Improved Power Quality Using D-Q Theory-Based Three-Phase Unified Power Flow Controller

by

INTRODUCTION

1.1 General

The current power distribution system is often organised as either a three-phase, three-wire or four-wire structure. It also includes a power-limit voltage source with high source impedance, as well as an accumulation of different kinds of loads. In an ideal scenario, the system should provide the loads with a balanced and pure sinusoidal three-phase voltage that is constant in amplitude. Moreover, the loads should draw a current from the line that has unity power factor, zero harmonics, and balanced phases. With four-wire systems, there should not be an excessive amount of current in the neutral. As a consequence of this, the maximum power capacity and efficiency of the energy distribution are accomplished, the disturbance caused to other appliances is kept to a minimum, and the operation is guaranteed to be risk-free. However, due to the rapidly growing number of applications of industry electronics that are currently connected to distribution systems, such as nonlinear, switching, reactive, single-phase, and unbalanced three-phase loads, a complex problem of power quality has emerged. This problem is characterised by the voltage and current harmonics, unbalances, and low Power Factor (PF).

In recent years, active techniques for controlling power quality have emerged as more desirable alternatives to passive approaches. This is owing to active methods' quicker reaction times, smaller sizes, and greater performance levels. Some active circuits were developed to compensate unbalanced currents as well as limit the neutral current. For instance, the Static VAR Compensator (SVC) has been reported to improve the power factor; the Power Factor Corrector (PFC) and the Active Power Filters (APF) have the ability to suppress current harmonics and correct the power factor. In a broad sense, converters that are linked in parallel have the capacity to increase the quality of the current, while regulators that are connected in series and positioned between the load and the supply may improve the quality of the voltage. Both series 2 and shunt converters are required for quality control of voltage and current. This combination is referred to as Unified Power Quality Conditioner (UPQC) and has been investigated in this thesis. UPQCs are important for controlling voltage and current. The UPQC was introduced in the year 1998. This kind of solution is able to correct for a variety of power quality issues, including voltage imbalance, flicker, reactive currents, and sags and swells. In most cases, UPQC is made up of a pair of voltage-source converters that share a single capacitive DC connection. Whereas the other of the converters is a series active filter, the first one is an active rectifier (AR), also known as a shunt active filter (SF). In addition, the connecting of the passive filter banks takes place at the point where the load is connected. In UPQC, the series active power filter gets rid of any flickering or unevenness in the supply voltage at the load terminal voltage. Moreover, it compels an existing shunt passive filter to absorb all of the current harmonics that are created by a nonlinear load. As the shunt active filter is responsible for regulating the voltage of the dc link, this results in the capacity of the dc link capacitor being significantly reduced. In this session, a variety of issues pertaining to power quality, as well as potential solutions, will be discussed, with a particular focus on the UPQC.

1.2 Importance of Clean Power

The technology of modern semiconductors is a tool that may help businesses increase their productivity and their profits. It is designed to function on electricity that is free of contaminants. The irony is that as the sophistication of this technology grows, so does its vulnerability to power disturbances. This is due to the fact that nonlinear devices, such as power electronics converters, inject harmonic currents into the ac system and increase the overall reactive power demanded by the equivalent load. Also, there has been a rise in the number of sensitive loads that need perfect sinusoidal supply voltages in order to function correctly. It is vital to add some kind of compensation in order to maintain the power quality within the limitations that are specified by the standards. The use of clean electricity in technology is analogous to the use of clean gasoline in cars.

1.3 Introduction of Power Quality

The term electric power quality broadly refers to maintaining a nearly sinusoidal power distribution bus voltage at rated magnitude and frequency. In addition, the energy supplied to a consumer must be uninterrupted from reliability point of view. Though power quality is mainly a distribution system problem, power transmission system may 3 also have impact on quality of power. Causes for power quality deterioration are explained in next section.

1.4 Power Quality Problems

Because of the ever-increasing use of highly complex controls and equipment in industrial, commercial, institutional, and governmental institutions, the continuity, dependability, and quality of the electrical service have become increasingly important to a large number of power users. Electrical systems are susceptible to a broad range of power quality issues, each one of which has the potential to halt production operations, negatively impact sensitive equipment, and result in downtime, scrap, and capacity losses. Alterations in the voltage for just a few period of time may have a catastrophic effect on productivity, but longer power outages have an even bigger influence.

After a detailed description of the issues has been gathered, it is simple to identify many of the power quality concerns that exist. Regrettably, the tensions that are produced by power concerns sometimes result in explanations of the situation that are either ambiguous or too dramatic. When there are issues with the power supply, it is important to make a note of the precise time the issue occurred, how it affected the electrical equipment, and whether or not any new equipment was recently installed that may have caused issues with the system.

An audit of the power quality may assist in determining the root causes of a person's issues and devising a methodical strategy for resolving those issues. The power quality audit examines the wiring and grounding in a facility to see whether or not it is suitable for the applications being used and whether or not it is up to code. The quality of the AC voltage itself, as well as the influence that the power system of the utility has, will be examined by the auditor. The results of the audit will be compiled into a report that will also detail any issues that were discovered and provide recommendations for potential fixes. A large number of companies and organisations depend on computer systems and other types of electrical equipment to carry out mission-critical operations; yet, many companies and organisations do not take precautions against the risks associated with an unstable power supply.

1.4.1 Source of Power Quality Problems

- Disturbances can be generated external to a facility.
- Disturbances can be generated internal to a facility.

External Origins:

- Lightning
- Grid Switching
- Power Factor Correction
- Inductive Load Switching
- Utility Fault Clearing

Internal Origins:

- Internal disturbances are typically more numerous and destructive.
- They are created by all the various electrical loads in your facility.
- The disturbance sources are also closer to sensitive devices which limit the damping effect of wiring.

1.4.2 Generic Power Problems

The following are the generic power problems: Blackouts & Brownouts, Sags, Surges, Impulses, Frequency Changes, Noise, Harmonics, and Power Factor Problems

1.4.3 Responsibility of utility

- Constant Voltage
- All the current needed (breaker limited)
- Protection for people and traditional loads (lights and motors) through grounding procedures.

1.5 The Most Common Power Quality Problems

A. Voltage Sags

Voltage sags are the most common power problem encountered. Sags are a short-term reduction in voltage (that are 80-85% of normal voltage) [5], and can cause interruptions to sensitive equipment such as adjustable-speed drives, relays, and robots. Sags are most 5 often caused by fuse or breaker operation, motor starting, or capacitor switching. Voltage sags typically are non-repetitive, or repeat only a few times due to recloser operation. Sags can occur on multiple phases or on a single phase and can be accompanied by voltage swells on other phases.

B. Power Interruptions

Power interruptions are zero-voltage events that can be caused by weather, equipment malfunction, recloser operations, or transmission outages. Interruptions can occur on one or more phases and are typically short duration events, the vast majority of power interruptions are less than 30 seconds [5].

C. Voltage Flicker

Voltage flicker is rapidly occurring voltage sags caused by sudden and large increases in load current. Voltage flicker is most commonly caused by rapidly varying loads that require a large amount of reactive power such as welders, rock-crushers, sawmills, wood chippers, metal shredders, and amusement rides. It can cause visible flicker in lights and cause other processes to shut down or malfunction.

D. Power Surges

A power surge takes place when the voltage is 110% or more above normal. The most common cause is heavy electrical equipment being turned off. Under these conditions, computer systems and other high tech equipment can experience flickering lights, equipment shutoff, errors or memory loss [1][5].

E. High-Voltage Spikes

High-voltage spikes occur when there is a sudden voltage peak of up to 6,000 volts. These spikes are usually the result of nearby lightning strikes, but there can be other causes as well. The effects on electronic systems can include loss of data and burned circuit boards.6

F. Switching Transients

Switching transients are extremely rapid voltage peak of up to 20,000 volts with duration of 10 microseconds to 100 microseconds. Switching transients take place in such a short duration that they often do not show up on normal electrical test equipment. They are commonly caused by machinery starting and stopping, arcing faults and static discharge. In addition, switching disturbances initiated by utilities to correct line problems may happen several times a day. Effects can include data errors, memory loss and component stress that can lead to breakdown.

G. Frequency Variation

A frequency variation involves a change in frequency from the normally stable utility frequency of 50Hz.This may be caused by erratic operation of emergency generators or unstable frequency power sources. For sensitive equipment, the results can be data loss, program failure, equipment lock-up or complete shut down.

H. Electrical Line Noise

Electrical line noise is defined as Radio Frequency Interference (RFI) and Electromagnetic Interference (EMI) and causes unwanted effects in the circuits of computer systems. Sources of the problems include motors, relays, motor control devices, broadcast transmissions, microwave radiation, and distant electrical storms. RFI, EMI and other frequency problems can cause equipment to lock-up, and data error or loss.

I. Brownouts

A brownout is a steady lower voltage state. An example of a brownout is what happens during peak electrical demand in the summer, when utilities can't always meet the requirements and must lower the voltage to limit maximum power. When this happens, systems can experience glitches, data loss and equipment failure.

J. Blackouts

A power failure or blackout is a zero-voltage condition that lasts for more than two cycles. It may be caused by tripping a circuit breaker, power distribution failure or utility power failure. A blackout can cause data loss or corruption and equipment damage.7

1.6 An Overview of Power Problems, Their Causes and Effects

There are number of power quality problems and each problem create significant effect. The overview of problem and their effects is summarized in following table

Table 1.1: Overview of Power Problems, Their Causes and Effects

Power Problems	Causes	Effects
Voltage Spikes and Surges	Lightning, Utility grid switching, Heavy industrial	Equipment failure, System lock-up, Data corruption, Data

	equipment	loss
Electrical Noise	Arc Welders etc..., Switch mode power supplies, Fault clearing devices, Ground not dedicated or isolated	Data corruption, Erroneous command functions, Loss of command functions, Improper wave shapes etc...
Harmonics	Switch mode power supplies, Nonlinear loads	High neutral currents, Overheated neutral conductors, Overheated transformers, Voltage distortion, Loss of system capacity
Voltage Fluctuations	Brownouts, Unstable generators, Overburdened distribution systems, Start-up of heavy equipment	System lock-up, System shutdown, Data corruption, Data Loss, Reduced performance, Loss of system control
Power Outage & Interruptions	Blackouts, Faulted or overload, conditions, Back-up generator start-up	System crash, System lock-up, Power supply damage, Lost data, Complete shutdown loss of control
Stable AC from DC source	DC power plant available, Remote areas	Unavailable AC power
Emergency power source transfer, Peak shave power	Back-up generator start-up, Power interruption transfer of utility source	System crash, System lock-up, Power supply damage, Lost data, Complete shutdown loss of control
Distribution Systems and Power quality questions	Lack of understanding of system problems or coordination	Unstable distribution system, Lost productivity and profitability.
High energy cost / Power factor correction	Need for energy savings and pay back for equipment investment.	Lost profits increased cost.

1.7 Power Quality Solutions

- Surge Suppressors
- Voltage Regulators
- Generators
- Filters

1.7.1 Surge Suppressors

Transient voltage surge suppression (TVSS) provides protection against transient surges, which can happen so quickly that they do not register on normal electrical testing equipment. Surge suppressors or surge protectors are the most basic form of power protection. A surge suppressor is often used to shield important, but less critical or highly sensitive equipment. It is also used as a complement to more comprehensive power protection solutions. They are passive electronic devices that protect against transient high-level voltages.

Transients are often the cause of "unexplained" equipment problems, computer lock-up, data loss, and other "gremlins" inside a facility. Transient voltage surge suppressors can be incorporated into voltage regulators, power conditioners, and UPS for added protection. Depending on the components involved, surge suppressors offer limited protection against power surges. In the case of frequent high voltage spikes, a high 9 quality surge suppressor is a good choice. When large equipment like AC motors are turned on and off, they create large, fast voltage changes (switching transients). However, low frequency surges (slow changes at 400 Hz or less) can be too great for a surge suppressor attempting to clamp that surge.

1.7.2 Voltage Regulators

A voltage regulator maintains the input voltage to the facility or system within a narrow range. Regulators provide excellent protection against sags, brownouts, surges and spikes, and moderate noise attenuation, but do not protect against blackouts. There are five types of voltage regulators:

- Ferro resonant
- Tap Switching Transformer
- Limited Range Variable Transformer
- Buck-Boost
- Hybrids

A. Ferro resonant Regulators

Ferro resonant constant voltage regulators use [77] a capacitor in series with a transformer coil, and tend to be high impedance devices that are sensitive to load changes, and therefore, do not handle [77] high inrush loads well. They can interact with switch mode power supplies to produce transients and electrical noise on the output. Their resonant circuits make them particularly sensitive to frequency changes. Applied carefully, Ferro resonant regulators can provide ±2% - ±5% output regulation, load isolation, and noise attenuation

B. Tap Switching Transformer Regulator

Regulators based on tap-switching transformers monitor output voltage and use solid state switching circuits for changing the transformer taps. Typically these units provide ±3% - ±5% output regulation. These regulators are extremely fast, but their fast response can sometimes cause problems with switch mode power supplies and can produce harmonics and radio frequency interference.

C. Limited Range Variable Transformer Regulator

Limited range variable transformer regulators use variable transformers to directly control the output voltage of the regulator. This places the transformer's brush assembly directly in the power path of the regulator, which could cause premature regulator failure. Limited range regulators provide excellent regulation, from ±1% - ±3%.

D. Buck-Boost

The buck-boos regulator consists of three basic components: a motorized variable transformer, a buck-boost transformer, and a controller. These regulators are very reliable and provide from ±1% - ±3% voltage regulation. The controller monitors the output voltage and then uses the feedback signals to determine drive commands for the transformers.

E. Hybrid Regulators

Ideally, a voltage regulator will combine two or more of these technologies in order to maximize the regulator's stability and output regulation. Called hybrid regulators, these units bring voltage regulation up to a power conditioning level, providing comprehensive power conditioning features such as harmonic suppression.

1.7.3 Generators

Generators are machines that convert mechanical energy into electrical energy. They are usually used as a backup power source for a facility's critical systems such as elevators and emergency lighting in case of blackout. However, they do not offer protection against utility power problems such as over voltages and frequency fluctuations, and although most can be equipped with automatic switching mechanisms, the electrical supply is interrupted before switching is completed, so it cannot protect against the damage that blackouts can cause to expensive equipment and machinery.11

1.7.4 Filters

- Passive filters
- Active power filters

A. Passive filters

Passive filters have been most commonly used to limit the flow of harmonic currents in distribution systems they are usually custom designed for the application. However, their performance is limited to a few harmonics and they can introduce resonance in the power system.

The passive filters use reactive storage components, namely capacitors and inductors.

Among the more commonly used passive filters are the shunt LC filters and the shunt low pass LC filters. They have some advantages such as simplicity, reliability, efficiency and cost. Among the main disadvantages are the resonances introduced into the ac supply; the filter effectiveness, which is a function of overall system configuration; and the tuning and possible detuning issues. These drawbacks are overcome with the use of active power filters.

1.8 Active Power Filters

Active power filters are basically of two types i.e. shunt active power filter and series active power filters.

1.8.1 Shunt Active Filter

The shunt active power filter, with a self controlled dc bus, has a topology similar to that of a static compensator (STATCOM) used for reactive power compensation in power transmission systems. Shunt active power filters compensate load current harmonics by injecting equal but opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180o

1.8.2 Series Active Power Filters

Series active power filters were introduced by the end of the 1980s and operate mainly as a voltage regulator and as a harmonic isolator between the nonlinear load and the utility system. The series connected filter protects the consumer from an inadequate supply voltage quality. This type of approach is especially recommended for compensation of voltage unbalances and voltage sags from the ac supply and for low power applications and represents economically attractive alternatives to UPS, since no energy storage (battery) is necessary and the overall rating of the components is smaller. The series active filter injects a voltage component in series with the supply voltage and therefore can be regarded as a controlled voltage source, compensating voltage sags and swells on the load side.

1.8.3 Series-Shunt Active Filters

As the name suggests, the series-shunt active filter is a combination of series active filter and shunt active filter. The shunt-active filter is located at the load side and can be used to compensate for the load harmonics. On the other hand, the series portion is at the source side and can act as a harmonic blocking filter. This topology is called as Unified Power Quality Conditioner. The series portion compensates for supply voltage harmonics and voltage unbalances, acts as a harmonic blocking filter and damps power system oscillations. The shunt portion compensates load current harmonics, reactive power and load current unbalances.

1.9 Harmonic Standards

Different standards that are followed are listed below

- IEEE 519: Harmonic control Electrical power systems [24].
- IEEE Harmonic‘s working group.

- IEC Norm 555-3, prepared by the International Electrical commission.
- IEC Power quality standards- numbering system (61000-1-X - Definitions and methodology; 61000-2-X - Environment (e.g. 61000-2-4 is compatibility levels in industrial plants); 61000-3-X - Limits (e.g. 61000-3-4 is limits on harmonics emissions); 61000-4-X - Tests and measurements (e.g. 61000-4-30 is power quality measurements); 61000-5-X - Installation and mitigation; 61000-6-X - Generic immunity & emissions standards; IEC SC77A: Low frequency EMC Phenomena -- essentially equivalent of "power quality" in American terminology).
- US Military Power Quality Standards (MIL-STD-1399, MIL-STD- 704E).
- EN 50 006, ―The limitation of disturbances in electricity supply networks caused by domestic and similar appliances equipped with electronic devices,‖ European standard prepared by CENELEC.
- West German Standards VDE 0838 for household appliances, VDE 0160 for converters, and VDE 0712 for fluorescent lamp ballasts.

In the thesis IEEE – 519 standards is taken for comparison with the obtained results from simulation and practical. This is common standard which is used, briefly the total harmonic distortion of current drawn must be below 5% and individual harmonic components shouldn‘t be greater than 3%. This also imposes restriction on supply voltage harmonics which are to be maintained below 3% by the utility or supplier.

1.10 State of Art

Unexplained computer network failures, premature motor burnouts, humming in telecommunication lines, and transformer overheating are only a few of the damages that quality problems may bring into home and industrial installations. Studies by the Canadian Electrical Association indicate that power quality problems, including voltage sags and surges, transients, and harmonics, are estimated to cost Canada about $1.2 billion annually in loss production. Most of the cost of harmonics is not incurred in the power system itself but rather within the customer‘s facility [1-2-3].

Power quality problems such as voltages Sag/Swell, flickers, harmonics, asymmetric of voltage have become increasingly serious. The voltage quality may contain amplitude errors, harmonics, phase unbalance, sag/dips, swells, flicks, impulses and interrupt 14 voltage. As far as the current quality is concerned harmonics, reactive component, unbalance, excessive neutral zero-sequence current are the main issues [4-5-6]

While system solutions are being searched and even power quality markets are being formulated in the present deregulated environments, the solution starts at the individual industrial and commercial facilities. With the risks and costs of pollution in mind, researchers and equipment manufacturers are looking for alternatives for protection, while industry and businesses are increasingly investing in sophisticated and innovative devices to improve power quality.[7-8]

Nowadays power quality problems are solved primarily with different Active Power Filter. Research into active power filter for medium voltage range is ongoing [9-10-11] The control strategies applied to active power filters play a very important role on the improvement of the performance and stability of APF; with the development of control strategies. The method used for current reference generation is simple by using newly proposed algorithm. The method used is indirect method of estimation but in other reference frame change the 3 phase supply in to 2 phase supply [12-13]. APF algorithm also compensate harmonics and reactive power separately. It is mainly based upon the desired capacity of the APF. Various simulation results are presented with ideal and distorted mains voltage and compared with other algorithms. [14-15]

APF is designed with controlled voltage source power converter as active power filter to generate a compensating voltage that is converters into compensating current via the series connected inductor and capacitor set. This is nothing but a hybrid topology to improve the performance of the active power filter. Performance of different topologies with hybrid topology is compared, in proposed topology they claim that the size of the inductor and capacitor are reduced.[16-17-18]

The shunt active power filter (STATCOM), used for reactive power compensation in power transmission systems. Shunt active power filters compensate load current harmonics by injecting equal but opposite harmonic compensating current[19-20]. In this 15 case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180o.

The STATCOM is a solidstate synchronous voltage generator, which consists of a multi-pulse, voltage-sourced inverter connected in shunt with the transmission line. The shunt active filter has proved to be useful device to eliminate harmonic currents and to compensate reactive power for linear/nonlinear loads. This reference presents a novel approach to determine reference compensation currents of the three phases shunt active power filter (APF) under distorted and/or imbalanced source voltages in steady state. The proposed approach is compared with three reviewed shunt APF reference compensation strategies.[9-21-22-23]

The STATCOM is superior in that it provides greater speed of response, does not increase short circuit current in the system and can provide symmetrical leading or lagging reactive current[8]. The smooth continuous control of the STATCOM minimizes source, compensating voltage sags and swells on the load side[24-25].

According to Industrial customer Voltage sag is the most sever power quality problem Voltage sag is common reasons for malfunctioning in production plants. According to IEEE standard 1159 voltage sag is ―a decrease in RMS voltage between 10 to 90 % at a power frequency for durations from 0.5 cycles to 1 minute‖ [5]. off large load. The effect of voltage swell is control delay tripping, overheating and many times destruction in electrical equipments [3].

One of the most efficient method is to mitigate voltage sag/swell DVR (Dynamic Voltage Restore). DVR inject an appropriate voltage magnitude with an appropriate phase angle dynamically [4]. Dynamic compensating signals are determine based on the difference between desired and actual values [5]. Main components of DVR are voltage source converter, injecting transformer, passive filter, and energy storage device. The performance of DVR depends on the efficiency control technique of switching of voltage source inverter (VSI). In this paper abc to dq0 based simple control method is used to 16 compensate voltage sag/swell. The proposed control technique is modeled based on MATLAB/ SIMULINK. [26-27-28]

Series active power filter working as a sinusoidal current source, in phase with the mains voltage. The amplitude of the fundamental current in the series filter was controlled through the error signal generated between the load voltage and a pre-established reference. The control allows an effective correction of power factor, harmonic distortion, and load voltage regulation. Compared with previous methods of control developed for series active filters, this method is simpler to implement, because in this approach the only thing required is to generate a sinusoidal current, in phase with the mains voltage, the amplitude of which is controlled through the error in the load voltage[29-30].

In different approach The main circuit of the APF consisted of voltage source inverter with a space vector modulation and high pass filter connected in parallel t o the power system. The proposed system had a function harmonic isolation between source and load, voltage regulation, and unbalance compensation. Therefore, the source current is maintained as a nearly sinusoidal waveform and the load voltage is regulated with a rated voltage regardless of the source variation condition. [31-32-33]

A protection scheme for series active power filters is presented and analyzed in this reference. The proposed scheme protects series active power filters when short-circuit faults occur in the power distribution system. The principal protection element is a varistor, which is connected in parallel to the secondary of each current transformer. After a few cycles of short-circuit currents flowing through the varistor, the gating signals applied to the active power filter switches are removed and the pulse-width-modulation (PWM) voltage-source inverter (VSI) is short circuited through a couple of anti parallel thyristors. [34-35-36-37]

STATCOM is mainly used for current harmonics and reactive power compensation and DVR used for voltage harmonics mitigation. The new method is combined system of series and shunt active filter been proposed. A new control method, which enables application of the combined system to compensation for cycloconverters, is proposed. 17 The relations between the harmonic current extraction circuit and the compensation characteristics have been developed. As a result, the combined system can be considered suitable for harmonic compensation.[38-39]

As the name suggests, the series-shunt active filter is a combination of series active filter and shunt active filter.. The shunt-active filter is located at the load side and can be used to compensate for the load harmonics. On the other hand, the series portion is at the source side and can act as a harmonic blocking filter. This topology is called as Unified Power Quality Conditioner. The series portion compensates for supply voltage harmonics and voltage unbalances, acts as a harmonic blocking filter and damps power system oscillations. The shunt portion compensates load current harmonics, reactive power and load current unbalances. In addition, it regulates the dc link capacitor voltage. The power supplied or absorbed by the shunt portion is the power required by the series compensator and the power required to cover Unified Power Quality Conditioner (UPQC) The UPQC gives power system operators the flexibility to overcome many of the transmission restraints facing the industry today.[40-41]

A UPQC equipped transmission line can independently control real and reactive flow to maximize line utilization and system capability. It also can be used to minimize reactive current flow, enabling users to reduce system losses. The UPQC provides simultaneous, real-time control of all three basic power transfer parameters (voltage, impedance and phase angle) in any combination to optimize the transmitted power. It can handle such conventional functions as reactive shunt compensation, series compensation and phase shifting. The UPQC allows the power delivery system operator to set and independently control the real and reactive flow on a specific power transmission line[13-14-16]].

Unified Power Quality Conditioner (UPQC), which is a combination of series APF and shunt APF. A control strategy based on unit vector template generation is discussed in this paper with the focus on the mitigation of voltage harmonics present in the utility voltage [42-43].18

Then this reference proposes an approach of One Cycle Control (OCC) for UPQC which can deal with most of the problems identified above as a whole. This proposed OCCUPQC consists of a serial three-phase three-leg and a parallel three-phase four-leg converter. The OCC-UPQC has the advantages of no reference calculation that results in simplicity, vector operation for reduced losses, modular approach with the flexibility to work in both three-wire or four-wire systems. The proposed UPQC provides a multifunctional, high performance, cost effective, and reliable solution for total power quality control[44].

Power quality of sensitive loads can be improved by a unified power quality conditioner (UPQC) which consists of back-to-back connected series and shunt active filters, and is modeled using state-space-averaging technique to analyze its behavior. The UPQC is modeled with reference to a synchronously rotating d-q-0 reference axes. Compared to the traditional low pass filtering methods, the proposed method is seen to result in a more rapid dynamic response. The proposed UPQC 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. The proposed direct compensation control method used in the series active filter and the moving window current calculation method used in the shunt active filter make the UPQC response very quickly to any sudden voltage change.[45-46]

A unified power quality conditioner (UPQC) that consists of two three-phase currentsource converters connected on the same inductive DC link has faster phase voltage control loop than its voltage-source converter based counterpart, as well as the inherent short circuit protection capability[47].

A new control design of UPQC for harmonic compensation in a power distribution system is introduced and the topology of this UPQC is based on two three phase voltage source inverters (VSIs) which share two dc link capacitors with midpoint grounded. The extraction circuit using an artificial neural network (ANN) controller with improved weights updating algorithm is proposed. The equivalent single phase representation of the ANN with hysteresis controlled UPQC Besides eliminating the harmonic components successfully, it can also correct the power factor of the supply current and mitigate.

However, the proposed design concept still needs to be validated by experimental results in the future[48-49]

1.11 The Motivation

Modern concept of FACT devices is an effective solution for power quality problems. One of the fact device is static compensator (STATCOM) used for reactive power compensation in power transmission systems. Shunt active power filters compensate load current harmonics by injecting equal but opposite harmonic compensating current [3][4]. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180o . Same way for series compensation FACT device used is Dynamic Voltage Restore (DVR). DVR inject an appropriate voltage magnitude with an appropriate phase angle dynamically [5].DVR effectively mitigates voltage sag/swell. Dynamic compensating signals are determine based on the difference between desired and actual values[6].

The present technique used for power quality solution is useful either for current issue or voltage power quality issue. At the Same time it is very complex and very costly. The control technique used decides the response of STATCOM and DVR[7]. Three phase combination of shunt and series FACT devises is very rarely and lately introduce. It is combination of shunt and series devices. It is known as Unified Power conditioner (UPQC). UPQC is a combination of fact devices. The design of UPQC is made up with STACOM and DVR [8][9] with innovative technique. This unique combination device able to reduce current and voltage related power quality issue effectively

The motivation behind the work presented in this thesis are :

1. Simulate the fast response STATCOM to eliminate the current harmonics

2. Using innovative technique design a DVR to mitigate voltage sags and swells 20

3. Main task is combine both device and used appropriate fast response control technique to filter out current and voltage harmonics.

4. Explore different control technique for UPQC to get optimum response

5. Simulate different types of loads like R- L and DC machine

6. To study the effectiveness of optimal adjustment of control circuit

LITERATURE SURVEY

2.1 INTRODUCTION

In this section, the survey of literatures that are reported by various researchers are discussed. The literature survey is made on the three types of compensators namely, Shunt Active Filter, Series Active Filter and Unified Power Quality Conditioner.

Ideally, all power utilities should provide their customers with a quality supply which has constant magnitude and frequency of sinusoidal voltage. Unfortunately it is a hard task to maintain this quality supply for constant magnitude and frequency of sinusoidal voltage. Poor power quality may result either from transient conditions developing in the power circuit or from the installation of non-linear loads.

Due to the increasing use of loads sensitive to power quality, e.g. communications and medical equipment, variable speed drives, rectifiers, Uninterruptible Power Supplies(UPS), Personal computers (PC), Television (TV) sets etc, the issue of power quality has gained renewed interest over the last two decades. Nowadays, power quality is an even more complex problem than in the past because the new loads are not only sensitive to power quality but also responsible for affecting adversely the quality of power supply.

Although transmission power systems may have an impact on the quality of power, most power quality problems occur in distribution systems. The power quality becomes significantly worse at the points where the loads are connected to the distribution grid. A single customer may cause significant reductions in power quality for many other customers. The presence of harmonics and reactive power in the grid is harmful, because it will cause additional power losses and malfunctions of the grid components.

Some types of the power quality problems are voltage sag/swell, interruption, voltage fluctuation, voltage unbalance, current harmonic, current unbalance and current unbalance. Among them, voltage sags/swells and current harmonics are the most common power quality problems. Some PQ reports indicate that poor PQ can cause large financial losses to different types of industries. The limits of PQ problems are generally set by IEEE and IEC standards. Custom Power is a concept based on the use of power electronic controllers in the distribution system to supply value-added, reliable and high quality power to its customers by eliminating PQ problems.

2.2 LITERATURE SURVEY OF SHUNT ACTIVE FILTER

Power electronics based devices/equipments are a major key component of today's modern power processing, at the transmission as well as the distribution level because of the numerous advantages offered by them. These devices, equipments, nonlinear load including saturated transformers, arc furnaces and semiconductor switches and so on, draw non-sinusoidal currents from the utility. Therefore a typical power distribution system has to deal with harmonics and reactive power support (Khadkikar et al 2009).

When a Static Synchronous Compensator is employed at the distribution level or at the load end for power factor improvement, active harmonic filtering, dynamic load balancing, flicker mitigation and voltage regulation alone it is called as DSTATCOM(Distributed Static Compensator). DSTATCOM is a fast-compensating reactive power source that's applied on the transmission or distribution system to reduce voltage variations such as sags, surges and flicker, along with instability caused by rapidly varying reactive power demand. DSTATCOM can also help provide quick recovery for the transmission system after contingency events such as loss of part of the system or individual equipment. DSTATCOM is well suited to Integration of renewable energy sources, such as wind, concentrated solar and tidal power generation. It allows these renewable energy sources to meet utility interconnection requirements, as well as the power factor, voltage output and low voltage ride-through requirements of various worldwide grid codes. When it is used to do harmonic filtering and reactive power compensation, it is called as Active Power Filter (Bhuvaneshwari et al 2008).

Passive filters are used to provide a low impedance path for current harmonics so that they flow in the filter and not the supply. Passive filters are suited only to particular harmonics, the isolating transformer being useful only for triple-N harmonics and passive filters only for their designed harmonic frequency. In some installations the harmonic content is less predictable. (Fujtha et al 1998).

Power Factor Correction (PFC) techniques include both passive and active solutions for eliminating harmonic distortion and improving power factor. The passive approach uses inductors, transformers, capacitors and other passive components to reduce harmonics and phase shift. The passive approach is heavier and less compact than the active approach, which is finding greater favour due to new technical developments in circuitry, superior performance and reduced component costs. Specially corrected transformers are effective only for certain harmonic frequencies and most passive filters, once installed and tuned, are difficult to upgrade and may generate harmful system resonance. As for active PFC techniques, they must be applied to each individual power supply or load in the system, which complicates architecture and results in high system cost.(Singh et al 1999).

APF supplies only the harmonic and reactive power required to cancel the reactive currents generated by nonlinear loads. In this case, only a small portion of the energy is processed, resulting in greater overall energy efficiency and increased power processing capability (Fujtha et al 1998).

APF utilizes harmonic or current injection to achieve PFC. APF determines the harmonic distortion on the line and injects specific currents to cancel the reactive loads. This technique has been used for years in high power, three phase systems, but high costs and complicated high speed circuitry made it impractical for low level power systems. However, new techniques that utilize simpler circuitry are making active power filtering more attractive and advantageous for low power, single phase systems. APF is connected in parallel to the front end or AC input of the system and corrects all loads directly from the AC line. This type of APF provides excellent harmonic filtering that complies with international harmonic regulations.

The basic representation of DSTATCOM is shown in Figure 2.1. APF system can be divided into two sections as: The control unit and the power circuit. Control unit consists of reference signal generation, gate signal generation, and capacitor voltage balance control and voltage/current measurement.

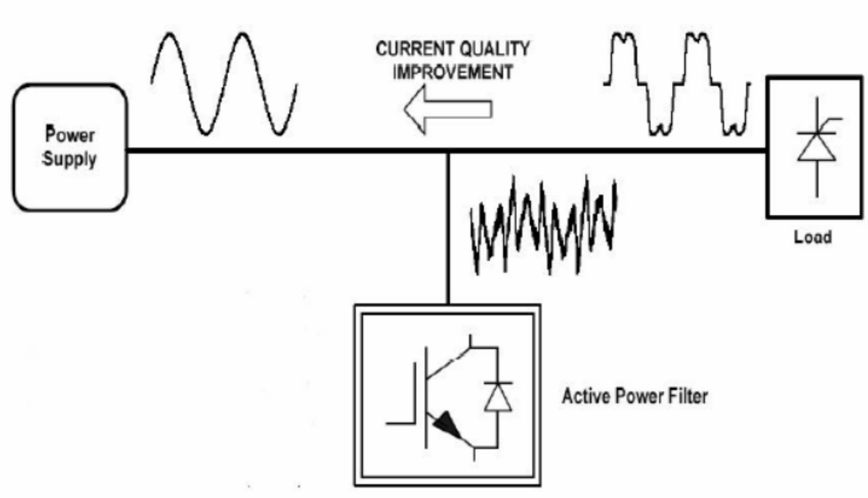


Figure 2.1. Basic representation of DSTATCOM

Power circuit of APF is generally comprised of energy storage unit, DC/AC converter, harmonic filter and system protection. Active power filters are generally designed to compensate current harmonic, reactive power, voltage harmonic and to balance the supply current and supply voltage. Control strategy is based on the overall system control, extraction of reference signal and capacitor voltage balance control.

The converter types of APF can be either Current Source Inverter or Voltage Source Inverter (VSI) bridge structure.VSI structures with Insulated Gate Bipolar Transistor (IGBTs) or Gate Turn Off Thyristor (GTO) have become more dominant, since it is lighter, cheaper and expandable to multilevel and multi step versions, to enhance the performance with lower switching frequencies. IGBTs are generally used up to 1 MVA rating, GTO thyristors are generally used higher than 1 MVA rating (Aredes et al 1998).

The presence of harmonics and reactive power in the grid is harmful, because it will cause additional power losses and malfunctions of the grid components. Conventionally, passive filters composed of tuned L-C components have been widely used to suppress harmonics because of their low initial cost and high efficiency. However, passive filters have many disadvantages, such as large size, mistuning, instability and resonance with load and utility impedances (Aredes et al 1998).

Active Power Filters have now become an alternative solution for controlling current harmonics in supply networks at the low to medium voltage distribution level or for reactive power and/or voltage control at high voltage distribution level (Afonso et al 2000). APF such as shunt APFs, series APFs, hybrid APFs, UPQC and other combinations have made it possible to mitigate some of the major power quality problems (Khadkikar et al 2009)

Control strategy in the frequency domain is based on the Fourier analysis of the distorted voltage or current signals to extract compensating current/voltage reference (Akagi et al 1984). Frequency domain approaches are suitable for both single and three-phase systems. The frequency domain algorithms are sine multiplication technique, conventional Fourier and Fast Fourier Transform (FFT) algorithms and modified Fourier series techniques (Das et al 2004).

Control methods of APF'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 (Chen et al 2004).

Time domain approaches are mainly used for three-phase systems. The time domain algorithms are dq method, synchronous flux detection algorithm, fictitious power compensation algorithm ,constant active power algorithm, constant power factor algorithm, Instantaneous active and reactive Power theory (Agaki et al 1984) and neural network (George et al2007). A component that has a frequency between the two frequencies is called an inter harmonic. A method for real-time detection and extraction of interharmonic components in a power signal with potentially time-varying characteristics (Fujitha et al 1998).

Classification according to current/voltage reference estimation techniques can be made as time domain control and frequency domain control that are processed by the open loop or closed loop control techniques .Active Power Filters have now become an alternative solution for controlling current harmonics in supply networks at the low to medium voltage distribution level or for reactive power and voltage control at high voltage distribution level.

APFs are used in low power (<100 kVA), medium power (100 kVA-10 MVA) and high power (>10 MVA) applications. For low power applications, APFs can be applied for single-phase and three-phase systems. For single-phase systems, APFs generally mitigate the current harmonics. For three phase systems, APFs generally provide acceptable solution for unbalanced load currents and mitigate the current harmonics. For medium and high power applications, the main aim is to eliminate or reduce the current harmonics.(Ghosh et al 2002).

Because of economic considerations, reactive power compensation using active filters at the high voltage distribution level is not generally regarded as viable. For high power applications, the harmonic pollution in high-power ranges is not such a major problem as in lower-power systems. One of the few applications of active filters in high power systems is the installation of parallel combination of several active filters because the control and co-ordination requirements of these filters are complicated (Karimi et al 2003).

Power circuit configuration of APFs can be parallel active filter, series active filter and combination of series and parallel filters. The purpose of parallel active filters is to cancel the load current harmonics fed to the supply. It can also perform the reactive power compensation and balancing of three-phase currents. The series active filter produces a PWM voltage 2waveform which is added or subtracted from the supply voltage to maintain a purely sinusoidal voltage waveform across the load. However, series active filters are less common industrially than their rivals, parallel active filters (Ghosh et al 2002).

\Combinations of several types of filter can achieve greater benefits for some applications. The examined combinations are combination of both parallel and series active filters, combination of series active and parallel passive filters, combination of parallel active and passive filters and active filter in series with parallel passive filters. Seven-level APF configuration is also examined in (Jindal et al2005).

Multilevel three-leg center-split VSIs are more preferable in medium and large capacity applications due to lower initial cost and fewer switching devices that need to be controlled. The series stacked multilevel converter topology, which allows standard three phase inverters to be connected with their DC busses in series (Gunther et al 1995). This converter has both regenerated energy generation and active power filtering capabilities. An inductance for output filtering of VSI is used to eliminate the harmonic at different frequencies. The different combinations of L and C filters to attenuate the switching ripple currents (Zhilli et al 2010).

A rectifier employing phase control with extra low inductance characteristic or load which high frequency input current, may affect APF and causing it to malfunction or shutdown. While APF is being applied to this type of load, a reactor (3% to 5%) is recommended to install at the input side of the load to reduce the rising rate of load input current. LC passive filter is used for harmonic elimination and reactive power compensation. LCL filter is used in (Rong et al2009) that gives advantages in costs and dynamic performance since smaller inductors can be used compared to L-filter in order to achieve the necessary damping of the switching harmonics.

APFs are basically categorized into four types, namely, single phase two-wire, three-phase three wire, three-phase three-wire with Zig-Zag transformer and three-phase four wire configurations to meet the requirements of the three types of nonlinear loads on supply systems. (Fujita et al 1998).

The power circuit of APF generally consists of DC energy storage unit, DC/AC converter and passive filter. DC capacitor serves two main purposes: (1) it maintains a DC voltage with a small ripple in steady state and (2) it serves as an energy storage element to supply the real power difference between load and supply during the transient period (Jayanthi et al., 2009).

DC link voltage can be controlled using proportional-integral (PI) controller, proportional-integral-derivative controller(PID) and fuzzy logic controller(FLC). DC link is fed from separate voltage supply to stabilize DC-side voltage within a certain range (Singh et al 2009). Switched capacitor APF that brings new dimension to APF as it reduces components and ratings while performing at low switching frequency is evaluated. DC link, instead of a capacitor, is used as a battery pack, which is charged from a photovoltaic array.(Razaeipour et al 2009).

The switching signals for the solid state devices of APF are generated using PWM, space vector modulation, fuzzy logic based control techniques, sliding-mode controller, hysteresis controller and multiresonant controller or dead beat controller (Fujita et al 2009).

The basic of the hysteresis current control is based on an error signal between an injection current (Iinj) and a reference current of APF (Iref) which produces proper control signals. The hysteresis band current controller decides the switching pattern of APF. The conventional hysteresis band current control scheme used for the control of APF is shown in Figure 2.2. There are bands above and under the reference current. When the error reaches to the upper limit, the current is forced to decrease. When the error reaches to the lower limit, the current is forced to increase.

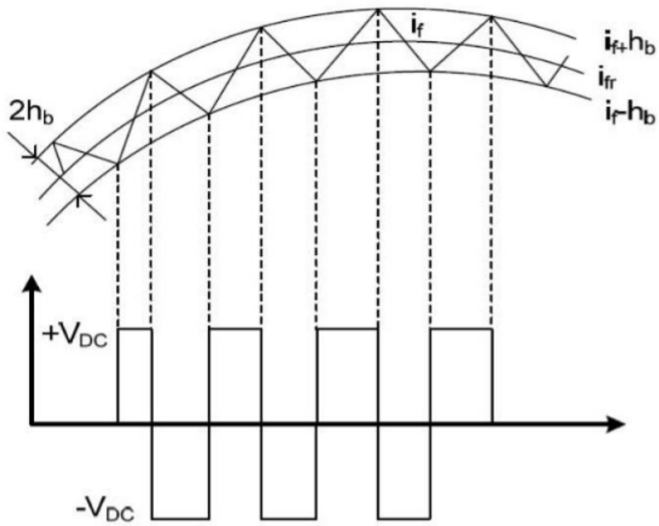


Figure 2.2 Voltage and current waveforms of hysteresis band controller

The switching logic is formulated as follows:

• If Iinj < (Iref hb) upper switch is OFF and lower switch is ON.

• If Iinj > (Iref + hb) upper switch is ON and lower switch is OFF as shown in Figure 2.2.

Some significant advantages of hysteresis controllers over other types of controllers designed with linear or nonlinear control techniques for APF applications are as follows.

- Switching behavior of the power inverter can be directly taken into account at the design level,
- Robustness to load parameters variation can be proved.Almost static response is achieved (the dynamics are obviously bounded by the DC-link voltage and by the actual switching frequency),
- Simple hardware implementation, based on logical devices, is possible according to Boolean nature of controller input/output variables.

2.3 LITERATURE SURVEY OF SERIES ACTIVE FILTER

Tap changing transformer is takes care of a limited range of voltage sag. The disadvantages of tap-changing transformer are slow in response, exhibits contact erosion, needs routine maintenance of its parts, has an uneconomical size and requires frequent replacement of transformer oil (Singh et al 1999).Compared to the other devices, DVR(Dynamic Voltage Restorer) is clearly considered to be one of the best economic solutions for its size and capabilities .

DVR also known as Static Series Compensator is a series connected custom power device which is to protect sensitive loads from supply side disturbances. Also, the DVR can act as a series active filter, isolating the source from harmonics generated by loads.

The DVR consists of a voltage-source PWM converter equipped with a dc capacitor and connected in series with the utility supply voltage through a low pass filter (LPF) and a coupling transformer. This device injects a set of controllable three-phase ac voltages in series and synchronism with the distribution feeder voltages such that the load-side voltage is restored to the desired amplitude and waveform even when the source voltage is unbalanced or distorted. Also it is used to compensating the voltage sag/swell, voltage unbalance and voltage harmonics presented at the point of common coupling (Zhilli et al 2006).

During standby operation, DVR neither absorbs nor delivers real power. However, when voltage sag/swell occurs in the system, DVR delivers/absorbs real power transiently to/from DC link. Many loads facilitated in industrial plants such as adjustable speed drives and process control equipments are able to detect voltage faults as minimal as a few milliseconds. Due to the sensitivity of the loads, DVR is required to response in a very high speed (Chen et al 2004). Basic representation of DVR is shown in Figure 2.3.

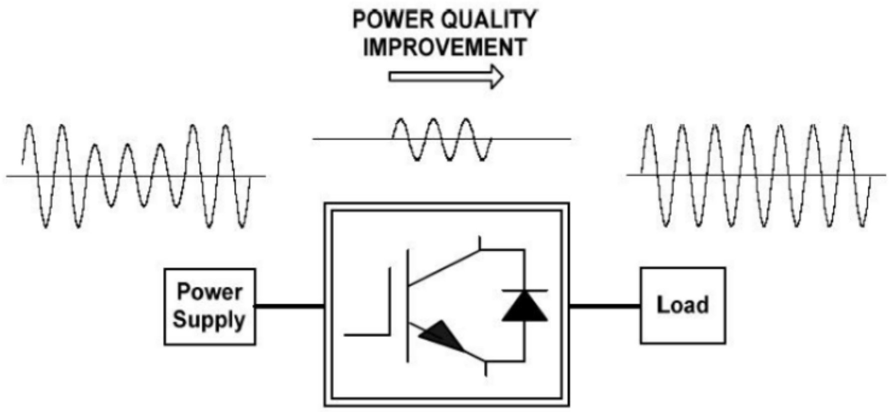


Figure 2.3 Basic representation of DVR

The inverter circuits convert DC power to AC power. The types of inverter are voltage source inverter (VSI) and current source inverter(CSI). Current source inverter is easy to limit over current conditions but the value of output voltage varies widely with changes in load. In the voltage source inverter, the values of output voltage variations are relatively low due to capacitor but it is difficult to limit current because of capacitor. Some types of this inverter are Cyclo converter based inverter, 6-bridge inverter, H bridge inverter and Multilevel inverter. VSIs have its drawbacks, such as a rather slow control of converters (LC filter) output voltage and current protection problems, DC bus voltage oscillations can be observed.(Zhilli et al 2010).

DVR is almost always in standby mode and conduction losses will account for the bulk of converter losses during the operation. The voltage rating of the transformer depends on the grid voltage level and the depth of voltage sag which will be compensated. The rated current multiplied by the injection voltage level gives the VA rating of each phase.The filter unit eliminates the dominant harmonics produced by inverter circuit. Filter unit consists of inductor (L) and capacitor (C).(Bhim Singh et al 1999).

The effect of harmonics generated by the inverter can be minimized using the inverter side or line side filtering. Inverter side filtering scheme has the advantage of being closer to the harmonic source thus high order current harmonics are prevented to penetrate into the series injection transformer but this scheme has the disadvantages of causing voltage drop and phase angle shift in the fundamental component of the inverter output. In line side filtering scheme, current harmonics penetrate into the series injection transformer but the voltage drops and phase shift problems do not disturb the system (Basu et al 2008).

The protection of a DVR against voltage surges and short circuit conditions to prevent its malfunction or destruction is discussed in (Peng et al 1998). The use of the transformer is eliminated applying the voltage boosting functions and a dynamic energy replenishing charging circuit.DVR is implemented using a multilevel inverter topology allowing the direct connection of DVR to the distribution network without using a bulky and costly injection transformer (Axente et al 2010).

DVR is most of time in standby mode and conduction losses will account for the bulk of converter losses during the operation. Its main tasks are connects DVR to the distribution network via the high voltage windings and transforms and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage (Ghosh et al 2008).

In standby mode, the injection transformer works like a secondary shorted current transformer using bypass switches delivering utility power directly to the load. Alternatively, during standby operation of DVR, two upper IGBTs in each phase of the inverter remain turned off while the two lower IGBTs remain turned on. A short circuit across the secondary (inverter side) windings of the series transformer through L filter is obtained eliminating the use of bypass switches (Han et al2006).

Voltage reference generation is achieved using dq method, instantaneous active and reactive Power theory ,artificial neural network, sliding mode,fuzzy logic and software Phase Locked Loop. Most of DVR controllers are using open-loop feed forward control in order to meet the fast compensation requirement. However, the presence of the switching harmonic LC filter would introduce voltage oscillations in transients. These oscillations increase damping response time of the system (Ghosh et al 2004).

Different topologies for DVR are transformerless, multilevel, four-leg DVR, H bridge and interline . Power circuit of DVR generally consists of DC link, DC/AC converter, LC filter and injection transformer. DVR can be used for low voltage, medium voltage and high voltage applications. DVR is generally designed as single phase, three phase three wire and three phase four wire.

DC link (energy storage unit) supplies required power for compensation of load voltage during voltage sag/swell or harmonics. For most DVR applications, the energy source can be an electrolytic capacitor bank. The selection of the optimum topology and DVR ratings is related with the distribution of the remaining voltage, the outage cost and investment cost. The topology of storage systems with auxiliary supply is applied to increase the performance when the grid of DVR is weak. In the topology of storage systems with grid itself, the remaining voltage on supply side or load side is used to supply necessary power to the system if DVR is connected to the strong grid (Ghosh et al 2004).

When the DC link is fed from the rectifier, the rectifier can be controlled using hysteresis or PI controllers. The saturation of the series injection transformer and the voltage drop across the inductor in steady state operation are other factors that affect the performance of DVR in open loop control. The load voltage may not be compensated to the desired value in open loop feed forward control. The problems stated above shows that closed loop control can reduce the damping oscillations coursed by the switching harmonic LC filter and the load voltage can track closer to the reference load voltage under varying load condition. Multi loop control and closed loop state variable control are closed loop control strategies of DVR .The performance of these control strategies are investigated with its dynamic and damping performance. These control schemes can reduce the damping oscillations, but cannot catch up with the fast dynamic response. (Ghosh et al 2001).

The generated reference signal is used to produce gate switching signals of the inverter. The main modulation techniques used in DVR are space vector PWM modulation, dead beat control ,PWM control and hysteresis control.

The hysteresis control has the advantages of quick controllability, easy implementation and variable switching frequency. PWM control has a great impact on its transient performance and higher operating frequency capability. PWM method is widely used for gate signal generation in custom power applications. The deadbeat controller has very fast transient response. (Ghosh et al 2004).

The space vector PWM technique can generate output voltages and currents with less harmonic Distortion. In phase advance method, decreasing the power angle between the remaining voltage and the load current minimizes real power consumed by DVR. In pre-sag compensation, the supply voltage is continuously tracked and the load voltage is compensated. On the other hand, in phase compensation, DVR voltage is always in phase with the measured supply voltage regardless of the load current and pre sage voltage.

In voltage tolerance with minimum energy injection method, the phase angle and magnitude of corrected load voltage within the area of load voltage tolerance are changed. The small voltage drop and phase angle jump on load can be tolerated by load itself and the size of the energy storage is minimized.(Rezaeipour et al 2008).

2.4 LITERATURE SURVEY OF UNIFIED POWER QUALITY CONDITIONER

The unified power quality conditioner is a power electronics based compensator which works on the principle of active filtering. The UPQC is a custom power device that integrates the series and shunt active filters, connected back-to-back on the dc side and sharing a common DC capacitor as shown in Figure 2.4. It employs two voltage source inverters (VSIs) that are connected to a common DC energy storage capacitor.

One of these two VSIs is connected in series with the feeder and the other is connected in parallel to the same feeder. Each compensator of the UPQC consists of an IGBT based full bridge inverter, which may be operated in a voltage or a current controlled mode depending on the control scheme. Series Compensator is connected in series with the supply voltage through a low pass LC filter and a transformer.

Shunt Compensator is connected in parallel to the load through a smoothing link inductor. Series Compensator operates as a controlled voltage source and compensates for any voltage disturbance in the network. Shunt Compensator operates as a controlled current source and compensates for reactive or harmonic elements in the load. It also acts as a real power path and maintains the DC link voltage at a constant value by charging the DC link capacitor continuously.

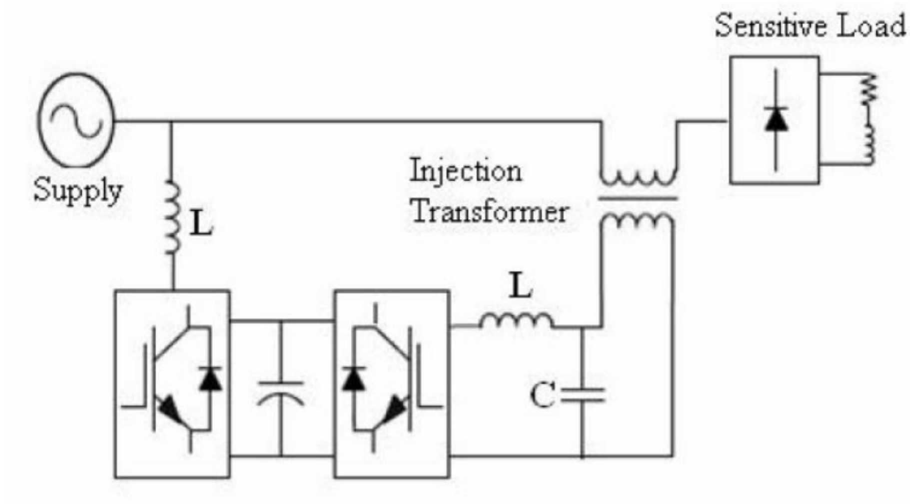


Figure 2.4 Schematic diagram of UPQC

The main advantage of UPQC is that it does not require any energy storage.It can be designed to mitigate any sag above a certain magnitude, independent of its duration. This could result in a device that is able to compete with the uninterruptible power supply (UPS) typically used for the protection of low-power and low-voltage equipment. UPQC is much more flexible than separately configured DSTATCOM. (Kolhatkar et al 2007).

UPQC is also known as the universal power quality conditioning system, universal active power line conditioner and universal active filter. UPQC is a combination of a shunt (Active Power Filter) and a series compensator (Dynamic Voltage Restorer) connected together via a common DC link capacitor, which facilitates the sharing of the active power (Aredes et al 1998).A wide diversity of solutions to power quality problems is available for both the distribution network operator and the end user .The power processing at supply, load and for reactive and harmonic compensation by means of power electronic devices is becoming more prevalent due to the vast advantages offered by them. (Singh et al 1999).

Various topologies of UPQC are multilevel topology, single-phase UPQC with two half-bridge converters, single-phase UPQC with three legs, H bridge topology (Ghosh et al 2004) and UPQC is connected between two independent feeders to regulate the bus voltage of one of the feeders while regulating the voltage across a sensitive load in the other. A new configuration, named multiconverter unified power quality conditioner (MC-UPQC), for simultaneous compensation of voltage and current in adjacent feeders (Khadkikar et al 2012).

To generate reference signals for shunt converter, Instantaneous reactive power theory is generally preferred for reference current calculation (Fujita et al 1998). An extended method based on Instantaneous reactive power theory in a rotating reference frame is used to suppress the harmonics and to correct the power factor. Adaptive detection technique is evaluated in (Karimi et al 2003) that minimizes the affects of noise or parameter variations. To generate reference signals for series converter, fuzzy control (Singh et al 1999), finite impulse response filter (Chen et al 2004) , using band pass filter and positive sequence calculation , dq transform, using peak detector and averaging method, vector template generation method (Khadkikar et al 2011), sinusoidal template vector algorithm , PI controller method (Basu et al 2008), adaptive detection (Rong et al 2009), are used .

Least squares algorithm, wavelet transform (Forghani et al 2007), neural network, positive sequence component method,linear quadratic regulator, unit vector template generation method, multi variable regulator based with kalman filters, artificial intelligence method (George et al 2007), pole shift control (Jindal et al 2005) and abc-dq transform method (Lee et al 2010) are employed to generate reference signals for both series and shunt converter simultaneously.

To generate gating signals for only shunt converter, predictive current regulation current controller and hysteresis controller (Basu et al 2008) are employed. Sinusoidal PWM (Basu et al 2008) and hysteresis controller (Khadkikar et al 2004) methods are employed to generate gating signals for only series converter. Space vector PWM ,fuzzy hysteresis control and SPWM strategy are preferred for both series and shunt side inverter signal generation(Lee et al 2010).

The overall power balance of UPQC is maintained through DC-link capacitor (Jayanti et al 2009). DC voltage control can be fulfilled by the traditional DC voltage feedback or PI control (Basu et al 2008) and composite control (Salam et al 2006).

Depending upon the location of the shunt compensator with respect to series compensator, UPQC model can be named as right shunt-UPQC or left shunt-UPQC. Typically the active power generated in one unit is consumed in the other unit maintaining the energy balance overall characteristics of the right shunt-UPQC are superior to those of the left shunt- UPQC (Ghosh et al 2002).

The protection of a UPQC against voltage surges and short circuit conditions to prevent its malfunction or destruction is discussed in (Zhilli et al 2010). The power circuit of UPQC generally consists of common energy storage unit, DC/AC converter, LC filter and injection transformer. The effect of harmonics generated by the inverter can be minimized using inverter side and line side filtering .Inverter side LC filtering is generally preferred for both series sides (Basu et al 2008) and inverter side L filtering is generally preferred for shunt side (Axente et al 2010).

UPQC can be used for medium voltage and low voltage applications. In case of low power applications, it is not convenient to install a UPQC, since DVR spends most of its time in standby mode. UPQC is generally designed as 3-phase 3-wire (3P3W) systems. 3-phase 4-wire (3P4W) system is also realized from (3P3W) system where the neutral of series transformer used in series part UPQC is considered as the fourth wire for 3P4W system (Khadkikar et al 2009).

UPQC is a Custom Power device and consists of combined series active power filter that compensates voltage harmonics, voltage unbalance, voltage flicker, voltage sag/swell and shunt active power filter that compensates current harmonics, current unbalance and reactive current (Khadkikar et al 2011).

Series converter of UPQC is most of time in standby mode and conduction losses will account for the bulk of converter losses during the operation. In this mode, the series injection transformer works like a secondary shorted current transformer using bypass switches delivering utility power directly to the load. UPQC without injection transformer has been designed (Basu et al 2002). A novel configuration of UPQC which can be connected to the distribution system without series injection transformers is presented in (Han et al 2006).

The shunt APF is usually connected across the loads to compensate for all current related problems such as the reactive power compensation, power factor improvement, current harmonic compensation and load unbalance compensation, whereas the series active power filter is connected in a series with a line through series transformer. It acts as controlled voltage supply and can compensate all voltage related problems, such as voltage harmonics, voltage sag, voltage swell, flicker, etc (Khadkikar et al 2008).

CONCLUSION

Widespread applications of power electronic based devices/equipments in industry have increased the importance and application of power quality studies. Custom Power (CP) devices devices including DVR, APF and UPQC are showing tremendous development. These devices have become very popular in recent years in both low voltage and medium voltage applications. The comprehensive reviews of articles concerning CP devices are presented to show the advantages and disadvantages of each possible configuration and control techniques. The literature survey reveals that new control algorithms and topologies for CP devices have been developed to minimize the power losses, increase the system flexibility and efficiency.

Chapter – 3

GENERALIZED THEORY OF ACTIVE POWER FILTERS

3.1 Introduction

The various nonlinear loads like Adjustable Speed Drives (ASD's), bulk rectifiers, furnaces, computer supplies, etc. draw non sinusoidal currents containing harmonics from the supply which in turn causes voltage harmonics. Harmonic currents cause increased power system losses, excessive heating in rotating machinery, interference with nearby communication circuits and control circuits etc.

It has become imperative to maintain the sinusoidal nature of voltage and currents in the power system. Various international agencies like IEEE and IEC have issued standards, which put limits on various current and voltage harmonics. The limits for various current and voltage harmonics specified by IEEE-519 for various frequencies are given in Table 3.1 and Table 3.2.

Table 3.1

IEEE 519 Voltage Limits

Bus Voltage	**Minimum Individual Harmonic Components (%)**	**Maximum THD (%)**
69 kV and below	3	5
115 kV to 161 kV	1.5	2.5
Above 161 kV	1	1.5

The objectives and functions of active power filters have expanded from reactive power compensation, voltage regulation, etc. to harmonic isolation between utilities and consumers, and harmonic damping throughout the distribution as harmonics propagate through the system. Active power filters are either installed at the individual consumer premises or at substation and/or on distribution feeders. Depending on the compensation objectives, various types of active power filter topologies have evolved.

3.2 Classifications of Active Power Filters

3.2.1 Converter based classification

Current Source Inverter (CSI) Active Power Filter (Fig 3.1) and Voltage Source Inverter Active Power Filter (VSI) (Fig 3.2) are two classifications in this category. Current Source Inverter behaves as a non-sinusoidal current source to meet the harmonic current requirement of the nonlinear loads. A diode is used in series with the self-commutating device (IGBT) for reverse voltage blocking. However, GTO-based configurations do not need the series diode, but they have restricted frequency of switching. They are considered sufficiently reliable, but have higher losses and require higher values of parallel ac power capacitors. Moreover, they cannot be used in multilevel or multistep modes to improve performance in higher ratings.

The other converter used as an AF is a voltage-fed PWM inverter structure, as shown in Fig 3.2. It has a self-supporting dc voltage bus with a large dc capacitor. It has become more dominant, since it is lighter, cheaper, and expandable to multilevel and multistep versions, to enhance the performance with lower switching frequencies. It is more popular in UPS-based applications, because in the presence of mains, the same Inverter bridge can be used as an AF to eliminate harmonics of critical nonlinear loads.

3.2.2 Topology based Classification

AF's can be classified based on the topology used as series or shunt filters, and unified power quality conditioners use a combination of both. Combinations of active series and passive shunt filtering are known as hybrid filters. Fig 3.3 is an example of an active shunt filter, which is most widely used to eliminate current harmonics, reactive power compensation (also known as STATCOM), and balancing unbalanced currents. It is mainly used at the load end, because current harmonics are injected by nonlinear loads. It injects equal compensating currents, opposite in phase, to cancel harmonics and/or reactive components of the nonlinear load current at the point of connection. It can also be used as a static VAR generator (STATCON) in the power system network for stabilizing and improving the voltage profile.

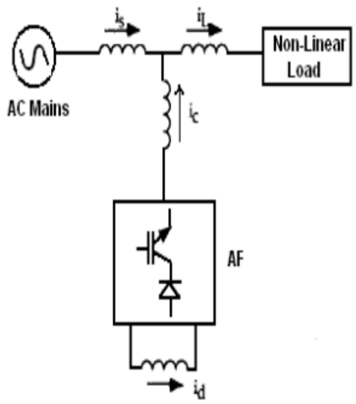


Fig 3.1 Current fed type AF

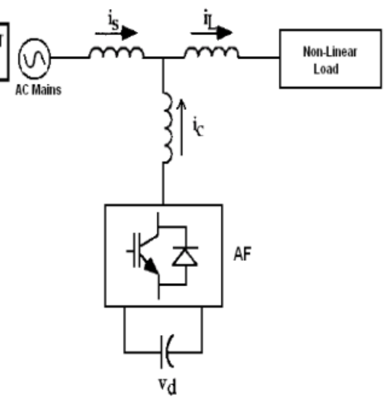
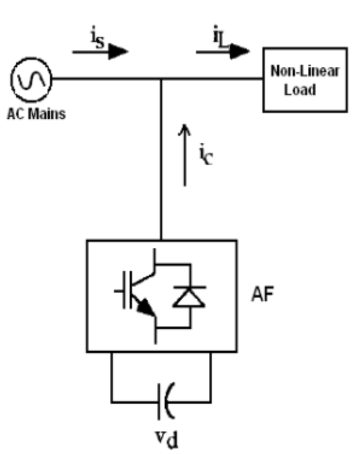


Fig 3.2 Voltage fed type AF

Fig 3.4 shows the basic block of a stand-alone active series filter. It is connected before the load in series with the mains, using a matching transformer, to eliminate voltage harmonics, and to balance and regulate the terminal voltage of the load or line. It has been used to reduce negative-sequence voltage and regulate the voltage on three-phase systems. It can be installed by electric utilities to compensate voltage harmonics and to damp out harmonic propagation caused by resonance with line impedances and passive shunt compensators.

Fig 3.5 shows the hybrid filter, which is a combination of an active series filter and passive shunt filter. It is quite popular because the solid-state devices used in the active series part can be of reduced size and cost (about 5% of the load size) and a major part of the hybrid filter is made of the passive shunt L–C filter used to eliminate lower order harmonics. It has the capability of reducing voltage and current harmonics at a reasonable cost.



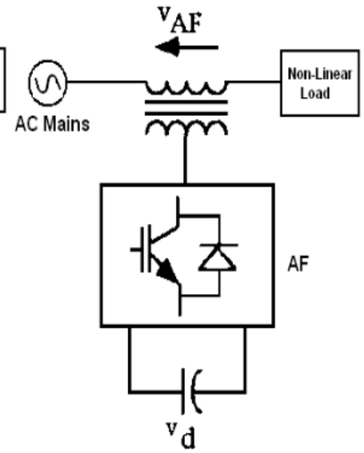
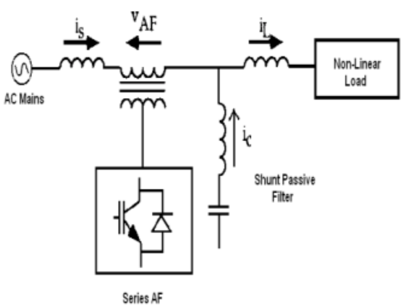


Fig 3.3 Shunt-type AF

Fig 3.4 Series-type AF



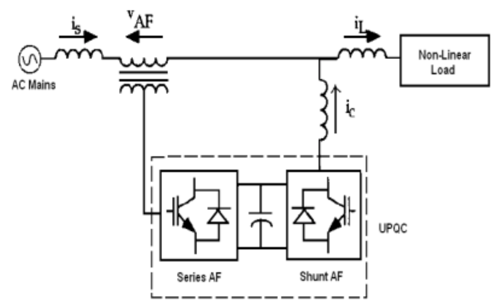


Fig 3.5 HybridfilterFig 3.6 Unified Power Quality Conditioner

Fig 3.6 shows a unified power quality conditioner (also known as a universal AF), which is a combination of active shunt and active series filters. The dc-link storage element (either inductor or dc-bus capacitor) is shared between two current-source or voltage-source bridges operating as active series and active shunt compensators. It is used in single-phase as well as three-phase configurations. It is considered an ideal AF, which eliminates voltage and current harmonics and is capable of giving clean power to critical and harmonic-prone loads, such as computers, medical equipment, etc. It can balance and regulate terminal voltage and eliminate negative-sequence currents. Its main drawbacks are its large cost and control complexity because of the large number of solid-state devices involved.

3.2.3 Supply-System-Based Classification

This classification of AF's is based on the supply and/or the load system having single-phase (two wire) and three-phase (three wire or four wire) systems. There are many nonlinear loads, such as domestic appliances, connected to single-phase supply systems. Some three-phase nonlinear loads are without neutral, such as ASD's, fed from three-wire supply systems. There are many nonlinear single-phase loads distributed on four-wire three-phase supply systems, such as computers, commercial lighting, etc. Hence, AF's may also be classified accordingly as two-wire, three-wire, and four-wire types.

- ***Two-Wire AF's:***

  Two-wire (single phase) AF's are used in all three modes as active series, active shunt, and a combination of both as unified line conditioners. Both converter configurations, current-source PWM bridge with inductive energy storage element and voltage-source PWM bridge with capacitive dc-bus energy storage elements, are used to form two-wire AF circuits. In some cases, active filtering is included in the power conversion stage to improve input characteristics at the supply end.

- ***Three-Wire AF's:***

  Three-phase three-wire nonlinear loads, such as ASD's, are major applications of solid-state power converters and, lately, many ASD's, etc., incorporate AF's in their front-end design. A large number of publications have appeared on three-wire AF's with different configurations. All the configurations shown in Figs 3.1–3.6 are developed, in three-wire AF's, with three wires on the ac side and two wires on the dc side. Active shunt AF's are developed in the current-fed type (Fig 3.1) or voltage-fed type with single-stage (Fig 3.2) or multi-step/multilevel and multi-series configurations. Active shunt AF's are also designed with three single-phase AF's with isolation transformers [18] for proper voltage matching, independent phase control, and reliable compensation with unbalanced systems. Active series filters are developed for stand-alone mode (Fig 3.4) or hybrid mode with passive shunt filters (Fig 3.5). The latter (hybrid) has become quite popular to reduce the size of power devices and cost of the overall system. A combination of active series and active shunt is used for unified power quality conditioners (Fig 3.6) and universal filters.

3) Four-Wire AF's:

A large number of single-phase loads may be supplied from three-phase mains with neutral conductor. They cause excessive neutral current, harmonic and reactive power burden, and unbalance. To reduce these problems, four-wire AF's have been attempted. They have been developed as: 1) active shunt mode with current feed and voltage feed; 2) active series mode; and 3) hybrid form with active series and passive shunt mode.

3.2.4 Compensated Variable Based Classification

(1) Harmonic Compensation

(2) Multiple Compensation

This is the most important system parameter requiring compensation in power systems and it is subdivided into voltage- and current-harmonic compensation. The compensation of voltage and current harmonics is interrelated.

Different combinations of the above systems can be used to improve the effectiveness of filters. The following are the most frequently used combinations.

· Harmonic currents with Reactive power compensation.

· Harmonic voltages with Reactive power compensation.

· Harmonic currents and voltages.

· Harmonic currents and voltages with reactive-power compensation.

3.2.5 Voltage Type Vs Current Type APF's

A clear trend for preferred type of APF's does not exist. A choice depends on source of distortion at the specified bus, equipment cost, and amount of correction desired.

Voltage-type has an advantage in that they can be readily expanded in parallel to increase their combined rating. Their combined switching rate can be increased if they are carefully controlled so that their individual switching times do not coincide. Therefore, using parallel voltage-type converters without increasing individual converter switching rates can eliminate higher order harmonics. Voltage type converters are lighter and less expensive than current-type converters.

The main drawback of voltage-type converters lies in the increased complexity of their control system. For systems with several connected in parallel, this complexity is greatly increased.

Current-type converters have advantages of excellent current controllability, easy protection and high reliability over Voltage source APF. More over CSI topology has superior characteristics compared to VSI topology in terms of direct injected current, which result in a faster response in time varying load environment and lower dc energy storage requirement. The drawback of the current source APF is larger power losses of the dc-link inductor. However, the current-type active power filter will become more attractive when the super conducting coils are available in the future. Losses are less important in low- power applications but very important in high power applications.

Since they are easily expandable, voltage type APF's are likely to be used for network wide compensation. Current type APF's will continue to popular for single-node distortion problems. In other words, electric utility interest will likely to be focused on voltage type converters, while industrial users likely to use both type of converters.

3.3 Operation of Three Phase Active Power Filters

In recent years, the power quality of the AC main system has become a great concern due to the rapidly increased number of electronic equipment. In order to reduce the harmonic contamination in power lines and improve the transmission efficiency Active power filters become essential. A current source is connected in parallel with nonlinear load and controlled to generate the harmonic currents needed for the load.

The basic configuration of a three-phase three-wire active power filter is shown in Fig 3.7. The diode bridge rectifier is used as an ideal harmonic generator to study the performance of the Active filter. The current-controlled voltage-source inverter (VSI) is shown connected at the load end. This PWM inverter consists of six switches with antiparallels diode across each switch. The capacitor is designed in order to provide DC voltage with acceptable ripples. In order to assure the filter current at any instant, the DC voltage V_{dc} must be at least equal to 3/2 of the peak value of the line AC mains voltage.

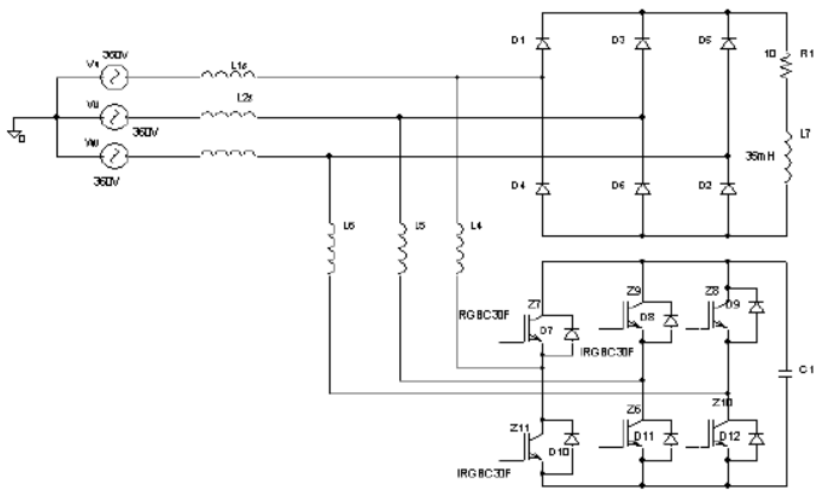


Fig 3.7 Configuration of the three phase, three wire Active filtering system.

Three aspects have to be considered in the design of APF.

a) The parameters of the inverter such as inverter switches and the values of the link inductances.

b) Modulation method used and

c) The control method used to generate the harmonic reference template.

3.3.1 Sample and Hold circuit's method for harmonic reference template

This method is simple, eliminates complicated transformations and mathematical operations such as multiplications and divisions, and permits good transient response. Fig 3.8 shows implementation of Sample and Hold method.

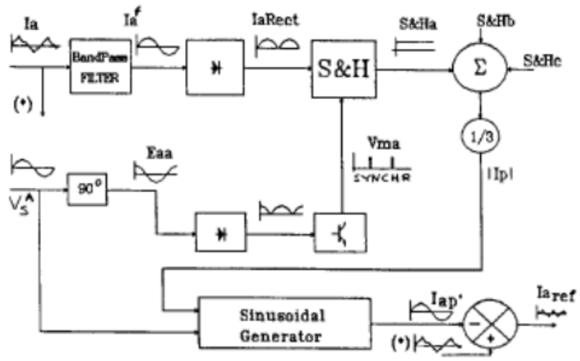


Fig 3.8 Control block of Sample and Hold circuit's harmonic reference template

The current in each phase of the load is filtered to get the fundamental phase current. A "Sample and Hold" circuit, synchronized with the peak value of the phase-to-neutral voltage, allows to get three dc signals, which are proportional to the amplitude of the active component of the current for each phase. Three dc signals, with the information of the total active power in the load, are averaged to balance the system. Then, by multiplying the averaged dc signal for a set of balanced reference waveforms (in phase with the mains voltages), three in phase balanced currents for each phase are obtained. Finally, these currents are subtracted from the real load currents to get the compensation currents. These harmonic are then able to correct the harmonic distortion, the power factor and the unbalances of the load.

Let to assume that I_L is the total load current in one phase. This current contains basically three components.

$$I_L = I_P + I_Q + I_H$$

Where IP, I_Q and I_H are the fundamental active, reactive and harmonic currents respectively. The APF will eliminate I_Q and I_H by subtracting I_P from I_L.

Extraction of I_P

First the load currents sensed and filtered to eliminate the (I_H) and then the total fundamental currents (one for each phase) are obtained. These currents have to be separated in their active and reactive components.

$$I = I_P + I_Q$$

Where

$$I_P = I \cos\phi$$

However the angle "ϕ" does need to be known, because the term "I cosϕ" can be obtained from the time function of the fundamental when the main voltage reaches the its maximum value. Fig 3.9 explains graphically the idea.

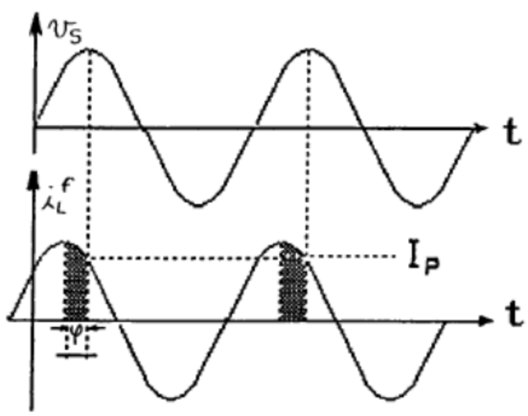


Fig 3.9 Method used to capture I_P.

I_P is captured and "stored" until the next sample of I_P is obtained to replace the old one. This action is executed with the help of "Sample and Hold" circuits, which are synchronized with the synchronization pulses to trigger the S&H are generated through the "zero-crossing" signals, obtained from the set of "in-quadrature voltages". These "in- quadrature voltages" are generated in the control block with the DZ0 connection, signal transformer.

The control circuit is also has the capability to avoid flickers and transient phenomena in the source, produced by sudden changes in load current. To do this, control system makes soft variation of I_P during these moments. However, this action will require to have the energy storage components in the APF. Hence the design of the control system has to take in account the characteristics of the power filter.

CHAPTER 4

UNIFIED POWER QUALITY CONDITIONER – UPQC

4.1. Power circuit structure and principle of operation

The UPQC is a combination of series and parallel active power filters connected back-to-back to a common dc energy storage capacitor, as mentioned earlier. One form of UPQC structure, which is used in three-phase three-wire systems, is shown in Fig.4.1.a. Other UPQC structures, including tree-phase four-wire systems.

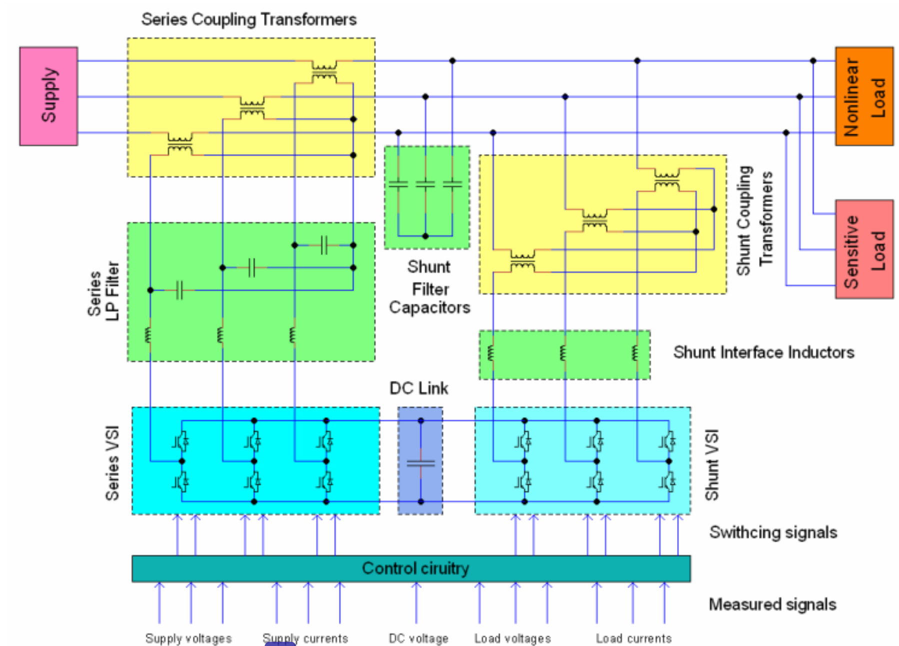


Fig.3.1.a. Power circuit diagram of a three-phase UPQC

The shunt active filter is responsible for power factor correction and compensation of load current harmonics and unbalances. Also, it maintains constant average voltage across the DC storage capacitor. The shunt part of the UPQC consists of a VSI (voltage source inverter) connected to the common DC storage capacitor on the dc side and on the ac side it is connected in parallel with the load through the shunt interface inductor and shunt coupling transformer. The shunt interface inductor, together with the shunt filter capacitor are used to filter out the switching frequency harmonics produced by the shunt VSI. The shunt coupling transformer is used for matching the network and VSI voltages.

In order to achieve its compensation goals, the shunt active filter injects currents at the point of common coupling such that the reactive and harmonic components of the load currents are cancelled and the load current unbalance is eliminated. This current injection is provided by the dc storage capacitor and the shunt VSI. Based on measured currents and voltages the control scheme generates the appropriate switching signals for the shunt VSI switches. The particular currents and voltages to be measured depend on the applied control strategy. The shunt VSI is controlled in current control mode. The appropriate VSI switches are turned on and off at certain time instances such that the currents injected by the shunt active filter track some reference currents within a fixed hysteresis band (assuming a hysteresis controller is used) according to the compensation objectives. The VSI switches alternately connect the dc capacitor to the system, either in the positive or negative sense. When the dc capacitor voltage is connected in the positive sense, it is added to the supply voltage and the VSI current is increasing. In the case of the dc capacitor connected in the negative sense, its voltage is in opposition to the supply voltage and the VSI current is decreasing. So, alternately increasing and decreasing the current within the hysteresis band, the reference current is tracked. This control technique is called "hysteresis band control" [3].

The dc side capacitor serves two main purposes: it maintains the dc voltage with a small ripple in the steady state, and it serves as an energy storage element to supply a real power difference between the load and source during the transient period [21]. The average voltage across the dc capacitor is maintained constant, and in order that the shunt active filter can draw a leading current, this voltage has to be higher then the peak of the supply voltage. This is achieved through an appropriate proportional-integral (PI) control, by regulating the amount of active current drawn by the shunt active filter from the system. The series active filter is responsible for voltage compensation during supply side disturbances, such as voltage sag/swell, flicker and unbalance. The series part of the UPQC also consists of a VSI connected on the dc side to the same energy storage capacitor, and on the ac side it is connected in series with the feeder, through the series low pass filter (LPF) and coupling transformers. The series LPF prevents the switching frequency harmonics produced by the series VSI entering the system. The series coupling transformers provide voltage matching and isolation between the network and the VSI.

The series active filter compensation goals are achieved by injecting voltages in series with the supply voltages such that the load voltages are balanced and undistorted, and their magnitudes are maintained at the desired level. This voltage injection is provided by the dc storage capacitor and the series VSI. Based on measured supply and/or load voltages the control scheme generates the appropriate switching signals for the series VSI switches. The series VSI is controlled in voltage-control mode using the well-known pulse-widthmodulated (PWM) switching technique described in detail in [17]. In order to produce the injected voltage of desired magnitude, waveform, phase shift and frequency, the desired signal is compared with a triangular waveform signal of higher frequency, and appropriate switching signals are generated. The dc capacitor is alternately connected to the inverter outputs with positive and negative polarity. The output voltages of the series VSI do not have the shape of the desired signals, but contain switching harmonics, which are filtered out by the series low pass filter. The amplitude, phase shift, frequency and harmonic content of injected voltages are controllable.

Two possible ways of connecting the UPQC to the point of common coupling (PCC) are discussed in [3]:

- Right-shunt UPQC compensation configuration: The shunt component is connected to the load side and the series to the supply side;
- Left-shunt UPQC compensation configuration: The shunt component is connected to the supply side and the series component to the load side.

Also, their control and characteristics are presented for both compensation configurations. Comparing the characteristics of these two configurations the following conclusions are made [3]:

- The right-shunt UPQC can operate in zero power injection/absorption mode, whereas the left-shunt cannot;
- The right-shunt UPQC can make the power factor unity at the load terminal, whereas for the left-shunt UPQC the power factor at the load terminal depends on the load;
- The shunt compensator in the right-shunt configuration can supply the entire load reactive power requirement, whereas in the case of the left-shunt UPQC the shunt compensator can only partially supply the load reactive power;
- It has been shown that the dc capacitor control of the right-shunt UPQC structure is simpler;

- Overall the characteristics of the right-shunt UPQC are superior to those of the left-shunt UPQC.

Thus, it can be concluded that the right-shunt UPQC is more advantageous. Therefore this configuration has been used in the UPQC simulation model (presented in section 4.4) and in the prototype UPQC (presented in section 3.5)

4.2. Power circuit design considerations

The design of UPQC power circuit includes the selection of the following three main parameters:

- shunt interface inductors;
- dc link reference voltage;
- dc link capacitor.

Design recommendations on selection of the above three parameters are presented in [19, 21, 52, 62]. The design of the shunt interface inductor and the dc reference voltage is based on the following criteria. Limiting the high frequency components of the injected currents; the instantaneous *di/dt* generated by the shunt active filter should be greater than the *di/dt* of the harmonic component of the load, so that the proper harmonic cancellation can take place. On one hand, for a better harmonic cancellation and reactive power compensation a higher inductance is preferable, but on the other hand, too high inductance will result in slow dynamic response of the shunt compensator and it could not be possible to compensate for some of the load harmonics. So, a compromise solution has to be found. A higher dc link reference voltage results in a higher *di/dt* of the shunt compensator, better dynamic response and reactive power compensation performance, but it also increases the stress experienced by the inverter switching devices. Again, a compromise solution has to be adopted. The dc capacitor size is selected to restrict the dc voltage ripple within reasonable limits. The dc voltage ripple is determined by both the amount of reactive power to be compensated and the active power supplied by dc capacitor during the transient.

To correct for the effects of supply voltage distortion, the series compensator is required to inject appropriate harmonic voltages. This unfortunately can present problems with unbalanced fluxes if conventional three-limb injection transformers are used. To avoid this, three separate injection transformers are utilized. This allows the flux-linkage in each to be dealt with separately and remains true regardless of the external configuration, star, or delta.

4.3. Control strategy

4.3.1. Control of the shunt active filter

The effectiveness of an active power filter depends basically on the design characteristics of the current controller, the method implemented to generate the reference template and the modulation technique used. The control scheme of a shunt active power filter must calculate the current reference waveform for each phase of the inverter, maintain the dc voltage constant, and generate the inverter gating signals. Also the compensation effectiveness of an active power filter depends on its ability to follow the reference signal calculated to compensate the distorted load current with a minimum error and time delay.

The shunt component of UPQC can be controlled in two ways:

- *Tracking the shunt converter reference current*, when the shunt converter current is used as feedback control variable. The load current is sensed and the shunt compensator reference current is calculated from it. The reference current is determined by calculating the active fundamental component of the load current and subtracting it from the load current. This control technique involves both the shunt active filter and load current measurements.
- *Tracking the supply current*, when the supply current is used as the feedback variable. In this case the shunt active filter ensures that the supply reference current is tracked. Thus, the supply reference current is calculated rather than the current injected by the shunt active filter. The supply current is often required to be sinusoidal and in phase with the supply voltage. Since the waveform and phase of the supply current is known, only its amplitude needs to be determined. Also, when used with a hysteresis current controller, this control technique involves only the supply current measurement. Thus, this is a simpler to implement method. Therefore it has been used in the UPQC simulation model (presented in section 4.4) and in the prototype UPQC (presented in section 4.5)

The current reference circuit generates the reference currents required to compensate the load current harmonics and reactive power, and also maintain the dc link voltage constant. There are many possibilities to implement this type of control, and the most popular of them will be presented in the following.

1) *Average dc voltage regulation.*

This approach is used for supply reference current determination and it is based on the fact that the magnitude of the supply current depends on power balance between the supply and the load. The dc capacitor serves as energy storage element. If the shunt active filter losses are neglected, in steady-state, the power supplied by the system has to be equal to the real power demand of the load, and no real power flows into the dc capacitor. The average dc capacitor voltage is thus maintained at reference voltage level. If a power unbalance caused by a load change occurs, the dc capacitor must supply the power difference between the supply and load that will result in reducing the dc capacitor voltage. To restore the average dc capacitor voltage to the reference level some active power has to be supplied to the dc capacitor, so the magnitude of the supply current has to be increased. When the average dc capacitor voltage increases, the magnitude of the supply current has to be decreased. So, by controlling the average voltage across the dc capacitor the amplitude of the supply current is automatically controlled. Applying this concept, the control circuit can by simplified and the number of current sensors reduced. Therefore, this control technique has been chosen to be used in the UPQC simulation model (presented in section 4.4) and in the prototype UPQC (presented in section 3.5). This approach is discussed in detail in [18-20]. The dc voltage regulation is achieved by using a proportional integral (PI) controller (the PI controller is used in many applications for its fast response and simple structure). The capacitor voltage is compared with some reference value and a PI controller processes the voltage error. The output of the PI controller is the magnitude of the reference supply current, and it is constant in steady-state. To get the source reference current, a sinusoidal template that is in phase with the supply voltage is multiplied by this magnitude.

2) *Instantaneous p-q theory*.

concept of instantaneous active and reactive powers and its application for shunt active filter reference currents generation was introduced by Akagi et al. in [25]. The instantaneous active and reactive powers for a three-phase three-wire system are defined as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{4.1}$$

where the three-phase voltages are transformed from *a-b-c* to α-β frame and vice versa using the following transformation relations:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{4.2}$$

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{4.3}$$

The same transformation matrices are used for the transformation of currents.

Then from (4.1) the currents $i\alpha$ and $i\beta$ are expressed:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \tag{4.4}$$

Both active p and reactive q powers defined above are composed of two components: constant (or dc) and oscillating.

$$\begin{aligned} p &= \overline{p} + \widetilde{p} \\ q &= \overline{q} + \widetilde{q} \end{aligned} \tag{4.5}$$

where p and q are the average active and reactive powers (dc values) originating from the symmetrical fundamental (positive sequence) component of the load current. p is the average active power delivered to the load, and q is the average reactive power drawn by the load. To improve the power factor, q has to be totally ($\cos\phi = 1$) or partially ($\cos\phi < 1$) compensated by the shunt active filter.

In the case where the shunt active filter is to compensate for making the supply currents symmetrical, undistorted and in phase with the supply voltages, the shunt active filter reference currents in the α - β reference frame will be calculated as:

$$\begin{bmatrix} i^*_{f,\alpha} \\ i^*_{f,\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} \tag{4.6}$$

The oscillating component $p\sim$ is obtained by filtering out the constant component p from the total active power p, using a high-pass-filter (HPF). The expression similar to (4.3) is used to transform the currents from $\alpha - \beta$ to *a-b-c* reference frame. For the regulation of the dc capacitor voltage the active power loss compensative component *ploss* has to be added to $p\sim$ in (4.6)

The instantaneous p-q theory and its application for reference currents calculation is discussed in detail in [3] and many supporting examples are presented. It is to be mentioned that when using this approach a Phase Lock Loop (PLL) is not needed. Being flexible and having a good dynamic response this approach has been addressed in many papers with various interpretations and modifications. Since this approach involves complex calculations it is difficult to imagine its practical implementation without using a DSP. The above-described technique for reference currents extraction only works when the supply voltages are balanced and harmonic free, as it was assumed above. As soon as the supply voltages become unbalanced or/and distorted, which is often the case in real power systems, the reference currents calculated with the expression (4.6) will result in poor compensation performance. One way of solving this problem is to extract the fundamental positive sequence voltages from the supply unbalanced or/and distorted voltages and use them in (4.6). This approach involves filtering, which requires even more calculations or additional hardware. Other approaches for reference currents extraction under unbalanced and/or distorted supply voltages are presented in [29-33].

4.3.2 Synchronous Reference Frame (SRF) Theory

The control strategy for the unified power quality conditioner is based on the synchronous reference frame (SRF) [8, 9] theory. In this theory controlling of the three-phase converters using the rotating frame theory by converting the source voltage and current to direct and quadrature axis is done. The voltage is converted to dq in the series controller and current is converted to dq in the series controller. Consider

The dq transform is again converted to the V^1abc in order to get the reference signal which is used for the generation of the pulse for the three-phase converter in the system. Consider The shunt converter performs the process of elimination of harmonics and series converter performs process of elimination of the voltage related problems. The control block diagram for the synchronous reference frame theory is shown in Figure 4.3.1

$$\begin{bmatrix} V_a \\ V_b \\ V_C \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \sin(\mathrm{wt}) & \sin\left(\mathrm{wt} - \frac{2\pi}{3}\right) & \sin\left(\mathrm{wt} + \frac{2\pi}{3}\right) \\ \cos(\mathrm{wt}) & \cos\left(\mathrm{wt} - \frac{2\pi}{3}\right) & \cos\left(\mathrm{wt} + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix}. \quad (4.7).$$

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \sin(\mathrm{wt}) & \cos(\mathrm{wt}) \\ \frac{1}{\sqrt{2}} & \sin\left(\mathrm{wt} - \frac{2\pi}{3}\right) & \cos\left(\mathrm{wt} - \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \sin\left(\mathrm{wt} + \frac{2\pi}{3}\right) & \cos\left(\mathrm{wt} + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} V'_a \\ V'_b \\ V'_C \end{bmatrix}. \quad (4.8)$$

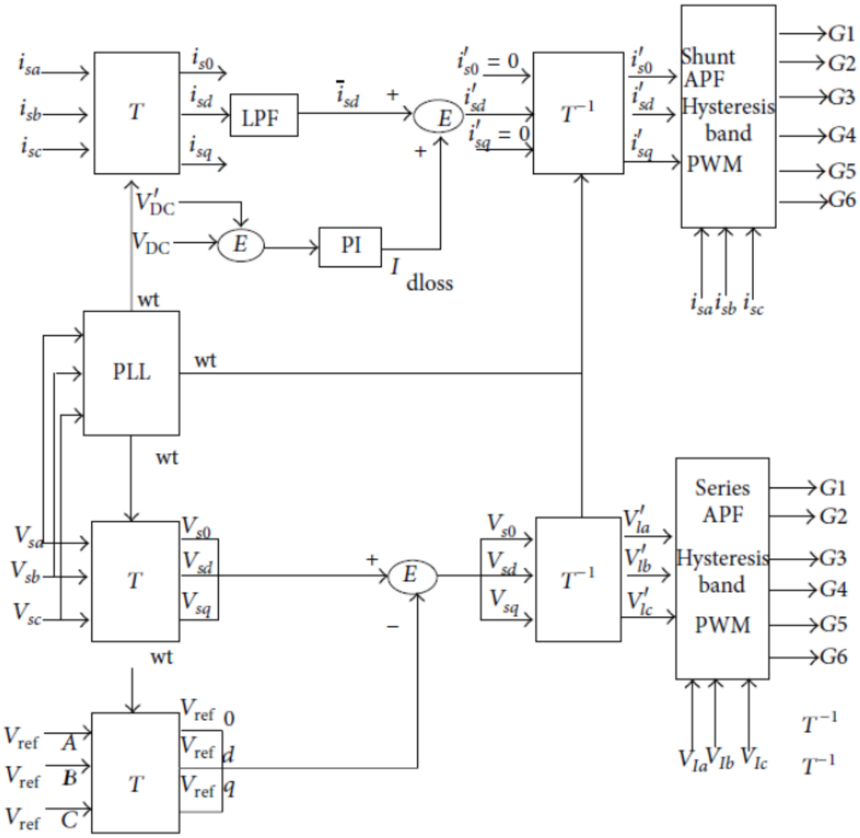


Figure 4.3.1: Control block diagram.

SIMULATION RESULTS

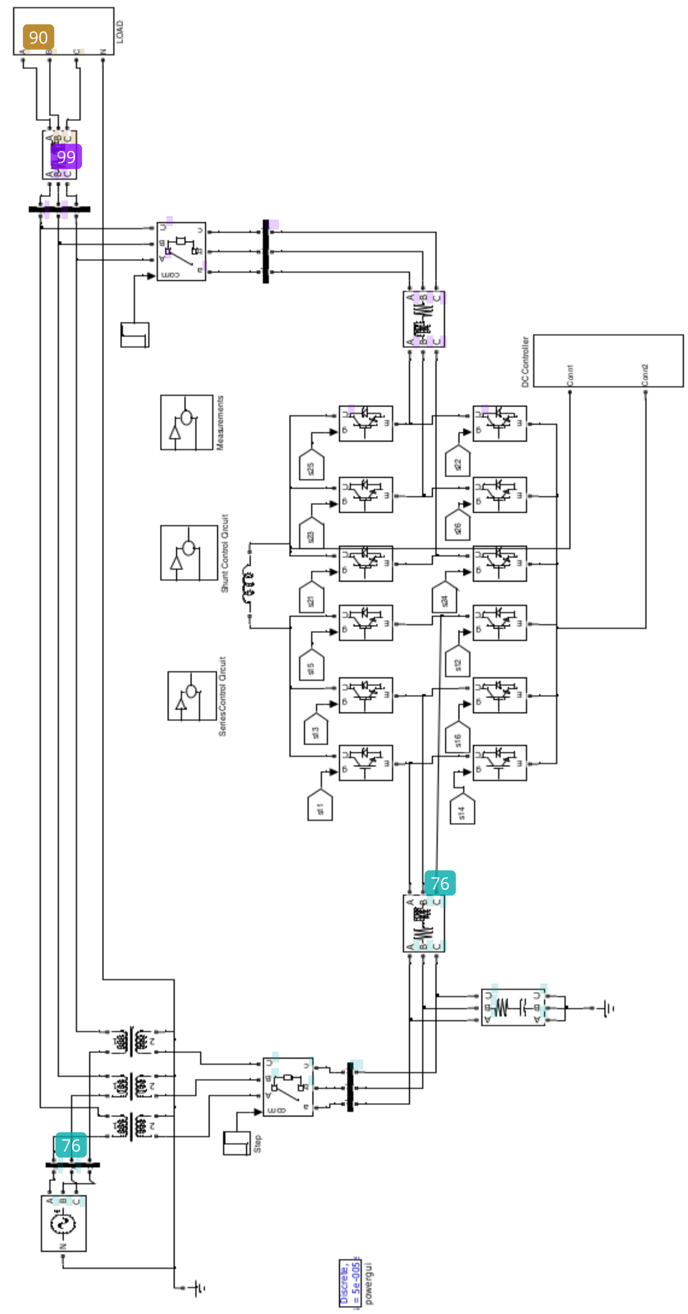


Figure : Simulink Circuit Diagram

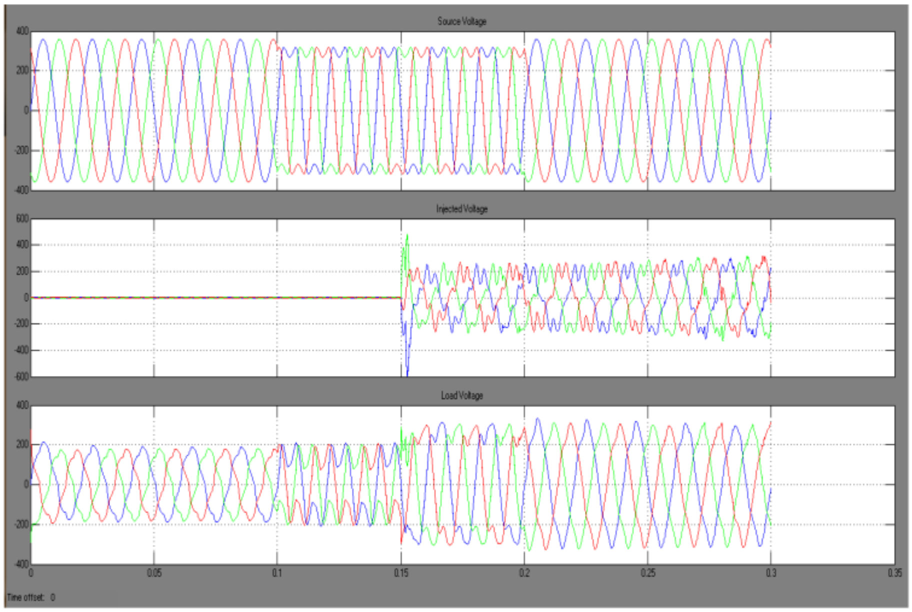


Figure: Simulation Result (a) Source Voltage, (b) Injected Voltage from UPQC,

(c) Load Voltage

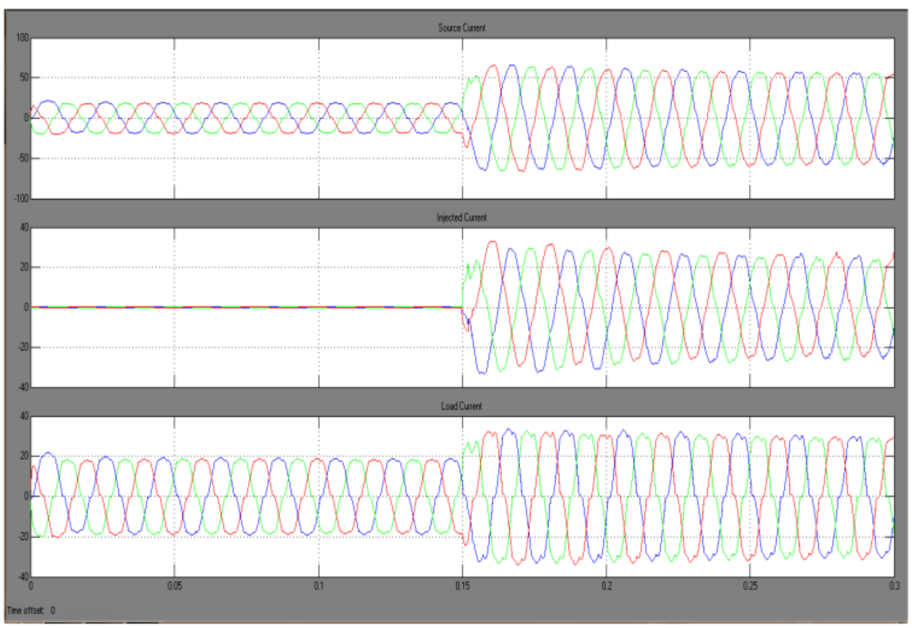


Figure: Simulation Result (a) Source Current, (b) Injected Current from UPQC,

(c) Load Current

Conclusion

In this project, synchronous reference frame theory based control method is implemented to control the working of unified power quality conditioner based on current source converter topology. The simulation results show that the device is capable of compensating the current harmonics under unbalanced and nonlinear load conditions, simultaneously mitigating voltage sag and swell. The proposed UPQC-CSC design has superior performance for mitigating the power quality problems. The series converter is capable of mitigating the voltage related problems and shunt converter is capable of mitigating the harmonics.

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