COMPENSATION IN DISTRIBUTION SYSTEM

A DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
POWER SYSTEMS

Submitted by:

Rahul Singh

2K19/PSY/15

Under the supervision of

Prof. Alka Singh

DEPARTMENT OF ELECTRICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

2021

DEPARTMENT OF ELECTRICAL ENGINEERING

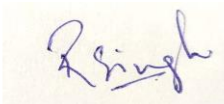
DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

CANDIDATE'S DECLARATION

I, RAHUL SINGH, Roll No. 2K19/PSY/15 student of M.Tech. (Power System), hereby declare that the project Dissertation titled "Compensation in Distribution System" which is submitted by me to the Department of Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associate ship, Fellowship or other similar title or recognition.



Place: Delhi **Rahul Singh**

Date: 16/08/2021

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

CERTIFICATE

I hereby certify that the major project titled "COMPENSATION IN DISTRIBUTION SYSTEM" which is submitted by RAHUL SINGH, Roll No. 2K19/PSY/15 ELECTRICAL ENGINEERING DEPARTMENT, Delhi Technological University, Delhi, in partial fulfillment of the requirement for the award of degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree to this University or elsewhere.

Place: Delhi | **Prof. Alka Singh**

Date: | **(SUPERVISOR)**

DEPARTMENT OF ELECTRICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

ACKNOWLEDGEMENT

I would like to express my gratitude towards all the people who have contributed their precious time and effort to help me without whom it would not have been possible for me to understand and complete the project. I would like to thank Prof. ALKA SINGH, Department of Electrical Engineering, DTU Delhi, my Project guide, for supporting, motivating and encouraging me throughout the period of this work carried out. Their readiness for consultation at all times, their educative comments, their concern and assistance even with practical things have been invaluable.

Rahul Singh
M.Tech (Power System)
Roll No. 2K19/PSY/15

ABSTRACT

The aim of supply utility is to satisfy its consumer power demand uninterruptedly with good power quality. The power demand in today's world is increasing rapidly. Also, the power demand is no longer the same as it was in the past, where maximum loads were typically linear. Now-a-days distribution system mainly supplies number of loads which are generally nonlinear, critical and voltage sensitive. Apart from these, various other connected loads like industrial drives, heat ventilation and air conditioning (HVAC), lighting, highly inductive and capacitive loads are present. These loads lead to harmonics in current and voltage, flickers as well as sag/swell in voltages and affect the power factor of supply system, performance of nearby sources and loads too. However the power quality concerns become more drastic with rapid increased use of equipment based on power electronics and solid state controllers. As a result, it is the customer's responsibility to inject as less distortion and harmonics into the system as possible in order to keep distribution system reliable and healthy.

Custom power devices are used to satisfy pre-specified standards in order to eliminate power quality concerns and preserve distribution system dependability. To enhance the power quality in distribution system already various authors reported various devices such as Shunt APF, Series APF and UPQC.

This thesis deals with designing of capacitor-supported shunt APF controller using Unit Vector Template (UVT) method, Synchronous Reference Frame (SRF) and Instantaneous Power Theory (IPT) and a PI-Controller is used to stabilize the capacitor DC-Link voltage and Hysteresis Current Controller to provide triggering pulses to converter of APF. The shunt APF is used to lower the harmonics in supply current by injecting compensating harmonics of same magnitude but phase shifted by 180^*, such that utility will supply only active power and shunt APF will provide reactive power to load. Supply system power factor is maintained to unity. The shunt APF performance is

analyzed for above mentioned three control techniques using MATLAB -Simulink to present THD in current, power flow and DC-Link voltage respectively.

The loads which consume high surge currents when they are switched ON such as heavy inductive loads, pumps, compressors, milling machines, welding machines and etc. lead to unbalance, flickers in system voltage. This affects the voltage quality of distribution system and causes mal-operation, failure of various nearby loads. In order, to preserve voltage quality devices such as DVR or Series APF are installed in series at PCC. The series APF corrects the load voltage to acceptable level by injecting and absorbing compensating voltage at PCC. In this thesis the designing, performance analysis of custom power devices is presented using UVT method and SRF theory is utilized to make reference injecting voltage for battery-supported Series APF and, hysteresis voltage controller provides the gate pulses to operate the APF's converter.

Based on the effectiveness of SRF theory controlled shunt and series APF, to mitigate power quality related concerns for both current and voltage simultaneously a device called UPQC have been developed in thesis. UPQC is a custom device which is having series and shunt APF sharing common DC-Link to preserve the balance of system power. In this PI-Controller well regulates the capacitor DC-Link voltage throughout the compensation process. It is capable of lowering the harmonics in current and abolishes the sag, swell and flicker in voltage under ideal grid conditions. Also it works well for non-ideal grid conditions i.e. when supply voltage is having distortions. This thesis presents MATLAB simulation-based findings to show the performance of UPQC during various disturbances, for %THD content in current and voltage, voltage during compensation, system power flow, study of capacitor voltage during normal operation, sag, swell, and polluted grid.

CONTENTS

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Cycle
DC	Direct Cycle
APF	Active Power Filter
RMS	Root Mean Square
UVT	Unit Vector Template
SRF	Synchronous Reference Frame
IPT	Instantaneous Power Theory
PLL	Phase Locked Loop
LPF	Low Pass Filter
VSI	Voltage Source Inverter
PCC	Point of Common Coupling
UPQC	Unified Power Quality Conditioner
THD	Total Harmonic Distortion
TDD	Total Demand Distortion

CHAPTER 1
INTRODUCTON

1.1 Overview

In electric power distribution system, different types of loads are connected to meet the demands of a wide range of customers. The aim of power utility is to supply a quality power to its consumer uninterruptedly with constant frequency, constant sinusoidal magnitude of voltage and current. However, the presence of voltage sensitive, critical, and nonlinear loads may impair power supply quality. These loads can be classified as;

- Power electronic Devices: Since the past few years, use of power electronic devices such as switching mode power supply (SMPS), variable speed drives, battery chargers (converters), rectifiers leads to introduction of harmonics in distribution system.
- Lighting loads: Consumers utilize these loads mostly for lighting. In addition, they might be both linear and non-linear in character.
- Use of Heating, Ventilation and Air Conditioning i.e. HVAC system in hospitals, multiplex and offices. Mostly these loads are combinations of linear and nonlinear.
- Industrial loads: welding machines, milling machines and electric furnaces are installed which may leads to voltage distortion.

All the nonlinear loads are real culprit and affect the power quality and pollute the distribution network. Poor quality power affects the nearby loads and sources as well. In addition it also causes failure or permanent damage to switch-gears, power system protection equipment and false tripping of circuit breakers.

The reason for the increased use of power electronic devices based loads and solid state controllers and their popularity is due to multiple benefits such as energy efficient, low cost, compact in size and easy in control and, low maintenance cost. Unfortunately, these loads are the most vulnerable to power quality issues, and they cause power quality issues because they employ solid-state controllers.

These power quality issues result in capacitor bank failure, increased distribution system and electric machine losses, vibrations, over-voltages, and excessive current owing to resonance and negative sequence currents in generators and motors, particularly rotor heating. Numerous power quality problems that arise as a result of the existence of nonlinear, current sensitive and critical loads in distribution system are:

- Sag/swell in voltage
- Overvoltage, under-voltage
- Harmonics in current and voltage
- Flickers or voltage fluctuations
- Poor power factor

Hence, it is necessary to improve the power quality of the distribution network for its reliable operation as per the IEEE standards.

- IEEE 519-1992 and, revised IEEE 519-2014 according to this standard the THD in current and voltage should not more than 5%.
- IEEE 1159-2019 recommends the power quality standards

To meet the above standards some compensation techniques must be provided to control harmonics in current and voltage, sag/swell in voltage at point of common coupling (PCC).

1.2 Electric Loads

1.2.1 Linear Loads

The load that obeys the Ohm's law i.e. current is proportional to voltage, $I(t) \alpha V(t)$. For the linear loads, voltage and current are only varies by phase shifts. Table 1.1 shows types of linear loads.

TABLE:1.1 Types of linear loads

Resistive Load	Capacitive Load	Inductive Load
1. Incandescent Lamps 2. Resistive Heaters	1. Underground cables 2. Insulated cables 3. Capacitors used in filters circuits	1. Induction generators (windmills) 2. Induction motors

1.2.2 Nonlinear Loads

These are the loads that do not obey the Ohm's law. Shape of current or voltage is different from sinusoidal. Fig. 1.1 shows the Matlab simulation based nonlinear rectifier load. Table 1.2 shows the types nonlinear loads.

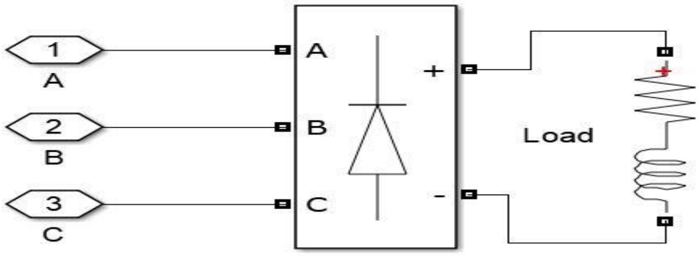


Fig. 1.1 Matlab simulation based nonlinear load

TABLE:1.2 Types of nonlinear loads

Power Electronic Devices	Industrial Equipment
1. Switching mode power supplies (SMPS) 2. Rectifiers 3. Variable speed drives 4. Inverters 5. Battery chargers and, etc.	1. Electric Furnace 2. Welding machine 3. Roll/ball mills

1.3 Power Quality problems

In this section various power quality parameter, its causes and effect are explained based on IEEE 1159-2019 and IEEE 519-2014.

1.3.1 Transients

1. Impulsive Transients

These relate to a sudden peak in current, voltage or both under steady state for a small duration of time interval. It's unidirectional in polarity i.e. either negative or positive and typical duration of occurrence can range from 5ns to 50ms.Switching ON of inductive loads or lightning are the primary causes of this phenomenon. It can create resonance in power system.

2. Oscillatory Transients

These relate to a sudden change in current, voltage or both under steady state for a small duration of time interval. It's bidirectional in polarity i.e. both negative & positive and, typical duration of occurrence can range from 0.3ms to 5μs.The major reasons of this phenomenon include energizing or de-energizing a capacitor bank for system power factor adjustment.

1.3.2 Short Duration Variations

1. Voltage sag

A fall or dip in RMS line voltage from its nominal value ranging from 10% to 90% or 0.1pu to 0.9pu. A typical duration of sag can range from 0.5 cycles to 1min. Fig. 1.2 shows the sag in voltage.

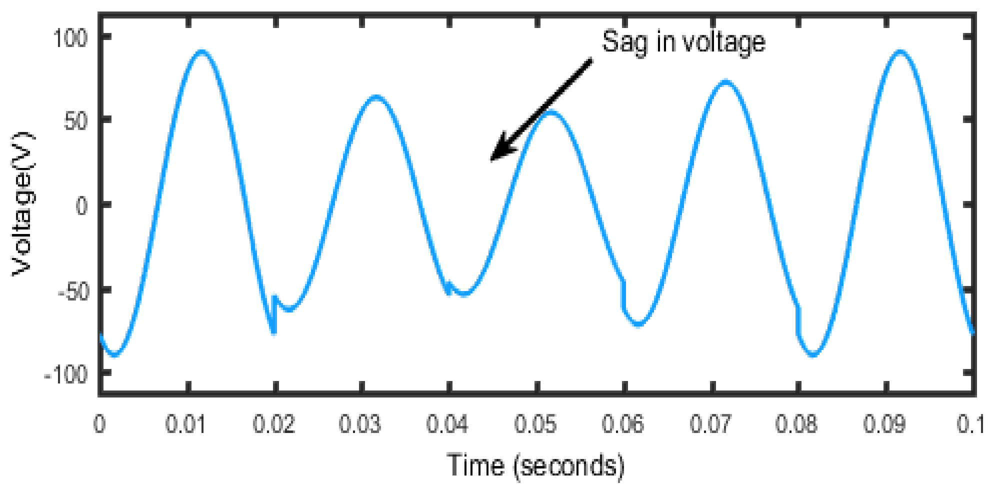


Fig. 1.2 Sag in voltage

The primary cause of this voltage sag is the starting of big induction motors and inductive loads. It can lead to protection malfunction and loss of power production.

2. Voltage swell

It refers to a rise in RMS line voltage from its nominal value ranging from 110% to 180% or 1.1pu to 1.8pu. A typical duration of sag can range from 0.5 cycles to 1min. Duration of swell can range from 0.5 cycle to 1min. Fig. 1.3 shows the swell in voltage.

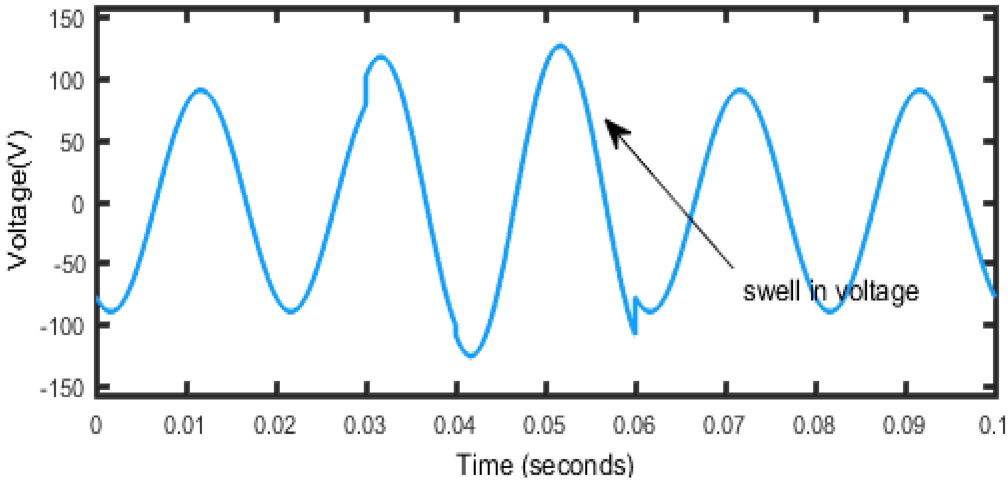


Fig. 1.3 Swell in voltage

The cause of voltage swell is dip in large loads, energizing/switching of capacitive loads. It leads to breakdown of insulation and stress on electrical equipment and appliances.

3. Interruption

A reduction in line voltage or current from its nominal value to less than 10% or 0.1pu is called interruption and its typical duration is greater than 3s to less than 1min. Fig. 1.4 shows the interruption in voltage.

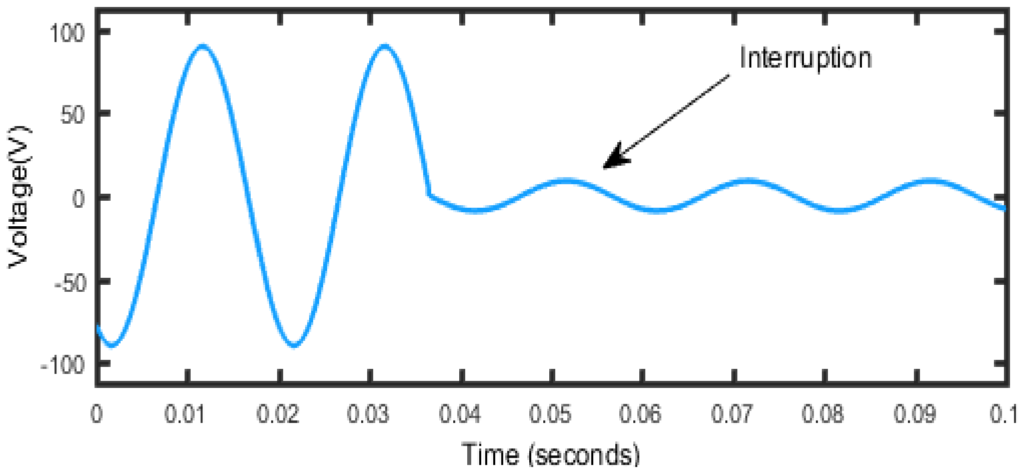


Fig. 1.4 Interruption in voltage

The primary cause for this phenomenon is occurrence of temporary faults. It can lead to false tripping of circuit breakers and electrical equipment.

1.3.3 Long Duration Variation

1. Under Voltage

A fall in RMS line voltage from its nominal value ranging from 80% to 90% or 0.8pu to 0.9pu and, it can able to sustain more than 1min.

The major cause of under voltage is switching ON loads and de-energizing of capacitor banks. It can lead to overheating or copper losses in electrical equipment.

2. Over Voltage

A rise in RMS line voltage from its nominal value ranging from 110% to 120% or 1.1pu to 1.2pu and, it can able to sustain more than 1min.

The major cause of overvoltage voltage is energizing of capacitor banks and switching OFF of loads. It can lead to mal-operation/damage of industrial and household appliances.

3. Sustained Interruption

A complete fall in voltage i.e. 0.0pu is called as sustained interruption. It can last for more than a minute.

The reason of sustained interruption is occurrence of permanent faults however, chances of permanent fault occurrence is very less.

1.3.4 Voltage fluctuations

The fluctuations in RMS line voltage magnitude from its nominal value ranging from 0.1 to 7% in intermittent state due to the change sudden in reactive and active power demand of the load. It is also called as “voltage flicker”.

Arc furnaces, air conditioner units, arc welding, rolling/ball mills, cyclo-converters, and equipment with high motoring speed is the cause of voltage fluctuations. It leads to failure of equipment insulation and flickering of electric lamps.

1.3.5 Voltage Imbalance

Voltage imbalance is the amplitude variation of the phase voltages in relation to one another. This voltage imbalance is mostly caused by different loads on the phases.

1.3.6 Waveform Distortion

Supply utilities are attempts to generate a sinusoidal voltage and current waveform, but owing to a flaw, it is unable to do so, and distortions result.

1. Harmonics

The aim supply utilities are to supply power to its consumer uninterruptedly. But now-a-days loads are generally nonlinear which draws current in multiple integers of fundamental frequency i.e. multiple of 50Hz. When this distorted harmonic current flows through source impedance leads to introduction of harmonics in voltage too, and hence, pollute the power system. Total harmonic distortion (THD) is used to measure the level of harmonics in voltage and current as per IEEE-519 standards.

2. Inter-harmonics

These are the harmonics which introduced in voltage and current whose frequency is not a multiple of supply power frequency and the source of these harmonics are cyclo-converters and arc furnaces.

3. Notching

Notching is a periodic voltage disturbance induced by regular power electronic device functioning when current is commutated from one phase to another.

4. Noise

It is categories as undesirable electrical signals that introduced in power system due to power line carrier communication (PLCC) interference with nearby communication lines.

5. DC Offset

Presence of DC quantity in AC voltage and current is called as DC offset. It leads to saturation of core of rotating machines, transformers.

1.3.7 Frequency variation

Power system is designed to operate with 50Hz frequency and maximum permissible variation in frequency is $\pm 0.1\%$

1.3.8 Harmonics Distortion& Indices

Sinusoidal current, voltage or any electrical quantity that operate at an integer multiple of the fundamental frequency are known as harmonics. The two harmonic indices are used to determine the level of harmonics in the system as per IEEE Std 1453-2015 and IEC 61000-4-15.

1. **Total Harmonic Distortion (THD) and,**
2. **Total Demand Distortion (TDD)**

is used to assess how much influence harmonic distortion has on a fundamental component, in the power system.

1. Total Harmonic Distortion (THD)

THD in the electrical quantity can be calculated as the ratio of RMS value of individual harmonic components to the fundamental component.

$$\%THD = \frac{RMS\ value\ of\ individual\ harmonic\ component}{RMS\ value\ of\ fundamental\ component} \times 100 \tag{1.1}$$

Mathematically it is given in (1.2)

$$\%THD_X = \frac{\sqrt{\sum_{i=2}^{n} X_i^2}}{X_1} \times 100 \tag{1.2}$$

Where X can be voltage or current

X_i is the individual harmonic component and X_1 is fundamental component.

Significances: lower the THD implies that lower is heating in electrical equipment, lower the peak current or vice-versa.

2. Total Demand Distortion (TDD)

It is used to determine the harmonic distortion in current with respect to fundamental peak load current. It is used to calculate the actual load in the system.

$$\%THD = \frac{RMS\ value\ of\ individual\ harmonic\ component\ of\ load\ current}{Fundamental\ peak\ load\ current} \times 100 \tag{1.3}$$

Mathematically it can be calculated as in (1.4)

$$\%THD_I = \frac{\sqrt{\sum_{i=2}^{n} I_i^2}}{I_L} \times 100 \quad (1.4)$$

Where I_i is the RMS value of harmonic components in current and I_L is fundamental peak load current at the PCC under normal operating conditions.

1.4 Methods to Improve Power Quality

To improve power quality related problems conventionally passive filters are used to mitigate sag/swell in voltage and harmonic distortion in current and voltage. However due to heavy weight, large in size, resonance phenomena and etc. use of passive filter is limited. Now-a-days active power filters (APF) are used as it has advantages over passive filters.

1. Passive Power Filters

Passive filters are one of the cheapest and simplest in construction. It consists of R, L, C components which are connected in series and parallel to compensate a specified harmonics in electrical network. Based on connection it can be parallel, series or, hybrid passive power filter.

The Passive parallel filters provides the low impedance path to flow the harmonic currents so, it does not enters to the system and, not affect the performance of neighboring loads and sources. It is connected parallel to nonlinear loads. Fig. 1.5 shows the example of passive parallel filters.

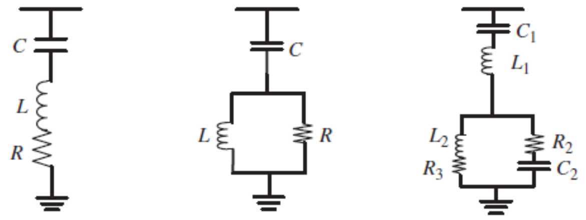


Fig. 1.5 Different types of passive parallel filters

Passive series filters provides the high impedance path to flow harmonic current and, thus blocks entrance of harmonics in electrical network and, it is connected in series to nonlinear loads. Fig. 1.6 shows the example of passive series filters

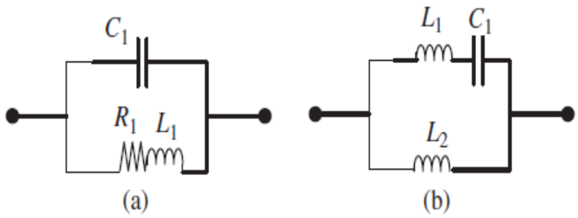


Fig. 1.6 Passive series filter

2. Active Power Filters (APF)

APF are the custom devices used in power system to enhance the power quality and, it more effective than that of passive power filters. As nowadays most of the loads at consumer ends are generally nonlinear i.e. SMPS, variable speed drives, power electronics device based which generate lot of harmonic currents. It leads to introduction of harmonics in distribution line too. However, loads like compressor, heavy motors lead to sag/swell in voltage and even sometimes harmonic currents flows though the source impedance which leads to distortion in supply voltage and hence affects the power quality of the electrical system.

Based on the requirement shunt APF, series APF and hybrid APF i.e. Unified power quality conditioners are used to enhance the power quality of the system and are connected at PCC. Shunt APF is connected in parallel at PCC used to mitigate power quality issues related to current harmonics. On the other hand series APF is connected in series using series voltage injecting transformer it is used to mitigate sag/swell in supply voltage.

UPQC consists of both shunt and series APF which are connected using interfacing dc-link capacitor. It is capable to balance the load voltage and mitigate harmonics in both current and voltage as per the IEEE 519 standards.

1.5 Organization of Dissertation

Chapter 1: This Chapter presents the brief overview of the problems due to the presence of nonlinear, sensitive and critical loads in distribution system, various power quality problems along with causes and the methods to mitigate power quality issues and organization of dissertation.

Chapter 2: This Chapter presents the brief introduction, literature review for shunt, series APF & UPQC and objectives of this dissertation.

Chapter 3: This Chapter presents an overview of three-phase shunt active power filters, designing and controlled using UVT method, SRF theory and PQ theory where PI controller is used to regulate the capacitor dc-link voltage, main components of shunt APF such as VSI and its control technique using hysteresis current controller. A detailed analysis of dynamic simulation results are presented along with comparison for the system supplying to nonlinear load.

Chapter 4: This Chapter gives an overview, design and control using UVT method and SRF theory for three-phase series active power filters presented along with its main component i.e. hysteresis voltage controller to drive its VSI and, simulation results are presented for disturbance like swell/sag in supply voltage.

Chapter 5: This Chapter presents an overview of three-phase UPQC, its control using SRF theory and mathematical analysis of power for UPQC connected to distribution system. A detailed analysis of dynamic results are presented for various disturbances such as sag/swell in voltage, distortion in current, for polluted grid and comparison of dc-link voltage along with active & reactive power flow.

Chapter 6: This Chapter presents the final conclusion and future work.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Power quality is now the most important variable in both transmission and distribution system. The various power quality parameter, its causes and effect are given by IEEE 1159-2019 [1], IEEE 519-2014 [2] and, the harmonic indices which are used to evaluate the level of harmonics in the system are given by as per IEEE1453-2015 [3] and IEC 61000-4-15 [4]. It is critical to maintain the permissible limits of power quality. N.G Hingorani *et al.* [5] introduced the fundamental notion of tailored power in 1995. It ensures the continuity of electricity flow. As supply utilities are required to supply harmonic free current and voltage, balanced voltage to load uninterruptedly. The existing power quality problems lead to development of various custom devices such as active power filters and UPQC [6], [7]. These custom devices are built with power electronic components such as IGBTs, diodes, and, thyristors [8].Y. Pal *et al.* [9] describe the wide range of custom devices used for the power quality improvement.

2.2 Literature Review

To suppress the harmonics introduced in supply current in distribution system due to the presence of nonlinear loads at consumer terminal, to correct the supply power factor of the system to unity [10] a three-phase shunt APF are connected parallel to the PCC. Various control techniques to generate reference source current are described in several literatures using UVT method, SRF theory and IPT theory [11], [12].

Kishore K. Pedapenki *et al.* [13] present the control of shunt APF using UVT method to get the required reference signals to trigger the VSI. To show the effectiveness of this simple method which consist less components, results was presented for THD and PF with and without APF for various loads along with the firing angle from $\alpha=0^{o}$ to $\alpha=60^{o}$. K. Bhattacharjee *et al.* [14] describes the SRF theory to generate the reference current which is then fed into the adaptive hysteresis current controller, which provides the switching pulses that activate the VSI, in addition to compensate the switching losses of the VSI PI-Controller is used to regulate the DC bus voltage and, results are presented which shows the SRF theory is effective to reduce the harmonics in distribution system. H. Akagi *et al*. [15] describes the instantaneous power theory (IPT) to generate reference 3-phase source current using αβ or Clarke transformation, PI controller is used to regulate the dc-link voltage for compensate the switching losses of the converter.

For the implementation of SRF theory and UVT method, PLL is required to synchronize the signals with source voltage. These control techniques requires the PI-controller to regulate the capacitor dc-link voltage of VSI is described in [16]. The hysteresis current controller is used to produce gate pulses to trigger the VSI of the shunt APF [17].

In distribution system due to the presence of high inductive, high current consuming, pumps compressors demands the high starting current which causes unbalance in voltage i.e. sag/swell, over-voltages, under-voltage and burden on distribution transformers. To balance the voltage in distribution system DVR or Series APF [18] are connected in series to protect voltage sensitive equipment. It absorbs or injects the compensating voltage to balance the load voltage [19], [20].The function of series APF is to examine the swell/sag in voltage, based on that it will compute the correcting the voltage, generates the triggering pulses to the inverter and, corrects the anomalies in the voltage by injecting/ absorbing compensating voltage at/ from PCC and, when the event has passed, the trigger pulses are terminated. [21] presents, the hysteresis voltage controller to trigger the VSI of series APF. B. Singh *et. al.* [22] discusses various control techniques for battery supported DVR to extract the reference compensating voltage. Similarly UVT method and SRF theory is utilized to generate reference compensating voltage.

UPQC [23] has been successfully utilised to minimise or suppress a wide range of power quality (PQ) issues, including voltage harmonics, voltage sag/swell, voltage flicker, voltage fluctuations, poor power factor, unbalanced voltages and currents, harmonics in current, and reactive power by M. Kesler *et al.* [24].The various topologies and classification of UPQC is presented in [25]. Application of UPQC is presented in [26]

S. Vinnakoti *et al.*[27] presents the SRF theory to control UPQC using modified PLL, Hysteresis current control is used for shunt converter and, SPWM control is used for series converter and, DC bus voltage is effectively controlled by using a simple PI controller. From the results, it have been observed that the harmonics in current and voltage, sag/swell, fluctuations in voltage is eliminated more easily as compared to UVT method, IPT and modified IPT based control and, during compensation utility is no longer supplying reactive power to nonlinear, which improves the power factor at the supply side, in addition active power exchange between shunt and series converter are also presented in that literature.

2.3 Objectives of this Dissertation

1. To design and investigate various shunt APF control strategies for suppressing harmonics in source current such that after compensation, the grid current should be pure sinusoidal.
2. To present the comparison of various control methodologies of shunt APF based on simulation results.
3. To study the control schemes of series APF using UVT and SRF theory to eliminate swell/sag, fluctuations, short duration variations in voltage.
4. To simulate and analyze the UPQC controlled using SRF theory in order to enhance the various power quality parameters such as elimination swell/sag, fluctuations, short duration variations in voltage and to reduce harmonics in current and voltage i.e. %THD not more than 5% under polluted grid conditions and to study the reactive & active power flow during compensation process.

CHAPTER 3
SHUNT ACTIVE POWER FILTERS

3.1 Overview

Shunt Active power filter (Shunt APF) is a custom device used in distribution system to compensate the current harmonics which introduced in system due to nonlinear, current sensitive electrical and electronic equipment. It injects compensating harmonic current of same magnitude but phase shifted by 180*, reduces the THD in current to an adequate level and, thereby improves the power factor. Thus, the sinusoidal waveform is maintained at source side. Fig. 3.1 shows the schematic diagram of Shunt APF connected in distribution system to supply the harmonic current demand of the nonlinear load. SAPF is connected in parallel at PCC by using coupling inductors. It consists of three legs i.e. six switches voltage source converter (VSC) with insulated gate bipolar transistor (IGBT). Shunt APF also supplies the reactive power demand of the load such that source will supply only active power.

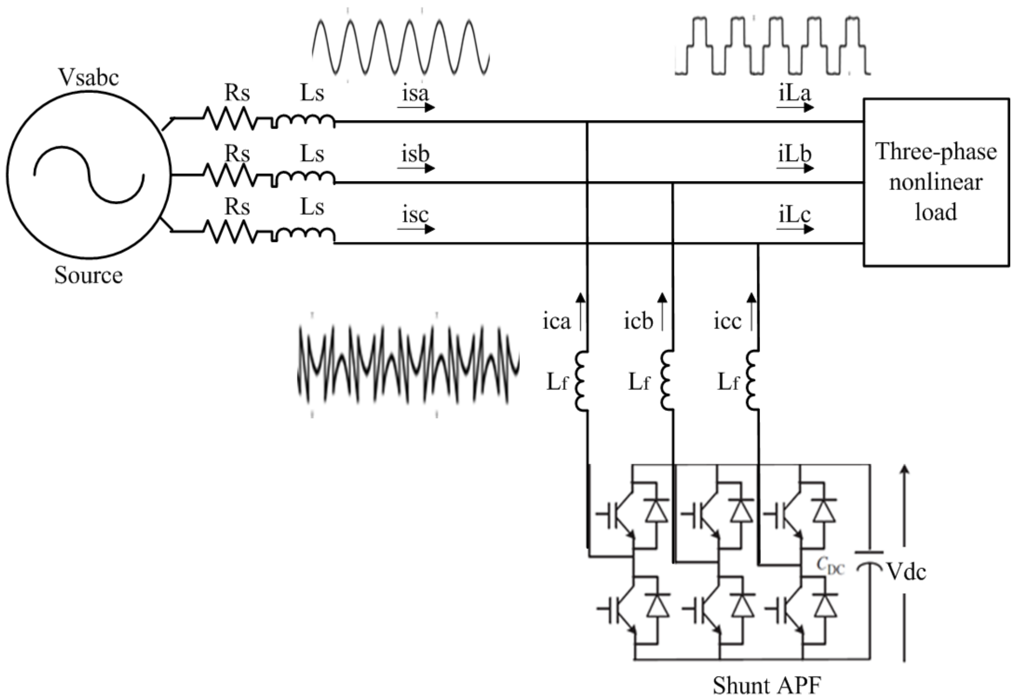


Fig. 3.1 Shunt APF connected to distribution system

Shunt APF mainly consists of three blocks

1. IGBT based VSI
2. Control Unit
3. DC-link voltage control

In this chapter mainly three algorithms are discussed to generate reference source current. These are Unit Vector Template generation (UVT) method, Instantaneous Power theory (IPT) and, Synchronous Reference Frame (SRF) theory.

3.2 Reference Current Generation Methods

The following control algorithms have been developed

i. Unit Vector Template generation (UVT) method
ii. Instantaneous Power theory (IPT)
iii. Synchronous Reference Frame (SRF) theory

3.2.1 Unit Vector Template Generation Method

This is one the simplest method used to generate reference source current. In this method unit vector template signals are generated by synchronizing with source voltage. In this method first source voltage V_{sabc} is sensed and given to phase-locked loop (PLL) circuit to generate the synchronized unit signal. This unit signal is then, multiplied with sin(ωt) function to generate the three-phase unit vector template and it is given by equations (3.1) to (3.3). Fig 3.2 illustrates the control scheme of shunt APF.

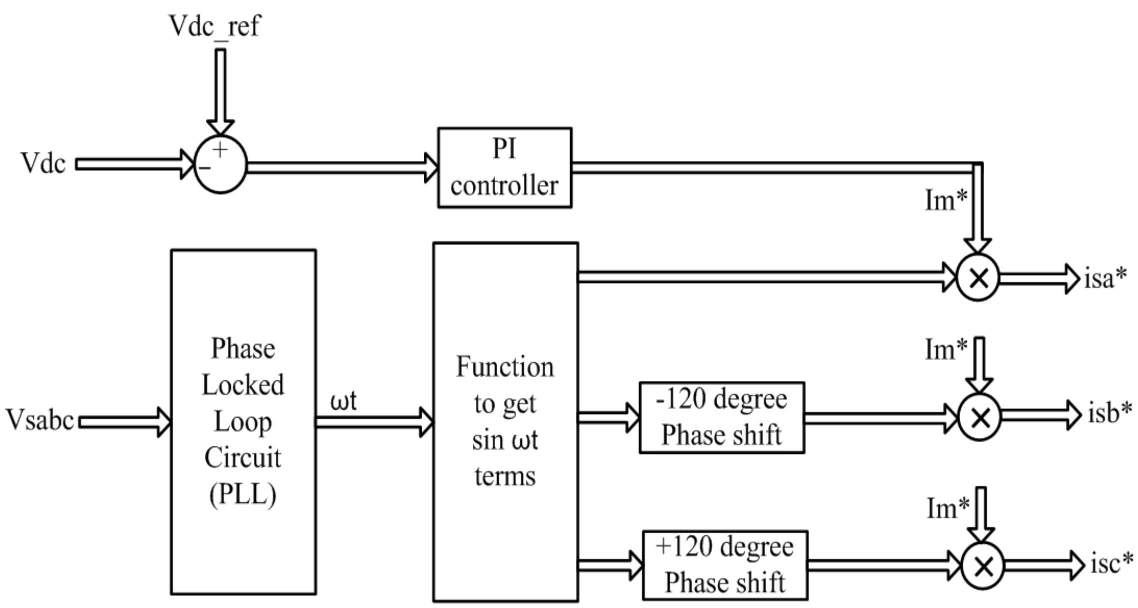


Fig. 3.2 Control scheme of shunt APF using UVT generation method

$u_a = 1\sin(\omega t)$ (3.1)

$u_b = 1\sin(\omega t - \frac{2\pi}{3})$ (3.2)

$u_c = 1\sin(\omega t + \frac{2\pi}{3})$ (3.3)

To compute the magnitude of reference source current, the sensed dc-link voltage V_{dc} of shunt APF is compared with reference dc-link voltage V_{dc}^* to generate an error signal. This voltage error signal is feed to PI controller. The output of PI controller is controlled reference current magnitude i.e. I_m^*. This I_m^* is then multiplied with unit vector templates u_a, u_b, u_c.

$I_{sa}^* = I_m^*\{1\sin(\omega t)\}$ (3.4)

$I_{sb}^* = I_m^*\{1\sin(\omega t - \frac{2\pi}{3})\}$ (3.5)

$I_{sc}^* = I_m^*\{1\sin(\omega t + \frac{2\pi}{3})\}$ (3.6)

Therefore, the generated reference source current is given by equations (3.4) to (3.6)

3.2.2 Synchronous Reference Frame Theory

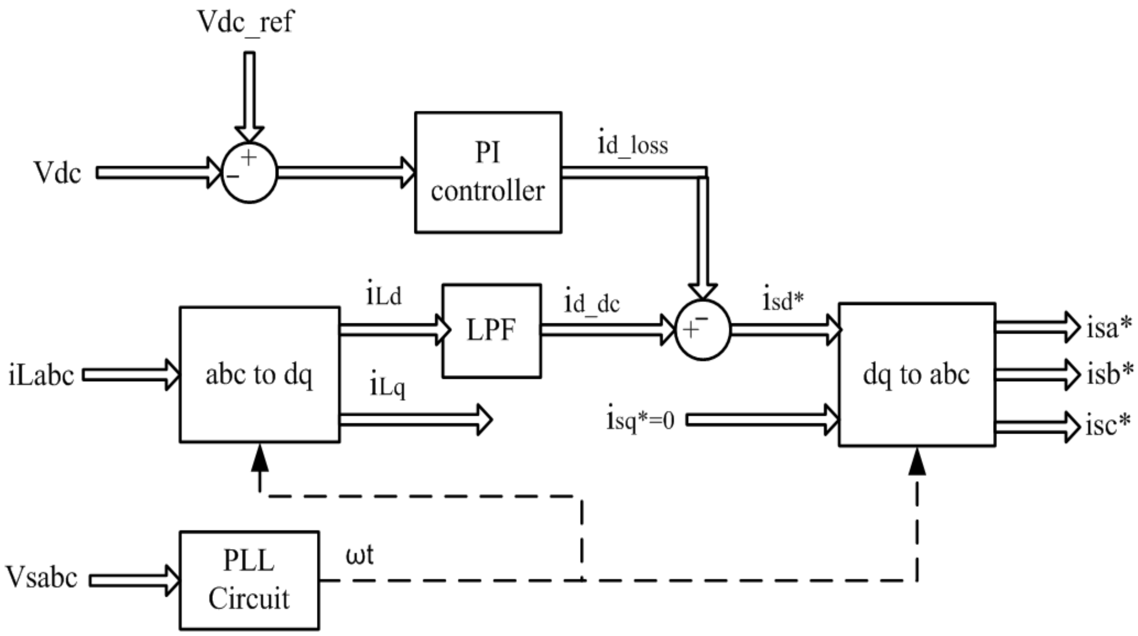


Fig. 3.3 Control scheme of shunt APF using SRF theory

This method of generating reference source current deals with Park's transformation i.e. quantities of abc coordinate transformed to dq0 frame. Fig. 3.3 depicts the control scheme of shunt APF using SRF theory.

For the implementation of this method first load current i_{labc} is sensed and transformed to dq0 frame by using (3.7). Synchronization of the transformed load current i_{ld},i_{lq} with source voltage V_{sabc} is done by PLL circuit.

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \tag{3.7}$$

The transformed current i_{ld},i_{lq} contains both fundamental (i_{d_dc}, i_{q_dc}) and harmonic components (i_{d_h},i_{q_h}) given by equation (3.8) and (3.9). Since, the source is required to supply only fundamental component of current to load therefore, harmonic component is need to suppress.

$$i_{ld} = i_{d\_dc} + i_{d\_h} \tag{3.8}$$

$$i_{lq} = i_{q\_dc} + i_{q\_h} \tag{3.9}$$

To suppress the harmonic content i_{d_h} the d-axis current i_{ld} is passed through a low pass filter (LPF) having cutoff frequency of 20Hz.

To maintain the capacitor dc-link voltage of shunt APF and, to compensate the switching losses of converter loss current i_{dloss} component is needed to be calculated. For the calculation of i_{dloss} , capacitor dc-link voltage is sensed and compared with its reference voltage to generate an error voltage signal. This error voltage is fed to a suitable PI controller whose function is to regulate the dc-link voltage and output is i_{dloss} .

$$i_{sd}^* = i_{d_{dc}} - i_{dloss} \tag{3.10}$$

$$i_{sq}^* = 0 \tag{3.11}$$

In equation (3.10) and (3.11) i_{sd}^* shows the source reference current of d-axis whereas i_{sq}^* is considered zero since it is used in indirect method of control.

On applying the inverse Park's transformation using (3.12) gives the reference source current i.e. i_{sa}^*, i_{sb}^*, i_{sc}^*.

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{sd}^* \\ i_{sq}^* \end{bmatrix} \tag{3.12}$$

3.2.3 Instantaneous Power Theory

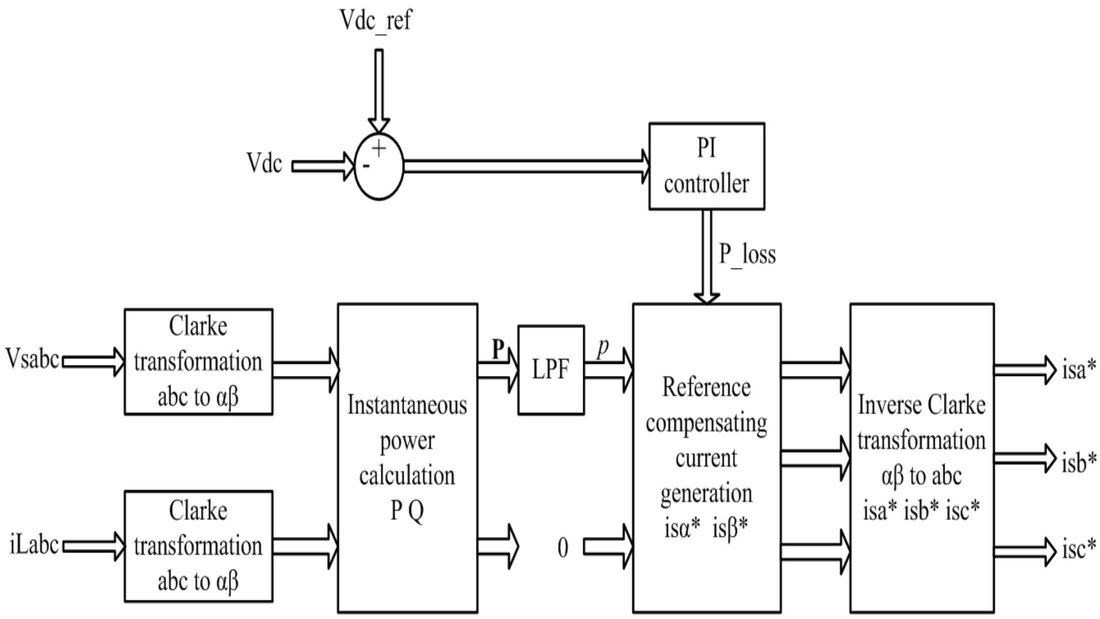


Fig. 3.4 Control scheme of shunt APF using IP-theory

"It was introduced by Akagi et al in 1983". The instantaneous active & reactive power (IPT) theory is based on time domain transformation. Here abc phases are transformed into αβ0 coordinates (Clarke Transformation) coordinates to define the instantaneous power on these coordinates. Then, further it is transformed from αβ0 to abc coordinates (Inverse Clarke Transformation) to generate reference compensating current. Hence, this theory always considers the three-phase system as a unit, not a superposition or sum of three single-phase circuits. Fig. 3.4 shows the basic implementation of this theory.

In this method source voltage $V_{sabc}$and load current i_{labc} is sensed and transformed into αβ0 coordinates from abc coordinates as shown in (3.13) and (3.14).

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{3.13}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \tag{3.14}$$

This transformed αβ signal is used to compute the instantaneous active P_L and reactive powers Q_L using (3.15)

$$\begin{bmatrix} P_L \\ Q_L \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3.15}$$

P_L , Q_L contains both fundamental as well as harmonic components i.e. dc and ac components shown in (3.16) and (3.17)

$$P_L = P_{dc} + p \tag{3.16}$$

$$Q_L = q_{dc} + q \tag{3.17}$$

where,

P_{dc} = Instantaneous active power and is treated as desired fundamental power component that is supplied by source to load.

p = Instantaneous active power containing harmonics and it is not required to compensate as it is not involved in power transfer from source to load.

q_{dc} = Instantaneous reactive power and related to the exchange of power between the load which results in undesired current, therefore it is required to compensate.

q = Instantaneous reactive power alternated value, it is similar to conventional reactive power that is required to compensate by using shunt APF.

Since, it's the indirect method for generating source reference current. Therefore,Q_L is considered to zero. As source will supply only active power to the load when shunt APF is connected in the system.

To get harmonic free component this P_L is possessed to a low pass filter (LPF) having cutoff frequency of 20Hz.

To maintain the dc-link voltageV_{dc}, actual capacitor dc-link voltage is compared with reference capacitor dc-link voltageV_{dc}^* to obtain an error, this error is possessed through PI controller to get desired active power loss component $P_{loss}$is provided to compensate the switching losses of the shunt APF converter.

Therefore, desired compensated active power P_c is given by (3.18)

$$P_c = P_{dc} - P_{loss} \tag{3.18}$$

Using this P_c the reference source current is calculated as shown in (3.19)

$$\begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} P_{dc} - P_{loss} \\ 0 \end{bmatrix} \tag{3.19}$$

By applying the inverse Clarke's transformation to (3.19) using (3.20) gives the reference source current in abc coordinates i.e. i_{sa}^*, i_{sb}^*, i_{sc}^*.

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} \tag{3.20}$$

3.3 Three Phase Voltage Source Inverter

Harmonic control is enabled via the voltage source inverter (VSI) used in the shunt active power filter. A dc-link capacitor serves as the inverter's input, and its voltage is maintained by a control mechanism. In an ideal condition, the inverter would require no active power. However, it draws a slight amount of active power from the capacitor due to switching losses and resistance in the coupling inductor. Harmonics equal in magnitude but 180* phase shifted to the load current are present in the current generated by the inverter. This ensures that the source current is free from harmonics. The hysteresis controller provides the switching pulses necessary to create the harmonic current.

VSI is made up of three legs with current reversible switches that are regulated for open and closure. Controlled switches (IGBT) with anti-parallel diodes are used to implement these switches, allowing free-wheeling currents to flow. Fig. 3.5 shows basic configuration of VSI with six switches (T1, T2, T3, T4, T5 and T6).

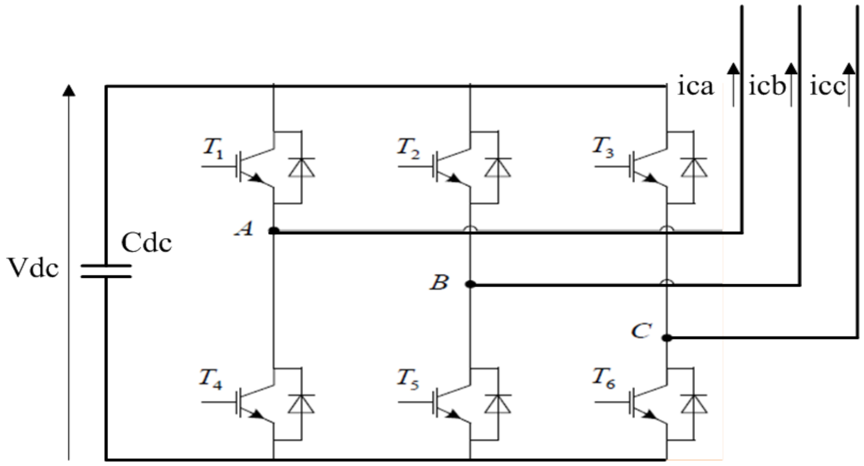


Fig. 3.5 VSI of shunt APF

3.4 PI Controller

The PI controller is a critical component of the shunt APF. Under ideal condition, the inverter would not absorb any active power, thus the capacitor dc-link voltage would be constant. However, the capacitor voltage drops due to switching losses or PWM and other inverter losses. When this capacitor dc-link voltage $V_{dc}$is compared to its reference value V_{dc}^*, an error signal is produced. This error is the PI controller's input.

The PI controller algorithm has two distinct parameters: proportional K_P and integral K_I.

$$H(s) = K_P + \frac{K_I}{s} \tag{3.21}$$

The value K_P and K_I is set to such a value so the PI controller is able to maintain the capacitor dc-link voltage V_{dc} to its reference voltage V_{dc}^*. The PI controller creates a reference current proportional to the losses, which is responsible for the capacitor voltage decrease. This current is combined with the generated reference source current. The hysteresis current controller receives these two currents and generates switching pulses for the inverter.

3.5 Control Technique of VSI

The objective of control of VSI is to force the source current to follow their predefined generated reference source currents. The main approach is based on the comparison of actual current with the reference currents generated by various extraction methods discussed in the previous sections.

3.5.1 Hysteresis Current Controller

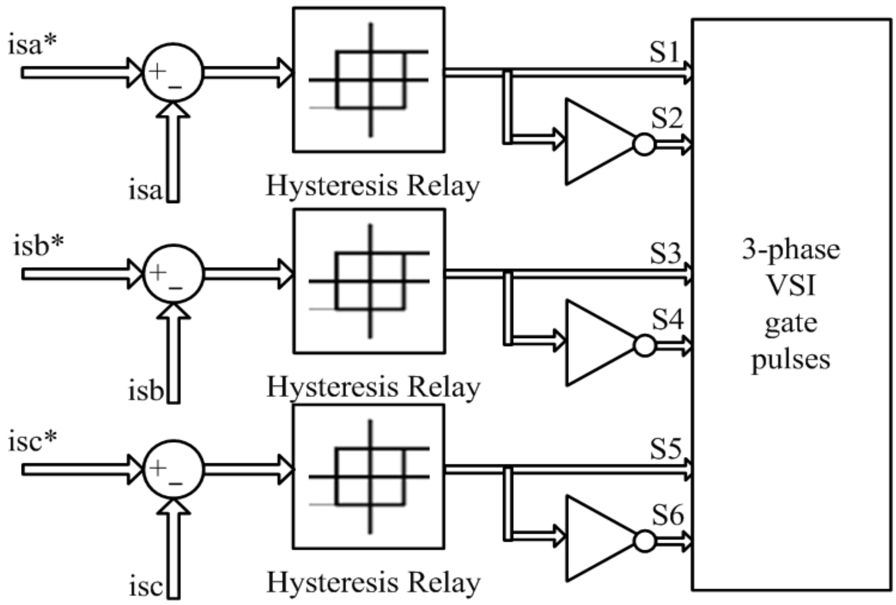


Fig. 3.6 Hysteresis current controller

Hysteresis current control is invented by Brod and Novotny in the year 1985. Fig. 3.6 shows the hysteresis current controller used for comparing reference current with its actual current, it creates the appropriate switching pulses for the inverter. In the relay, an upper and lower limit will be defined. These restrictions determine whether the relay is on or off. The relay is triggered when the actual quantity differs from the reference value and exceeds specified limits. As a result, the current is kept within the relay-set hysteresis band, where, i_{sa}^*, i_{sb}^*, i_{sc}^* represent the reference source currents and i_{sa}, i_{sb}, i_{sc} represent the actual source currents.

3.6 Simulation Results

In this section dynamic performance of the shunt APF will be investigated for the THD content in source current; power flow of source, load and shunt APF and analysis of capacitor dc-link voltage when system is connected to nonlinear load. The performance is evaluated based on three control methods which are discussed in the previous sections. Below Fig. 3.7 shows the MATLAB simulation diagram of Shunt APF. Parameters used for the simulation is given in Table 3.1 and 3.2

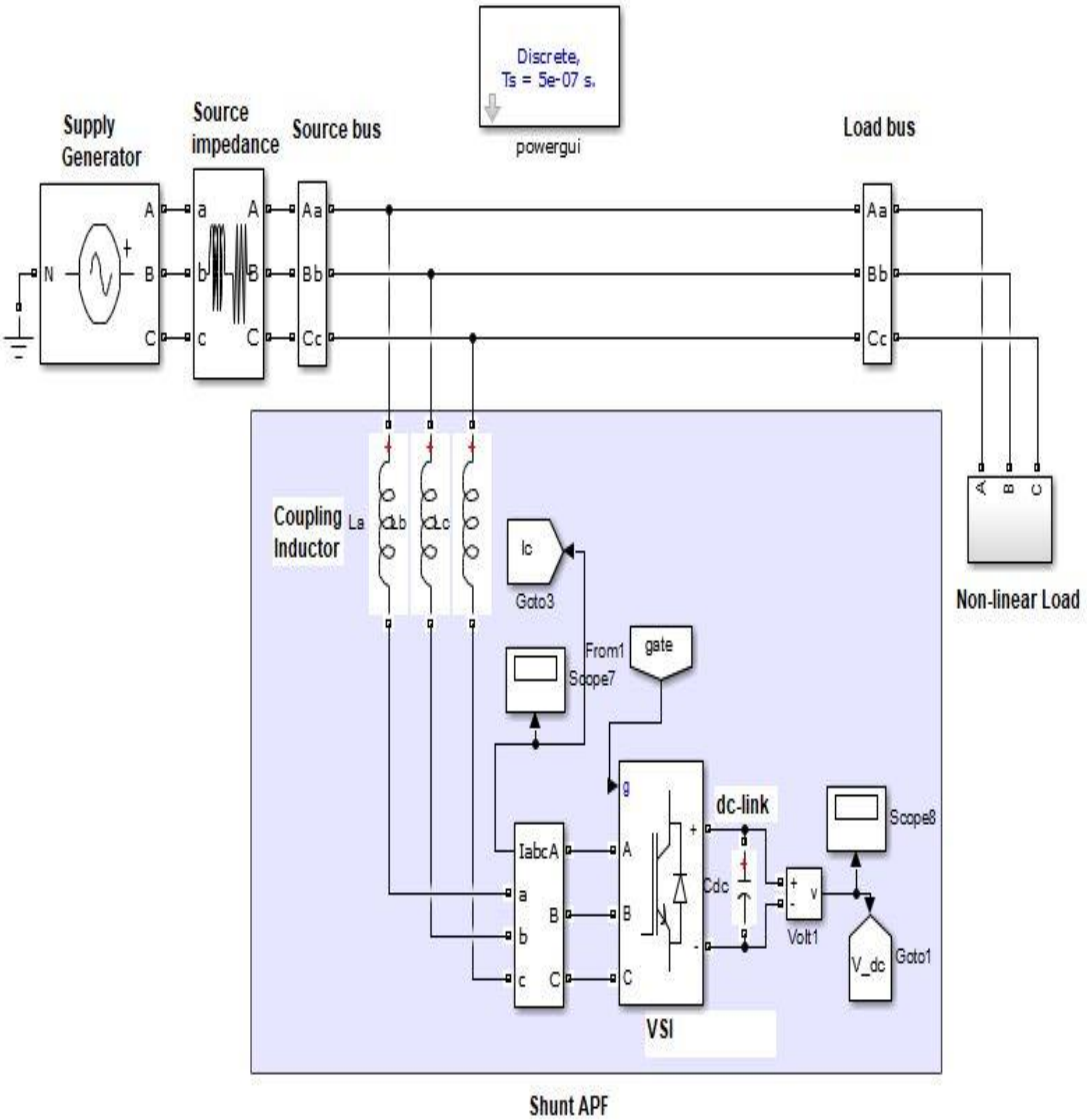


Fig. 3.7 MATLAB simulation model for Shunt APF connected to distribution system

Table 3.1: Parameters and values for the shunt APF Matlab simulation

Parameters		**Values**
Source	Voltage	110V RMS
	Frequency	50Hz
	Resistance and inductance	0.1mΩ ; 1µH
Shunt APF	Coupling inductance	0.5mH
	dc-link capacitor	1600µF
	dc-link voltage	200V
Load	Rectifier RL load	50Ω ; 90mH

Table 3.2: Parameters for PI controller

PI Controller Value	**K_P**	**K_I**
UVT	0.12	2.9
SRF	0.24	0.4
IPT	1	16

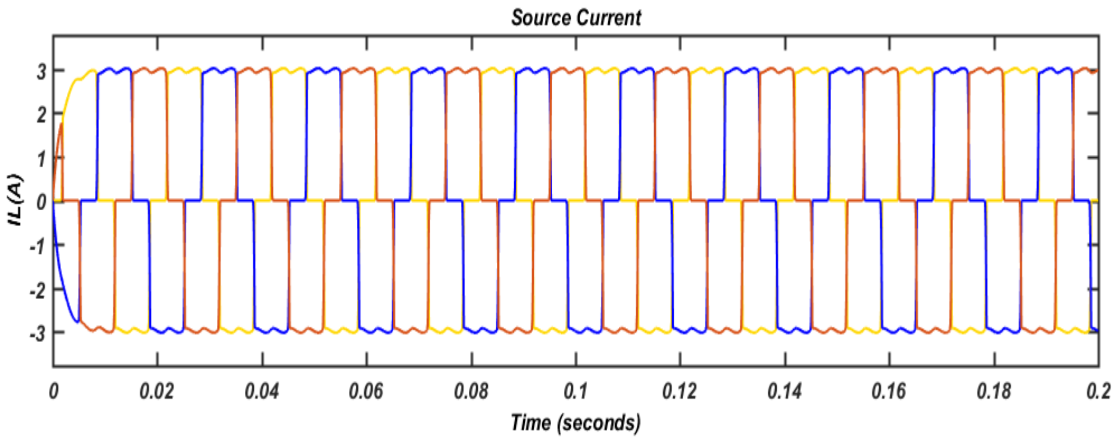


Fig. 3.8 Source current before compensation

Fig. 3.8 shows the source current having harmonics of order 5th, 7th ,11th , and higher order but 5th and 7th order harmonics are more dominant and thereby, affects the distribution system performance. These current harmonics not only affects the distribution system performance but also affects the nearby loads and sources as well.

The below Fig. 3.9 shows the source and load voltage. It is free from harmonics as nonlinear load affects the current waveform only.

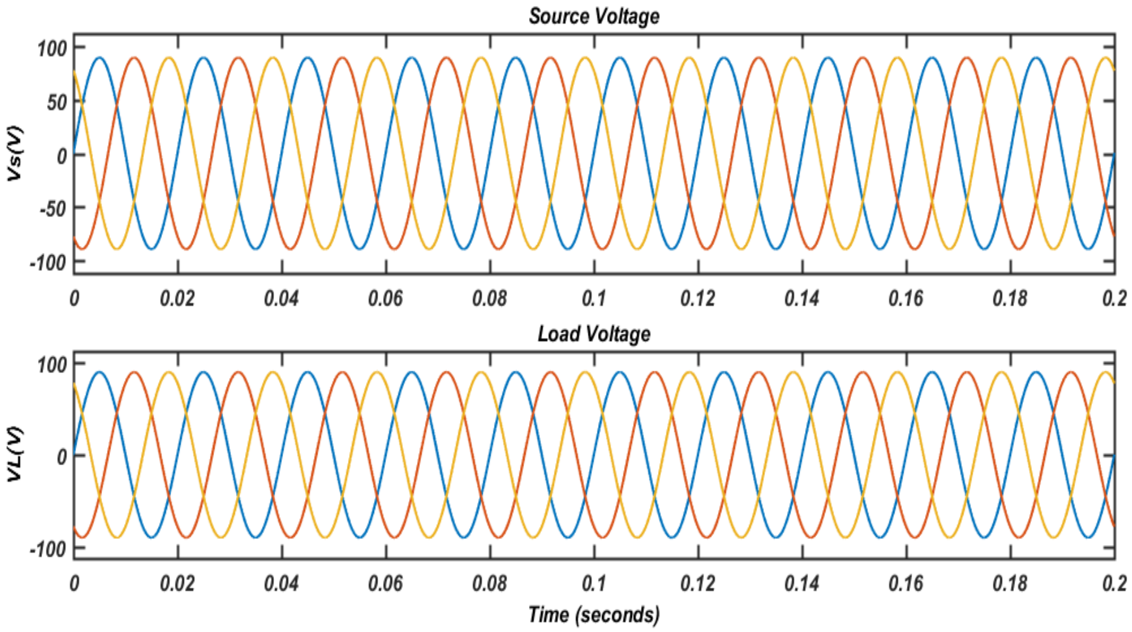


Fig. 3.9 Source and load voltage

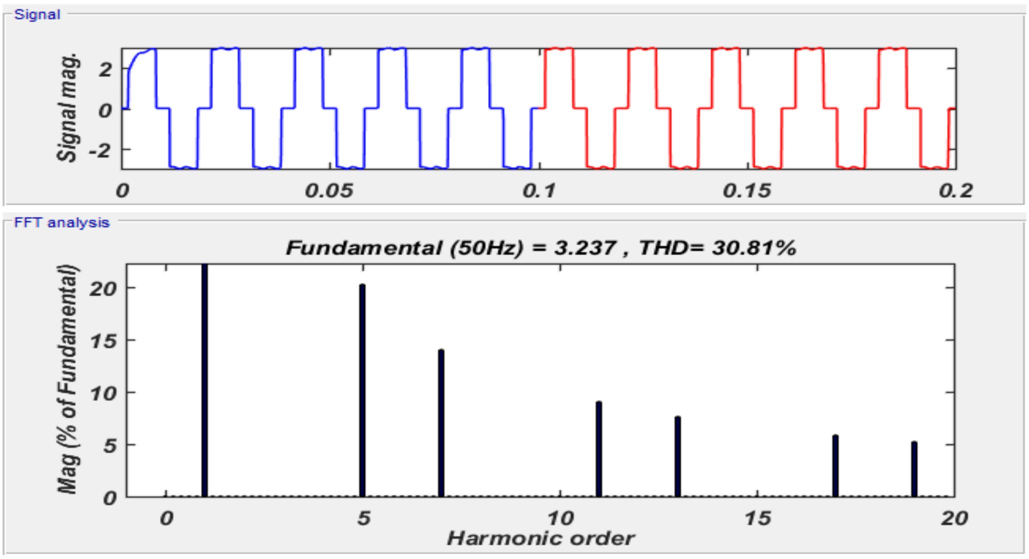


Fig. 3.10 THD in source current before compensation

Fig. 3.10 shows the THD content in source current without compensation and the value of THD is 30.81% >5% i.e. more than IEEE prescribed standards. Therefore some compensation techniques should be used in order to reduce the harmonics in the source current. In the next subsequent sections compensation results for UVT, IPT, SRF method are discussed.

3.6.1 UVT method Controlled Shunt APF

In this section dynamic performance of shunt APF controlled using UVT method is evaluated.

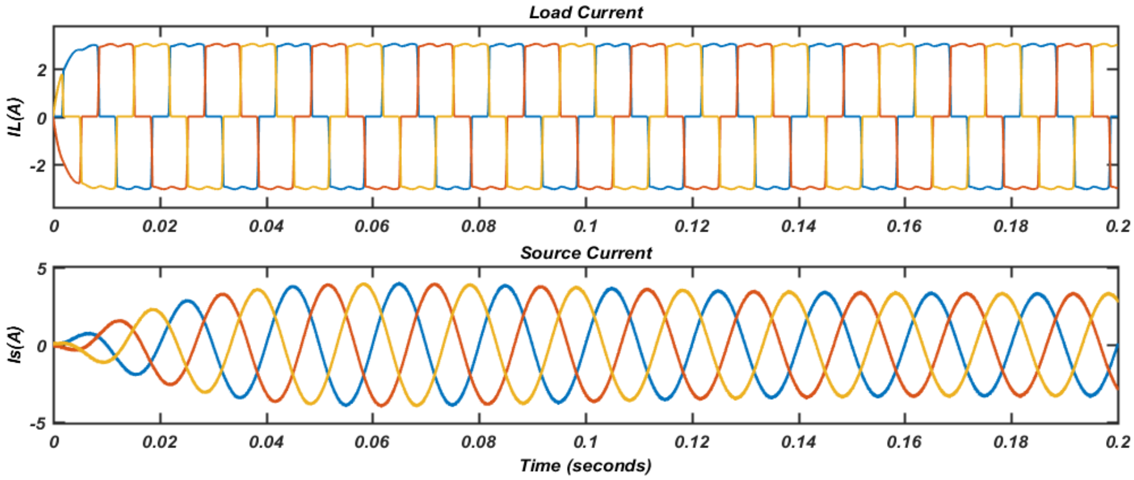


Fig. 3.11 (a) Load current and, (b) Source current after compensation using UVT method controlled shunt APF

Fig. 3.11(a) shows the load current with harmonics as nonlinear load is connected to load bus. As a result harmonics are introduced in the system. To, get pure sinusoidal source current as shown in Fig. 3.11(b) shunt APF is connected at PCC which will examine and provides the compensating harmonic current shown in Fig. 3.12(a) and reactive power demand as shown in fig. of the load. During, the compensation process capacitor dc-link voltage as shown in Fig. 3.12(b) is maintained constant to 200V by using a suitable PI controller.

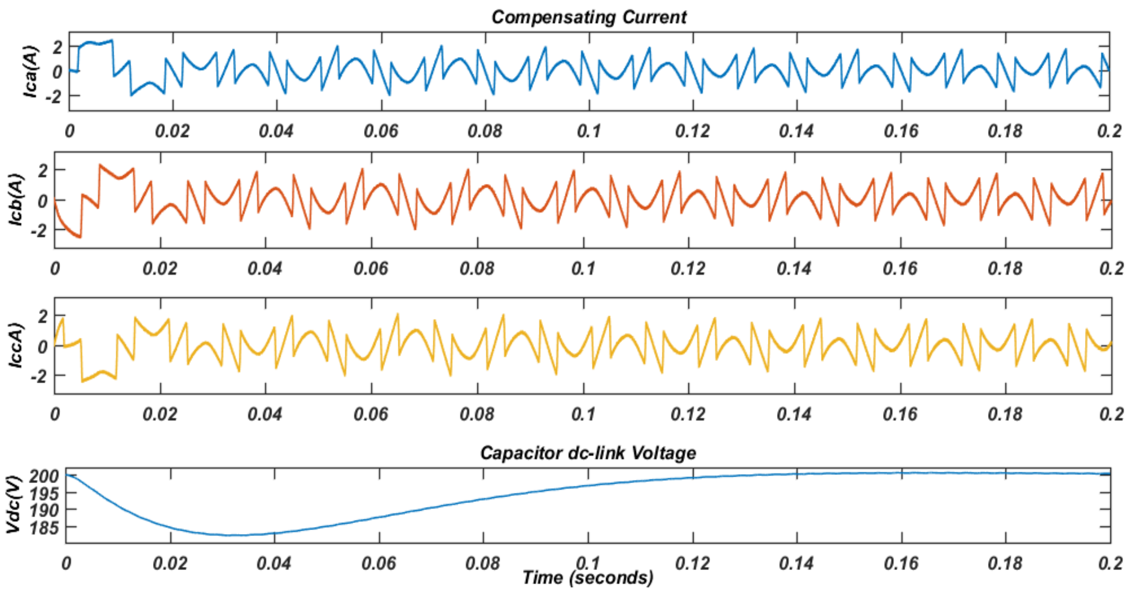


Fig. 3.12 (a) Compensating current and, (b) Capacitor dc-link voltage for UVT method controlled shunt APF

After the compensation the magnitude of source current is 3.27A and THD is reduced to 2% from 30.81% as shown in Fig. 3.13

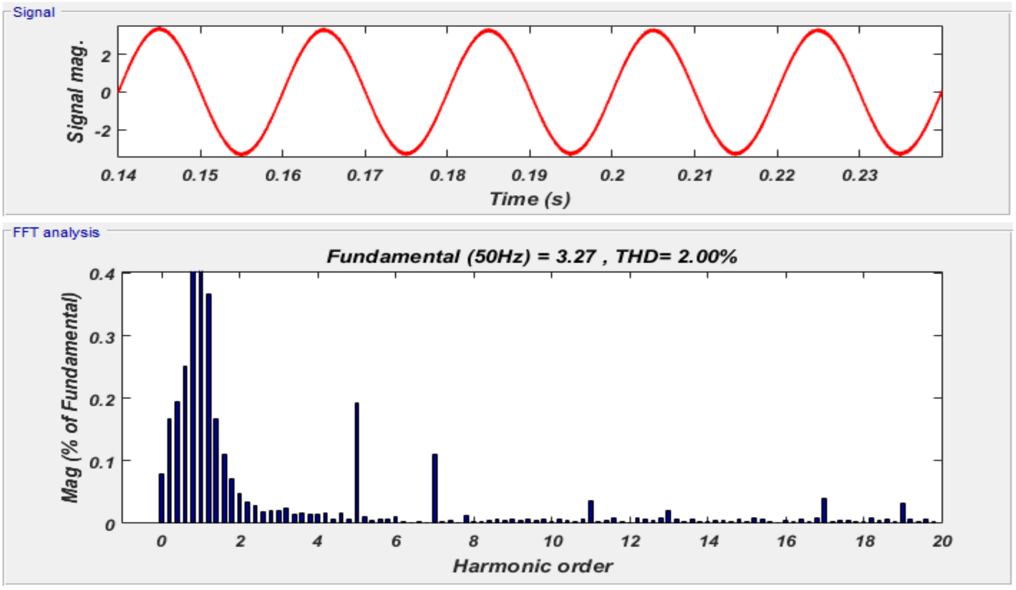


Fig. 3.13 THD in source current after compensation for UVT method controlled shunt APF

During the compensation process the active power demand (439.60W) of the load is supplied by the source whereas, reactive power demand (128.77VAR) is provided by shunt APF. Therefore the system power factor is maintained near to unity i.e.0.99. At the same time a small amount of real power is absorbed by the shunt APF to compensate the switching losses of the converter. Fig. 3.14 shows the active& reactive power flow of the source, shunt APF and load.

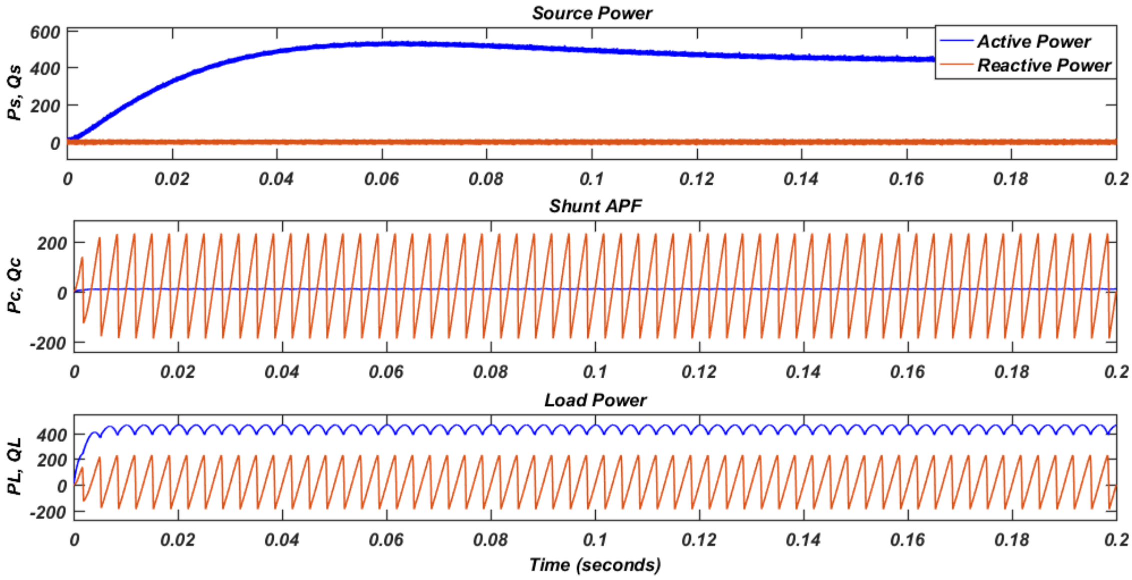


Fig. 3.14 Active & Reactive power flow of source, shunt APF and load for UVT method controlled shunt APF

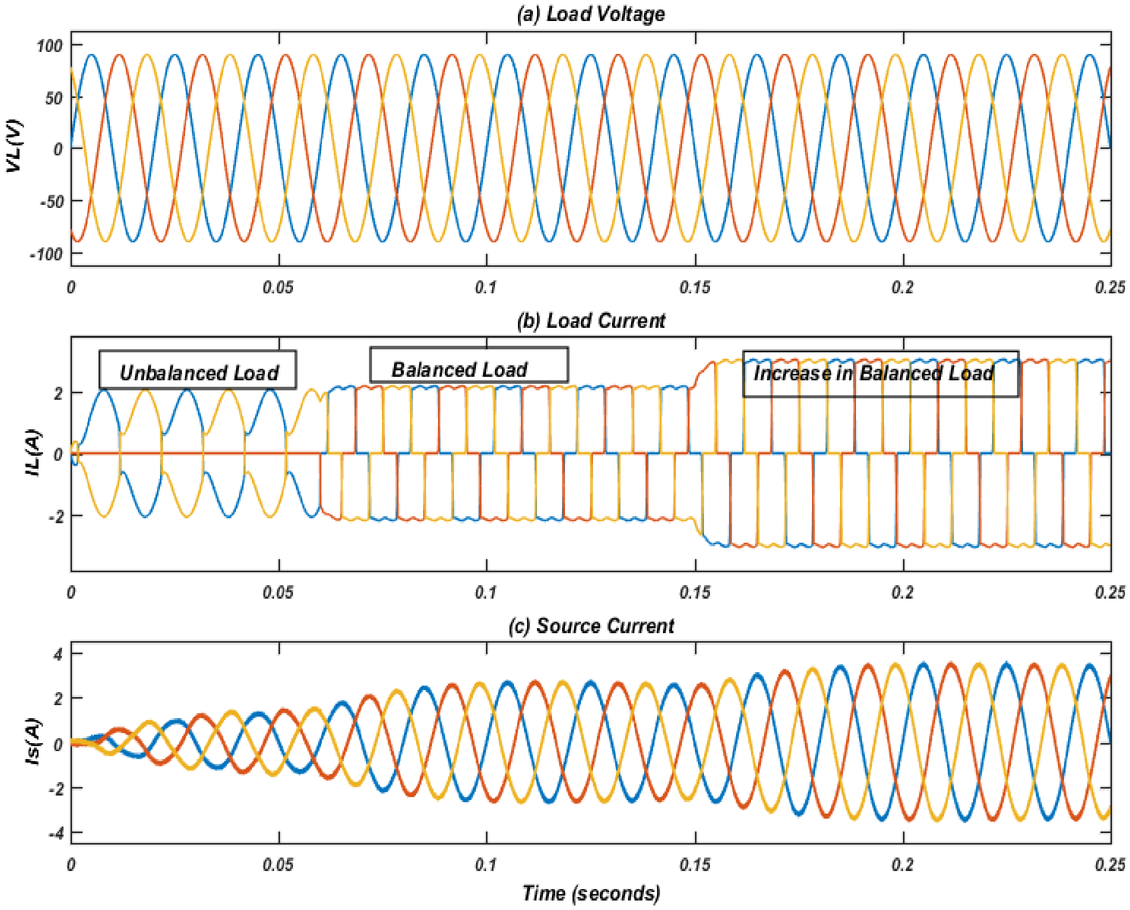


Fig. 3.15 (a) Load Voltage, (b) Load Current and, (c) Source Current under different load dynamics for UVT controlled shunt APF

Fig. 3.15(a) shows the load voltage that remains balanced, Fig. 3.15(b) shows the nonlinear load current and, Fig. 3.15(c) presents the linear unbalanced source current during different load dynamics i.e. for unbalanced load, balanced load and, increase in balance load for time interval of 0-0.06s ,0.06s-0.15s ad, 0.15s-0.2s respectively.

3.6.2 SRF Theory Controlled Shunt APF

In this section dynamic performance of shunt APF controlled using SRF method is evaluated.

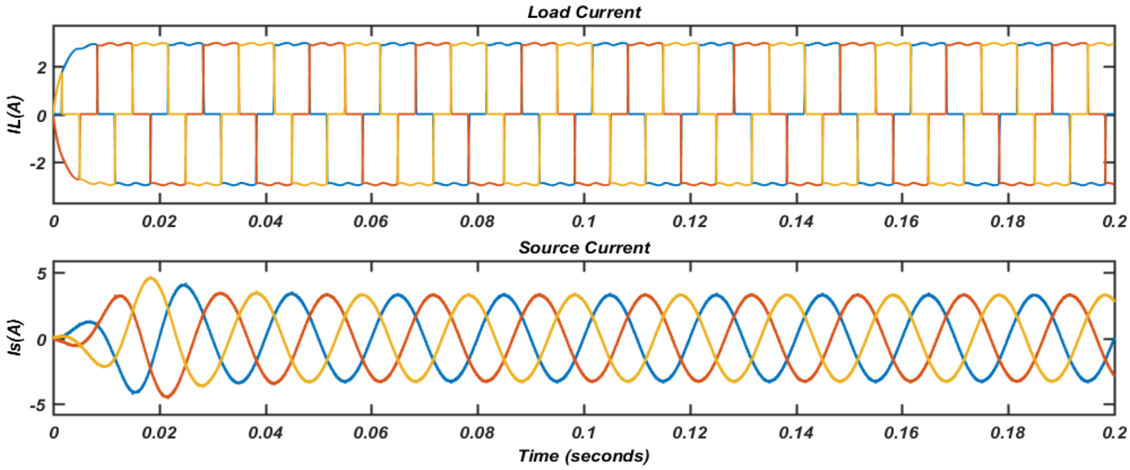


Fig. 3.16 (a) Load current and, (b) source current after compensation for SRF theory based controlled shunt APF

The Fig. 3.16(a) shows the nonlinear load current as it contains the harmonics and the harmonic current demand before the compensation is provided by the source. Due to this harmonics are introduced in source current which affects the system performance. When shunt APF is connected at PCC the harmonic current demand as shown in Fig. 3.17(a) and reactive power demand of the load is provided by the converter of the shunt APF. As, a result source will supply pure sinusoidal current as shown in Fig. 3.16(b)

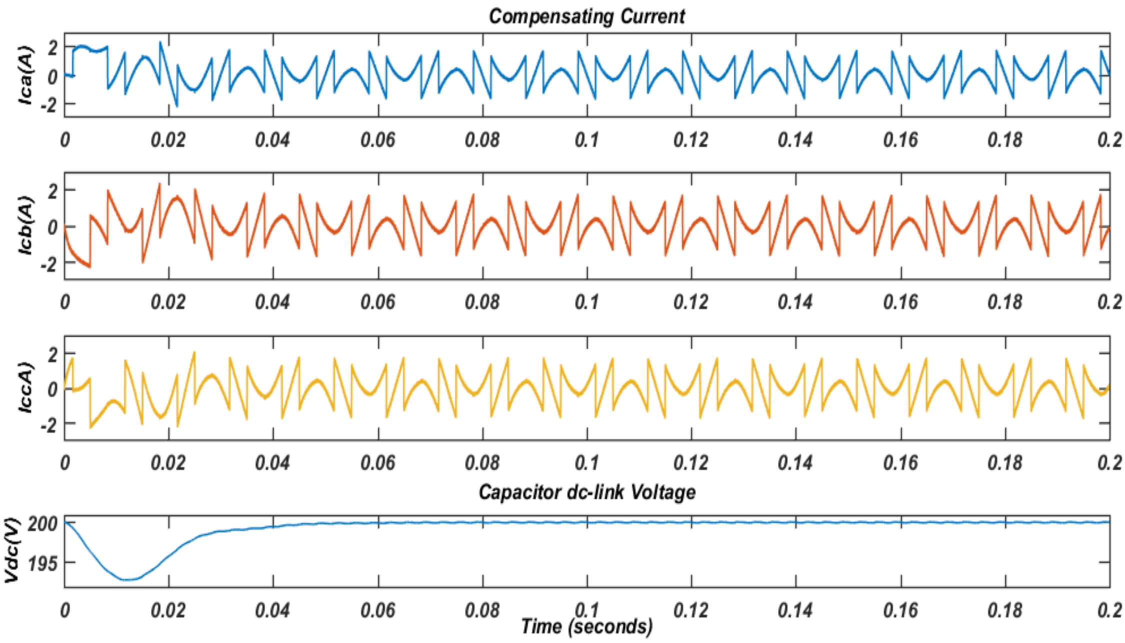


Fig. 3.17 (a) Compensating current and, (b) Capacitor dc-link voltage for SRF theory controlled shunt APF

The capacitor dc-link voltage is maintained to 200V as shown in Fig. 3.17(b) with the help of a suitable PI voltage controller. After the compensation the waveform of source current become pure sinusoidal and, having magnitude of 3.245A and THD is reduced to 1.99% from 30.81% as shown in Fig. 3.18

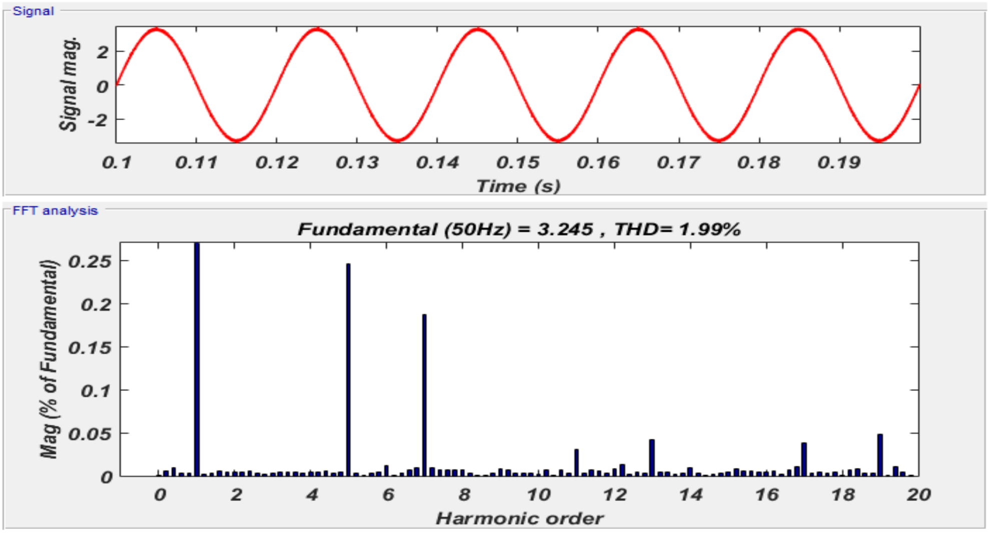


Fig. 3.18 THD in source current after compensation for SRF theory controlled shunt APF

During the compensation process the active power demand (436.50W) of the load is supplied by the source whereas, reactive power demand (132.80VAR) is provided by shunt APF. Therefore the system power factor is maintained near to unity i.e.0.99. At the same time small amount of real power is absorbed by the shunt APF to compensate the switching losses of the converter. Fig. 3.19 shows the active& reactive power flow of the source, shunt APF and load

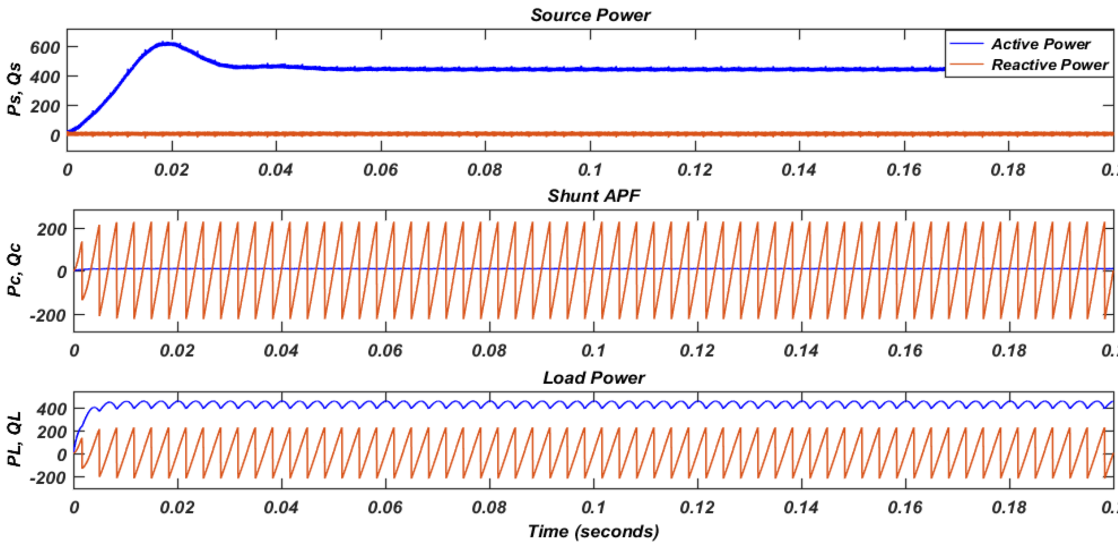


Fig. 3.19 Active & Reactive power of source, shunt APF and, load for SRF theory controlled shunt APF

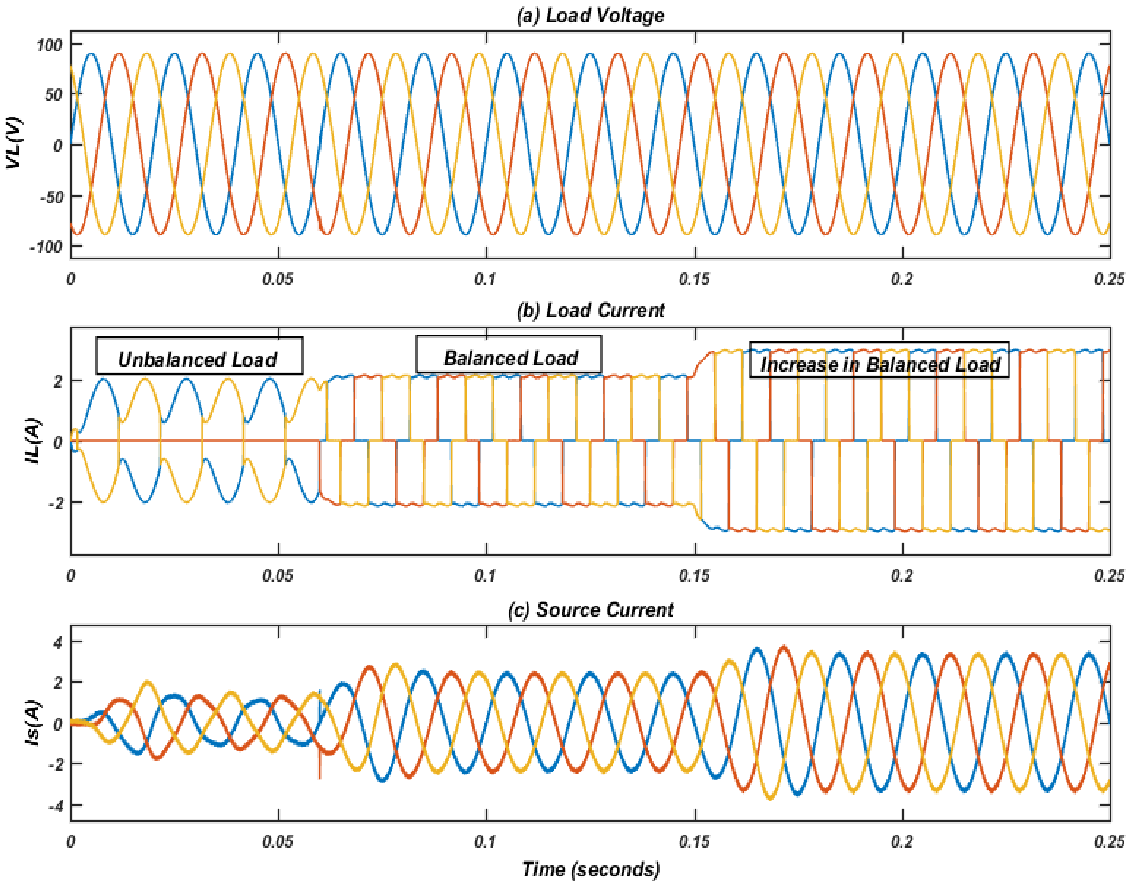


Fig. 3.20 (a) Load Voltage, (b) Load Current and, (c) Source Current under different load dynamics for SRF controlled shunt APF

Fig. 3.20(a) shows the load voltage that remains balanced, Fig. 3.20(b) shows the nonlinear load current and, Fig. 3.20(c) presents the linear unbalanced source current during different load dynamics i.e. for unbalanced load, balanced load and, increase in balance load for time interval of 0-0.06s ,0.06s-0.15s ad, 0.15s-0.2s respectively.

3.6.3 IP-Theory based Shunt APF

In this section dynamic performance of shunt APF controlled using SRF method is evaluated. Fig. 3.21(a) shows the load current having harmonics and before connecting the shunt APF harmonic current along with fundamental component of current. As a result performance of the system is affected.

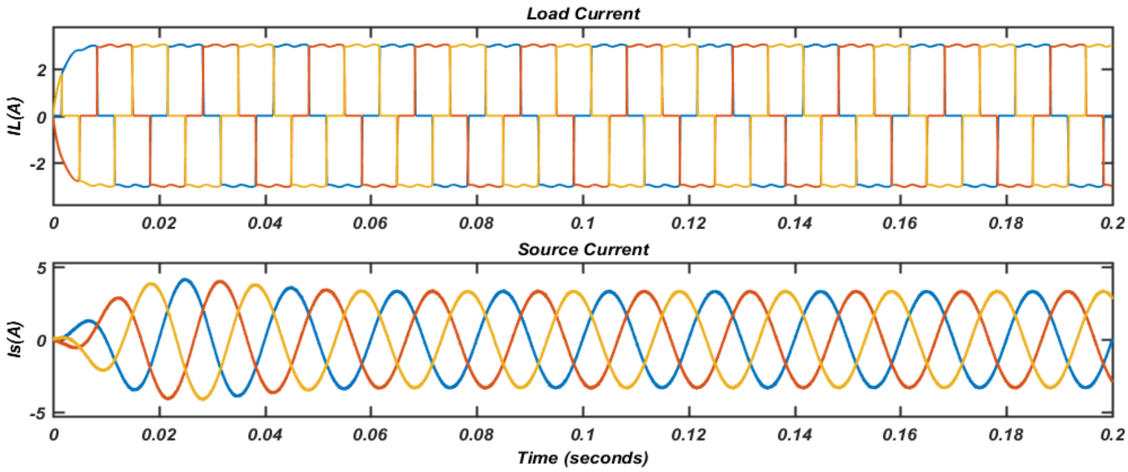


Fig. 3.21 (a) Load current and, (b) source current after compensation for IPT controlled shunt APF

When shunt APF is connected at PCC. It will examine and provides the harmonic current shown in Fig. 3.22(a) and reactive power demand as shown in Fig. 3.21 of the load. The compensated source current is shown in Fig. 3.21(b) and capacitor dc-link voltage is maintained constant to 200V by using a suitable PI controller as shown in Fig. 3.22(b)

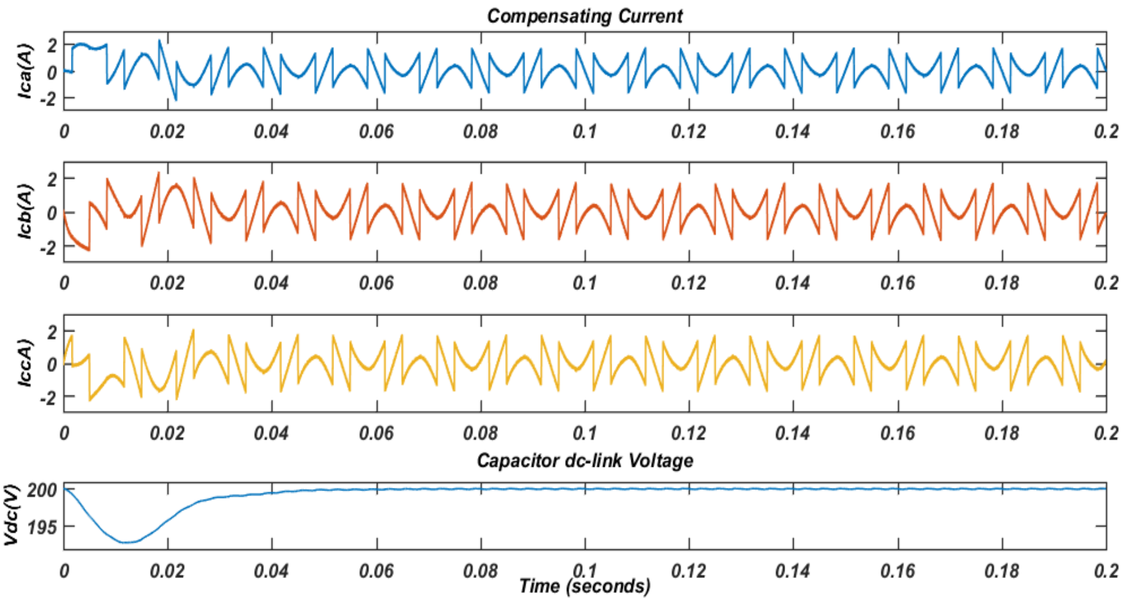


Fig. 3.22 (a) Compensating current and, (b) Capacitor dc-link voltage for IPT controlled shunt APF

After the compensation the waveform of source current become pure sinusoidal, having magnitude of 3.29A and THD is reduced to 1.88% from 30.81% as shown in Fig. 3.23

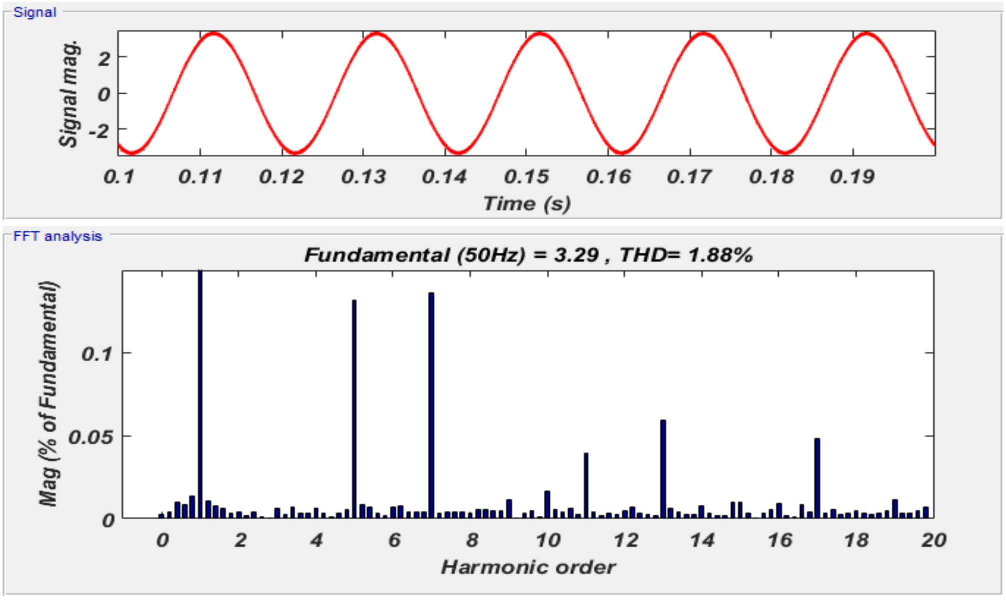


Fig. 3.23 THD in source current after compensation for IPT controlled shunt APF

Fig. 3.24 shows the active & reactive power flow of source, shunt APF and load during the compensation process. The active power demand (442.40W) of the load is supplied by the source whereas, reactive power demand (134.46VAR) is provided by shunt APF. Therefore the system power factor is maintained near to unity i.e.0.99

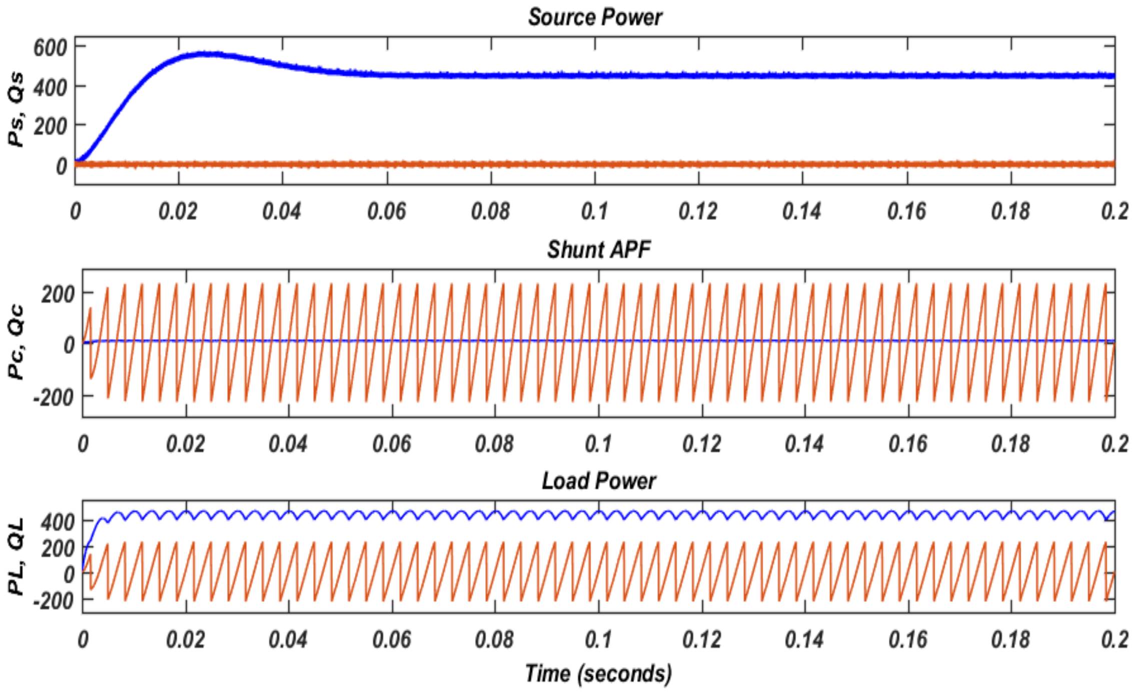


Fig. 3.24 Active & Reactive power of source, shunt APF and, load for IPT controlled shunt APF

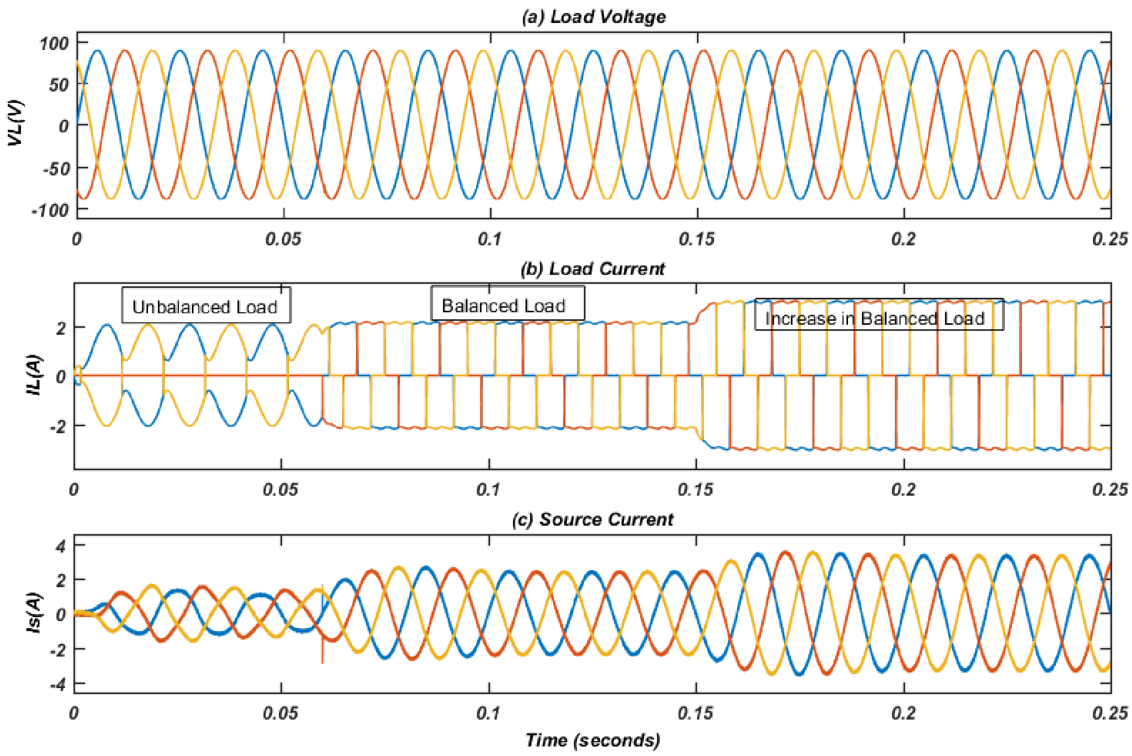


Fig. 3.25 (a) Load Voltage, (b) Load Current and, (c) Source Current under different load dynamics for IPT controlled shunt APF

Fig. 3.25(a) shows the load voltage that remains balanced, Fig. 3.25(b) shows the nonlinear load current and, Fig. 3.25(c) presents the linear unbalanced source current during different load dynamics i.e. for unbalanced load, balanced load and, increase in balance load for time interval of 0-0.06s ,0.06s-0.15s ad, 0.15s-0.2s respectively.

3.6.4 Comparison of Results

Fig. 3.26 below shows the comparison of capacitor dc-link voltage for UVT, SRF, PQ theory based controlled shunt APF. It is observed that for the same parameters of the system SRF based control have faster response over the UVT and IP-theory based control.

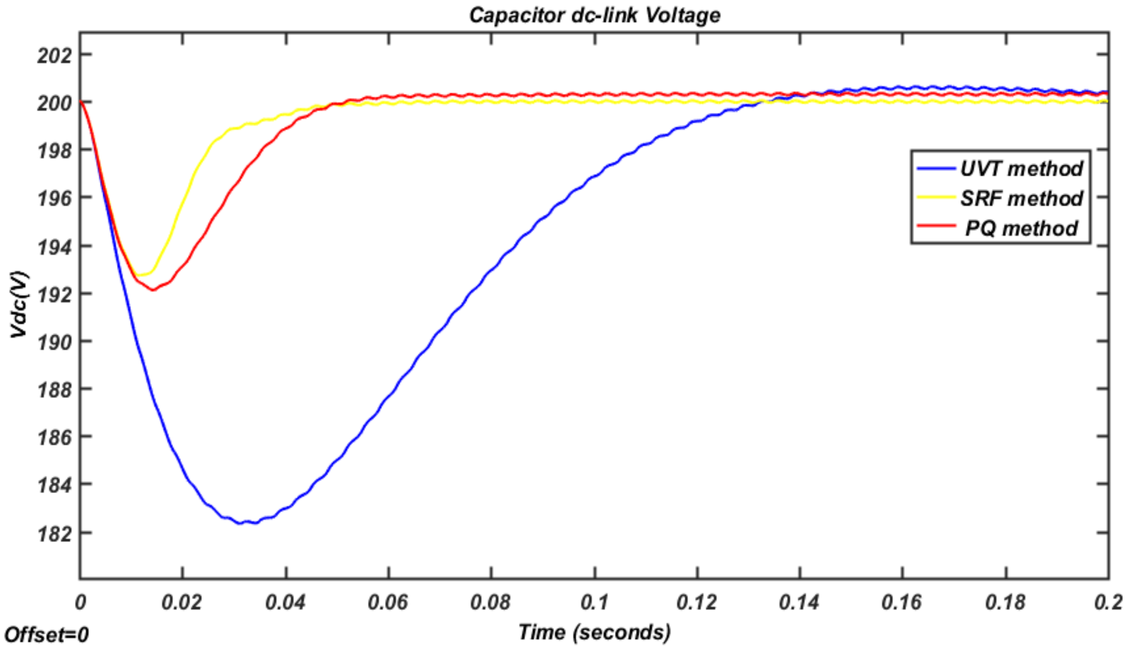


Fig. 3.26 Capacitor dc-link voltage for UVT, SRF and IPT controlled shunt APF

Table 3.3 shows the comparison of power flow of source, shunt APF and load and Table 3.4 shows the comparison of source current magnitude and %THD content before and after the compensation based on UVT, SRF and PQ theory based controlled shunt APF.

Table 3.3: Power flow of source, shunt APF and load

Parameter	Power supplied by the source		Shunt APF power flow		Power absorbed by the Load	
	Active power, Ps(W)	Reactive power, Qs(VAR)	Active power, Psh(W)	Reactive power, Qsh(VAR)	Active power, PL(W)	Reactive power, QL(VAR)
UVT	440.45	6.71	0.85	122.06	439.60	128.77
SRF	437.35	6.70	0.85	126.10	436.50	132.80
IPT	443.15	5.89	0.75	128.57	442.40	134.46

Table 3.4: THD in source current before and after compensation

Parameter	Source current Without compensation		Source current With compensation	
	Magnitude(A)	THD(in %)	Magnitude(A)	THD(in %)
UVT	3.237	30.81	3.27	2.00
SRF	3.237	30.81	3.24	1.99
IPT	3.237	30.81	3.29	1.88

Fig. 3.27(a) shows the extracted fundamental current component I_m^* which is multiplied with UVT u_a, u_b, u_c to get fundamental reference source current, this I_m^* is the output of PI-controller, while Fig. 3.27(b) presents the dc-link voltage during load change dynamics from unbalanced to balanced, increase in balanced load for time interval of 0-0.06s, 0.06s-0.15s and 0.15s-0.25s respectively for UVT method.

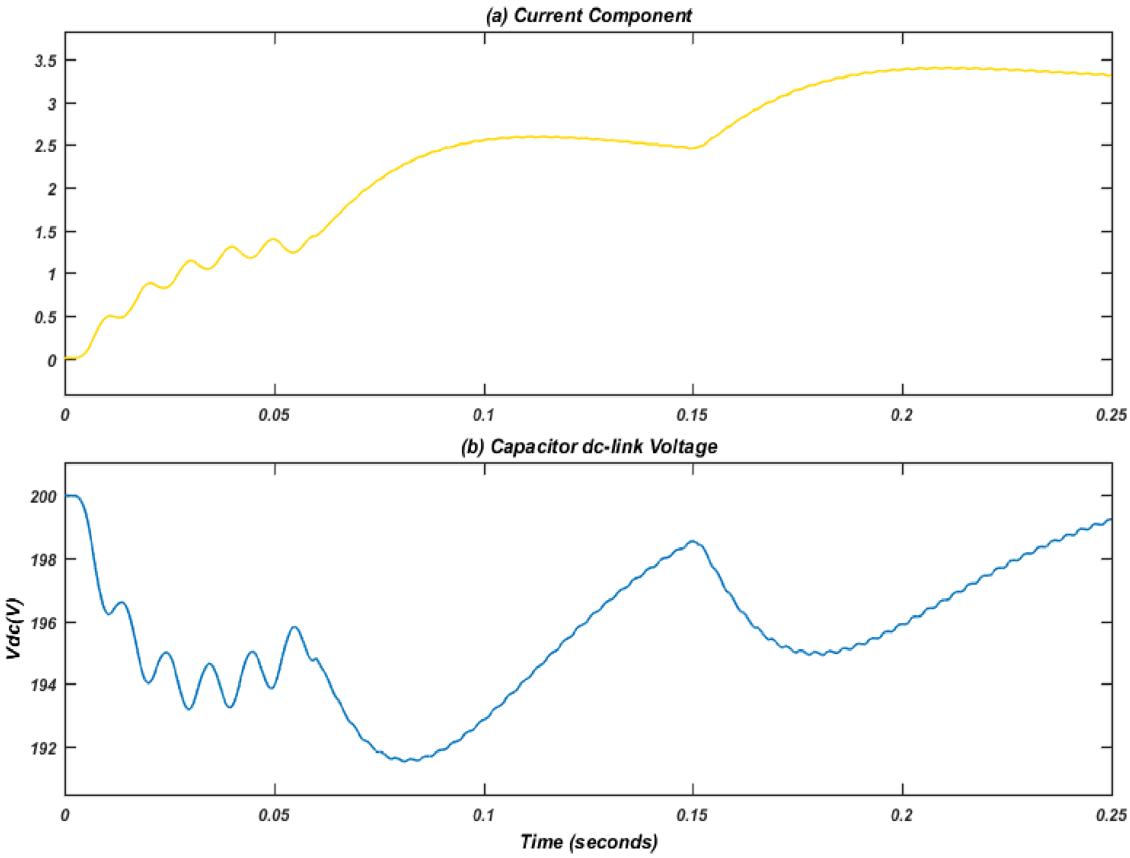


Fig. 3.27 (a) Extracted Current Component and, (b) dc-link Voltage under load change dynamics for UVT controlled shunt APF

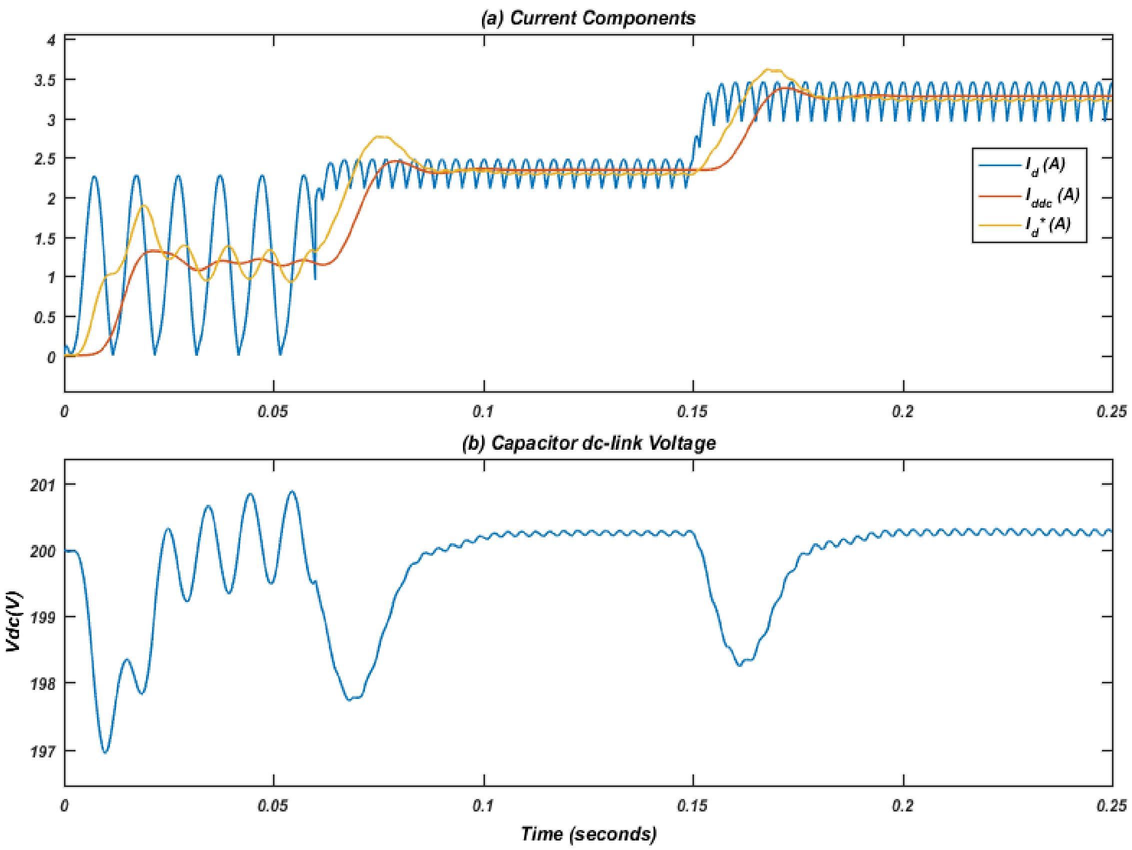


Fig. 3.28 (a) Extracted Current Components and, (b) dc-link Voltage under load change dynamics for SRF controlled shunt APF

During the load change dynamics i.e. sudden change in load from unbalanced to balanced and increase in balanced load for time interval of 0-0.06s, 0.06s-0.15s, 0.15s-0.25s respectively. **Fig. 3.28(a)** ***shows the extracted d-axis current component*** $\boldsymbol{i_d}$ ***before filter denoted by blue legend, fundamental extracted current component*** $\boldsymbol{i_{d\_dc}}$ ***after filter circuit denoted by red legend i.e. LPF and, d-axis reference source current component*** $\boldsymbol{i_d^*}$ ***(*** $\boldsymbol{i_d^* = i_{d\_dc} - i_{dloss}}$ ***) denoted by yellow legend,*** is used to drive the fundamental reference source current in abc coordinates and, Fig. 3.28(b) shows the capacitor dc-link voltage for SRF theory controlled shunt APF.

For IPT controlled shunt APF, **Fig. 3.29(a)** ***shows the extracted power component*** $\boldsymbol{P\ (W)}$ ***of source which contains both AC and DC component denoted by blue legend, desired fundamental active power component*** $\boldsymbol{P_{dc}\ (W)}$ ***after filtering circuit (LPF) denoted by red legend and, the compensated desired reference fundamental active power component (*** $\boldsymbol{P_c = P_{dc} - P_{loss}}$ ***) is denoted by yellow legend ,*** is used to generate reference fundamental source current and, Fig. 3.29(b) shows the dc-link voltage during load change dynamics from unbalanced to balanced , increase in balanced load for time interval of 0-0.06s, 0.06s-0.15s and 0.15s-0.25s respectively.

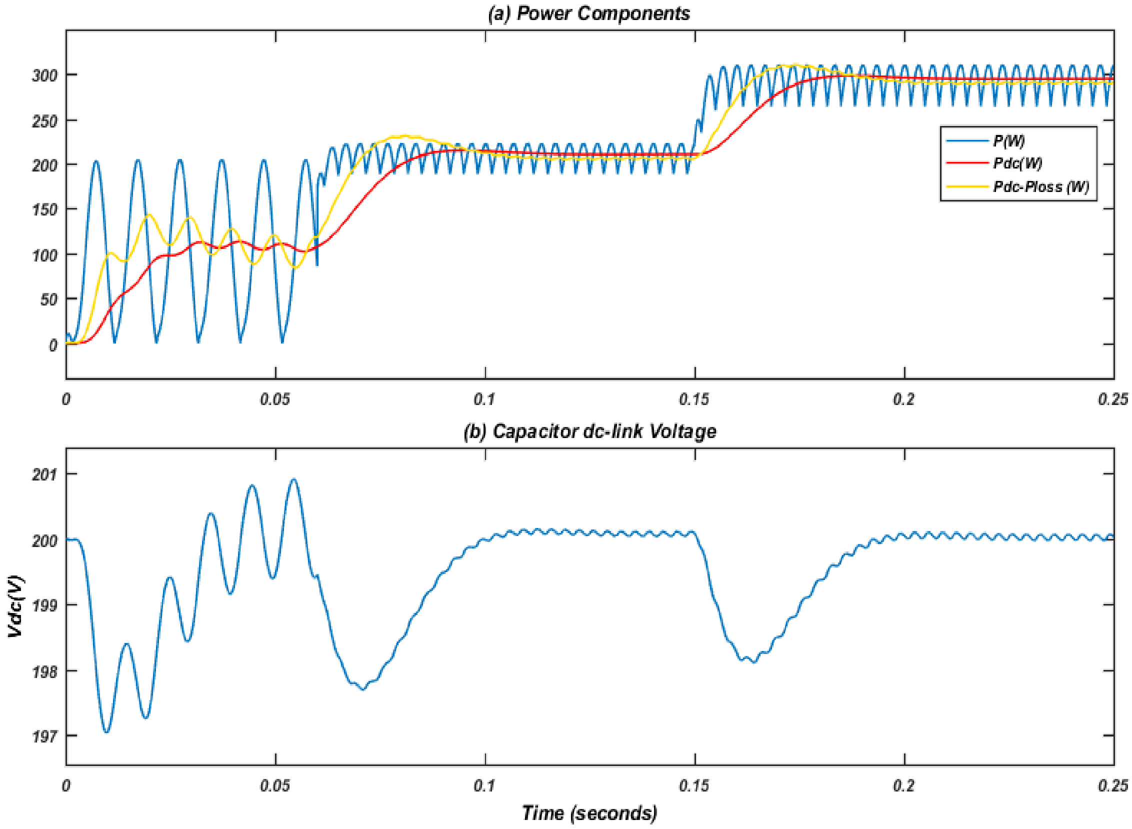


Fig. 3.29 (a) Extracted Power Components and, (b) dc-link Voltage under load change dynamics for IPT controlled shunt APF

Table 3.5 presents the comparative analysis of fundamental quantity required to generate reference source current using UVT method, SRF theory and, IP-theory.

Table 3.5: Comparison of fundamental component required to generate reference source current

Method	**Components required to generate reference source current** $i^*_{sa}, i^*_{sb}, i^*_{sc}$
UVT	Output of PI-controller $I_m{}^*$
SRF	Extracted current components i_d, i_{d_dc}(fundamental) and, i^*_d
IPT	Extracted active power components P, P_{dc} (fundamental) and, P_c

3.7 Conclusions

- UVT, SRF, and IPT controlled shunt APF reduces the THD in source current to an acceptable level i.e. 2%, 1.99%, and 1.88% respectively shown in Table 3.4.
- After connecting shunt APF to the distribution system nearly entire reactive power demand of the load is supplied by the shunt APF, whereas source will supply only active power demand. Thereby maintains the supply utility's unity power factor.
- SRF theory controlled shunt APF have smallest rise time, settling time and peak undershoot to reach the 100% of dc-link voltage i.e. 200V to achieve the steady state as shown in Fig. 3.26.
- To extract the reference source current using UVT method, SRF theory and, IP-theory the fundamental quantities i.e. PI-controller output current I_m^*, current component i_{d_dc}(fundamental),i_d^* and, power component P_{dc} (fundamental), P_c is used respectively as shown in Table 3.5.

CHAPTER 4
SERIES ACTIVE POWER FILTERS

4.1 Overview

A series APF is a custom device used in transmission & distribution system to balance the voltage at consumers end in three-phase system. It compensates supply voltage sag/swell and unbalance by injecting voltage in phase at the point of common coupling (PCC).Series APF consists of three leg voltage source inverter (VSI) with IGBT and are connected in series between supply and load terminals by three-phase series transformer of 1:1 turns ratio. A small RC filter is connected across the secondary of transformer to eliminate high switching ripple content in injecting voltage Fig. 4.1 shows the series APF connected to distribution system. This device is used to examine unbalance, sag and swell in load voltage and inject the three-phase compensating voltage. Series APF used in this chapter is of battery supported and, the gating signal for the inverter to generate compensating voltage is provided by using hysteresis voltage controller.

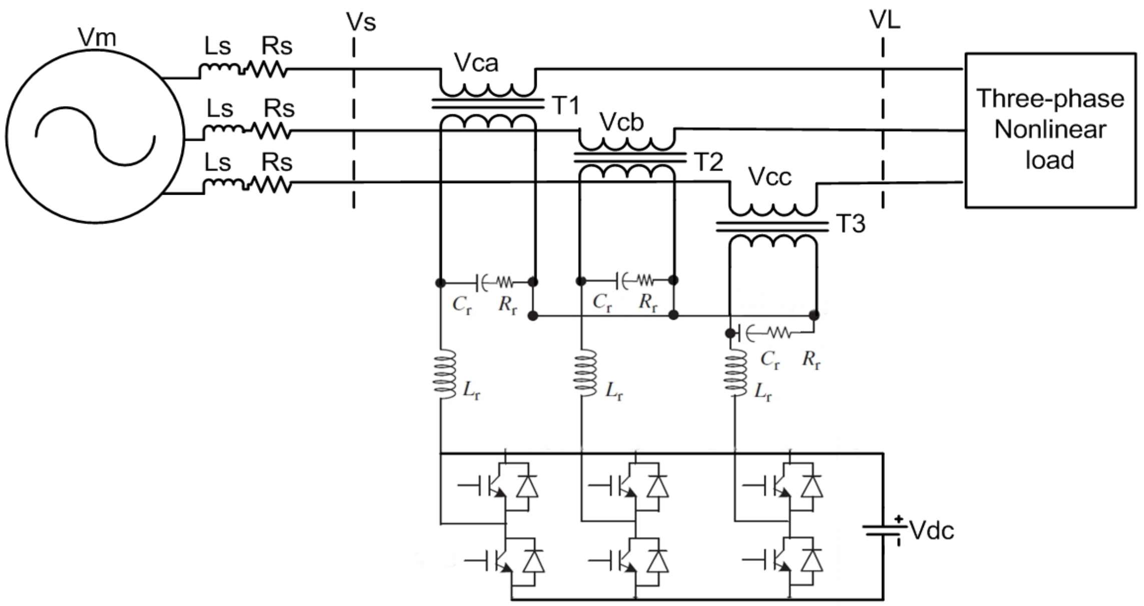


Fig. 4.1 Series APF connected to distribution system

4.2 Reference Voltage Generation Methods

In this section the reference compensating voltage is generated by using two methods;

i. Unit Vector Template (UVT) Generation method and,

ii. Synchronous Reference Frame (SRF) Theory

4.2.1 Unit Vector Template Generation Method

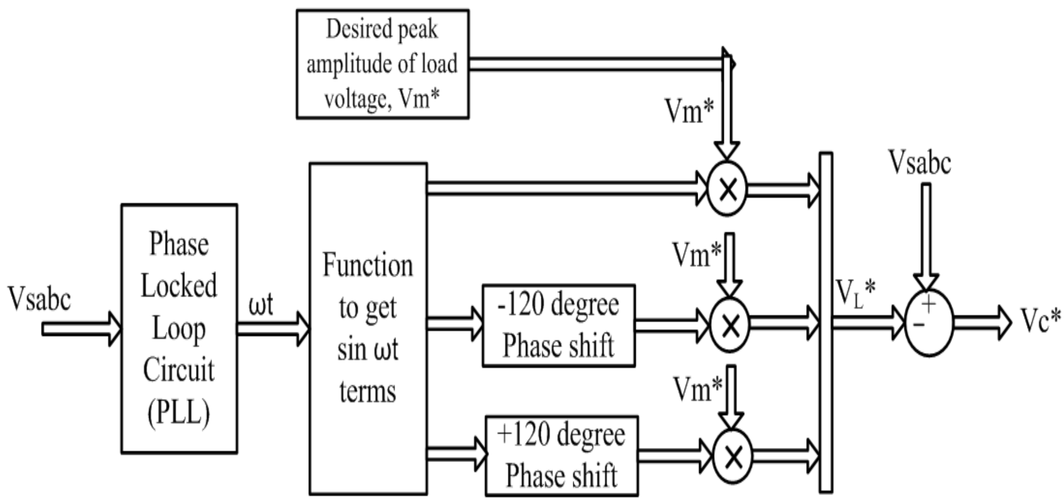


Fig. 4.2 Control scheme of series APF using UVT method

This is one the simplest method used to generate reference compensating voltage. In this method unit vector template signals are generated by synchronizing with source voltage. Fig. 4.2 illustrates the control scheme of series APF using UVT method. In this method first source voltage V_{sabc} is sensed and given to phase-locked loop (PLL) circuit to generate the synchronized unit signal. This unit signal is then, multiplied with $\sin(\omega t)$ function to generate the three-phase unit vector template and it is given in equation (4.1) to (4.3)

$$u_a = 1\sin(\omega t) \tag{4.1}$$

$$u_b = 1\sin(\omega t - \frac{2\pi}{3}) \tag{4.2}$$

$$u_c = 1\sin(\omega t + \frac{2\pi}{3}) \tag{4.3}$$

The calculation of reference load voltage Vm* magnitude is done by using (4.4)

$$V_m^* = \sqrt{\frac{2}{3}} \times (desired\ RMS\ value\ of\ load\ voltage) \tag{4.4}$$

This V_m^* is then multiplied with unit vector templates u_a, u_b, u_c

$$V_{La}^{*} = V_m^{*}\{\sin(\omega t)\} \quad (4.5)$$

$$V_{Lb}^{*} = V_m^{*}\{\sin\left(\omega t - \frac{2\pi}{3}\right)\} \quad (4.6)$$

$$V_{Lc}^{*} = V_m^{*}\{\sin\left(\omega t + \frac{2\pi}{3}\right)\} \quad (4.7)$$

This generated reference load voltage is given by (4.5) to (4.7) is subtracted with sensed source voltage to generate the reference compensating three-phase voltage Vc*.

4.2.2 Synchronous Reference Frame Theory

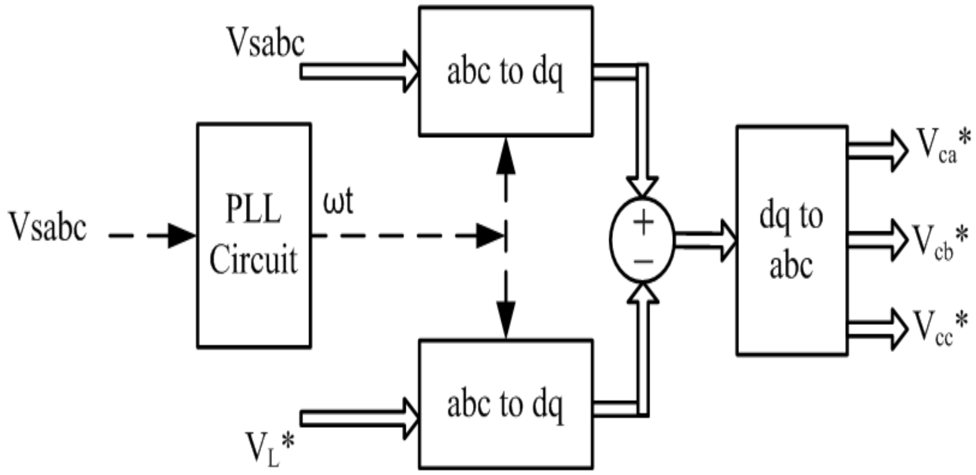


Fig. 4.3 Control scheme of series APF using SRF theory

This method of generating reference compensating voltage deals with Park's transformation i.e. quantities of abc coordinate transformed to dq0 frame. Fig. 4.3 shows control scheme of series APF using SRF theory.

To implement this method source voltageV_{sabc} is sensed and transformed to dq0 frame by using (4.8) and the reference load voltage V_l^{*} is generated in a similar way discussed in previous section 4.2.1. Synchronization of the transformed voltages with source voltage V_{sabc} is done by PLL circuit.

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad (4.8)$$

The transformed source and reference load voltages are subtracted to get compensating voltage in dq-coordinates V_{cd}^{*}, V_{cq}^{*}

By applying the inverse Park's transformation using (4.9) gives the reference compensating voltage i.e. V_{ca}^{*}, V_{cb}^{*}, V_{cc}^{*}.

$$\begin{bmatrix} V_{ca}^* \\ V_{cb}^* \\ V_{cc}^* \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_{cd}^* \\ V_{cq}^* \end{bmatrix} \tag{4.9}$$

4.3 Three-phase VSI for Series APF

In the above discussed series APF battery supported VSI is used. It is connected in series with three-phase series transformer to feed the compensating three-phase voltage at PCC in system. VSI is made up of three legs with current reversible switches that are regulated for open and closure. Controlled switches (IGBT) with anti-parallel diodes are used to implement these switches, allowing free-wheeling currents to flow.

4.4 Control Technique of VSI

The objective of control of VSI is to force the compensating voltage to follow their predefined generated reference compensating voltage. The main approach is based on the comparison of actual compensating voltage with the reference compensating voltage generated by various extraction methods discussed in the previous sections.

4.4.1 Hysteresis Voltage Controller

Hysteresis voltage controller is invented by Brod and Novotny in the year 1985. Fig. 4.4 shows the hysteresis voltage controller which is used to compare reference voltage with its actual voltage. The hysteresis controller creates the appropriate switching pulses for the inverter. In the relay, an upper and lower limit will be defined. These restrictions determine whether the relay is ON or OFF. The relay is triggered when the actual quantity differs from the reference value and exceeds specified limits. As a result, the voltage is kept within the relay-set hysteresis band. Where, V_{ca}^*, V_{cb}^*, V_{cc}^* represents the reference compensating voltage and V_{ca}, V_{cb}, V_{cc} represents the actual compensating voltage generated by the series APF.

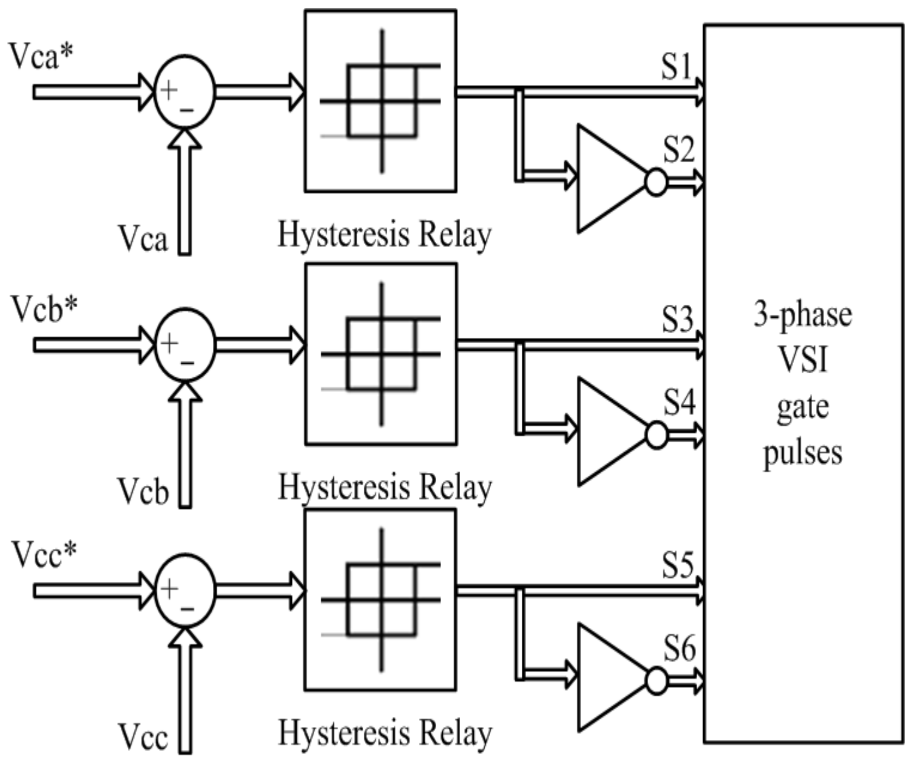


Fig. 4.4 Hysteresis voltage controller

4.5 Simulation Results

In this section dynamic performance of series APF is evaluated for the three-phase sag/swell or unbalance in supply voltage for both UVT and SRF based controlled series APF. Fig. 4.5 shows the MATLAB based simulation model of the series APF connected to a distribution system between source and load terminals. Series APF is connected in series to inject/absorb voltage into/from the system to balance the voltage at consumer ends. For evaluating the performance the sag/swell is given to source side in the MATLAB based simulation.

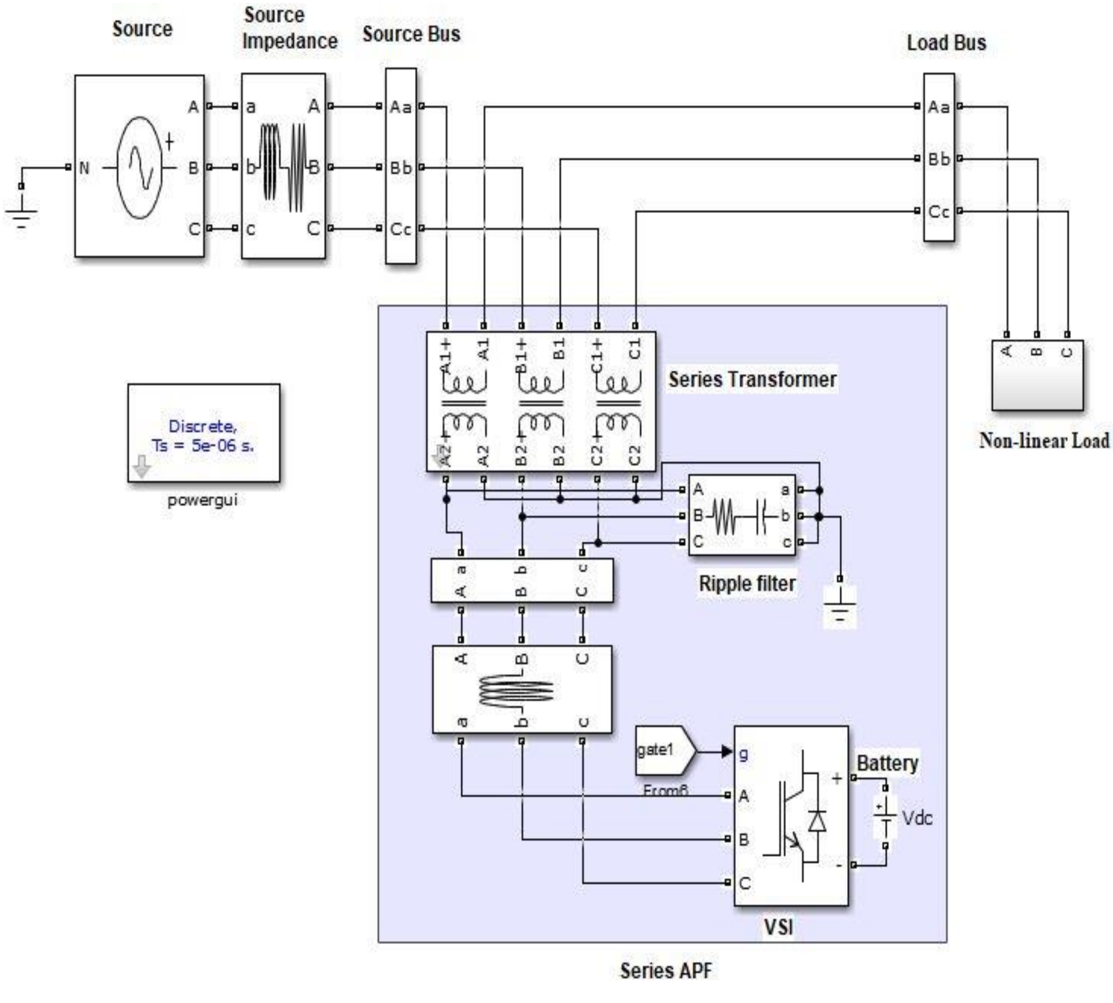


Fig. 4.5 Matlab based simulation model of Series APF

Before connecting the series APF to the system if a LG, LLG, LLLG fault or any unbalance occurs in supply system then, it will reflects to the load terminals. Thus, results to mal-operation, overheating, insulation failure of electrical and electronic equipment. Sometimes breakdown of transformer insulation also occurs which may leads to failure of grid. Therefore to improve the system performance series APF is connected to the system. Tale 4.1 shows the designing parameters of series APF.

Table 4.1: Parameters values for the series APF Matlab simulation

Parameters		**Values**
Source	Voltage	110V RMS
	Frequency	50Hz
	Resistance and inductance	0.1mΩ ; 1μH
Series APF	Series injecting three-phase transformer Rating	1.3KVA
	Ripple filter RC	2Ω ,20μF
	Interfacing Inductor	1mH
	dc-link voltage	200V
Load	Rectifier RL load	50Ω ; 90mH

4.5.1 UVT Controlled Series APF

A three-phase 30% sag and swell is given in source voltage for the time interval of 0.03s to 0.07s and 0.1s to 0.13s respectively as shown in Fig. 4.6(a). During sag, series APF injects compensating voltage with 180* phase shift.

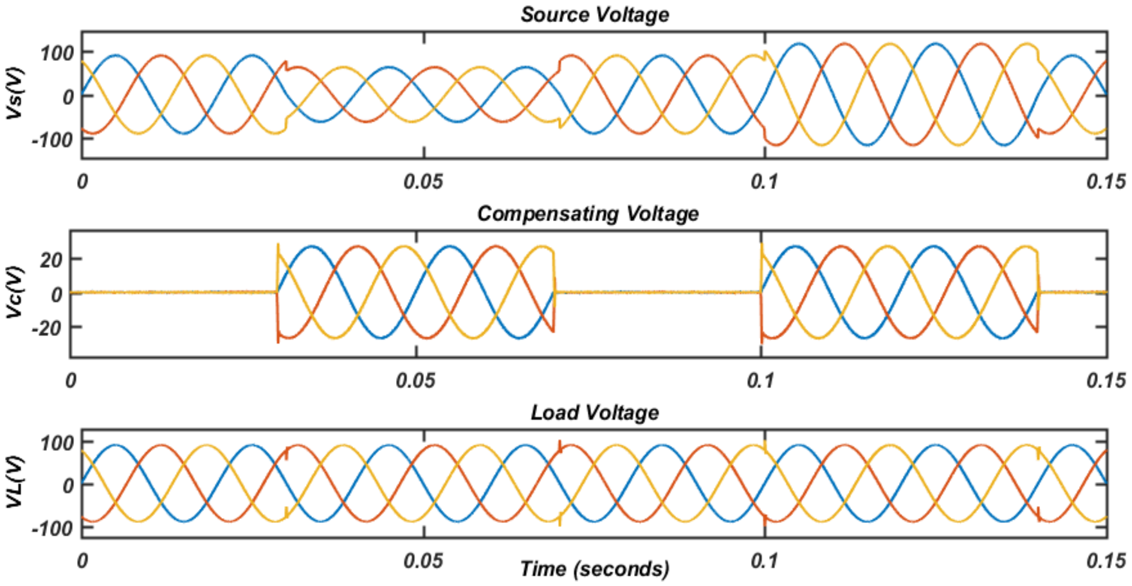


Fig. 4.6 (a) 3-phase sag/swell in source, (b) Compensating and, (c) Load voltage during compensation for UVT method controlled series APF.

While during swell, the series APF absorbs the voltage from the supply system in-phase as shown in Fig. 4.6(b) to balance the voltage at consumer ends as depicted in Fig. 4.6(c)

Fig. 4.7 shows the unbalanced source voltage for the time interval of 0.03s to 0.07s and 0.1s to 0.13s respectively. Series APF provides the voltage compensation by absorbing/injecting the voltage to the system, to get the balanced three-phase voltage at load terminals.

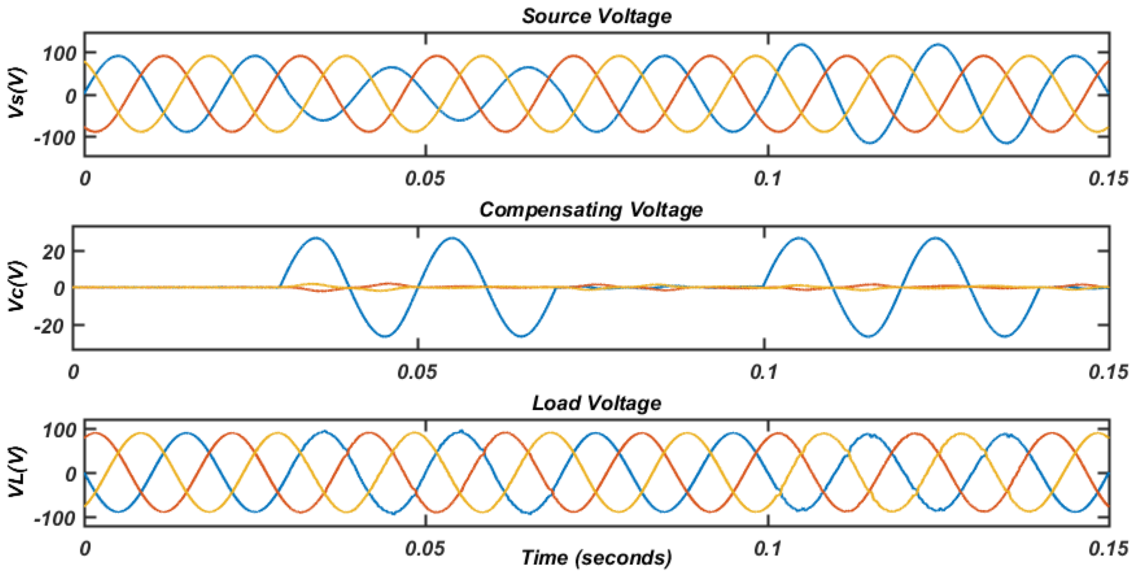


Fig. 4.7 (a) Unbalanced source, (b) Compensating and, (c) Load voltage during compensation for UVT method controlled series APF.

4.5.2 SRF Theory Controlled Series APF

For testing the performance for SRF based controlled series APF, a three-phase 30% sag and swell is given in source voltage for the time interval of 0.03s to 0.07s and 0.1s to 0.13s respectively as shown in Fig. 4.8(a). During sag, series APF injects compensating voltage with 180* phase shift. While during swell, the series APF absorbs the voltage from the supply system in-phase as shown in Fig. 4.8(b) to balance the voltage at consumer ends as depicted in Fig. 4.8(c)

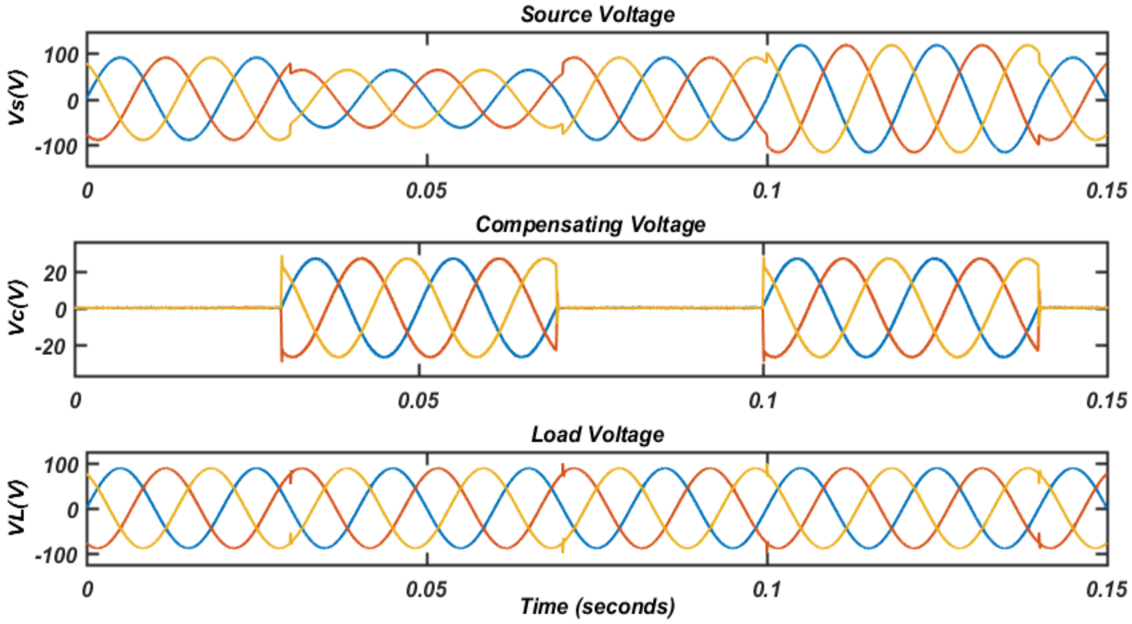


Fig. 4.8 (a) 3-phase sag/swell in source, (b) Compensating and, (c) Load voltage during compensation for SRF theory controlled series APF

Fig. 4.9 shows the unbalance in source voltage for the time interval of 0.03s to 0.07s and 0.1s to 0.13s respectively. Series APF provides the voltage compensation by absorbing/injecting the voltage to the system, to get the balanced three-phase voltage at load terminals.

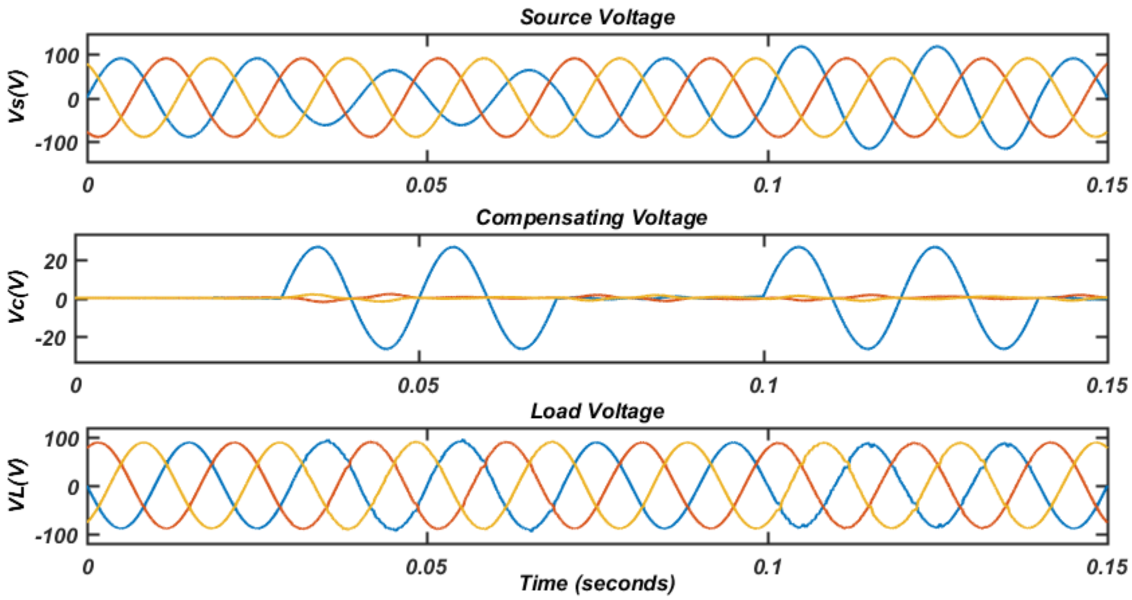


Fig. 4.9 (a) Unbalanced source, (b) Compensating and, (c) Load voltage during compensation for SRF theory controlled series APF

4.6 Conclusions

The simulation results lead to the following assertions;

- Both UVT and SRF controlled series APF are capable of eliminating 3-phase sag and swell in voltage.
- Series APF capable of eliminating sag and swell occurs in one phase supply voltage.

CHAPTER 5
UNIFIED POWER QUALITY CONDITIONER

5.1 Overview

An electrical utility must provide quality power to its customers and failure to do so might result in equipment malfunction, permanent breakdown or poor performance of the equipment. With rapid increase in nonlinear power electronics loads, load current has high harmonic content. While the unbalance/ distortion in voltage at load side may lead to increase in burden on distribution transformer during voltage swell condition, overheating and insulation breakdown of transformer windings, failure of electrical and electronic equipment. Therefore, a device called UPQC is used to improve power quality in distribution system. It consists of shunt and series APF connected in a cascaded manner using a dc-link capacitor. Shunt APF is connected to the point of common coupling (PCC) using coupling inductor, whereas Series APF is connected by using series transformer of 1:1 turns ratio. In this configuration shunt APF is connected towards the load side and series APF is connected towards source side. Harmonics produced by the switching operation of the converters are filtered using ripple filters. For the operation of both the APFs simultaneously, two reference signals are generated viz. for source current and load voltage. Synchronous Reference Frame (SRF) theory control based UPQC is analyzed in this chapter. Hysteresis controller is used to generate the switching pulses to operate the voltage source converter (VSC) with insulated gate bipolar transistor (IGBT) to inject compensating voltage and current in the system.

5.2 Reference Signal Generation for UPQC using SRF Theory

In this approach load current and source voltage are sensed and, transformed to a rotating frame (dq0). For the synchronization of transformed signals with source voltage is done by PLL circuit. The transformation angle (ωt) denotes the suggested reference frame's angular position and, it is rotating with constant speed. Under the defined condition of nonlinear load, the compensating reference source current and load voltage is generated in (dq0) frame. And finally converted back to (abc) coordinates.

5.2.1 Reference Load Voltage Generation

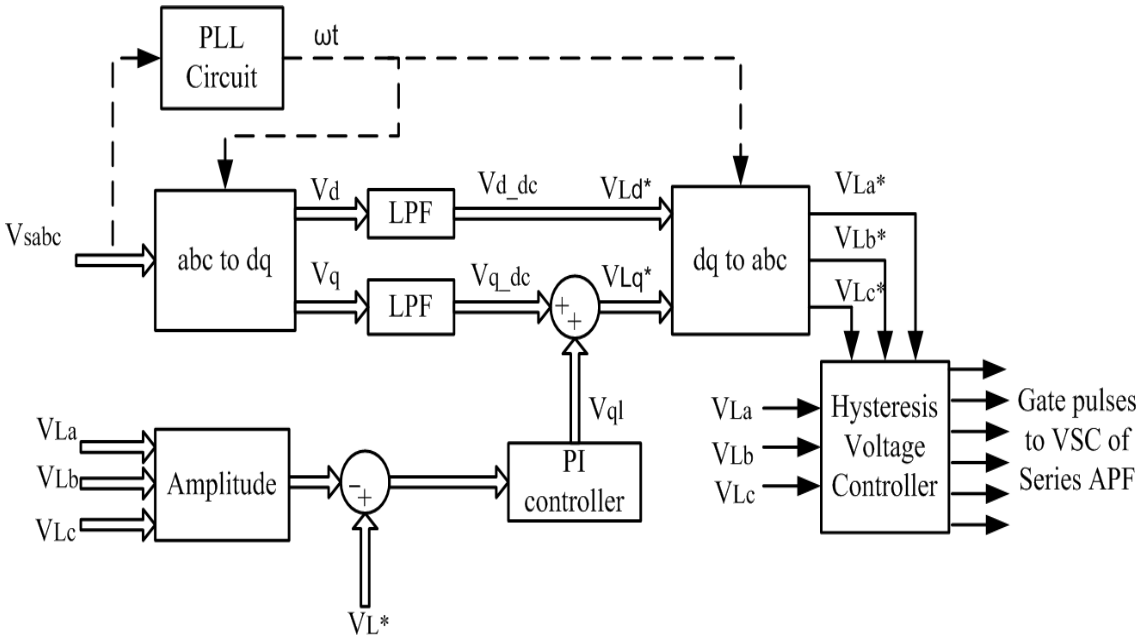


Fig. 5.1 Control block diagram for Series APF of UPQC using SRF theory

In this control first source voltage V_{sabc} signal is sensed and transformed to dq0 frame using equation (5.1). Fig. 5.1 illustrates the control block diagram for Series APF of UPQC using SRF theory

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{5.1}$$

The transformed d-axis and q-axis voltages V_d, V_q contains both fundamental as well as harmonic component respectively, is shown by equation (5.2), (5.3).

$$V_d = V_{d\_dc} + V_{d\_h} \tag{5.2}$$

$$V_q = V_{q\_dc} + V_{q\_h} \tag{5.3}$$

- For the synchronization of transformed signals with source voltage is done by PLL circuit. The transformation angle (ωt) denotes the suggested reference frame's angular position and, it is rotating with constant speed.
- To extract fundamental/dc component from the transformed voltages, the d-axis and q-axis voltages are passed through a LPF which gives fundamental components V_{q_dc} and V_{d_dc} free from harmonics as an output.
- A PI controller is used for regulation of the ac magnitude of the load voltage V_l in relation to its reference voltage V_l^*.

Where V_l ,V_l^* is given by using equation(5.4) and (5.5)

$$V_l = \sqrt{\frac{2}{3}(V_{la}^2 + V_{lb}^2 + V_{lc}^2)} \tag{5.4}$$

$$V_l^* = \sqrt{\frac{2}{3}} \times (desired\ rms\ value\ of\ load\ voltage) \tag{5.5}$$

Using this V_l and V_l^* an error signal is generated and given to PI voltage controller which gives a regulated output voltage V_{ql} . This V_{ql} is added to extracted fundamental component V_{qdc}. Therefore the reference the load voltage in dq frame is given by equation (5.6) and (5.7)

$$V_{Ld}^* = V_{ddc} \tag{5.6}$$

$$V_{Lq}^* = V_{q\_dc} + V_{ql} \tag{5.7}$$

By applying the inverse Park's transformation to equation (5.6) and (5.7) using (5.8) gives the reference load voltage in abc coordinates i.e.V_{la}^*, V_{lb}^*, V_{lc}^*.

$$\begin{bmatrix} V_{la}^* \\ V_{lb}^* \\ V_{lc}^* \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_{Ld}^* \\ V_{Lq}^* \end{bmatrix} \tag{5.8}$$

The generated reference load voltage V_{la}^*, V_{lb}^*, V_{lc}^* is compared with original sensed load voltage using hysteresis voltage controller to generate the gate pules to drive the converter of series APF.

5.2.2 Reference Source Current Generation

In this scheme load current i_{labc} is sensed and transformed to dq0 frame by using equation (5.9). Synchronization of the transformed load current i_{ld},i_{lq} with source voltage V_{sabc} is done by PLL circuit. Fig.5.2 illustrates the control technique of shunt APF using SRF theory.

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \tag{5.9}$$

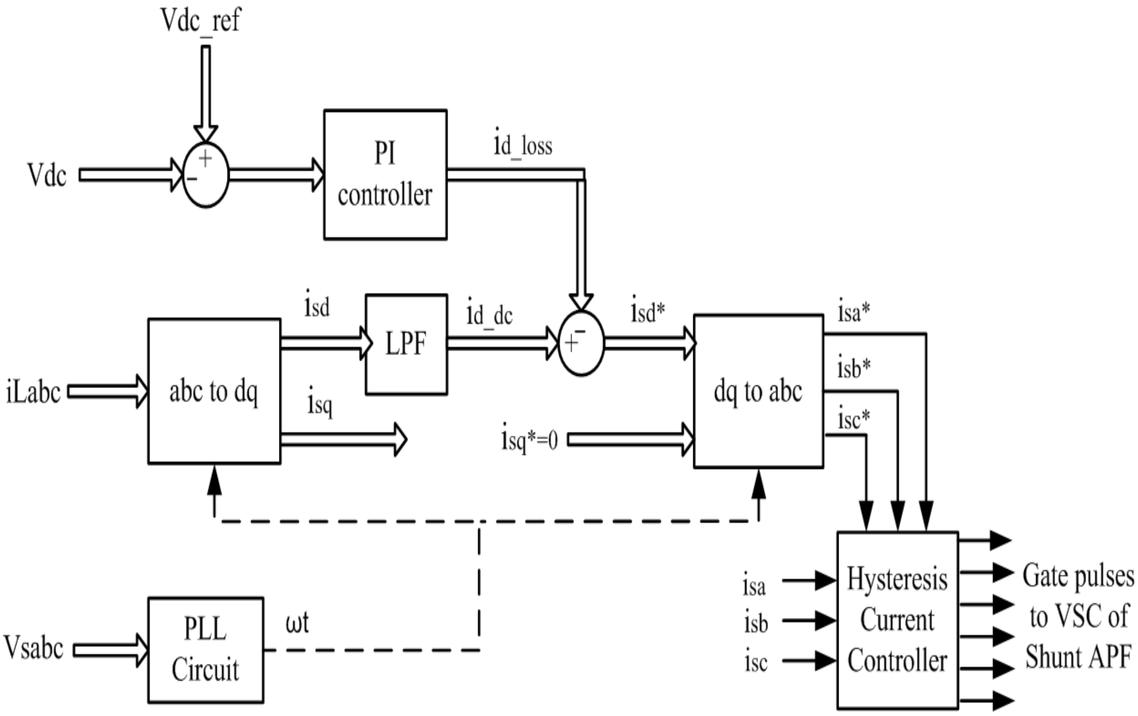


Fig. 5.2 Control block diagram for the Shunt APF using SRF theory

The transformed current i_{ld},i_{lq} contains both fundamental (i_{d_dc}, i_{q_dc}) and harmonic components (i_{d_h},i_{q_h}) as given in equation (5.10) and (5.11). Since, the source is required to supply only fundamental component of current to load therefore, harmonic component is need to suppress.

$$i_{ld} = i_{d\_dc} + i_{d\_h} \tag{5.10}$$

$$i_{lq} = i_{q\_dc} + i_{q\_h} \tag{5.11}$$

To suppress the harmonic content i_{d_h} the d-axis current i_{ld} is passed through a low pass filter (LPF) having cutoff frequency of 20Hz.

To maintain the capacitor dc-link voltage of shunt APF and, to compensate the switching losses of converter loss current i_{dloss} component is need to be calculated. For the calculation of i_{dloss}, capacitor dc-link voltage is sensed and compared with its reference voltage to generate an error voltage signal. This error voltage is feed to a suitable PI controller whose function is to regulate the dc-link voltage and output is i_{dloss}. Apart from this capacitor dc-link voltage also provides power balance in the electrical system during sag/swell as series APF absorbs/supplies active power from/to the system.

$$i_{sd}^{*} = i_{d\_dc} - i_{dloss} \tag{5.12}$$

$$i_{sq}^{*} = 0 \tag{5.13}$$

Equation (5.12) and (5.13) represents, i_{sd}^{*} is source reference current of d-axis whereas i_{sq}^{*} is considered zero since it is used in indirect method of control.

On applying the inverse Park's transformation using (5.14) gives the reference source current i.e. i_{sa}^{*}, i_{sb}^{*}, i_{sc}^{*}.

$$\begin{bmatrix} i_{sa}^{*} \\ i_{sb}^{*} \\ i_{sc}^{*} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{sd}^{*} \\ i_{sq}^{*} \end{bmatrix} \tag{5.14}$$

The generated reference source current i_{sa}^{*}, i_{sb}^{*}, i_{sc}^{*} is compared with original sensed source current. Using hysteresis current controller the gate pulses are generated to drive the converter of shunt APF.

4.2 Power Flow Analysis of UPQC

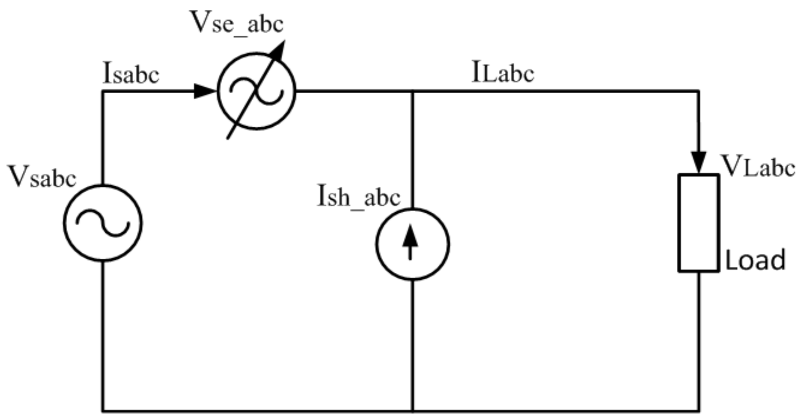


Fig. 5.3 Equivalent circuit diagram for UPQC connected between source and load terminals

From the Fig. 5.3, the voltage absorbed/injected by series APF is given as,

$$V_{SEabc} = V_{labc} - V_{sabc} = -kV_{labc} \tag{5.15}$$

Where, V_{sabc},V_{Labc}, V_{SEabc}, I_{sabc}, I_{labc} and k are source voltage, load voltage, source current, load current and oscillation constant respectively.

For the analysis of the power flow in line and UPQC mathematically, UPQC is considered to be ideal. Therefore active power of source P_{sabc} and load P_{labc} are equal.

$$V_{sabc}I_{sabc} = V_{labc}I_{labc}\cos(\theta) \tag{5.16}$$

$$(1+k)V_{labc}I_{sabc} = V_{labc}I_{labc}\cos(\theta) \tag{5.17}$$

$$I_{labc} = \frac{I_{labc}}{(1+k)}\cos(\theta) \tag{5.18}$$

Apparent S_{SEabc}, active P_{SEabc} and reactive Q_{SEabc} power of series APF is given as;

$$S_{SEabc} = V_{SEabc}I_{sabc} \tag{5.19}$$

$$P_{SEabc} = V_{SEabc}I_{sabc}\cos(\theta) \tag{5.20}$$

$$Q_{SEabc} = V_{SEabc}I_{sabc}\sin(\theta) \tag{5.21}$$

After the compensation the power factor of the system is unity i.e. $\cos(\theta) = 1$

Therefore, $P_{SEabc} = V_{SEabc}I_{sabc}$; $Q_{SEabc} \cong 0$

Or $P_{SEabc} = -kV_{labc}I_{Sabc}$

When UPQC is not connected to the system the active as well as reactive power demand of the load is supplied by the source as shown in Fig. 5.4(a).

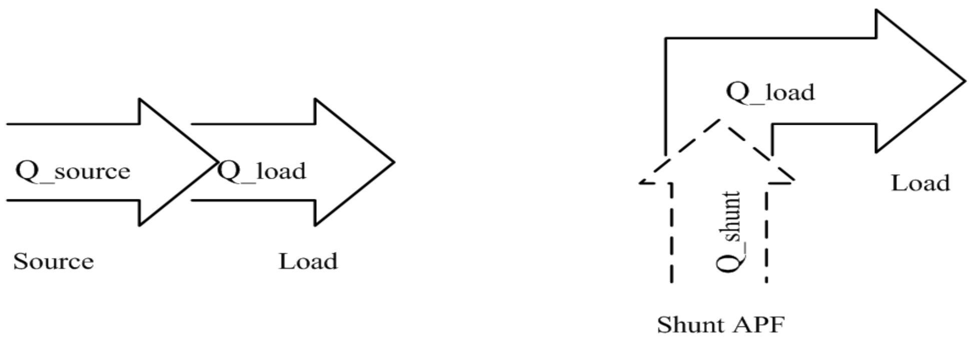


Fig. 5.4 (a) Reactive power flow without shunt APF, (b) with shunt APF

Now, when UPQC is connected to the system the active power demand is supplied by source whereas, reactive power is supplied by the shunt APF as shown in Fig. 5.4(b).

➢ ***For voltage sag condition,***

$V_{sabc} < V_{Labc}$, $k < 0$the series APF supplies the real power to the load by absorbing from shunt APF via dc-link. Whereas, shunt APF absorb this real power from the source to maintain the balanced voltage at load terminals as shown in Fig. 5.5

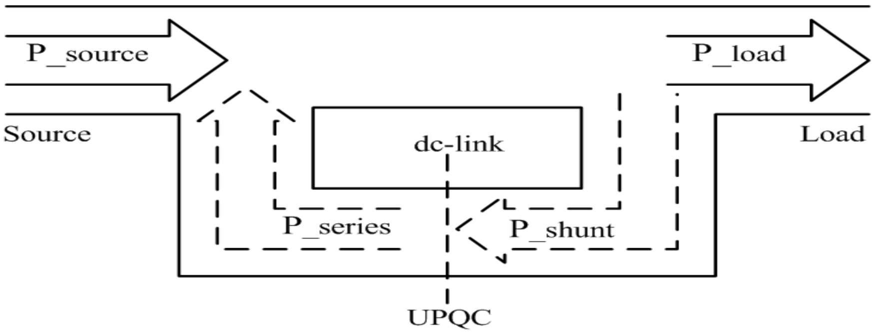


Fig. 5.5 Active power flow during sag in voltage with UPQC

➢ ***For voltage swell condition,***

$V_{sabc} > V_{Labc}$, $k > 0$the shunt APF supplies the real power to load by absorbing from series APF via dc-link. Whereas, series APF absorb this real power from the source to maintain the balanced voltage at load terminals as shown in Fig. 5.6

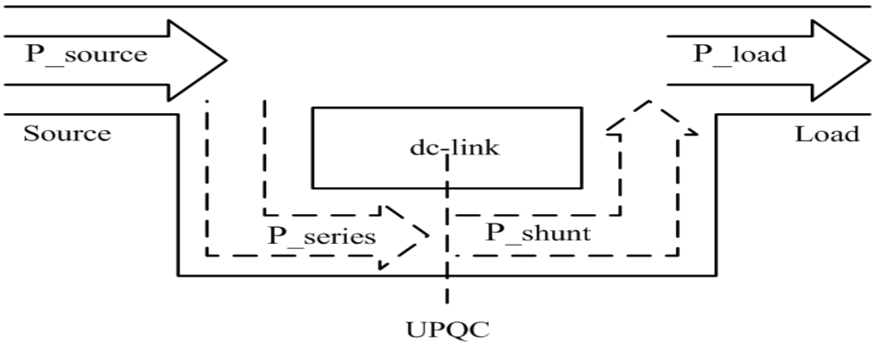


Fig. 5.6 Active power flow during swell in voltage with UPQC

5.3 Simulation Results

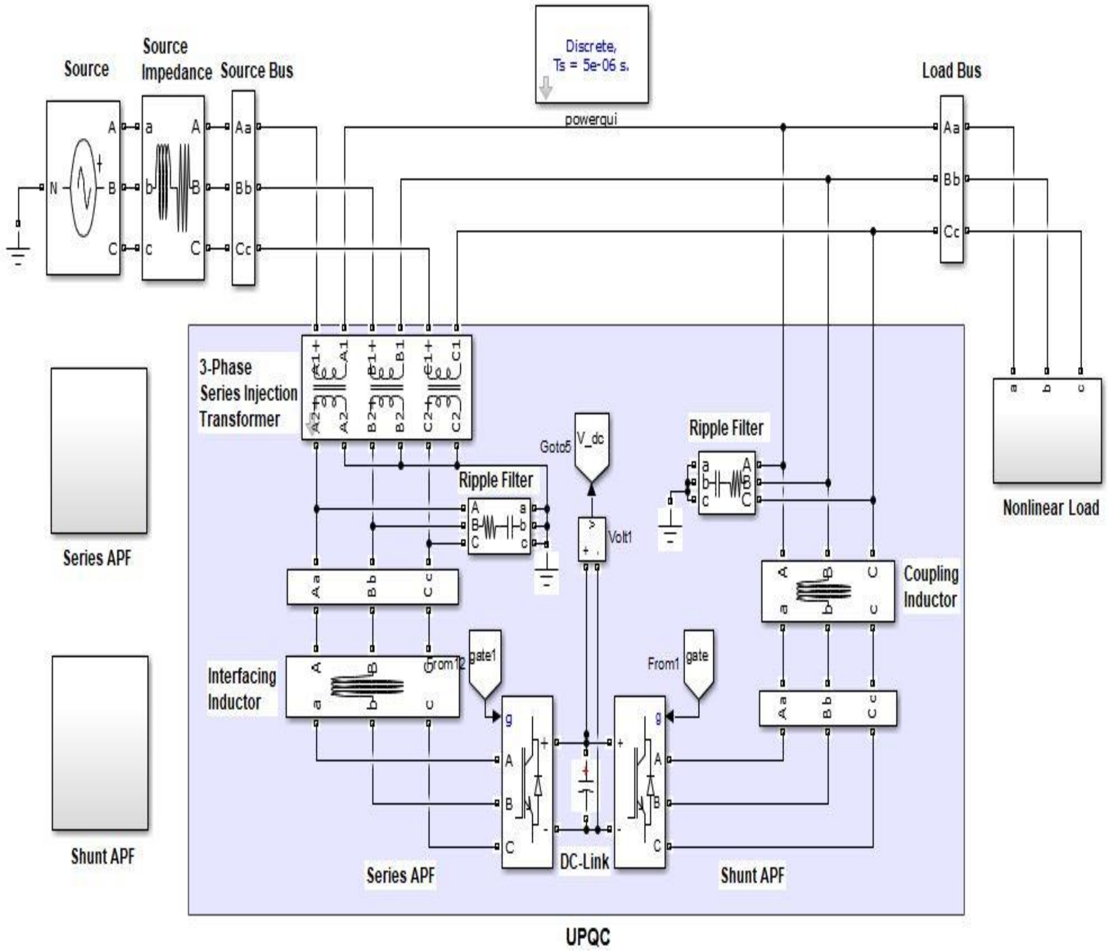


Fig. 5.7 Matlab simulation model of UPQC

The Fig. 5.7 shows the Matlab simulation model of UPQC connected to the distribution system to enhance the power quality for the different disturbances in the supply system i.e. sag/swell in voltage, polluted grid voltage at the same time system is containing harmonic currents.

The dynamic performance of UPQC is examined in this section for various disturbances in the source voltage for the system connected to a nonlinear load. Along, with power flow and capacitor dc-link voltage analysis. The percent THD content in current and voltage before and after connecting the UPQC in the polluted grid distribution system is investigated. Table 5.1 shows the parameters used for the modeling of UPQC in Matlab simulink (shunt & series APF)

Table 5.1 Parameters for the modeling of UPQC in Matlab simulink

Parameters		**Values**
Source	Voltage	220V RMS
	Frequency	50Hz
	Resistance and Inductance	0.1mΩ ; 1µH
Series APF	Injection series transformer rating	2.5KVA
	Interfacing Inductor	7mH
	Ripple Filter RC	1Ω , 30µF
	PI controller K_P& K_I	0.5, 7
Shunt APF	Coupling Inductor	3mH
	Ripple Filter RC	5Ω , 10µF
	PI controller K_P& K_I	5, 40
DC-link	Capacitor	4500µF
	Voltage	400V
Load	Rectifier RL load	20Ω ; 90mH

5.3.1 Voltage Sag under Ideal Grid

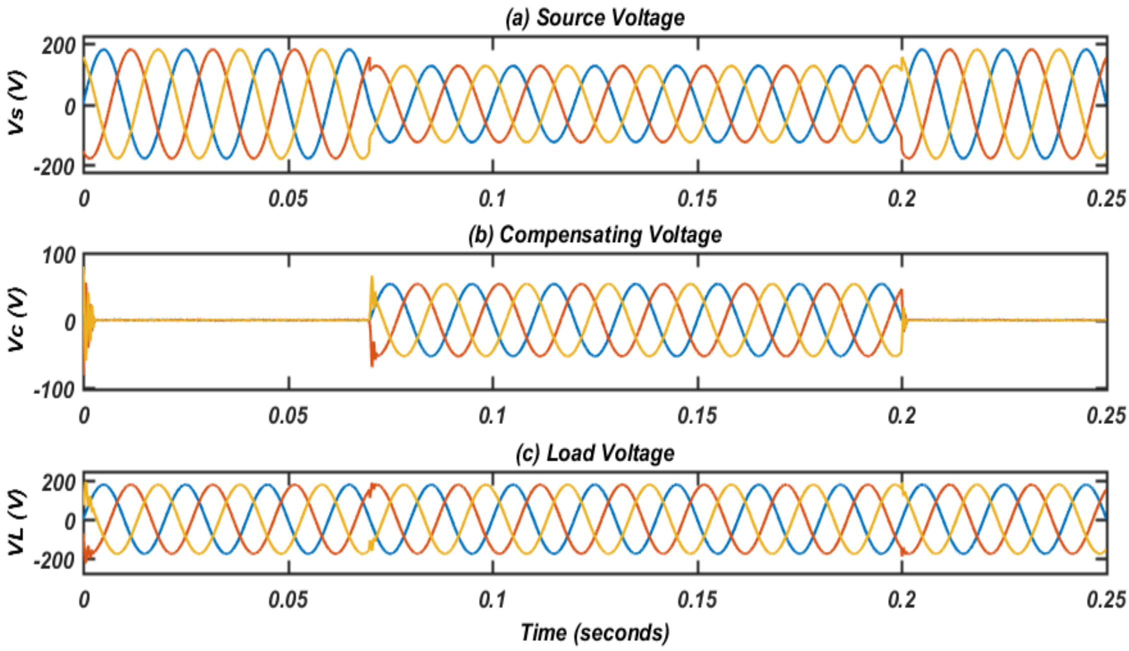


Fig. 5.8 (a) Source voltage, (b) Compensating voltage and, (c) Load voltage during sag in source voltage

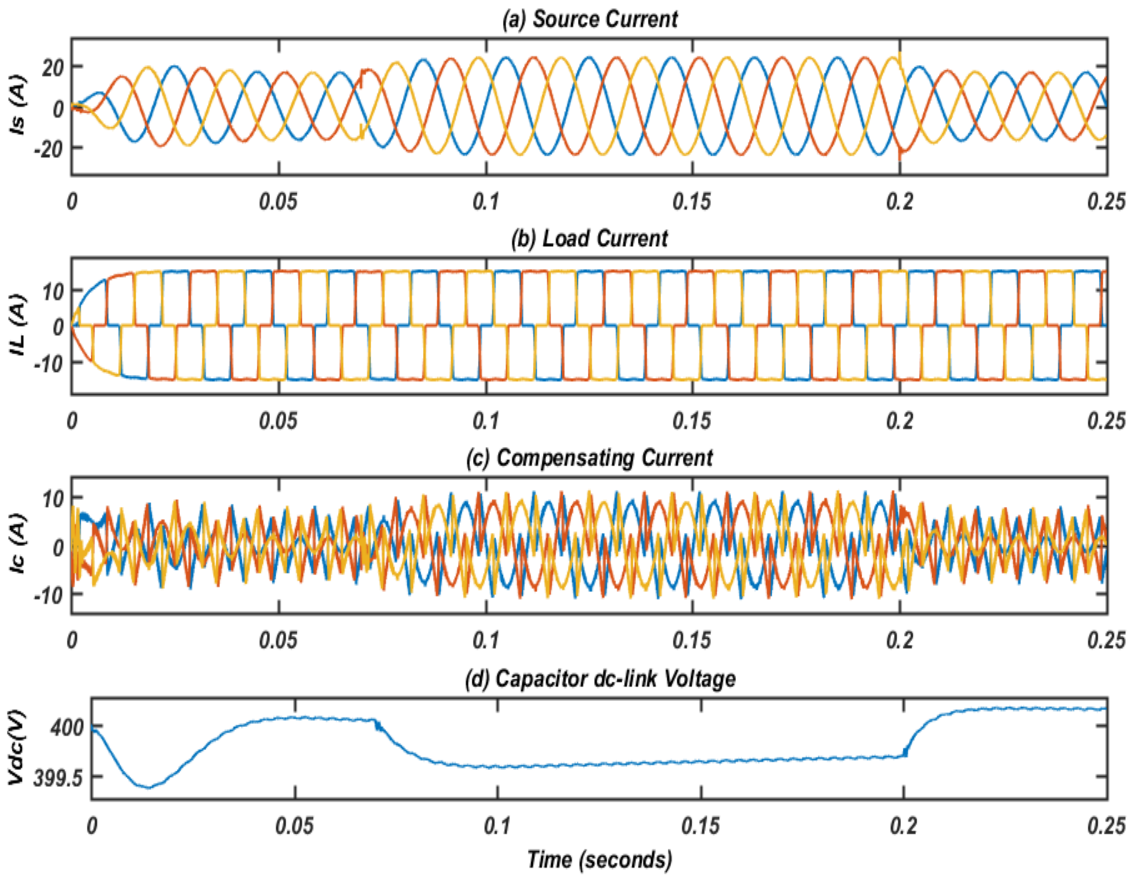


Fig. 5.9 (a) Source current, (b) Load current, (c) Compensating current and, (d) dc-link voltage during sag in source voltage

During voltage sag condition, a 30% sag is given in source voltage for the time interval to 0.07s to 0.2s as shown in Fig. 5.8(a). Since the UPQC is connected to the system, the series APF examines the sag in source voltage and starts injecting compensating voltage to the PCC as shown in Fig. 5.8(b) to maintain the balanced sinusoidal voltage at the load terminals as shown in Fig. 5.8(c). A drop in capacitor dc-link voltage is noticed due to sudden sag introduction in source voltage as shown in Fig. 5.9(d). At the same instant, shunt APF deliver some amount of active power to series APF via capacitor dc-link by absorbing from the source terminals. This causes the system to absorb extra current from the source terminals in order to maintain system power balance. Hence, this leads to rise in magnitude of compensated source current for sag interval as shown in Fig. 5.9(a). Simultaneously, as indicated in Fig. 5.9(c), the shunt APF delivers the harmonic current demand of the load. Fig. 5.9(b) depicts the significantly distorted load current. The capacitor dc-link voltage is well regulated by the PI controller to a specified reference value of 400V

Fig. 5.10 shows the active and reactive power flow of source, series APF and load during sag in source voltage under ideal grid condition.

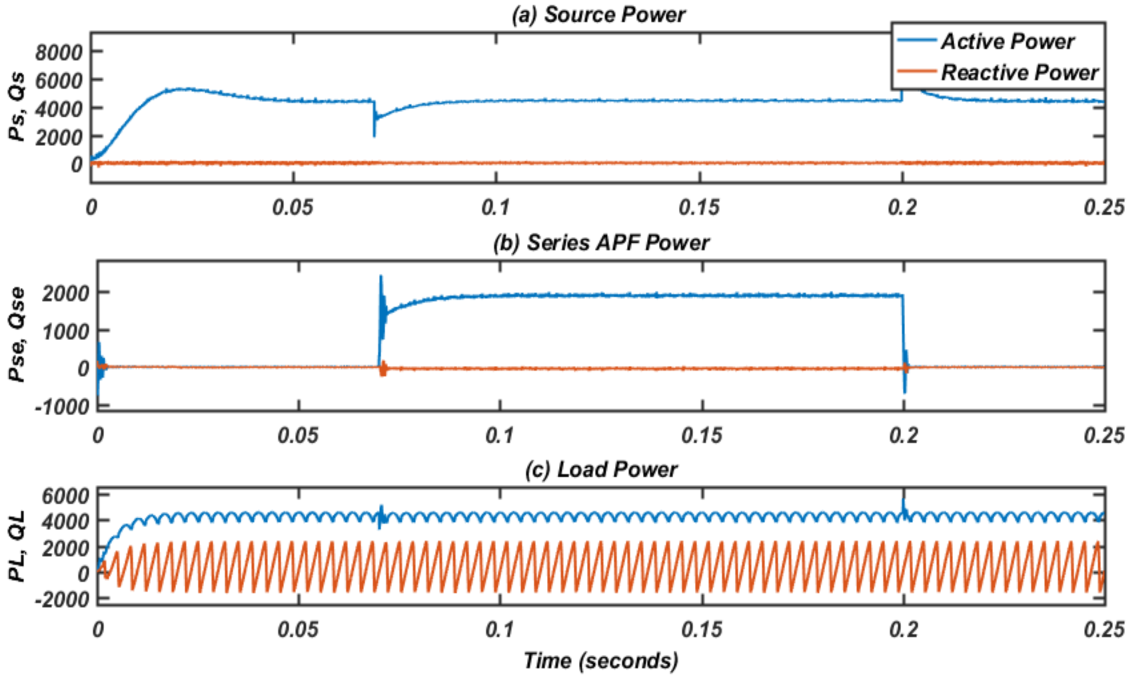


Fig. 5.10 Active and Reactive power flow for source, series APF and load during sag in source voltage

5.3.2 Voltage Swell under Ideal Grid

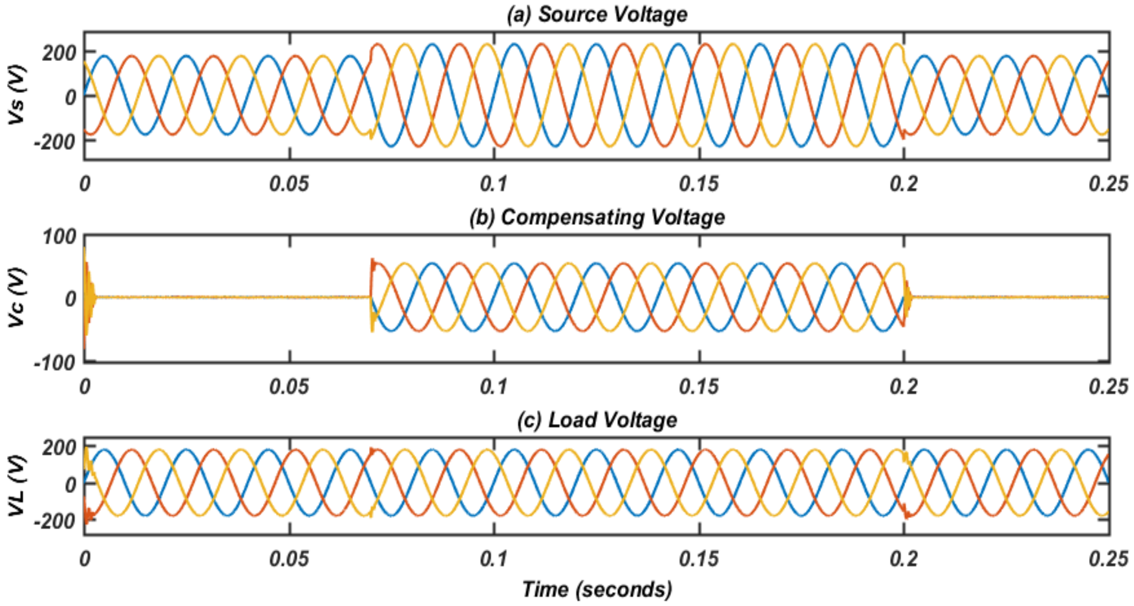


Fig. 5.11 (a) Source voltage, (b) Compensating voltage and, (c) Load voltage during swell in source voltage

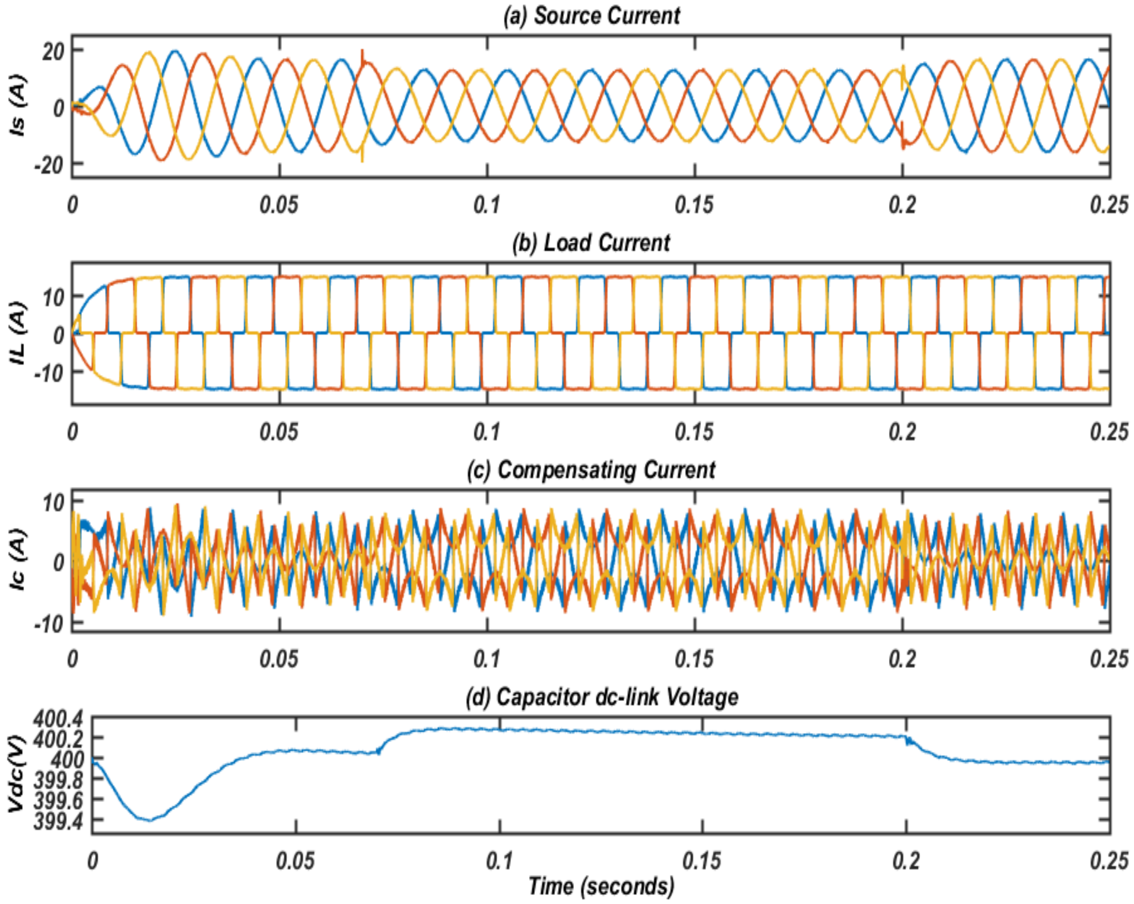


Fig. 5.12 (a) Source current, (b) Load current, (c) Compensating current and, (d) dc-link voltage during swell in source voltage

For the analysis during voltage swell condition, a 30% swell is given in source voltage for the time interval to 0.07s to 0.2s as shown in Fig. 5.11(a). Since the UPQC is connected to the system the series APF examines the swell in source voltage and starts absorbing the excess voltage from the PCC as shown in Fig. 5.11(b) to maintain the balanced sinusoidal voltage at the load terminals as shown in Fig. 5.11(c). A rise in capacitor dc-link voltage is noticed due to sudden swell introduction in source voltage as shown in Fig. 5.12(d). To maintain the power balance in the system series APF deliver a small amount of active power to shunt APF via capacitor dc-link by absorbing from the source terminals. This causes the system to absorb less current from the source terminals. Hence, this leads to fall in magnitude of compensated source current for swell interval as shown in Fig. 5.12(a). Simultaneously, as indicated in Fig. 5.12(c), the shunt APF delivers the harmonic current demand of the load. Fig. 4.12(b) depicts the significantly distorted load current. The capacitor dc-link voltage is well regulated by the PI controller to a specified reference value of 400V

Fig. 5.13 shows the active and reactive power flow of source, series APF and load during swell in source voltage for the interval of 0.07s to 0.2s to maintain power balance in the system.

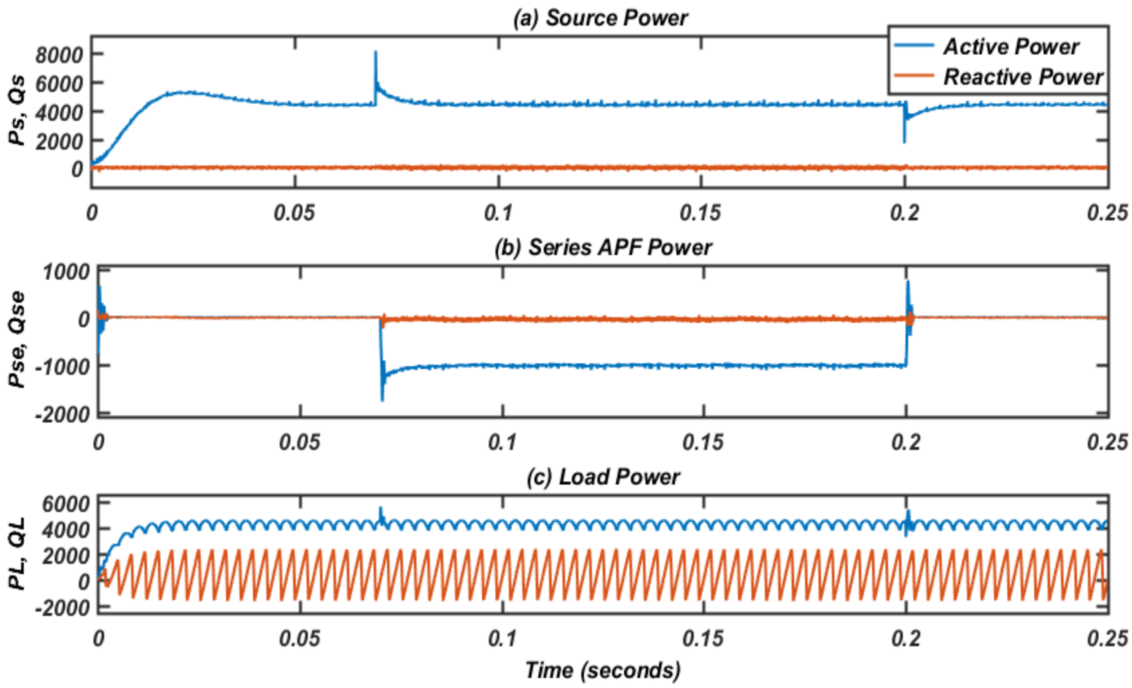


Fig. 5.13 Active and Reactive power flow for source, series APF and load during swell in source voltage

5.3.3 Polluted Supply

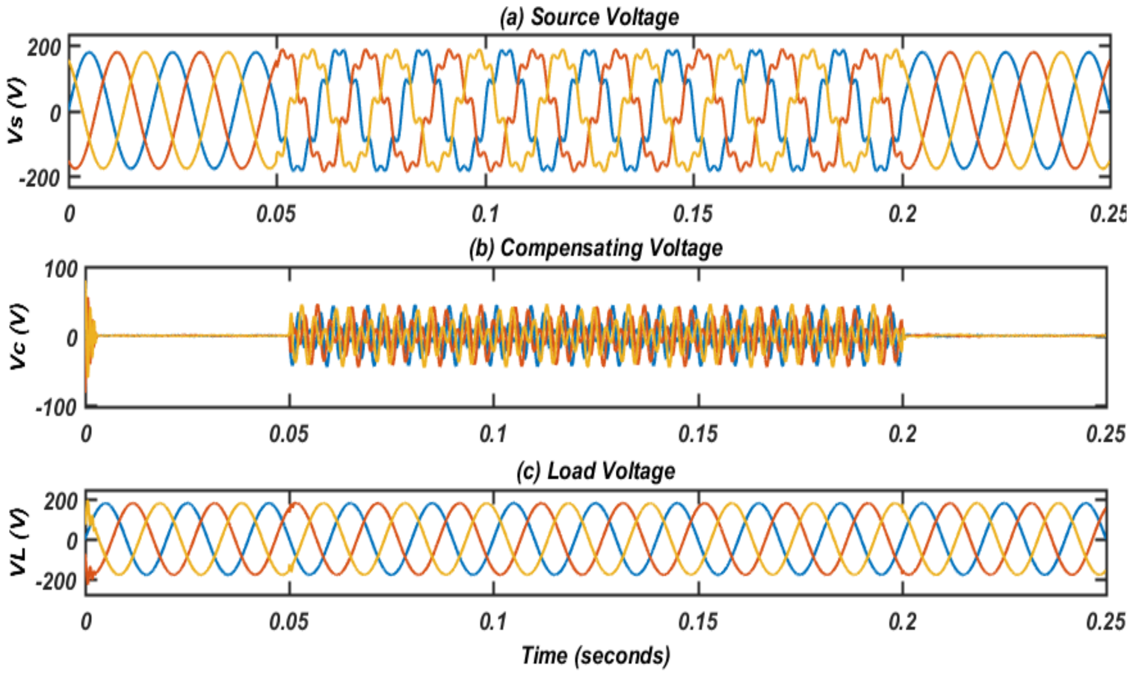


Fig. 5.14 (a) Source voltage, (b) Compensating voltage and, (c) Load voltage during polluted source voltage

For the evaluation of dynamic performance of the UPQC for polluted grid, 5th and 7th order harmonics of 15% and 10% in magnitude respectively are introduced in source voltage for the time interval of 0.05s to 0.2s as shown in Fig. 5.14(a)

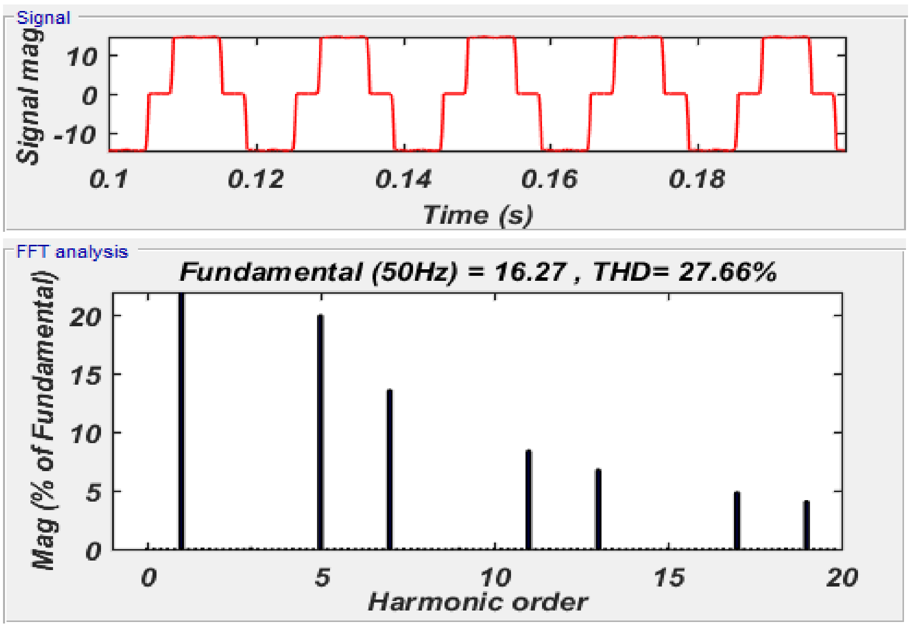


Fig. 5.15 THD in source current before compensation

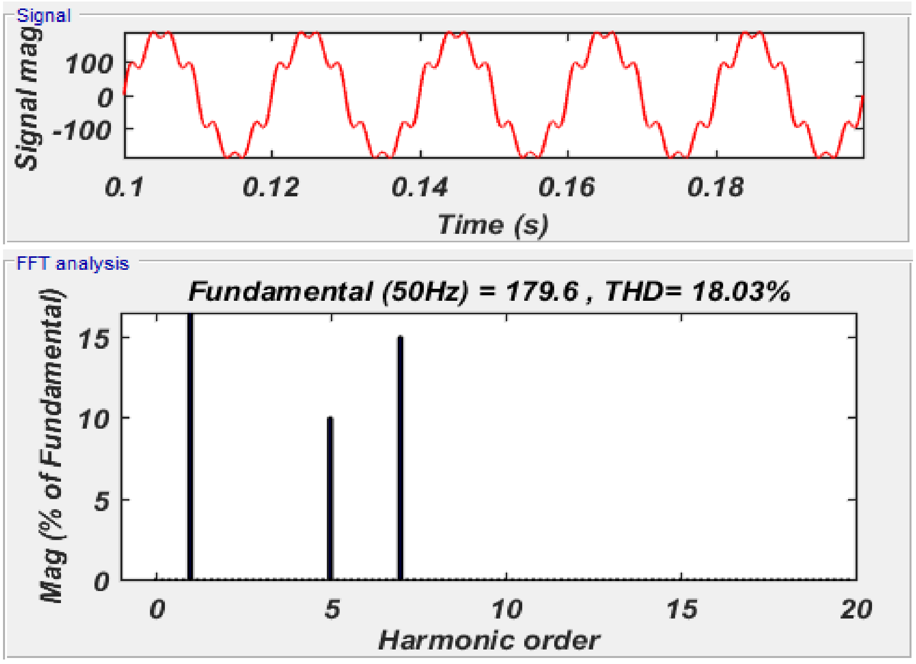


Fig. 5.16 THD in polluted source voltage before compensation

Prior to connecting the UPQC to distribution system the nonlinear load draws the non-sinusoidal harmonics containing current from the polluted supply, which affects the performance of neighboring loads and sources as well. The THD in current and voltage is 27.66% and 18.03% respectively as shown in Fig. 5.15 and 5.16

To eliminate the harmonics the UPQC is connected to the system, the series APF will start injecting compensating voltage component as shown in Fig. 5.14(b) into the system to compensate the harmonics present in the load voltage. It is able to reduce the THD content in load voltage to 1.07%. In contrast, shunt APF will supply the deviated fundamental current component as shown in Fig. 5.17(c) to remove the harmonics present in the source current, resulting in a THD in source current after compensation is 3.22%. Fig. 5.17(a) and 5.14(c) shows the compensated source current and load voltage, respectively. Fig. 5.17(d) shows the capacitor dc-link voltage that is kept balanced by utilising the Shunt APF's PI controller. During the compensation process, the UPQC delivers the nonlinear load's reactive power requirement in order to keep the source current in phase.

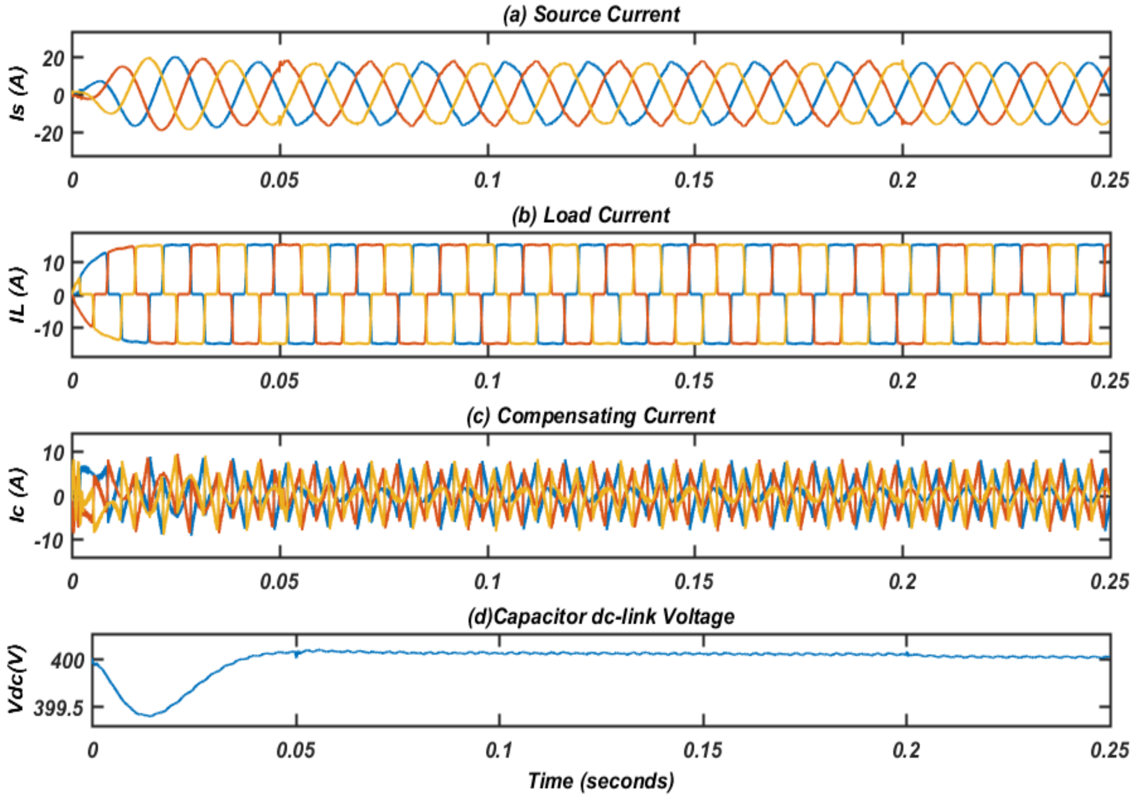


Fig. 5.17 (a) Source, (b) Compensating and, (c) Load voltage during polluted source voltage

Fig. 5.18 shows the active & reactive power flow of source, series APF and load for polluted grid when UPQC is present in the system.

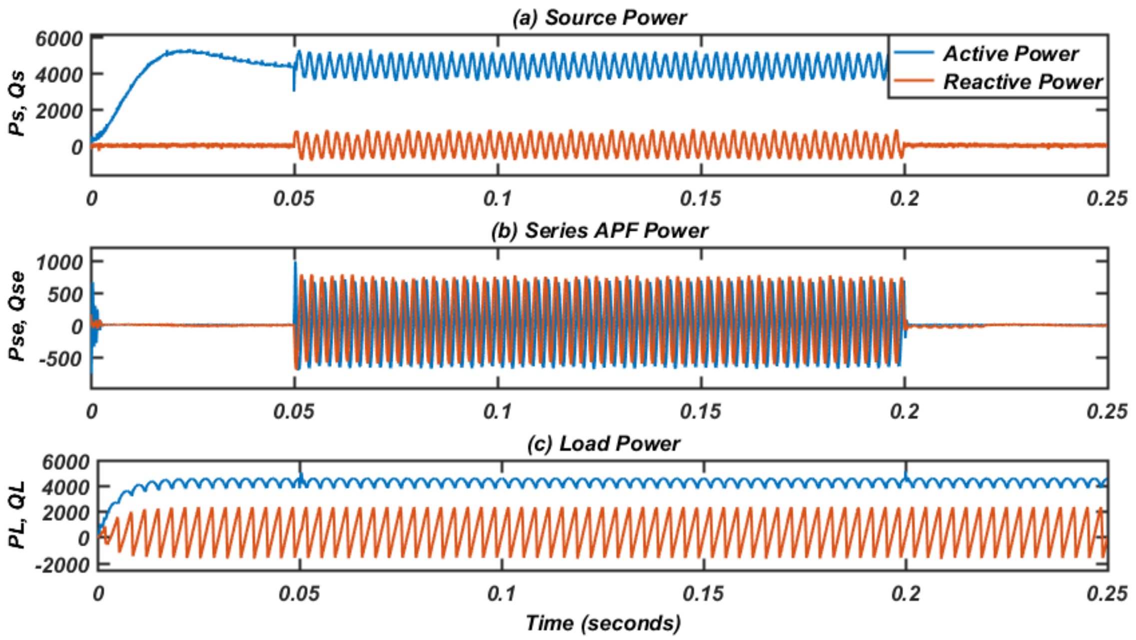


Fig. 5.18 Active and Reactive power flow for source, series APF and load during polluted source voltage

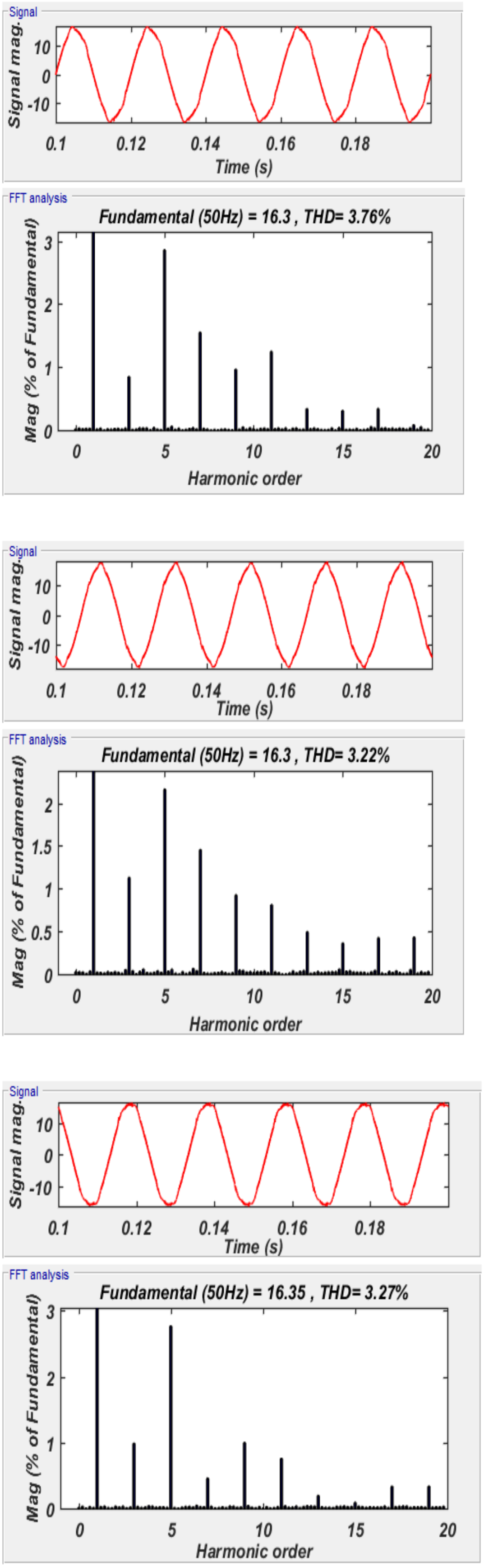


Fig. 5.19 THD in source current after compensation with UPQC

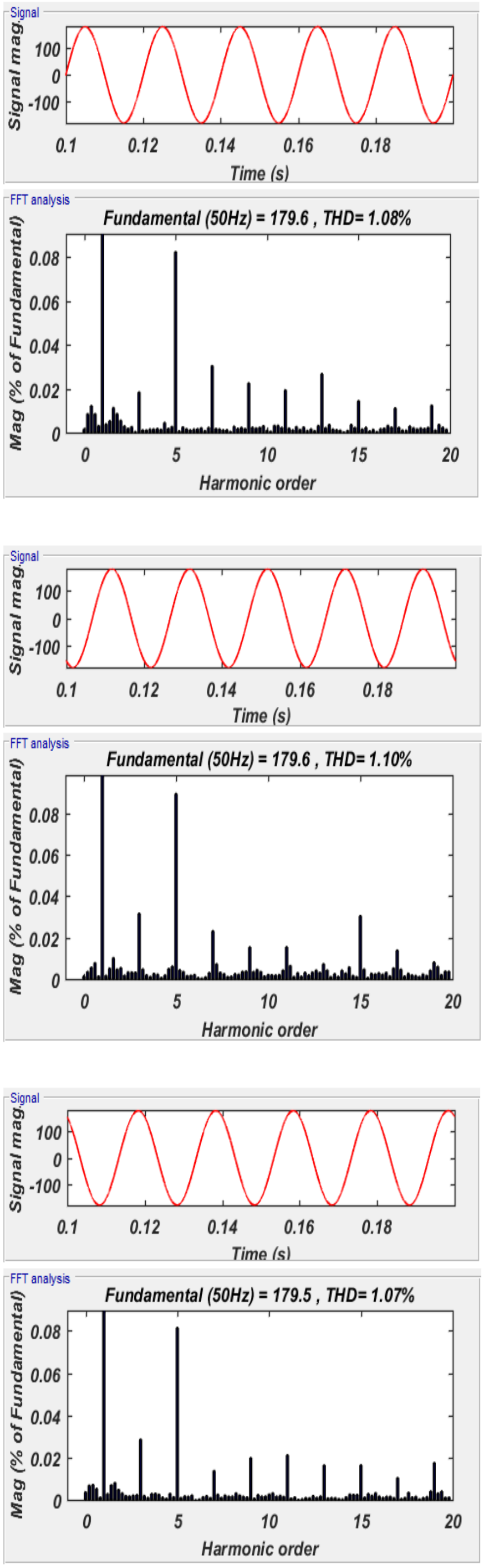


Fig. 5.20 THD in load voltage after compensation with UPQC

Table 5.2: Comparison of magnitude and THD in source current and load voltage without & with UPQC

Parameters		**Without UPQC**		**With UPQC**	
		Magnitude	**THD (in %)**	**Magnitude**	**THD (in %)**
Source Current	$\mathbf{I_{sa}}$	16.27A	27.66	16.30A	3.76
	$\mathbf{I_{sb}}$	16.27A	27.66	16.30A	3.22
	$\mathbf{I_{sc}}$	16.27A	27.66	16.35A	3.27
Load Voltage	$\mathbf{V_{La}}$	179.6V	18.06	179.6V	1.08
	$\mathbf{V_{Lb}}$	179.6V	18.06	179.6V	1.10
	$\mathbf{V_{Lc}}$	179.6V	18.06	179.5V	1.07

Fig. 5.19 and 5.20 shows THD in current and voltage after connecting UPQC to the distribution system. Table 5.2 shows the comparison of magnitude and THD in source current and load voltage without and with UPQC. The THD of both the load voltage and supply current have been reduced to a level of <5% with the application of UPQC.

5.3.4 Comparison of Capacitor DC-Link Voltage

In this section comparative analysis of capacitor dc-link voltage is presented during normal operation, sag/swell and for polluted source voltage when source is supplying to nonlinear load.

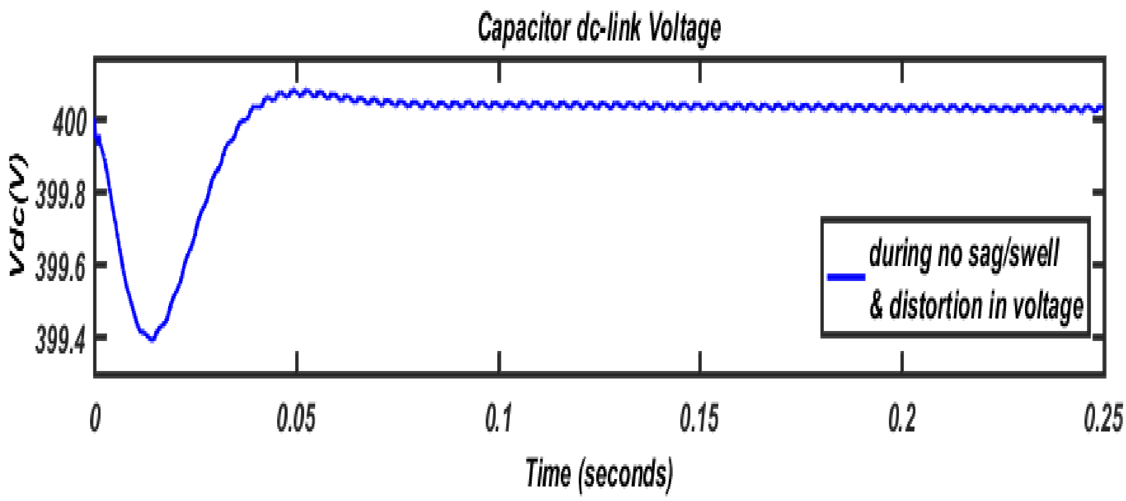


Fig. 5.21 Capacitor dc-link voltage under no sag/swell and distortion

Fig. 5.21 shows the capacitor dc-link voltage when distribution system is free from sag/swell and distortion in source voltage. Source will supply only active power to load whereas, shunt APF of UPQC supplies the reactive power and harmonic current demand of the nonlinear load and, thereby PI controller maintains the dc-link voltage Vdc constant to 400V.

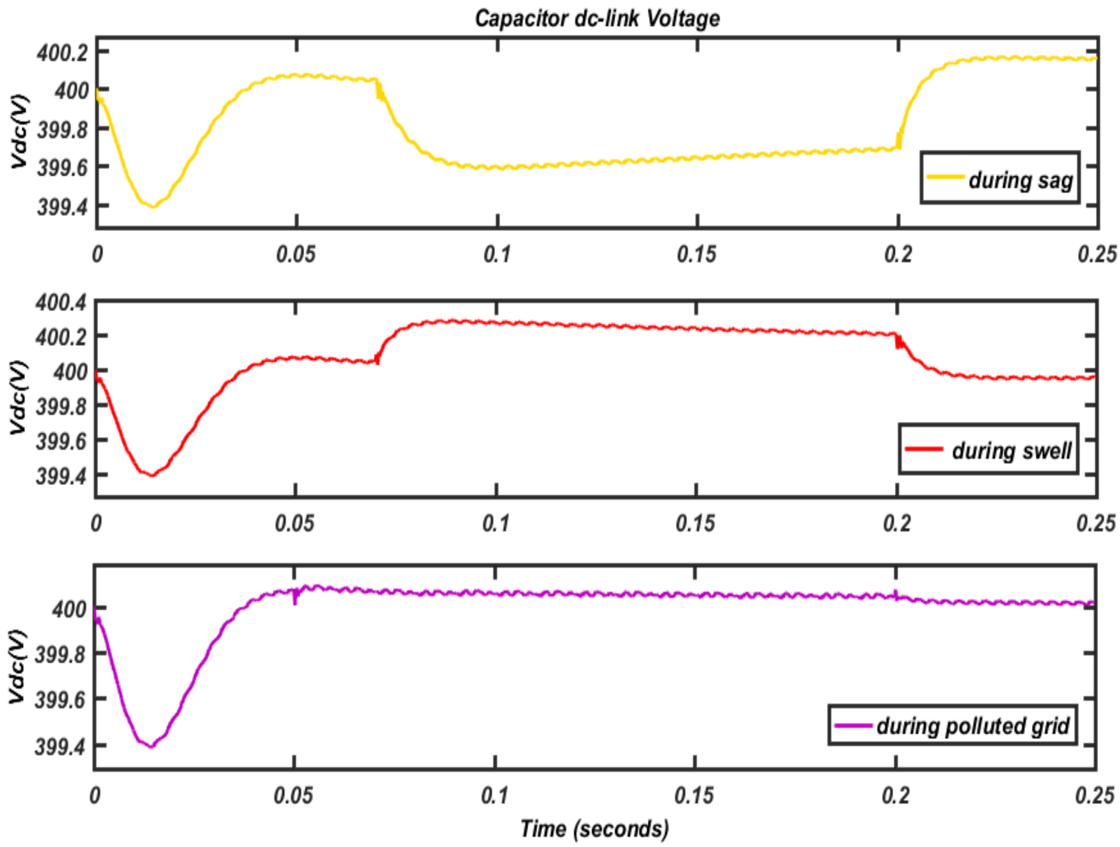


Fig. 5.22 Capacitor dc-link voltage (a) sag, (b) swell and, (c) polluted grid

During sag/ swell in source voltage, the dc-link voltage varies i.e. fall/rise for sag/swell interval as shown in Fig. 5.22(a), (b). It is stabilized with the use of a PI regulator. Under sag condition, the dc-link voltage V_{dc} drops. The active power to load is delivered by the series APF and, this power is drawn from the source by shunt APF. In contrast, under swell condition, the dc-link voltage V_{dc} rises and, to maintain the quality of voltage at load terminals as shown in Fig. 5.22(b). The active power to load is being supplied by shunt APF and, this power is drawn by series APF from the source. Whereas, shunt APF will supplies entire reactive power demand of the load. Fig. 5.22(c) shows when the source voltage is polluted, there is a small rise in dc-link voltage V dc is observed. In order to balance the load voltage and source current, UPQC provides compensatory harmonic current and voltage to the system.

5.4 Conclusions

The findings of this chapter can lead to the following conclusions.

- Sag/swell in load voltage is completely eliminated by the use of UPQC.
- During sag/swell and distortion in voltage, the dc-link voltage stabilization is perfectly maintained by the PI controller of the shunt APF.
- Under voltage sag/swell a small rise/fall in compensated source current magnitude is observed to maintain the power balance in the system.
- The THD in source current and load voltage is well compensated by UPQC for polluted grid i.e. <5% as per IEEE standards.
- By connecting the UPQC to the distribution system, the entire reactive power demand is supplied by the shunt APF.

CHAPTER 6
CONCLUSIONS & FUTURE WORK

6.1 Conclusions

- The capacitor-supported shunt APF controller is designed utilizing three control techniques using same operating parameters, namely UVT, SRF, and IPT. Their converter is driven by providing triggering pulses using hysteresis controller. It is concluded from the MATLAB simulation results that SRF theory controlled shunt APF have fast response to maintain DC-link voltage and effectively alleviates the current harmonics in distribution system which is introduced because of nonlinear load.
- To eliminate the frequent fluctuations, sag and swell in load voltage two methods are designed and analyzed, to evaluate the performance of series APF controllers using UVT method and SRF theory. It is found that both the methods are effective to enhance voltage quality at consumer bus.
- From the simulation results of shunt and series APF it seen that response of SRF theory based controller is more effective to eliminate harmonics in current and swell/sag from load voltage respectively.
- A UPQC model is built using SRF theory, with series and shunt APF sharing the common DC-link to maintain the system power balance using PI-controller during compensation process.
- The frequent sag and swell in voltage is successfully eliminated by using UPQC under ideal grid conditions.
- UPQC effectively lowers the %THD in current and voltage for polluted grid “i.e. <5% which lies within IEEE-519 standards”. Also, the complete reactive power is delivered by UPQC to nonlinear load and maintains the supply utility’s unity power factor.

6.2 Future Work

- In laboratory, a prototype of Series APF, Shunt APF & UPQC model may be established.
- The UPQC model presented here was for right shunt UPQC; however, a model for left shunt UPQC can be built in the future.
- Furthermore, the UPQC presented in this thesis is a three-wire, three-phase system, it may be expanded to a four-wire system.
- UPQC can be integrated with PV solar systems, wind turbines to enhance power quality at the consumer's end.

PUBLICATIONS

1. "Comparative Performance Analysis of Three-phase, Three-wire Shunt Active Power Filter and Dynamic Voltage Restorer" is accepted by IEEE Mysore Sub Section

Gmail

Rahul Singh <rahul164singh@gmail.com>

Acceptance Notification: Paper Id-288

1 message

IEEE MysuruCon <mysurucon@gmail.com> Tue, Aug 10, 2021 at 7:50 PM

To: Rahul Singh <rahul164singh@gmail.com>, alka singh <alkasingh.eed@gmail.com>

Dear Author,

Congratulations!!!

Greetings from IEEE Mysore Sub Section!!!

We are pleased to inform you that your paper has been **Accepted** for Oral presentation at the 2021 IEEE Mysore Sub Section International Conference (MysuruCon-2021) in association with IEEE Bangalore Section during 24-25 October 2021 at NAVKIS College of Engineering, Hassan.

The conference proceedings will be submitted to the IEEE Xplore® digital library.

Please read the following guidelines carefully before submitting the final version of paper:

1. Please prepare your Camera-ready paper (Word Document) by strictly following the guidelines mentioned below:**Any revisions in the manuscript should be marked as RED Colour.**
    a. The Final Camera Ready Copy should be strictly according to IEEE format given by IEEE Use the A4 size template at http://www.ieee.org/conferences_events/conferences/publishing/templates.html
    b. Mention affiliations of all the authors & mail id of all the authors. Do not mention Salutations like "Dr./Mr./Mrs./Prof./ Research Scholar/Student"
    c. Run a Spellcheck and proofread your paper thoroughly to ensure that it contains no typo and grammatical errors
    d. Include good quality figures/graphics, Tables must be drawn in table format, not as an image.

2 "Performance Evaluation of Three-Phase Unified Power Quality Conditioner controlled using SRF"

Remark: Has been submitted to IEEE conference for the accpetance.

REFERENCES

[1] "IEEE recommended practice for monitoring electric power quality," IEEE, Piscataway, NJ, USA, 2019

[2] "IEEE recommended practice and requirements for harmonic control in electric power systems," IEEE, Piscataway, NJ, USA, 2014.

[3] "IEEE recommended practice for the analysis of fluctuating installations on power systems," IEEE, Piscataway, NJ, USA, 2015.

[4] Y. Y. Chen, G. W. Chang, and S. C. Lin, "A digital implementation of IEC 61000-4-15 flickermeter," in *2015 IEEE Power & Energy Society General Meeting*, 2015.

[5] N. Hingorani, "Introducing Custom Power," *IEEE Spectrum*, Vol.32, Issue: 6, June 1995,pp 41-48.

[6] H. Akagi, "Trends in active line conditioner," *IEEE Transactions on Power Electronics*, vol.9, no.3, 1994.

[7] H. Fujita and H. Akagi, "The Unified Power Quality Conditioner: The integration of series and shunt active filters," *IEEE Transactions on Power Electronics*, vol.13, no.2 March 1998.

[8] H. Awad, M. H. J Bollen, "Power Electronics for Power Quality Improvements," *IEEE Symposium on Industrial Electronics*, 2003, vol.2, pp. 1129-1136

[9] Y. Pal, A. Swarup, and B. Singh, "A review of compensating type custom power devices for power quality improvement," in *2008 Joint International Conference on Power System Technology and IEEE Power India Conference*, 2008.

[10] B. Singh, K. Al-Haddad, and A. Chandra, "A review of active filters for power quality improvement," *IEEE Trans. Ind. Electron.*, vol. 46, no. 5, pp. 960–971, 1999.

[11] A. Panchbhai, N. Prajapati, and S. Parmar, “Comparative study of reference current generation for shunt active power filter,” in 2017 International Conference on Power and Embedded Drive Control (ICPEDC), 2017.

[12] N. M. Chamat, V. S. Bhandare, S. P. Diwan, and S. Jamadade, “Instantaneous reactive power theory for real time control of three-phase shunt Active Power Filter (SAPF),” in *2014 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2014]*, 2014.

[13] K. K. Pedapenki and G. Swathi, “Analysis of shunt active power filter with unit voltage template method,” in *2017 International Conference on Computation of Power, Energy Information and Communication (ICCPEIC)*, 2017.

[14] K. Bhattacharjee, “Harmonic mitigation by SRF theory based active power filter using adaptive hysteresis control,” in 2014 POWER AND ENERGY SYSTEMS: TOWARDS SUSTAINABLE ENERGY, 2014.

[15] H. Akagi, E. Watanabe, and M. Aredes, “more power to you (review of Instantaneous Power Theory and Applications to Power Conditioning by Akagi, H. et al.; 2007) [book review],” *IEEE Comput. Applic. Power*, vol. 6, no. 1, pp. 80–81, 2008.

[16] K. K. Pedapenki, S. P. Gupta, and M. K. Pathak, “Comparison of PI and neural network based controllers for shunt active power filter,” in *2015 International Conference on Control, Instrumentation, Communication and Computational Technologies (ICCICCT)*, 2015

[17] M. Linca, C. V. Suru, and C. A. Preda, “Indirect current control algorithm implementation for an active filtering system using constant switching frequency hysteresis controllers,” in *2018 International Conference on Applied and Theoretical Electricity (ICATE)*, 2018.

[18] T. Devaraju, V. C. Veera Reddy, and M. Vijay Kumar, “Modeling and Simulation of Custom Power Devices to Mitigate Power Quality Problems,” *International Journal of Engineering Science and Technology,* Vol. 2, No. 6, pp. 1880-1885, 2010.

[19] C. Huann-Keng, L. Bor-Ren and W. Kuan-Wei, "Study of dynamic voltage restorer under the abnormal voltage conditions," *in Proc. Int. Conf. Power Electronics and Drives Systems*, Vol.1, pp.308-312, 2005.

[20] C.S. Chang, Y.S Ho and P.C. Loh, "Voltage quality enhancement with power electronics based devices," *IEEE Power Engineering Society Winter Meeting*, Vol. 4, pp. 2937-2942, 23-27 Jan. 2000.

[21] H. Ezoji, A. Sheikholeslami, M. Tabasi and M.M. Saeednia, "Simulation of Dynamic Voltage Restorer Using Hysteresis Voltage Control," *European Journal of Scientific Research ISSN 1450-216X*, Vol.27 No.1, pp.152-166, 2009.

[22] Y. Pal, A. Swarup, and B. Singh, "Comparison of three control algorithms for single-phase UPQC," in *2011 International Conference on Energy, Automation and Signal*, 2011.

[23] M. A. Hannan and Azad Mohamed, "PSCAD/EMTDC simulation of unified series-shunt compensator for power quality improvement," *IEEE Transactions on Power Delivery*, Vol. 20, No. 2, pp. 1650-1656, April 2005.

[24] M. Kesler and E. Ozdemir, "Synchronous-reference-frame-based control method for UPQC under unbalanced and distorted load conditions," *IEEE Trans. Ind. Electron.*, vol. 58, no. 9, pp. 3967–3975, 2011.

[25] V. Khadkikar, "Enhancing electric power quality using UPQC: A comprehensive overview," *IEEE Trans. Power Electron.*, vol. 27, no. 5, pp. 2284–2297, 2012.

[26] S. Devassy and B. Singh, "Design and performance analysis of three-phase solar PV integrated UPQC," *IEEE Trans. Ind. Appl.*, vol. 54, no. 1, pp. 73–81, 2018.

[27] S. Vinnakoti and V. R. Kota, "Performance analysis of unified power quality conditioner under different power quality issues using d-q based control," *J. Eng. Res.*, vol. 5, no. 3, 2017.

[28] Q. N. Trinh and H. H. Lee, "Improvement of power quality under distorted source and nonlinear load conditions," in *Proceedings of The 7th International Power Electronics and Motion Control Conference*, 2012.

[29] N. Zaveri, A. Mehta, and A. Chudasama, "Performance analysis of various SRF methods in three phase shunt active filters," in *2009 International Conference on Industrial and Information Systems (ICIIS)*, 2009.

[30] B. Singh, and Jitendra Solanki, "A Comparative Study of Control Algorithms for DSTATCOM for Load Compensation," *in Proc. IEEE Int. Conf Industrial Technology*, pp. 1492-1497, 2006.