POWER ANGLE CONTROL SCHEME FOR INTEGRATION OF UPQC IN GRID CONNECTED PV SYSTEM

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BY

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Certificate

This is to certify that the work in the thesis entitled "***POWER ANGLE CONTROL SCHEME FOR INTEGRATION OF UPQC IN GRID CONNECTED PV SYSTEM***" by ***NAKKA PRUTHVI CHAITHANYA*** is a record of an original research work carried out by him under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of Master of Technology with the specialization of **Power electronics & Drives** in the department of **Electrical Engineering**, National Institute of Technology Rourkela. Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

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Abstract

The quality of electric power is greatly affected by the proliferation of non-linear loads in electrical energy processing applications like switched mode power supplies, electric motor drives, battery chargers, etc., The custom power devices like UPQC has gained more importance in power quality arena as it gives the best solution for all power quality issues. UPQC is the combination of both shunt and series active power filters connected through a common DC link capacitor. The shunt active power filter is the most corrective measure to remove the current related problems, power factor improvement by supplying reactive power and regulates DC link voltage. The series APF acts as controlled voltage source and corrects voltage related problems, like sag or swell, flickering, harmonics, etc.,. As a combination of both of these, UPQC improves service reliability. In the present work, shunt inverter control is based on modified active-reactive (p-q) power theory, uses High selectivity filter (HSF) for reference current generation. The series APF uses Power Angle Control (PAC) scheme for compensating sag/swell, interruption and voltage related problems along with sharing a part of load reactive power demand with shunt APF and thus ease its loading and makes the utilization of UPQC to be optimal. The topology uses three phase three leg inverters for both shunt APF and series APF. The gating signals were generated using Hysteresis controller. The output of High step-Up DC-DC Converter is used to work as DC voltage source for both APFs. The input voltage for the converter is provided by Photo Voltaic array incorporated with P&O MPPT technique. The use of high step-up DC-DC converter is for high voltage gain with better efficiency. The present topology avoids the PLL in shunt active power filter.

The simulation results are presented to show the effectiveness of the three phase, three-wire PV-UPQC and here obtained an acceptable THD for source current and kept load voltage at its nominal value.

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LIST OF ABBREVATIONS

APF	:	Active Power Filter
DVR	:	Dynamic Voltage Restorer
DSTATCOM	:	Distribution Static Compensator
EMI	:	Electro Magnetic Interference
FFT	:	Fast Fourier Transform
HSF	:	High Selectivity Filter
MPP	:	Maximum Power Point
MPPT	:	Maximum Power Point Tracking
P&O	:	Perturb and Observe
PCC	:	Point of Common Coupling
PLL	:	Phase Locked Loop
PQ	:	Power Quality
PV	:	Photo Voltaic
SSB	:	Solid State Breaker
SSCL	:	Solid State Current Limiter
SSTS	:	Solid State Transfer Switch
THD	:	Total Harmonic Distortion
VSI	:	Voltage Source Inverter
UPQC	:	Unified Power Quality Conditioner

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

The term power quality got significant importance in the electric power industry. The increasing application of electronic equipment and distributed generation has led to the degradation of power quality by injecting harmonics, flicker and voltage imbalance into the system. In addition, switching of capacitor banks, lightning strikes on transmission lines and various faults on the network also creates the power quality issues such as transients, voltage sag or swell, interruptions, etc.,.. The equipment which is increasingly susceptible to the variations in Power Quality is termed as Sensitive Equipment or Sensitive Load [4]. For proper load operation, it requires pure sinusoidal voltage. With fast growing digital technology, the devices that depending upon volatile memory chip for storages are increasing and these are potentially at risk from power quality events.

To achieve this pure sinusoidal voltage and to meet the power quality standards, it is necessary to use some compensation techniques. Previously passive filters using tuned LC components have been used to mitigate the harmonics, which are low in cost, simple in configuration. But this has drawbacks of fixed compensation, bulky in size and creates resonance problems. Hence a modern solution is found in the form of active power filtering. The shunt APF is suitable for suppressing source current harmonics and the series APF is suitable to compensate source voltage imperfections.

The power electronic controllers used in distribution system for the purpose of supplying a level of reliability or power quality, which is essentially required by sensitive load, is termed as custom power devices [4]. These devices have the ability to perform voltage regulation and current interruption functions within the distribution system and hence it can be treated as power conditioning device.

UPQC is one of those efficient custom power devices which is the combination of both shunt and series active power filters connected through a common DC link capacitor [1], [2], [6]. The shunt active power filter is the most corrective measure to remove the current related problems, power factor improvement by supplying reactive power and regulates DC link voltage [6]. The series APF acts as controlled voltage source [6] and corrects voltage related problems such as sag/swell, flickering, harmonics etc.,. As a combination of both of these, UPQC improves service reliability.

In the present work a modified p-q theory is used for reference current generation shunt APF. It uses two high selectivity filters (HSF) [15], [16], which are used to obtain the fundamental components from current and voltage signals in α-β reference frame. The fixed power angle control scheme [2], [5], is used to generate the reference voltage signals for series APF.

During voltage sag condition the amount of power in UPQC will be increased to a large extent. The normal UPQC can't compensate for the long duration power quality issues as the voltage across DC-Link falls steeply. But the proposed high step-up DC-DC converter operated PV-UPQC system overcomes this difficulty and able to compensate for long term voltage interruption, sag/swell, harmonics and reactive power. The additional energy will be supplied by the PV-array. While interconnecting the PV-UPQC to the grid, the voltage injected by series APF depends upon the measurement of power angle. As it creates the phase difference between the source voltage and load voltages, here both active and reactive power transitions getting involved. Usage of HSF in shunt APF reduces a considerable amount of THD in source current and avoiding the PLL improves its dynamic response. With the power angle control scheme, series APF shares a part of load reactive power demand along with the shunt APF. Thus reduces burden and rating of the shunt APF [1], [2], [5].

1.2 POWER QUALITY

A sinusoidal signal of constant amplitude and of single frequency which is constant is characterized as an ideal voltage or current signal. Further it is required to maintain both voltage and current in phase. Hence the quality of voltage quality or current quality is the quality of voltage delivered to the consumer or taken from the utility. Power quality problem is nothing but the deviation of voltage/current from its ideal value. Though the generator voltage is at or near pure sinusoidal, the current passing through the load may create disturbance to it and viz. voltage quality and current quality together is termed as power quality.

The process of supplying and grounding the sensitive equipment with power such that the operation of such equipment is satisfactory is nothing but power quality. Power Quality has different meanings and significances according to the requirement for which it has been defined. In the perspective of designer or manufacturer, power quality is defined in a manner that there should be no variation in voltage and no noise generation in the grounding system. In view of utility engineer, it is voltage availability or outage minutes. For the end users the feasibility in using the available power for driving all kinds of loads is termed as power quality.

So a nonstandard voltage, current or frequency that causes maloperation of end user equipment is termed as power quality problem. Although the entire power system has impact on power quality, most of the problems occur in distribution system itself. The power quality became significantly worse at points where the loads are connected to the distribution grid.

1.3 CLASSIFICATION OF POWER QUALITY DISTURBANCES AND THEIR EFFECTS

The presence of the power quality disturbance creates the following effects:

1.3.1 Transients

In power system the term transient is reserved for the occurrence of an unwanted event which elapses for short duration. Transients are majorly classified in to impulsive and oscillatory transients.

1.3.1.1 Impulsive transients:

It is a sudden, non-power frequency change in the steady state condition of voltage, current, or both, which is unidirectional in nature. The rise and delay times characterizes these transients which can also be obtained by their spectral content.

1.3.1.2 Oscillatory transients:

A sudden, non-power frequency change in the steady state condition of voltage, current, or both, which extends in both the directions i.e. bidirectional in nature is termed as oscillatory transient.

Effects:

The following are the undesirable effects caused by the transients.

It causes flashover and damages the equipment. It may lead to insulation failure. It may cause malfunctioning of electronic equipment.

1.3.2 Voltage Imbalance

It is defined as the ratio of maximum deviation from the average of the three phase voltages or currents to the average of the three phase voltages or currents, expressed in percent. Voltage imbalance can be defined making the use of symmetrical components as well.

Effects:

It effects the operation of Induction motors by slowing down and heating it by creating negative sequence fields.

1.3.3 Waveform Distortion

Waveform distortion is the steady state deviation from an ideal sinusoidal waveform of power frequency and its characteristics are primarily defined by the spectral content of the deviation. These are further categorized in to five types. Those are DC Offset, Harmonics, Inter harmonics, Notching and Noise [4].

1.3.3.1 DC Offset

DC Offset is defined as the existence of a dc voltage or current in an ac power system.

1.3.3.2 Harmonics

The frequency components present in sinusoidal waveforms which are integral multiples of fundamental frequency can be termed as harmonic components. Distorted waveforms can be decomposed into a sum of the fundamental frequency and the harmonics. The nonlinear characteristics of devices and loads on the power system are responsible for the injection of harmonics in to the system.

Inter Harmonics:

Voltages or currents with frequency components which are non-integral multiples of the fundamental frequency are said to possess inter harmonics.

Effects:

It causes heating, tripping of controlled process equipment, and equipment failure.

1.3.4 Notching

It is a periodically repeating voltage disturbance occurred due to the presence of power electronic devices especially during current commutation. The associated frequency components are very high and can't be characterized with measurement equipment which are in common use for harmonic analysis.

Effects:

It introduces harmonic and non-harmonic frequencies in the radio frequency range that cause negative operational effects, such as signal interference introduced into communication circuits and creates EMI issues.

1.3.5 Voltage Sag

Voltage Sag is defined as a decrease in rms voltage at the power frequency for durations from 0.5 cycles to 1 minute. Voltage sag is a very significant PQ issue for voltage-sensitive loads such as process control equipment, adjustable speed drives (ASD) and computers.

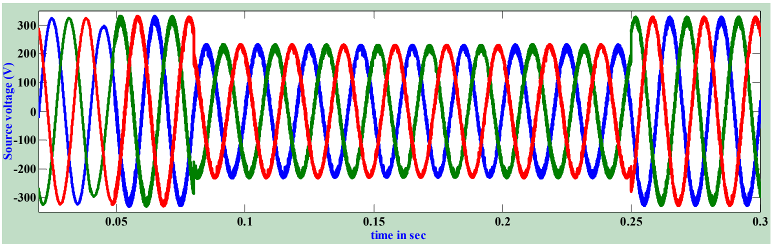


Fig. 1.1 Voltage sag in supply voltage

Voltage sag (dip) is short duration reduction in voltage due to sudden increase of the current. The most common situations for it are such as transformer energizing, motor starting, and faults.

Effects:

The major effect of voltage sag includes tripping of relays, malfunctioning of loads, damage or shut down of the equipment.

1.3.6 Voltage Swell

It is defined as an increase in the rms supply voltage between 1.1p.u. to 1.8 p.u., and lasting from half a cycle to 1 min. They are normally appears due to switching off large loads, by energizing capacitor banks, or by faults produced within power system. These are less probable to appear when compared to voltage sags, but are much more harmful to sensitive equipment.

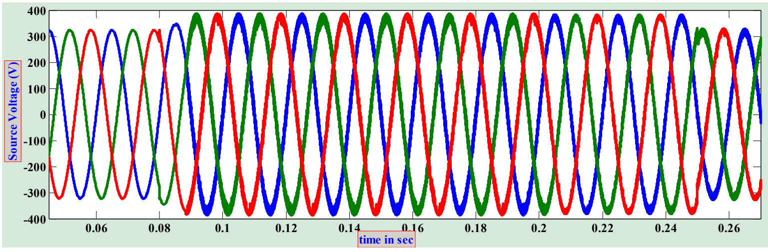


Fig. 1.2 Voltage swell in supply voltage

Effects:

This causes damage or tripping of the equipment which leads to shutdown of whole process.

1.3.7 Voltage Flicker:

The voltage flicker is a phenomenon of cyclic variation of the voltage waveform envelope resulting in poor performance of the lighting and other voltage sensitive loads. The voltage flicker occurs as result of randomly changing reactive power demand of sudden switching of loads such as arc furnaces, rolling mills, Unbalanced and other fluctuating loads.

Effects:

It causes irritation to human eyes, reduces life span of electronic devices.

1.4 LITERATURE SURVEY

Vinod Khadkikar et al. [1]-[3],[4] presented an overall review on UPQC to improve the electric power quality at distribution systems and also classified the possible configurations of UPQCs, its compensation techniques and future scope of each. The author proposed the PAC approach to improve the utilization factor of series APF.

Basu M et al. [6] presented a series APF that injects voltage at 90° with the supply and consumes no active power at steady state. It is also shown that the burden of shunt APF is reduced by sharing a part of load reactive power during voltage sag. But it won't operate under voltage swell condition.

Mahesh K. Mishra et al. [7] authors have derived mathematical expressions for calculating various parameters in voltage source inverter configured active power filters used in UPQC working under unbalanced and distorted conditions.

Ahmed M.A.Haidar et al. discussed the parameters that are affecting the UPQC performance during voltage sag and harmonic distortion. The authors analyzed the effect of varying parameters of series APF and shunt APF and calculated THD for both voltage and current in each case.

Akagi H et al. [14] explained about the physical meaning of instantaneous reactive power and presented how to generate the reference compensating currents to compensate the reactive power in three-phase system.

M. Suresh et al. [13] presented the detailed comparison in the performance of instantaneous p-q and i_d-i_q strategies to generate reference currents of shunt active power filters operating under distorted and unbalanced conditions. It is proved that i_d-i_q method gives lower THD under distorted and unbalanced condition.

M.C.Benhabib et al. [15] discussed the three control methods which are based on instantaneous power theory and the same are compared. The advantages and disadvantages of each are discussed.

Bhupinder Singh et al. [19] compared the two control techniques, p-q method and i_d-i_q method, for reference current generation in Shunt APF using PI controller under balanced condition and showed that the transient response for i_d-i_q method is better than the other.

Hong-seok Song et al. proposed a method to estimate positive and negative sequence voltages separately for an active power filter operating under voltage sag/swell or unbalanced condition without any measurement delay.

Abdusalam M et al. [23] authors have developed self-tuning filters (STF) based reference currents generation topology for shunt active power filter control under distorted voltage conditions

Shahram Karimi et al. [20] presented two high selectivity filters to generate the reference currents for the positive sequence harmonics, negative sequence harmonics and reactive power compensation simultaneously without using PLL.

Esram T et al. [17] discussed the different MPPT techniques used to extract the MPP in photovoltaic (PV) arrays and showed the advantages and disadvantages of each technique along with estimated cost.

Yi-Ping Hsieh et al. [24] proposed the concept of high step-up boost converter using two capacitors and one coupled inductor which reduces the stress on main switch and recycles the stored energy in leakage inductor by using clamping capacitor. The high voltage gain is obtained by using voltage lift technique.

Fan Ng et al. [9] presented analysis and control algorithm of a three phase four-wire UPQC based on p-q-r instantaneous power theory.

1.5 MOTIVATION

Several control techniques had developed for improving the PQ using UPQC and other custom power devices. But still less attention is paid on improving the utilization factor of series APF which is increasing the rating and cost of UPQC and ability to mitigate the long term power quality problems such as voltage sag/swell, interruption, harmonics and reactive power. These became primarily motivation for the current project.

1.6 OBJECTIVES

The objectives of this project include:

- To improve the voltage compensation and current compensation capabilities of the Three-Phase Three-Wire (3P3W) UPQC with power angle control and modified instantaneous active-reactive power (p-q) method using High Selectivity Filters (HSF) respectively.

- To model the perturb and observe MPPT algorithm based and high step-up DC-DC converter operating Photo Voltaic Power generating system to provide compensation against long term power quality issues.

1.7 ORGANIZATION OF THESIS

The entire thesis is organized in to six chapters. The explanation in each chapter will be as follows:

Chapter 1 explains briefly about the introduction to power quality, power quality disturbances and their effects, literature survey, motivation and objective of the project. The standard definitions of power quality disturbances and thesis organization also describe in this chapter.

Chapter 2 describes about what is custom power, the different types of custom power devices and their functioning. Here it describes the operation of DSTATCOM, DVR and UPQC. Many different topologies for UPQC like UPQC-P, UPQC-Q , UPQC-VA_{min} and UPQC-S are also presented.

Chapter 3 starts with the photo voltaic power generating system followed by modeling of solar cell, P&O MPPT and high step-up dc-dc converter. The necessity of using high step-up dc-dc converter along with its functioning is presented. The P&O MPPT technique is used to control the duty ratio of the high step-up boost converter.

Chapter 4 explains about the complete prosed system description followed by generation of reference voltages for series APF, reference signal generation for shunt APF and switching commands generation for both the inverters. This chapter also explains in detail about the PAC approach and advantages. The novelty in the reference signal generation for shunt APF is due to the usage of HSF and so it is discussed in detail.

Chapter 5 is provided with the MATLAB/SIMULINK simulation results and shows the effectiveness of proposed PV-UPQC to mitigate the power quality issues. The simulation results are carried out for voltage sag, swell and interruption cases. The advantages of using PAC scheme, HSF and P&O MPPT operated high step-up boost converter are validated.

Chapter 6 gives the conclusion followed by the references.

CHAPTER 2

CUSTOM POWER DEVICES

Power quality problems are not very new, traditionally these are mitigated using passive filters composed of inductors and capacitors. These L and C components are tuned to suppress specific harmonic frequencies. But these are having many disadvantages, some of these includes:

- These will have fixed range of operation
- It introduces resonance into the ac supply
- Bulky in size
- As time passes by, their impedance value varies.
- The effectiveness of its operation depends upon overall system performance and etc.,

The design of notch filter gives best results for a particular harmonic frequency, but in power system load varies, as much as 0.5Hz is possible. To overcome all these difficulties we use active power filtering.

2.1 Custom Power

The term custom power indicates the enhanced power quality and reliability which is delivered to the customers using power electronic controllers. Under this scheme customer will be free from power interruptions, fluctuations in voltage and current magnitudes, flickering and Harmonic which may damage to their equipment. In short, it uses power electronic controllers to keep supply voltage, current and frequency within specified limits.

2.2 Custom Power Devices

The power electronic devices, which are connected in series or in shunt or a combination of both [4] to enhance the power quality, are called Custom Power Devices. These are broadly classified into two types

i. Network reconfiguring devices and
ii. Compensating devices.

The network reconfiguring devices are used either to limit or to break or to transfer the current, which are usually called switch gear. The solid state or static versions of the devices are called Solid state current limiter (SSCL), Solid state breaker (SSB) and Solid state transfer switch (SSTS).

The compensating devices are either used to improve the quality of voltage i.e., sag, swell, flickering, etc., or to improve the quality of current, or both by injecting compensating voltage or current or both respectively. These devices include:

a) Distribution STATCOM (DSTATCOM)
b) Dynamic Voltage Restorer (DVR)
c) Unified Power Quality Conditioner (UPQC)

2.3 DSTATCOM

The shunt compensating device in distribution system is termed as DSTATCOM. It acts as controlled current source to mitigate the load harmonics. The main intention of connecting the shunt compensating device is to

- provide harmonic isolation between the load and source
- provide load VAR compensation and to operate source nearly at unity power factor
- suppress the dc offset in loads such that source current offset is eliminated
- balance the source current even if the load is unbalanced

➢ maintain voltage across the DC-Link capacitor to a reference value in VSI mode.

The block diagram of DSTATCOM is shown in below fig. 2.1

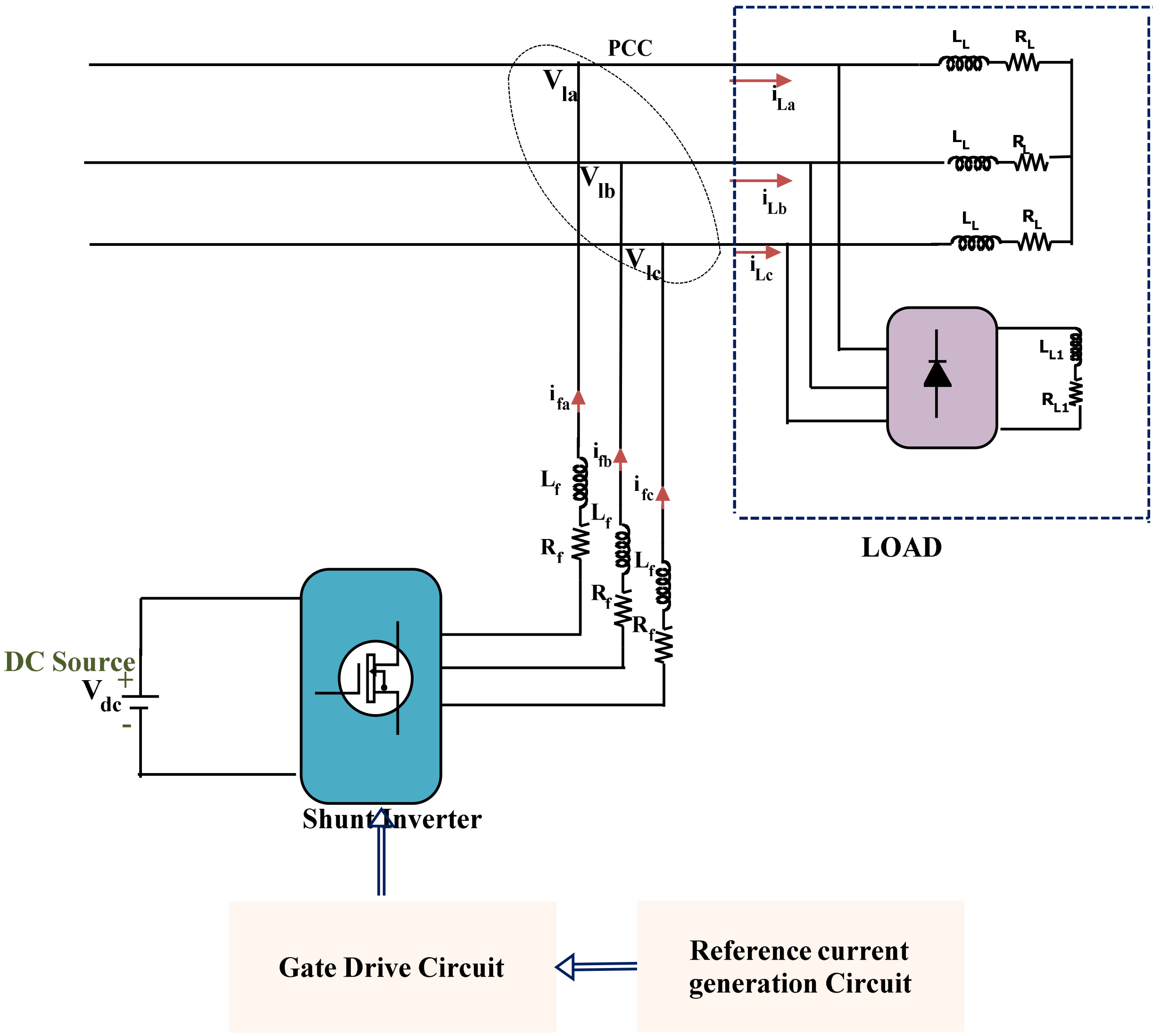


Fig. 2.1 Block diagram of DSTATCOM

The circuit is realized by an inverter, Inductor filters, DC source (usually capacitor), control circuit to generate reference currents, gate drive circuits for inverter switches. The capacitor acts as DC source and inverter is used to convert the DC input into AC output and is connected to PCC and injects current through an inductor or transformer. The PCC refers to the location in the network where other customers may be connected. Hence the voltage distortion at PCC is limited from the view point of safety to customer's equipment. The important aspect in its operation is that the injected currents should track the reference currents. For that, the control circuit with appropriate reference current generating techniques will be used. The gate drive circuit operates the switches accordingly and inverter tracks the reference currents. And thus the harmonic currents will be compensated.

2.4 DVR

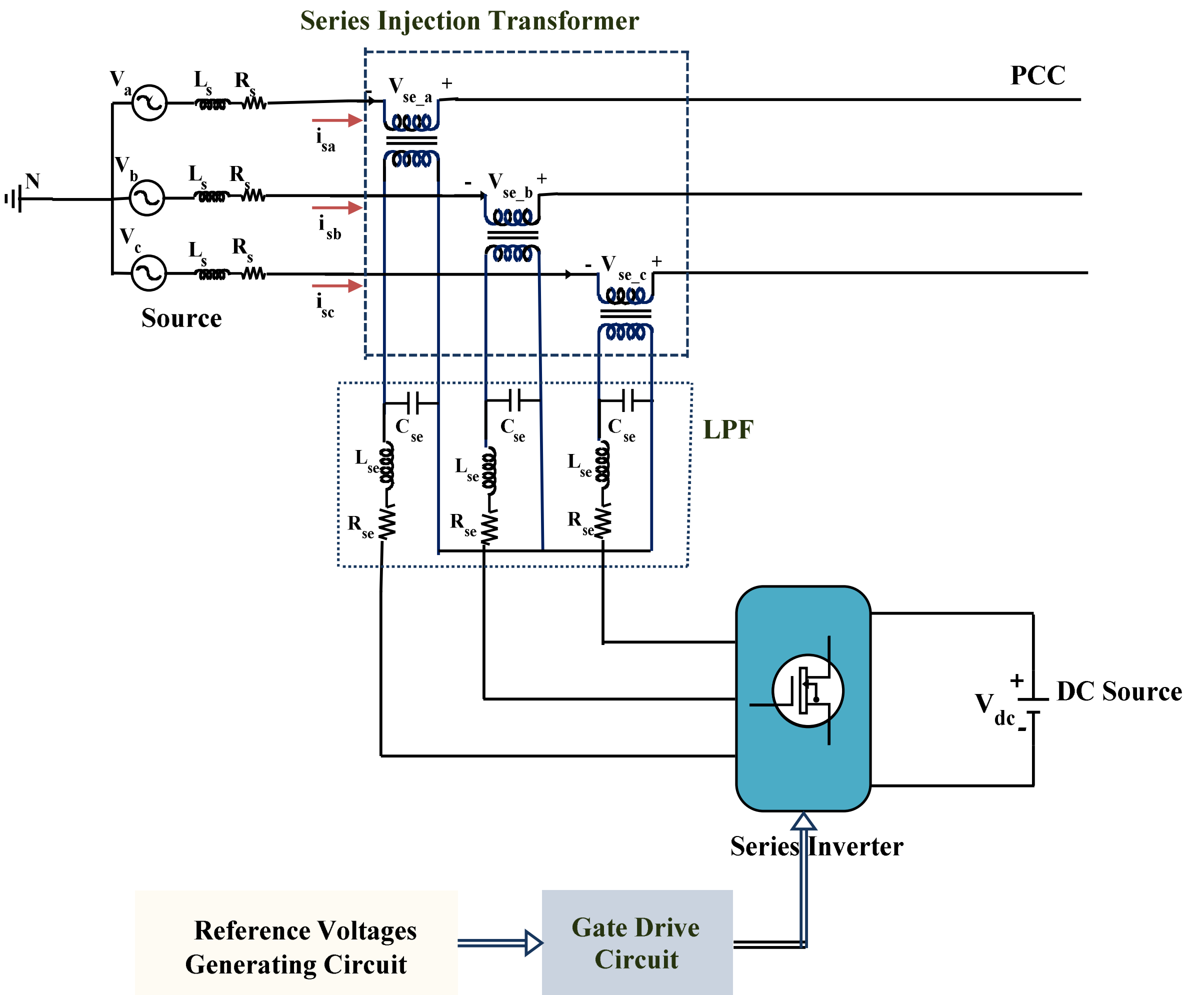


Fig. 2.2 Block diagram of DVR

The DVR is nothing but a series compensating device in distribution system. It acts as controlled voltage source. It is used to regulate the supply voltage quality and maintains the voltage at PCC to be insensitive to the supply voltage problems such as sag, swell, flickering, unbalance, interruptions, and other supply voltage disturbances. It injects the compensating voltage between supply and load in such a way that the terminal voltage or voltage at its PCC is equal to its nominal value for all time. Depending upon the construction of DVR, it may involve in active power transitions with the line or reactive power transition with the line or both. The block diagram of DVR is shown below fig. 2.2:

2.5 UPQC

The combination of both shunt and series compensators used in distribution system is termed as UPQC (Unified Power Quality Conditioner). It combines the advantages of both DSTATCOM and DVR. Hence it is used to compensate both the Load current quality issues such as Harmonics, reactive power, unbalance, etc., and source voltage quality issues such as sag, swell, unbalance, flicker, interruptions, etc.,. Thus it improves the overall service reliability [2], [3], [5]. The general block diagram of UPQC is shown in fig. 2.3

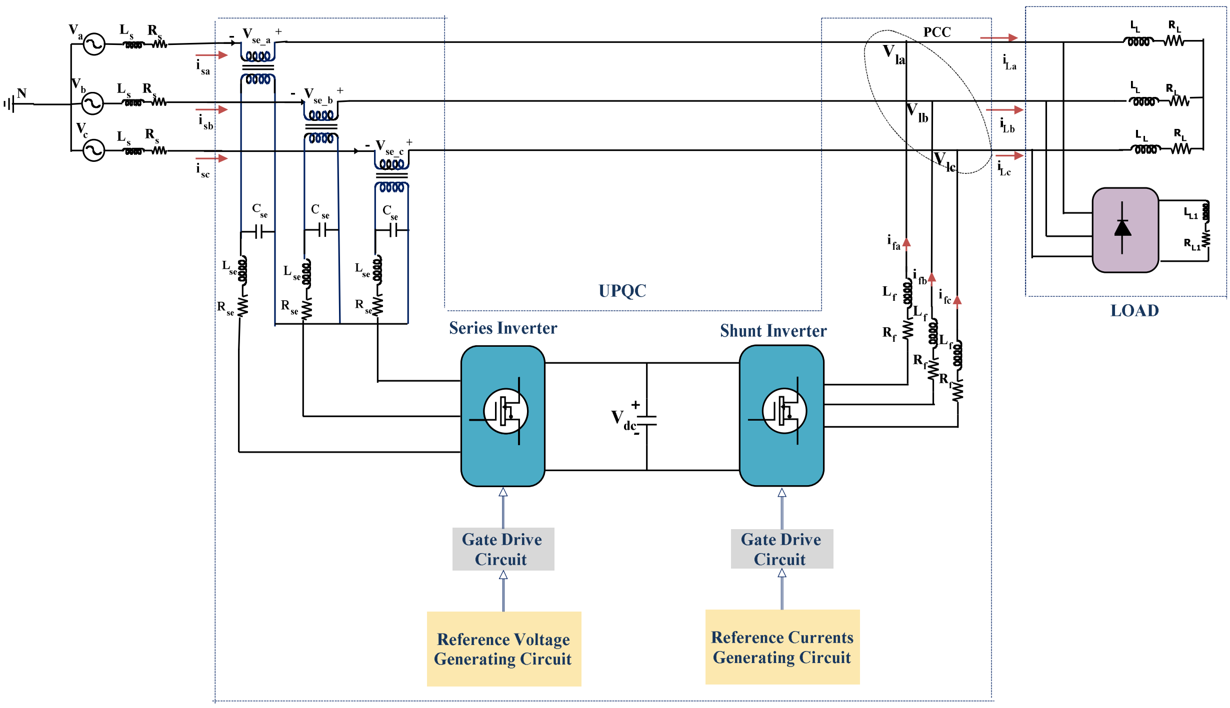


Fig. 2.3 Block diagram of UPQC

The block diagram consists of series inverter and shunt inverter connected back to back across a common DC-Link capacitor. The output of shunt inverter is connected to PCC through an inductor (L_{sh}) or isolating transformer. The series inverter output is connected to the injection transformers through a Low pass filter formed by L_{se} and C_{se} circuit. The operation of series APF is same as DVR and of shunt APF is same as DSTATCOM.

The shunt inductor is used for smoothening the current harmonics and also an interface between shunt inverter and PCC. The series LPF is used to inject only lower order harmonics in to the line. It also helps to provide isolation between the line and series inverter. The shunt inverter regulates the DC voltage across capacitor using a feedback controller which is tuned in such a way that its value remains fixed at set reference value under dynamic conditions with minimum over shoot and settling time.

2.5.1 TYPES OF UPQC

2.5.1.1 Classification based on the Physical Structure

Different UPQC topologies are utilized such as two, three phase three-leg (3P3L) VSIs with split capacitor, a three-phase three-Leg (3P3L) VSI for shunt APF and three-phase four leg(3P4L) VSI topology for series and two three phase- phase four-leg (3P4L) VSI topology for enhancing power quality in a three phase four wire system. For three phase three wire system (3P3W) it usually uses three two three phase three- leg VSIs. For single phase UPQC, the VSI may be based on two H-bridge inverters or half bridge inverters or single phase three-leg topology.

2.5.1.2 Classification based on UPQC system to compensate the voltage sag

The four existing methods to compensate voltage sag in literature are as follows:

a) **UPQC-P:** In this method, the injected voltage, which is equal to the reduced magnitude of nominal voltage at PCC, will be in series with the line, which involves injection of active power in to the line [1], [5]. In conventional UPQC, the shunt APF draws the required active power to be injected by the series APF and the losses occurred in shunt APF from supply, which increases the source current magnitude during voltage sag.

b) **UPQC-Q:** In this method the series voltage is injected in quadrature with the load voltage such that the voltage at PCC is equal to the rated voltage. Thus the voltage sag is mitigated by injecting the reactive power in to the system. Hence it is called UPQC-Q [6] method. The shunt APF maintains the source power factor at unity, which avoids the requirement of active power to compensate the voltage sag.

Here the resultant voltage achieved is greater than the voltage injected in UPQC-P for same percentage of voltage sag. Hence the rating of UPQC will be increased. Another disadvantage of UPQC-Q is its inability to compensate the voltage swell.

c) **UPQC-VA$_{min}$:** If the injected voltage is neither in series nor in quadrature with load voltage but makes an optimal angle with the source current such that the loading of UPQC will be min during the voltage sag condition is termed as UPQC-VA$_{min}$ method [1], [2], [5]. Another advantage of this method is that, at steady state, both shunt APF and series APF will supply the load reactive power demand, which reduces the rating of shunt APF.

d) **UPQC-S:** This method is similar to UPQC-VA$_{min}$, but the change is that the series APF is used to load up to its rated value. Thus the series APF delivers both active and reactive power [1]-[3], [5].

2.6 SUMMARY

The poor Power Quality causes a huge financial losses and inconvenience to the end users. To avoid this and to improve the reliability, the need of custom power distribution has arisen. Custom power devices are static power electronic controllers, includes DVR, DSTATCOM and UPQC with different topologies used to eliminate the power quality issues in distribution system. These will improve the service reliability and allows end users equipment to operate in an appropriate manner by mitigating voltage issues or current issues or both. In this chapter types of custom power devices, different possible topologies and their circuit configurations are discussed.

The next chapter explains about the photo voltaic power generating system using high step-up dc-dc converter and P&O MPPT technique.

CHAPTER 3

PHOTO VOLTAIC POWER GENERATING SYSTEM

Photo voltaic power generation uses solar cells to convert solar irradiation into electrical energy. A grid connected PV system converts light energy into electrical energy directly and thus it mainly reduces the energy extracted from the electrical utility. The development in power electronics and material science has helped to develop compact but efficient systems to withstand the high power demand. The PV cell exhibits nonlinear I–V and P–V characteristics. The series connected solar cells, which are basic building blocks of it, forms a PV module. These PV modules are connected either in series or in parallel depending upon its power rating forms a PV array. The maximum power produced varies with temperature and irradiance. Each cell has different current and voltage maximum positions as these have non-linear characteristics. But the power maximum point is unique, which mainly depends upon Temperature and Irradiation. To track that maximum power point, it is essential to use MPPT algorithm.

The maximum power point tracking (MPPT) algorithm is used to extract the maximum power from PV panels from instantaneous variations of irradiation, temperature and PV module characteristics.

3.1 SOLAR CELL

The PV array model is developed by the basic equations of photovoltaic cells, including the effects of temperature changes and solar irradiation level. Each cell is capable of producing 0.5- 2Volts. And here it is modeled to give 36V as its output using P&O MPPT, which acts as input to dc-dc boost converter.

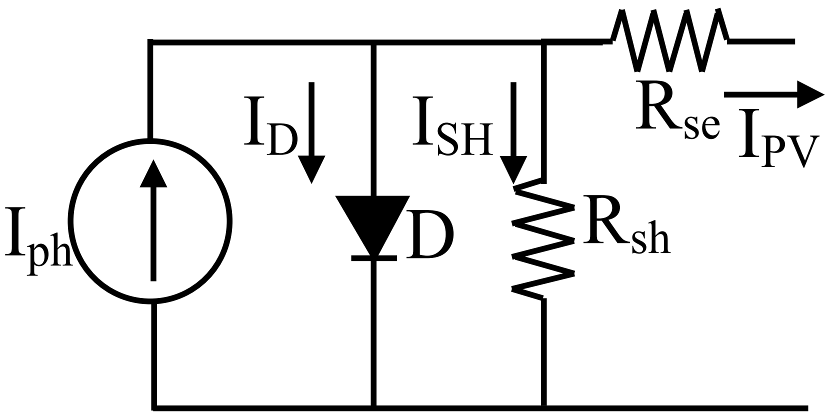


Fig. 3.1 Photo Voltaic Cell

The PV cell is modeled by using following equations:

$$I_{pv} = I_{ph} - I_s[\exp(\frac{q(V + I_{pv}R_S)}{N_s A K_b T}) - 1] - \frac{V + I_{pv}R_S}{R_{sh}} \qquad (3.1)$$

$$I_o = I_{rr}\left[\exp\left(\frac{qV}{K_b T}\right) - 1\right] \qquad (3.2)$$

$$I_{rr} = \frac{I_{ss}}{\left[exp\left(\frac{qV}{N_s A K_b T_c}\right) - 1\right]} \qquad (3.3)$$

$$I_S = I_{rr}\left({}^{T}/_{T_C}\right)^3 exp\left[\frac{qE_g\left(\frac{1}{T_C} - \frac{1}{T}\right)}{K_b N}\right] \qquad (3.4)$$

$$I_s = \frac{I_{sc} + K_i(T - T_C)}{exp\left(q\left(V_{oc} + \frac{K_v(T - T_c)}{A N_S K_b T}\right) - 1\right)} \qquad 3.5)$$

Where q is the charge the of electron= 1.602 $\times e^{-19}$C,

I_{rr} =Reverse saturation Current; I_S =Diode saturation current; V_{oc} = Open circuit voltage;

I_{sc} = Short circuit current; I_{ph} =Photo generated current; T= Actual temperature; T_C = Nominal temperature; K_i= Short circuit current temperature coefficient; K_b= Boltzmann constant; R_s= series resistance=0.001 Ω; N_S= Number of series cells.

3.2 P&O MPPT TECHNIQUE

Maximum Power Point Tracking technique uses maximum power transfer theorem, which states that, the output power is maximum when thevinins impedance of circuit is equal to the load impedance. Hence tracking the maximum power point is nothing but tracking the impedance matching point. There are many MPPT techniques available like perturb and observe technique, Perturb and Observe (P&O), Incremental Conductance method, Neural networks method, Fractional open circuit voltage method, Fractional short circuit current method, Fuzzy logic method [17], etc.,. The suitability of technique depends on different parameters like cost, application, dynamic performance and ease of implementation. Here we considered P&O MPPT technique for our application. The P&O MPPT uses only one voltage sensor. Hence it is cost effective and easy to implement.

The P&O MPPT algorithm states that when the power converter operating duty cycle varies and the PV array voltage is perturbed by a small increment and if the resulting change in power, ΔP is positive, then it means that it is going in the direction of MPP. Hence it keeps on perturbing in the same direction. If ΔP is negative then it means it is going away from the direction of MPP and the sign of perturbation is to be changed. Thus this method uses the sign of perturbation and sign of change in power to vary the duty cycle to be operated to track the MPP. The flow chart for P&O MPPT is shown in below fig. 3.2

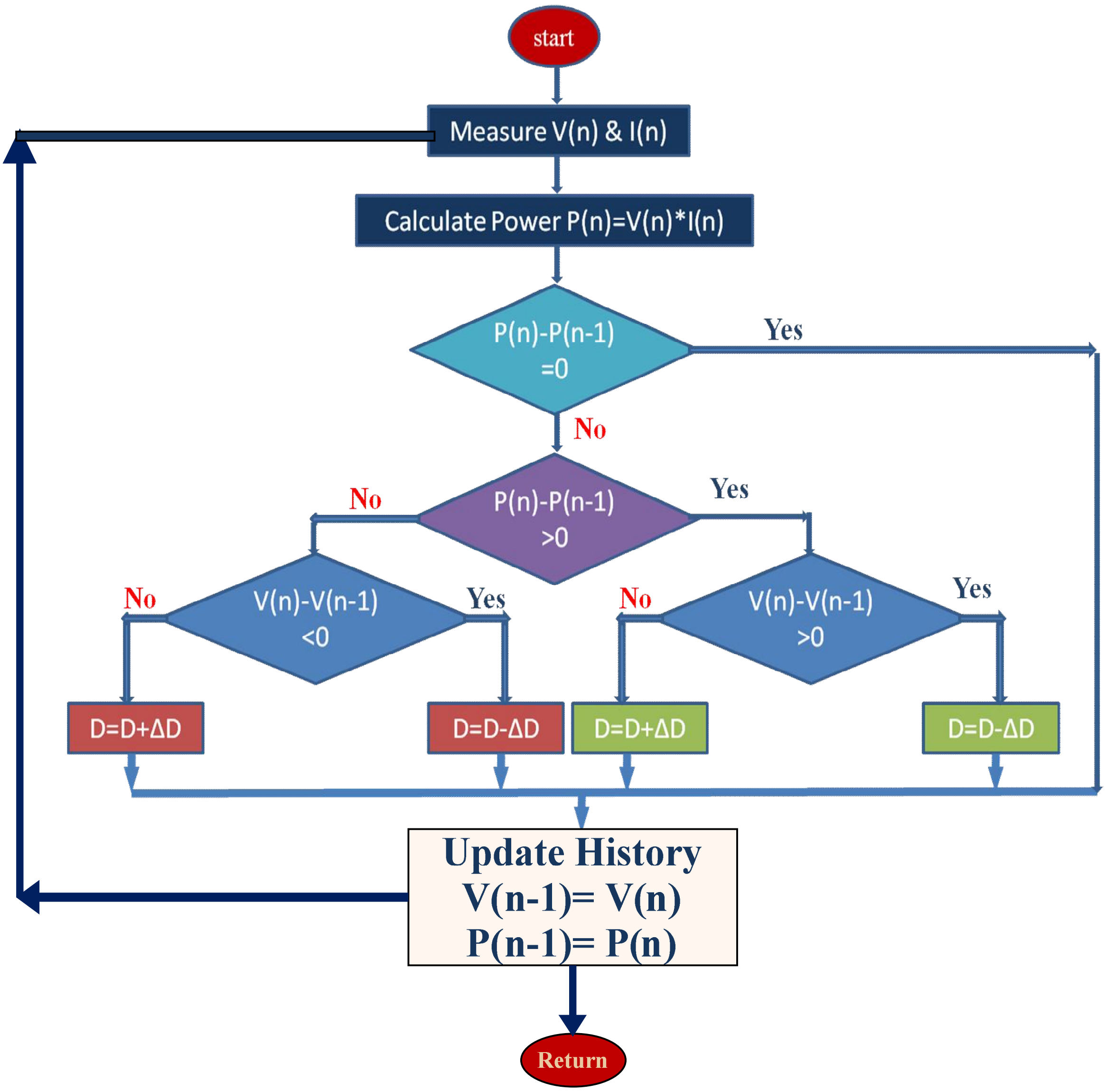


Fig. 3.2 Flow chart for Perturb and Observe MPPT algorithm

3.3 HIGH STEP-UP DC-DC CONVERTYER

The voltage generated using Perturb and Observe MPPT is not sufficient to maintain the voltage across DC-Link which is to be maintained around 650V (in the current project). Hence we use "a high step-up DC-DC converter" [24], which is having large conversion ratio, high efficiency and compact size. To achieve these requirements the present boost converter uses three capacitors, three diodes and one coupled inductor as shown in below fig. 3.3

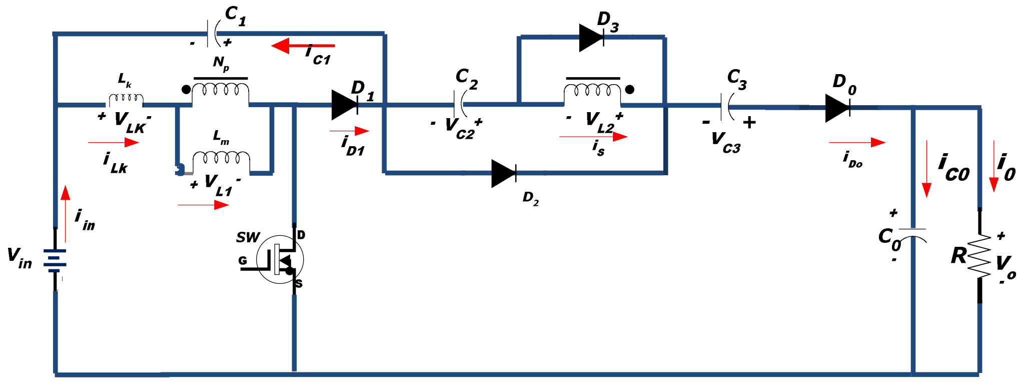


Fig. 3.3 High step-up DC-DC converter circuit diagram

The circuit consists of:

DC input voltage V_{in}, MOSFET switch SW, coupled inductors N_p and N_s, one clamp diode D_1, clamp capacitor C_1, two capacitors C_2 and C_3, two diodes D_2 and D_3, output diode D_o, and output capacitor C_o, magnetizing inductor L_m, leakage inductor L_k, and an ideal transformer. The capacitor C1 is used to recycle the energy stored by the Leakage inductor (L_k). Thus it clamps the voltage across switch, SW to a lower value which reduces the voltage stress on the switch. The CCM operation of the converter is explained below:

When switch is ON:

Diodes D_1, D_2 and D_3 are turned off and D_0 is turned ON. The current flows through the path as shown in fig. 3.4

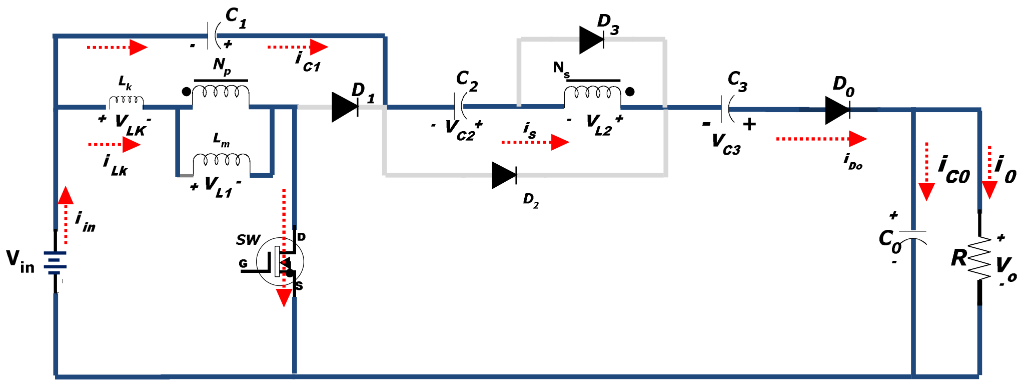


Fig. 3.4 High step-up dc-dc converter when switch is on

The magnetizing inductor stores the energy developed by the input source voltage, V_{in}. The same energy is transferred to the secondary side of the coupled inductor. Thus the voltages V_{in}, V_{C1}, V_{C2} and V_{C3} will be connected in series and it discharges the energy to the capacitor C_0 and load R. The output voltage is given by

$$V_0 = V_{in} + V_{c1} + V_{c2} + V_{c3} + V_{L2} \quad (3.6)$$

When switch is OFF:

Diodes D_1, D_2 and D_3 are turned on and D_0 is turned off. The current flow path is shown in fig. 3.5

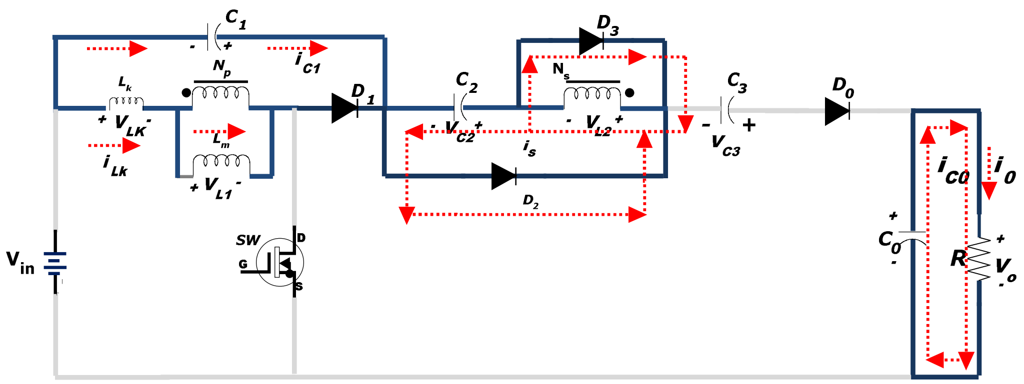


Fig. 3.5 High step-up dc-dc converter when switch is off

The energy stored in L_k and L_m are charged the clamping capacitor C_1. Output capacitor C_o discharges the energy to Load R. And t he energy saved in the magnetic inductor L_m is released via the secondary side of coupled inductor to charge the capacitors C_2 and C_3 in parallel. Here the voltage across capacitor C1 is given by:

(3.7)

Let *k* is the coupling coefficient, n is the coupled inductor turns ratio and D is the duty cycle then the voltages V_{C1}, V_{C2}, and V_{C3} are given by:

$$V_{c1} = \frac{D}{D-1} V_{in} \frac{(1+k)+(1-k)n}{2} \quad (3.8)$$

$$V_{c2} = V_{c3} = \frac{nDk}{D-1} V_{in} \tag{3.9}$$

$$V_{L2} = kV_{in} \tag{3.10}$$

Where V_{C1}, V_{C2}, and V_{L2} are voltage across capacitors and V_{L2} is the voltage across inductor respectively. Substituting the above equations gives the voltage gain as

$$\frac{V_0}{V_{in}} = \frac{1+nk}{1-D} + \frac{D}{1-D} \cdot \frac{(k-1)+n(1+k)}{2} \tag{3.11}$$

At k=1,

$$\frac{V_0}{V_{in}} = \frac{1+n+nD}{1-D} \tag{3.12}$$

The major role of this converter is to maintain constant voltage across the DC-Link of the two inverters by operating itself at the duty ratio of obtaining MPP of PV array. This duty ratio is obtained by Perturb and Observe MPPT algorithm.

The output voltage of the converter for an input voltage of 36 volts and operated at duty ratio (D) =0.65 is shown below fig. 3.6 and fig. 3.7:

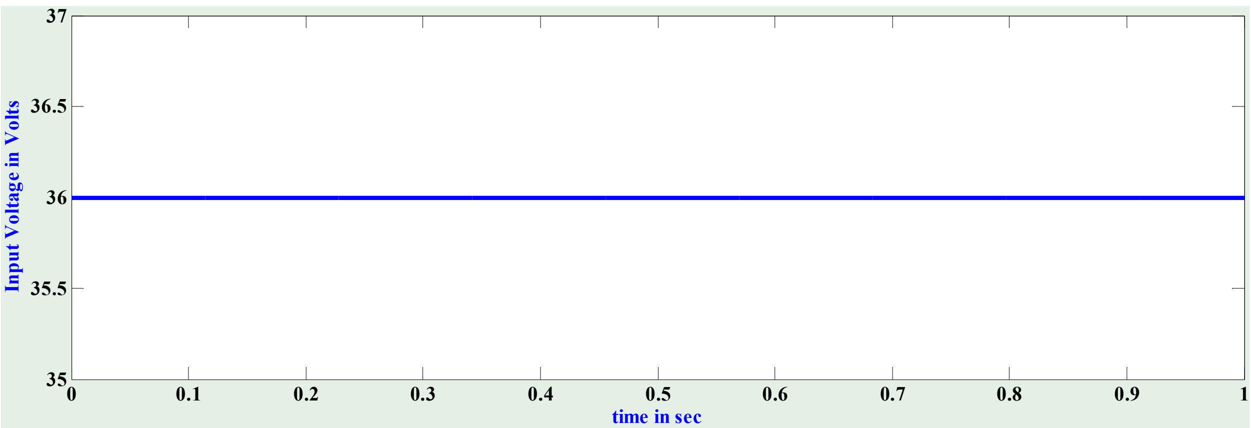


Fig. 3.6 Input voltage applied for high step-up dc-dc converter

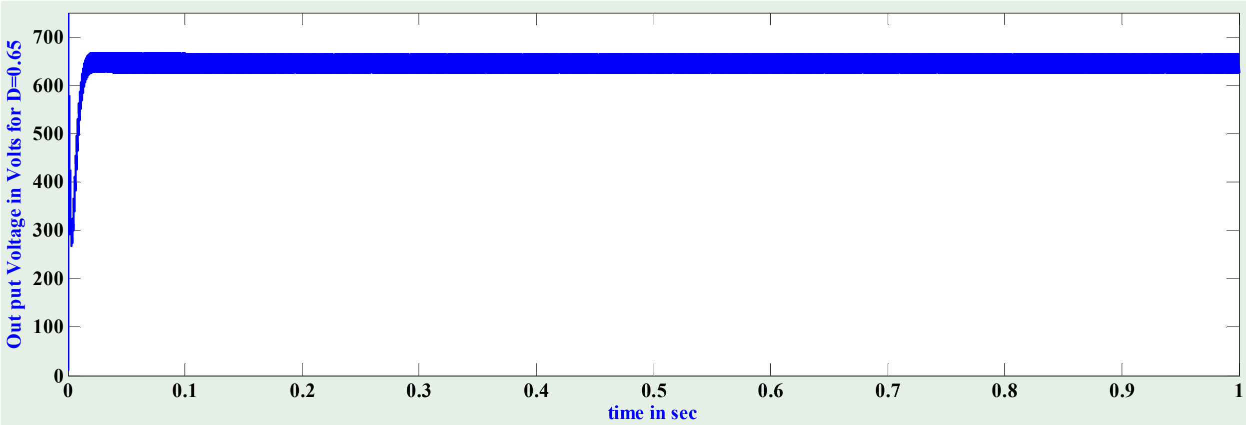


Fig. 3.7 Output voltage appeared across load for high step-up dc-dc converter

From the waveforms we can say that the high step-up DC-DC converter can be used to get a high voltage gain. It is also clamping the voltage across the switch to a low value (compared to its output voltage) using the clamping capacitor. the energy stored in leakage inductor will be recycled to charge the capacitors in parallel and thus increases overall efficiency of the system. These features made the present work to replace the conventional boost converter with high step-up DC-DC converter. Also we operate this converter at MPP of PV array by varying duty ratio according to the Perturb and Observe MPPT algorithm.

3.4 SUMMARY

The PV generating is used to convert irradiant power into real power. The increased need of grid support for continuity in power supply has led to incorporate the custom power devices in distribution system. But these devices can function optimally for a long term power quality issues only when they had enough back up during situations like interruption. This back up is provided using the PV array along with its MPPT operated boost converter. This chapter describes briefly the modeling of solar cell, need of MPPT algorithm and the operation of high step-up DC-DC converter to achieve a high voltage gain along with its advantages. At the end the simulation result for high step-up boost converter for an input voltage of 36 volts is shown to indicate its voltage lift capability. P&O MPPT technique is being used to generate the required duty ratio, which is simple and easy to implement.

CHAPTER 4

PROPOSED CONTROL STRATAGY

4.1 PROPOSED SYSTEM DESCRIPTION

The PV-UPQC system consists of two voltage source inverters, a common DC-link capacitor which acts as source, PV array and a high step-up boost converter operating with MPPT algorithm. The block diagram of the proposed system is shown in below fig. 4.1.

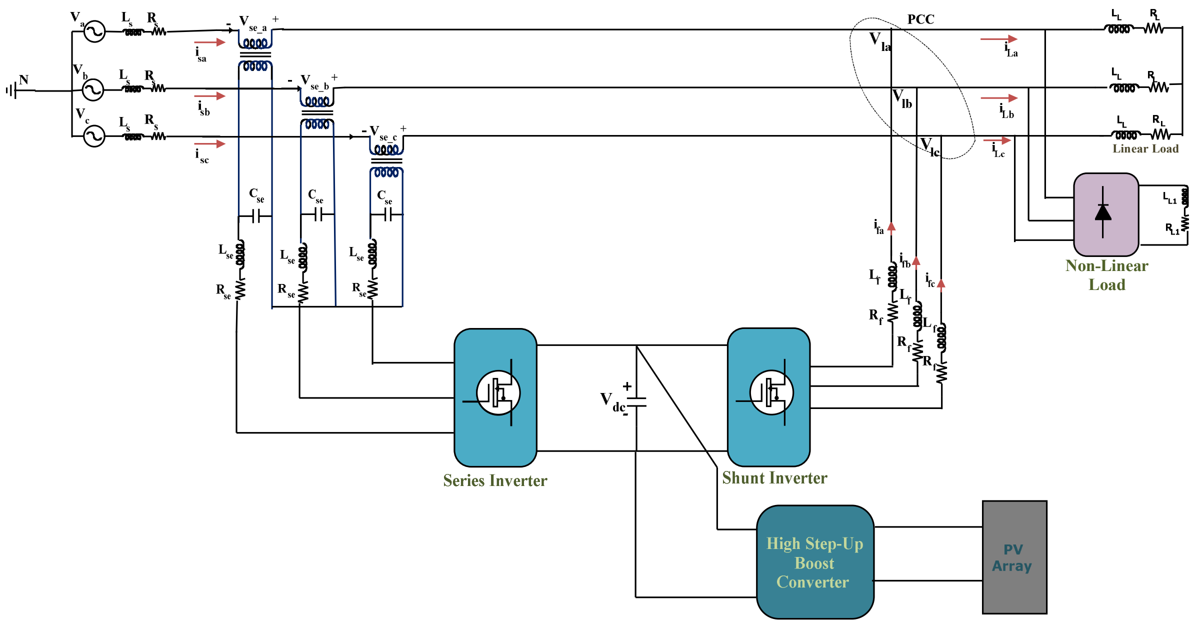


Fig. 4.1 System description block diagram

A three phase source of rated voltage 326 Volts (L-G$_{peak}$) is connected to the load through a feeder having an impedance of 1+**j** 0.314 *Ω*. The Load considered here is of combination of linear load and non-linear load. The linear load may be thought of a transformer or an induction motor or any other load which can be modeled as an R-L load in distribution system whose rating is 5KW +j5KVAR. The non-linear load is diode bridge rectifier with R-L load.

The series APF consists of a three phase injection transformer which is connected in series with the line which is used to inject the compensating voltage and provides isolation. This voltage is generated by the three phase three-leg series inverter connected across the DC-

Link. The series inverter is connected to the series injection transformer through an LPF formed by R_{se}, L_{se} and C_{se}, whose purpose is to remove distortions resulted by switching of inverter. The shunt APF is used to inject the current at PCC through the inductor filter to mitigate the current harmonics and to maintain a constant voltage across the DC-Link.

The PV array is connected to the grid through the UPQC. It uses the high step-up DC-DC converter whose operating duty ratio is generated by Perturb and Observe MPPT algorithm. The output of this high step-up boost converter is connected across the dc-link, whose voltage remains constant.

4.2 GENERATION OF REFERENCE VOLTAGES FOR SERIES APF

The generation of reference voltages for series APF is based on the power angle control scheme. The brief explanation and advantages of the scheme is explained in the following section.

4.2.1 POWER ANGLE CONTROL SCHEME

The rating of series APF used in UPQC depends upon the maximum percentage of sag/swell that it should compensate. But these are of small duration issues. But the shunt APF operates as long as the non-linear currents are drawn from the source. It supplies the reactive power continuously, which leads to increased utilization of it compared to series APF. The power angle control scheme is mainly used to increase the utilization factor of series APF without causing any additional burden on it. Here the series APF is used to share a part of load reactive power demand along with compensating voltage sag/swell by creating a power angle difference between source voltage and load voltage.

The compensation of sag can be done by active power approach or reactive approach or by both of these in UPQC. Here this scheme uses both active and reactive power approach to compensate the sag/swell by maintaining a constant load voltage. The operation is better explained using the phasor diagram shown in below fig. 4.2

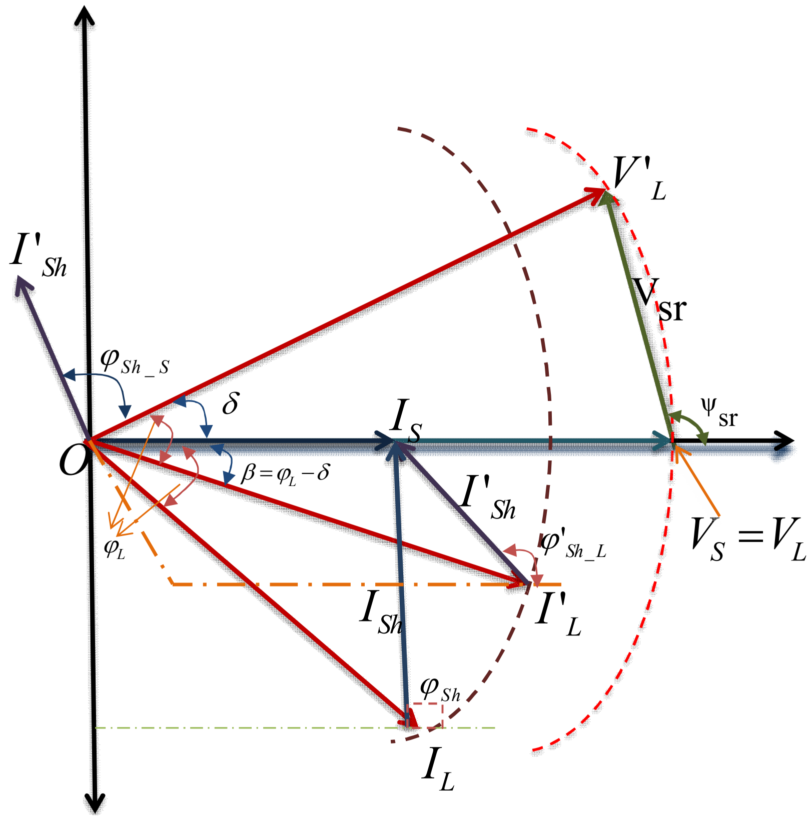


Fig. 4.2 Phasor representation of PAC scheme

Let $|V_{sr}| = |V_L| = |V_L^*| = k$ be the required voltage magnitude. And its assumed to have no sag/swell initially and the load current is I_L and phase angle is $\boldsymbol{\varphi}_L$. When we inject a series voyage of $V_{sr} \angle \psi_{sr}$ such that the resultant voltage across PCC is constant, then its load current varied to I_L' and creates a phase angle reduces to φ_L' due to the creation of a power angle, between the source and load voltages. This reduces the amount of reactive power supplied by the source i.e. that same amount of reactive power is supplied by the series APF. And the shunt APF needs to supply the remaining reactive power demanded by load. Hence it can be rated accordingly. Thus by controlling the power angle, we can reduce the burden on shunt APF and can improve the utilization factor of series APF.

Let the fluctuation in supply voltage (v_x) because of voltage sag/swell from reference load voltage is expressed as:

$$k_f = \frac{V_s - V_L^*}{V_L^*}$$, where K_f is the fluctuation factor (4.1)

Then from the phasor diagram we can calculate the required series injected voltage V_{sr} and angle (ψ_{sr}) as:

$$V_{sr} = \sqrt{2} * k * \sqrt{1 - \cos\delta}$$

(4.2)

$$\psi_{sr} = 180^\circ - \angle\gamma = 180° - \tan^{-1}\left(\frac{\sin\delta}{1-\cos\delta}\right)$$

(4.3)

$$\delta = \sin^{-1}\left[(1+k)\left(\frac{Q_L - Q_{sh,\max}}{P_L}\right)\right]$$

(4.4)

Where V_{sr}= series injected voltage

V_L = Load Voltage

V_L' = Resultant Load voltage

V_L^* = Reference Load voltage

ψ_{sr} = Series injected phase angle

δ = Power angle

P_L = Load active power

Q_L = Load reactive power

$Q_{sh,\max}$ = Maximum reactive power rating of shunt inverter

4.2.2 REFERENCE VOLTAGES CALCULATION FOR SERIES INVERTER

The reference voltages generation for series inverter using PAC approach can be done in two steps. The first step is to insert the required dc component to mitigate the sag voltage and the second step is to create power angle difference between the source and load voltages.

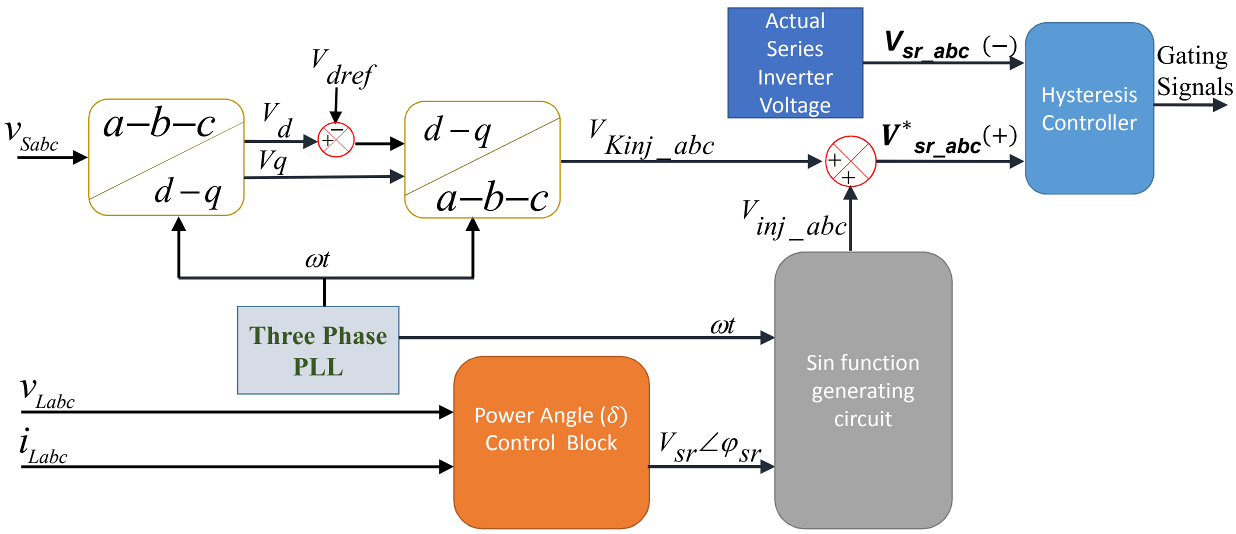


Fig. 4.3 Reference voltage signal generation block diagram for series inverter

The first step is carried out by transforming the source voltage into d-q frame using the parks transformation. Then the actual d-axis voltage (V_d) is compared with the reference voltage (V_{dref}). The difference signal will indicates the error component which represents sag/swell and supply voltage harmonics present in the supply.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix}_{ref} = \begin{bmatrix} V_d \\ V_q \end{bmatrix} - \begin{bmatrix} V_{dref} \\ 0 \end{bmatrix}$$

(4.5)

This error component will be transformed into a-b-c coordinates (V_{kinj_abc}) using inverse Park's transformation. During the second step, this error component is added to the $V_{sr}\angle\psi_{sr}$ measured from power angle control measurement block using equations (4.1) to (4.4) and the output voltage , $V^*_{sr\_abc}$, is compared with series APF output voltage for the PWM pulse generation of series APF inverters using Hysteresis controller. For tracking the supply frequency it uses PLL. The complete approach is summarized in the block diagram shown in fig. 4.3.

4.3 GENERATOIN OF REFERENCE CURRENTS FOR SHUNT INVERTER

The reference currents for shunt inverters are generated using modified p-q theory. Here we are using the two HSFs in place of classical extraction filters such as LPF and HPF, which are used to extract the fundamental components of both voltage and current directly from $\alpha - \beta$ frame.

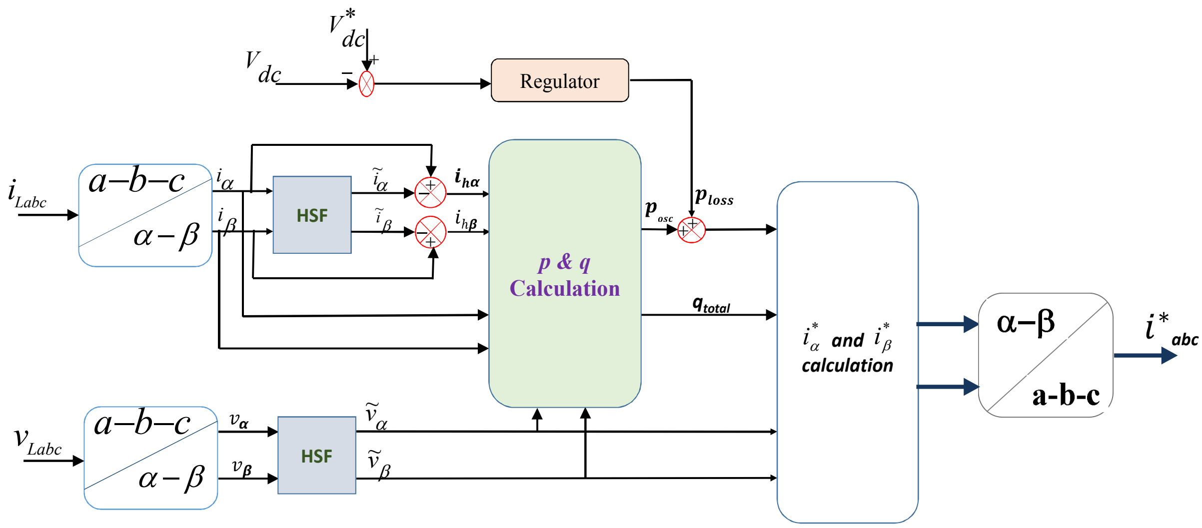


Fig. 4.4 Control block diagram for modified instantaneous *p-q* Theory

The line currents are transformed to α-β frame using the a-b-c to α-β coordinates using Clarke's transformation. Using HSF the fundamental current is being extracted and compared with actual current. The difference current will gives the required Harmonic currents $i_{h\alpha}$ and $i_{h\beta}$.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{4.6}$$

$$\begin{bmatrix} i_{h\alpha} \\ i_{h\beta} \end{bmatrix} = \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} - \begin{bmatrix} \tilde{i_{\alpha}} \\ \tilde{i_{\beta}} \end{bmatrix} \tag{4.7}$$

Similarly using HSF, the fundamental components of Load voltages are extracted after transforming it into α-β frame. These will be used to calculate the instantaneous oscillating active and total reactive components of power.

$$\begin{bmatrix} v_{\alpha} \\ v_{\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} \tag{4.8}$$

$$\begin{bmatrix} p_{osc} \\ \tilde{q} \end{bmatrix} = \begin{bmatrix} \tilde{v}_{\alpha} & \tilde{v}_{\beta} \\ -\tilde{v}_{\beta} & \tilde{v}_{\alpha} \end{bmatrix} \begin{bmatrix} i_{h\alpha} \\ i_{h\beta} \end{bmatrix} \tag{4.9}$$

But the total reactive power is given by $q = \tilde{q} + \hat{q}$ i.e.,

$$q = i_{\beta}\tilde{v}_{\alpha} - i_{\alpha}\tilde{v}_{\beta} \tag{4.10}$$

The loss component of power is added to the oscillating component of active power. The loss component of power is proportional to the difference between V_{dc}^{*} and V_{dc} .PI controller is used to regulate the voltage across dc-link and is used to measure the loss component of power directly. These are used to generate the reference currents in α-β frame using following equations.

$$p_{loss} = K_p(V_{dc}^{*} - V_{dc})^2 + K_i \int (v_{dc}^{*} - v_{dc})^2\, dt \tag{4.11}$$

$$\begin{bmatrix} i_{\alpha}^{*} \\ i_{\beta}^{*} \end{bmatrix} = \frac{1}{v_{\alpha}^2 + v_{\beta}^2} \begin{bmatrix} v_{\alpha} & v_{\beta} \\ -v_{\beta} & v_{\alpha} \end{bmatrix} \begin{bmatrix} -p_{osc} + p_{loss} \\ -q \end{bmatrix} \tag{4.12}$$

These are transformed into a-b-c frame using the inverse Clarke transformation:

$$\begin{bmatrix} i_{a}^{*} \\ i_{b}^{*} \\ i_{c}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{\alpha}^{*} \\ i_{\beta}^{*} \end{bmatrix} \tag{4.13}$$

The measured currents are compared with actual shunt APF currents in order to generate the gating signals for shunt inverter using Hysteresis controller. The corresponding block diagram is shown in fig. 4.4.

4.4 EXTRACTING FUNDAMENTAL COMPONENT USING HSF

The performance of modified instantaneous active- reactive power method depends upon how accurately we generate the harmonic currents in reference current generation. This mainly depends upon the Filter we used to extract the fundamental. The conventional LPF and HPF had lower bandwidth and hence create a measurement delay. And this creates a sluggish response which should be avoided to protect the sensitive equipment. This problem can be alleviated by using the High Selectivity Filter (HSF) as it suppresses the negative sequence field produced by unbalance or distortion in the signal. And it allows only fundamental component, which is selected as its cut-off frequency to pass through it in $\alpha - \beta$ frame. The other advantages of the HSF includes: operates effectively in transient state and offers unity gain at the fundamental frequency.

The integration in the synchronous reference frame is defined for an instantaneous signal U_{xy} is given by:

$$V_{xy}(t) = e^{j\omega t} \int e^{-j\omega t} U_{xy}(t) dt \tag{4.14}$$

The transfer function of the system can be expressed as:

$$H(s) = \frac{V_{xy}(s)}{U_{xy}(s)} = \frac{s + j\omega}{s^2 + \omega^2} \tag{4.15}$$

Here a constant K is introduced in the transfer function H(s), to obtain a cutoff frequency ω_c in the HSF. Now, the new transfer function is:

$$H(s) = \frac{V_{xy}(s)}{U_{xy}(s)} = k \frac{(s + K) + j\omega_c}{(s + K)^2 + j(\omega_c)^2} \tag{4.16}$$

Where, X can either be a current or a voltage. The above equations can be expressed as follows:

$$\hat{X}_{\alpha} = \frac{k}{s}\left[X_{\alpha}(s) - \hat{X}_{\alpha}(s)\right] - \frac{\omega_c}{s}\left[\hat{X}_{\beta}(s)\right] \quad (4.17)$$

$$\hat{X}_{\beta} = \frac{k}{s}\left[X_{\beta}(s) - \hat{X}_{\beta}(s)\right] - \frac{\omega_c}{s}\left[\hat{X}_{\alpha}(s)\right] \quad (4.18)$$

The block diagram of the HSF for a cut-off frequency ω_c, is shown in figure for extracting the fundamental component $X_{\alpha\beta}(s)$ from the signal $\hat{X}_{\alpha\beta}(s)$ in the α-β reference frame is shown in below fig. 4.5.

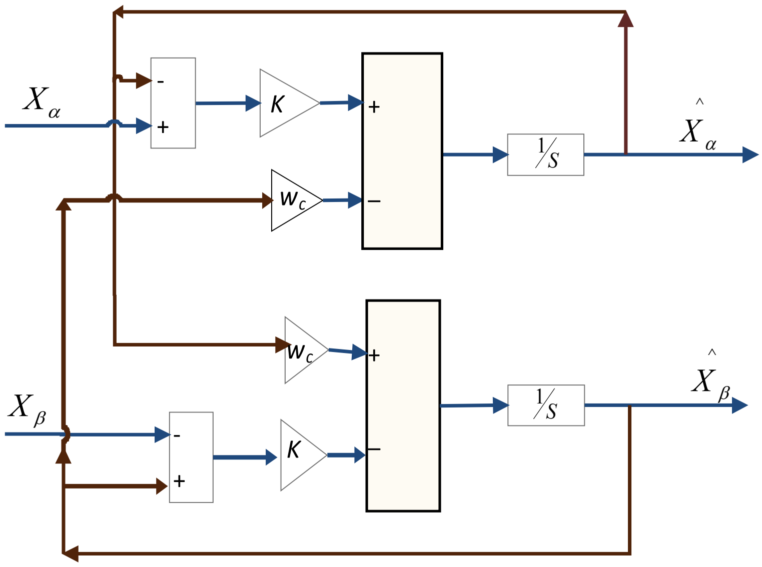


Fig. 4.5 Block diagram of HSF

Here the selectivity and dynamic response of the filter and hence reference signal generation depends upon the value of gain 'K'. Hence it should be selected optimally.

4.5 GATING SIGNAL GENERATION FOR SHUNT AND SERIES APF

Hysteresis band control method is used to generate the switching commands for both the series and the shunt inverters. It has good dynamic performance and limits the peak current in addition to ease in its implementation.

The inverters in shunt and series APFs constitute of two switches (S_{xx} and S'_{xx}) in each leg and the gating signals given to these are complementary to each other. Here the first suffix 'x' indicates series or shunt APF and the second suffix 'x' indicates phase leg such as a, b or c of the particular inverter. Hysteresis band controller is a feedback control system with two level comparators. The actual signals and the reference signals obtained from the control circuits are fed to the comparators. There it generates the error signal. If the error signal generated here is greater than the upper band i.e. the switch S_{xx} is OFF. If it is less than the lower band then S_{xx} is ON. As the inverters switches of a particular leg is having complementary switching scheme, switch (S'_{xx}) complementary to S_{xx}. Hence the switching commands are given according to its tolerance bands specified ($\pm h$). This scheme for both shunt APF and series APF is shown in table below:

	$i_{fx} > i_x^* + h1$	$i_{fx} \leq i_x^* + h1$
S_{xx}	0	1
S_{xx}'	1	0

Table 1(a). The gating signal for series APF using Hysteresis band controller

	$V_{sr} \geq V_{inj}^* + h_2$	$V_{sr} < V_{inj}^* + h_2$
S_{xx}	0	1
S'_{xx}	1	0

Table 1(b). The gating signal for shunt APF using Hysteresis band controller

In the current project, we considered the tolerance band for reference voltage generation is h=$\pm$6 volts and for reference current signal generation is h=± 0.5A.

4.6 SUMMARY

The performance of UPQC depends on how accurately the reference signals are generated for the APFs. This chapter provides the complete description about the power angle control scheme and modified p-q theory to generate the reference signals accurately for the series and shunt APFs respectively. It also describes how the PAC approach is useful to reduce the cost and the burden on shunt APF. To increase the performance of shunt APF the conventional filters are replaced by HSF in shunt APF. This HSF is used to reduce the harmonic distortion in the line to a great extent. The dynamic performance of system is improved by using the Hysteresis controller for generating the switch commands to the inverters with suitable hysteresis band selection.

Next chapter presents the information about system parameters selected for the current project and presents the simulation results carried out to show the performance of the proposed system.

CHAPTER 5

SIMULATION RESULTS AND DISCUSSION

The simulation results are carried out by considering both Linear and Non-Linear Loads. The PV-UPQC system parameters are rated as below:

Source:	System Voltage (L-G) = 326V
	System Frequency, f= 50 Hz
Load: `	Linear Load of rating= 5KW +j5KVAR and
	Non-Linear Load: Diode bridge rectifier with R-L load;
	where R_L=30Ω and L_L=1mH.
Feeder:	Impedance = 1+**j** 0.314 Ω
The Series APF parameters:	R_{se}=0.6; L_{se}=4.2 mH; C_{se}= 60µF;
	Injection transformer rating: 1:1, 120 Volts
The Shunt APF parameters:	L_f = 2.5 mH; and R_f = 5mΩ;
	DC Link Capacitor, C_{dc} =2200µF;
	DC-Link Voltage, V_{dc}= 650 V;
PI Controller:	K_p= 0.1; and K_I= 20;
PV Array:	No. of series cells= 6×8,
	Voltage at MPP= 36Volts,
	Current at MPP= 7Amps,
	Nominal voltage= 12Vots;
High Step-Up DC-DC Converter:	DC input voltage = 36 V
	Output Voltage = 650V
	Capacitors C_1= 56µF, C_2=C_3= 22µF and C_0 = 180µF;
	N_p:N_s = 1:4, L_m =48µH;

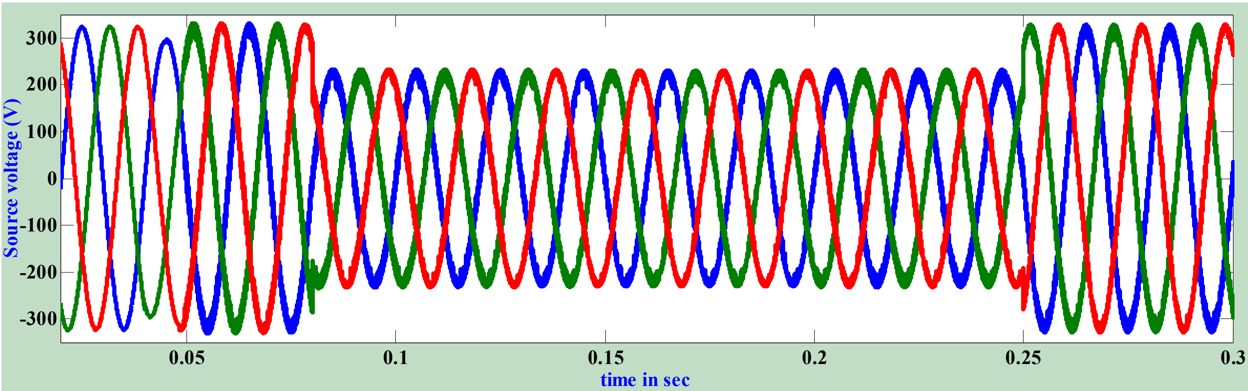
Switching frequency = 50 KHz;

The initial Load power factor of load = 0.837

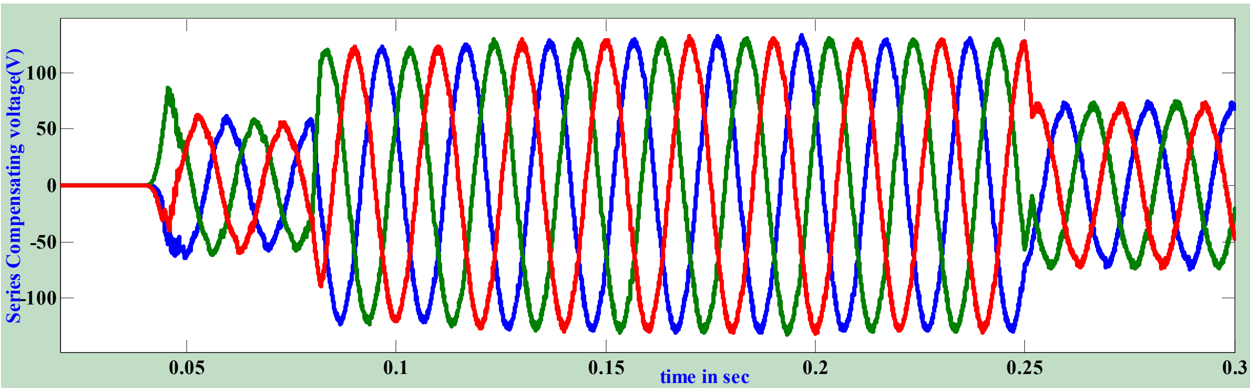
The proposed PV-UPQC is evaluated using MATLAB/Simulink software for voltage Sag, Swell and Interruption and the simulation results are given below.

5.1 RESULTS FOR VOLTAGE SAG

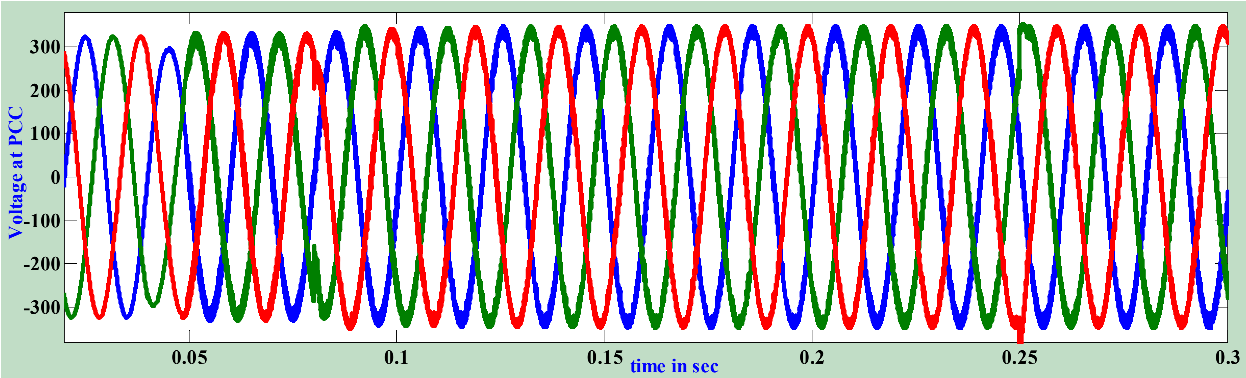
In this case, the results are carried out for 29.5% voltage sag, which is occurred between time t=0.08sec and t=0.25 sec.



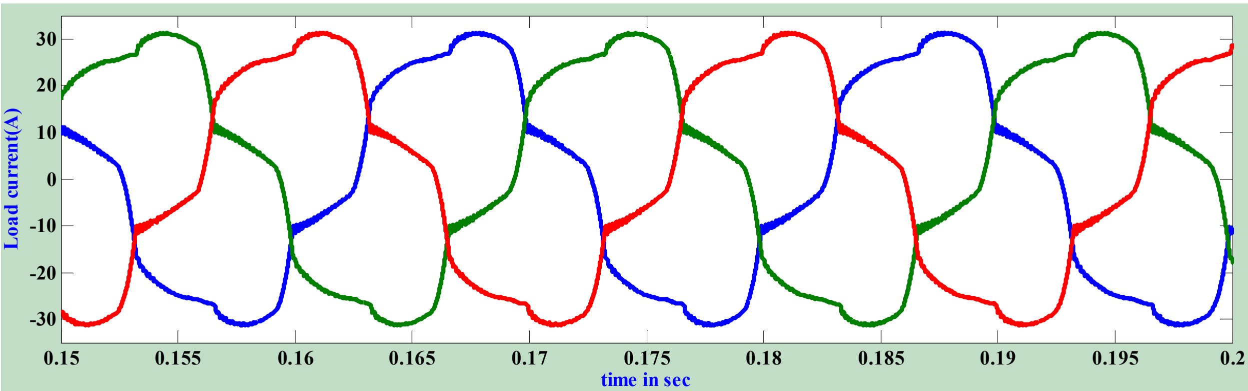
(a) Source Voltage



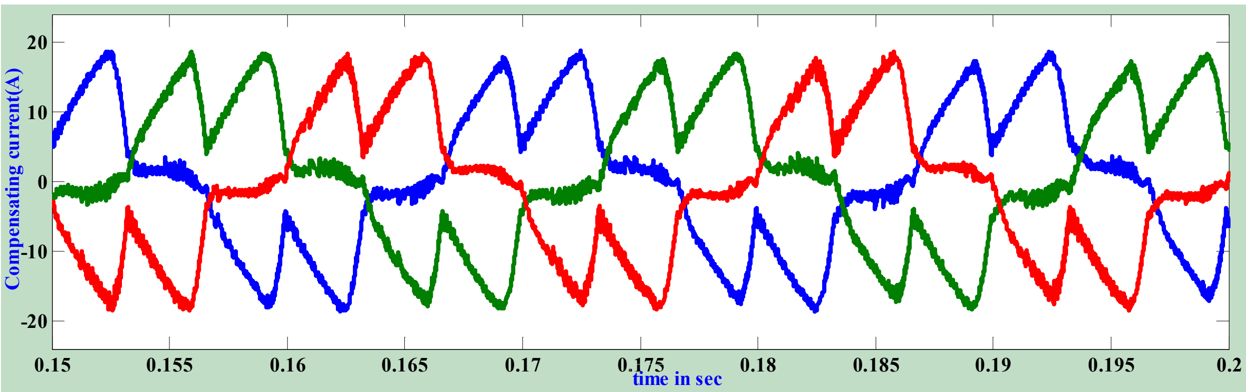
(b) Series Compensating Voltage



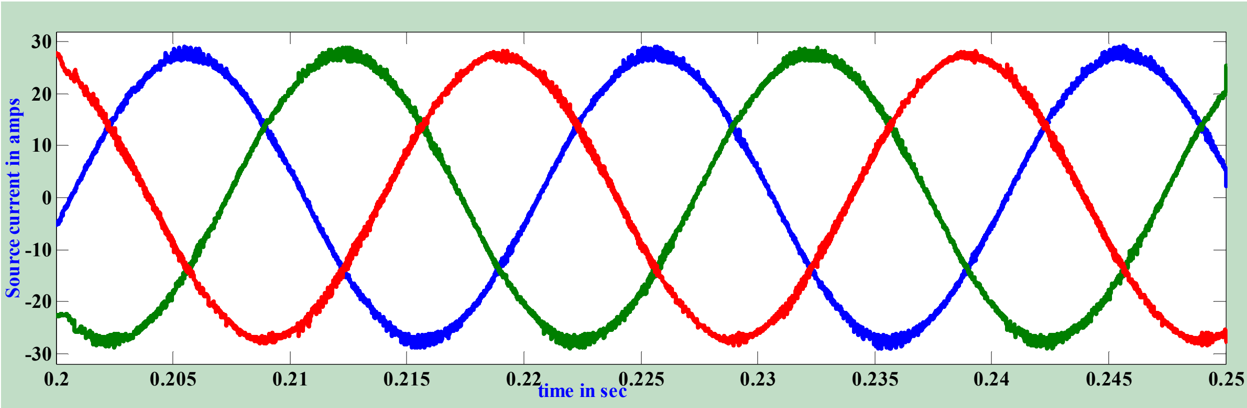
(c) Voltage across PCC



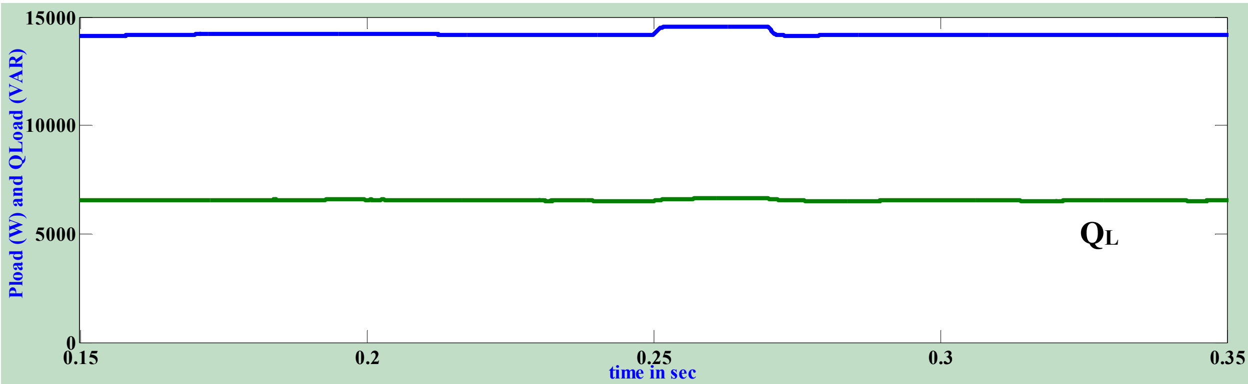
(d) Load Current



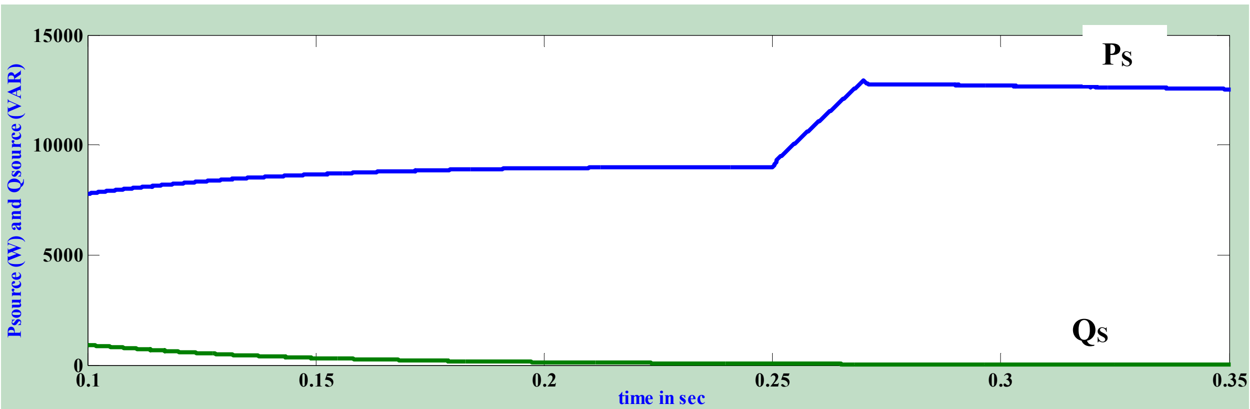
(e) Compensating current supplied by shunt APF



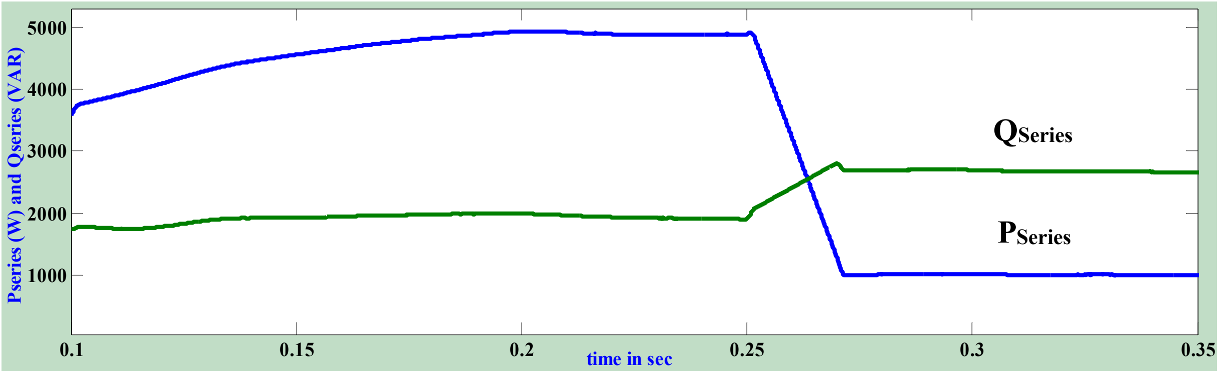
(f) Source current after compensation



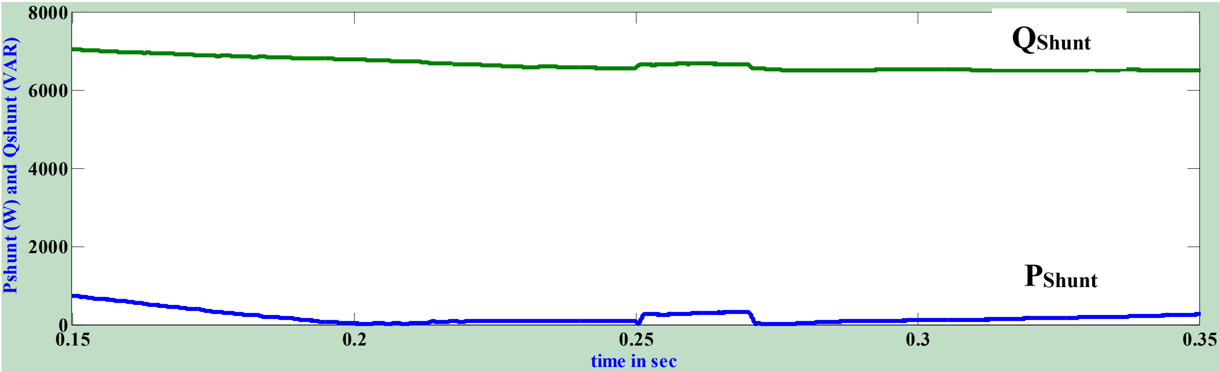
(g) Load demanded active and reactive power



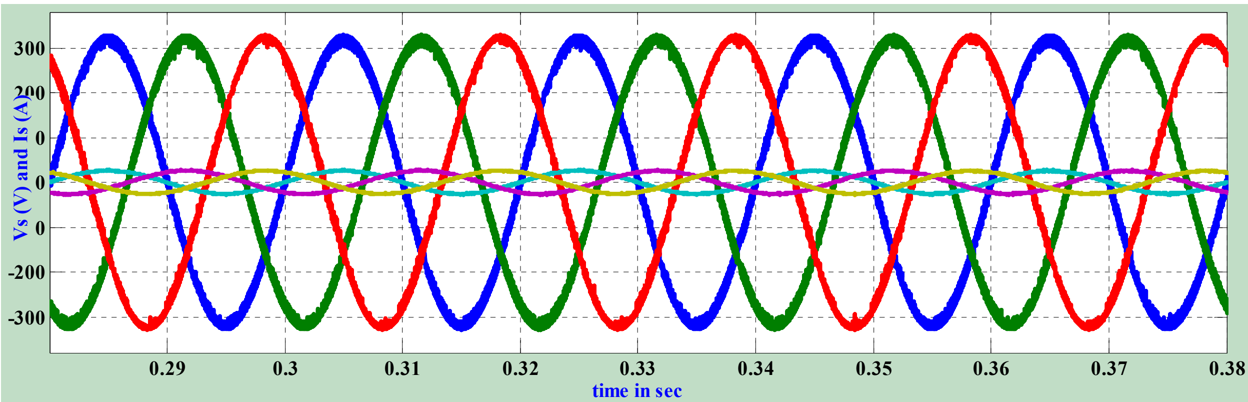
(h) Source supplied active and reactive power



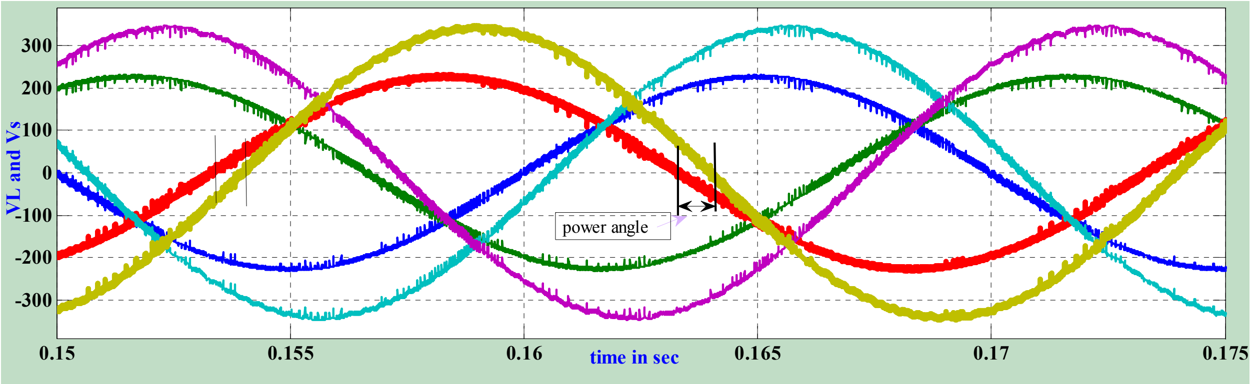
(i) Active and Reactive power supplied by Series APF



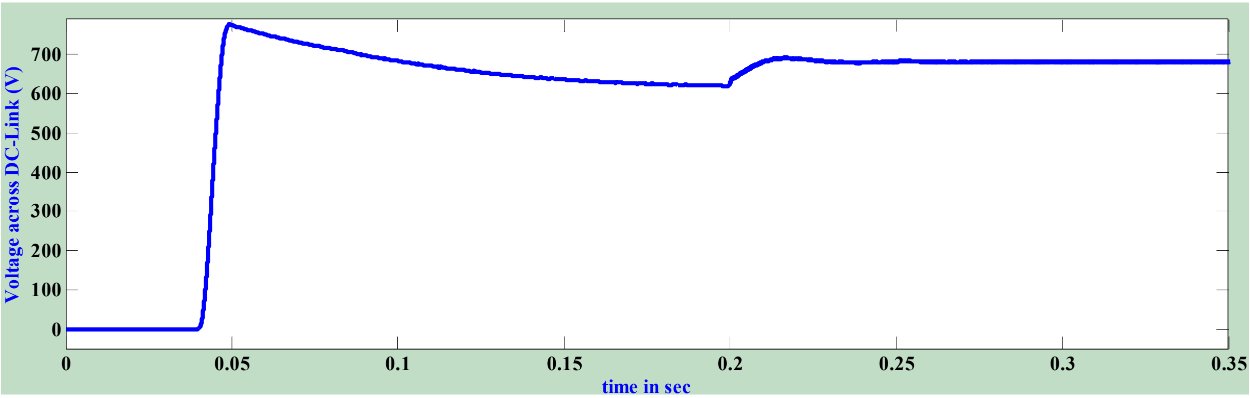
(j) Active and Reactive power supplied by Shunt APF



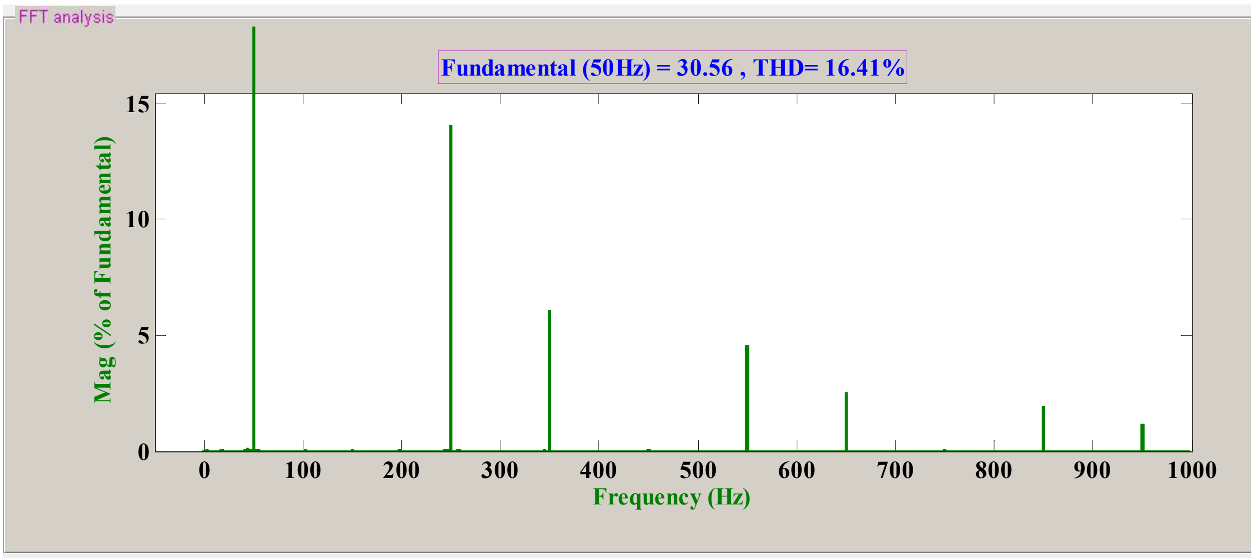
(k) Variation of V_S and I_S after compensation



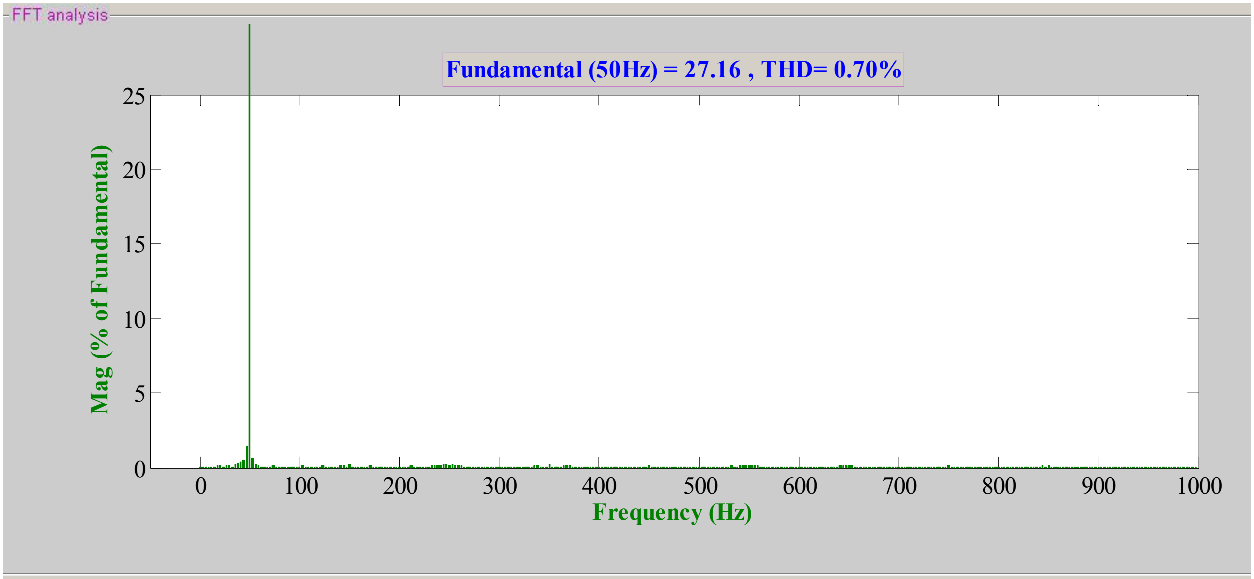
(l) Variation of V_S and V_L (δ= 12.86°)



(m) Voltage across DC-Link



(n) FFT analysis of Load current

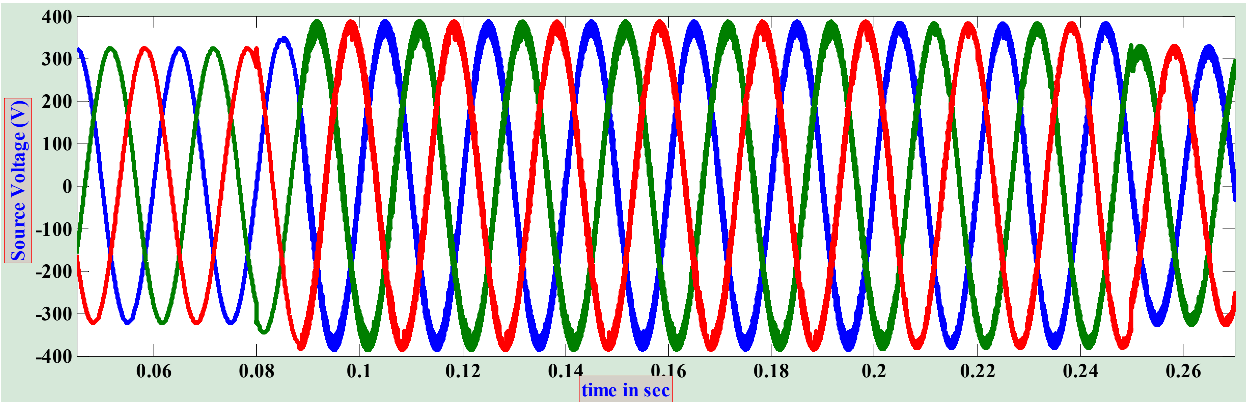


(o) FFT analysis of Source current

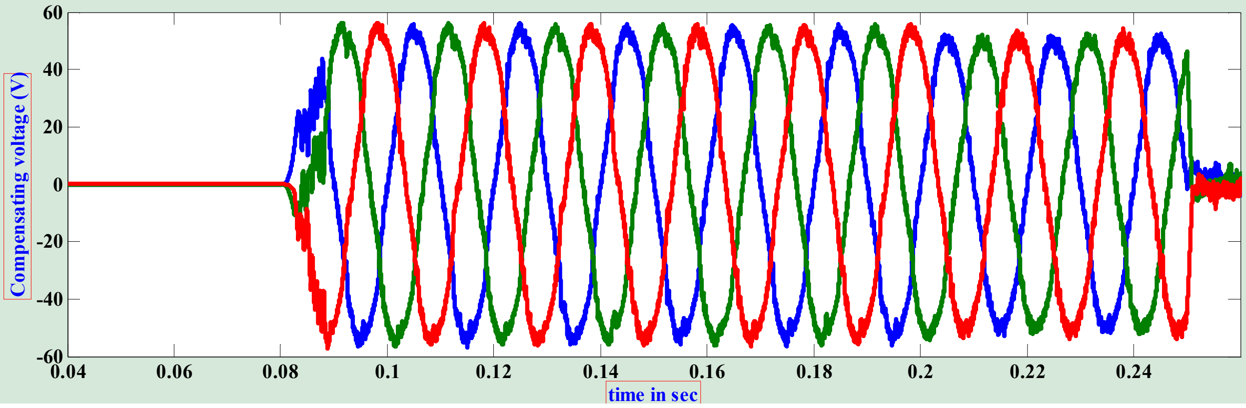
Fig. 5.1 Simulation results under voltage sag condition

5.2 RESULTS FOR VOLTAGE SWELL

In this case, the results are carried out for 16.56% voltage Swell, which is occurred between time t=0.08sec and t=0.25 sec.

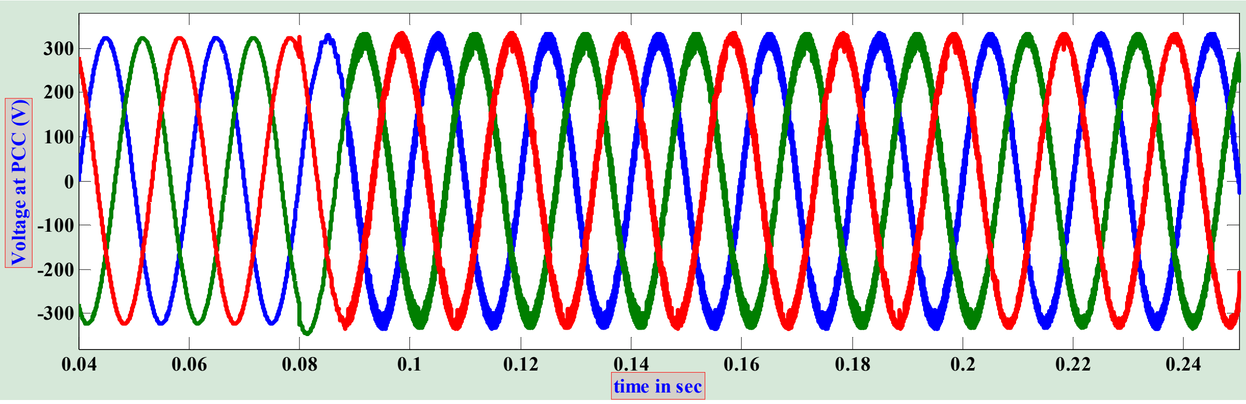


(a)) supply voltage

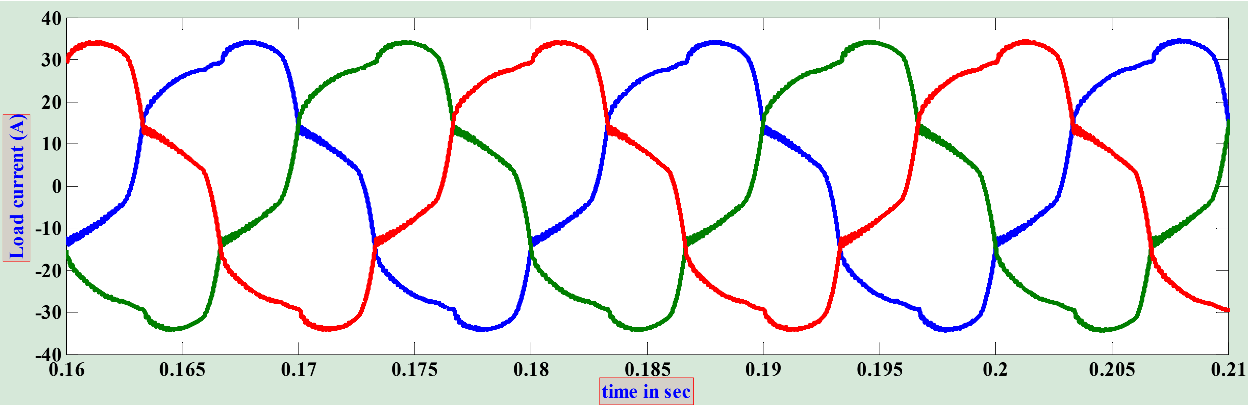


(b)) series inverter injected

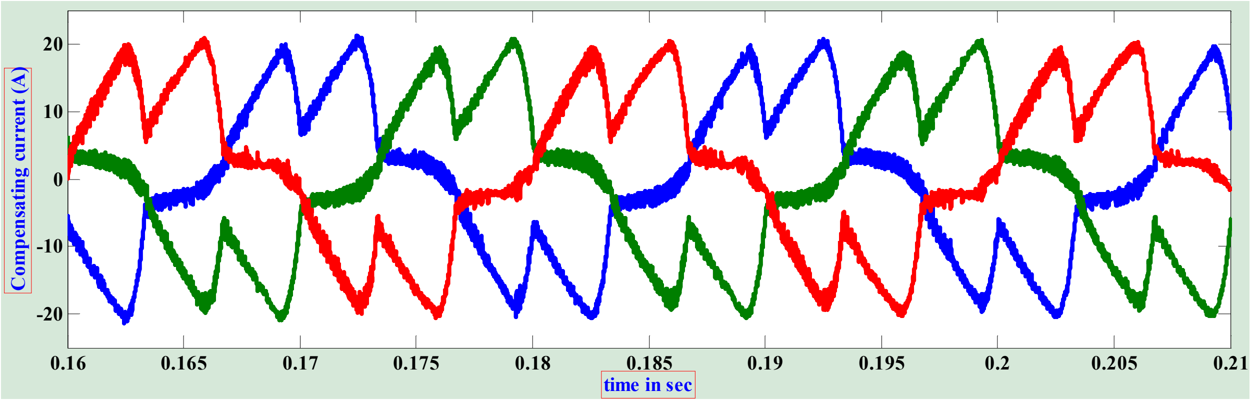
voltage



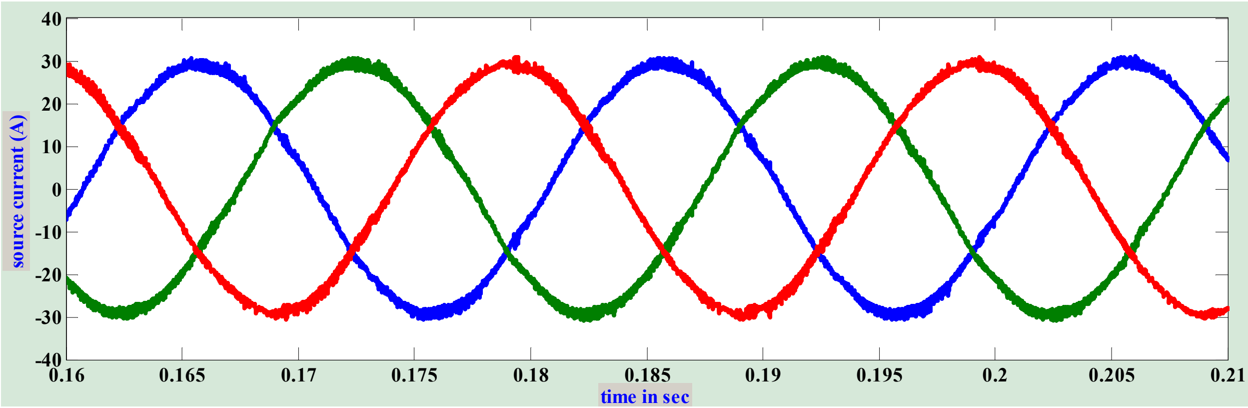
(c) Voltage across PCC



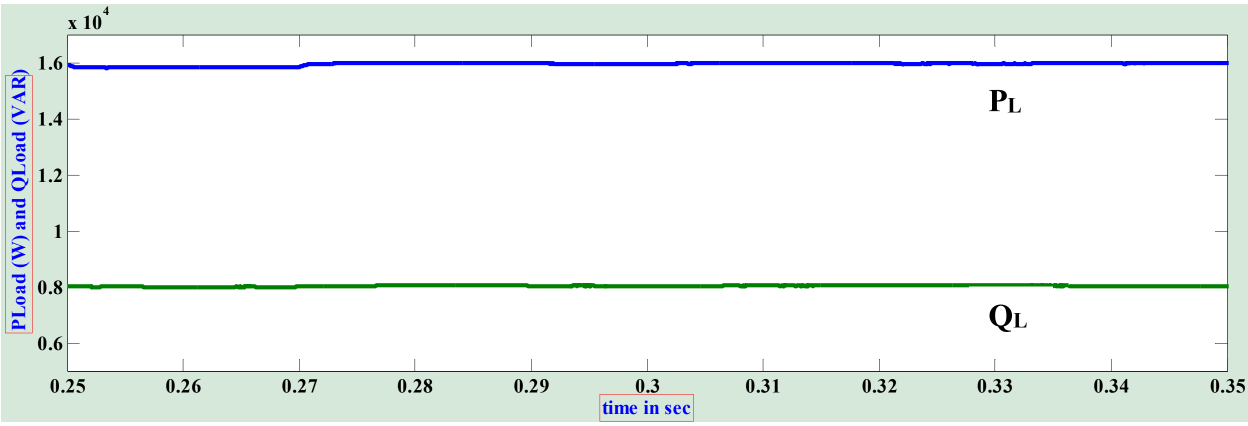
(d) Source current before compensation



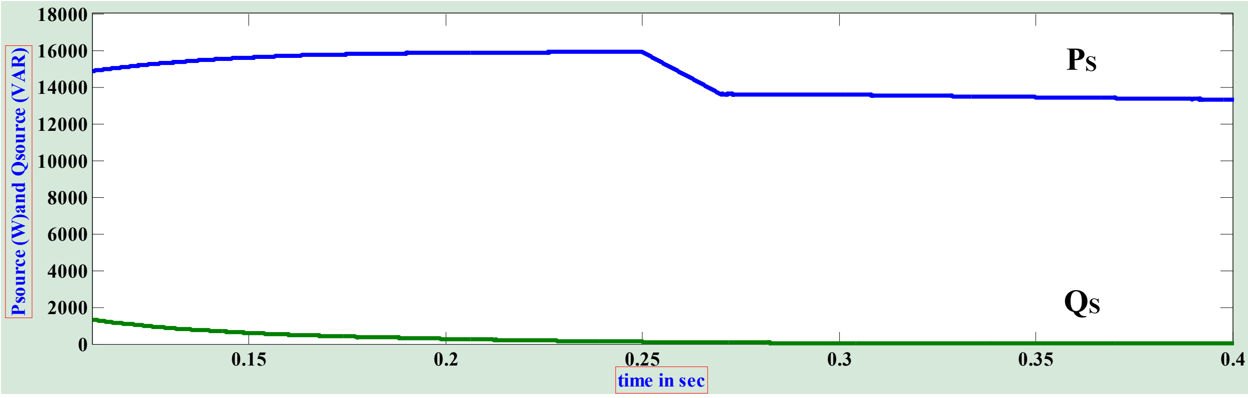
(e) Compensating current injected by shunt APF



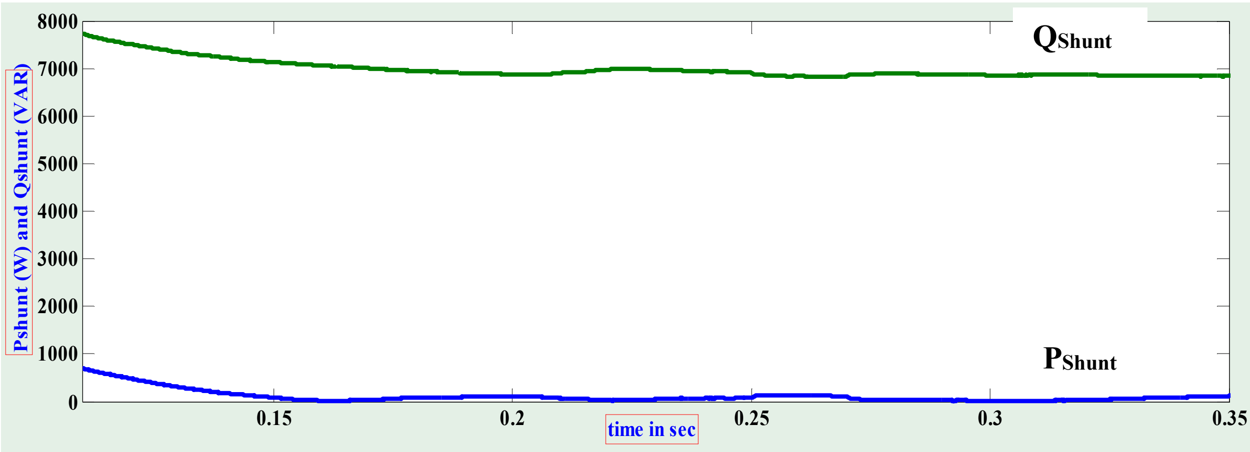
(f) Source current after compensation



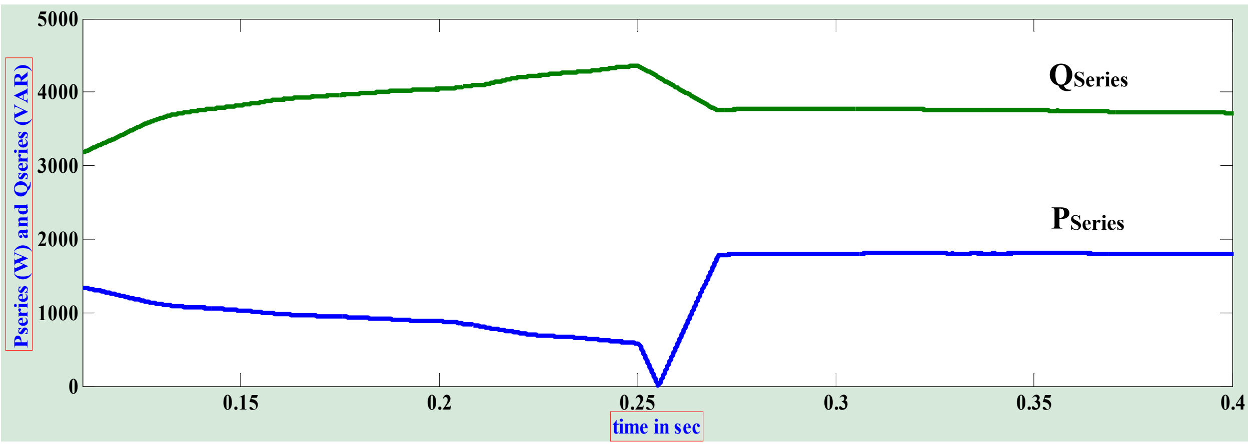
(g) Load demanded Active and Reactive Powers



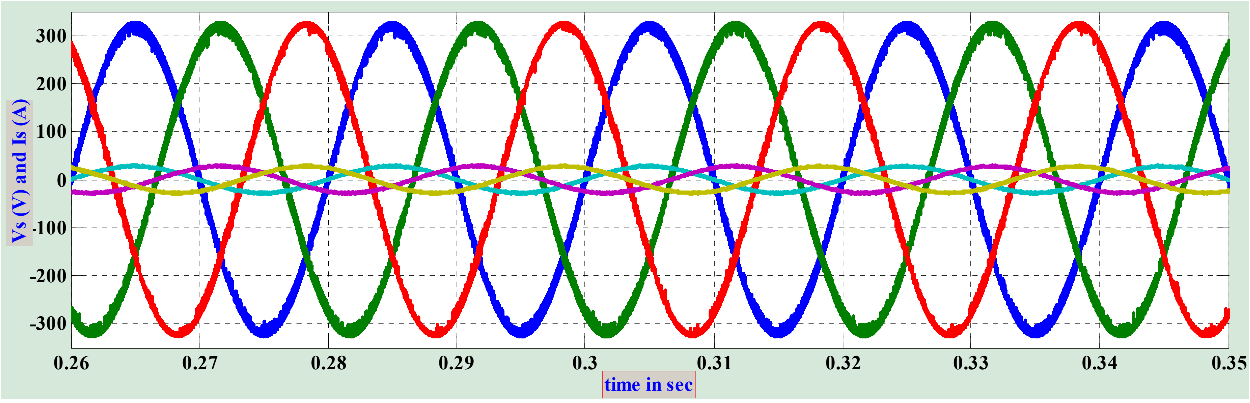
(h) Source supplied Active and Reactive Powers



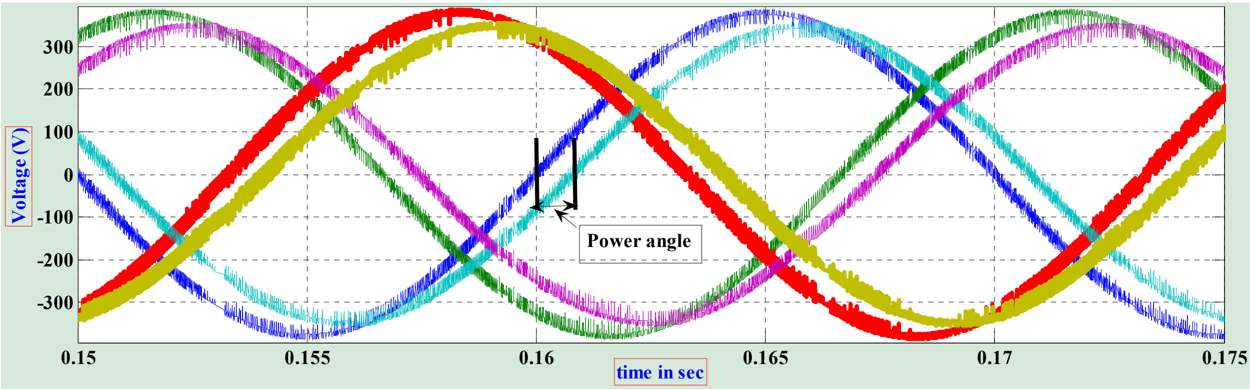
(i) Shunt APF supplied Active and Reactive Power



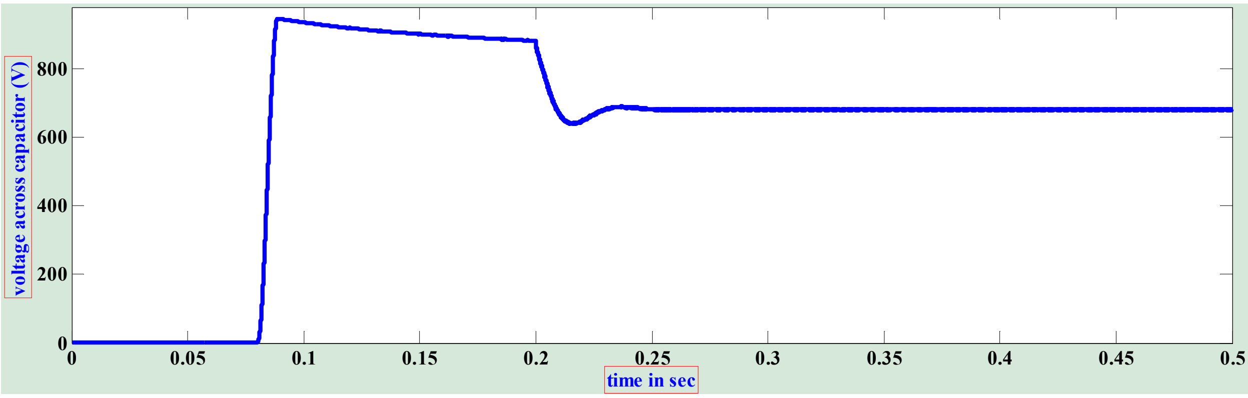
(j) Series APF supplied Active and Reactive Power



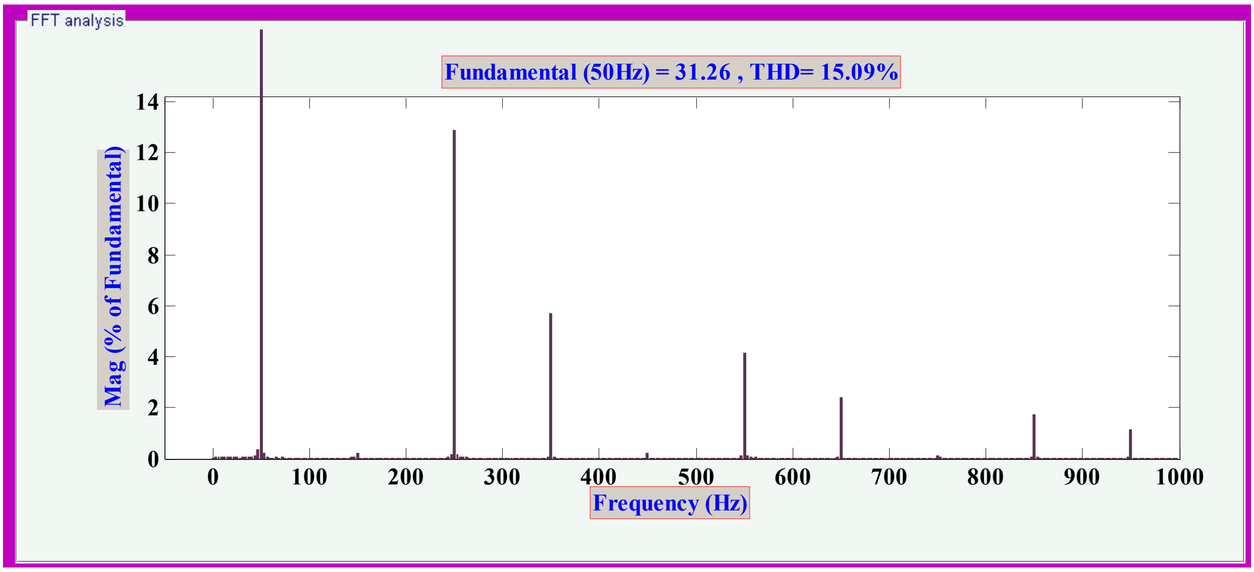
(k) Variation of V_S and I_S after compensation



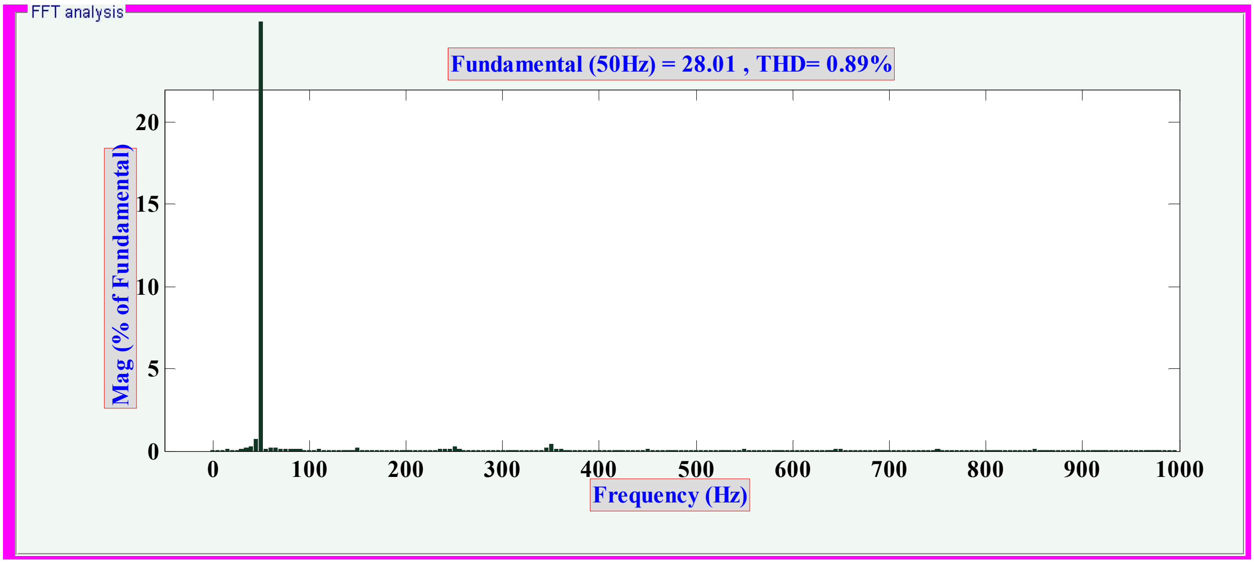
(l) Variation of V_S and V_L (δ= 14.85°)



(m) Voltage across DC-Link



(n) FFT analysis of Load current

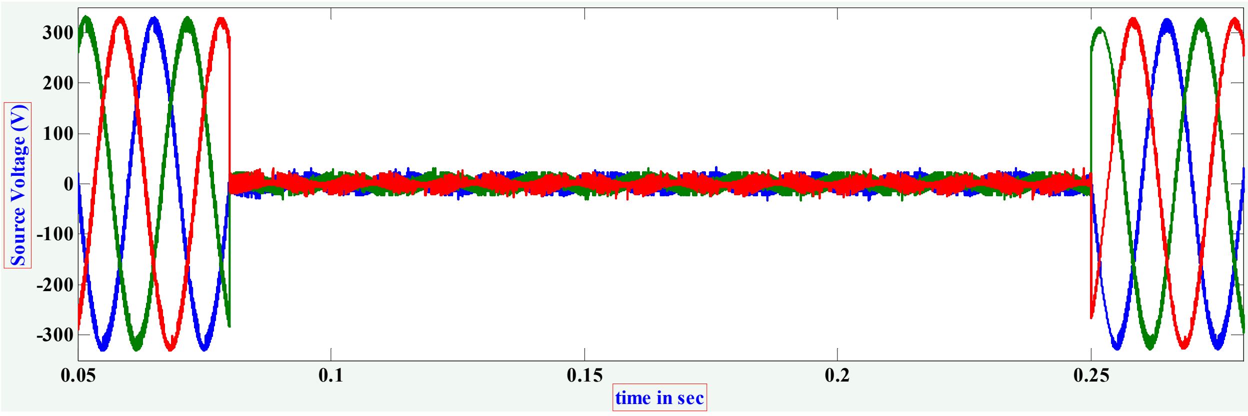


(o) FFT analysis of Source current

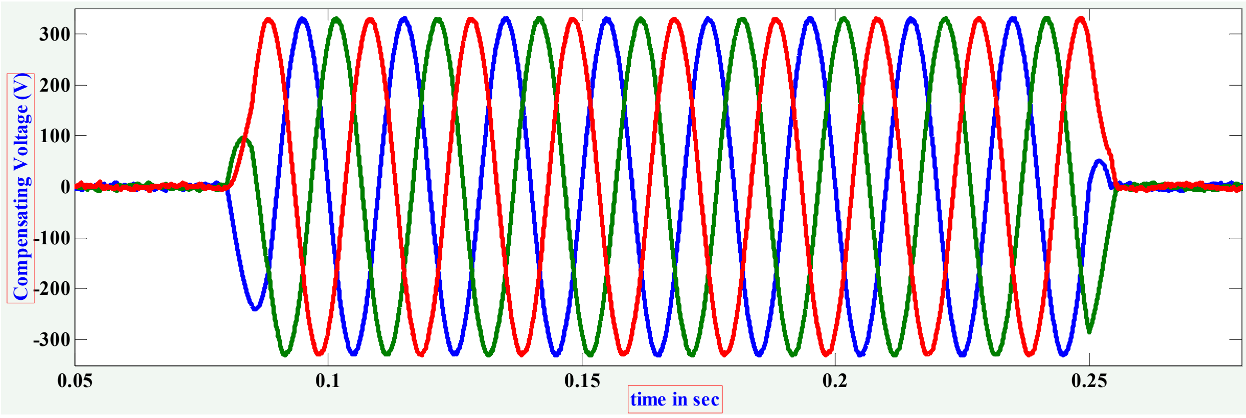
Fig. 5.2 Simulation results under voltage swell condition

5.3 RESULTS FOR VOLTAGE INTERRUPTION

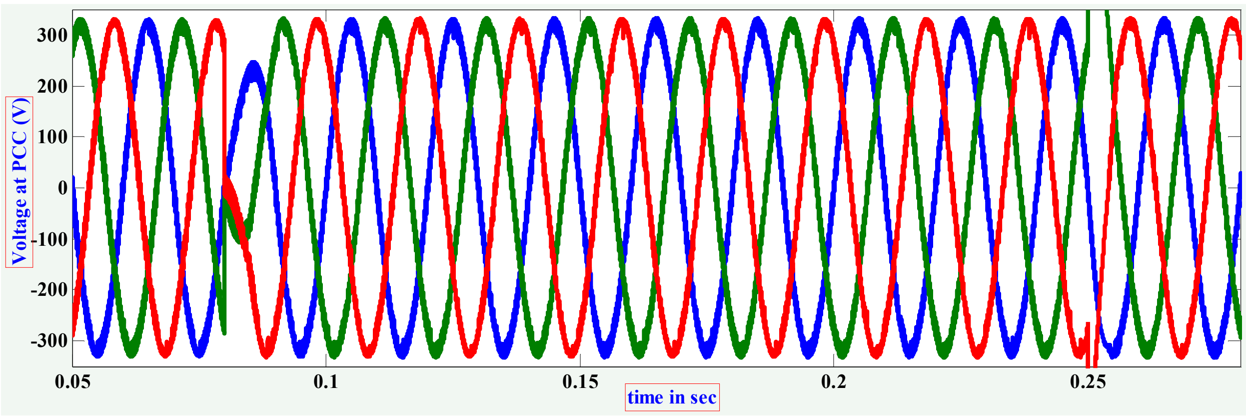
In this case, the results are carried out for voltage Interruption, which is occurred between time t=0.08sec and t=0.25 sec.



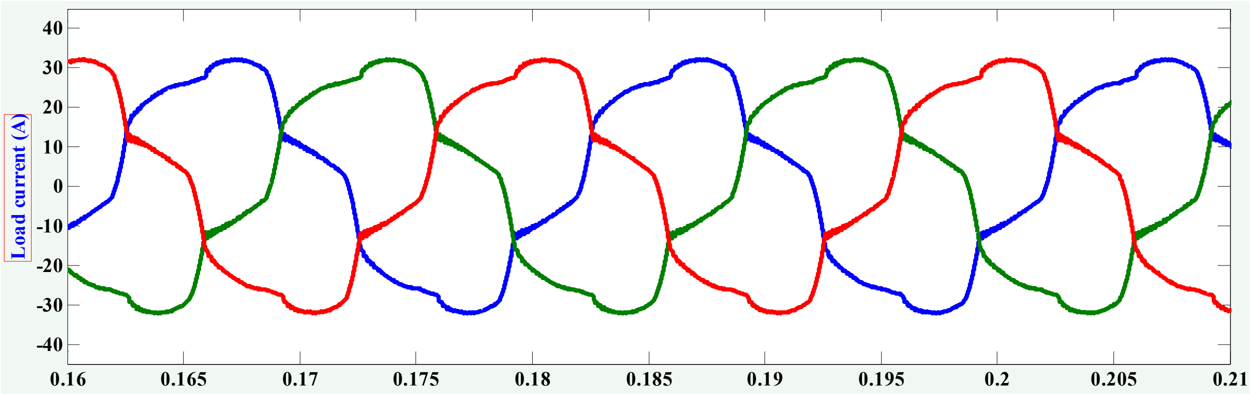
(a) Supply voltage



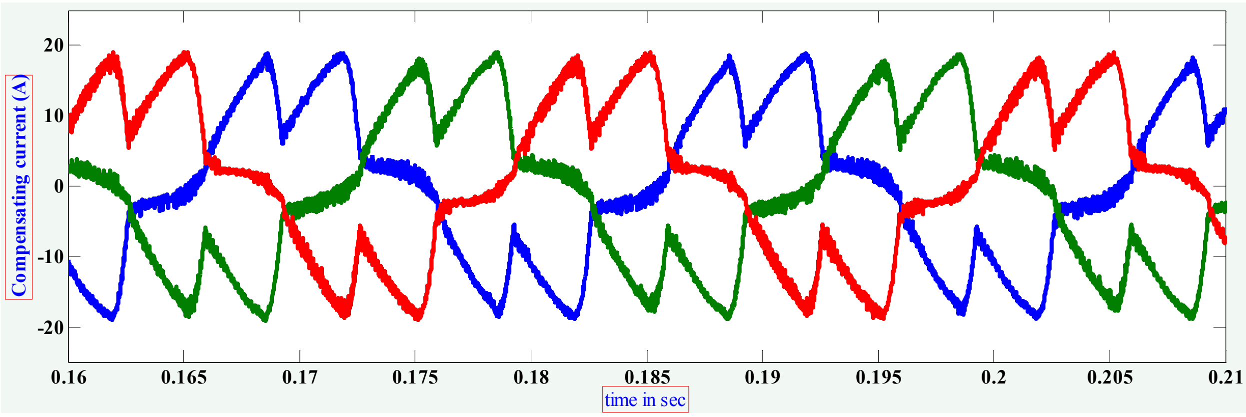
(b) Series inverter injected voltage



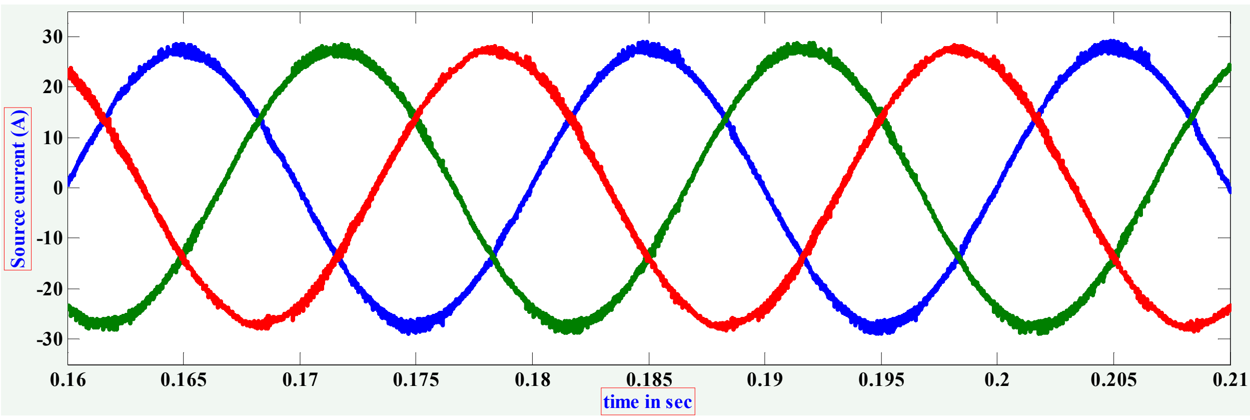
(c) Voltage across PCC



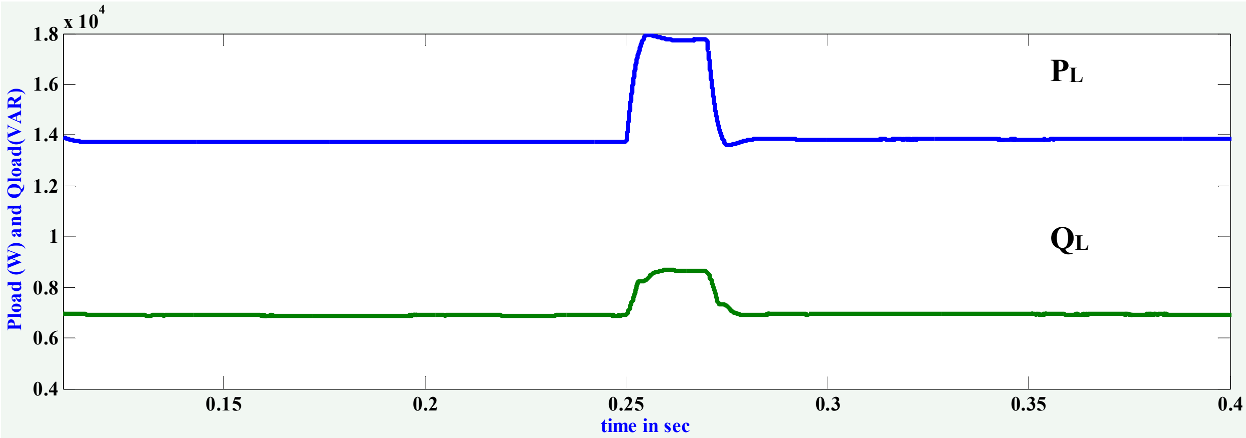
(d) Source current before compensation



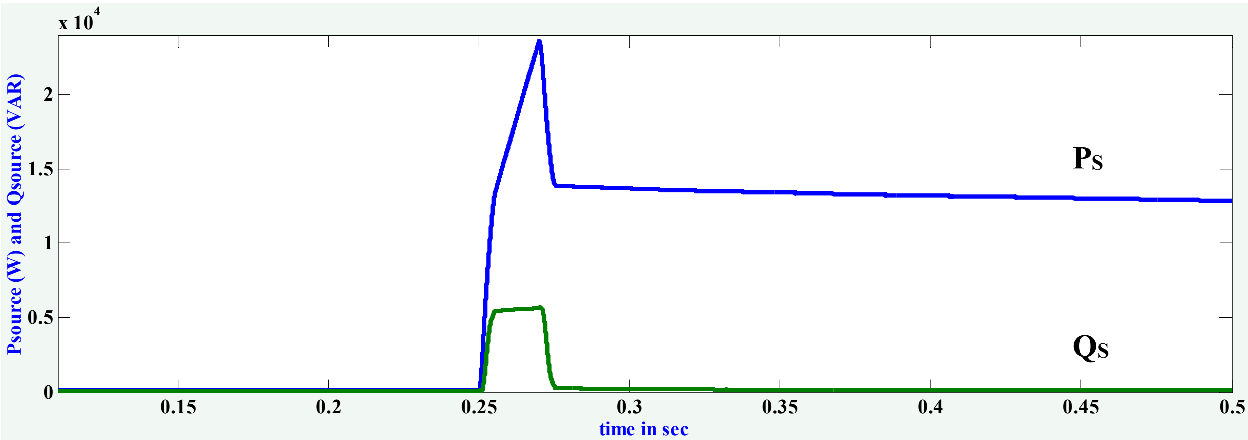
(e) Compensating current injected by shunt APF



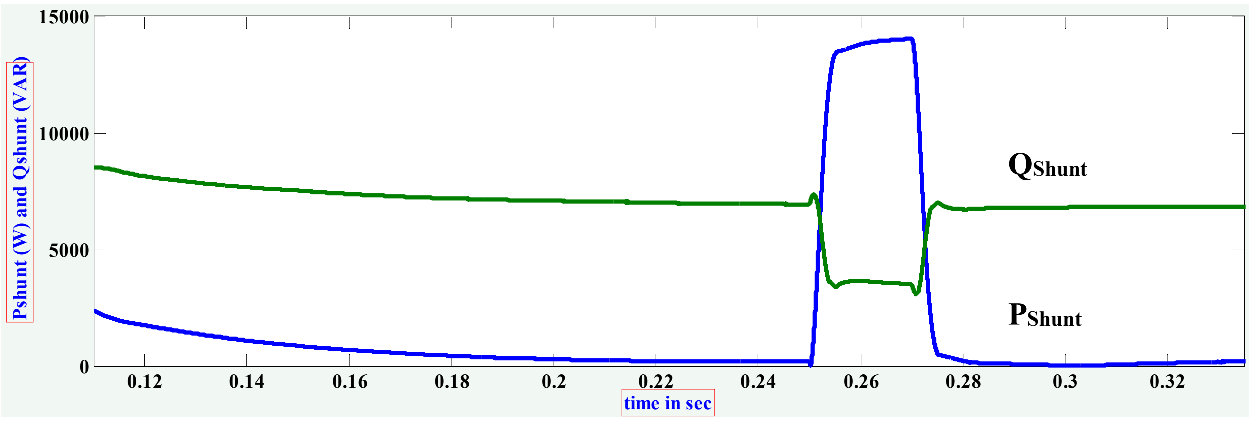
(f) Source current after compensation



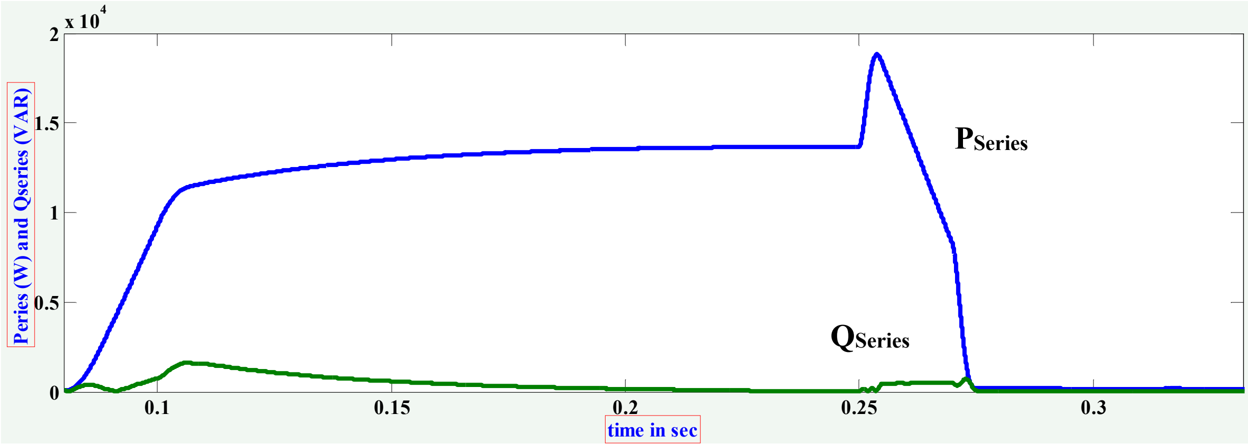
(g) Load demanded Active and Reactive powers



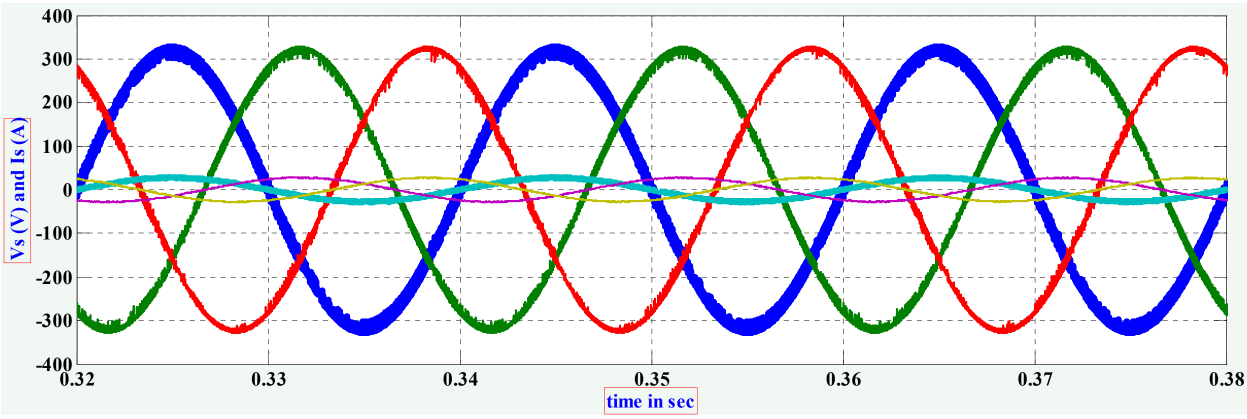
(h) Source supplied Active and Reactive powers



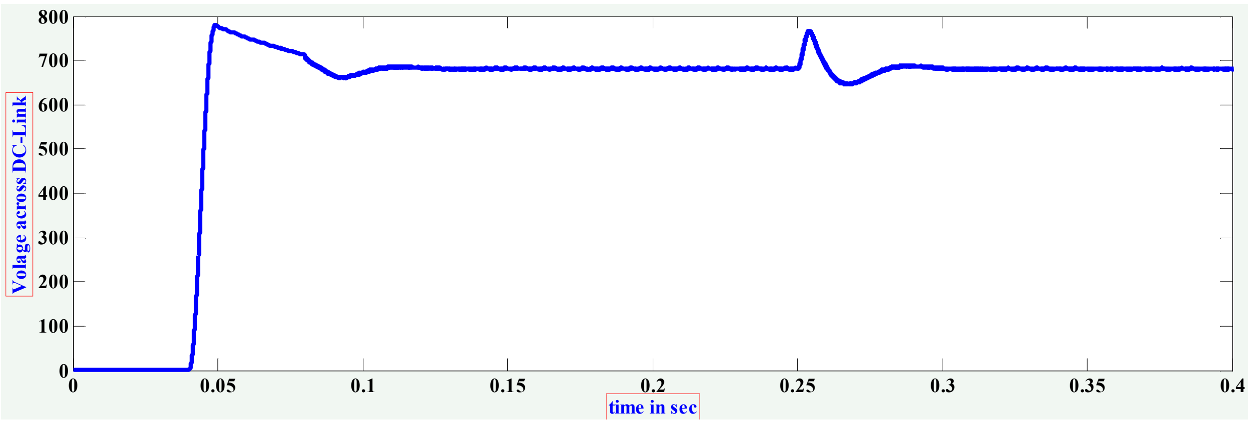
(i) Shunt APF supplied Active and Reactive powers



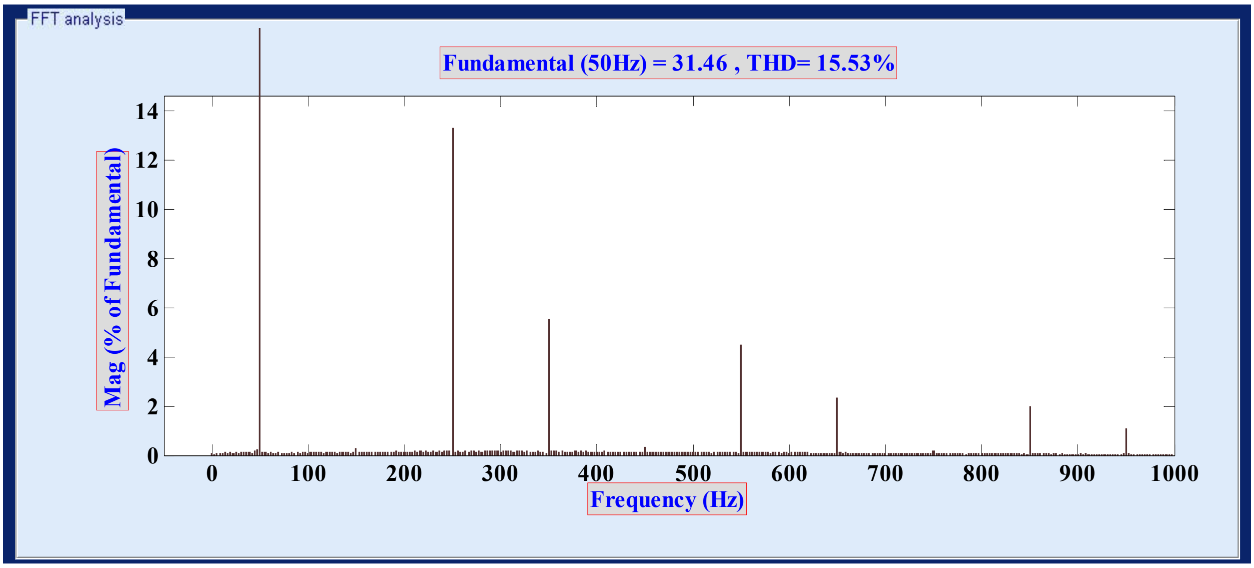
(j) Series APF supplied Active and Reactive powers



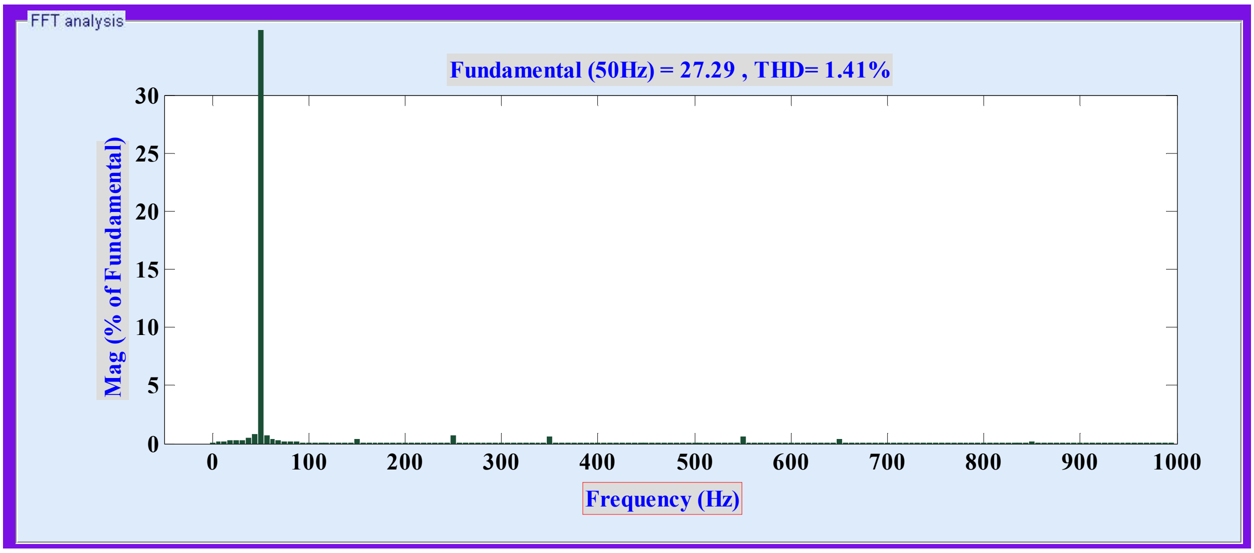
(k) Variation of V_S and I_S after compensation



(l) Voltage across DC-Link



(m) FFT analysis of Load current



(n) FFT analysis of Source current

Fig. 5.3 Simulation results under voltage interruption condition

From the results the following observations are concluded:

- The voltage Sag, Swell and Interruptions are effectively compensated by series APF which is shown in Fig. 5.1 (a), (b), (c), Fig. 5.2 (a), (b), (C) and Fig 5.3 (a), (b), (c) respectively.
- The shunt APF effectively compensating the Load current Harmonics in all the three cases as shown in the Fig. 5.1 (d), (e), (f), Fig. 5.2 (d), (e), (f) and Fig. 5.3 (d), (e), (f)

respectively. The THDs obtained are reduced to 0.7%, 0.89% and 1.41% from 16.41%, 15.09% and 15.53% respectively. The reason behind of obtaining such low THD is the usage of HSF, which extracted the fundamental component thoroughly.

- From the waveforms we can observe that the rms value of Load current is greater than the rms value of source current and the values of Load currents are 23.72A, 23.08A and 24.22A and of source current are 19.78A, 20.41A and 19.62A respectively.
- As shown in fig. 5.1 (*l*) and fig. 5.2 (*l*) the power angle (δ), between the source voltage and load voltage is maintained at 12.86° and 14.85°.
- As shown in the fig. 5.1 (j), 5.2 (j) and 5.3 (j) the Series inverter supplies both active power and reactive power in all the three cases, which means, the injected voltage is neither in series nor in quadrature with i_s. As it is supplying the reactive power demanded by load at steady state, the burden on the shunt APF is reduced.
- The advantage of Photo Voltaic System is observed from fig. 5.3 (h), (j) and (*l*), in the Voltage interruption mode, which is switched at t=0.08sec. When it is on, the high step-up DC-DC converter is maintaining nearly a constant voltage of 650 volts across DC-Link from the position of rapidly drooping as shown in fig. 5.3 (*l*). During this period, the entire load demanded power is supplied by series APF only i.e., source supplied power is almost zero due to interruption. During the voltage sag and swell it is switched at t=0.2 sec, and then on the voltage across DC-Link is maintained constant as shown in fig. 5.1 (m) and fig. 5.2 (m) respectively.
- The Load demanded power supply from Source, Shunt APF and Series APF are shown in the above fig. 5.1 (g), (h), (i) and (j), fig. 5.2 (g), (h), (i), (j) and fig. 5.3 (g), (h), (i) and (j) respectively. From these we can observe that, at steady state the active power supplied by the shunt inverter is zero, i.e., it involves only in reactive power compensation in steady state.

- The operating source power factor is achieved to nearly unity in all the three cases as shown in fig. 5.1 (k), fig. 5.2 (k) and fig. 5.3(k).

5.4 SUMMARY

This chapter demonstrates the effective compensation capabilities of the proposed PV-UPQC system with the MATLB/SIMULINK results for the voltage sag, swell and interruption cases. From the results it has shown that the PV-UPQC capable of supplying long term power quality problems which avoids the individual back-up systems for the end users. Using the power angle control scheme the burden and rating of the shunt APF, which reduces the overall cost of the system. Apart from that here it also showed the power flow analysis and improvement in power factor of the system.

The next chapter explains about the significant conclusions that are obtained using proposed system.

CHAPTER 6

CONCLUSION

6.1 CONCLUSION

In this work the PV-UPQC is simulated for Voltage Sag, Swell and Interruption modes using MATLAB SIMULINK and showed that the burden and on shunt APF is reduced, which also reduces the overall rating and cost of UPQC. The PV-UPQC is showed to be advantageous in order to supply power under voltage interruption mode and long duration power quality issues, which cannot be done by the conventional UPQC and thus improving the overall service reliability too. The usage of two high selectivity filters reduced THD below acceptable level. The simulation results had shown the effectiveness of mitigating voltage and current related problems. Overall the proposed PV-UPQC helps the end users to avoid installation of individual back-up systems.

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