MITIGATION OF HARMONICS AND REACTIVE POWER COMPENSATION IN GRID CONNECTED PV SYSTEM

A DISSERTATION

Submitted in partial fulfillment of the

requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

(With specialization in Electric Drives and Power Electronics)

By

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CANDIDATE'S DECLARATION

I hereby declare that this thesis report entitled **MITIGATION OF HARMONICS AND REACTIVE POWER COMPENSATION IN GRID CONNECTED PV SYSTEM**, submitted to the Department of Electrical Engineering, Indian Institute of Technology, Roorkee, India, in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electrical Engineering with specialization in Electric Drives and Power electronics is an authentic record of the work carried out by me during the period June 2015 through May 2016, under the supervision of **Dr.M.K.PATHAK, Department of Electrical Engineering, Indian Institute of Technology, Roorkee.** The matter presented in this thesis report has not been submitted by me for the award of any other degree of this institute or any other institutes.

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Place: Roorkee

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CERTIFICATE

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

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ABSTRACT

The upsurge in demand of energy has been accentuated by industrial drives system, domestic appliances etc. The drive system and many household/domestic equiments has to its core semiconductor based switches. The very nature of these switches is 'non-linearity', which comes into play between the voltage and current relationship. This distorts the wave-shape of current vis-a-vis the voltage. It is found on using mathematical analysis like Fourier analysis that current not only contains fundamental frequency but also those 'unwanted' frequncies called as harmonics. These harmonics when they flow through the wires and cables would cause unnecessary heating and associated loss of power. This results in failure of insulation, breakdown of equipments, equipment to be underutilised , electromagnetic interference etc. This gives rise to power quality issues to be addressed.

The power quality problem has been a focus area for electrical engineers. To mitigate the problem filters have been devised. These filters are available either passive filters or active filters. Other than cost the active filters finds comparative advantages vis-a-vis passive filters. The dissertation work focuses on the development of a PV fed inverter which could inject the reactive power and meet the load reactive power demand under all irridation condition as well as mitigate the harmonics produced by a combination of loads(non-linear and linear load). Also the simulation investigates whether it is possible to obtain real power from the PV array by not effecting the reactive power and harmonic mitigation aspect for the loads. Also what will be the win-win situation under all circumstances so that reactive and harmonic mitigation is not compromised.

In laboratory a 2 level inverter prototype was developed and was tested using DSpace 1104 .

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Chapter 1

Introduction

The menace of climate change produced by relentless consumption of fossil fuel has forced human race to rethink its present strategy towards growth. This threat has brought us at cross-road where new impetus is being given to non-conventional sources of energy. Solar energy is being hailed as one of such sources which could help us contain the menace.The use of solar energy for consumption purpose i.e for use in industry and for domestic use is on the rise through the production of electrical energy from it. The present work envisage the use of solar PV for harmonic mitigation and reactive power compensation.

1.1 Literature survey

In 1991 H. Akagi, Y Kanazawa, and A. Nabae , conceptualised the instantaneous reactive power theory . The theory is applicable to both balanced and unbalanced conditions of voltage and current. A reactive power compensator was built, comprising switching devices without energy storage components. This compensator could eliminate both the fundamental reactive power in transient states and harmonic currents. For example, the harmonic currents having the frequencies of

$$f \pm 6f_0 \tag{1.1}$$

in three-phase naturally commutated cycloconverter was eliminated, where f is the input frequency and f_0 is the output frequency.

In 1990 Joseph S. Subjak. and John S. Mcquilkin[3] put forth the fact that rectification generates harmonic voltages and currents that causes problems, e.g. insulation failures due to overheating and overvoltages malfunction of solid-state equipment, communication interference, etc.

In 1984 H Akagi[2] gave active power line conditioners, which are classified into shunt and series categories, and were primarily meant for industrial uses. A 900 KVA shunt active filter and a shunt passive filter of rating 6600 KVA was installed to suppress the harmonics produced by a large capacity cycloconverter for steel mill drives.

In 1999 B. Singh, K. Al-Haddad, and A. Chandra[6] presented paper which contains a comprehensive review of active filter (AF) configurations, control strategies, selection of components, other related economic and technical considerations, and how to select them for specific applications. It gave a broad perspective on active filter technology to researchers and application engineers dealing with power quality issues.

In 2000 Afonso, Joo L., Carlos Couto, and Jlio S. Martins[5] proposed that shunt active filters can compensate current harmonics and unbalance, along with power factor correction, and this provides much better solution than the passive filter approach. Their paper hails the p-q theory as a suitable tool for the analysis of non-linear three-phase systems and as well as for the control of active filters. Two control strategies for shunt active filters were described, one for constant instantaneous supply power and the other for sinusoidal supply current. According to them active filters based on the p-q theory are effective solutions, which allow the use of a large number of low-power active filters close to each problematic load or group of loads.

In 2003 Grandi, G., Casadei, D., and Rossi, C.[7] together gave the concept of photovoltaic sources can be used with power active filters in order to regulate both the active and the reactive power injected into the grid. Therefore, phase unbalances, power flickers, and low-order current harmonics can be eliminated, thus improving the power quality. The intermediate DC-DC chopper is removed, a direct coupling between the PV panels and the DC-link of the voltage source inverter is done. There is a continuous regulation of DC-link voltage between upper and lower limits so that tracking of maximum power point of the PV is achieved.

In 2009 Lee and et.al[16] presented a transformerless grid-connected photovoltaic (PV) system with active and reactive power control. They proposed a system operations which can be categorised into sunny mode and night mode. An night , it compensates for the reactive power demanded by nonlinear loads. During daytime, it not only supplies active power from the PV array to the grid or loads, but also injects reactive power to improve the power factor and also reduces the harmonic current.

Chen and et.al[29] presented an advanced photovoltaic inverter which can deliver the maximum power from photovoltaic arrays to the utility grid for all sunlight conditions, also provides provide power conditioning to suppress power line distortions. A new control strategy was also given to maximize the inverter output from the photovoltaic array and to suppress current harmonics in the power line using a single phase inverter.

An Luo and et.al[19] gave an improved reactive current detection and power control method for active power control and reactive power compensation. To detect quickly the loads reactive current, a fast reactive current detection method using the derivative and i_p - i_q algorithm was presented. In the inner current loop, the quasi-proportional-resonant (QPR) control method with grid voltage feed-forward is used to analyse inner loop stability. In the outer loop, proportionalintegrator (PI) controller is applied to stabilize the dc-link voltage, and power feed-forward is introduced to speed up system response.

F. Delfino, G. B. Denegri, M. Invernizzi and R. Procopio[22] presented an advanced control scheme for a PhotoVoltaic unit (PV) to suitably drive the injection of both active and reactive power into distribution grid. The algorithm allowed a decoupled control of active and reactive power by properly adjusting the modulating signals of the PWM for inverter. The control algorithm was applied to a grid-connected PV power plant to verify the effectiveness of the adopted regulation. The positive effect of reactive power support was highlighted on grid current and voltage profile.

1.2 Objectives of dissertation work

The objectives of this dissertation work include:

1. Propose a scheme for mitigation of harmonics and reactive power compensation based on solar fed inverter.

2. Simulate the scheme on MATLAB.

3. Implement the proposed scheme.

4. Evaluate the hardware results vis-a-vis simulation.

1.3 Organisation of report

This report is organized as follows:
Chapter 1. It gives the introduction and literature review based on work that has been done on this topic.

Chapter 2. Working of photo-voltaic array and maximum power point tracker is explained.

Chapter 3. It is about harmonic and reactive compensation. Elaborates the details on how harmonics come into existence and their ill effect on system. Moreover, the importance of reactive power from stability point of view is explained.

Chapter 4. Inverter and modulation technique with focus only on two-level inverter.

Chapter 5. This chapter is dedicated on photovoltaic fed inverter.

Chapter 6. Simulation of proposed system, along with output graphs.

Chapter 7. This chapter is dedicated to hardware output.

Chapter 8. Conclusions and scope for future work are stated.

At the end there is a bibliography .

Chapter 2

Working of PV and MPPT

The solar energy incident on earth is tapped using PV array which consist of modules. Each module is made of many PV cells connected in series and shunt configuration. The basic structure is PV cell is made of silicon and work as photo diode. The equations and diagram in subsequent sections elaborate the same. To tap the energy at the maximum level under various instances of solar radiation the help of Maximum Power Point Tracker(MPPT) is taken. It work on the logic that when irridation change take place the current and voltage level of the PV should correspond to the maximum power point current and voltage. This assures that power tapped is always at maximum.

2.1 Photovoltaic cell

Photovoltaic cell is made of semiconductor material and silicon is the preferred choice. When solar radiation is incident on any such cell, the electron abosorb the photon of solar radiation and get excited to higher energy level. Such excited electrons are forced by the electric field to flow and when circuit is completed by connecting some external resistance current starts flowing. In this way both voltage and current can be tapped out side the PV cell in the form of power in watts.

2.2 PV module and array

The power and voltage rating of single PV cell is minuscule, and therefore not of much use. This shortcoming is overcome by connecting the cell in parallel and series configuration. This results in enhancement of voltage and power rating and can be put to some use. When cell are connected in series and parallel it gives rise to module. When many such module, depending on the need, are connected together it gives rise to an array. Such combinations raise the level of current as well as voltage and power.

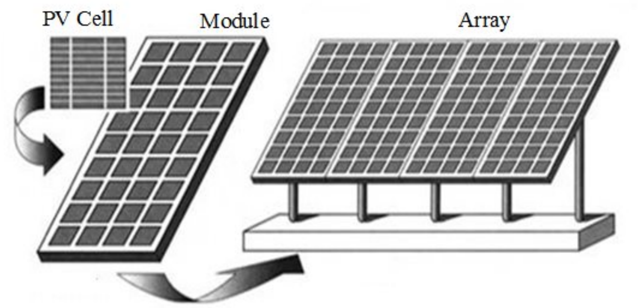

FIGURE 2.1: PV Cell , Module and Array

2.3 Electric circuit representation of PV cell

The cell functions as photo-diode junction. Therefore, it is represented as a current source I. Current is produced because of photo action inside the pn junction. The diode in shunt is the representation of the photo diode. Resistance R_s represents the resistance to the flow of current through the diode. Resistance R_{sh} represents the leakage of current at the terminal. R load is connected as the load and V is the volatge at terminal of the PV cell. Under ideal condition R_s should be zero and R_{sh} infinite. The R_s value effects the output and its increase reduces the output significantly.

The open-circuit voltage V_{oc} of the cell is obtained when the load current is zero and is given by the following:

$$V_{oc} = (I - I_d)R_{sh} \tag{2.1}$$

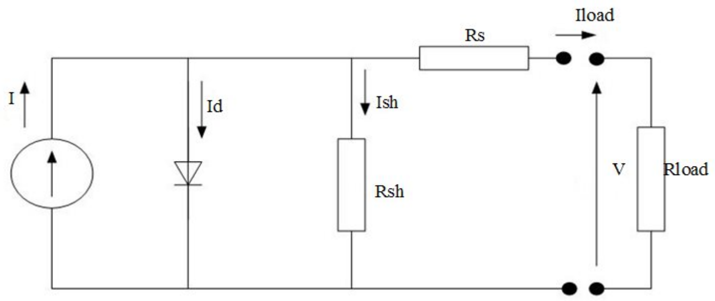

FIGURE 2.2: Electric circuit representation of PV cell

The diode current is given by the classical diode current expression:

$$I_d = I_o\big[\exp\big(\frac{qV_{oc}}{AkT}\big) - 1\big] \tag{2.2}$$

Where, I_o is the saturation current of the diode (in Amp), q is electron charge 1.6×10^{-19}°C, A is curve-fitting constant, K is Boltzmann constant 1.38×10^{-23} J/°K, T is temperature on absolute scale °K. Thus, the load current is given by the expression:

$$I_{load} = I - I_d - I_{sh} \tag{2.3}$$

Two most important quantities for PV cell are (a) Open circuit voltage(V_{oc}) and (b) Short-circuit current(I_{sc}). Both the quantities are considered under full-illumination condition. Ignoring leakage current and small diode current

$$I_{sc} \approx I \tag{2.4}$$

Similarly, the expression for open circuit voltage can be calculated as given below :

$$V_{oc} = \frac{AkT}{q} ln(\frac{I}{I_d}) \tag{2.5}$$

V_{oc} is the maximum voltage that a photo-volatic can produced.

2.4 Current-voltage and power-voltage curves

The figure 2.3 shows the V-I curve of a PV cell. This curve shows the variation of current and voltage when cell resistance varies from zero to infinity. The point at which the voltage is zero is called the short-circuit current. This is the current measured with output terminal shorted. On the other hand, the point at which current is zero is known as open-circuit voltage. This is the voltage measured with output terminal open. Somewhere in the middle of the two regions, the curve has a knee point. At the knee point the power is maximum given by P_{mpp}

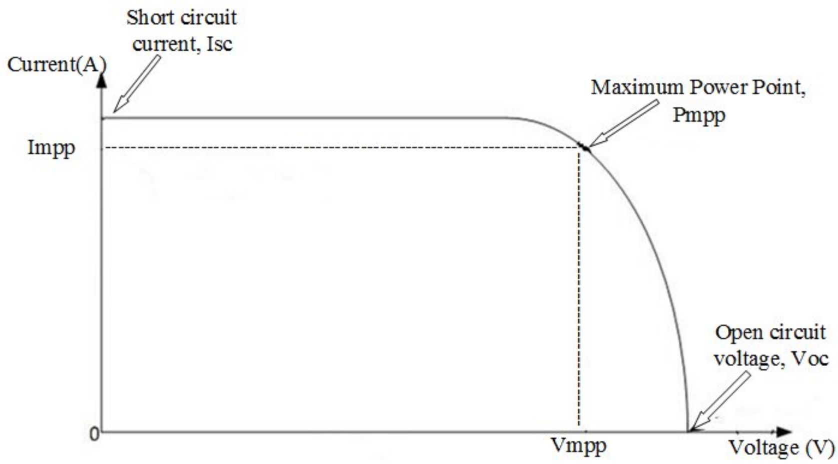

FIGURE 2.3: V-I characteristics of PV cell

The power output of the panel is the product of the voltage and current outputs. Power is plotted against the voltage which is V-P curve of the PV cell. The cell produces no power at zero voltage or zero current, and produces the maximum power at the voltage corresponding to the knee point of the V-I curve. The PV circuit is modeled approximately as a constant current source in the electrical analysis.

2.5 Maximum power point tracker

The non-linear current versus voltage (V-I) and power versus voltage (V-P) characteristics has been depicted in previous diagrams. However, environmental conditions have an important bearing on the perfromance of the PV. Output voltage and current, and

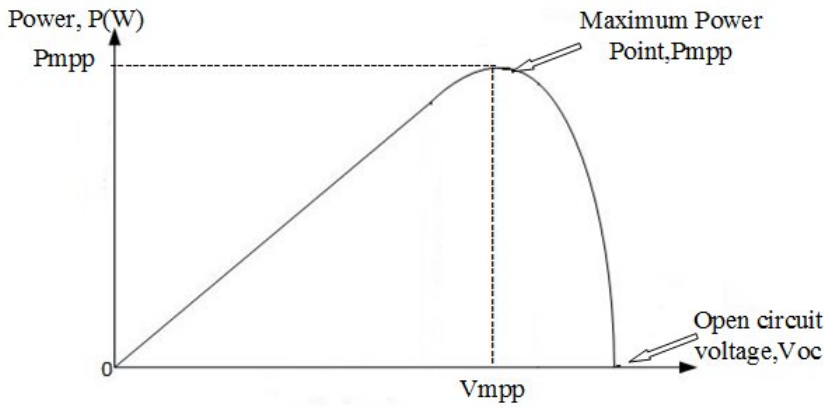

FIGURE 2.4: P-V characteristics of PV cell

therefore the power delivered by the PV panel varies with variation in environmental condition of irradiance and temperature. To tap the maximum power from PV panel under environmental condition efficient MPPT techniques are required.

Various MPPT techniques are used and have been developed for the efficient tapping of solar power. MPPTs have been developed for both grid-tied as well as stand-alone PV system. Of these many only perturb and observed (P and O) type has been used for the dissertation. Each of these available techniques vary in terms of their complexity, type of hardware implementation, application etc. Some of the available MPPT algorithm techniques are :

- Open circuit voltage
- Short circuit current
- Purturb and Observe
- Incremental Conductance
- Fuzzy logic based
- Partial swarm optimization based

to name a few.

2.5.1 Perturb and Observe

The initial PV voltage and current are first measured and initial power of PV is calculated, say P_1. Let a small perturbance is there in voltage,say ΔV, either increase or decrease. Let now the power be P_2, this power is calculated with the previous power P_1. If difference is positive then change is in right direction, else it should be reversed. Thus maximum power is always kept track of. Using the value of this power voltage at maximum power can be calculated.

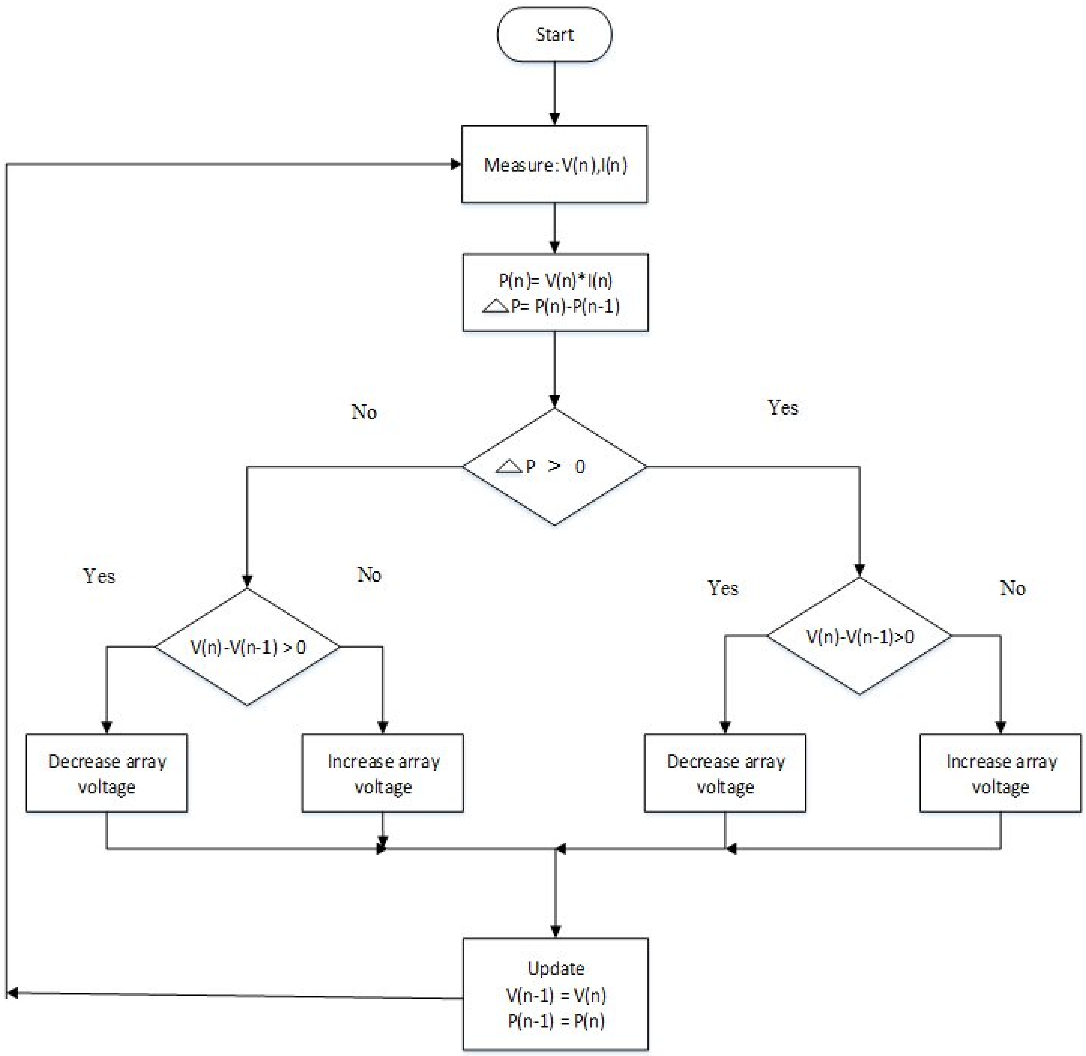

Figure 2.5: Purturb and Observe algorithm

However, the P and O based MPPT suffer from disadvantage that it gets affected in it's performance because of atmospheric variability, particularly the oscillation that appear with change in environmental conditions.

Chapter 3

Harmonic and reactive power compensation

The upsurge in utilisation of drive system in industries along with the use of electronic goods in household system, which are all based on semiconductor devices, has immense affect on grid. As semiconductor devices have non-linear characteristics they tend to draw current which when analysed is found to consist of frequecies other than the fundamental frequency. These frequencies are multiples of fundamental frequency and can be of both odd and even types.

The terms 'linear' and 'non-linear' is defined as a relationship of current and voltage waveform. A linear relationship exists between the voltage and current when there is one-to-one correspondance between them. A non-linear relationship occurs when such a correspondance is missing. There is a discontinuous current relationship such that current does not correspond to the applied voltage waveform.

3.1 Definition of harmonics

Harmonics are defined as all those frequencies that are an integral or fractional multiple of the fundamental power frequency.

3.1.1 Order of harmonics

The order 'h' of any harmonics is given by h=np+1, where n is any integer, p is number of pulses per cycle. However, when the converters are not operating in steady state or the supply is not symmetrical other harmonics similar to dc will get introduced, called as 'non-characteristic' harmonics.

3.1.2 Total harmonic distortion and total demand distortion

Total harmonic distortion(THD) is the distortion caused by all the harmonic frequencies (voltage or current) to the fundamental. They occur as a result of modern electronic equipments occuring in large number of computers,uninterruptible power supplies (UPSs),variable frequency drives (AC and DC) or any electronic device using solid state power switch. Non-linear loads create harmonics by drawing current which are more like a pulse, rather than smooth sinusoidal manner.

$$\%THD_V = \frac{\sqrt{\sum_{\lim n=2} V^2}}{V_1} \tag{3.1}$$

$$\%THD_I = \frac{\sqrt{\sum_{\lim n=2} I^2}}{I_1} \tag{3.2}$$

But during conditions when load current is low using THD may not be the right proposition. Therefore, the concept TDD(Total Demand Distortion) is used. It is defined as the percentage ratio of rms of harmonic content to that of rms of maximum demand load current. It is given by the expression below :

$$\%TDD_I = \frac{\sqrt{\sum_{\lim n=2} I_h^2}}{I_L} \tag{3.3}$$

3.1.3 Harmful effects of harmonics on power system equipments

1. Generators are effected as excessive heating is caused by harmonics. As a result they are derated if operated under such harmonic environment. Moreover, they suffer torque pulsations and localized heating.

2. Transformers suffer as there is increase in core losses and also copper losses as well as stray flux losses. There is additional heating and result in insulation breakdown. Moreover, there is vibration in core because of harmonics which can be heard as audible noise.

3. Induction motors also suffer in the same vein as transformer or generator. There is increase in copper loss in stator, rotor as well as in the core of the machine. The problem compounds because of skin effect at frequency above 300 hz. The machine bearing and insulations are badly affected and needs special care.

4. Cable losses are increased because of the presence of harmonic current. The skin effect and proximity effect changes the value of dc resistance. This gets compounded at higher frequencies.

5. Capacitors installed for power factor correction can experience the phenomeon of resonance, which can effect and damage other equipments.

6. There is a chance of EMI because of presence of harmonics in vicinity of telephone conductors and telemetry equipments.

7. The metering equipment misread because of distortion in voltage and currents.

3.2 Harmonic compensation

The harmonic compensation methods are many and are in use since ages. Some of the conventional methods are described below :

1. Use of line reactors provide cheapest cost effective means of suppressing the harmonics. Such reactors are connected in series with a non-linear load. Placing line raectors introduce additional inductive reactance in the circuit, thus help in attenuating harmonics and also absorb voltage transients. However, the magnitude of harmonic distortion as well as the spectrum of harmonics depend on how effectively the impedance of the reactor is in relation to the load.

2. K-factor transformer design is focused onto bear the temperature rise caused by heating due to current harmonics in the transformer windings, apart from the

losses caused by fundamental frequency current. K-factor is that constant which indicates the ability of the transformer to handle heating due to harmonics, given by a multiple of the normal eddy current losses and sinusoidal current in the transformer windings. Transformer losses, which cause transformer heating, are comprised of both I^2R losses, and core losses, which are dependent on both the current and frequency. The K-factor is calculated using the harmonic spectrum and informations derived from it. The K-Factor depends on two variables:(a) magnitude of harmonic current (b)harmonic order. It is observed that the when the load consist of both linear and non-linear loads, the K-factor requirement is lower than when the transformer only supplies non-linear loads. However, K-factor transformers are usually costlier then isolation transformers.

3. Isolation transformer help in changing the input circuit reactance, which is a main factor for the magnitude of harmonics that will be come into picture and flow through an individual load. The circuit impedance is changed due to leakage impedance of the isolation transformer. Usually a delta-star connected transformer is used. At fundamental frequency the inductance is low and fundamental current can flow easily, but inductance increases for harmonic frequencies and therefore, offering higher impedances which can attenuate the harmonic currents. Moreover, the primary and secondary can be electrostatically isolated. The capacitive coupling thus created between each winding and the shield, offers a low impedance path. In this manner a path is created to attenuate not only noise, but also the transients and zero sequence currents. Moreover, any disturbance that may originate either in primary or secondary is isolated from the other side. Its main drawback are large size, losses and commercial price.

4. Phase shifting transformers are either a single transformer with two separate windings otherwise two transformers one connected in delta on primary and star on secondary or vice-versa. Quasi 12-pulse methods is used to reduce harmonic distortion. Two sets of non-linear loads can be fed by two phase shifted transformer windings. Like the 12-pulse rectifier system, cancellation of the 5th and 7th harmonic is achieved on the primary side of the transformers depending on how much balanced the currents are on in each of the transformers.

5. Passive filters are the options available and are widely used. They consist of passive elements inductor and capacitors. They operate on the basis of principle of resonance. There is a characteristics variation in filter impedance as it is varied over a wide frequency range. A the resonance frequency they behave as pure resistor. At harmonic frequency a very low impedance is offered to the flow of harmonic current and it is shunted out. Therefore, the harmonic current flow between filter and load and not affecting the source. It is always suggested to use a fixed tune filter if power factor is low and constant. However, if the power factor varies over a range then hybrid solution are prefered. The hybrid solution use a fixed part and a automatic part, former takes care of fixed reactive power demand abd later the fluctuating reactive power demand. If both power factor and harmonics vary then only automatic solution is to be used. However, there are number of disadvantages with passive filters.

6. 12 and 18 pulse rectifiers. This technique involves a special type of rectifier and transformer configuration. It is specially designed as it involves internal changes to the input rectifier section. Six pulse rectifier caused a predictable harmonic spectrum consisting of the 5th, 7th, 11th, 13th, 17, 19th $\ldots 6n \mp 1$ harmonics. Therefore, 12 and 18-pulse rectifiers will normally cause the following harmonic frequencies to be present in the input current spectrum: with 12-pulse 11, 13, 23, 25 ...etc and with 18-pulse 17, 19, 35,37 .... In both the cases, the 5th and 7th harmonics, having the largest magnitudes of all of the individual harmonics, are eliminated. However, 2-3 percentage harmonic mitigation can also occur by phase shifting one bridge rectifier against the other causing specific harmonics from one bridge rectifier to cancel those from the other. Phase shifting is achieved by use of the multiple secondary windings of the transformer. In the case of the twelve pulse system, the transformer has two separate secondary windings one in star and one in delta. The eighteen pulse system use a transformer with three phase shifted windings. The degrees of phase shift between each secondary winding is $360^0 \div p$ (the number of rectifier pulses). Having nearly eliminated the normally strong 5th and 7th harmonics, these rectifier schemes can achieve low levels of harmonic distortion. It is important that both 12 and 18 pulse rectifier currents drawn by each rectifier bridge be balanced and that source voltages for all phases

are balanced. The presence of unbalanced line voltages can cause triplen harmonics to flow and will increase the residual harmonic current distortion. Likewise, unbalanced rectifier bridge currents will increase the harmonic distortion. Therefore, interphase reactors are used so that rectifier bridge currents are similar. When properly applied under conditions that achieve balanced bridge currents, 12-pulse rectifier systems can achieve input current distortion levels between 10% and 20% THD_I, while 18-pulse systems may achieve between to 10% THD_I. These levels can be expected at full load conditions, but the THD_I will increase as the load is reduced.

3.3 Active filters

Equipments used for compesating current or voltage harmonics originating from the operation of non-linear load. These equipments are power converters based unlike passive filters which are based on passive elements. They are broadly classied under three categories based on their configuration :

- Shunt active filter
- Series active filter
- Hybrid active filter

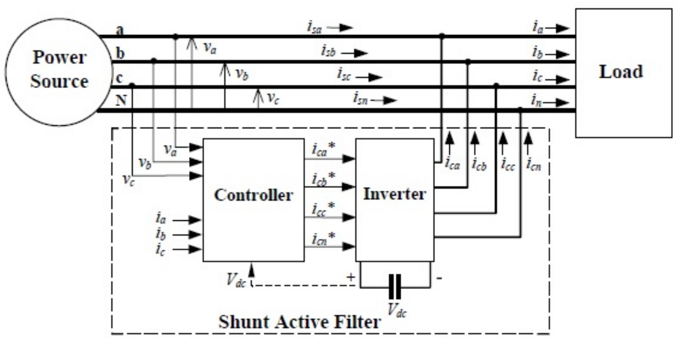

FIGURE 3.1: Shunt active filter

In shunt scheme the filter is connected in shunt configuration with respect to the source. The harmonic current produced by the non-linear load is compensated by injecting the compensating current produced by the filter. In series active filter

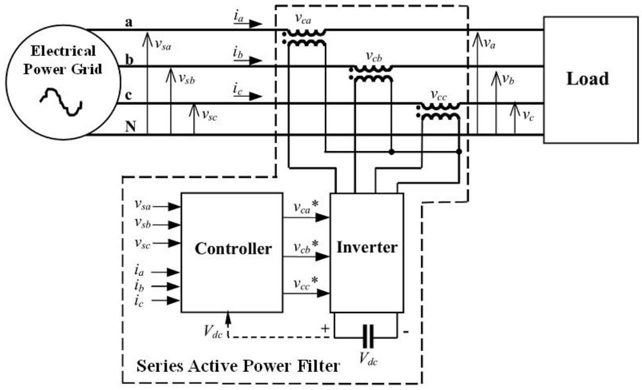

FIGURE 3.2: Series active filter

compensating filter is connected in series with the voltage source. This results in the cancellation of harmonics in voltage, that are introduced by the flow of harmonic currents drawn the non-linear load.

Hybrid active filters have both shunt and series parts. The shunt part mitigates the current harmonics whereas the series part takes care the voltage harmonics. The control circuit operates in a manner that both shunt and series part operate in unison. In all three configuration the basic idea is to compensate the harmonic part and the reactive power compensation.

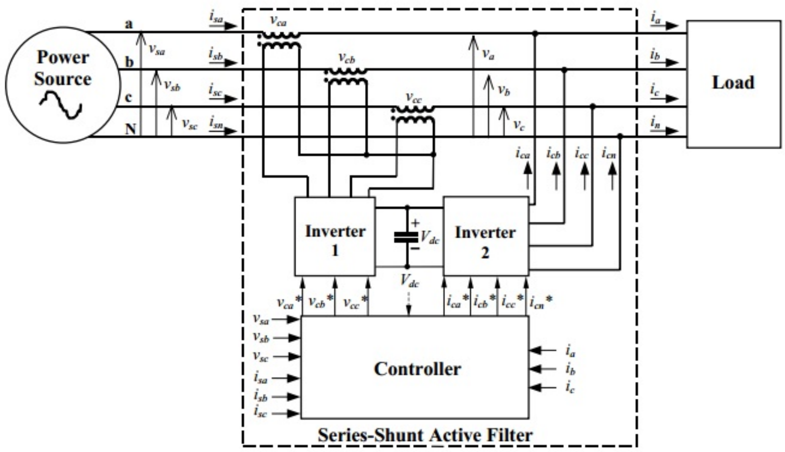

FIGURE 3.3: Hybrid active filter

3.4 Reactive power and its significance

Reactive power is defined as the double frequency power which is shared between source and the load in such a manner that net consumption over a cycle time is zero. This power is not consumed but is only shared. The lack of presence of this power leads to voltage instabilty and voltage collapse. Therefore, reactive power is needed to be injected to arrest the fall of voltage. Moreover, it is always preferred to be locally produced to avoid any loss due to its flow.

3.4.1 Limitation of reactive power and its control

- Reactive power has a rigid nature and do not flow in the system easy. Therefore, it is always recommended to be produced locally.
- Its control is required to maintain the nominal voltage. Lack of reactive power may lead to sag in voltage whereas its excess leads to voltage swell.

3.5 PQ theory

The concept of PQ theory[2] was put forth by Akagi in his seminal paper. P-Q theory uses the transformation of abc-to-0 in stationary reference frame also called Clarke transformation. No restriction is imposed either to voltage or current waveform. Moreover, it is equally applicable to transient as well as steady state analysis.

3.5.1 Clarke Transformation

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \sqrt{(2/3)} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3.4}$$

The above transformation converts three phase instantaneous voltages v_a , v_b, v_c into instantaneous voltages on the $\alpha\beta 0$ axes v_α ,v_β and v_0. Similarly, equation for three phase instantaneous currents i_a, i_b and i_c onto three axes i_α, i_β and i_0 can be written as follows :

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{(2/3)} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.5}$$

The quantities v_0 and i_0 are present only during unbalanced condition, therefore can be neglected when quantities are balanced. The equation can be written for voltage and current respectively as :

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{(2/3)} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3.6}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{(2/3)} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.7}$$

For a three phase system the total power can be given as :

$$P_{3phase} = v_a i_a + v_b i_b + v_c i_c \tag{3.8}$$

Using the property of power invariance the same can be written as

$$P_{3phase} = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 \tag{3.9}$$

Components of three phase instantaneous active power are: the instantaneous zero-sequence power

$$p_0 = v_0 i_0 \tag{3.10}$$

the instantaneous real power

$$p = v_\alpha i_\alpha + v_\beta i_\beta \tag{3.11}$$

the instantaneous imaginary power

$$q = v_\beta i_\beta - v_\alpha i_\alpha \tag{3.12}$$

The equation in matrix form can be written as :

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & v_\beta & -v_\alpha \end{bmatrix} \tag{3.13}$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \tag{3.14}$$

With balanced system $p_0 = 0$ and therefore, three phase instantaneous active power

$$p_{3phase} = p \tag{3.15}$$

For a three phase, three wire system instantaneous complex power 's' can be written

$$s = vi^* \tag{3.16}$$

$$s = (v_\alpha + v_\beta) \times (i_\alpha - i_\beta) \tag{3.17}$$

$$s = (v_\alpha i_\alpha + v_\beta i_\beta) + j(v_\beta i_\alpha v_\alpha i_\beta) \tag{3.18}$$

With zero sequence components neglected p and q can be written as

$$\begin{bmatrix} p_\alpha \\ p_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha i_\alpha \\ v_\beta i_\beta \end{bmatrix} \tag{3.19}$$

$$\begin{bmatrix} p_\alpha \\ p_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha i_{\alpha p} \\ v_\beta i_{\beta p} \end{bmatrix} + \begin{bmatrix} v_\alpha i_{\alpha q} \\ v_\beta i_{\beta q} \end{bmatrix} \tag{3.20}$$

The three phase instantaneous active power in Clarke terms is equal to the instantaneous real power which is equal to sum of p_α and p_β.

$$p = v_\alpha i_{\alpha p} + v_\beta] i_{\beta p} + v_\alpha i_{\alpha q} + v_\beta i_{\beta q} \tag{3.21}$$

$$p = \frac{v_\alpha^2}{v_\alpha^2 + v_\beta^2} p + \frac{v_\beta^2}{v_\alpha^2 + v_\beta^2} p + \frac{v_\alpha v_\beta}{v_\alpha^2 + v_\beta^2} q + \frac{-v_\alpha v_\beta}{v_\alpha^2 + v_\beta^2} q \tag{3.22}$$

Instantaneous active power on α-axis

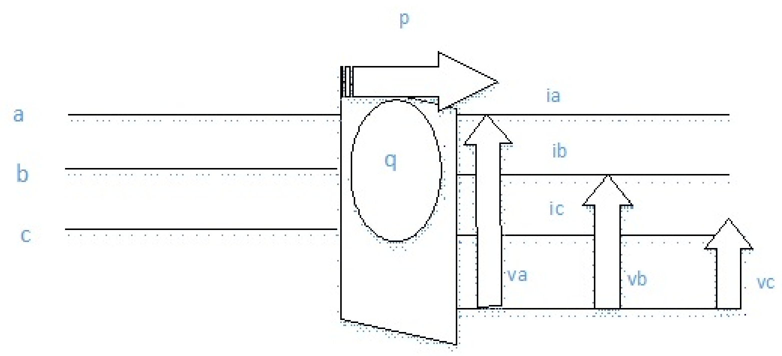

Figure 3.4: p and q power in three phase system

$$p_{\alpha p} = v_\alpha i_{\alpha p} \tag{3.23}$$

$$p_{\alpha p} = \frac{v_\alpha^2}{v_\alpha^2 + v_\beta^2} p \tag{3.24}$$

Instantaneous reactive power on α-axis

$$p_{\alpha q} = v_\beta i_{\beta p} \tag{3.25}$$

$$p_{\alpha q} = \frac{v_\alpha v_\beta}{v_\alpha^2 + v_\beta^2} q \tag{3.26}$$

Instantaneous active power on β-axis

$$p_{\beta p} = \frac{v_\beta^2}{v_\alpha^2 + v_\beta^2} p \tag{3.27}$$

Instantaneous reactive power on the β-axis

$$p_{\beta q} = \frac{-v_\alpha v_\beta}{v_\alpha^2 + v_\beta^2} q \tag{3.28}$$

The theory has been used for reference current generation in simulation and is elaborated further in chapter 5.

Chapter 4

Inverter and modulation techniques

Inverter or DC-to-AC converter as they convert unidirectional voltage into bi-directional voltage, sinusoidal or otherwise. They are primarily used in industrial applications(large rating) or for domestic purposes. The three phase inverter operate on the some modulating scheme and has been discussed in the later portion.

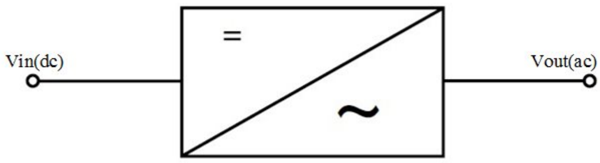

FIGURE 4.1: DC to AC converter

4.1 Classification of three phase inverter

One classification of three phase inverter is based on whether output is single phase or three phase. Therefore, they are called as single phase inverter or three phase inverter.

The other classification categorise it as a Voltage Source Inverter(VSI) or Current Source Inverter(CSI) depending on whether the input source is either a DC battery or a current source.

4.2 Modulation techniques

Also called Pulse Width Modulation(PWM) technique. These techniques are schemes for deciding turn-on and turn-off durations of inverter switches. The various primary factors which decides which PWM technique is to be employed are:

1. Better utilization of DC link voltage, so that there is higher output voltage for the same DC link voltage.
2. Linearity between voltage and current control.
3. Harmonic content in the output voltage/current should be low, particulary in low frequency region.
4. Low switching losses.

4.2.1 Sinusoidal PWM

In this scheme sine wave is used as the modulating signal which is compared continuously with the carrier signal, a triangular wave. The frequency of sine wave is denoted by f_m, called as modulating frequency and that of carrier is denoted by f_c, called as carrier frequency. By comparing a reference sine wave (the modulating wave) with a high frequency triangular wave (the carrier wave) the instants for on and off can be calculated. The frequency of the output voltage is same as that of modulating signal. The rms valus of output is determined by a constant called modulating index, m_a and given by

$$m_a = \frac{V_m}{V_{tri}} \tag{4.1}$$

where V_m is the peak value of modulating/control/reference signal and V_{tri} is the peak value of carrier signal.

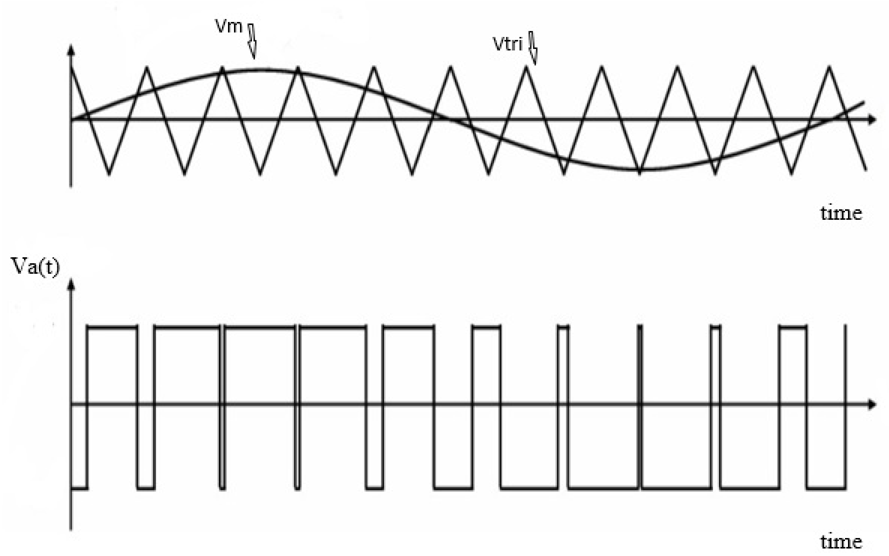

FIGURE 4.2: Single phase sine PWM

Similarly, trigger pulse for three phase inverter can also be obtained. Sine PWM can be both unipoar as well bipolar type. In bipolar switching, the switches of two different leg as A and B (one top switch and other bottom switch) are triggered simultaneously. Whereas, in unipolar switching the switch are of any two legs are controlled independently based on whether

$$V_m \geq V_{tri} \tag{4.2}$$

top switch is 'on' else bottom switch is 'on'. When top switch is on output is V_d else output is zero. The output voltage is between V_d and $-V_d$ whereas in unipolar scheme it is either V_d or $-V_d$.

In terms of harmonics the unipolar switching scheme is better because harmonics appear as side band at twice the switching frequency as compared to bipolar switching scheme where harmonics appear as sideband of switching frequency.

Similarly, for three phase sine PWM, three sine wave are compared with a high frequency triangular wave so that instances for switching can be generated for the switches.

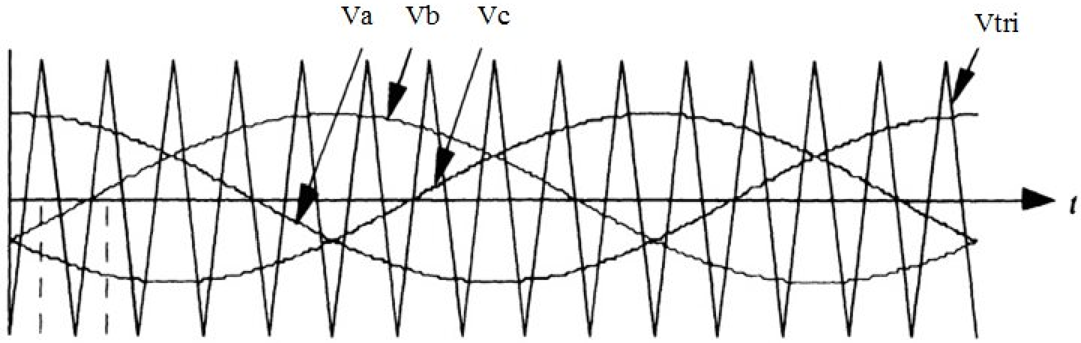

FIGURE 4.3: Three phase sine PWM

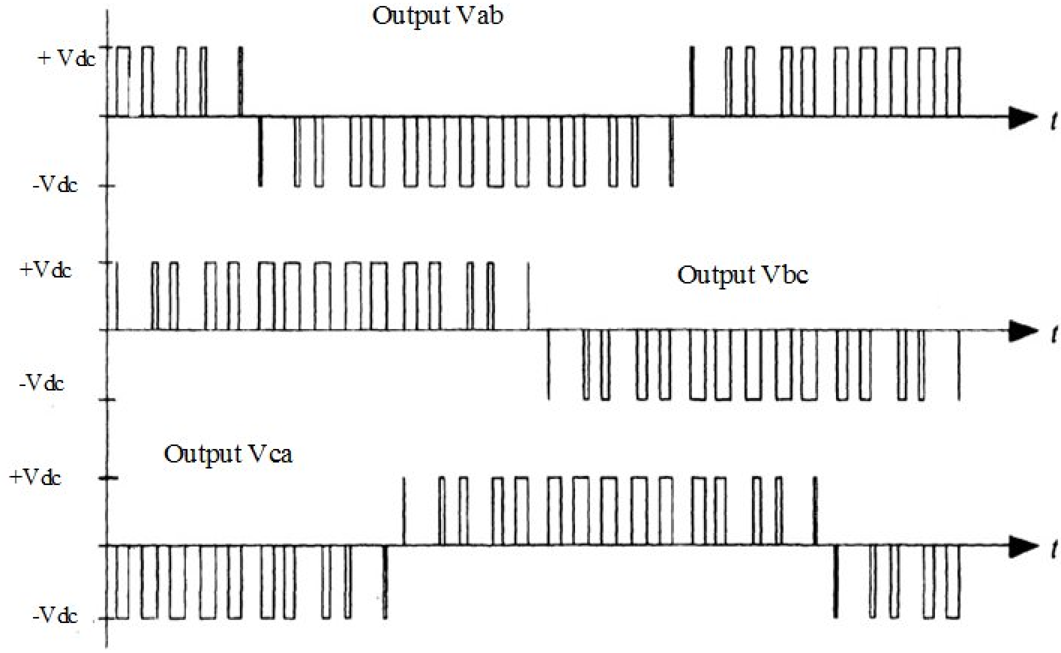

FIGURE 4.4: Line voltage outputs

Three sinusoidal 120^0 displaced sinusoidal voltages are used as reference[33]

$$V_{an}^{*} = V_0 sinwt = mV_{dc} sinwt \quad (4.3)$$

$$V_{bn}^{*} = V_0 sin(wt - 120^0) = mV_{dc} sin(wt - 120^0) \quad (4.4)$$

$$V_{an}^{*} = V_0 sin(wt + 120^0) = mV_{dc} sin(wt + 120^0) \quad (4.5)$$

where 'm' is modulation index and V_{dc} is the voltage on dc link side. for line to line voltage the expression can be written as

$$V_{ab}^{*} = m\sqrt{3}V_{dc}sin(wt + \frac{\pi}{3}) \quad (4.6)$$

$$V_{bc}^{*} = m\sqrt{3}V_{dc}sin(wt - \frac{\pi}{2}) \quad (4.7)$$

$$V_{ca}^{*} = m\sqrt{3}V_{dc}sin(wt + \frac{5pi}{2}) \quad (4.8)$$

The maximum value $\sqrt{3}V_{dc}$ compared to $2V_{dc}$. Following observations are made for line to line voltages :

- Carrier harmonics will not appear.
- Side band harmonics with even number will not appear.
- Triplen harmonics will not appear.

4.2.2 Hysterisis band PWM

Hysteresis current control operates the voltage source inverter by comparing the current error against the fixed-hysteresis bands. This block diagram for the operation pertaining to two-level hysteresis current controller is depicted in subsequent page. The current error is the difference between the reference current and the actual current. When the error surpass the upper limit, lower switch is turned-on and vice-versa. As a result, the current starts falling or rising depending on the error value. Therefore, the current stays within the hysteresis band. In this manner actual current keeps tracking the reference current within the hysteresis band. Say phase 'a' switch is to be operated then

$$S = off \quad (4.9)$$

if $i_{sa(t)} > i_{sa}^{*}(t)$ + Hysteresis band else

$$S = on \quad (4.10)$$

This is how a two-level hysteresis PWM operates.

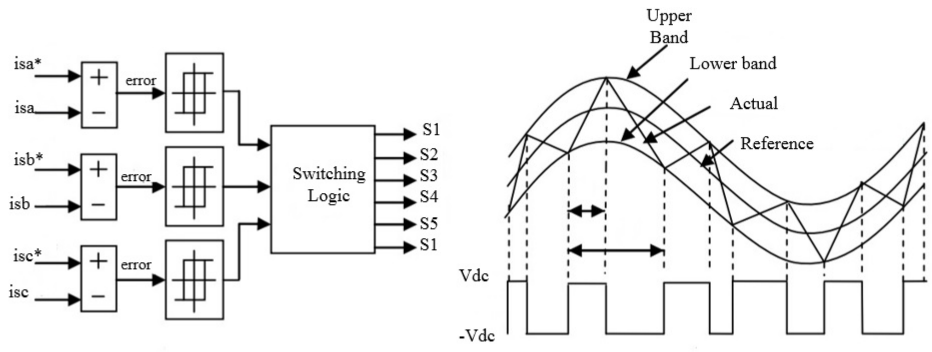

FIGURE 4.5: Hysteresis band PWM

Even though there are other modulation techniques for multilevel inverters, but they are not being consider here as the inverter topology used in this dissertation is only two level inverter.

Chapter 5

Photovoltaic fed inverter

The basic operation of inverter has been expalined in Chapter 4. A photovoltaic fed inverter can be used for any of the 3 mode :

1. For active generation only.
2. As a full active filter(FAF) for harmonic elimination and reactice power compensation without any active generation.
3. As a partial active filter(PAF) for reactive power compensation and active generation along with harmonic compensation.

This thesis work focuses on 2 and 3 .

5.1 Full active filter(FAF)

As the name suggest, full active filters are those electrical equipments which are capable of eliminating both harmonics as well as compensate for reactive power. When the irridation level is low PV fed inverter should be operated as FAF. Based on choice of response speed and simplicity of implementation, any of the reference current generation technique can be used so that cancellation of harmonics is done. In this way the three

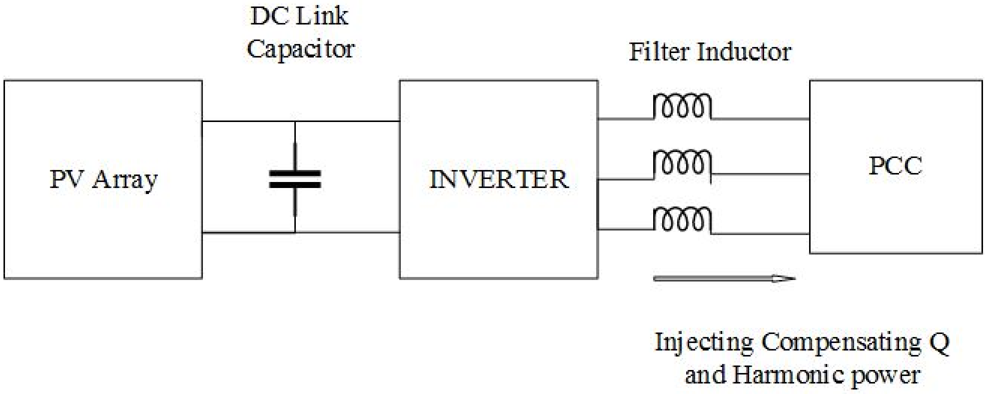

FIGURE 5.1: Full active filter

phase supply source can be saved from menace of harmonics. Moreover, other loads connected at PCC whose performance otherwise would get affected by the presence of harmonics can be given an immunity from the same. Also, the reactive power injected at PCC would locally meet the reactive power demand and help maintain the voltage profile. For this part of thesis work PQ theory has been utilised. The simulation and its output is shown in Chapter 6.

5.2 Partial active filter(PAF)

The partial active filter compensates for reactive power Q , harmonics and also produces real power P. Similar to FAF, PAF can use any of the reference current generating techniques. The simulation part of this thesis has focussed on PQ theory for reference generation and detection. The reference generation and current control has been elaborated in subsequent sections. When irridation is at high level PV fed inverter should be operated as PAF.

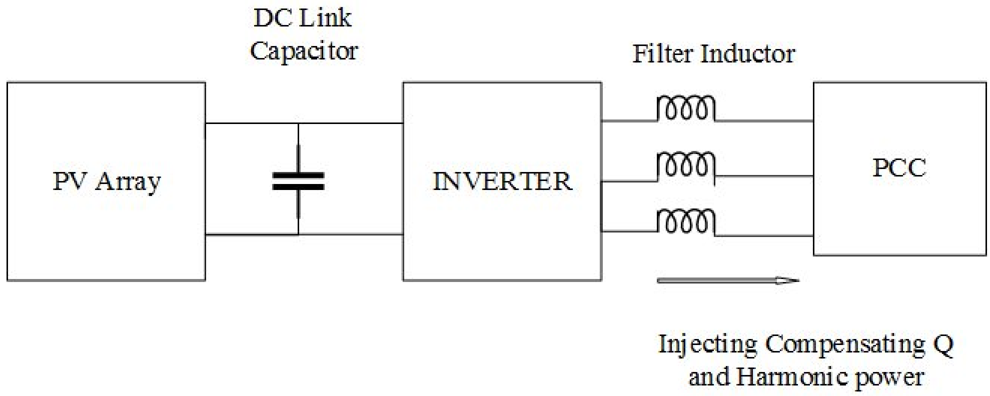

FIGURE 5.2: Partial active filter

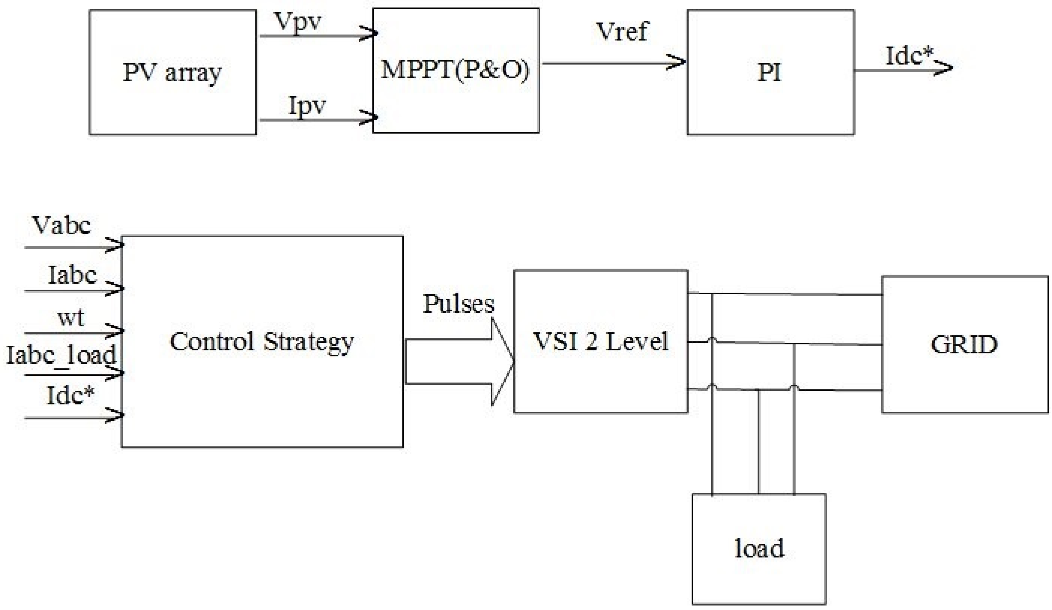

FIGURE 5.3: Control scheme

5.3 Reference current generation techniques

Reference current extraction for detection are available both in time domain and frequency domain. Time domain method is based on simple algebraic calculaton whereas frequency domain method is suitable for accurate detection of single or multiple harmonic load current. The important methods in time domain are p-q theory, SRF(synchronous reference frame),Fryze power method whereas FFT based methods are used in frequency domain.

5.3.1 PQ theory for reference generation

Some aspects of PQ has been explained in Chapter 3 from mathematical point of view. For reference current generation voltage v_a, v_b and v_c along with i_a, i_b and i_c are first transformed into $\alpha\beta$ quantities v_α, v_β and i_α,i_β using Clarke's tranformation. Based on the transformed voltages and currents instantaneous real and reactive power are calculated using equ.(3.11)a and equ.(3.12). The harmonic real power associated with "p" is extracted using a LPF and subsequently added to I_{dc}, which represents the real generation from PV.

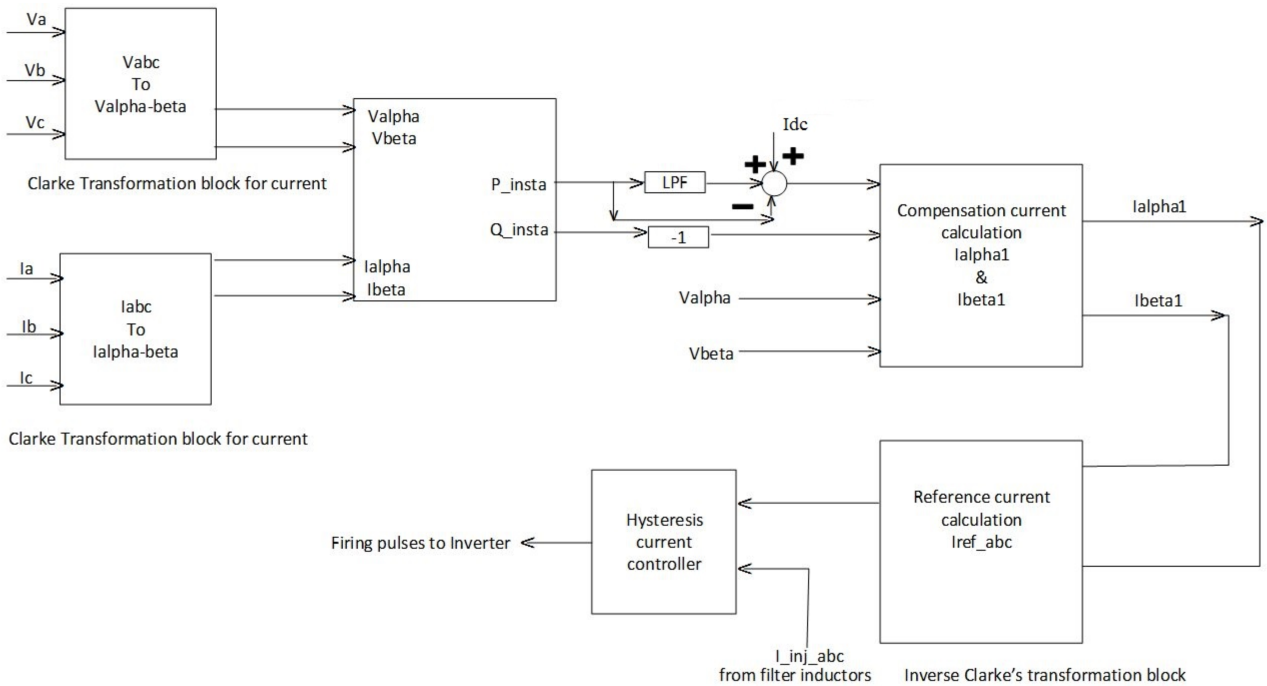

FIGURE 5.4: Block diagram for reference generation using PQ theory

Using the equations as mentioned below :

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\beta \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \tag{5.1}$$

The i_α and i_β current are converted into i_{abc} using Inverse Clarke's transform. This current act as reference current and is compared with the injected current of filter. The error so produced is passed through the hysteresis controller for generation of instances of pulses for the driver circuit.

5.4 Current control techniques

The basic idea behind current control is to supply the anti-harmonics, so that harmonic cancelletion is done properly with load change. The current control techniques are mostly based on PWM methods. The objective is to keep the supply current in response to refernce current and they must be as close as possible. Therefore, any technique used must meet following requirements :

1. Low loss in switching.
2. Reference and actual current should be as close as possible.
3. VSI should be better utilised.
4. Lower order harmonics must be minimum in output voltage.
5. Should be applicable over wide linear modulation range.
6. Fast and easy in implementation.

Current control technique can be broadly classified as:1. Indirect technique 2.Direct technique

5.4.1 Indirect current control technique

The voltage signals v_a, v_b, v_c and V_{dc} and source currents i_a, i_b and i_c are sensed using sensors and used for computation. The sensed currents are compared with their reference currents and pulses thus produced are used for the gate driver circuits. The switches are inturn pulsed by gate driver in manner such that required harmonics are eliminated in the current drawn from source as well as the dc-link capacitor voltage is maintained constant. Indirect current control technique is found to be faster compared to the direct current technique and because of this switching ripples are less and harmonics are more efficiently eliminated for a given THD of load current.

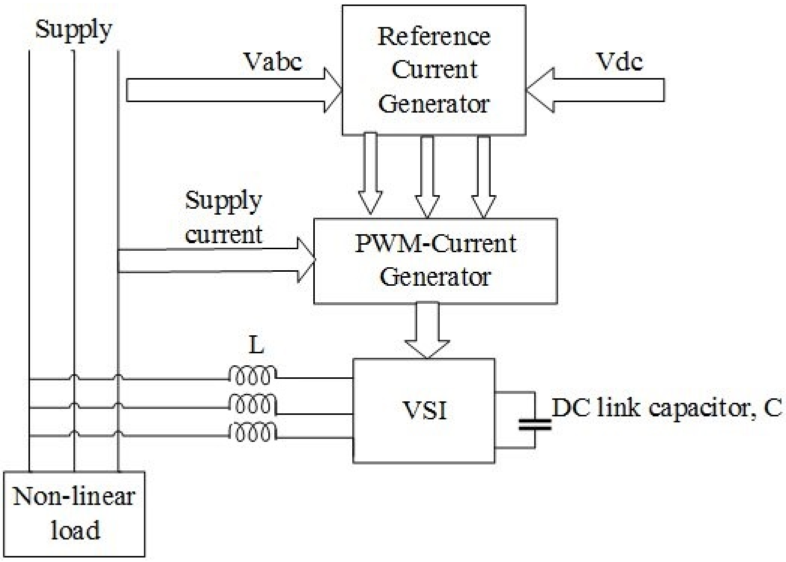

FIGURE 5.5: Indirect current control

5.4.2 Direct current control technique

In direct current control technique, the signals from supply v_a,v_b and v_c ,from V_{dc} and injected currents are sensed and processed. With the help of reference current extraction method, three output refernece signals are generated. The injected currents are compared with generated reference currents and PWM pulses are produced for triggering the switches. This method gives slower response compared to the indirect current control method.

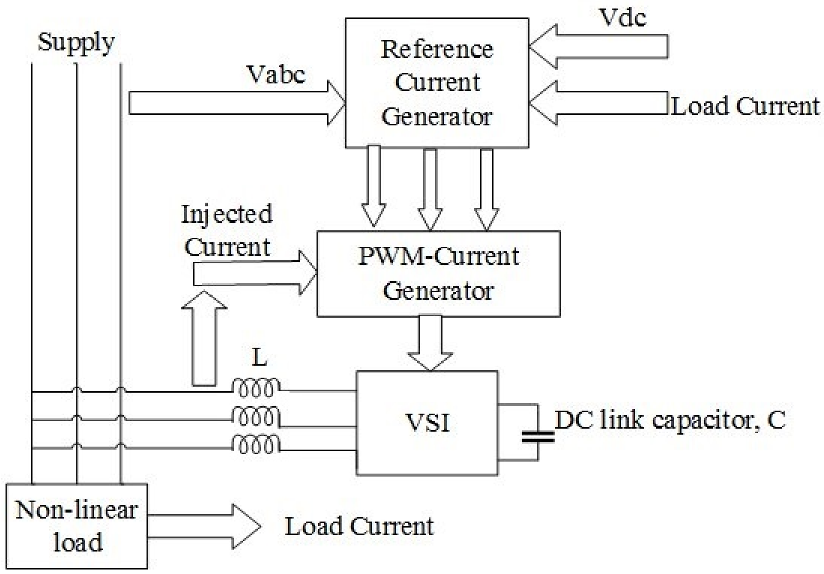

FIGURE 5.6: Direct current control

5.5 DC link capacitor

The equation below is refrenced from[15]

$$C_{dc} = \frac{\pi I_{f\ rated}}{\sqrt{3}\omega V_{dc\ p-p}} \tag{5.2}$$

Where I_{frated} is fundamental rated filter current ,$V_{dc\ p-p}$ is maximum value of ripple voltage which can be taken as 5-10 % of reference value.

5.6 Filter inductor

Filter inductor must fulfil the below requirements :

1. Transfer unattenuated harmonics as requested by control circuit.
2. Must provide reactive power compensation for obtaining unity power factor operation.
3. Filtering of inverter output current and voltage ripples.

4. The peak-to-peak compensation current is chosen as the criterion for designing filter inductor.

The equation below is refrenced from[15]

$$L_f = \frac{V_s}{2\sqrt{6} f_s \Delta I} \tag{5.3}$$

Where V_s is the rms source voltage, f_s is the switching frequency = 10 kHz, ΔI is taken as 15 % of peak-to-peak compensation current .

Chapter 6

Simulation results

The simulation has been done in MATLAB SIMULINK environment. The block diagram is shown below. Considering a situation of irridation say $1000W/m^2$. In later sections simulation results for low level of irridation $400W/m^2$ and simulation results pertaining to a unbalanced load conditions are presented.

6.1 Simulink block diagram

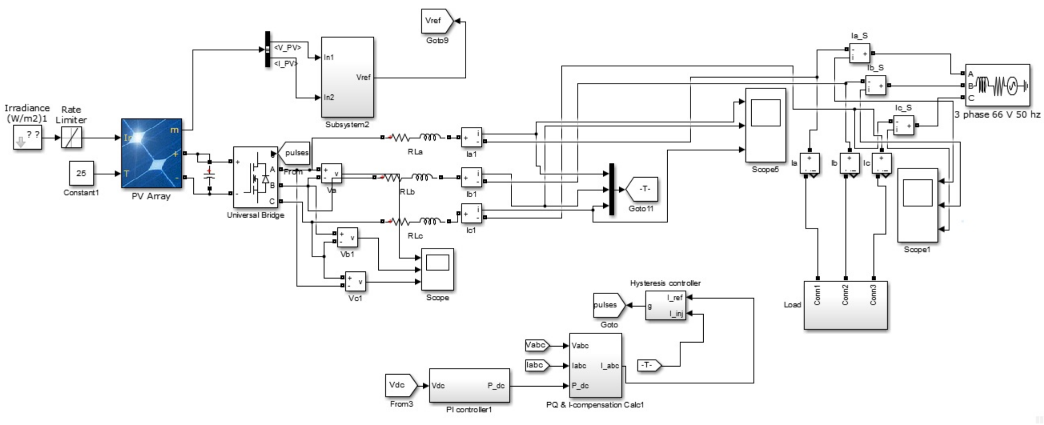

FIGURE 6.1: Simulink block diagram

During high insolation condition, the PV fed inverter is working at MPP to inject real power. At the same time control strategy is working to enable the reactive power injection as well as to mitigate the harmonic power of the load. Two simulation results at $1000W/m^2$ follows :

6.2 Simulation results for high real power injection from PV at irridation $1000W/m^2$

6.2.1 Voltage, current and power from PV array

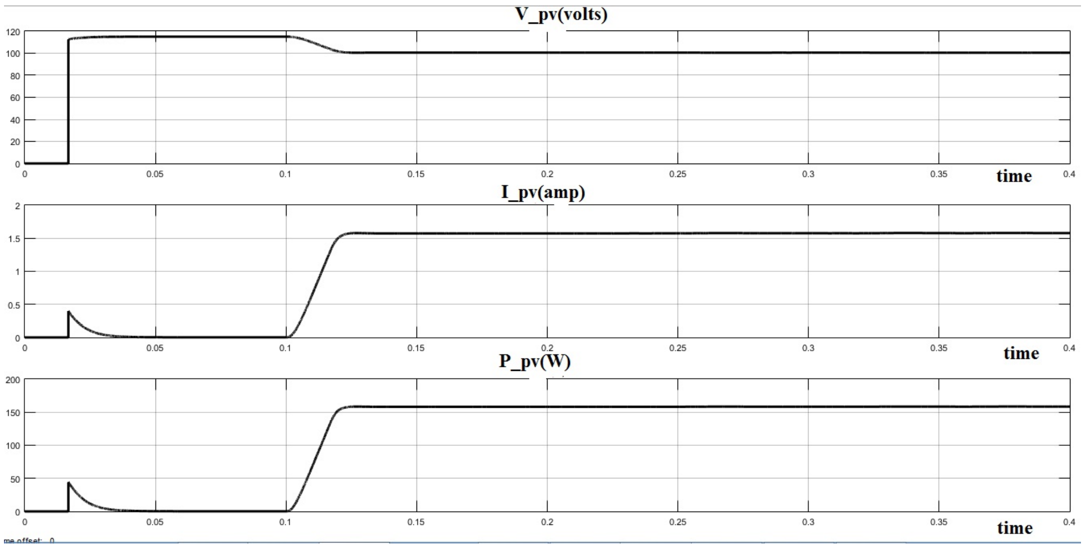

FIGURE 6.2: V,I and P from PV

6.2.2 Phase voltage and current of inverter

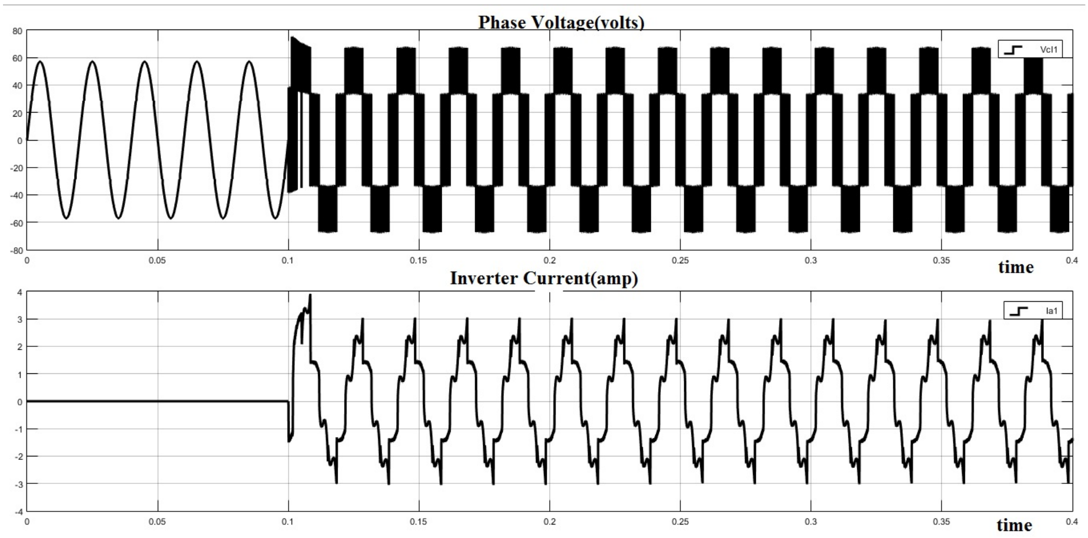

FIGURE 6.3: Voltage and current of inverter

6.2.3 Real power, reactive power and current of inverter

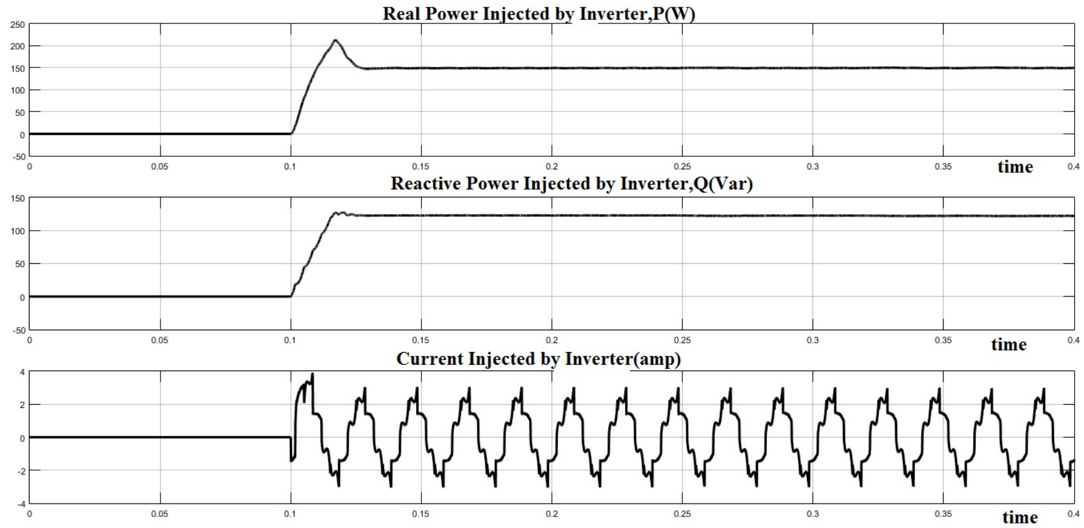

FIGURE 6.4: P, Q and I of inverter

6.2.4 Real and reactive power from grid

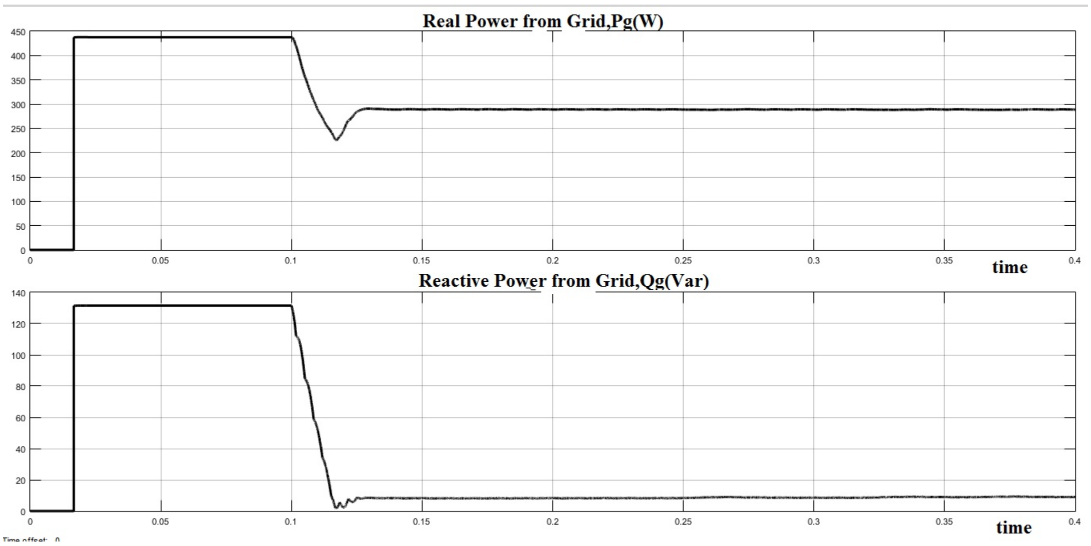

FIGURE 6.5: P and Q from grid

6.2.5 Real and reactive power demand of load

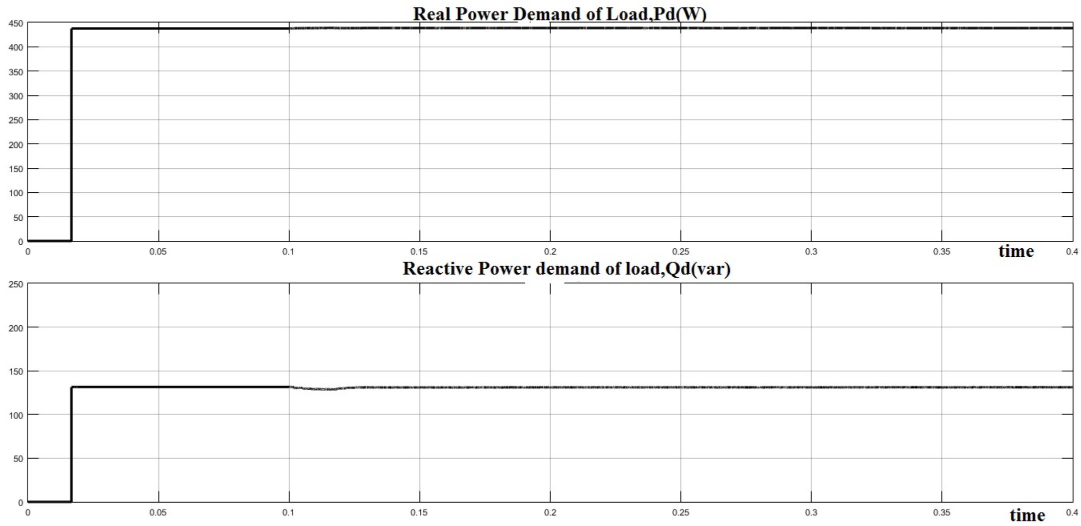

FIGURE 6.6: P and Q demand of load

6.2.6 Grid voltage and current

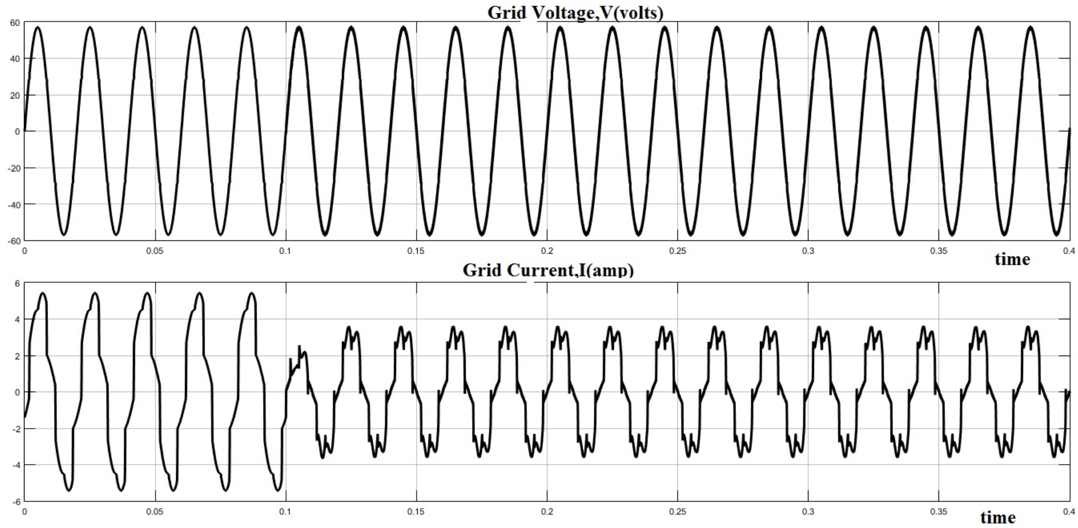

Figure 6.7: V and I of grid

6.2.7 Grid voltage THD

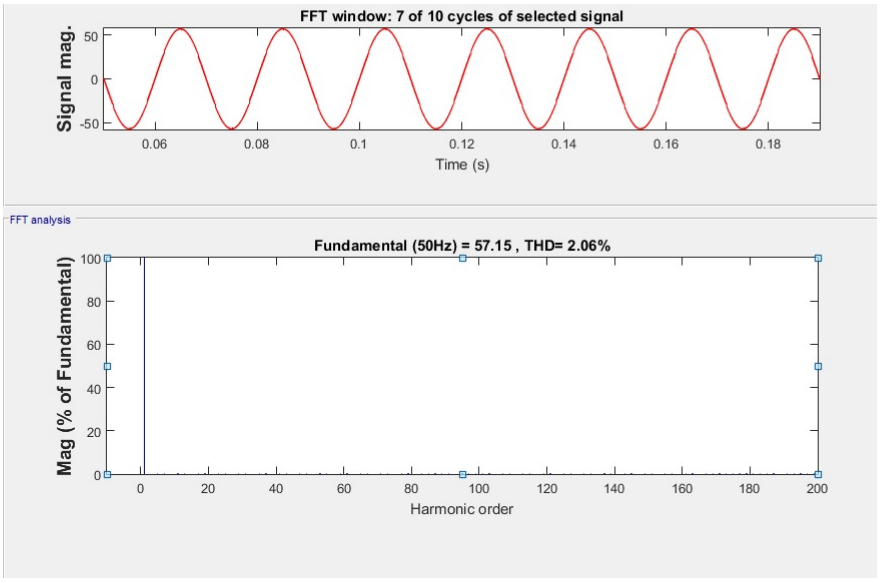

Figure 6.8: Grid voltage THD

6.2.8 Grid current THD

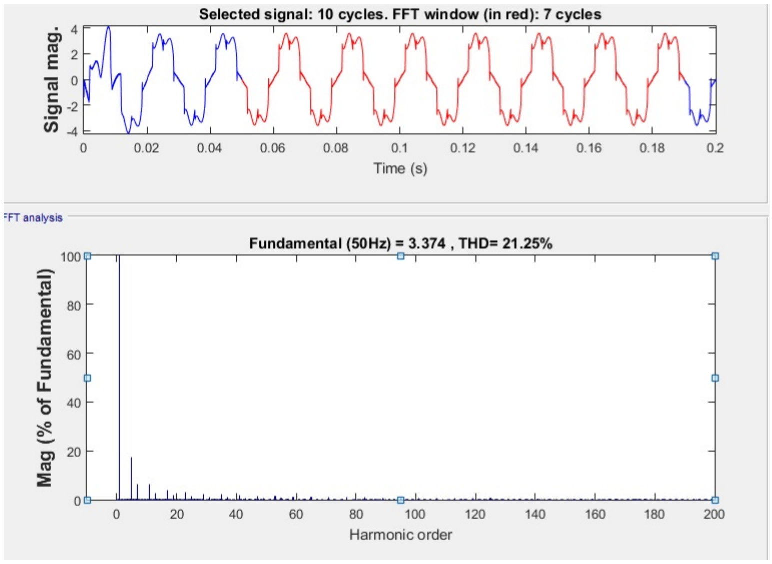

FIGURE 6.9: Grid current THD

Even though the load demand real and reactive power were met and reactive power fed by grid was not zero. Also from results it is evident that the current THD has exceeded its IEEE 519 standard. At the same time reactive power demand and harmonic mitigation objective should always be met. However, the simulation results show that if real power taken from PV is high there is overall effect on the harmonic mitigation of load current. Therefore, real power taken from the PV should only be that much enough which do not effect the harmonic mitigation. It is proposed that real power drawn from PV be reduced so as to keep the THD of grid current within limits.

6.3 Simulation results for low real power injection from PV at irridation $1000W/m^2$

6.3.1 Voltage, current and power from PV array

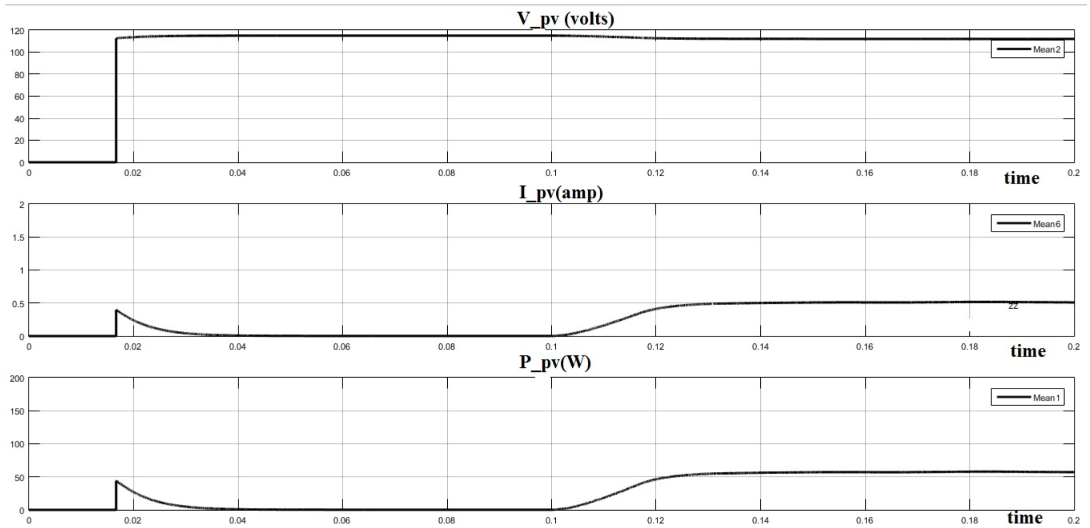

FIGURE 6.10: Voltage, current and power from PV array

6.3.2 Phase voltage and current of inverter

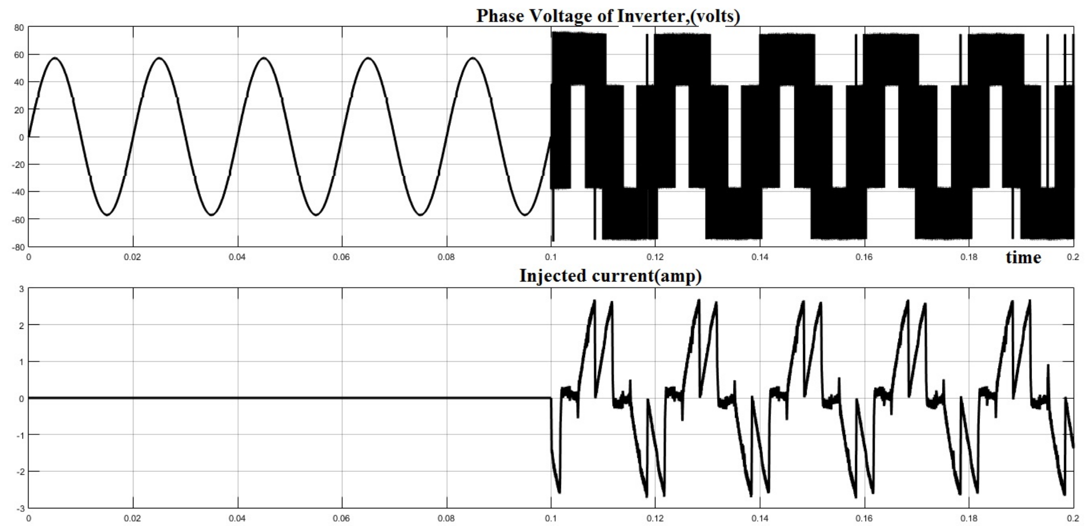

FIGURE 6.11: Phase voltage and current of inverter

6.3.3 Real power and reactive power from inverter

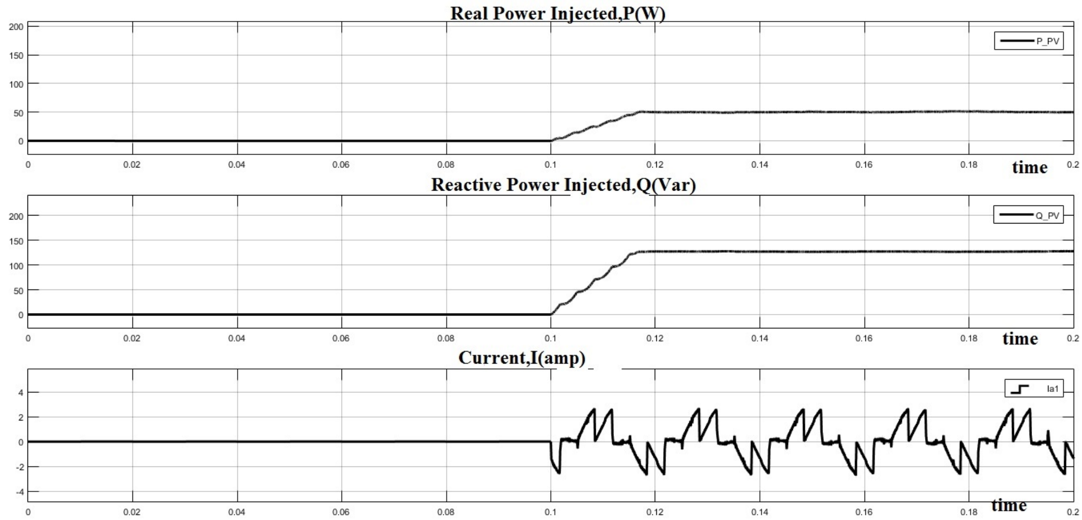

FIGURE 6.12: P and Q from inverter

6.3.4 Real and reactive power from grid

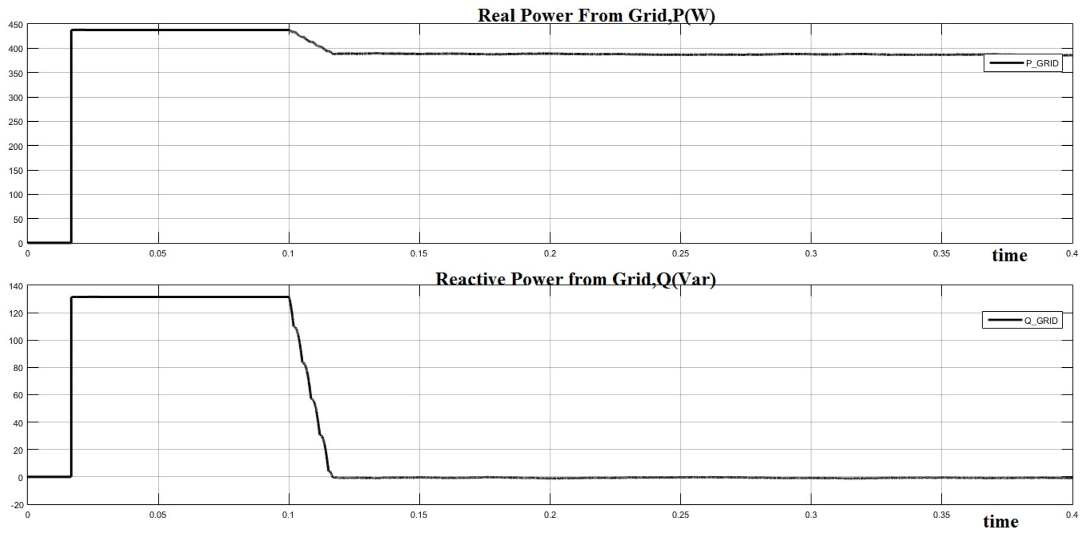

FIGURE 6.13: P and Q from grid

6.3.5 Real and reactive power demand of load

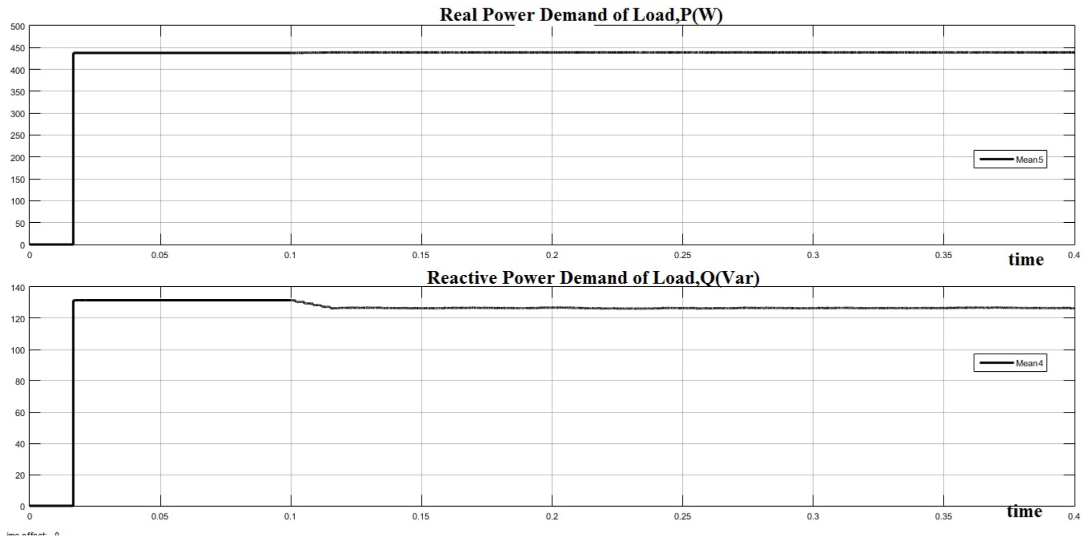

FIGURE 6.14: P and Q demand of load

6.3.6 Grid voltage and current

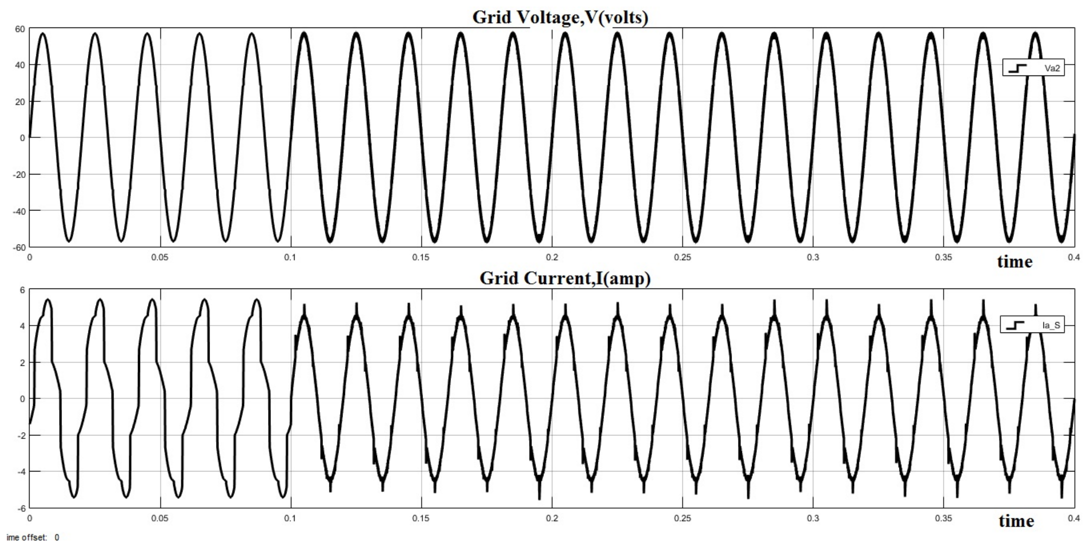

FIGURE 6.15: V and I of grid

6.3.7 Load current THD

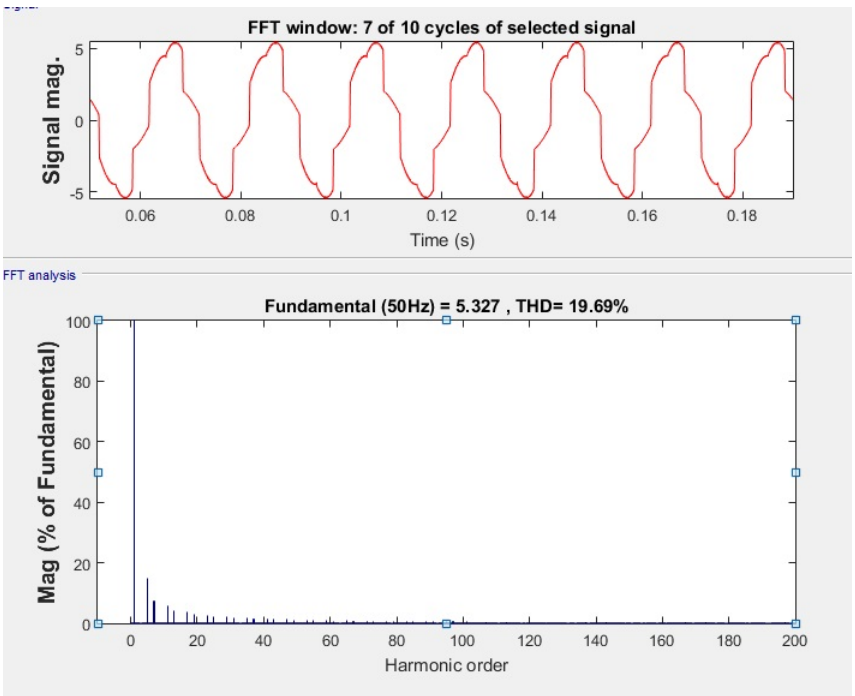

FIGURE 6.16: Load current THD

6.3.8 Grid Voltage THD

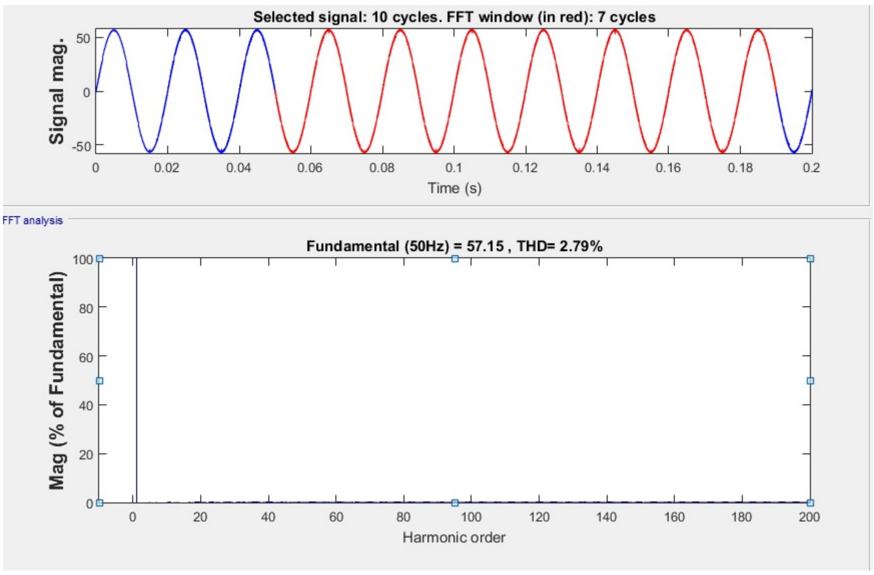

FIGURE 6.17: Grid voltage THD

6.3.9 Grid current THD

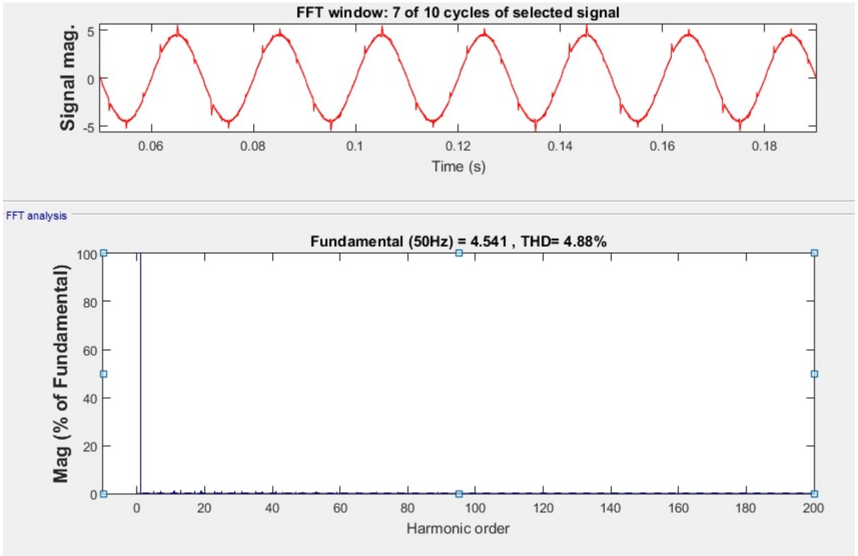

FIGURE 6.18: Grid current THD

With low real power drawn from the PV array the grid volatage THD has been brought within standard limits.

6.4 Simulionation results at very low irridat

6.4.1 Irridation $400W/m^2$

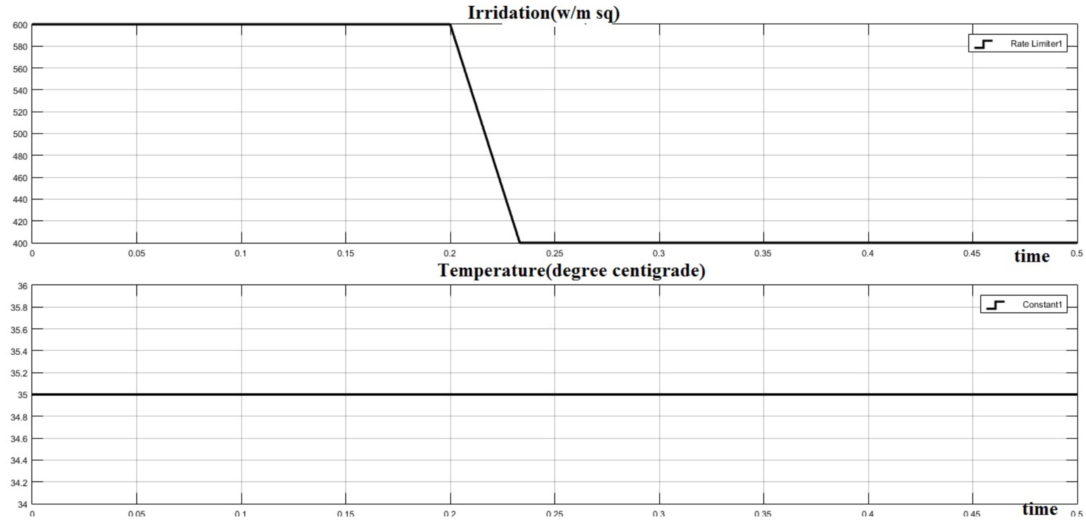

FIGURE 6.19: Irridation and temperature

6.4.2 Voltage, current and real power from PV

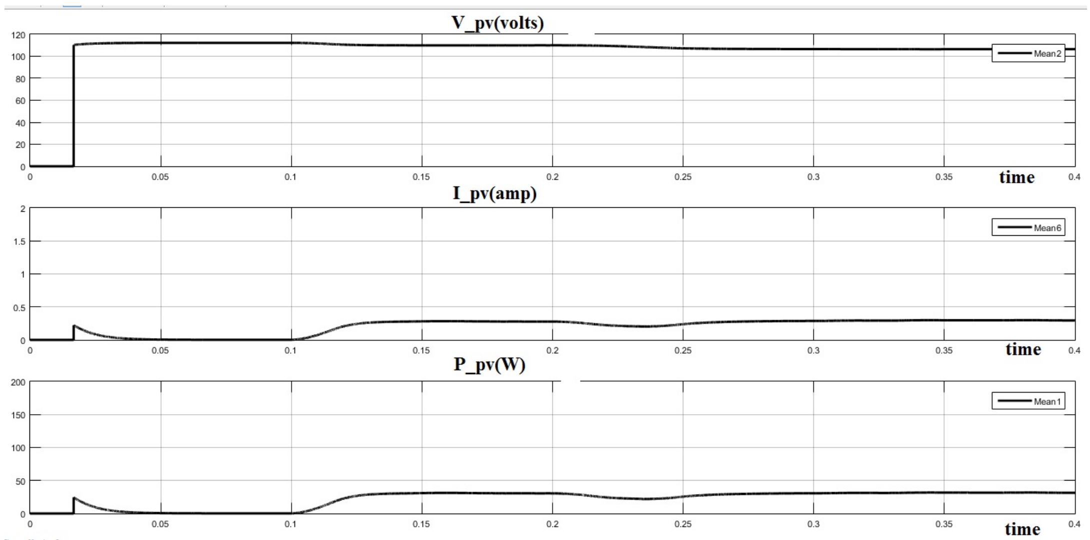

FIGURE 6.20: V,I and P from PV array

6.4.3 Phase voltage and current of inverter

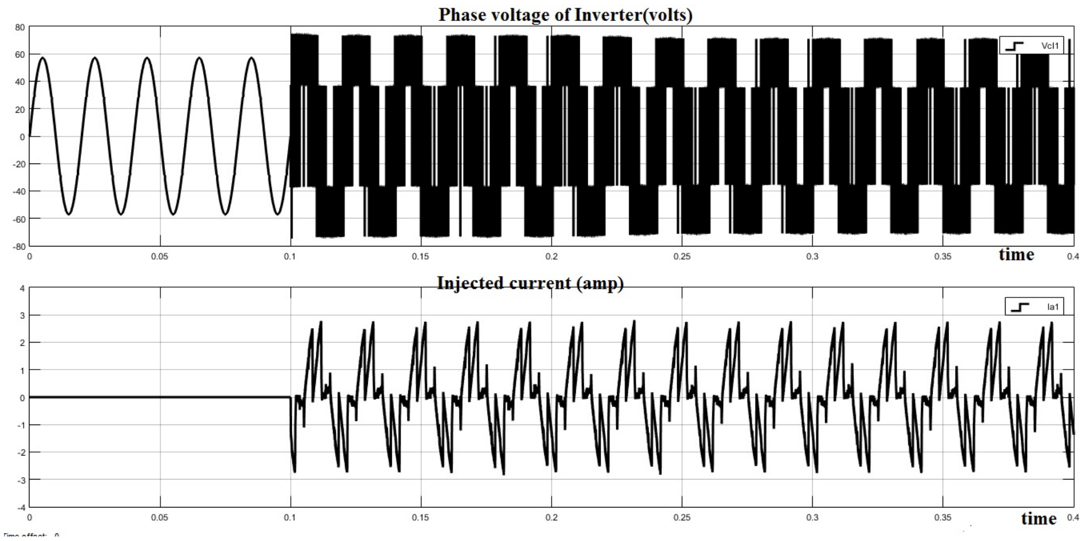

FIGURE 6.21: V and I of inverter

6.4.4 Reference and injected current

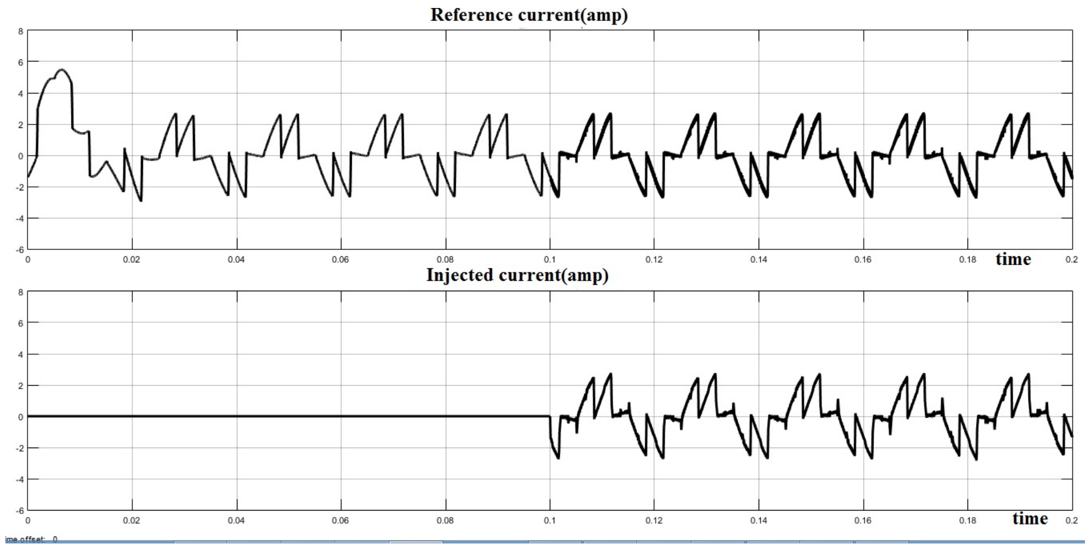

FIGURE 6.22: Reference current and injected current

6.4.5 Real and reactive power from inverter

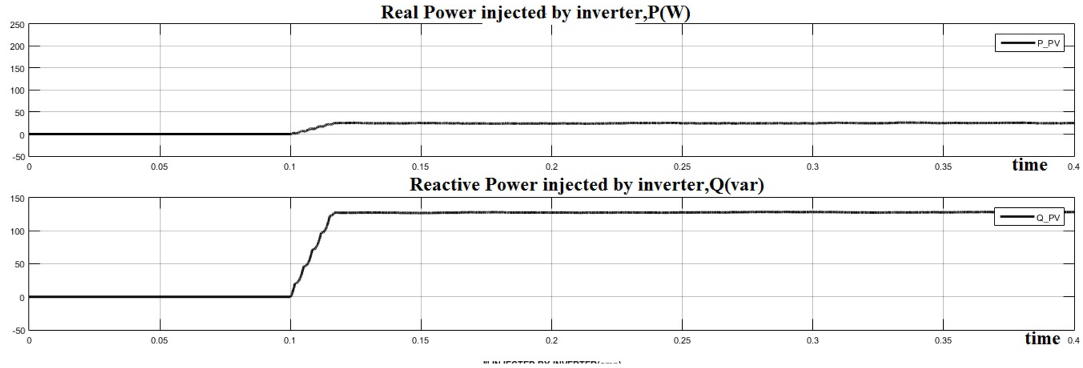

FIGURE 6.23: P and Q from inverter

6.4.6 Real and reactive power from grid

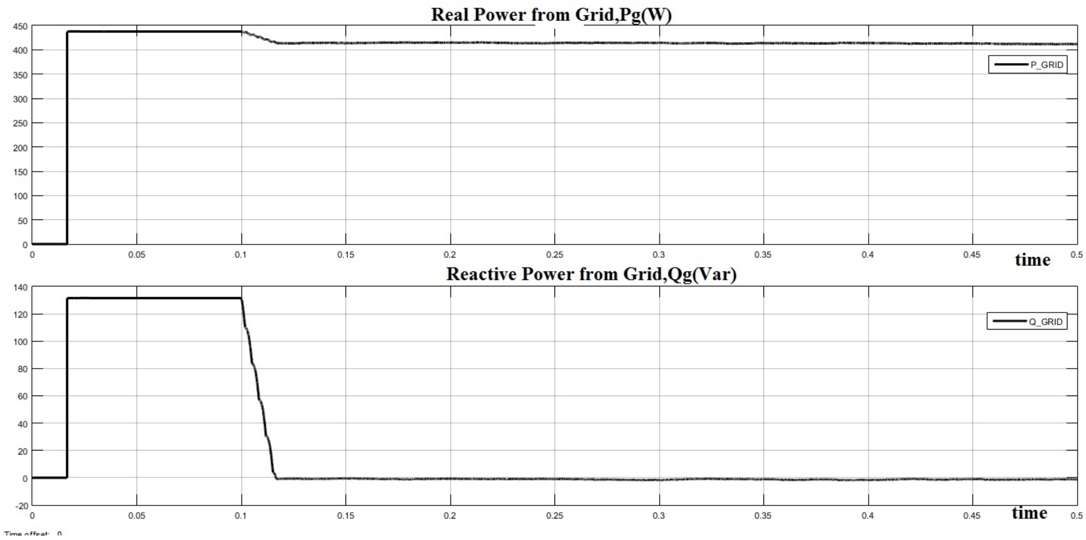

FIGURE 6.24: Real and reactive power from grid

6.4.7 Real and reactive power demand of load

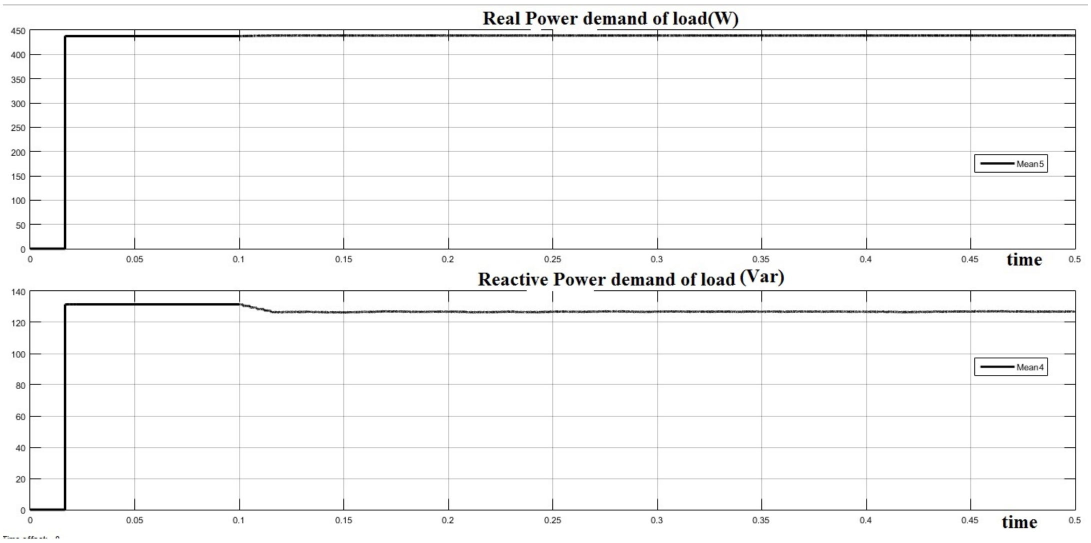

FIGURE 6.25: Real and reactive power demand of load

6.4.8 Grid voltage THD

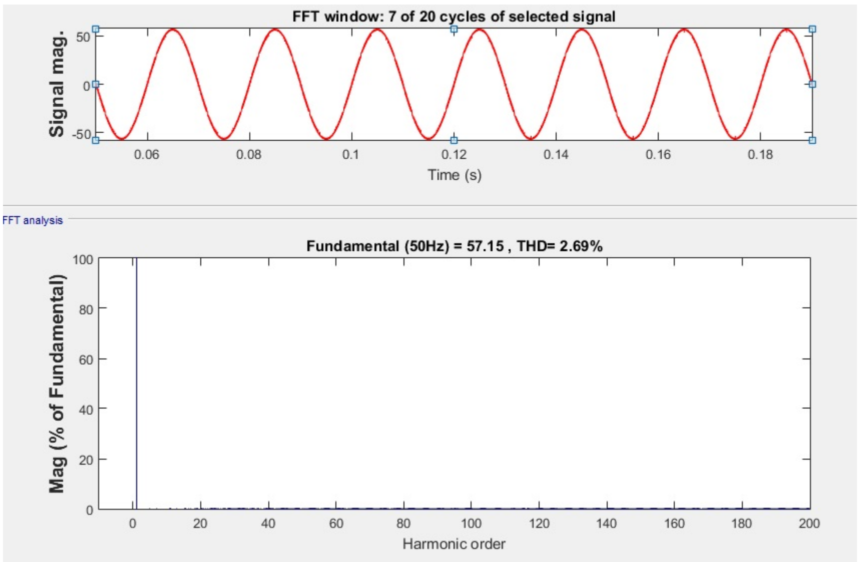

FIGURE 6.26: Grid voltage THD

6.4.9 Grid current THD

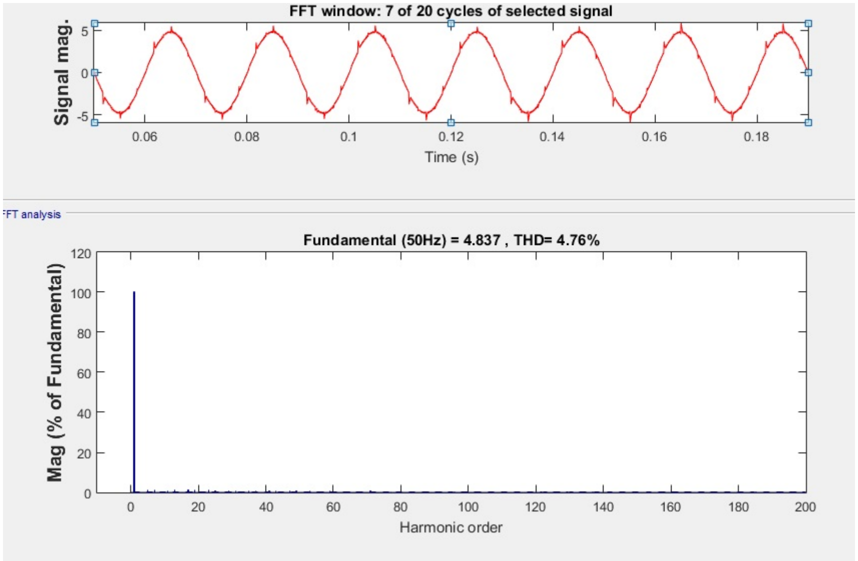

FIGURE 6.27: Grid current THD

The above results confirms with the set limits of THDs for both voltage and current. The is no real power injection by the PV array, however the reactive and harmonic power is being compensated. Therefore, when PV array is used under low irridation condition only reactive and harmonic power compensation should be the target. But during high irridation reactive, harmonic as well as real power can be taken from PV array with THD of grid current as a factor taken into consideration.

6.5 Simulation results for unbalanced load connected to grid

6.5.1 Unbalanced load current

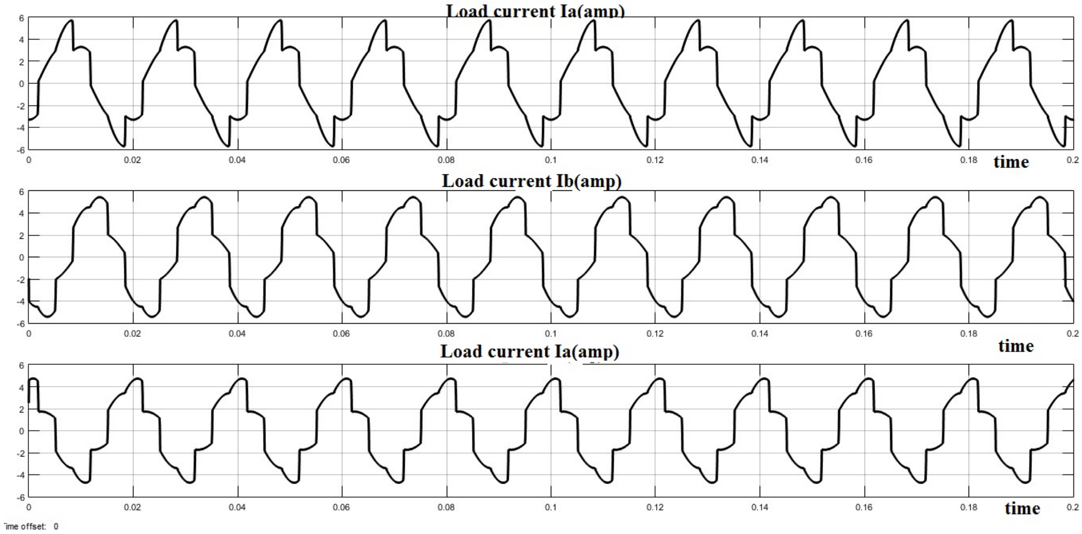

FIGURE 6.28: Unbalanced load current

With out the compensation above nature of unbalanced load current is drawn. Each of these currents has it own THD ranging from 19.68 percent to 24.05 percent. The objective is to mitigate the harmonics and get the required reactive power compensation.

6.5.2 Voltage, current and power from PV array

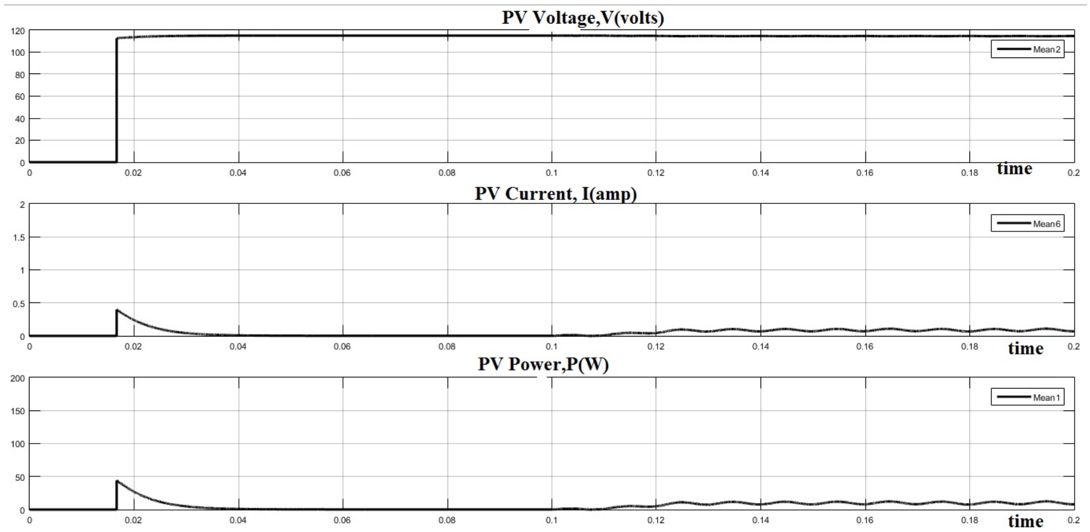

FIGURE 6.29: Voltage, current and power from PV array

6.5.3 Reference and injected currents

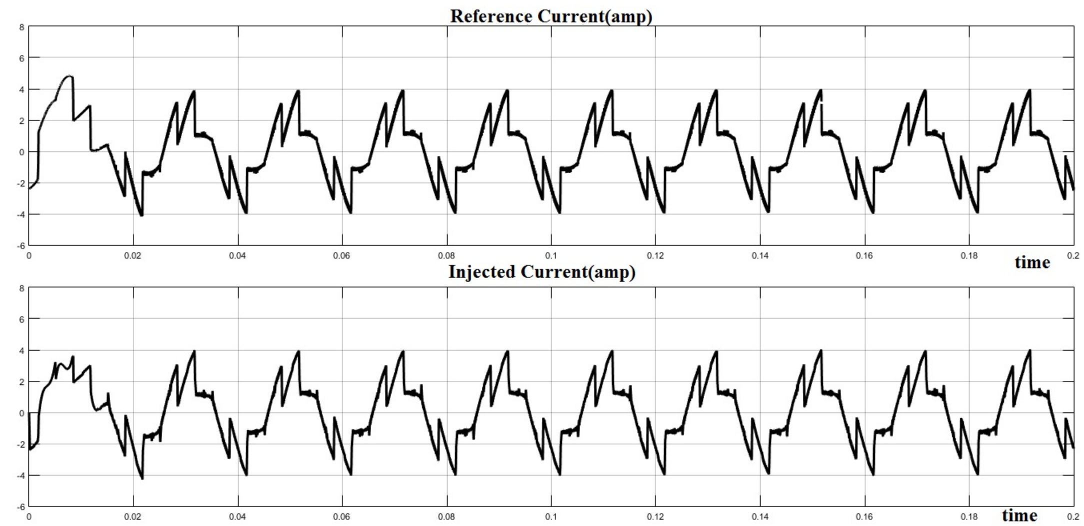

FIGURE 6.30: Reference and injected currents

6.5.4 Real and reactive power injected by inverter

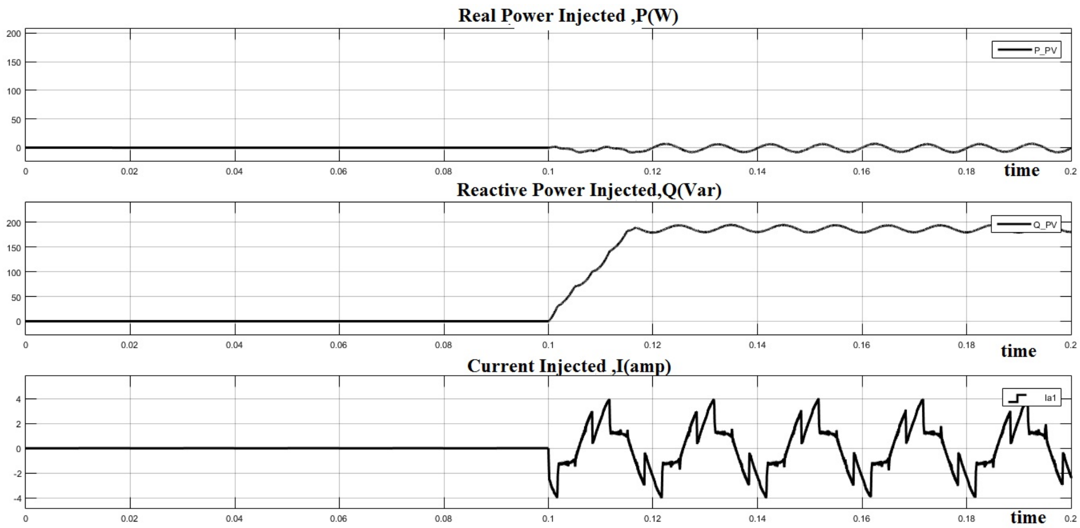

FIGURE 6.31: Real and reactive power injected by inverter

6.5.5 Real and reactive power from grid

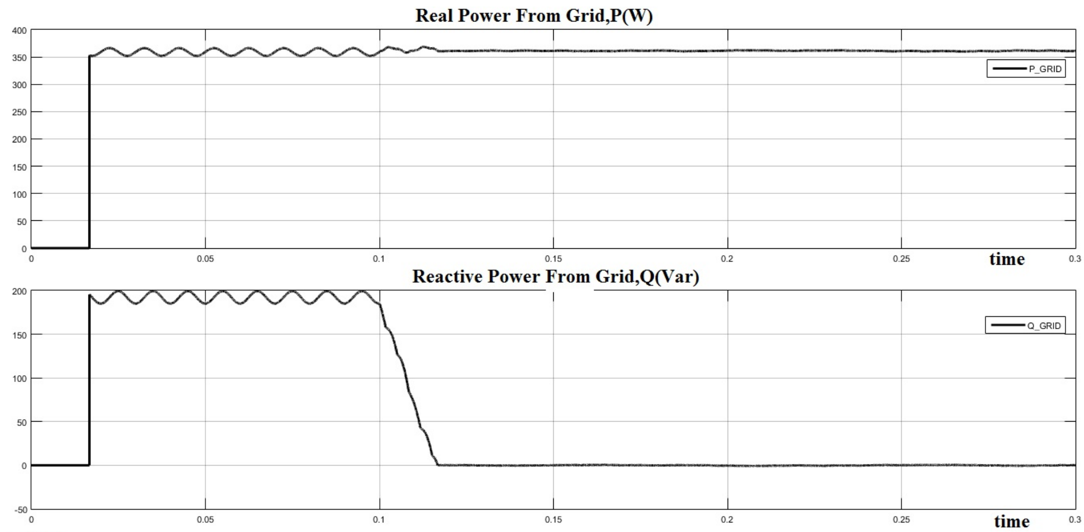

FIGURE 6.32: Real and reactive power from grid

6.5.6 Real and reactive power demand of load

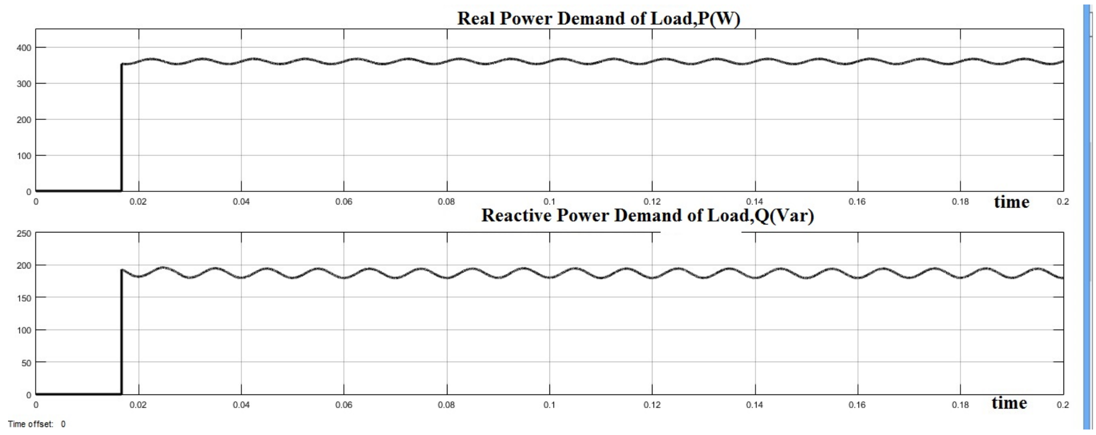

FIGURE 6.33: Real and reactive power demand of load

This proves that real and reactive power demands are balanced .

6.5.7 Grid voltage THD

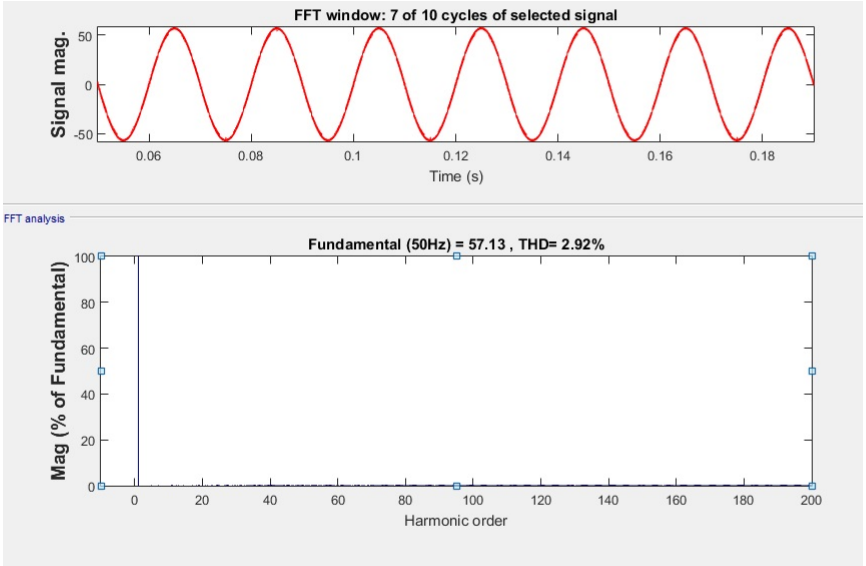

FIGURE 6.34: Grid voltage THD

6.5.8 Grid current THD

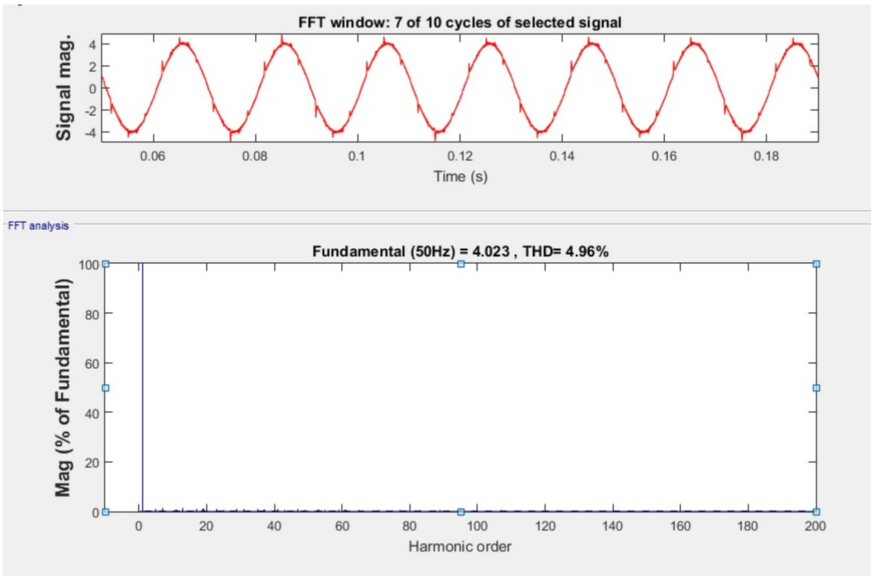

FIGURE 6.35: Grid current THD

6.5.9 Load current after compensation

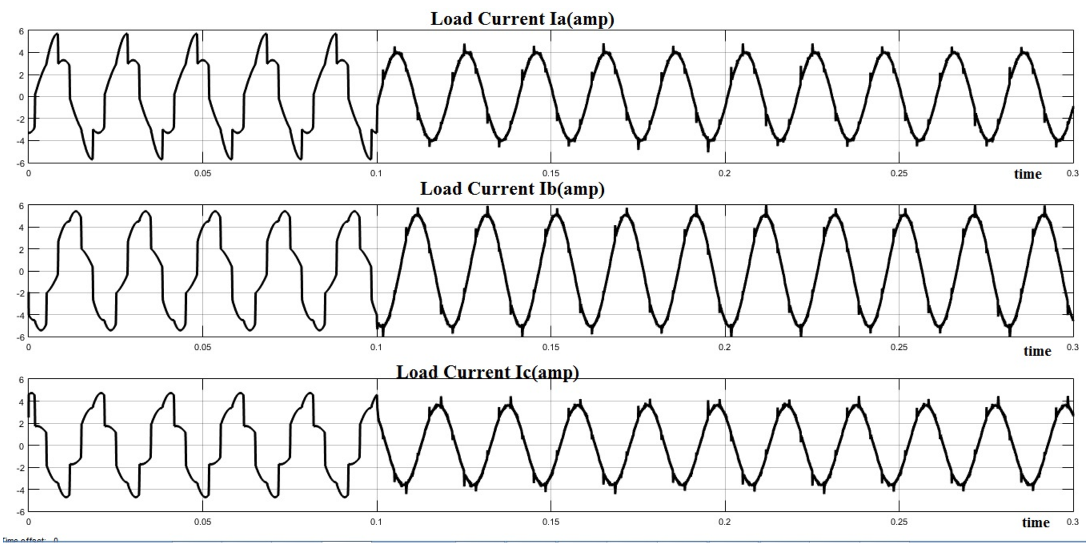

FIGURE 6.36: Load current after compensation

The above results proves that inspite of unbalance nature of load current the current THD as well as voltage THD has been brought within acceptable limits. The compensation of load demand reactive power has also been achieved.

All the three different simulation results show that reactive and harmonic power for load (non-linear + linear) can be compensated with PQ based reference current generation and detection technique. However, there is a limitation over the real power that can be taken from PV array without vilating the THD standards for voltage and current.

Chapter 7

Hardware

The hardware set up has been envisaged to consists of an two level inverter, with PV panels feeding the power. A laboratory prototype of was developed. Diode bridge rectifier with resistive load was used .In order to implement the control algorithm in closed loop, DC link voltage is sensed and then compared to the reference value. The error is fed to a PI controller. Output of the PI controller is considered for the compensation of real power. PQ theory is used for reference current generation as discussed in previous chapter. The actual currents are compared with the reference currents to generate an error signal. This is fed to a hysteresis band PWM controller for generation of firing pulses. In laboratory dSPACE 1104 was used for generation of trigger pulses for driver circuit.

The setup will consist of following :

1. non linear and a linear load
2. power circuit
3. measurement of parameters, like source voltages, source currents, PV voltage and PV current.
4. power supplies

7.1 Two level inverter

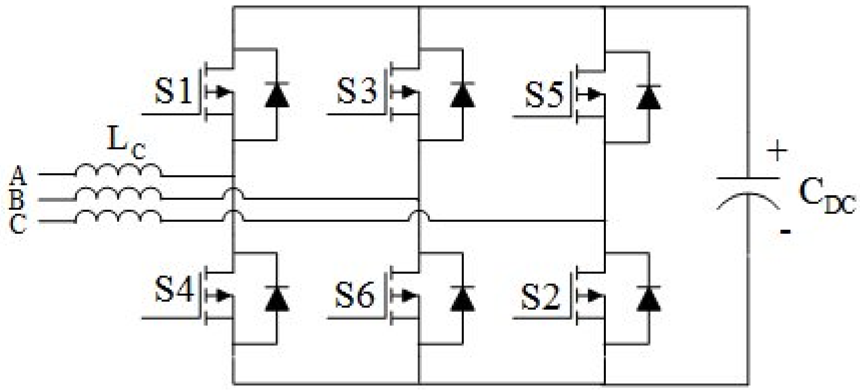

FIGURE 7.1: Inverter

Voltage transient and current transient during turn-on and turn-off are dangerous to devices like MOSFET. The protection aganinst such high voltages and currents are necessary and provided by the snubber circuits. It consists of a capacitor and to protect the high rate of change of voltage during turn-on and a diode connect across resistor R_s to prevent the discharge of current during turn-off. Metal oxide varistor gives additional protection against voltage transients.

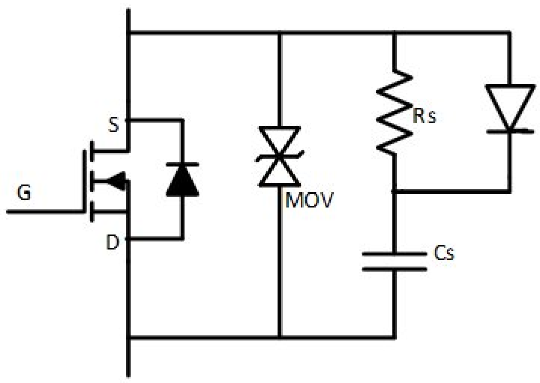

FIGURE 7.2: Snubber circuit

7.2 Driver circuit

The pulse amplification circuit for MOSFET is shown in figure below.The opto coupler HCPL301 provides necessary isolation between the low voltage isolation circuit and high voltage power circuit. The pulse amplification circuit is provided by the output amplifier transistor 2N2222. When the input gating is +5v level, the transistor saturates, the LED conducts and the light emitted by it falls on the base of the phototransistor, thus forming its forming its base drive. The output transistor thus receives no base drive and remains in the cut-off state and a +12v pulse (amplified) appears at its collector terminal.

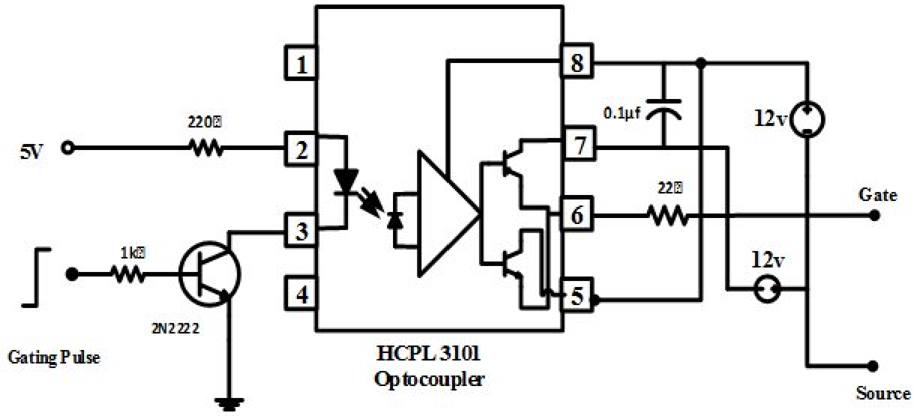

FIGURE 7.3: Driver circuit

7.3 Power circuit

It involves three things :

1. Selection of reference voltage V_{dc} .
2. Selection of filter side inductor L_f.
3. Selection of dc side capacitor C_{dc}

The design of the above three is based on following assumptions:

1. Source voltage is sinusoidal.

2. For design of Lf the ac side line inductance is assumed to be 5

3. Reactive compensation capability of active filter is fix .

4. Converter is assumed to be operating in linear region i.e ma = 0 to 1 .

5. Selection of switching frequency is done on the basis of highest order of harmonic frequency to be compensated.

7.4 AC current sensing

AC source currents are sensed using Hall Effect current sensors . These current sensors isolation between high voltage power circuit and the low voltage control circuit and require a nominal supply voltage of the 12v to 15v. It has the transformation ratio of 1000:1; hence its output is scaled properly.

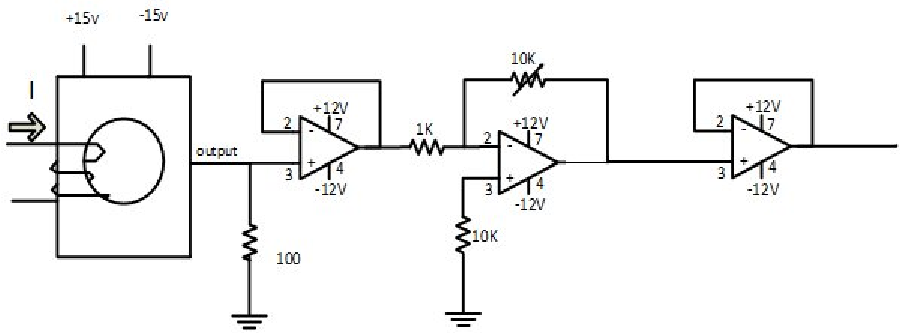

Figure 7.4: AC current sensing

7.5 AC voltage sensing

AC source voltages vsa,vsb and vsc(phase to neutral) are required to generate the unit current sine vectors(esa, esb and esc) in phase with the respective source voltages. Only sensing two voltage are sufficient for three phase three wire system, but all the three voltages are sensed to avoid the delay introduced due to the subtraction circuit. the circuit diagram of the sensing ac voltage is shown in the figure. Resistors are used to scale down the voltage within the range of AD202 (isolation amplifier).

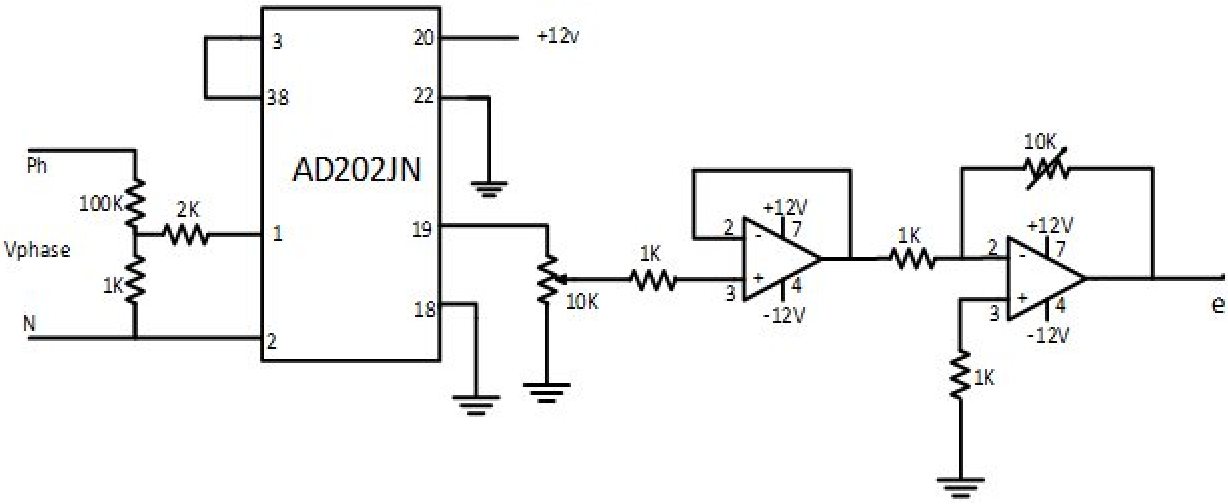

FIGURE 7.5: AC voltage sensing

7.6 Power supplies

DC regulated supplies (+12V, -12V and +5v) are required for providing biasing to various circuits like pulse amplification and isolation circuits, hysteresis controller and voltage detectors etc. using regulator ICs 7812, 7912 and 7805 for +12V, -12V and +5v respectively. The circuit diagram of the power supplies is as shown in following figures below .

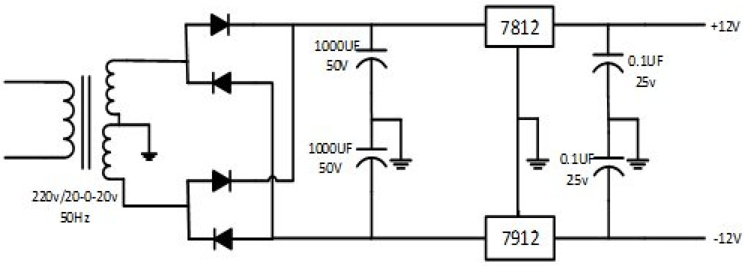

FIGURE 7.6: +12V power supplies

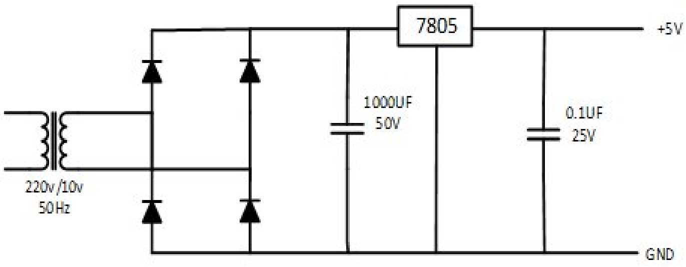

FIGURE 7.7: +5V power supplies

7.7 Result of inverter testing

The prototype 2 level inverter was tested in laboratory .

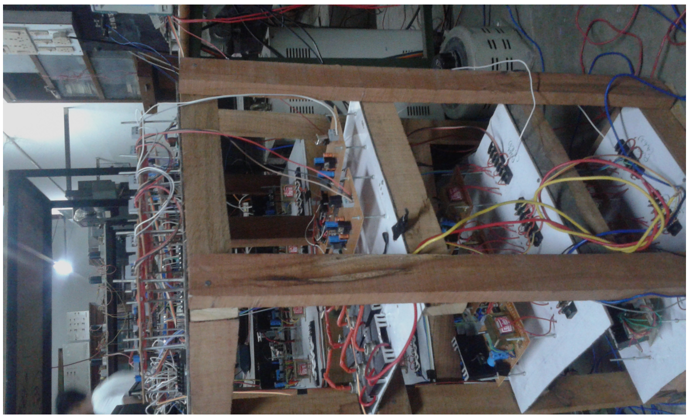

FIGURE 7.8: Prototype inverter

High requency pulse from the dSpace for driver circuit.

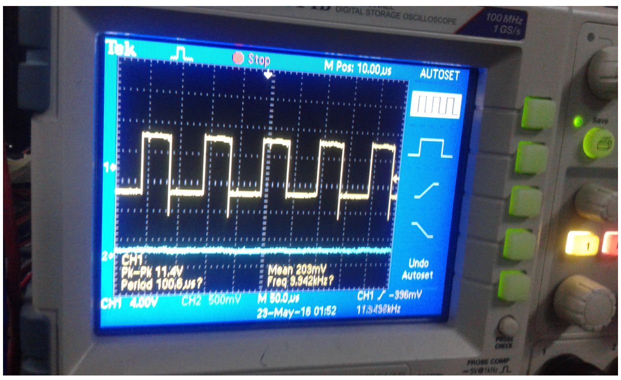

FIGURE 7.9: Pulse obtained for firing

Chapter 8

Conclusion and scope for future work

The dissertation objective has looked into the issue that whether use of PV array can be made to fulfill the reactive and harmonic power demand of the loads connected to the grid. With the increase in power consumption and semiconductor switches finding applications from simple mobile chargers to complex system like industrial drives. The energy demand is poised to increase in the coming time. The demand is being planned to be met by non-conventional energy sources like solar energy.

Simultaneous, the power network which mets the load demand is burdened by not only beacuse it carries the real power demand, but is required to met the reactive demand as well. This put a huge challenge on the system, at the same time the increase in non-linear load give an extra burden of the associated harmonics. The reactive power demand has at times leads to the voltage stabilty problem. And there are similar problems with harmonic current flowing in the system, which has been discussed in the previous chapters.

The simulation were carried for diffrent set of situations like change in irridation, change of load demand as well as under unbalance load condition. Moreover, there is a scope for trying a different version of algorithm for extracting real power from PV other than

MPPT. The scope is there to evalute the response for the case of unbalanced supply voltages for harmonic mitigation. As well as there is a scope for the use of other reference generation techniques other than PQ based reference generation and make a comparative evaluation.

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