Design of a Shunt Active Power Filter with Grid connected Inverter Control for a Photovoltaic System

Thesis Submitted in Partial Fulfillment of the Requirements
for the Award of the degree of

Master of Technology

In

Power Electronics and Drives

Submitted by

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National Institute of Technology, Rourkela-769008

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Under the Guidance of

Prof. B.D. SUBUDHI

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2015

CERTIFICATE

This is to certify that the project thesis entitled "**Design of a Shunt Active Power Filter with Grid connected Inverter Control for a Photovoltaic System**" being submitted by Biswabharati Majhi (213EE4326), Department of Electrical Engineering, National Institute of Technology Rourkela, Rourkela on partial fulfilment of the requirements for the award of the Degree of Master of Technology in Power Electronics and Drives specialization, Department of Electrical Engineering, National Institute of Technology Rourkela is an authentic work carried out by her under my supervision and guidance.

To the best of my knowledge, the matters embodied in this Project thesis have not been submitted to any other University or Institute for the Award of any other Degree or Certificate.

Date: 21-05-2015

Place: Rourkela

Prof. B.D. SUBUDHI

Department of Electrical Engineering

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DECLARATION

I hereby declare that the research work carried out in the thesis has been carried out by me. The work is original and has not been submitted earlier as a whole or in part for a degree/diploma at this or any other institution / University.

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Abstract

In this thesis, a shunt active filter (SAF) has been designed for a PV system. Due to the presence of nonlinear load and the inverter connected to the photovoltaic system, harmonics appear in the load current. Hence, to reduce the harmonics, a shunt active filter is connected between the inverter and the load at the point of common coupling. The power quality is improved by reducing the THD. The SAPF connected to PV system has been implemented using MATLAB/SIMULINK. From the obtained results, it is seen that the PV system with shunt active filter provides reduced THD.

Further, the inverter control for integrating the PV system to the grid is presented. The three phase inverter works as a multi-functional device and it is used to supply the power to the grid as power converter as well as harmonic eliminator. The inverter control has simulated using MATLAB/SIMULINK. This control strategy incorporates PQ solution as in shunt active power filter technique to reduce harmonics in the current due to non-linear loads in the system and also the THD value is reduced.

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LIST OF SYMBOLS

Iph	Photocurrent
Id	Reverse saturation current of diode
I	Cell output current
K	Boltzmann constant (1.38 × 10-23 J/0K)
Rse	Series resistance of cell
Rsh	Shunt Resistance
T	Temperature
V	PV cell output voltage
V_{PV}	Output voltage taken from PV system
K_p	Proportional gain
K_i	Integral gain

CHAPTER 1

INTRODUCTION

1.1 Introduction

The power demand always exceeds the available power generation in any developing country. Hence, renewable power generating systems such as PV and wind energy conversion systems are used to supplement the fossil fuel based power generation. But due to the non-linearity of the load that is diode bridge rectifier with RL- load, there is harmonics in the load currents. Hence, harmonics reduction and reactive power compensation simultaneously can be done by using a voltage source inverter connected in parallel with the system which acts as a shunt APF for reducing the distortions produced due to non-linear load in the load current. This active filter generates a compensating current which is of equal in magnitude as harmonic current and opposite in phase with it to reduce the harmonics present in the load current.APF is classified as series, shunt or combination both series and shunt but shunt APF is preferred here as the principle of the shunt APF is to produce compensating currents of equal in magnitude but opposite in-phase to those harmonics that are present due to non-linear loads. SAPF is a closed loop structure where non-linear loads act as linear. It can compensate reactive power and can also mitigate harmonics and distortions.

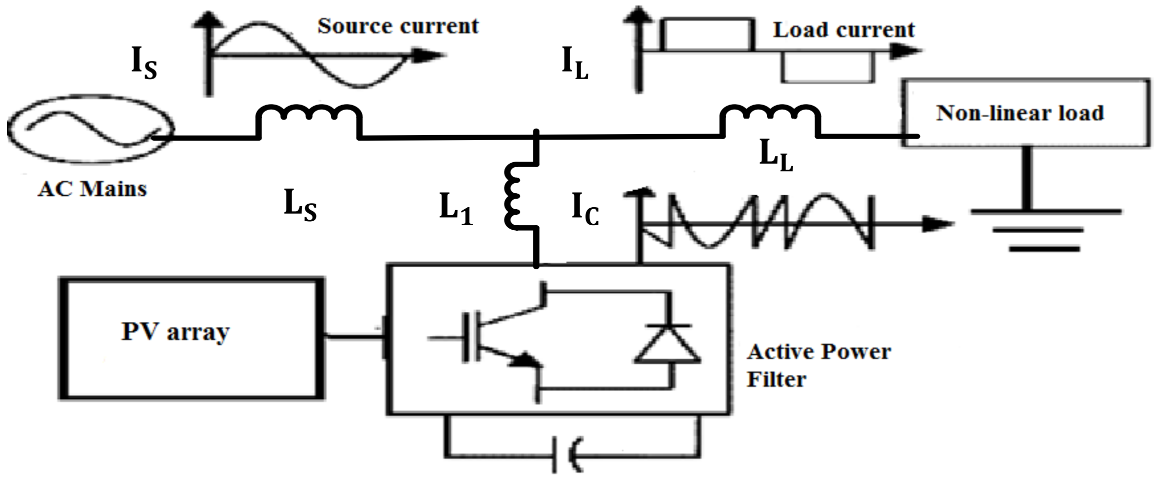

Fig.1.1 Principle of shunt APF

In Fig. 1.1 AC mains is connected to the non-linear load that is diode bridge rectifier with RL-load where,

I_S - Source current

I_L - Load current produced due to non-linear load

I_C – Compensating current produced by shunt APF to mitigate harmonics

L_S - Source inductance

L_L - Load inductance

L_1 – Coupling inductance

Here, the shunt APF produced compensating currents of equal in magnitude but opposite in-phase to those harmonics that are present due to non-linear loads which results in mitigation of harmonics at load current. Generally, the voltage source inverters (VSI) are used to convert the power of the PV system to inject it to the distribution system. But here, the VSI act as a multifunctional device which is used for energy conversion and also for harmonics elimination as well as reactive power compensation simultaneously.

This control strategy incorporate P-Q solution as in shunt active power filter technique. This control technique is same as technique used in shunt filter to reduce harmonics in the distribution network due to non-linear loads in the system.

1.2 Literature Review on Harmonics Extraction from PV Panels using Shunt APF and Grid connected inverter control technique

Due to the presence of non-linear loads harmonics are generated in the load current. Hence, it is required to reduce the load current harmonics. So, Shunt APF is needed for harmonics reduction and for reactive power compensation.In 2011 Chaitanya et. al described the PV array mathematical modeling and also the MPPT algorithm implementation on a boost converter to track maximum power during rapid change in environment conditions. The complete PV model is simulated and P-V and I-V curves are drawn using MATLAB/SIMULINK and the results are discussed from which it is clear that the P-V and I-V curves are dependent on temperature and irradiation. Using MPPT algorithm, a PV system can be operated at maximum efficiency [19]. In 2014 Jeevanathan et. al described that a SAPF is a current control system that is used for reduction of harmonics in current by injecting a current of equal magnitude but opposite in phase of the harmonics in current and also reactive current produced from the non-linear loads such that only fundamental active currents can be supplied from the ac source to the loads. This technique is used for both harmonic reduction along with reactive compensation produced due to non-linear loads. As a result, efficiency of the system is increased with reduced value of THD in source current [18]. In 2014 Remya et. al discovered that due to increase in power demand, the power distribution also increased so

Renewable Energy Sources (RES) are connected to the distribution systems where inverter, converter and non-linear loads are present hence, harmonics are present in currents and power quality decreases. So, they used to reduce the harmonics as well as for reactive power compensation. Here, the PV system is connected to the grid through a three-phase inverter which is used as a multi-functional device as it is used as power converter also for harmonics elimination [21]. In 2014 Boukezata et. al presented a paper where active filter is used to compensate the reactive power and to inject active power simultaneously whenever needed by the nonlinear loads. The PV array model with boost converter and MPPT controller is directly connected to the dc-side voltage source inverter(VSI) and the PV system is connected to the grid through this inverter using Direct Power Control Algorithm [10]. In 2013, Belaidi et. al described the analysis and simulation of shunt active filter (SAPF) where a PV system is connected to shunt power active filter and it can be used for the harmonics elimination which is generated by a nonlinear load and also reactive power compensation is done here. For the reference current calculation of Shunt Active Filter We are using the synchronous d-q-o reference frame algorithm (SRF) and the carrier-based PWM modulation is used for gating signal generation for the voltage source inverter. This system produced current in sinusoidal form only in multiples frequency of fundamental and also reactive power compensation occurred [16]. In 2012, Blorfan et. al presented a paper where a hybrid three-phase active power filter(HAPF) is configured and a passive high-pass filter is connected in parallel with an active power filter and then to a photovoltaic system. This configuration is able to improve the filtering capability of an active filter (APF) using sliding mode control and was able to filter out small band as well as wideband harmonics. This sliding mode method track the reference current and also give source current THD at a very lesser value which indicates the effectiveness of the system [4, 15].

1.3 Motivations

- PV system is connected to load through power electronics elements like converters, inverters and also loads that may be linear or linear which is the main cause for harmonics.
- Hence, there is a need for harmonics elimination and THD reduction.

1.4 Objectives

- To design and simulate a shunt active filter based on p-q theory to compensate harmonics and reactive power requirement while a nonlinear load is connected to the PV system.
- To design a grid connected PV system with inverter control method to reduce harmonics where inverter acts as a multi-functional device and converts the power as well as reduces the harmonics using active filter technique.

1.5 Thesis Organization

This thesis is organized chapter wise as follows

Chapter 1 provides the introduction part of the PV system along with thesis motivation and basic objectives of this project.

Chapter 2 presents an overview on PV cell, its basic theory, connections modelling and effect of temperature and irradiation on PV panel. It also described MPPT P & O algorithm and its implementation for maximum power extraction from a PV system connected to a DC/DC Boost converter and its need in PV power generation along with its waveforms.

Chapter 3 presents shunt APF design and its control algorithm with implementation of shunt APF control technique for inverter control.

Chapter 4 describes the obtained simulation results and its discussions

Chapter 5 presents the conclusion along with scope for future work.

CHAPTER 2

GRID CONNECTED PV SYSTEM WITH MPPT

2.1 PV system with MPPT

It can be connected to the Grid in two stages

- Stage-1 The PV system is connected to DC-DC boost converter and then fed to a DC-AC converter for grid connection.

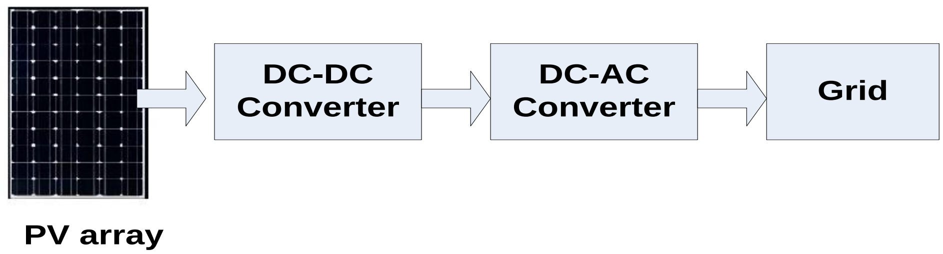

Fig.2.1 PV system connected to grid with DC-DC converter and DC-AC converter

- Stage-1 Further PV system can be directly connected to DC-AC converter and then to grid connection.

Fig.2.2 PV system connected to grid with DC-AC converter

But PV system connected to grid with DC-DC converter and inverter is preferred as DC-DC converters are also useful for noise isolation and power bus regulation.

2.2 Theory of Photovoltaic Cell

It is a PN-junction semiconductor which is made up of silicon. It is the basic structure of photovoltaic system. When the light strikes on the surface of semiconductor electron and holes are generated. Hence, positive and negative terminals are created which is responsible for generation of electric field.

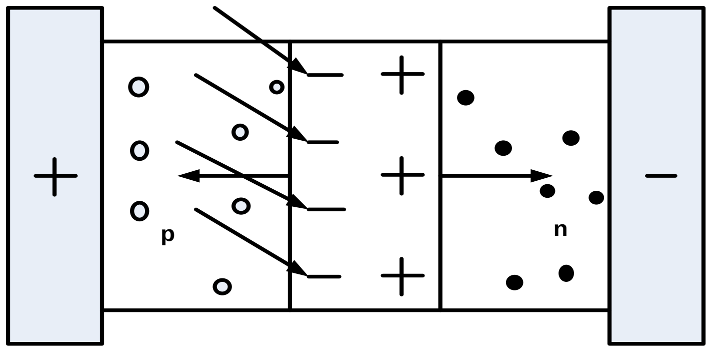

Fig 2.3 P-N junction illustration of PV cell

In Fig. 2.3 when the light strikes on the surface of semiconductor electron and holes are generated as shown above. The bubbles in P-region represent the presence of holes and in N-region electrons are present. Hence, positive and negative terminals are created as shown the middle portion of the Fig.2.3.When both the terminals are in touch with conductor electrons run toward P-type semiconductor and holes run toward N-type semiconductor. Here, both the end portions indicated with + and – sign represents the P-type semiconductor and N-type semiconductor. Thus,current will flow in between them and electricity is generated. Thus, PV system directly converts solar energy to electricity.

2.3 PV Cell, Module or Panel and Array

Number of PV cells are required to produce high power in solar power generation system so for higher power demand they are connected in series or in parallel for formation of Solar Module or Solar panel and also form Array.

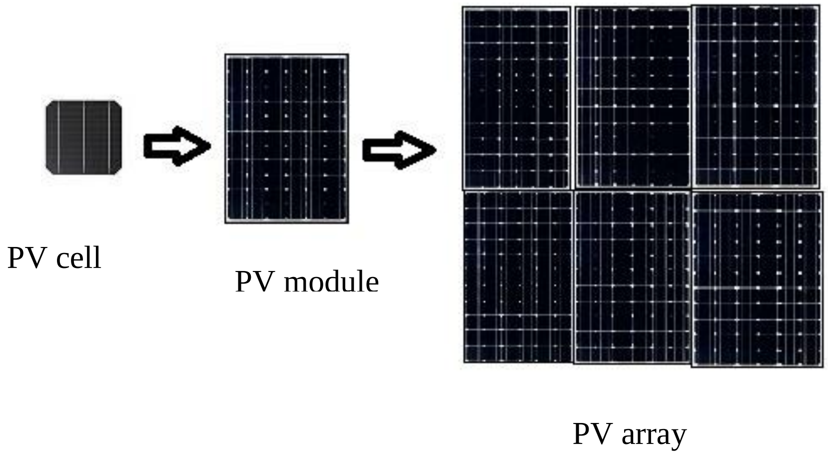

Fig. 2.4 Formation of solar Module and solar Array

PV Module

A group of PV cells are in series connection to form solar panel or module. A photovoltaic module is a systematic arrangement of series connected PV cells.

PV Array

A group of solar panels or modules connected together electrically in series and parallel structure to form solar array and this solar array is responsible to produce higher amount of power.

2.4 Solar Cell Modeling

For the modelling of a PV array it is needed to model the individual PV cells. These PV cells are combined together to form the PV array used for MPPT technique. An equivalent electrical circuit is derived from the physical presentation and mechanism of a solar cell. Mostly, two circuits are accepted as equivalent electrical circuit of solar cell, one is a simplified model of a single diode solar cell and another for two diodes circuit, one diode for reflecting diffusion and other for carrier.

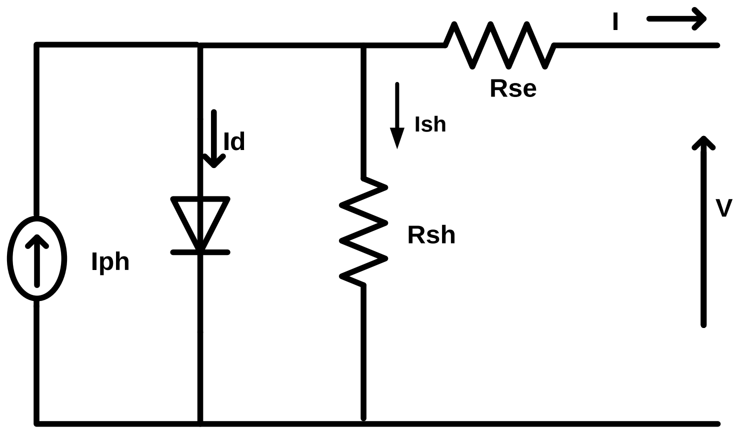

Fig. 2.5 Equivalent circuit of single diode solar cell

where,

Iph - Photocurrent

Id - Reverse saturation current of diode

I - Cell output current

K - Boltzmann constant (1.38 × 10-23 J/0K)

Rse - Series resistance of cell

Rsh - Shunt Resistance

T - Temperature

V- Cell output voltage

The main effect of series resistance is to reduce the fill factor and excessively high values may also reduce the short-circuit current. When Rse value is very high the MPP voltage drop occures. Hence, the resultant decrease in efficiency can be overcome by reduction of series resistance for PV cell applications. Low shunt resistance causes power losses in PV cells which provides an alternate current path for the light-generated current. Due to such a diversion the amount of current flowing through the PV cell junction reduces and the voltage from the solar cell also reduces.

Applying node equation in figure 2.5

$$I = I_{ph} - I_d - I_{sh}$$

$$I = I_{ph} - I_{sat}(\exp(q(V + I \times R_{se} \div aKT)) - 1) - (V + I \times R_{se} \div R_{sh})$$

where ‘a’ is the ideality factor and its value is between 1 and 2.

36 solar cells having 9 modules (85 watt each) are connected in series and parallel connection to form a PV array with 1000 w/m² isolation using MATLAB/SIMULINK.

2.5 Power versus Voltage and Current versus Voltage Characteristic Curves of Photovoltaic (PV) Panel

When positive and negative terminals of a Photovoltaic module are shorted, the maximum current is produced which is short circuit current I_{SC} of Photovoltaic panel. At this condition the voltage across terminals is zero.

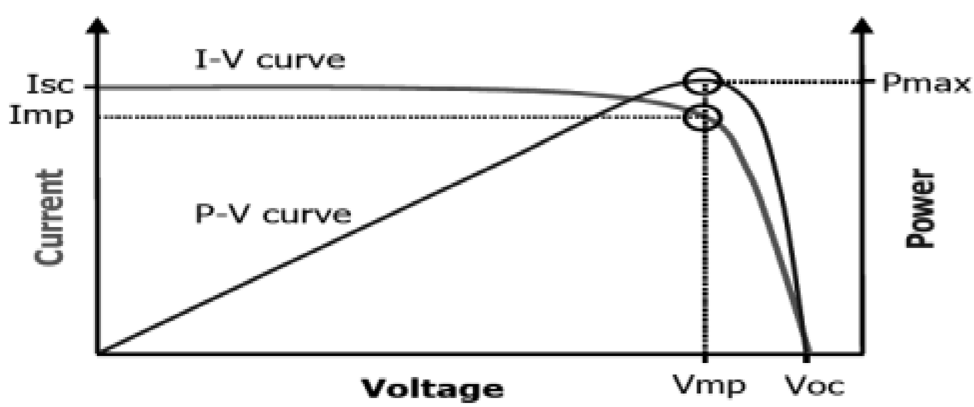

Fig.2.6 Power versus Voltage and Current versus Voltage Characteristic of the Photovoltaic (PV) Panel

When both terminals are kept open circuited then the voltage is maximum called open circuit voltage V_{oc} of that panel. As the current is zero the panel has infinite resistance. Different pair of points of current and voltage is achieved between these two extreme points under different load resistance conditions. By connecting these points we find a curve called Current versus Voltage curve of Photovoltaic (PV) panel. Fig.2.6 shows the Power versus Voltage and Current versus Voltage curves of the Photovoltaic (PV) panel.

As Fig. 2.6 shows, $V_{oc}$is occurred when current is zero and I_{sc} is occurred when voltage is zero and by multiplying both the current and voltage at a particular point the power can be calculated of that panel.

2.6 Effect of Solar Irradiation on Power versus Voltage and Current versus Voltage Curves of Photovoltaic Panel

Power versus Voltage and Current versus Voltage characteristic curves mainly depend upon the solar irradiation. When the environmental condition changes then the solar irradiation level also changes which results in different maximum powers. Hence, MPPT technique is used to maintain the maximum power constant when there is any change in solar irradiation level. When the irradiation is high, then the solar cell input is high which results in higher value of power keeping the voltage value as same. Also the open circuit voltage increases with increase in solar irradiation. Because, when more solar light strikes on the solar cell, higher excitation energy of the electrons increases, as a result the electrons have higher mobility level and thus more power is generated.

2.7 Temperature effect on Power versus Voltage and Current versus Voltage Curves of Photovoltaic Panel

Due to change in temperature also the Power versus Voltage and Current versus Voltage curves of the Photovoltaic panel vary. Increasing temperature results in change in power generation capability which is not a desirable situation. When the temperature increases the open circuit voltage decreases hence, band gap also increases which requires more energy to cross the barrier. Hence, the efficiency of the solar cell decreases.

2.8 Maximum power point Tracking

In photovoltaic system Maximum power point tracking is a very essential part. In photovoltaic system there must be unique operating point which gives maximum power and this MPPT is used to track this operating point. MPPT is an electronic arrangement that is used to find out the voltage (VMPP) and current (IMPP) at which PV system gives maximum output power during change in environmental conditions. This method permits the PV modules to operate in such a way that can produce maximum power it is capable of. For implementation of the tracking algorithm to the dc-dc converter require some desired feature for the efficient use of MPPT. These desired features of MPPT are described as below:

- Price is less.
- Implementation is easy.
- Rapid tracking response in dynamic analysis.

•There should not be any oscillations at the maximum power point during steady state condition analysis.

•The MPPT must have the capability for tracking the maximum power point with large range of change in solar irradiation and temperature.

DC to DC converters is needed for MPPT implementation as in Boost converter, input voltage (DC) is a smaller than output voltage (DC).That means input PV-voltage is lesser than the output voltage of boost converter. Hence, boost converter is required for MPPT to boost-up the voltage of the PV system.

MPPT works effectively during these conditions:

• **cold or winter days:** Generally, PV system extracts less energy in winter seasons so MPPT(maximum power point tracker) is used more efficiently to extract maximum possible power presented.

- **During discharged condition of battery:** When the battery charge is less the MPPT extracts more current and able to charge the battery.

2.9 Importance of MPPT in photovoltaic system

Solar irradiation may change in a wide range depending upon the seasons, hours of a day, latitude, orientation of the solar field. Hence, the solar irradiation that hits on the PV system may vary.

Considering these conditions, the MPPT is essential to identify the operating points at each instant on the V-I curve at which maximum power should be transferred to the grid system will occur at the PV generator. Generally, the efficiency of solar panels is low but the energy to be generated from PV systems must be maximum. Due to this reason PV systems are equipped repeatedly with maximum power point(MPP) tracker for tracking maximum possible power. Several maximum power point tracking techniques are proposed and implemented in recent years.

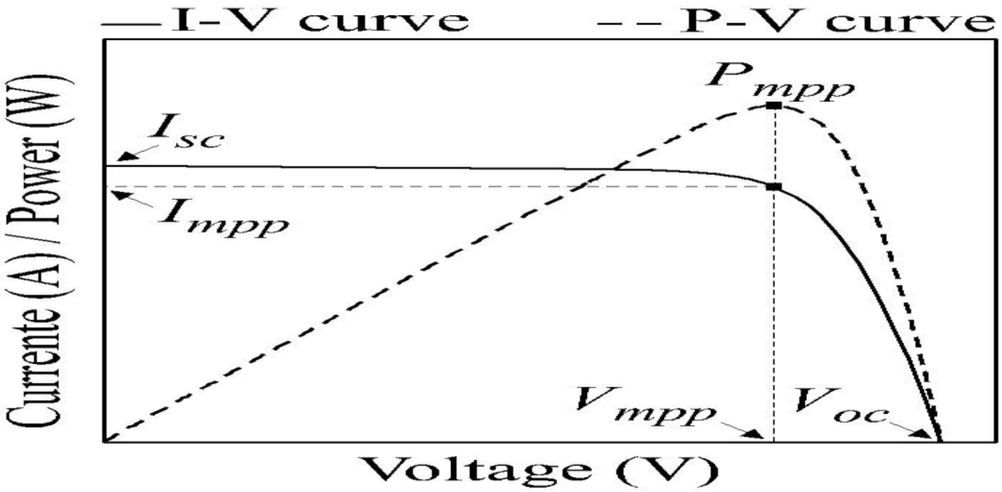

Fig.2.7 P-V and I-V curve of a PV panel showing MPP

Depending on the PV system control technique for generation methodology during steady state condition, it is normally classified into following groups:

1. Offline methods

- Open circuit voltage(OCV) method
- Short circuit current(SCC)
- Artificial intelligence

2. Online method

- Perturb and observe(P&O) method
- Extreme seeking control method(ESC)
- Incremental conductance method (Inc. Cond)

3. Hybrid methods

2.10 Perturb and Observe (P&O) MPPT

P&O technique is the most common in all type of MPPT algorithm methods. This technique contains a simple arrangement with minimum parameters. In this technique, the module-voltage is to be perturbed regularly and the resulting output-power is to be compared with the power of the previous perturbation. This method also detects a small perturbation in the system which results in change in the solar module power. If increasing power occurs during the present condition then the perturbation should be in the same-direction. But when the maximum power is reached at MPP(maximum power point) then the power should be zero and decrease thereafter which results in reverse in perturbation after that.

But during stable condition it starts oscillating around the peak power point. To maintain a small power variation the size of perturbation should be chosen very small. This is an advanced technique which is able to set a reference voltage corresponding to the peak voltage of the module. Then according to that voltage level the PI controller transfers the module operating point to particular level. During fast changing atmospheric conditions there may be power loss present due to the perturbation which results in failure of tracking the maximum power, still this algorithm is most preferred due to its simplicity and is popular too.

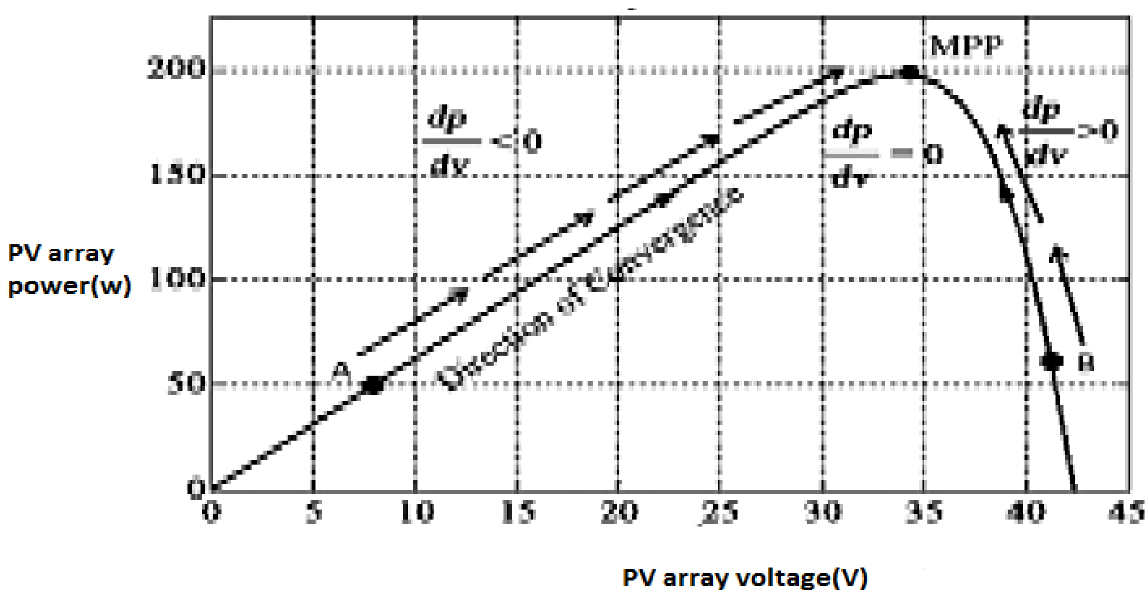

Fig.2.8 PV characteristics showing MPP and operating points A and B [9]

2.11 Flow Chart of (P&O) Algorithm

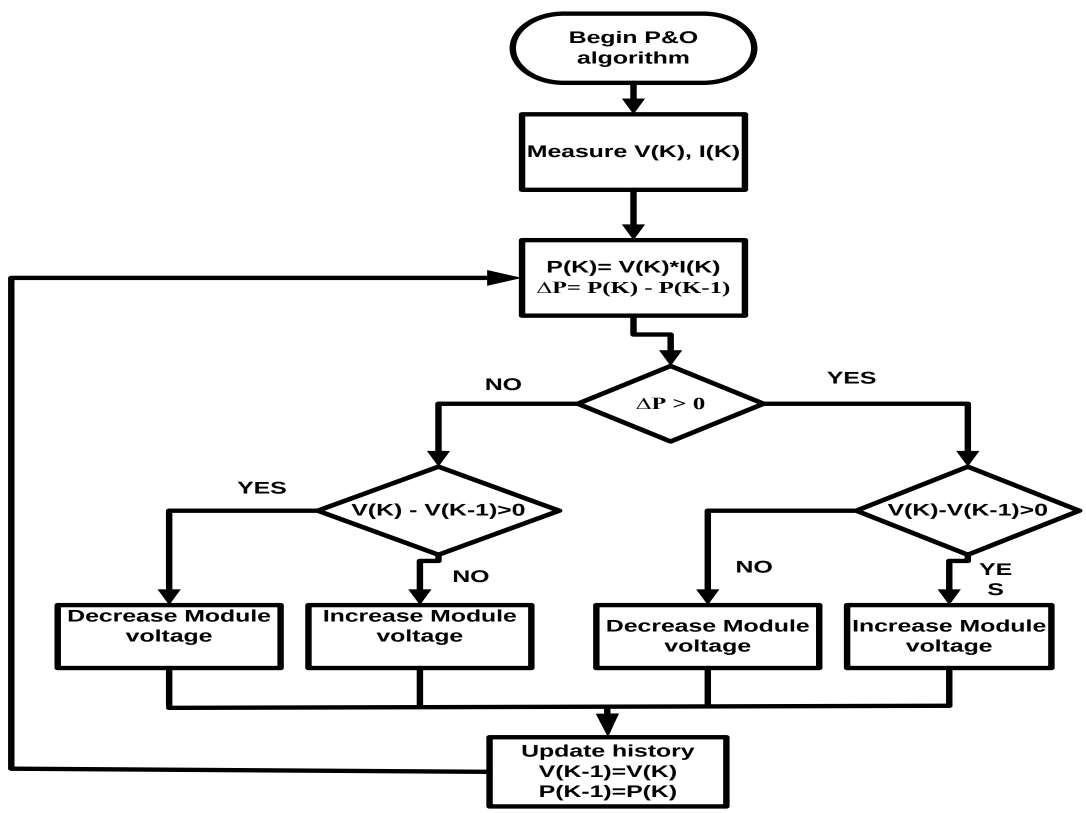

Fig.2.9 Flow Chart of (P&O) Algorithms

In the Fig.2.9

V(K) – voltage of the present perturbation

I(K) – Current of present perturbation

P(K) – Power of present perturbation

P(k-1) - Power of previous perturbation

ΔP – Change in power between present and previous perturbation

Referring to the flowchart

If $\Delta p>0$ and $\Delta v>0$, that means current power is present in the left side of the maximum power point hence, increase in voltage occurs, similarly if $\Delta p<0$ and $\Delta v>0$ current power is present in right of the maximum power point then decrease in voltage occurs at this situation. At $\Delta p=0$ the available power is the maximum power point.

2.12 Boost Converter

DC to DC converters is needed for MPPT implementation as in Boost converter, input voltage (DC) is a smaller than output voltage (DC).That means input PV-voltage is lesser than the output voltage of boost converter. Hence, boost converter is required for the PV system with MPPT technique to boost-up the voltage of the PV system. DC-DC Converters are used for dc-input voltage which is then converted to desired dc-output voltages where the magnitude of the output voltage must differ than the input voltage magnitude. Normally, DC-DC converters are classified into three types namely: buck, boost and buck-boost Converter and here boost converter is preferred as we need to step up the PV output. DC-DC converters are also useful for noise isolation and power bus regulation. The DC-DC boost converter contains a inductor, capacitor, diode and a IGBT as it is a high frequency switch. It produces higher voltage during power supply to the load. Based on the switch duty cycle the output voltage may change. Generally transformer can step up the voltage, but there may be losses in the transformer. So to overcome this loss DC-DC Boost converter is used to get desired output voltage.

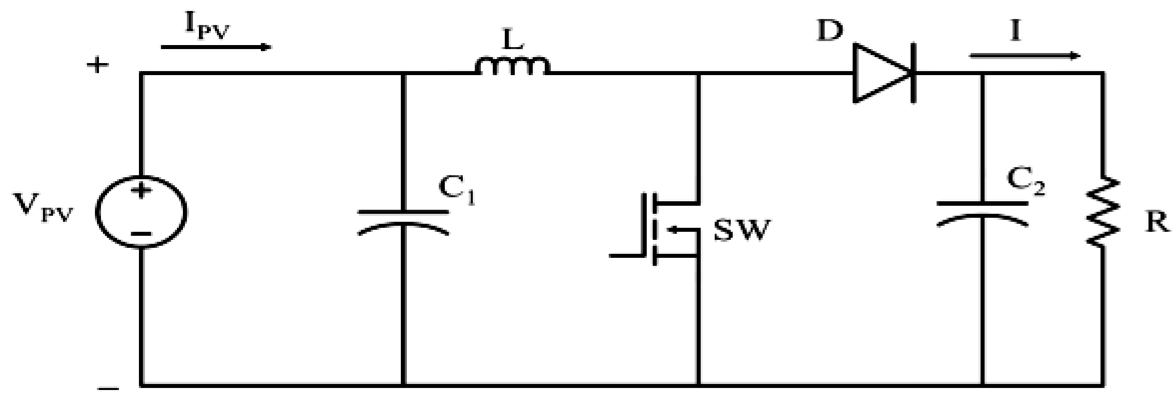

Fig.2.10 Diagram of a Boost converter

This boost converter is designed using MATLAB/SIMULINK where,

V_{PV}= input voltage taken from PV system

C_1= capacitor connected across the PV input (2mF)

The diode connected in series with Resistance (R_{on}) = 0.001Ω and forward voltage V_f = 0.8V

L = Inductor connected in series (0.01 H)

R = Resistance (10Ω) connected in parallel with capacitance C_2 (2mF)

D = Duty ratio

The conversion ratio for the boost converter can be determined by assuming the inductor and capacitor having large value that can be enough to take voltages and currents as DC values. The switch can be replaced by an equivalent voltage source having value (1-D)V_{out} . The complementary duty cycle presents the duration during which the diode conducts can be expressed as D' = (1 - D). During this period it is assumed as an ideal diode, where the intermediate voltage is shorted to V_{out}. The intermediate voltage is shorted to ground during on this condition of the switch. Hence, the average value is equal to (1 – *D)* V_{out}. Since at DC condition, the inductor is short circuited hence,

$$V_{in} = (1\text{-D})\ V_{out}$$

The above equation shows that the conversion ratio of the boost converter depends on duty cycle assuming constant-frequency operation. A boost converter can operate with both constant on-time and constant off-time switching. But in both the cases, change in duty cycle results in change in frequency. So here a constant-frequency boost converter is taken.

2.13 Modes of Operation

In DC-DC boost converters two modes are available and depending on the switch (higher frequency) opening and closing operation these modes are decided. In 1st mode operation the inductor is charged as the switch is closed so this mode is called as charging mode of boost converters. In the 2nd mode the inductor is discharged as the switch is open and is called as discharging mode of boost converters.

2.13.1 Mode-1 or charging mode of Operation

In 1st mode the switch is closed, hence by using battery inductor is charged and so energy is stored as a result there is exponential rise in inductor current but we are assuming linear inductor current in both the modes (charged and discharged mode). The load current remains constant, supplied by discharging of the capacitor as the diode blocks the current flow during this mode.

2.13.2 Mode-2 or discharging mode of Operation

In 2nd mode switch is opened which results in short circuit of diode. So the stored energy stored in 1st mode of inductor is discharged with opposite polarity during this mode and as a result the capacitor is charged. But the load current is at constant value always.

2.14 Waveforms

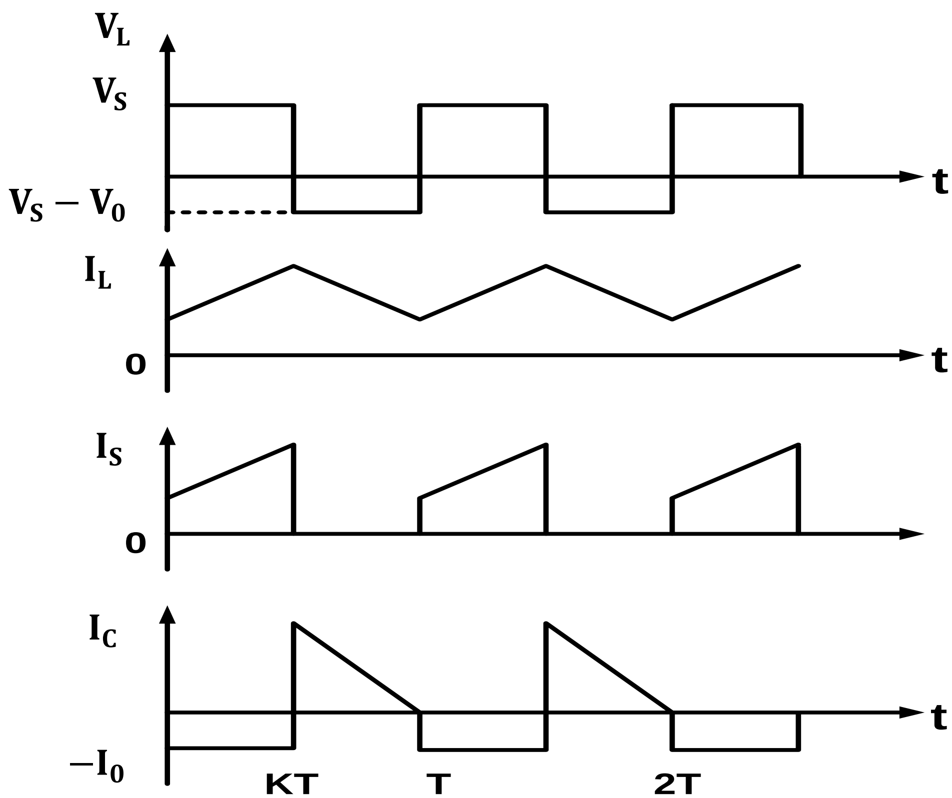

Fig.2.11 Waveforms of boost converter

In the Fig.2.11 V_L represents the voltage across the inductor. When the switch is closed, by using battery inductor is charged and so energy is stored as a result there is exponential rise in inductor current and capacitor current at constant value. Hence, inductor voltage is at value equals to source voltage and supply current also increases. When the switch is opened, the stored energy in inductor is discharged with opposite polarity during this mode and as a result the capacitor is charged. So, the inductor current falls till the switch is closed again in the next half cycle.

2.15 Chapter summary

This chapter described generation of PV cells and their connections. It also represented the modelling of PV cell and effect of solar irradiations and temperature on it and described the grid connected PV system with MPPT P & O algorithm and DC-DC boost converter along with its modes of operation and waveforms.

CHAPTER 3

GRID CONNECTED PV SYSTEM WITH ACTIVE POWER FILTER

3.1 Shunt active power filter with a PV system

A Shunt Active Filter (SAPF) is the bidirectional current converter with six switches having combination of both switching network and filter-components. Structure of this power filter is dependent on the control technique of VSI having a capacitor for the purpose of DC energy storage and the inverter output has been connected to Non-linear load having diode rectifier bridge with a RL-load. In each of the switches the diodes are connected in anti-parallel arrangement with the IGBTs to permit current flow in either direction. For compensation of reactive power the PV interconnected shunt APF injects real PV power to a distribution line at PCC and also reduces harmonic in load currents caused by nonlinear loads by injecting compensating current. This filter is connected in shunt that means in parallel with the nonlinear load. This active filter has capability of detecting the harmonic currents caused by the nonlinear loads and then injects a current of equal magnitude and opposite in phase with the non-linear load current which is called compensating current to reduce the harmonics present in load currents due to Non-linear load. Hence, the resulting current is in form of a fundamental frequency sinusoidal current which is drawn at PCC in distribution network.

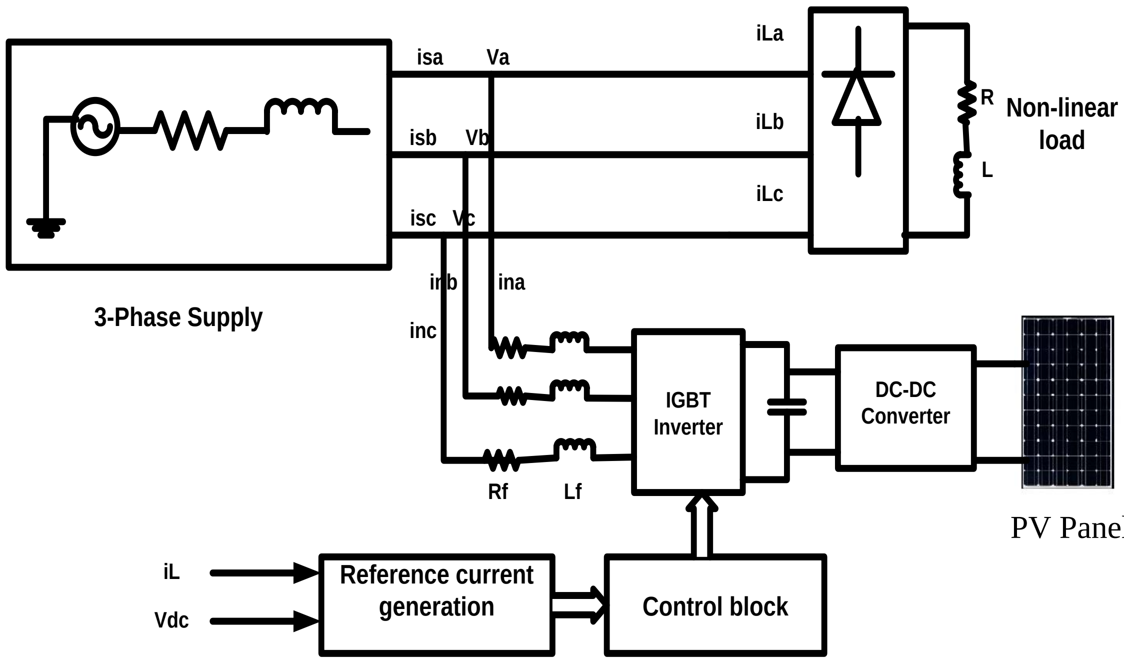

Fig.3.1 Schematic diagram of a PV system connected to a Shunt APF

A Shunt APF generally consists of the following Blocks:

i) IGBT based voltage source inverter (VSI)

ii) DC energy storage

iii) Active control unit

Operation and voltage source shunt APF control algorithm is presented in this chapter**.** Here, an instantaneous active-reactive power (p-q compensation) theory control algorithm have been used for Shunt APF for compensating harmonics produced in current by providing equal but opposite in phase to current harmonics into system. Here, the shunt APF operation is considered as harmonics compensator produced by load with 180° phase. As a result, at the power distribution system nonlinear load and the APF have seen as an ideal resistor.

For shunt APF harmonics reduction compensating current must be equivalent to the distorted current which can be achieved by shaping the compensating current waveform by using VSI switches. By evaluating the load current, the compensation current shape can be easily obtained by subtracting it from the reference current to obtain a sinusoidal source current which must be free from harmonics having only fundamental component of current.

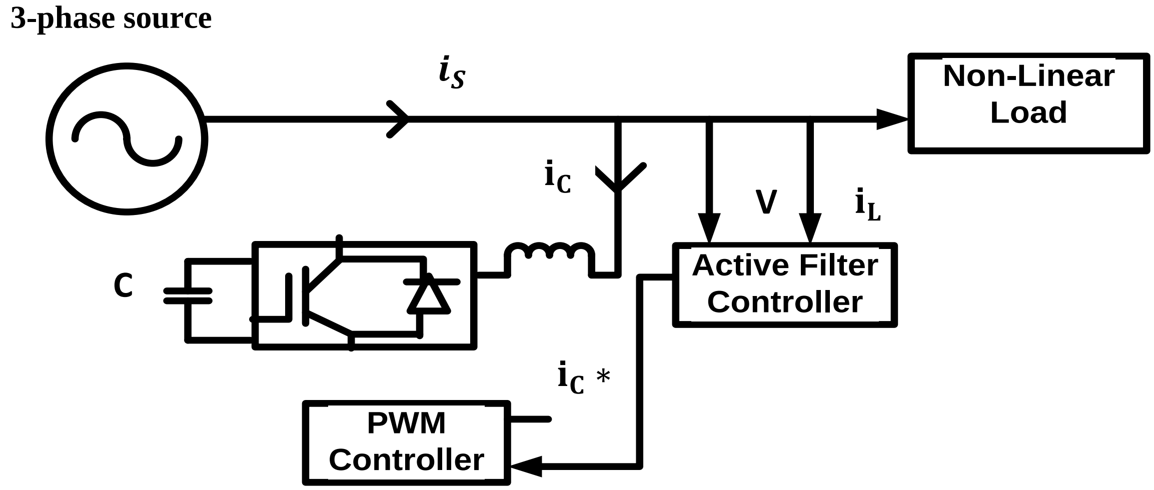

Fig.3.2 Schematic diagram of a shunt APF

3.2 Shunt APF Reference current generation

Shunt APF reference current may be generated by following various methods that are classified according to frequency, time and time-frequency.

1. In frequency domain

- Fast Fourier Transform(FFT)
- Adaptive Neural Network(ANN)

2. In time domain

- d-q-0 theory (that is SRF)
- P-Q theory

3. In time with frequency domain

- Small wave method
- One cycle control or digital/analogue filters separation

Various control strategies have already proposed for harmonic reduction but active-reactive Power (P-Q) theory is most preferable till now. This theory is allowed for steady-state or transient state operations where it is used for controlling APF in real-time.

3.2.1 *p–q* theory based control

Akagi et al in 1983 [3] developed P-Q theory or "instantaneous active-reactive Power theory" for controlling *the* active filters. This can be achieved by transforming the voltage and load current into α-β co-ordinates.

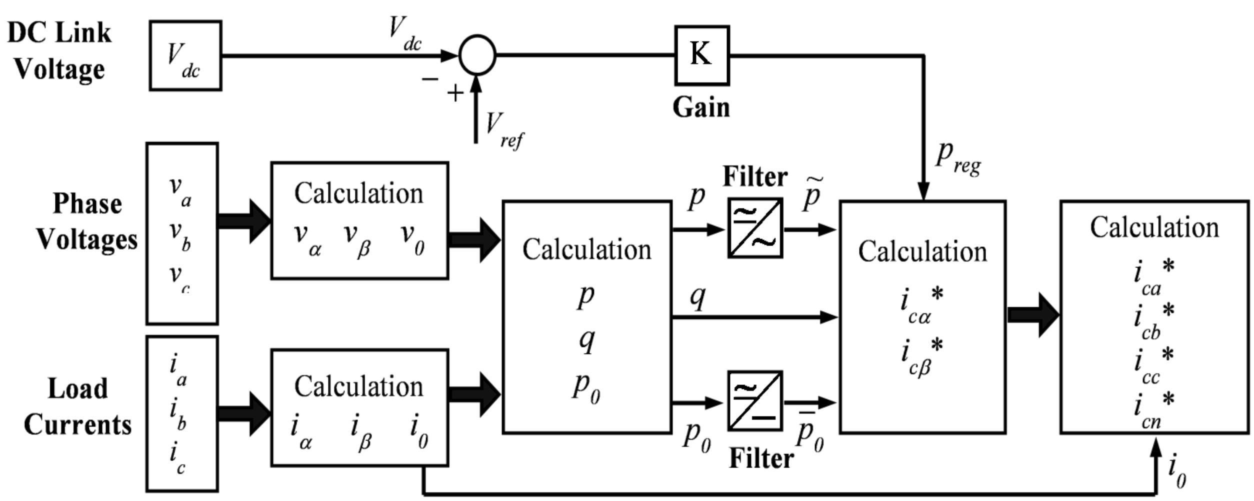

Fig.3.3 Block diagram of p-q compensation theory

P-Q theory can be achieved by transforming the voltage and load current into α-β co-ordinates as following

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

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

The instantaneous active power p_L and reactive power q_L can be expressed as

$$\begin{bmatrix} p_L \\ q_L \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix}$$

These p_L and q_L power can be divided into oscillatory and average terms as following

$$p_L = \bar{P} + p$$

$$q_L = \bar{Q} + q$$

where,

$\bar{P}$= Instantaneous real power Mean value and is treated as desired power component that can be transferred from source to load.

p= Instantaneous real power alternated value and has to be compensated as it is not involve in power transfer between the source to load.

$\bar{Q}$= Instantaneous imaginary power mean value and it is related to the exchanges of power between the load phases which results in undesired current, so it has to be compensated.

q= Instantaneous imaginary power alternated value and is same as conventional reactive-power that has been compensated by using the APF.

In p-q theory assumed voltages are sinusoidal in nature so the power is to be calculated using these sinusoidal voltages.

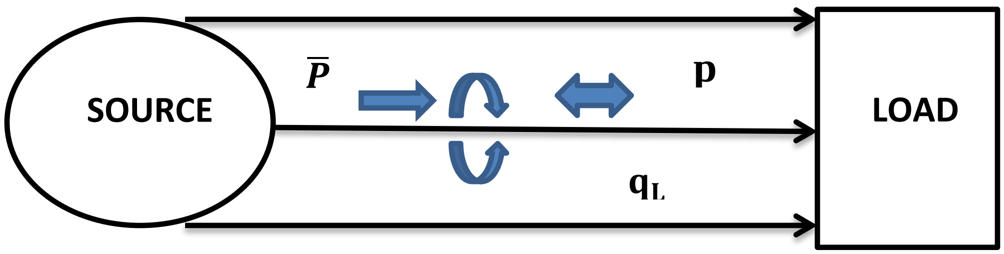

Fig.3.4 p-q theory power components

The powers that have to be compensated are described as below

$$p_c = -p + p_{loss}$$
$$q_c = -q_L$$

where,

p_{loss} = desired active power for compensating filter loss and for desired dc link voltage.

By inverting the matrix we can obtain the reference compensation currents as follows

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{{V_\alpha}^2 + {V_\beta}^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} -p + p_{loss} \\ -q_L \end{bmatrix}$$

$$\begin{bmatrix} i_{ca} * \\ i_{cb} * \\ i_{cc} * \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix}$$

- For separation of the instantaneous power direct term from alternating one a Low Pass Filter (LPF) with feed-forward effect is used.
- DC-link voltage regulator is responsible for compensation as well as for transient response.

Hence, the actual value of DC-capacitor voltage has to be compared with the reference one and the Differential error is fed to a PI-control.

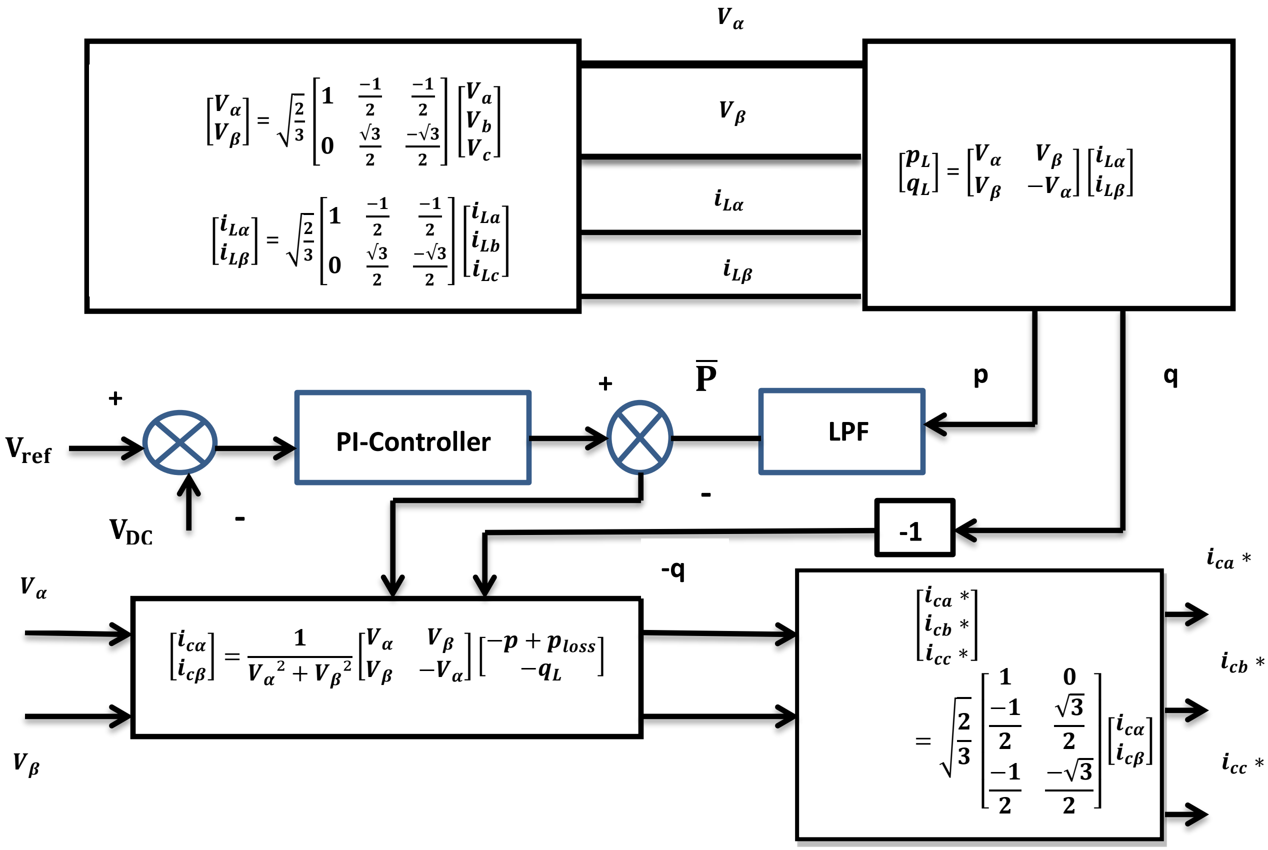

Fig.3.5 Control block for the instantaneous active reactive power control strategy

In the Fig.3.5,

V_{DC}= DC-link voltage

$V_{a,b,c}$= Phase voltages

$I_{a,b,c}$= Phase Load currents

p_L= Instantaneous active power

q_L= reactive power

$i_{ca}*$, $i_{cb}*$, $i_{cc}*$ = Reference compensation currents

3.3 Three Phase Voltage Source Inverter

Here, the DC-link capacitor is used to decouple the source to the grid and converters have an independent control over both sides of the DC-link and this DC link is connected between solar system and three phase grid connected inverter. The three-phase VSI is a basic element of this system as it is interfaced between the PV system with the grid connection and is used to deliver the generated power to the grid. It is also used to convert the stored DC voltage in the storage equipment which is a capacitor in this case into a output voltage in the form of three phase AC. A three phase four leg VSI is used here where the load neutral current is reduced by using the inverter fourth leg. By using IGBTs a three-phase VSI has been modeled in simulation.

Due to semiconductor switching there is presence of harmonics in generated current which can be reduced by output filter which is an L filter or L_{SH}. This filter is also considered as coupling inductance. An electrical grid is a network used as an interconnection between the suppliers and consumers for delivering electricity and also used to store electricity on a large scale Grid using some methods. Normally, electrical energy is stored during the time when production from power plants is more than consumption and those stored energies are used during the period when energy consumption is more than production.

In a linear load the current is directly proportional to voltage. But in non-linear loads the relationship between current and voltage is not proportional which is used to apply to AC loads. These non-linear loads are the cause to generate harmonics in the current waveform. So due to the current distortion there is presence of distortion in the voltage waveform.

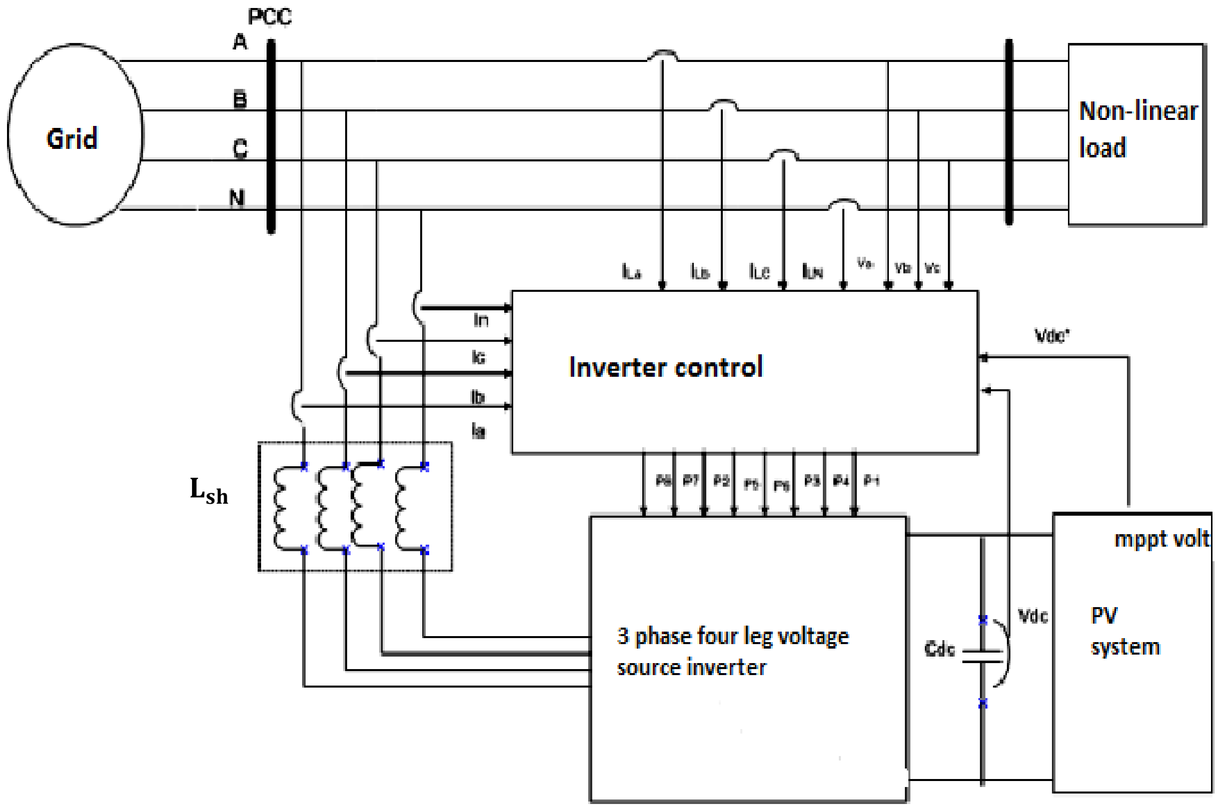

Fig.3.6 Schematic diagram of grid integrated inverter controlled PV system

3.3.1 Control Techniques for Grid interfacing with inverter

The block diagram for the control technique of inverter in a photovoltaic system for improvement in power quality is presented in Fig.3.6. When the power quality is managed, the VSI control technique is done in a way that it can draw as well as supply fundamental real power from/to grid. During the PCC connection with non-linear load or Power electronics load or unbalanced load or both balance and unbalanced load combination, then this inverter control technique is used for compensating the harmonics in load currents, and also used for reduction in unbalanced current and for compensating the neutral current and it supports the demand of load reactive power. This control technique is similar to the three-phase APF technique used for improving Power Quality of Grid using P-Q theory for Renewable Energy Sources like solar energy source. Here, this grid interfacing Inverter control technique is used in over-all operation for the reduction of harmonics in currents due to non-linear loads.

3.3.2 Hysteresis control method of VSI

Hysteresis current control is invented by Brod and Novotny in the year 1985 which is a method used for controlling an output current of a VSI by following the reference current. The source ref. current is calculated and then compared to that of APF actual line current in a Hysteresis Current Controller for generating the switching pulse for the VSI. HCC is simplest technique according to implementation. There is only one disadvantage is that it does not have any limit for maximum switching frequency hence, additional circuit can be used for limiting the frequency.

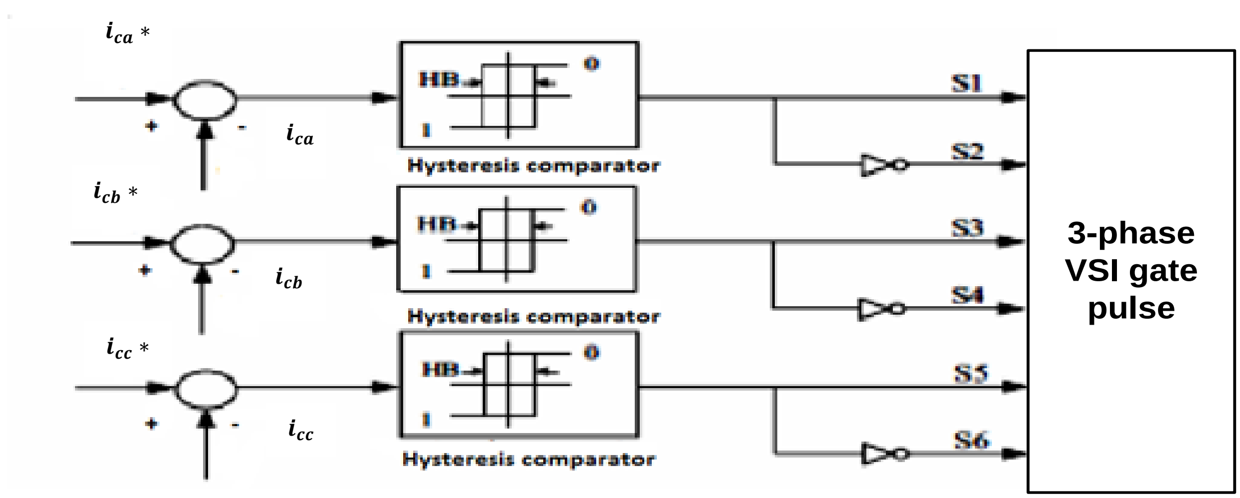

Fig.3.7 Hysteresis band current control

Here,

i_{ca} *, i_{cb} *, i_{cc} * = Reference compensation currents

i_{ca}, i_{cb}, i_{cc}= Actual line current of APF

The Reference compensation currents are compared with the actual line current of APF

By using hysteresis band comparator to generate the gate pulse for VSI.

For phase a:

When i_{ca}< (i_{ca} ∗-HB) the upper switch has to be deactivated and lower switch has to be activated hence, S1=0 and S2 =1.

When i_{ca}> (i_{ca} ∗+HB) the upper switch has to be activated and lower switch has to be deactivated such that S1=1 and S2 =0.

Switching pulses for phase b and c has to be determined in the similar manner by considering reference and measured currents of that phase with width of hysteresis band (HB).

3.3.3 Control loop design

DC-bus Voltage control is performed by adjusting the dc-capacitor power and hence, Control the compensating conduction-loss as well as switching-loss. PI-controller is used here for eliminating the steady state error and for reduction of ripple voltage and is expressed as

$$H(S) = K_p + \frac{K_i}{s}$$

where,

$K_p =$ Proportional gain and $K_i =$integral gain and these are set to such a value to keep the actual V_{dc}equal to reference value of V_{dc}. This PI-controller is used for ripple voltage reduction of the PWM current controlled VSI.

3.3.4 Effect of DC Capacitor

The advantage of DC-link capacitor is as follows

I) It is used for maintaining a constant DC voltage.

ii) During transient condition it is used as energy storing element for supplying difference in real power within load and source.

3.4 Chapter summary

This chapter represented the voltage source shunt active filter control technique where, P -Q theory control algorithm have been used for Shunt APF current harmonics compensation by injecting equal-but-opposite compensating currents into the system. The VSI control technique which includes p-q based theory with hysteresis control for gate pulse generation of VSI is described in this chapter.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Results and Discussions

For the simulation results of the grid connected PV system with APF, a PV array with MPPT technique to track maximum power is further connected to boost converter for voltage boost-up and then connected to a shunt APF. Hence, maximum efficiency of PV system occurred as the harmonics are eliminated by shunt APF. Here, the non-linear load is a diode bridge rectifier with RL-load which causes harmonics in load current. A shunt APF simulation model is developed to control the energy of a PV system based on p-q theory for controlling the harmonics in current due to nonlinear load. Here the shunt APF technique is also implemented to three-phase VSI for the same purpose.

Table 4.1 PV array parameters [21]

PARAMETER	**VALUE**
Open circuit voltage	17.8 V
Short circuit current	8.214 A
Rated current at MPP	6.14 A
Rated voltage at MPP	13.62 V
Maximum power P_{max}	90 watt
No. of Solar Cells	36

SIMULINK Implementation of a PV system with MPPT

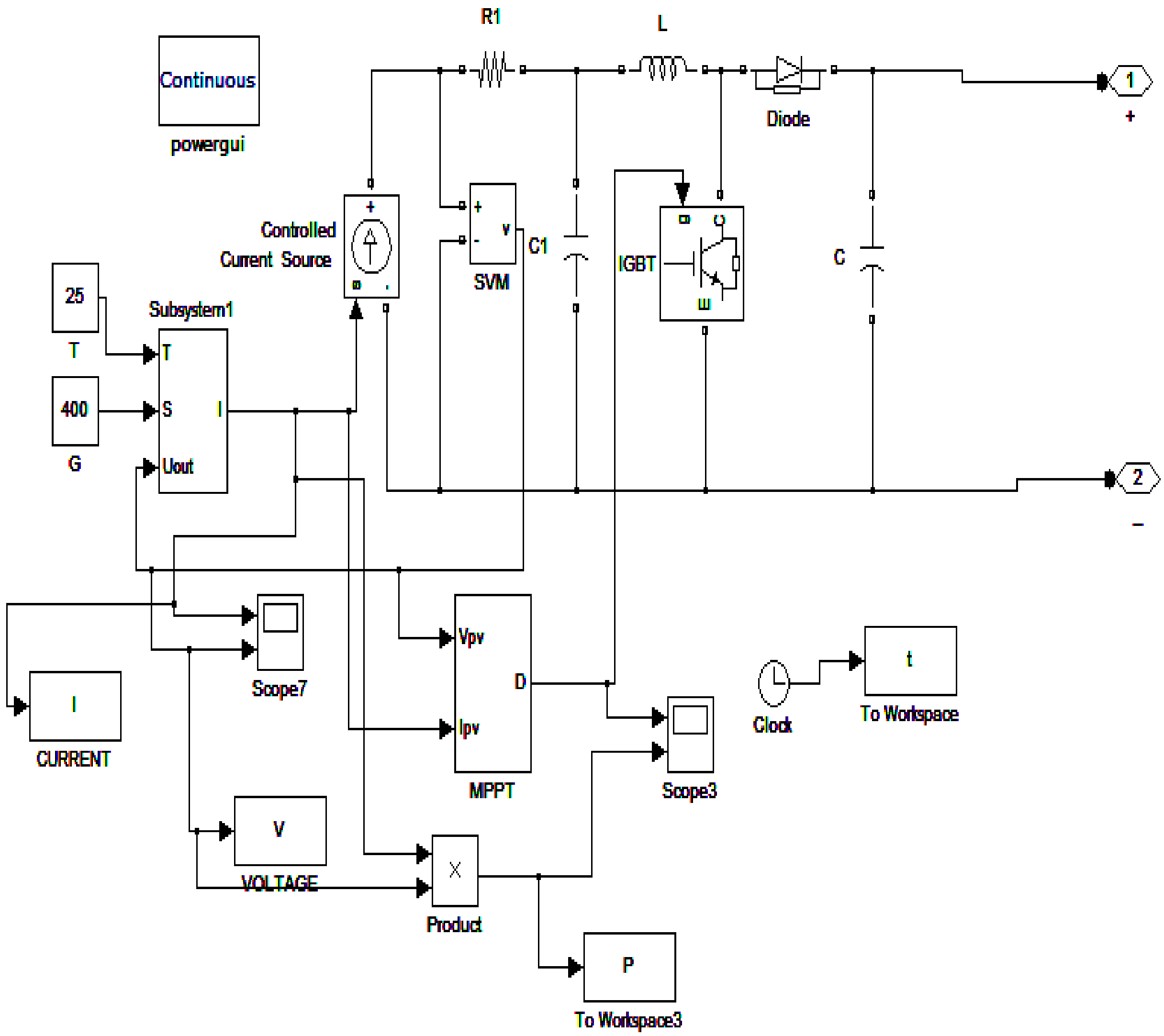

Fig 4.1 Simulink Implementation of a PV array with boost converter and MPPT P & O

In the Fig.4.1, the PV cell is simulated considering the equations

$$I = I_{ph} - I_d - I_{sh}$$

$$I = I_{ph} - I_{sat}(\exp(q(V + I \times R_{se} \div aKT)) - 1) - (V + I \times R_{se} \div R_{sh})$$

Hence, by taking the combination of 36 PV cells PV array is simulated and the MPPT algorithm is applied to the output voltage and current of PV array to get the duty cycle. Then, the boost converter equation

$$V_{in} = (1\text{-D})\, V_{out}$$

is applied for the output voltage of the DC-DC boost converter which is further connected to a VSI. Here, the PV array with irradiance=400 w/m² at temperature=25^0 C is connected to a MPPT controller to extract the maximum power. The DC-DC converter contains a inductor, capacitor, diode and a IGBT as it is a high frequency switch. It produces higher voltage during power supply to the load. Based on the switch duty cycle the output voltage is changed.

Table 4.2 Shunt APF parameters [13]

PARAMETERS	**VALUE**
DC Link Voltage	850 V
DC Capacitor	2 mF
Coupling Inductor (L_f)	1.2mH
Unbalance Load (R_1, R_2 ,R_3)	(2, 4, 6 Ω)
Diode Load (R,L)	10 Ω ,100mH

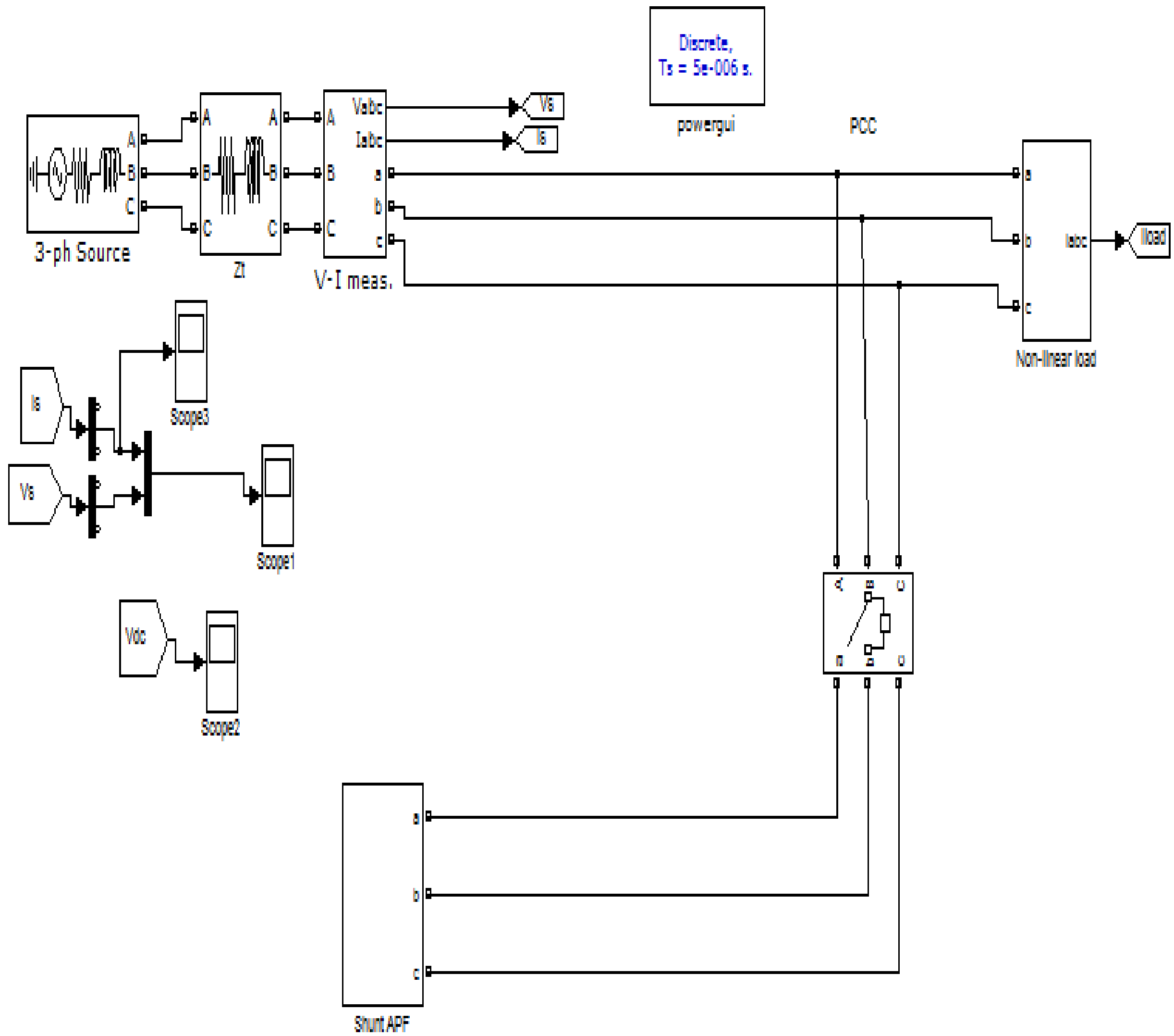

Fig.4.2 SIMULINK model implementation of Current Control Scheme

Here, the shunt APF has capability of detecting the harmonic currents caused by the nonlinear loads and then injects a current of equal magnitude and opposite in phase with the non-linear load current which is called compensating current to reduce the harmonics present in load currents due to Non-linear load. Hence, the resulting current is in form of a fundamental frequency sinusoidal current which is drawn at PCC in distribution network.

Fig.4.2 shown is a SIMULINK implementation of a PV system with MPPT controller and boost converter for current control technique. Here, the shunt APF block contains the P-Q compensation theory and inverter gate pulse control by using hysteresis current control method.

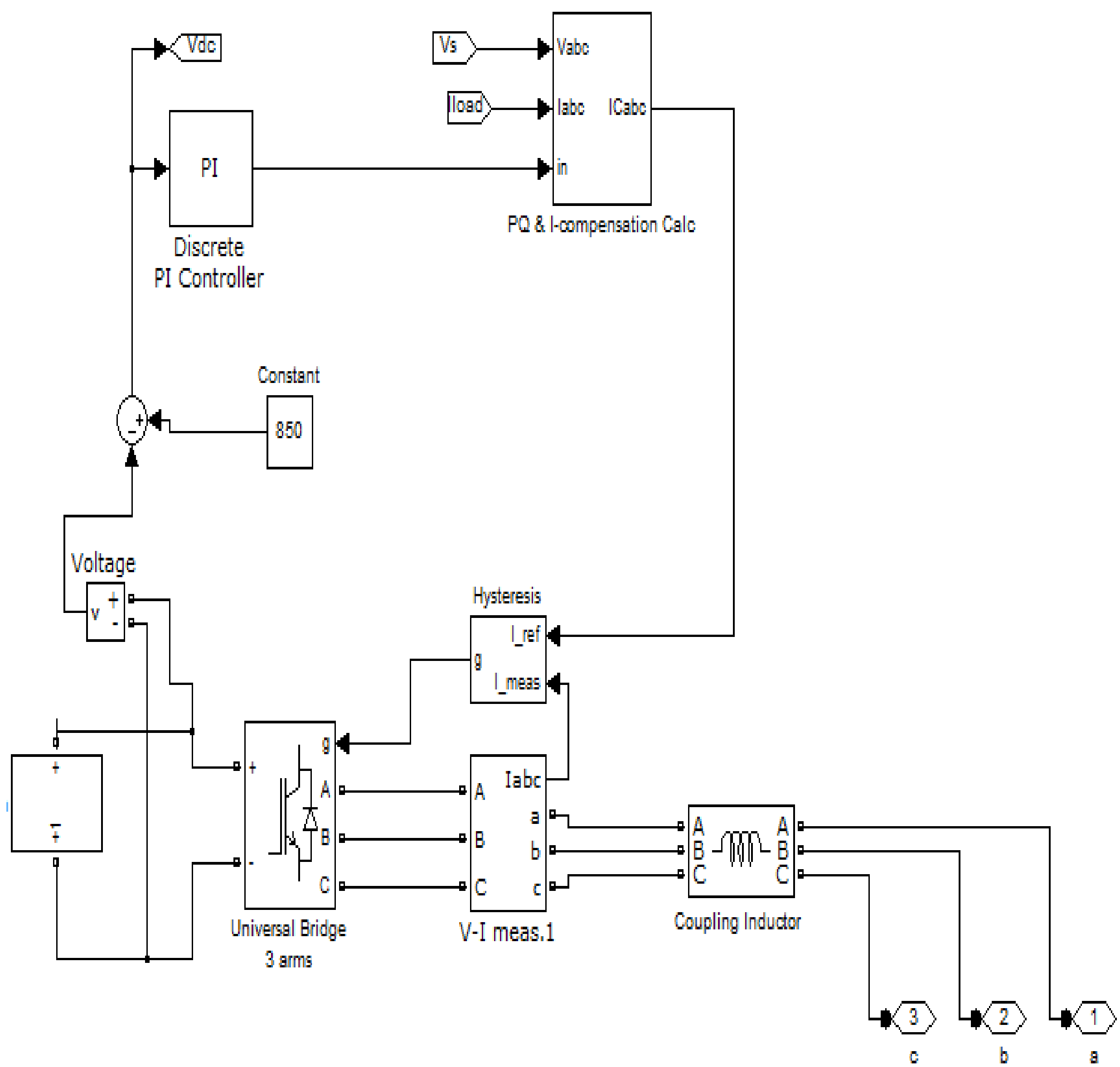

Fig 4.3 SIMULINK model for implementation of shunt APF in a PV system

The Fig.4.3 shown is a SIMULINK implementation of shunt APF in PV system. Here, the PV system with MPPT is connected to the 3-phase inverter and then by P-Q compensation theory the reference current is calculated which is further compared with the measured current to give the controlled pulse to the inverter. This can be achieved by transforming the voltage and load current into α-β co-ordinates by

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

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

The instantaneous active power p_L and reactive power q_L can be expressed as

$$\begin{bmatrix} p_L \\ q_L \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix}$$

These p_L and q_L power can be divided into oscillatory and average terms as following

$$p_L = \bar{P} + p$$

$$q_L = \bar{Q} + q$$

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{{V_\alpha}^2 + {V_\beta}^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} -p + p_{loss} \\ -q_L \end{bmatrix}$$

$$\begin{bmatrix} i_{ca} * \\ i_{cb} * \\ i_{cc} * \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix}$$

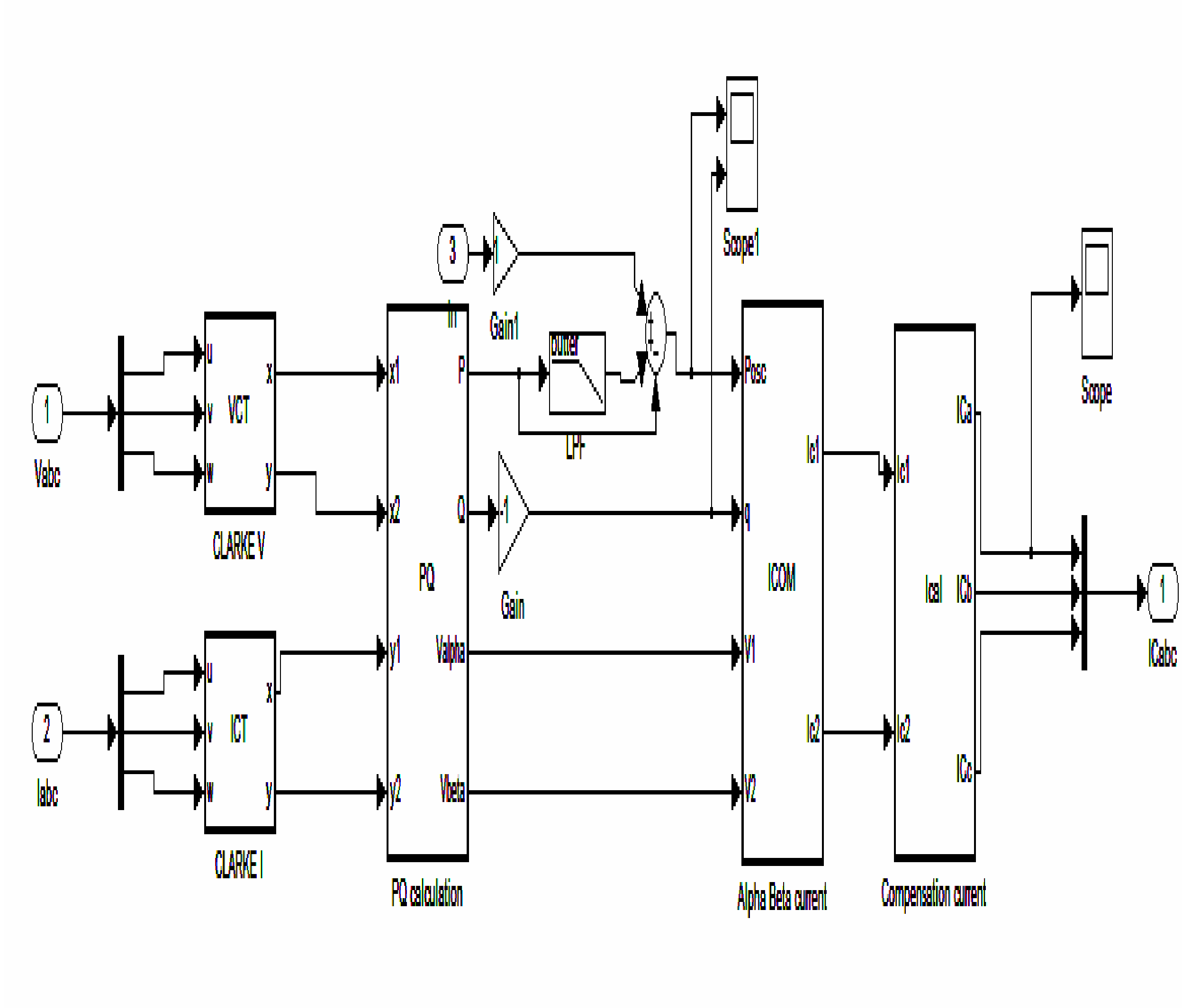

Fig 4.4 SIMULINK implementation for Compensation current calculation

This simulation implementation represents the operation and control of shunt APF by calculating compensating current**.** Here, Instantaneous p-q Theory has been used for Shunt APF where harmonics in current have been compensated by injecting equal magnitude with opposite phase currents to the PV system. This can be achieved by transforming the voltage and load current into α-β co-ordinates. Then considering the instantaneous active power p_L and reactive power q_L , $i_{c\alpha}$ and $i_{c\beta}$ are calculated and then the compensating currents in a, b, c co-ordinate are generated. The complete simulation model of shunt APF based on P-Q theory have been designed as shown above.

4.2 SIMULINK Results and Discussions

Here, the PV array is simulated with various irradiations at constant temperature value that is at 25^0 C to get the I-V and P-V curves change with irradiations.

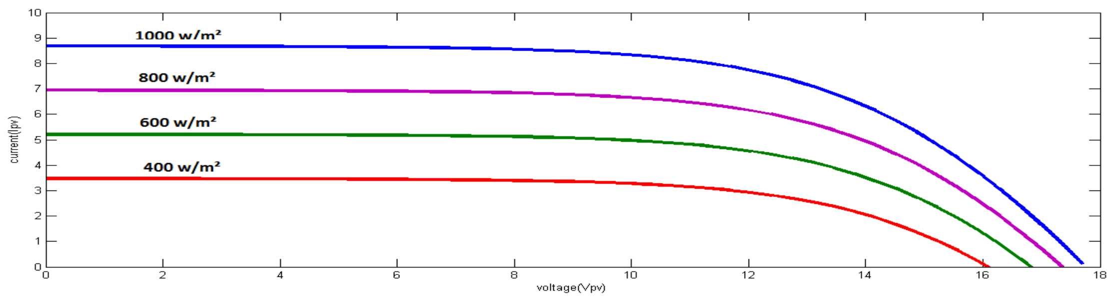

Fig.4.5 V-I characteristics with different irradiance at constant temp=25°C

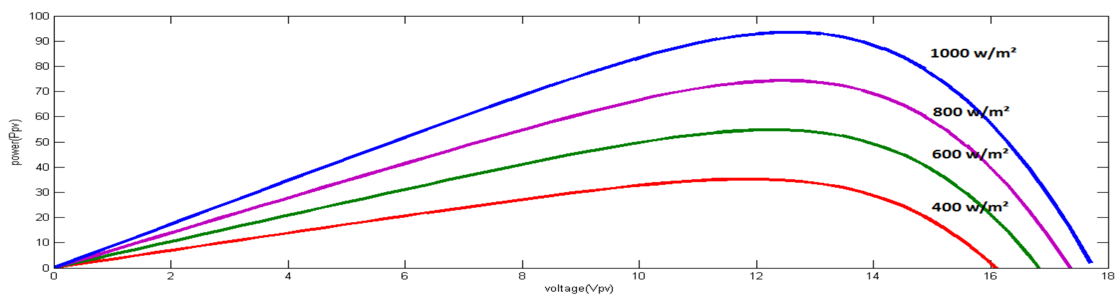

Fig.4.6 P-V characteristics with different irradiance at constant temp=25°C

From the waveforms shown in Fig.4.5 it is cleared that if Irradiance decreases then, current decreases as I_{PH} depends on irradiance and Fig.4.6 represents decrease in power when Irradiance decreases as P=V*I.

Here, the PV array is simulated with various temperature values to get the change in P-V and I-V curves at constant irradiance=1000 W/m².

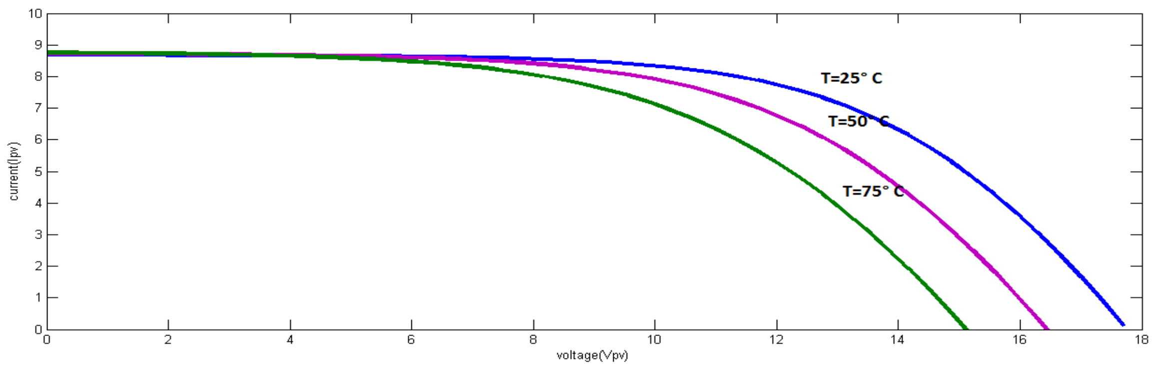

Fig.4.7 I-V characteristics with different temperature at Constant irradiation=1000 W/m²

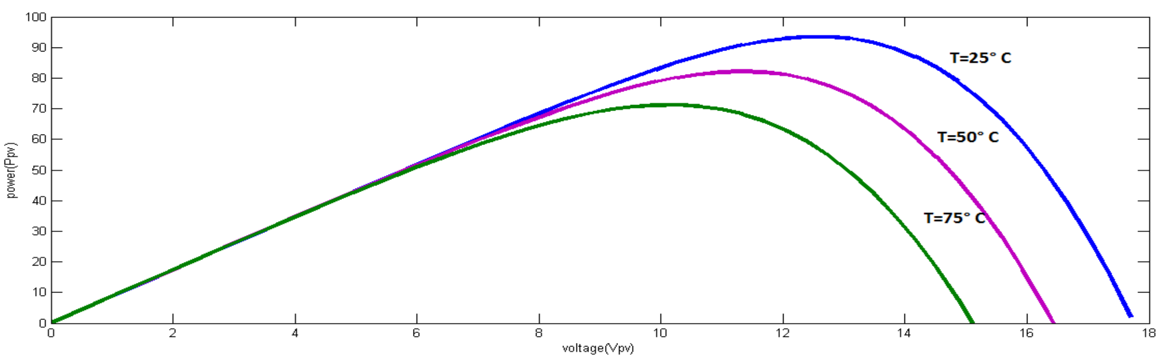

Fig.4.8 P-V characteristics with different temperature at Constant irradiation=1000 W/m²

From the above waveforms shown in Fig.4.7 and Fig.4.8 it is cleared that when the temperature increases the open circuit voltage decreases hence, band gap also increases which requires more energy to cross the barrier. Hence, the efficiency of the solar cell decreases.

The PV array with MPPT algorithm is implemented for simulation to get the effect the MPPT technique on current, voltage and power before and after its application.

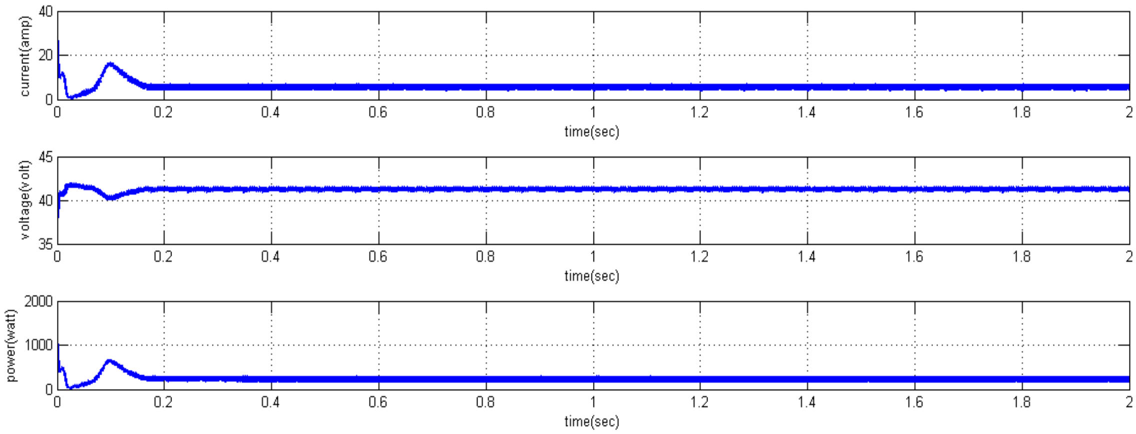

Fig.4.9 Current (I), voltage (V) and power (P) waveforms of boost converter without P&O

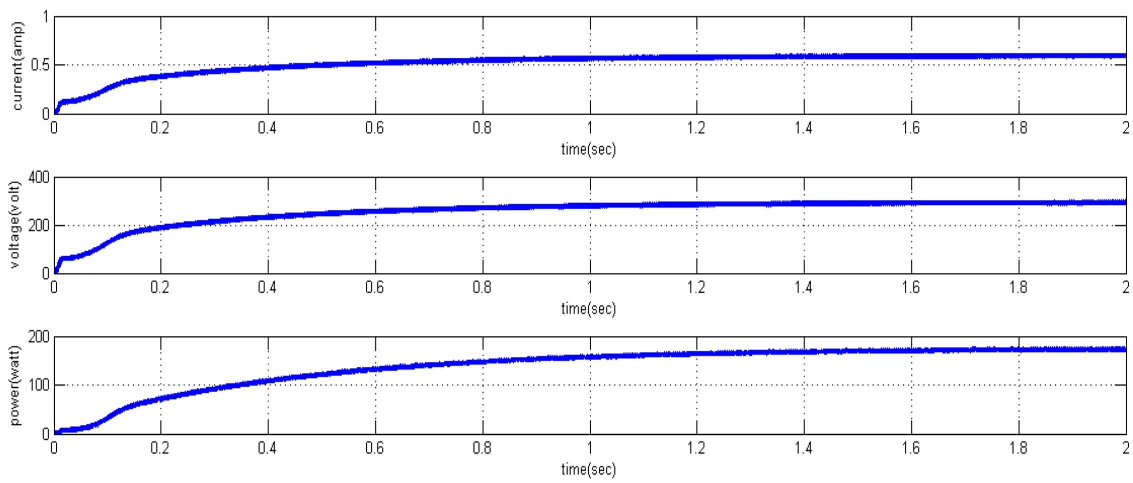

Fig.4.10 Current (I), voltage (V) and power (P) waveforms of boost converter with P&O

From Fig.4.9 it is noticed that at T=25^{o}C and S=400 W/ m², I= 5.445 Ampere, V=41.23 volt, P= 224.5 watt and in Fig.4.10 at T=25^{o}C and S=400 W/ m², I= 0.5915 Ampere, V=292.9 volt, P= 173.2 watt.

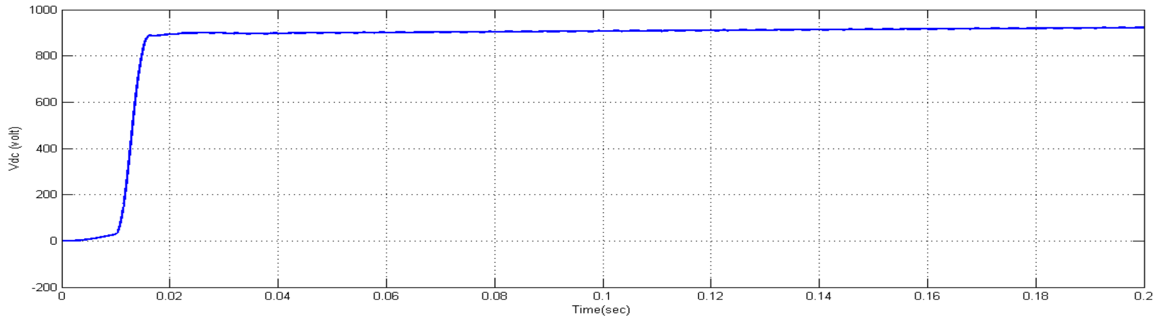

Fig. 4.11 Capacitor Voltage

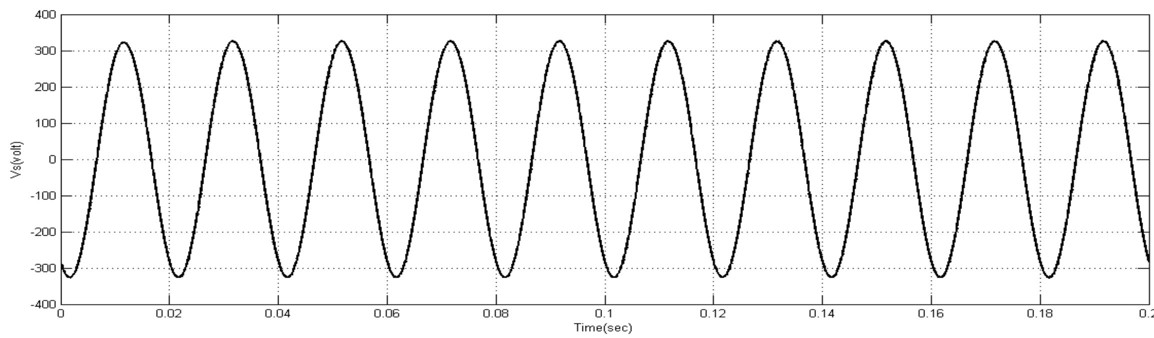

Fig.4.12 Source Voltage

From the waveform in Fig.4.11 it is cleared that capacitor voltage has settled down at V_{dc} value that is 850 volt and Fig.4.12 represents source voltage of 330 volt.

In the waveforms shown below in Fig.4.13 and Fig.4.14 the simulation is done for the load current before and after the shunt APF implementation to find the harmonics compensation by using shunt APF.

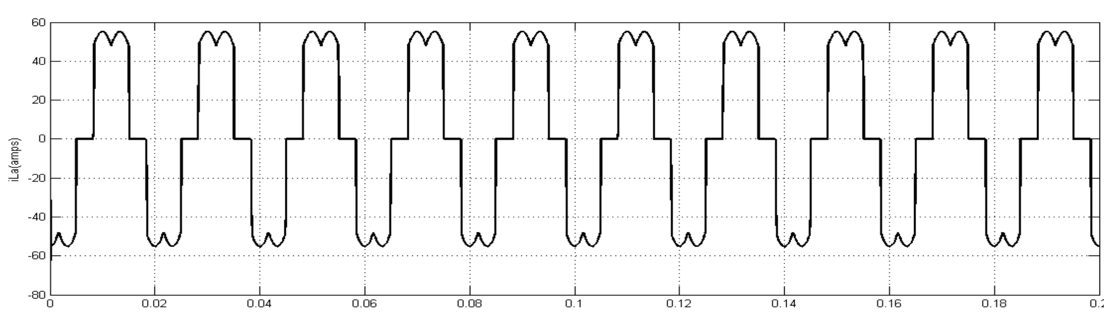

Fig.4.13 Load Current before filtering

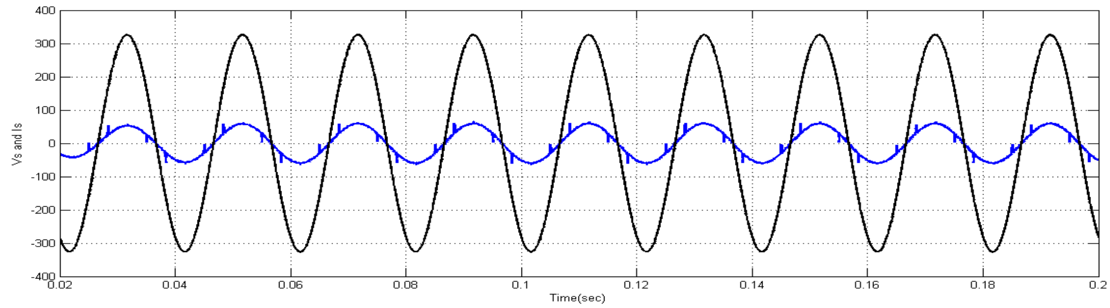

Fig.4.14 Source Voltage and Source current after filtering

The waveform shown in Fig.4.13 and Fig.4.14 represents source current at time before and after when shunt filter is connected that means before compensation and after compensation, where the result is almost sinusoidal with less harmonic content.

For the THD analysis of load current before and after the Shunt APF application, on the SIMULINK page FFT analysis option in the powergui is chosen which results in display of THD percentage of the load current before and after compensation. FFT function is used for the spectral analysis. It is normally used to find the total harmonic distortion in a particular signal.

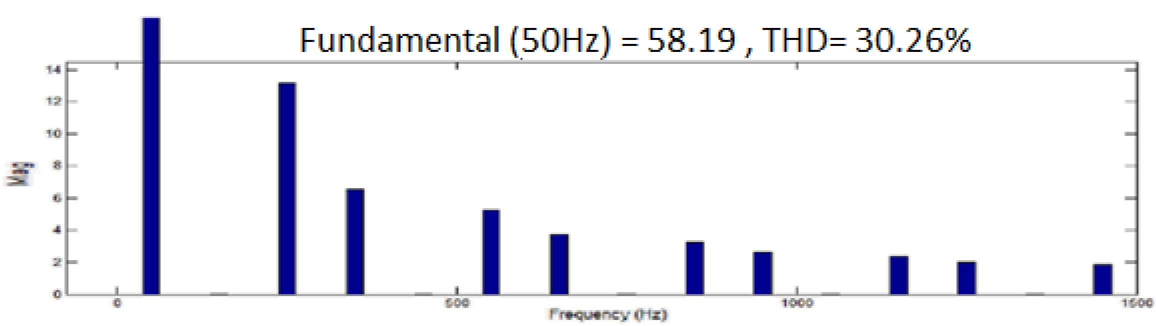

Fig.4.15 THD of Load Current before filtering

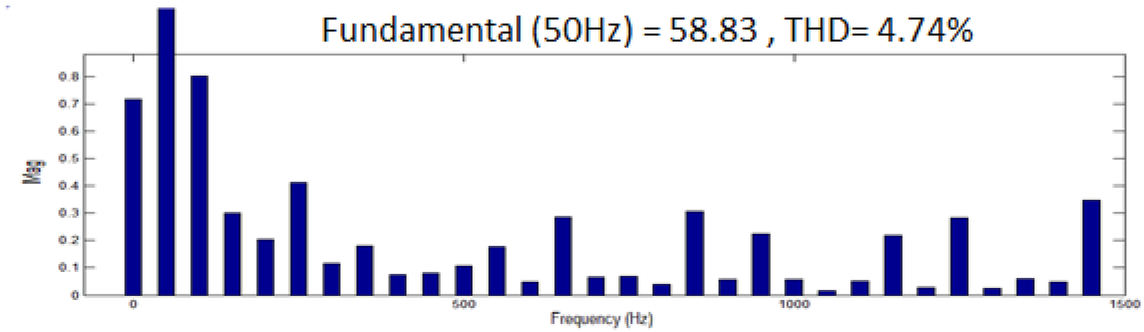

Fig.4.16 THD of Source Current after filtering

It is noticed from Fig.4.15 and Fig.4.16 that THD of source current is reduced to 4.74 % from 30.26 % by using shunt APF. Hence, by shunt APF implementation the THD value is reduced.

Table 4.3 Parameters for grid connected inverter control technique [2]

PARAMETERS	**VALUE**
Grid (ph-ph)	V_g= 170V at 50Hz
DC-link capacitance	C_{dc}=3000µF
DC-link voltage	V_{dc}=850V
Coupling inductance	L_{sh}=2mH
Unbalance Load (R1, R2 ,R3)	R_1, R_2 ,R_3=26.66Ω, L_1=10mH, C_2=1000µF
Diode Load (R,L)	36.66 Ω, 10mH

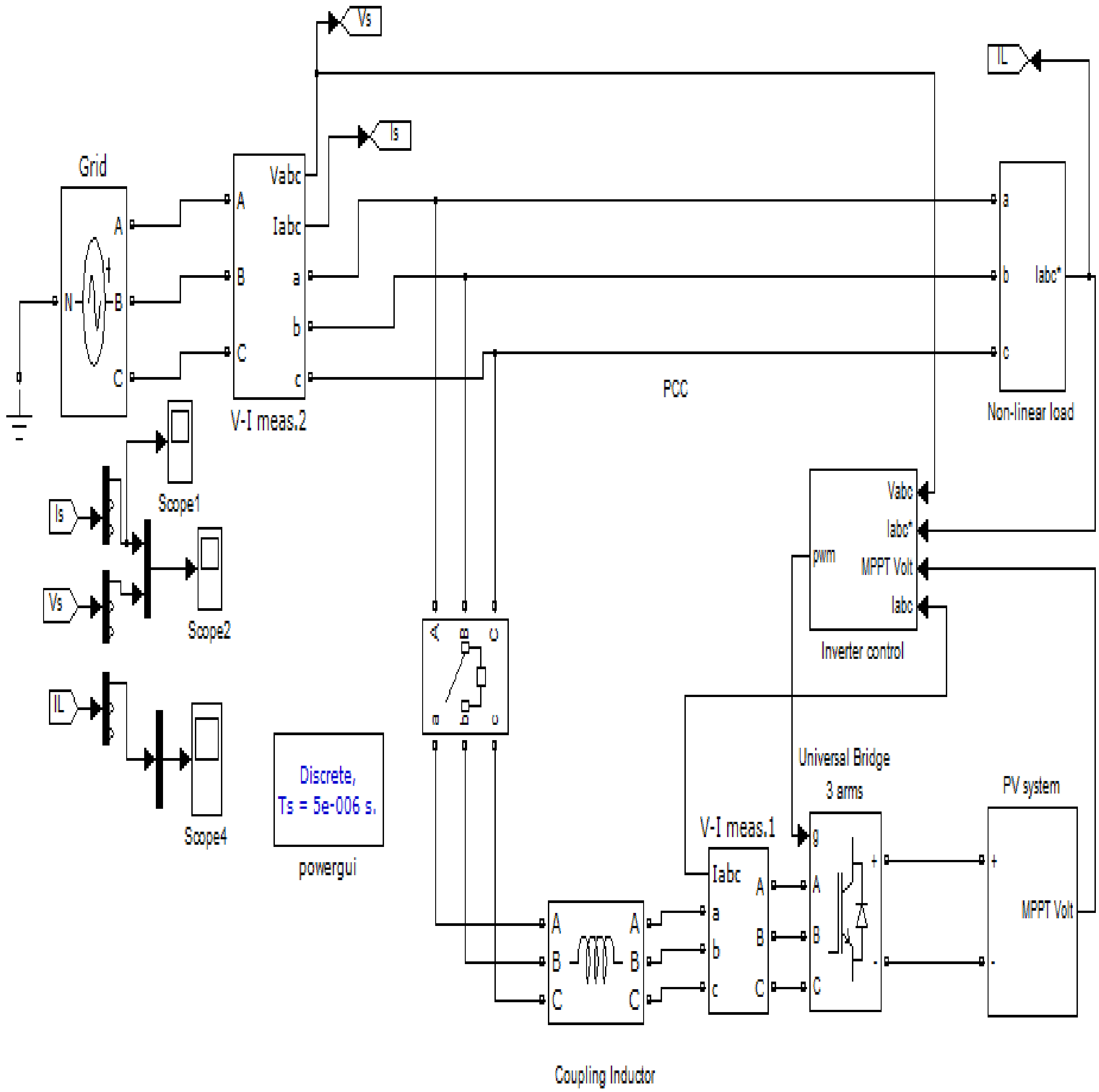

Fig 4.17 Simulation model representing grid connected inverter control technique

Fig.4.17 shows the SIMULINK implementation of grid connected inverter control technique where the inverter control involves the P-Q compensation theory and hysteresis control for generation of gate pulse for the VSI. This inverter control is applied at the PCC to get the sinusoidal load current.

The load current I_L before and after inverter control application is done by Simulink and the below waveforms shows the effect of inverter control.

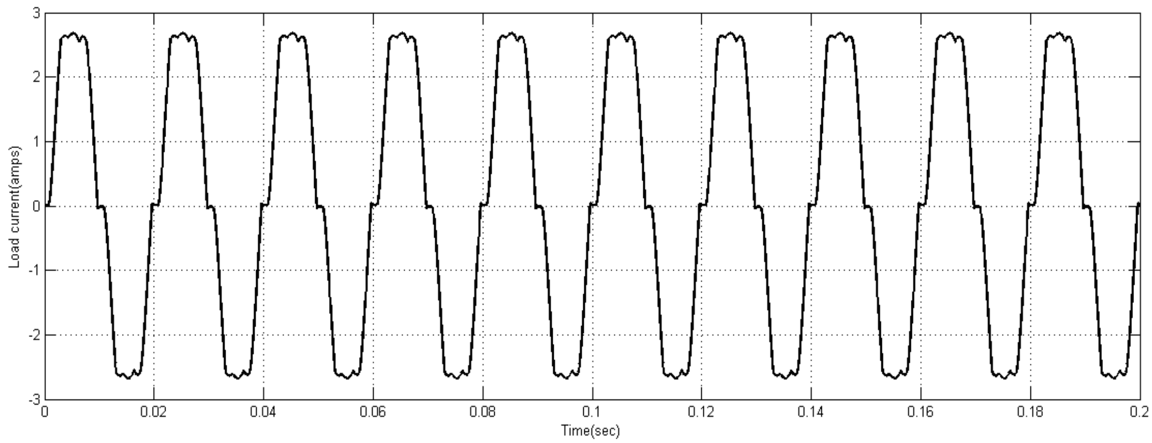

Fig.4.18 Current before inverter control

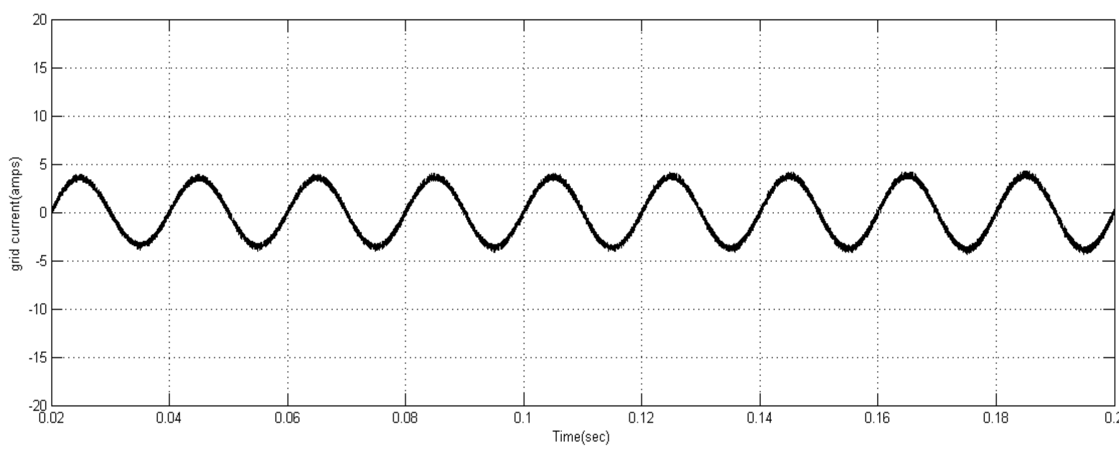

Fig.4.19 Current after inverter control

The waveform shown in Fig.4.18 and Fig.4.19 represents current at time before and after inverter control technique is implemented, where the result after inverter control is almost sinusoidal with less harmonic content.

The source voltage and source current are generated using SIMULINK as shown below.

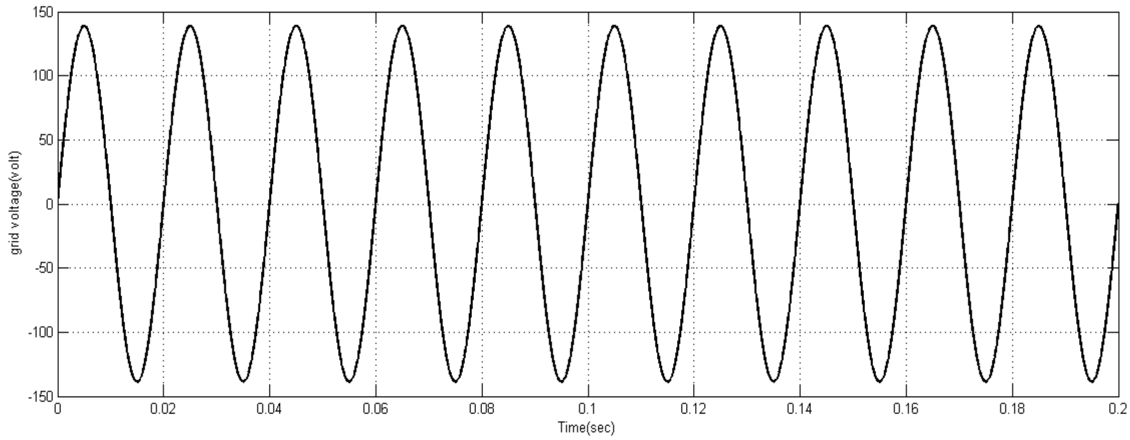

Fig.4.20 Grid Voltage

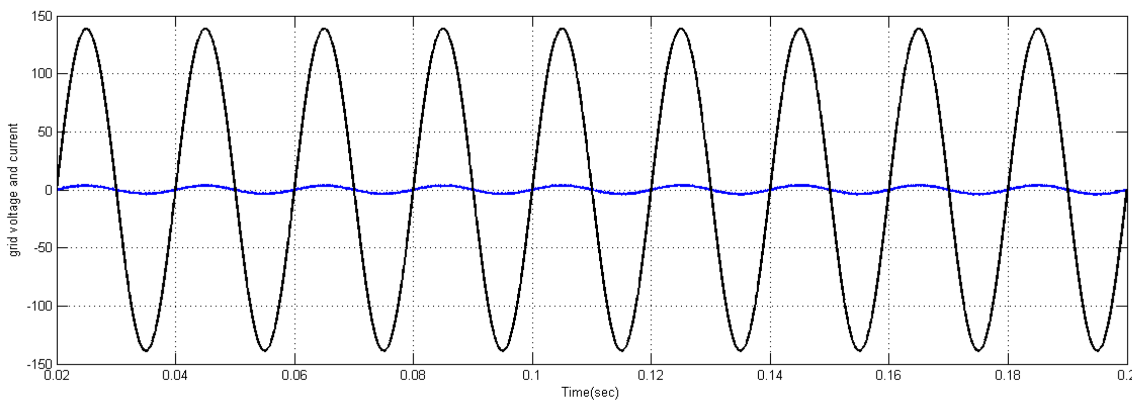

Fig.4.21 grid Voltage and grid current

The waveform in Fig.4.21 represents that grid voltage and grid current are in same phase hence, unity power factor (UPF) occurred and in Fig.4.20 grid voltage has shown whose value is 140 volt.

For the THD analysis of load current before and after the inverter control technique application, on the SIMULINK page FFT analysis option in the powergui is chosen which results in display of THD percentage of the load current before and after compensation. FFT function is used for the spectral analysis. It is normally used to find the total harmonic distortion in a particular signal.

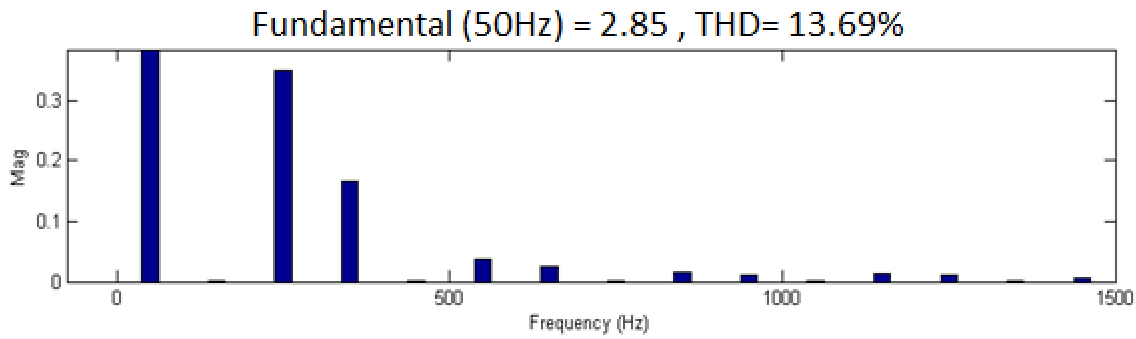

Fig.4.22 THD of Load Current before inverter control

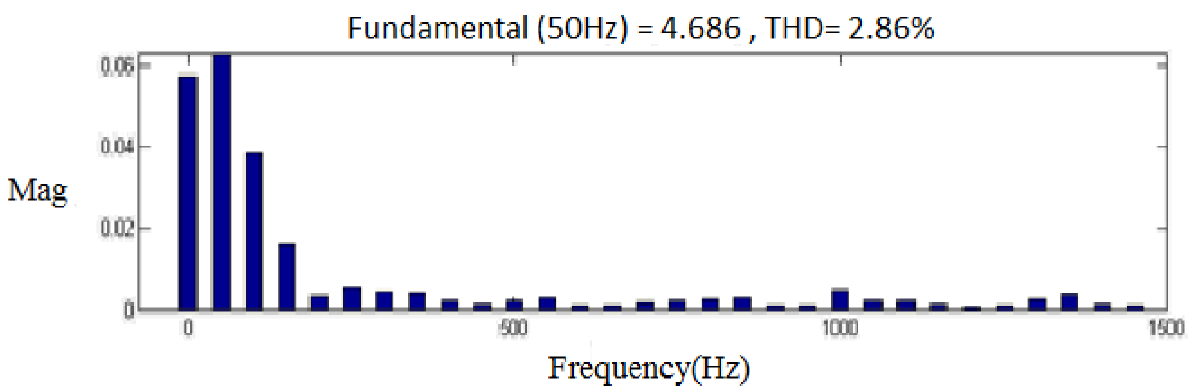

Fig.4.23 THD of grid Current after inverter control

The waveform in Fig.4.21 represents that grid voltage and grid current are in same phase after inverter control technique is applied. Hence, unity power factor occurs. It is noticed from Fig.4.22 and Fig.4.23 that THD of grid current is reduced to 2.86 % from 13.69 % by inverter control technique.

CHAPTER 5

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

5.1 Conclusions

In this thesis, a Shunt APF is designed for a Grid connected PV system. Here, the PV system is connected to the MPPT controller to extract the maximum power. From the Simulink results it is cleared that the voltage versus Power characteristics and Voltage versus Current characteristics of a solar cell are mainly dependents upon the solar irradiation and temperature. When the Irradiance decreases then, current decreases as I_{ph} depends on irradiance and also results in decrease in power when Irradiance decreases as P=V*I. From the waveforms shown it is also cleared that when the temperature increases the open circuit voltage decreases hence, band gap also increases which requires more energy to cross the barrier. Hence, the efficiency of the solar cell decreases. Boost Converter Simulation with Perturb and Observe MPPT method is implemented in MATLAB-SIMULINK. From the Simulink results it is cleared that the MPPT method simulated here is capable of improving the dynamic and steady state performance of the PV system simultaneously. Through simulation it is observed that the system completed the MPPT successfully irrespective of fluctuations. With the sudden change in external environment the system can track the maximum power point quickly.

In this thesis the Shunt APF is designed for a PV system with non-linear load which generates the distortion in load currents. Hence, the Shunt APF is designed using SIMULINK to reduce the harmonics present in the load currents. This simulation implementation represents the operation and control of shunt APF by calculating compensating current**.** Here, Instantaneous p-q Theory has been used for Shunt APF where harmonics in current have been compensated by injecting equal magnitude with opposite phase currents to the PV system. The complete simulation model of shunt APF based on P-Q theory have been designed. Here, the PV system with MPPT is connected to the 3-phase inverter and then by P-Q compensation theory the reference current is calculated which is further compared with the measured current to give the controlled pulse to the inverter. For the THD analysis of load current before and after the harmonics compensation by shunt APF application, on the SIMULINK page FFT analysis option in the powergui is chosen which results in display of THD percentage of the load current before and after compensation. Simulation results show that the current obtained after filtering and the voltage waveforms are in same phase by shunt APF. Also, the current THD is reduced from 30.26% to 4.74% which confirms the good filtering quality of current harmonics and compensation of reactive power which improve the power quality.

In this thesis also the Simulink implementation of grid connected inverter control technique has done by SIMULINK where the inverter control involves the P-Q compensation theory and hysteresis control for generation of gate pulse for the VSI. This inverter control is applied at the PCC to get the sinusoidal load current. The load current before and after inverter control application is done by Simulink and the waveforms shows the effect of inverter control, where the result after inverter control is almost sinusoidal with less harmonic content. For the THD analysis of load current before and after the inverter control technique application, on the SIMULINK page FFT analysis option in the powergui is chosen which results in display of THD percentage of the load current before and after compensation. Hence, it is seen that in case of inverter control technique total harmonic distortion in load current is 13.69% before inverter control and it reduces to 2.86% after inverter control and also grid current is in same phase with grid voltage that is unity power factor(UPF) occurs. So inverter plays a novel role to control the harmonics and reactive power compensation to provide only real power at the PCC of the distribution system. Hence, it can be concluded that by use of Shunt APF the harmonics due to a non-linearity of load is compensated to a large value to provide sinusoidal output current of multiple of fundamental frequency and also reactive power is compensated to provide only real power at the distribution system.

5.2 Scope for Further Work

Further work in this area may use different MPPT method and modified algorithms for increasing efficiency of the PV system by reducing the harmonics in load current in fast changing environmental conditions. Try to design such model for solar PV system which should compact size and cheaper and also its maintaining and operating cost should be less so that people attract to use in behavior and do not go for conventional sources even for isolated systems. Inverter should be design by using SMPS circuits if further implementation will happen from this project. Over all physical implementation of the PV system with various harmonics compensation methods will remains for the future research.

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