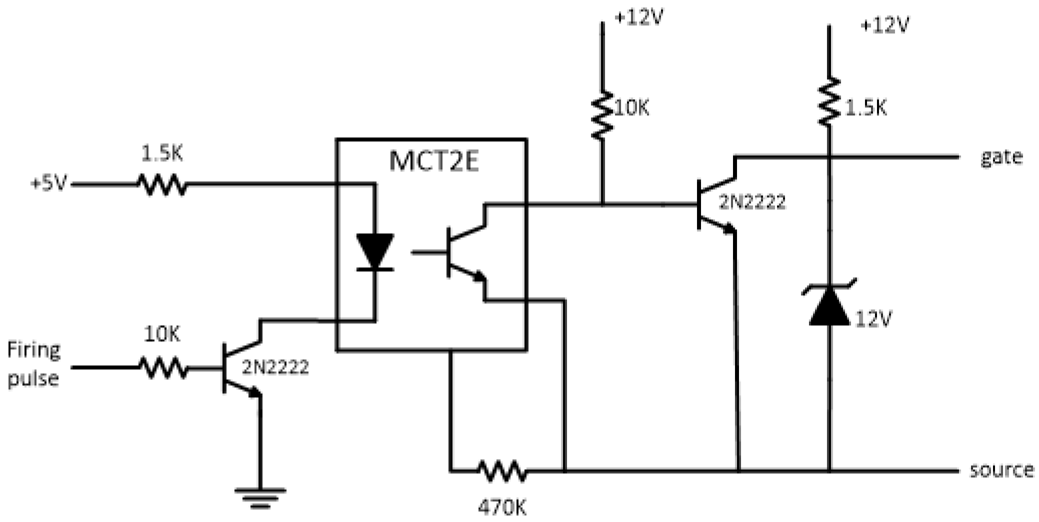

Fig 8.2 Isolation & Amplification circuit using MCT2E

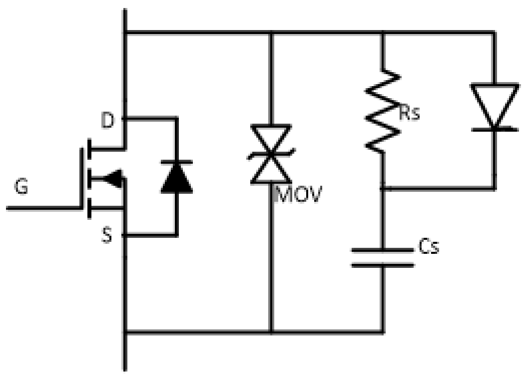

Fig 8.3 Protection circuit schematic for MOSFET

8.2.2 Testing of Driver circuit

The driver circuit for MOSFET IRFP 460 discussed above was designed and its hardware was implemented. Square wave pulses of different frequencies were given to the optocoupler through the base of the transistor and the waveform obtained across Gate to Source of the MOSFET was observed using a Digital Storage Oscilloscope. Square wave pulses of +12V was obtained across Gate & Source of the MOSFET for a frequency up to 5 kHz. The results and driver circuit are displayed below:

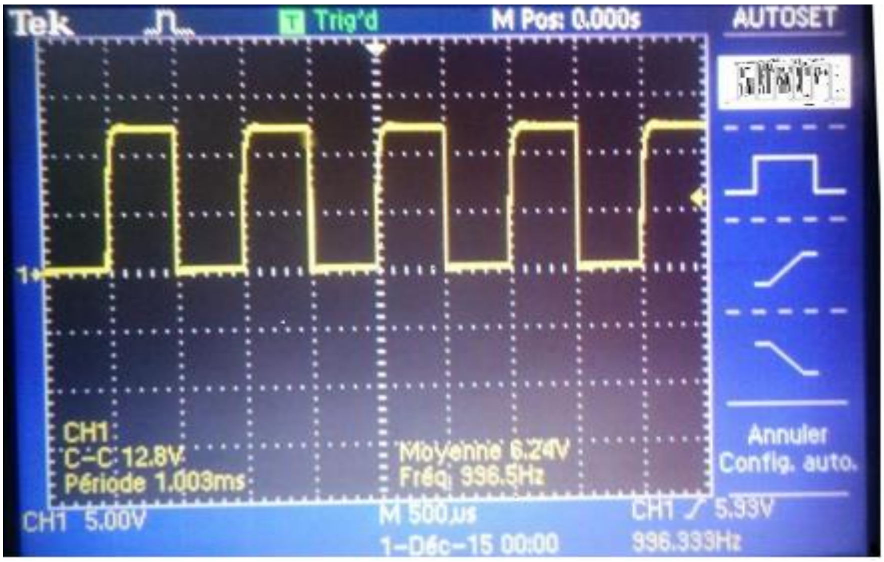

Fig 8.4 Pulse across Gate to Source of MOSFET for a frequency of 1 kHz

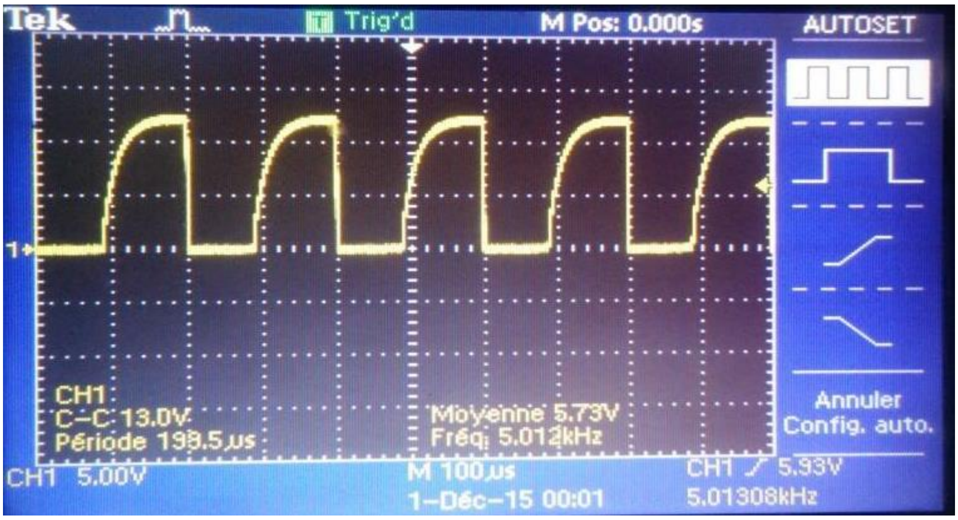

Fig 8.5 Pulses across Gate to Source of MOSFET for a frequency of 5 kHz

The pulses obtained for a frequency more than 5 kHz is found to have a variation from the ideal square shape. So, for this particular driver circuit using MCT2E optocoupler, the switching frequency of inverter is limited to less than 5 kHz.

So, inorder to obtain better switching pulses for higher frequencies, a new driver circuit based on HCPL 3101 IC was developed and tested. The circuit diagram of the new driver circuit is a s shown in the Fig 8.6.

8.2.3 Driver Circuit with HCPL3101

The opto-coupler HCPL301 provides necessary isolation between the low voltage isolation circuit and high voltage power circuit. Transistor 2N2222 provides the pulse amplification. When the input gate pulse to the base of transistor is +5V level, the transistor gets saturated. This will make the light emitting diode to conduct and the light emitted by it falls on the base of the phototransistor, creating the required base drive. Thus, the output transistor receives no base drive and remains in the cut-off state and a +12V pulse comes across the collector.

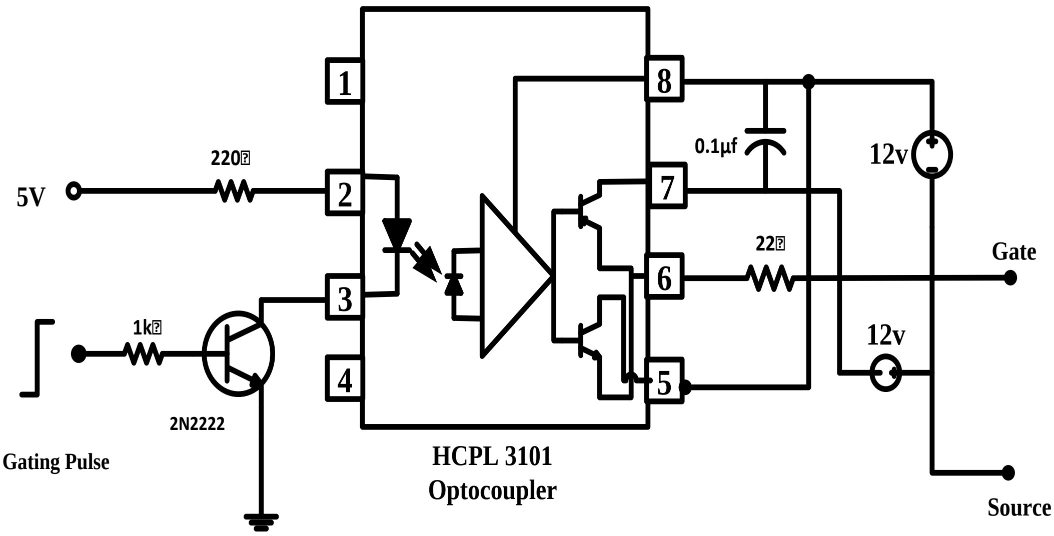

Fig. 8.6 Pulse amplifier and Isolation circuit using HCPL3101

This driver circuit can be employed for higher switching frequencies. Proper pulses have been generated for switching frequencies higher than 10kHz.

8.3 Power Supplies

DC power supplies are required for the functioning of sensor circuits, driver circuits, isolation amplifiers etc. Voltage and current sensor circuits require ±12V and ±15V. This can be developed by using a single phase centre tapped full wave rectifier and voltage regulator IC 7812, 7912, 7815 and 7915. The circuit schematic of ±12V and ±15V is as shown in the below figures. For MOSFET driver circuit, +5V supply is required and is made by using single phase diode bridge rectifier and IC 7805. Fig 8.9 shows the schematic of +5V supply.

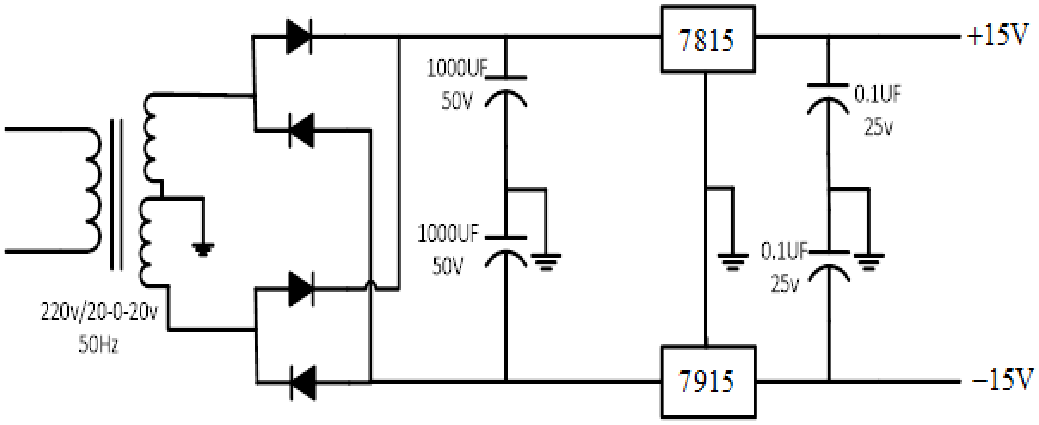

Fig 8.7 Schematic of ±15V Power supply

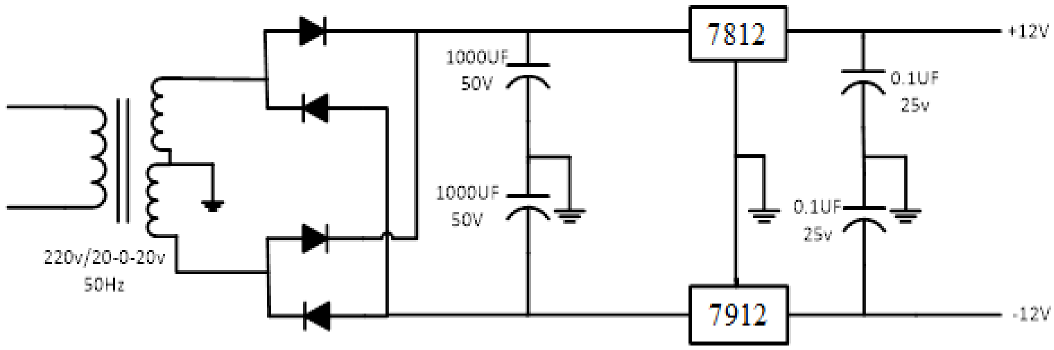

Fig 8.8 Schematic of ±12V Power supply

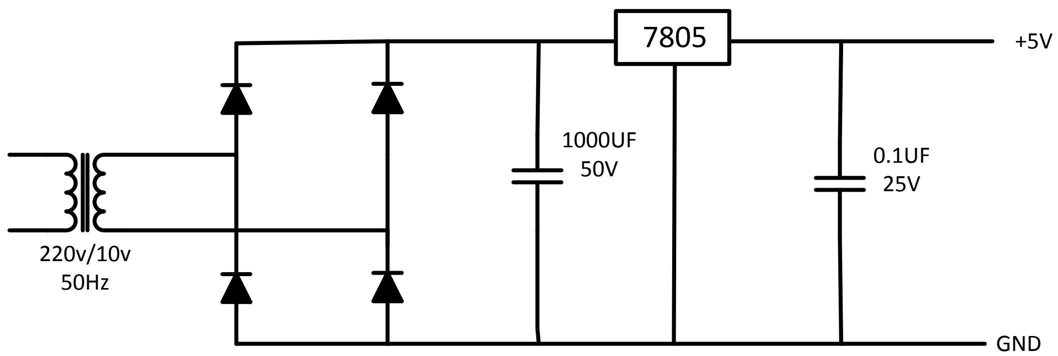

Fig 8.9 Schematic of +5V Power supply.

8.4 Voltage Sensor

The AD202JN is an isolation amplifier in the present experimental setup. It has good accuracy and wide bandwidth. It consumes less power and is small in size. The power circuit voltage which is in the range of ±500 V is converted into ±5V range. Voltage to be sensed is applied between pins 1 and 2 through a voltage divider circuit. Output is sensed between pins 19 and 18. This is fed to a buffer circuit for impedance matching. Output of buffer is scaled by using a scalar buffer circuit which is basically an inverting Op-amp and is varied by using a pot. The schematic diagram for voltage sensor circuit used is shown in Fig 8.10

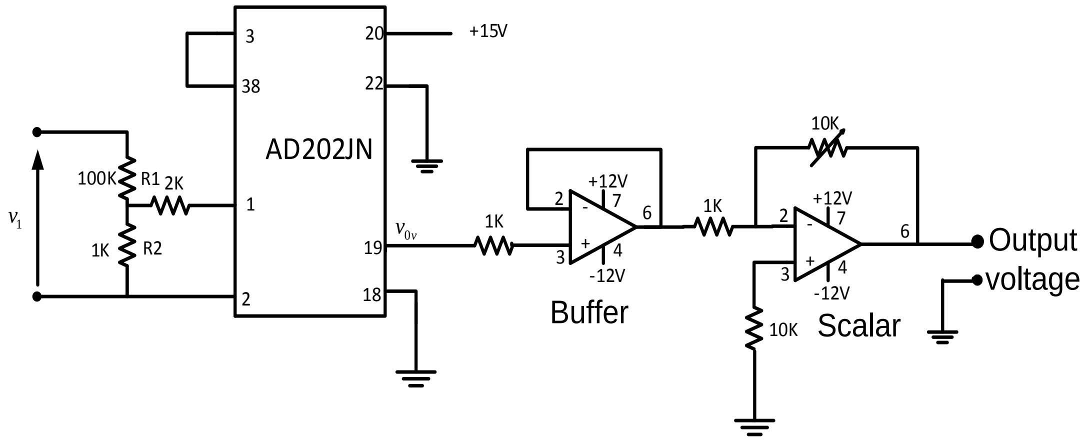

Fig 8.10 Voltage sensor circuit

8.5 Current Sensor

The current sensor circuit is based on Hall Effect current sensors using TELCON HTP25. HTP25 is a closed loop Hall Effect current transformer which can measure currents upto 25A. These current sensors provide galvanic isolation between high voltage power circuit and the low voltage control circuit and require a nominal supply voltage of the ±12V to ±15V. It has a transformation ratio of 1000:1 and the output resistance of the current sensor is scaled properly. The voltage input to the buffer circuit is calculated by the equation$v_{oi} = R_o\left(\frac{N_p i}{cr_i}\right)$. Thus the voltage v_{oi} is scaled properly with the scalar circuit. The schematic diagram of the current sensor is shown in Fig 8.11

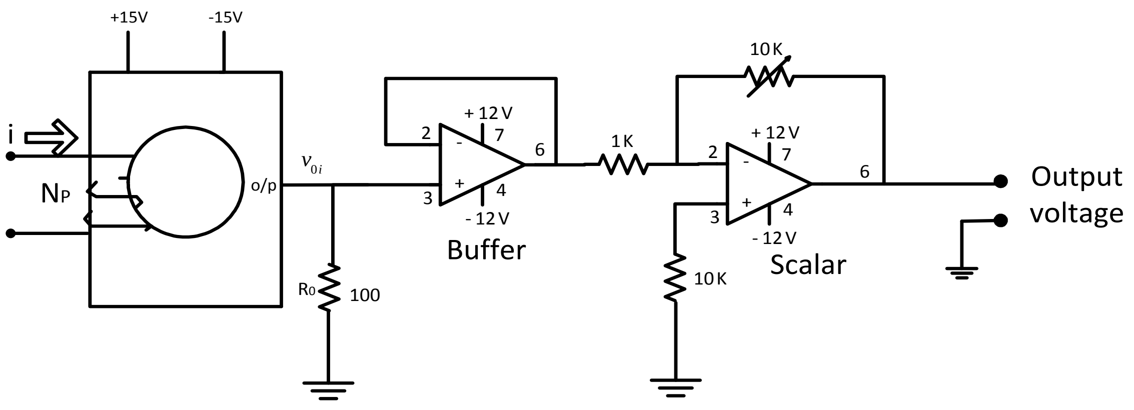

Fig.8.11 Current sensor circuit

8.6 Hardware Prototype development

A complete hardware setup of the UPQC was built. Two voltage source based, simple two level inverters supported on a common DC link capacitor makes the major part on the filter side. On the load side, a diode bridge rectifier with R load has been connected. Voltage and current sensor circuits for closed loop control have also been developed. The picture of the hardware setup is as shown in Fig 8.12.

Fig 8.12 Hardware prototype developed in the laboratory

The voltage source inverter circuits were tested using Arduino Uno controller. The DC side of the inverter was driven by a controlled DC voltage source and the load side was connected to a 3 phase resistive load. Firing pulses in 120° mode were generated and were applied to the inverter. A DC input voltage of 50V was applied. The output voltage developed in the AC side was measured. The voltage waveforms obtained in the AC side of the inverter is as shown below:

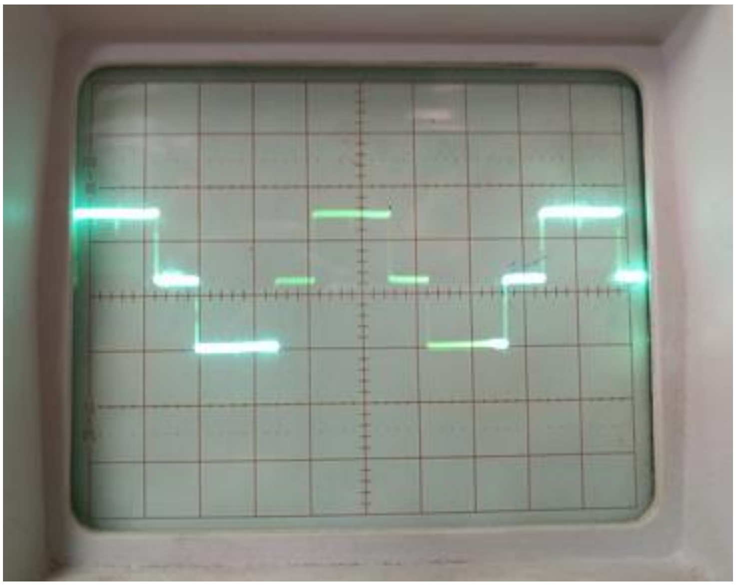

Fig 8.13 Phase voltage obtained in 120° mode

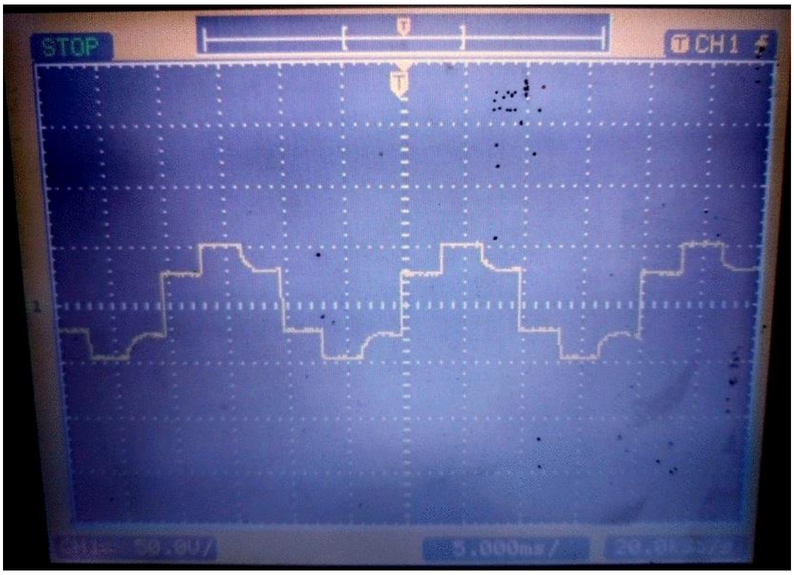

Fig 8.14 Line voltage obtained in 120° mode

Chapter 9: CONCLUSION & FUTURE WORK

This thesis work includes the performance analysis of a Unified Power Quality Conditioner (UPQC) that can be used for harmonic compensation at the distribution side. Detailed study on the series and shunt filter parts of the UPQC has been carried out. A three phase three wire system with a non-linear load has been taken under consideration and the effect of UPQC on it is analysed. Unit Vector Template generation technique has been applied for the reference signal generation and a hysteresis controller is used for firing pulse generation. Simulation studies have been made, in MATLAB/Simulink environment, of the complete system and the results obtained are found to be meeting the IEEE standards.

Also, a modified topology of UPQC that can effectively reduce the DC link voltage rating of the capacitor has been developed in the same three phase three wire system under study. Series capacitors have been included in cascade with the coupling inductor on the shunt active filter part of UPQC in order to realise this. Simulation studies prove the robustness of the proposed topology in reducing the voltage rating without making a compromise on the harmonic mitigation.

In future, this work can be extended to realise UPQC with improved performance by carrying out wide research on topology, control scheme, application on renewable energy sources.

- Topology: UPQC can be realised using a reduced number of switches, by eliminating the third leg of the inverter, thereby reducing the losses. Also, research can be done on replacing the series injection transformer with low cost, less size equipment like capacitor.
- Control strategy: Better control schemes like model predictive control, Adaline based control can be employed for improved performance. The use of hysteresis controller has a drawback of variable switching frequency. This can be overcome by using other PWM techniques.
- Application to Renewable energy sources: The UPQC control scheme for the grid connected wind energy generation system for power quality improvement is a new area of interest in the field of research.

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