GRID TIE INVERTER IN A DISTRIBUTED GENERATION SYSTEM WITH REACTIVE POWER CAPABILITIES

A Thesis

Presented to

The Faculty of the Department of Electrical and Computer Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in Electrical Engineering

by

Abraham Oladepo

August 2016

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Abstract

This thesis presents a single phase grid tie inverter with reactive power controller for renewable energy applications in a distributed generation system (DGS). This allows the local renewable energy sources in the DGS to provide the necessary reactive power support to the grid. The inverter utilizes a control algorithm to provide reactive power support to improve the voltage profile of the grid.

A traditional grid tie inverter becomes a dynamic reactive power compensator, by regulating the output voltage of the inverter. The reactive support for the grid was implemented by sensing the inverter output voltage to generate its direct and quadrature component in order to generate a reference current signal for a current control loop and thereby controlling the inverter. The system was modeled with Simulink to verify the functionality of the reactive power control in a DGS.

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CHAPTER 1 INTRODUCTION

This chapter discusses distributed power generation systems with a main emphasis on Photovoltaic (PV) generation. The power control system of the energy sources is described. This chapter concludes with the aim of the research, the motivation behind the thesis and the thesis layout.

1.1 Distributed Generation System

Distributed generation (DG) is the small scale generation of power located at or near the load which is an environment friendly, reliable and secure source of power.

The commonly used DGs are photovoltaic, fuel cells, combustion gas turbines, micro turbines and wind turbines. This DG technologies are also called alternate energy systems as they provide alternative ways to the traditional electricity sources such as oil, gas, coal, water etc., and can also be used to enhance the performance of existing electrical power system. Deficit power can be supplied from the grid when there is not enough power from the DG system. DGs are becoming increasingly popular due to their low emission, low noise levels and high efficiency. One of the main advantages of DG is its close proximity to the consumer loads. DG can play important role in improving the reliability of the grid, reducing the transmission losses, provide better voltage support and improve the power quality. In traditional generation sometimes the grid failure leads to blackouts but with Distributed Generation, the system is less susceptible to blackouts [1].

The major obstacle for the distributed generation has been the high cost. However, the costs have been decreasing significantly in the last decade. The distributed generation also reduces pollution because most of its sources provide clean and efficient energy. A comparison of traditional and DG system is shown in Figure 1.1.

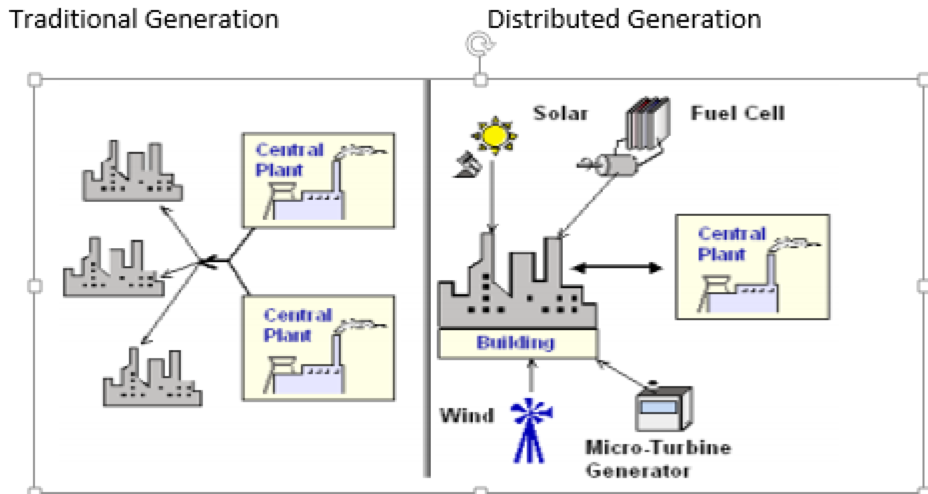

Figure 1.1 Central Generation vs. Distributed generation

1.2 Overview of Grid tie PV Sources

The use of renewable energy has increased in the last few years in the wind and solar area. For wind and solar systems, power electronics converters are used to integrate to the grid or load. With recent advances in power electronics, these renewable systems are now capable of supplying many ancillary services that traditional energy sources cannot supply. Grid connected PV systems account for more than 99% of PV installations compared to stand-alone systems using batteries for energy storage. In grid-connected PV systems, batteries are not needed because all the power generated by the PV can be fed to the grid for direct transmission, distribution, and consumption. The generated PV power minimizes the use of other energy sources supplying power to the grid, such as hydro or fossil fuels, whose savings act as energy storage in the system, providing the same function of power regulation and backup as a battery would deliver in a stand-alone system [2]. Since grid-connected systems do not need batteries, they are more cost effective and require less maintenance and investment than stand-alone systems.

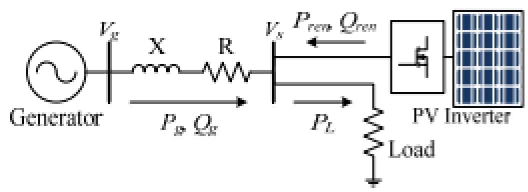

Figure 1.2 Grid-tie inverter [4]

Figure 1.2 shows a grid tie inverter connected to a grid. The grid consists of the generator, load and transmission line. The distributed generation systems consists of multiple PV and other energy sources connected to the grid. Most grid-tie inverters are used in applications where the output of a power source is DC but the consumer application uses AC power. Energy sources such as solar energy produces DC power, and hence power electronics converter and associated control equipment are required to convert the DC power to AC power. There are two types of inverter system; stand-alone system and grid-connected system. The stand-alone system is used in off-grid application with battery storage to store power when the system is not fully utilized by a load. In the case of residential renewable energy system (RES), the electricity demand of the building is met by the RES and only the excess is fed into the grid. Its control function must follow the voltage and frequency of the utility-generated power presented on the distribution line [3]. The feeding of electricity into the grid requires the transformation of DC into AC by a grid tie inverter. Solar grid-tie inverters should be designed to operate within allowable power quality limits set by the grid standards.

Increase in load demand has led to new strategies for maximizing the generation of electricity, which includes distributed generation. Growing concerns about environmental pollution have brought into focus RES such as wind, solar photovoltaic. The increase in the use of renewable energy and distributed generation system (DGS) has created new challenges for the control of power system. These RES cannot be connected directly to the distribution grid, but are integrated by means of a power converter. For example a PV is connected to the grid through an inverter, the distribution of the renewable sources makes it difficult to control the total power generation and to predict the load demand which could lead to an imbalance in the supply and demand causing grid instability [4].

To reduce transmission losses and improve voltage at the point of common coupling (PCC) between the grid and inverter, it is necessary to support the reactive power demand through distributed generation. In the future, it is anticipated that the utility would expect the DGS will provide support to the power system such as power factor correction, grid stability and reactive power support apart from injecting active power into the grid [5].

Grid tie inverters are connected between the power grid and the renewable energy sources to convert energy and to supply the energy to the power grid. Vector control divides the AC line currents into real and imaginary axis components in the synchronous rotating frame which makes it easier to control the active and reactive power respectively. The control of the instant active and reactive power can be achieved by regulating the real and imaginary axis converter currents using regulators [6]. A grid tie inverter can make use of reactive and active power control to regulate the voltage at the point of common coupling

(PCC) between the grid and the filtered inverter output and maximize the power output from the PV.

1.3 Inverters

Inverters are devices that convert DC power to AC power. The function of the inverter is to transfer power from a DC source to an AC load by changing its input DC voltage to an output AC voltage of desired magnitude and frequency. Inverters can be either a single phase or a three phase system. The single phase inverters can be used in low power residential applications while the three –phase can be used in utility or commercial applications. This thesis focuses on single phase inverter systems.

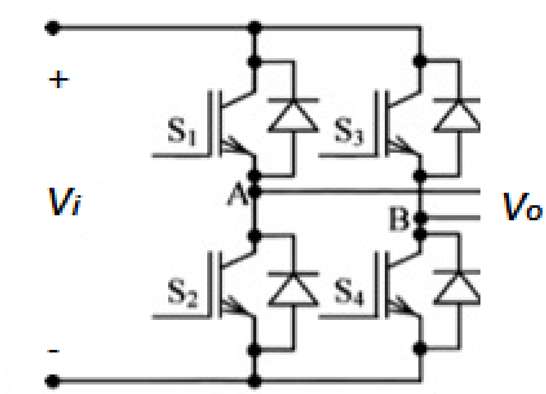

Figure 1.3 Single-Phase inverter

Figure 1.3 shows a voltage controlled source single-phase inverter. The inverter consists of four switches. With a DC voltage input V_i, the switching pattern for these switches produces an AC voltage across the inverter output, V_o.

1.4 Reactive Power

AC systems can supply or consume two types of power; real power and reactive power. Real power accomplishes useful work while reactive power supports the voltage that must be controlled for system reliability. Unlike active loads such as resistors, inductors and capacitors store energy momentarily and thus reactive power oscillates between the two. Reactive power occurs when the voltage and current are not in phase.

In AC power system, voltage is controlled by managing production and absorption of reactive power. When there is not enough reactive power support, the voltage sags down and it is not possible to push the power demanded by loads through the lines. Electrical energy is usually generated, transmitted and consumed as alternating current. In AC systems, the reactive power flows in the line together with the active power, which is a drawback is AC power system. Apparent power in the AC system is a measure of reactive power and active power. Most of the components in the power system are either generating or absorbing reactive power. Unlike real power, reactive power does not do work. Reactive power for an AC system with sinusoidal current is equal to the product of the magnitude of the current, voltage and sine of the phase difference between current and voltage. It is being measured in the Volt-Ampere-reactive (VAR). The reactive power is a flow of stored energy into a circuit which is deduced from the stored energy cycle. Motors loads and other loads require reactive power to convert the flow of electrons into useful work [7]. The power factor determines whether reactive power needs to be provided or absorbed. An ideal power factor is unity at normal operating conditions, in which only real power is being delivered

If a voltage V and current I from a load are given. The power triangle of the load is shown in Figure 1.4

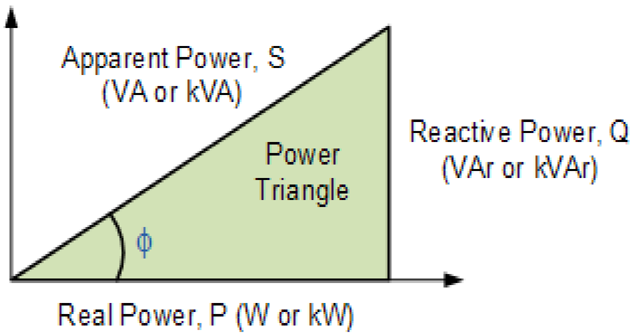

Figure 1.4 The power triangle

The magnitude of the apparent power S is given as

$$|S| = |V||I| \text{ and} \tag{1.1}$$

$$|S| = \sqrt{P^2 + Q^2} \ . \tag{1.2}$$

The reactive power is

$$Q = V{\cdot}I{\cdot}\sin\phi, \tag{1.3}$$

where ϕ is the power angle.

1.5 Literature Review

Different ideas on how the PV inverters can be improved and more efficient have been proposed and discussed in [4-6, 8-9]. Major problems such as power conversion efficiency under low irradiation and the amount of power generated changes with weather conditions. The maximum power point (MPP) is a unique point on the IV curve, which is at the knee of the curve. In [10, 11], a power control algorithm was used to optimize the power generated by the PV panels using maximum point power tracking (MPPT). Tracking the MPP automatically adjusts the power extracted from the PV cell to maintain the maximum power by utilizing a control circuit.

Many techniques have been proposed to reduce the size of a DC link capacitor while maintaining a good inverter power quality. According to [12], a technique for sizing DC link capacitors in inverter systems. The dc link-capacitor is balancing energy storage element between the DC and AC sides of a voltage source inverter (VSI). This component is connected parallel to the input of the inverter in order to maintain a stiff dc link voltage across the VSI. A required amount of DC current ripple is needed to suppress the interference caused by pulsed inverter current and stray inductance and resistance of the PV output. Therefore, the selection of an appropriate DC-link-capacitor is necessary for desired electrical performance of the inverter.

Reactive power compensation of the inverter has not been mainly focused in literatures compared to other research areas such as MPPT. Authors in [4-8, 15- 17] have proposed control strategies used for reactive power compensation from the inverter when the grid is in need of reactive power.

1.5.1 Reactive Power Control Methods in Inverters

1.5.1.1 Static Compensator

As demonstrated in [8] and [14], a static compensator (STATCOM) as shown in Figure 1.5 was designed to compensate reactive power in the grid. This has a disadvantage because of additional bulky device to the system and capacitors can increase the voltage of the system when there is not much load being absorbing power in the DGS. Reactive power compensation done without additional elements such as capacitors will be favorable.

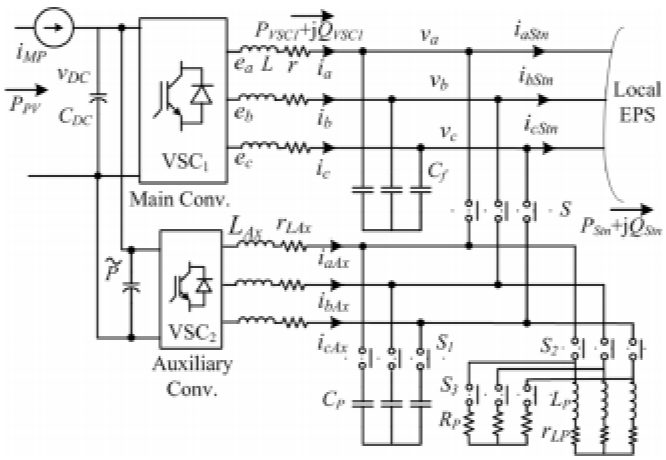

Figure 1.5 STATCOM with reactive power bank used for reactive power compensative in DGS [8]

Capacitors are the most common reactive power compensators, but the use in the inverter system design may require an additional converter, which makes the system expensive and bulky. Other works published in the area of power control of the inverters focus on using the Stationary Reference frame (*αβ*) and synchronous rotating reference frame (*d-q*) controllers in 3-phase inverters systems without the use of additional devices to the system. But the works in 3-phase systems can be applied to single phase systems with additional modifications, which will be discussed in Chapter 3. The single phase controller converts the grid current from the inverter and its emulated orthogonal component from *αβ* to DC quantities *dq* using *αβ* - *dq* transform. This controller will be capable of injecting active and reactive power into the grid or load. This controller can also be applied to wind turbine converters.

1.5.1.2 Stationary Reference Frame Controller

In this controller, an AC variable such as current form the grid is transformed into a two time-varying quantities. The grid current from the inverter is transformed into stationary reference frame, $\alpha\beta$ quantities, using a transformation technique. Then the transformed quantities are compared with their references. The current reference quantities are generated by active and reactive power controllers, then transformed into $\alpha\beta$ quantities. The reference $\alpha\beta$ quantitates are compared with the measured $\alpha\beta$ current from the grid and the errors in each quantities are fed to proportional-resonant (PR) regulators to generate a reference voltage for the inverter [7]. A block diagram of a stationary reference frame controller is shown in Figure 1.6. Since the transformed variables are time varying, it is not suitable to work with this kind of controller.

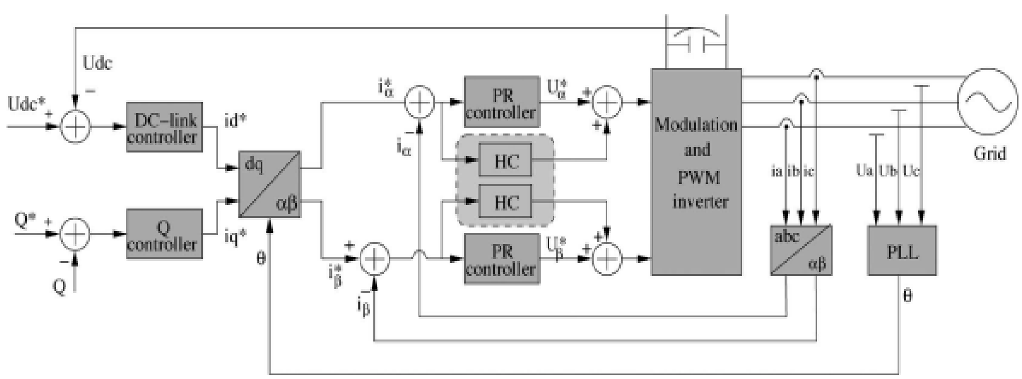

Figure 1.6 General structure for stationary reference frame control for three phase inverters [7]

1.5.1.3 Synchronous Rotating Frame Controller

Synchronous rotating frame also called Direct-Quadrature (DQ) frame control uses a reference frame transformation module, to transform the grid current and voltage waveforms into a reference frame that rotates synchronously with the grid voltage. This control method changes AC variables to DC values, which makes the controlling of a time varying parameter easier to achieve [7]. A schematic of the *dq* control is represented in Figure 1.7. The references for the direct and quadrature current are compared with the measured grid values. The *dq* control structure is normally associated with proportional–integral (PI) regulators since they have a satisfactory behavior when regulating dc variables. The few literature using this control method assume a zero magnitude for quadrature reference current making the inverter to control only active power, but with an additional grid voltage control support, the reactive power can be controlled by injecting a quadrature reference current to the control system which yields an improved grid voltage profile with reactive power support.

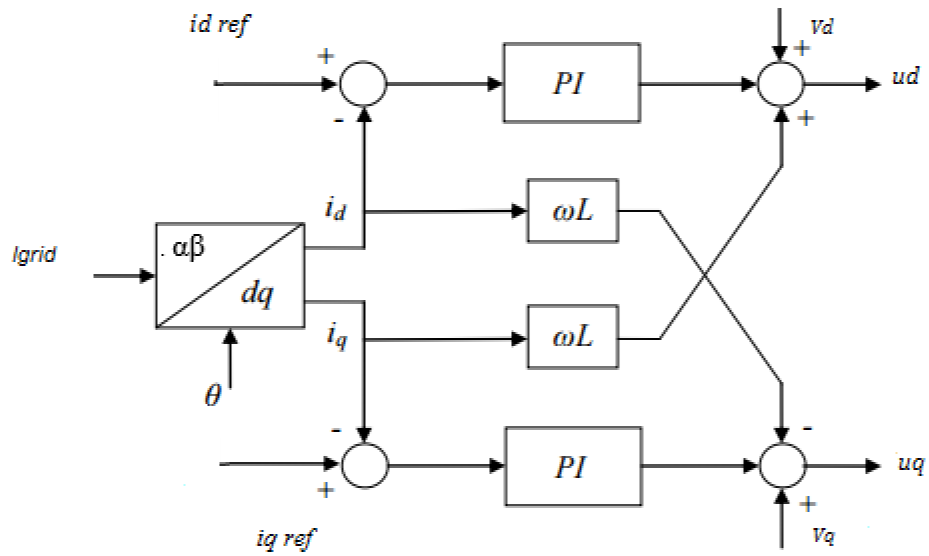

Figure 1.7 Control structure for synchronous rotating frame control for single phase inverters

This thesis proposes a DQ controller which extracts both the parallel component and the orthogonal component from the grid voltage while filtering out grid distortions. The control method provides the inverter the capability of controlling the reactive power generation without the use of additional devices such as STATCOM.

1.6 Research Background and Motivation

The use of RES in generating power contributes an important role to the environment and cost of generation. The reducing cost of PVs has caused a dramatic increase in the residential PV installation. Residential PV systems utilize single phase inverters because single phase power system is the kind of AC system being utilized in a residence. It can be seen in Figure 1.8 that the residential PV installations have increased over the last decade. Compared to the non-residential installations, there are more residential PVs installed being installed in recent years, which is a motive behind this research for single phase inverters.

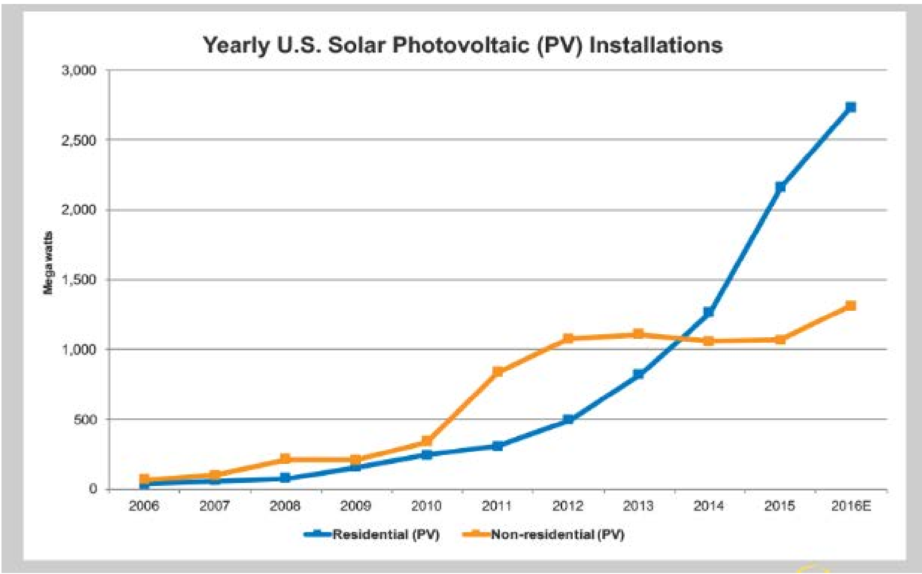

Figure 1.8 Residential and Non-residential PV installation per Megawatts DC

The high reactive power demand of the distributed loads and line reactance are the major factors responsible for stretching the local area voltages all the way up to the specified limits. The US has a 5% upper and lower tolerance from the nominal grid voltage. If proper compensating elements are not in place, they cause voltage to fluctuate higher or lower than normal which leads to the deterioration of the quality of electricity and causing considerable adverse impact on the critical loads. Grid connected PV inverters should be able to extract maximum power from the PV and supply to the utility grid. Transformers, transmission lines and motors require reactive power.

For example, in August 2003, there was a blackout in Ohio caused by insufficient reactive power support from the generation plants [18]. This problem can be avoided by having an inverter in a DGS supply more reactive power to the grid in conditions where the load connected to the grid needs more reactive power than the grid can supply. Currently, most inverters used in a DGS only provides active power control loop and only supply active power to the power grid. It will be beneficial that the single phase grid connected inverters are able to provide reactive power support so that the voltage of the grid doesn't fluctuate below the nominal value.

Nowadays, the increase in demand of solar and PV makes it important to research and develop better power converters to get a reliable and efficient power conversion system. With reactive power demand from the feeder side, high penetration PV sources may lead to extensive voltage variation because of the conventional methods of operation of inverters and variation in the solar radiation levels have reported that reverse power flow over a feeder is a major cause of voltage rise in power grid during high solar[9,15,16]. Reactive power is a major influencing parameter in AC systems due to its impact on the voltage. The behavior of the system will be improved substantially due to better controllability of reactive power compensation. The increased reactive power capacity can be utilized for mitigating under and over voltages. Almost all equipment used in a power system has for a rated voltage. Deviations from the rated voltage level can lead to reduced performance or could damage the electrical power device. Reactive power demand of local loads can be fed by the PV station, relieving the power system from reactive power support [8]. One of the motives behind the single phase inverter reactive power support is because of its use in small scale residential applications and its cheap implementation compared to three phase inverters. Also residential applications make use of single phase power and users are allowed to connect their own personal RES to the utility grid in order to save electricity cost.

Local reactive power being absorbed is generally compensated by placing capacitors in the generation system. Large consumers of non-linear loads use series and shunt capacitor configurations to minimize voltage variations. The placing of capacitors along different paths in a power system helps improve voltage and optimize power flow in the lines. However, capacitors are limited to generating reactive power. If the voltage rises, and there is no load to absorb the reactive power, the capacitor will contribute to the increase of voltage. In short circuit cases, capacitors can be hazardous because they produce high over-voltages. For this reason, a power converter tied to the grid should be designed for the flow of reactive power when needed in DGS system.

By controlling the voltages in the grid, reactive power can be compensated. The reactive power flow in the system is dependent on the voltage and vice versa. By controlling the voltage, the reactive power can be controlled and the losses caused by reactive power flows can be minimized.

1.7 Thesis Layout

The contents of this thesis are organized in the following manner:

Chapter 2 discusses about the single phase grid tie inverter system and the selection of its switching techniques, the DC link capacitor and output filter design at the inverter.

Chapter 3 focuses on the control methods of the inverter and its control system, the grid synchronization technique and the application of single phase system in the rotating synchronous frame.

Chapter 4 shows the Simulink simulation results for the grid connected inverter and the reactive power control using current controller and the voltage controller.

Chapter 5 summarizes the thesis and future works that can be investigated.

CHAPTER 2 SINGLE PHASE GRID-TIE PV SYSTEMS

2.1 Photovoltaic (PV) Cell

A PV cell can be modelled by five elements. It consists of a current source in parallel with a diode and shunt resistance in series with a series resistance. PV cells have non-linear properties as they are formed from a p-n junction. In order to understand the electronic behavior of the PV cell, it is useful to create an equivalent circuit based on electrical components whose behaviors are well known. Such an equivalent circuit is shown Figure 2.1. The light generated current source I_L represents charge carrier generation in the semiconductor caused by incident sun radiation on the surface of the PV. The shunt diode represents recombination of these charge carriers at a high forward-bias voltage. The shunt resistor R_{sh} allows high-current paths through the semiconductor.

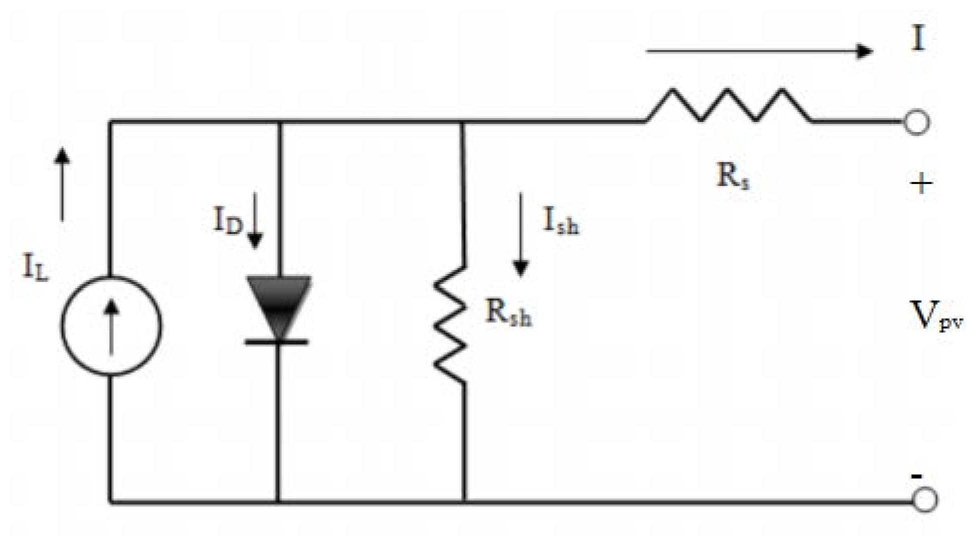

Figure 2.1 PV Electrical model of a PV cell

From Figure 2.1, the PV output current I is represented by the equation given by

$$I = I_L - I_D - I_{sh}\,, \tag{2.1}$$

and the diode voltage, V_D from Figure 2.1 is given by

$$V_D = V_{pv} + R_{sh}.I\,. \tag{2.2}$$

The equation for the diode current is

$$I_D = I_{sat}\,[exp(\frac{V_D}{nV_T}) - 1]\,, \tag{2.3}$$

where V_T is given by

$$V_T = \frac{KT}{q} \cdot nI \cdot Ncell\,. \tag{2.4}$$

The variables used in equation 2.3 and 2.4 are defined as:

I_D diode current (A),
V_D diode voltage (V),
I_{sat} diode saturation current (A),
nI diode ideality factor,
k is the Boltzman constant = 1.3806×10^{-23} J.K^{-1},
q is the electron charge C,
T is the cell temperature (K),
$Ncell$ is number of cells connected in series in a module.

The current through the shunt resistance, I_{SH} is

$$I_{SH} = \frac{V_{PV} + R_S \cdot I}{R_{SH}}\,. \tag{2.5}$$

Therefore the current I from the pv output is

$$I = I_L - I_{sat}\left(e^{\frac{V_{PV}+R_S \cdot I}{nV_T}} - 1\right) - \frac{V_{PV}+R_S \cdot I}{R_{SH}}\,. \tag{2.6}$$

The PV cell is characterized by its maximum open circuit voltage (Voc) at zero output current and its short circuit current (Isc) at zero output voltage. The cell generates no power in short-circuit or open-circuit. The cell delivers maximum power $Pmax$ when operating at a point on the characteristic where the $I.V$ product has a maximum value. The voltage-current (*IV*) and Power-voltage (*V vs. P*) curves of two different percentage of sun irradiation are shown in Figure 2.2, and the position of the maximum power point is at the knee of the *I-V* curve.

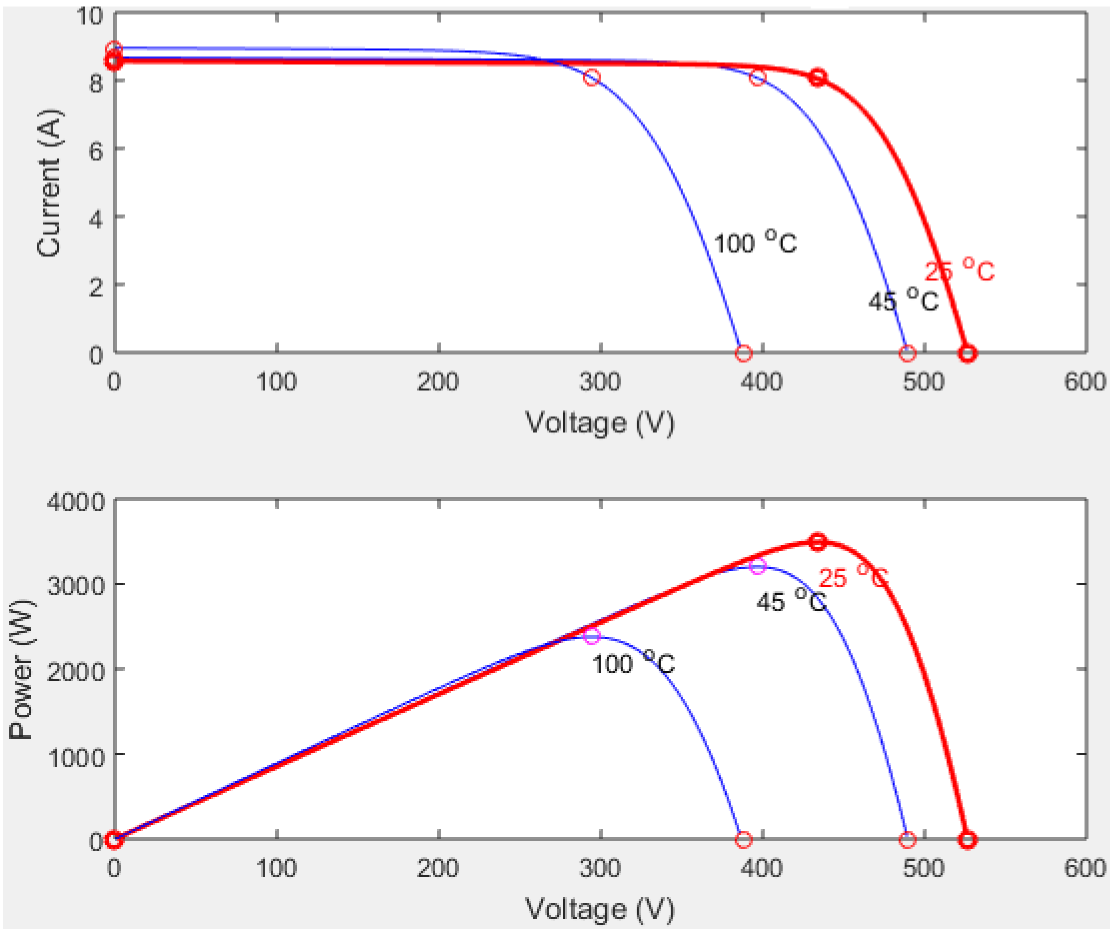

Figure 2.2 IV cure and Power-Voltage curve of PV cell

2.2 Grid Connected PV Inverter System

Grid connected PV systems are designed to operate in parallel with the utility grid. The main component in a grid connected PV system is the inverter. It converts direct current (DC) into AC power consistent with the voltage and power of the grid. Nowadays DGS use current regulated PWM voltage source inverters (VSI) for synchronizing the grid with the DG source in order to support grid stability [15].

2.2.1 PV Single Stage Converter

The first generation of the grid connected PV system was implemented by connecting an array of PV modules to the grid through a DC/AC inverter as shown in Figure 2.3. The PV modules are connected in series know as PV strings to provide sufficient output voltage. The PV strings are then connected in parallel through string diodes in order to achieve high power production. In this configuration, the inverter is subjected to handle, maximum power point tracking (MPPT), grid current control and voltage amplification if necessary. This thesis utilizes the single stage converter topology.

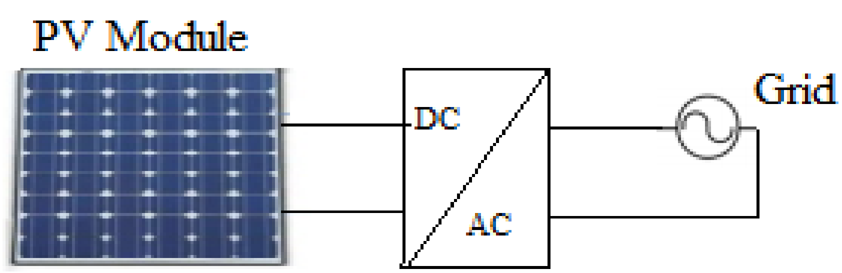

Figure 2.3 Single Stage PV converter connected to the grid

2.2.2 PV Two- Stage Converter

In order to improve the power capabilities and design, DC/DC converters, which perform MPPT for each PV string can be connected in the middle between the PV modules and the DC/AC inverter. The system shown has its point of common coupling at the AC terminal. As shown in Figure 2.4, the two stage converter has a DC/DC converter can be used for stepping up or stepping down the output voltage from the PV output if necessary based on the application of the system. The output from the DC/DC converter in this configuration can be either a low ripple DC voltage, or a modulated current that follows a rectified sine wave.

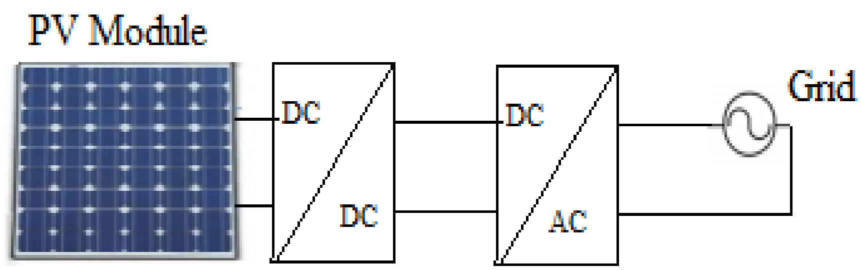

Figure 2.4 Two stage PV converter connected to the grid

2.3 Grid tie Inverter System

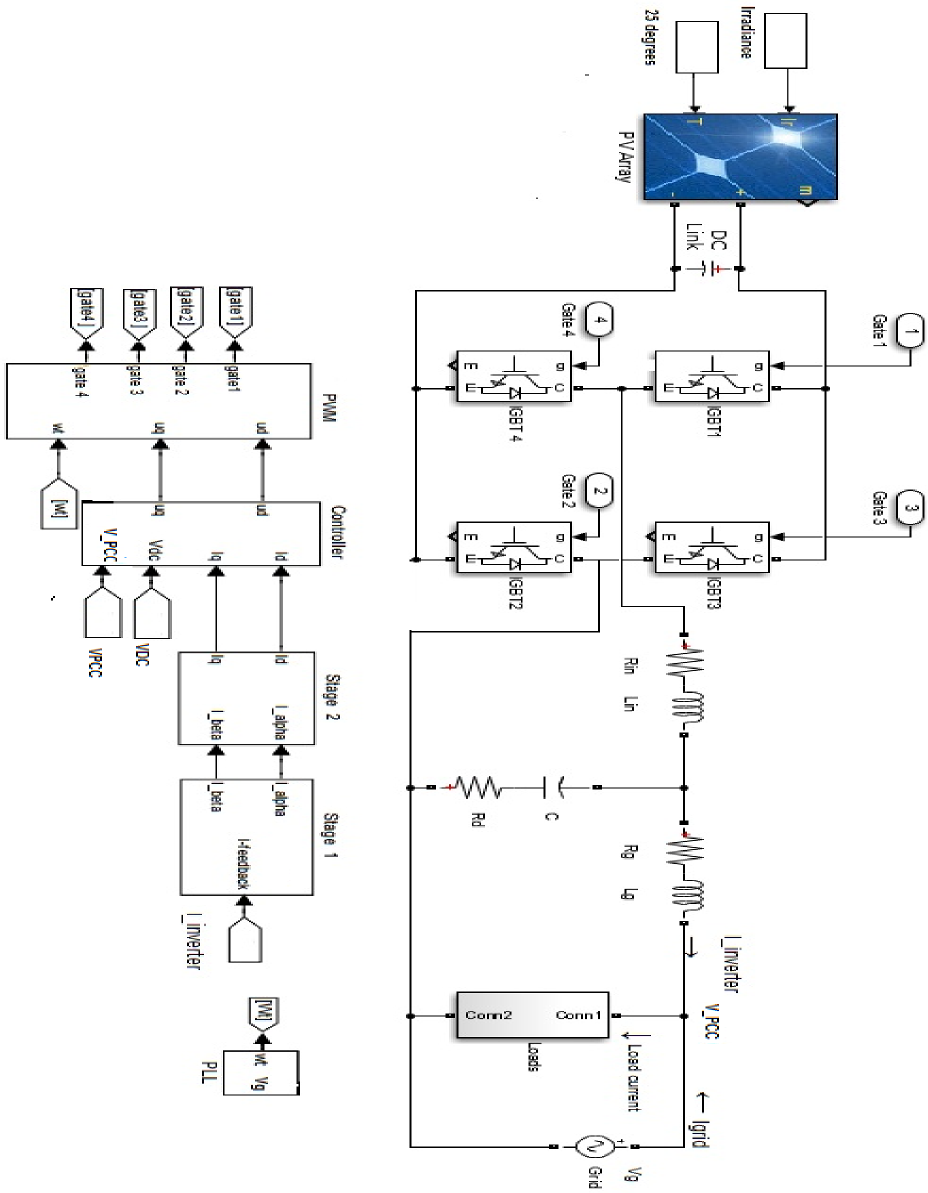

Figure 2.5 Grid tie Inverter with LCL Filter

The grid tie inverter system shown in Figure 2.5 consists of a PV being the source of power, the output power of the PV is fed to an inverter through a DC link capacitor, and then AC power from the inverter is fed to the grid. The inverter is connected to the grid through an LCL filter. With an input voltage of V_{dc} from to the inverter from the PV output, the inverter converts the DC voltage input to an AC output. From the system in Figure 2.5, the IGBT'S acts as a switch and the output voltage can be either +V_{dc}, -V_{dc}, or zero, depending on which IGBTS are ON. The control of the IGBT gate can be done with different method discussed later in the chapter. The output voltage transition of the inverter is shown in table 2.1

Table 2.1 Inverter voltage output coordination

IGBT ON	**Inverter Output voltage**
IGBT 1 and IGBT 2	**+Vdc**
IGBT 3 and IGBT 4	**-Vdc**
IGBT 1 and IGBT 3	**OFF**
IGBT 2 and IGBT 4	**OFF**

2.4 Inverter DC link Capacitor

Voltage source converters can work either as inverter or rectifier. The DC voltage from the PV source is connected to the inverter through a capacitor to a DC link capacitor. It is necessary to include a DC-link capacitor between the PV system front-end source and the inverter. The capacitor is normally added to the input of the DC/AC converter to limit ripple on the output DC-link voltage, and to support the load. The larger the capacitor, the lower the output voltage ripple will be. However the system transient response will be slower and the capacitor cost will increase. The inverter controller is designed to regulate the power supplied by the inverter in order to ensure the DC-link voltage does not drop below the minimum required for the inverter to be able to supply the peak output voltage

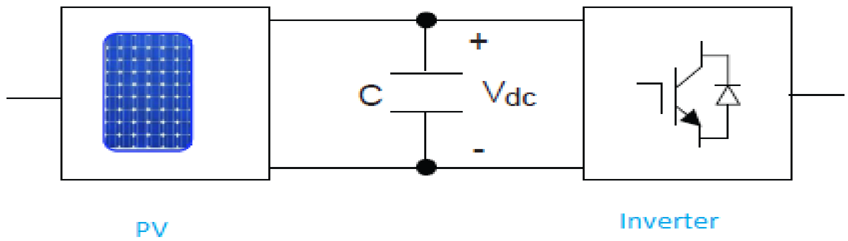

Figure 2.6 DC link capacitor between the PV and Inverter

With a specified output DC voltage ripple limit, $V_{dc,maxripple}$, the grid frequency ω_g and a power input to the inverter, *Pdc,* the DC link capacitor, C can be calculated as

$$C = \frac{P_{dc}}{2\omega_g \cdot V_{dc} \cdot V_{dc,maxripple}} . \quad (2.7)$$

2.5 Control Strategies of Grid tie inverters

The common techniques for output control for a single phase VSI are the predictive, hysteresis band PWM, and sinusoidal pulse width modulation control (SPWM).

Predictive control uses a calculation based on the possible values of voltage and then switching state that makes the nearest predictive current to the selected reference current. In [19], this kind of control strategy is summarized as a control that can be considered as any algorithm that uses a model of the system to predict its future behavior and selects the most appropriate control action based on a criterion. It is produces fast dynamic response, easy inclusion of nonlinearities and constraints on the system. In [13], the authors proposed a robust predictive current control for the grid connected inverter with LCL filter.

Hysteresis band current controller uses a variable switching frequency control method in which carrier frequency varies with the output waveform to generate an output current at the inverter. This control method has good accuracy, faster response and unconditioned stability but could have unwanted features such as uneven switching frequency that causes noise and difficult designs for input filters [14]. It is composed of a hysteresis around the inverter reference current and assigns the switching pattern of the grid inverter. The rate of change of the current vary the switching frequency, which is not constant throughout the switching operation. As shown in Figure 2.7, the output voltage of the inverter is regulated by comparing the upper and lower limit of the reference current with the output current. The voltage is increased, when the output current is lower than the reference lower limit and decreased when the output current is higher than the upper limit reference current. In [15], it can be seen that the dynamic response of the hysteresis current controller is better than the adaptive hysteresis current controller. The disadvantage of this method is that the switching frequency mainly depends on the load.

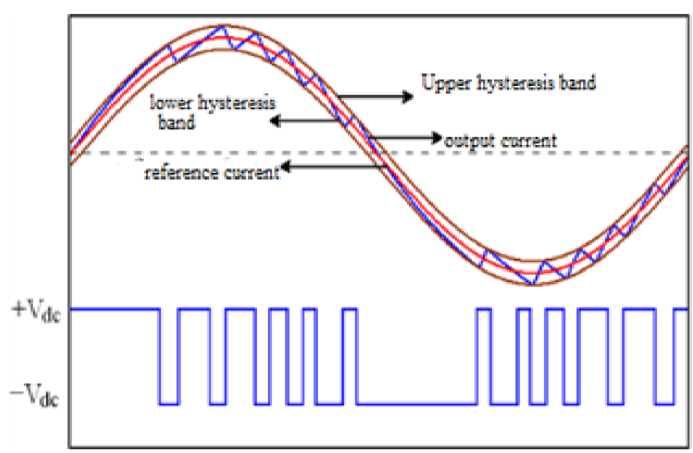

Figure 2.7 Hysteresis PWM

In SPWM, the power switching control are usually implemented with semiconductor devices. A reference signal is compared with a carrier wave signal that controls the switching frequency. The ratio of the amplitude of the modulating wave, $V_{m,refrence}$ to the amplitude of the carrier wave $V_{m,carrier}$ is defined as the amplitude modulation ratio m_a which is given as

$$m_a = V_{m,refrence}/V_{m,carrier} \ . \tag{2.8}$$

The relationship of the fundamental frequency output of the voltage is proportional to m_a, the relationship is given as

$$V_{1,output} = m_a \cdot V_{dc} \ . \tag{2.9}$$

However, during the ON/OFF switching, little power is lost due to the voltage and current being non-zero at transition between the states. The power lost is small compared to the output power delivered by the inverter. Devices such as MOSFETs or insulated gate bipolar transistors (IGBTs) are suitable for higher efficiency and high power applications when compared to other switches. The main goal of the PWM is to produce an average output equivalent to its reference signal.

SPWM is a form of PWM switching control is easy to implement. It uses proportional-Integral (PI) controller to in a feedback loop to regulate the output current of the inverter. Both the inverter output and load current are transformed into the DQ frame, which are input to a PI controller to eliminate the error between them. The output PI controller output is then used to command the PWM generator by changing the amplitude and phase of the command signal [9, 16]. The thesis uses the SPWM PI control technique to implement the current controller.

2.6 Switching Circuit

A full H-bridge inverter with SPWM switching technique was used for the switching technique for the inverter design in this thesis as shown in Figure 2.5. The inverter uses IGBTs as the switching devices. The two PWM switching scheme are unipolar and bipolar switching. The output of a unipolar inverter is shown in Figure 2.8.

In this thesis, bipolar switching technique was used because of less leakage current from the inverter output. The harmonics in the bridge output begin around m_f, where m_f is the modulation ratio of the carrier frequency to the reference signal.

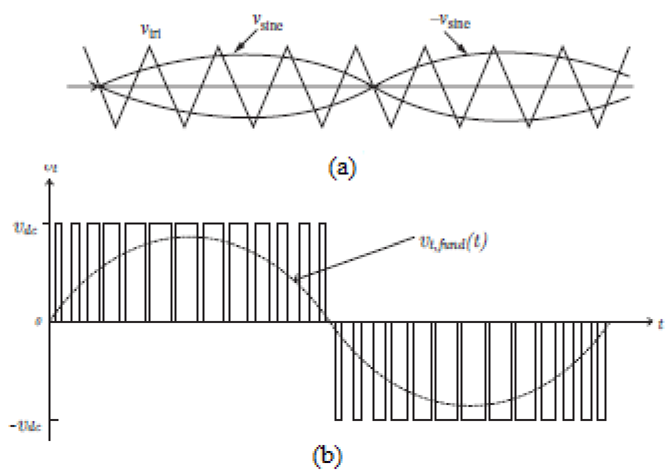

Figure 2.8 Unipolar switching

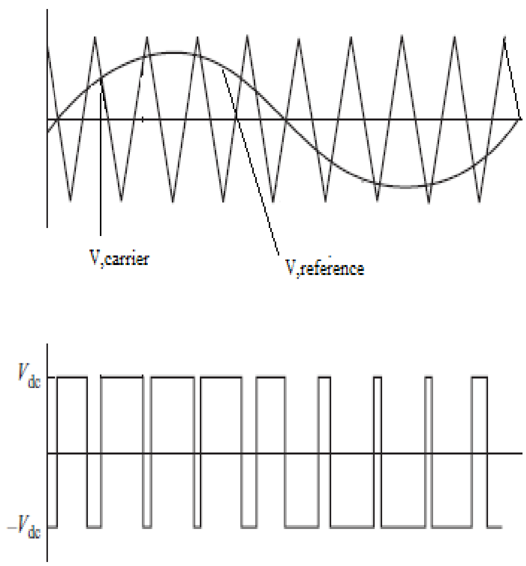

Figure 2.9 Bipolar switching

The frequency of the carrier wave leads to the inverter switching frequency with amplitude $V_{carrier}$ and switching frequency f_s. The reference signal $V_{reference}$ is at a frequency of the desired output of the inverter. Using a bipolar PWM output technique, the switch S1 and S2 are on when $V_{reference} > V_{carrier}$, S3 and S4 are on when $V_{reference} < V_{carrier}$. The output of a bipolar inverter is shown in Figure 2.9. The PWM output can be filtered to obtain a sinusoidal AC output.

2.7 Harmonics

Many electrical system output quality is based on the harmonic components in the output voltage and current. The harmonics could be from a load or a source which are caused by presence of non-linear loads or non-sinusoidal voltage or current sources. Harmonics can be prevented by using filters from entering the system. Assuming no, DC component in the output of the inverter, the quality of a non-sinusoidal wave can be expressed in terms of total harmonic distortion (THD) [20].

2.8 Output Filter

An inverter causes high-order harmonics which cause losses in the system and instability to other devices connected to it. Due to the bipolar switching scheme, the harmonic on the output voltage of the inverter appeared near the m_f. The output current of the grid side inverter has ripple due to the effect of switching in the inverter. A filter is needed in order to obtain a cleaner output with lower total harmonic distortion. A Filter can be used to reduce the harmonics near the switching frequency for the inverter.

2.8.1 LCL Filter

An LCL filter is needed to filter the PWM output from the inverter and to attenuate the high frequency components in the output signal. From Figure 2.5, the impedance of the grid side Z_g, the capacitor Z_c and the input side impedance Z_i of the filter are derived in Equations 2.10, 2.11 and 2.12 respectively.

$$Z_g = sL_g + R_g \text{ ,} \tag{2.10}$$

$$Z_c = 1/sC \text{ , and} \tag{2.11}$$

$$Z_i = sL_{in} + R_{in} \text{ .} \tag{2.12}$$

Then the input current I_{in}, the grid voltage V_g, the input Voltage to the LCL filter V_{in} are given in Equation 2.13, 2.14 and 2.15 as

$$I_{in} = I_g + I_c \text{ ,} \tag{2.13}$$

$$V_g = V_c - I_g \cdot Z_g, \text{ and} \tag{2.14}$$

$$V_{in} = V_c + I_{in} \cdot Z_{in} \text{ .} \tag{2.15}$$

At high frequency, the voltage at the grid is considered short circuit and Equation 2.15 can be rewritten as

$$V_c - I_g \cdot Z_g = 0 \ , \tag{2.16}$$

$$I_c \cdot Z_c = I_g \cdot Z_g, \text{ and} \tag{2.17}$$

$$V_{in} = Z_{in} \left(I_{in} + I_g \cdot Z_g / Zc \right) + I_g \cdot Z_g) \ . \tag{2.18}$$

In order to avoid resonance effect due to the capacitor and inductor in the LCL filter, a damping resistor is introduced. The damping resistor is added in series with the capacitor. Adding a damping resistor attenuates the current amplification. The transfer function of the filter is given in equation 2.13 as

$$H(s) = \frac{1 + sR_dC}{s^3C(L_{in}L_g) + s^2\,C(R_dL_{in} + R_dL_g + R_gL_{in} + R_{in}L_g) + s(L_{in} + L_g + CR_gR_d) + CR_gR_{in} + CR_{in}R_d + R_{in} + R_g} \ . \tag{2.13}$$

2.9 Grid Synchronization and Current Control

The current injected from the inverter has to be synchronized with the grid which requires a synchronization algorithm. The algorithm should provide the phase of the grid voltage which is used to synchronize the control variables such as the D-Q transform. Different methods to output the phase angle have been presented and developed in literature [13]. The three commonly used methods are zero-crossing method, grid voltage filtering and the phase locked loop (PLL) technique.

The most common and efficient technique used nowadays is the PLL technique, which has been used in the thesis. PLLs are frequently used in three phase grid tie inverters, but can also be used in the single phase inverters. Recently, synchronous frame PLLs are commonly used in grid tie inverters. This type of PLL is implemented in the *dq* synchronous rotating frame. The PLL converts the grid voltage into its orthogonal components by using $\alpha\beta \rightarrow dq$ transform. In [15], a PI regulator, is used to control either the real component of the grid voltage V_d or the imaginary component of the grid voltage V_q to be zero so that the phase of the d or q component can be locked.

CHAPTER 3 PROPOSED CONTROL FOR SINGLE PHASE GRID-TIED INVERTERS

This describes each modules used in controlling the inverter, such as the PLL, the current controller and the voltage controller used for reactive power support.

3.1 Phase Locked Loop

An important part of grid connected converters is the synchronization module. A phase locked loop (PLL) in the synchronous rotating frame has been used in this thesis to connect the distributed system with the grid, the DGS system has to be synchronized with the grid voltage. The inverter quantities such as voltage, phase and frequency should track the grid quantities continuously to maintain a relationship between the systems. Not maintaining the synchronization between the inverter and the grid may cause large circulating currents which may damage the inverter and its associated devices. The main goal of the PLL is to output the phase and frequency of the grid parameters. A block diagram of a PLL is shown in Figure 3.1.

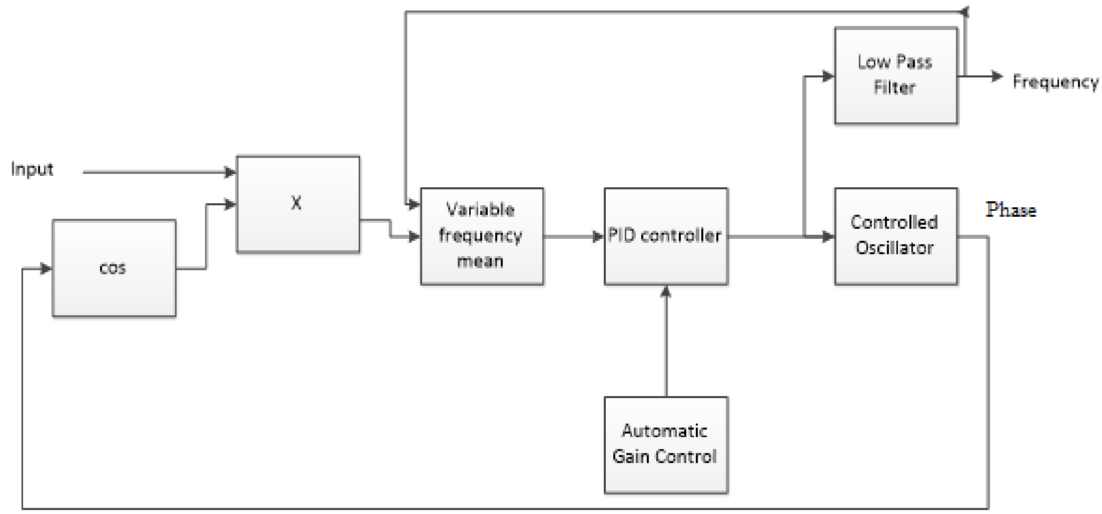

Figure 3.1 PLL Block Diagram

For the SPWM, the reference voltage needs to be in the form of a space-vector, specified with a magnitude and a phase. The magnitude information comes from the control algorithm, but the phase information should be generated from the grid voltage using a PLL. A PLL is used to obtain the phase information for the reference frame transformation blocks.

The PLL block is closed-loop control system, which tracks the frequency and phase of a sinusoidal signal by using an internal frequency oscillator. The control system adjusts the internal oscillator frequency to keep the phase difference to 0. The input signal is mixed with an internal oscillator signal. The DC component of the mixed signal is extracted with a variable frequency mean value. A Proportional-Integral-Derivative (PID) controller then keeps the phase difference to 0 by acting on a controlled oscillator. The PID output, corresponding to the angular velocity, is filtered and converted to the frequency which is used by the mean value. When the system does not have any error the output signal of the oscillator is the natural frequency.

The synchronization algorithm is expected to gives the phase of the grid voltage vector which can be used to synchronize the grid parameters with the inverter. When the control algorithm gives out the d-axis and q-axis reference voltages for the inverter, the Pulse Width Modulator (PWM) should generate its signals such that the reference voltages are seen at the output of the inverter.

The goal is to obtain the phase angle from the grid voltage. To achieve this, dq reference frame is employed. The grid voltage, V_{grid} is transformed to dq-frame. From dq the frame, only $V_{grid,q}$ is taken into consideration, and , $V_{grid,q}{}^{*} = 0$ is the voltage reference. After comparing if the error between the grid voltage and its reference. If zero, then the dq frame is rotating at the same frequency. The output of the PI controller is the frequency which is compared with the grid frequency.

3.2 Single Phase D-Q Transform

DQ Rotating Frame transformation is mostly used in three phase inverter analysis and control design. It is a form of transformation between stationary and rotating frames. Parameters such as current or voltage of a three phase converter are transformed into $\alpha\beta$ frame by the Clarke transformation which is a two-phase stationary coordinate. After transforming the 3-phase parameters into $\alpha\beta$ frame, a transformation from $\alpha\beta$ to DQ rotating frame is applied. The synchronous Rotating Frame (SRF), proposed by Park in 1929 [16]. The rotating frame has the same angular frequency as the fundamental frequency of the inverter and the result of the transformation is a DC quantity model of the three phase inverter. Since most three phase system are symmetrical, which means that the sum of the phase quantities is always zero. Thus, by transforming $\alpha\beta$ from the stationary frame to the synchronous rotating frame (*dq*) via Park transformation matrices, the *d*-*q* coordinates are arranged to rotate synchronously with the power line frequency. To create a DQ model at least two independent phases are required; thus the concept is most often applied to three phase but not to single phase converters due to limitation of only one available phase in the system. Considering the q-axis to be leading the d-axis by 90 degrees in three phase systems, the transformation from abc of three phase current signals I_a, I_b , I_c to *dq*0 signals I_d, I_q is given as

$$\begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} . \tag{3.1}$$

As mentioned above the phase angle information is obtained using PLLs. The inverse transformation of *dq*0 to abc is

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + 2\pi/3) & -\sin(\theta + 2\pi/3) & 1 \end{bmatrix}\begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} . \tag{3.2}$$

To apply this transform to single phase systems, the approach adopted in this research is a technique to create an imaginary orthogonal phase by generating a phase shift of 90 degrees with respect to the real phase [16,21,22]. The original phase delay of 1/4 of the line phase of system can create another component (β) orthogonal with the original signal (α). The imaginary orthogonal component is estimated from the real component, and it introduces the dynamics of a quarter cycle delay in the construction of it.

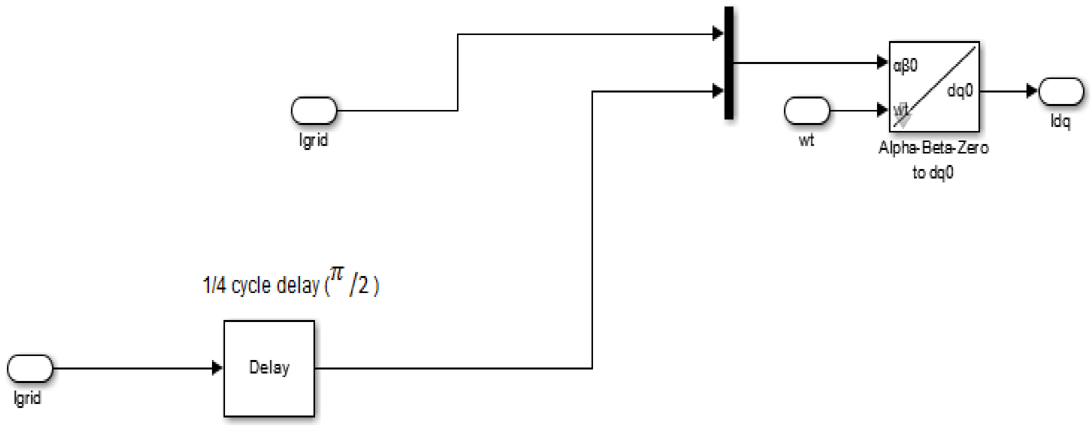

Figure 3.2 Block diagram of grid's inverter current *dq* transformation

The orthogonal stationary component (X_β) is created by an integer delay (k − n) of the real signal component. The sampling frequency fs = 4nf, where f is the inverter fundamental frequency and n is an integer equal to the quarter fundamental frequency sampling, T is the fundamental period, Ts is the sampling period, k is the sample number (at time $t = k\ Ts$, n = T⁄4Ts is the delay in generating a stationary orthogonal component).

The imaginary signal is a delayed version of the original signal X_α and given as

$$X_\beta = X_\alpha \text{ (k−n)}. \tag{3.3}$$

The real signal X_{real} and imaginary signal X_{imag} are given as

$$X_{real} = X\cos\,(wt + \phi) = X_\alpha \text{ and} \tag{3.4}$$

$$X_{imag} = X\cos\,(\omega t + \phi - \pi/2) = X_\beta\ . \tag{3.5}$$

The transformation matrix T is given as

$$T = \begin{bmatrix} \cos wt & \sin wt \\ -\sin wt & \cos wt \end{bmatrix}. \tag{3.6}$$

The transformed signal in the dq frame is

$$X_{dq} = \begin{bmatrix} X_d \\ X_q \end{bmatrix} = \begin{bmatrix} cos\ wt & sin\ wt \\ -\sin wt & cos\ wt \end{bmatrix} . \begin{bmatrix} X_{real} \\ X_{imag} \end{bmatrix}, \tag{3.7}$$

while inverse transform to the original signal is given as

$$X_{\alpha\beta} = \mathrm{T}^{-1} . X_{dq} = \begin{bmatrix} cos\ wt & -sin\ wt \\ \sin wt & cos\ wt \end{bmatrix} . \begin{bmatrix} X_{real} \\ X_{imag} \end{bmatrix} . \tag{3.8}$$

3.3 Single Phase Inverter Controller

In grid-tied inverters for renewable energy applications, inverters are designed to deliver regulated AC mains power from sources which may have a variable input voltage. Inverters must supply a fixed output voltage at a fixed frequency to the load. The DC-link voltage is set constant. This is effected by a PI controller and an error amplifier that compares the actual DC bus voltage to the reference value generated by the MPPT controller. The PI controller's output provides the active current component of the required current vector. The other component of the current vector represents the reactive current, and it can be fixed at a desired level for power factor or voltage control. A block diagram showing the current reference and the system is shown in Figure 3.3

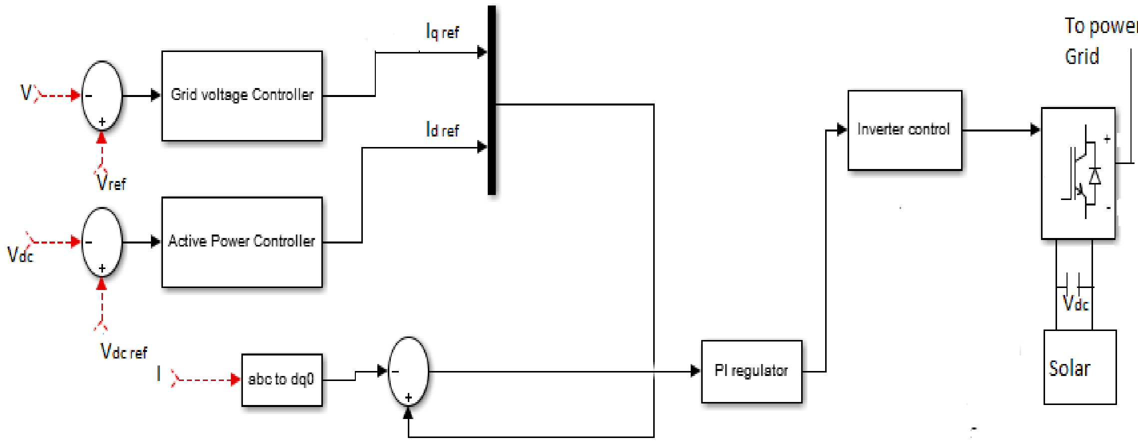

Figure 3.3 System and Inverter control Block diagram

The transformed *d-q* currents are compared with their reference values and the result is fed to the compensators to generate the feedback voltage references in the synchronous reference frame. The reference currents are calculated from the reference active and reactive power.

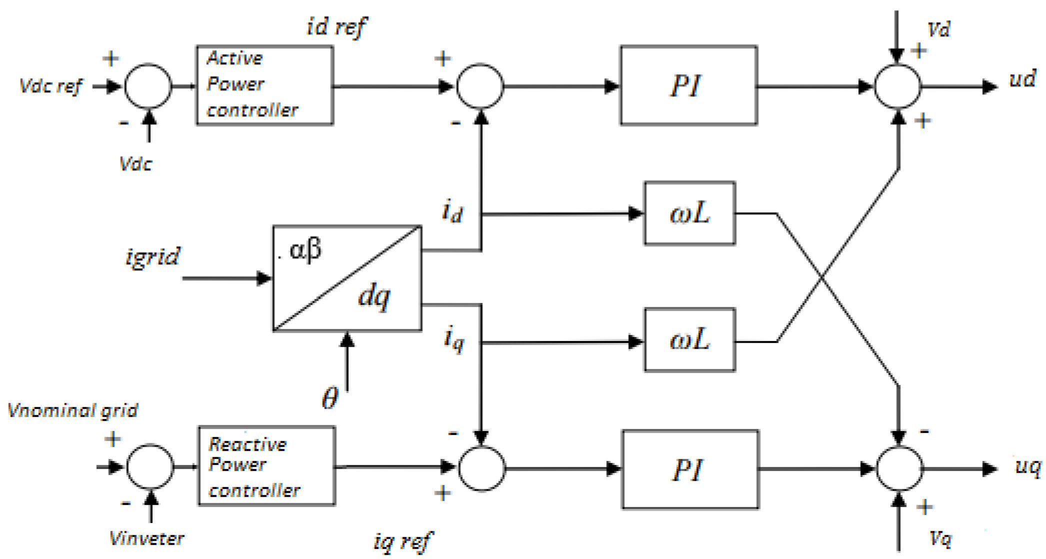

Figure 3.4 Current regulator for Inverter control

The active and reactive power consists of a combination of feed-forward signals and decoupling of the inductive cross coupling, the d-axis control voltage u_d does not only depends on the d axis current but also on the q axis current and vice versa, i.e, two first order systems, are interacting with each other resulting a cross coupling. These cross-coupling terms are due to the interaction between the inverter, filter circuit and PWM modulation scheme. The decoupling eliminates this coupling in the feedback controller between the d and q channels and yields two independent current controller channels after decoupling. The active power P and reactive power Q supplied by the inverter using the synchronous rotating frame *dq* quantities for the single phase inverter system are given as

$$P = u_d\, i_d + u_{qiq} \text{ and} \tag{3.9}$$

$$Q = u_d\, i_q - u_q\, i_d \,. \tag{3.10}$$

u_d and u_q are the inverter control voltages in d and q axes respectively, and will get updated upon a change in the reference quantities which in turn will change the active or reactive power delivered by the inverter. But since the quadrature component of the grid voltage, u_q is set to zero then equation 3.9 and 3.10 can be rewritten as

$$P = u_d\, i_d \text{ and} \tag{3.11}$$

$$Q = -u_d\, i_q \,. \tag{3.12}$$

The voltage references are added to the feedback reference signal to form the total d and q axis voltage references. In the SPWM technique, it is then necessary to transform from the *dq* rotating frame variables to the *αβ* stationary frame variables. By inverse transformation from rotating synchronous frame to the stationary frame, the modulator can then generate the switching device gate signals for the inverter. The relation between reactive power flow Q and q-axis component of injected current is i_q is given by

$$i_q = -\frac{Q}{Ud}. \tag{3.13}$$

The single-phase inverter model was derived using a synchronous rotating reference frame in which the controller should also operate in the *d-q* reference frame. The controller consists of two d and q channel, and each channel contains two feedback loops, outer voltage loop and inner current loop as well as PI compensators in each loop.

In order to obtain the values of the gains for the different PI controllers designed in this project, the Sisotool toolbox from Matlab was used. The output voltage and current are from the inverter and the two orthogonal stationary reference frames are generated. The transformation into the synchronous rotating reference frame is then applied. The controller tracks active current in channel d, and tracks reactive current in channel q, including the cross-coupling terms. This is followed by the last step in the controller procedure; to produce switching gate signals by transforming the controller output vector into a pulse width pattern in the SPWM block. To transform the inverter's grid current from the inverter signal to the DQ frame using the time delay method we can refer to the actual current signal as the real current, I_{real}, and the time delayed version the imaginary current, $I_{imaginary}$ where the real current corresponds to the α and the imaginary to the β. Equations for ideal sinusoidal versions of these currents are given in equations 3.14 and 3.15 as

$$I_{real} = Acos\,(wt + \phi) = I_\alpha \text{ and} \tag{3.14}$$

$$I_{imaginary} = Acos\,(wt + \phi - \frac{\pi}{2}) = I_\beta. \tag{3.15}$$

A transformation matrix for transforming to the *dq*-frame is given as

$$T = \begin{bmatrix} cos\,wt & sin\,wt \\ -\sin wt & cos\,wt \end{bmatrix}. \tag{3.16}$$

The dq transform of the current can be derived using the transformation matrix. The dq transform and $\alpha\beta$ transform of the currents are given in Equation 3.17 and 3.18 as

$$I_{dq} = \begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos wt & \sin wt \\ -\sin wt & \cos wt \end{bmatrix} . \begin{bmatrix} I_{real} \\ I_{imag} \end{bmatrix} \text{ and} \tag{3.17}$$

$$I_{\alpha\beta} = \mathrm{T}^{-1} . I_{dq} = \begin{bmatrix} \cos wt & -\sin wt \\ \sin wt & \cos wt \end{bmatrix} . \begin{bmatrix} I_{real} \\ I_{imag} \end{bmatrix} . \tag{3.18}$$

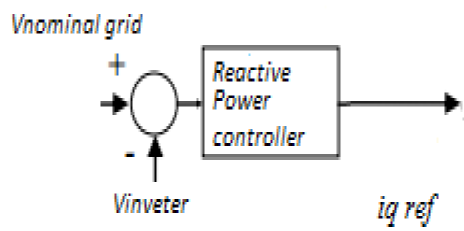

Figure 3.5 Grid voltage control for reactive power

To compensate for reactive power from the inverter using the controller in Figure 3.5, the output voltage of the inverter is sensed and compared to the nominal grid voltage (240Vrms), of which the error is applied to a voltage controller to generate the reactive power control signal for the inverter. To compensate for reactive power, quadrate reference current *iq ref* is generated and fed to the current controller for the inverter. The reactive power supported can be calculated using Equation 3.12. Consequently, the inverter provides dynamic reactive power compensation to the grid, thereby improving the grid's voltage stability. In this operation mode, the inverter output voltage may vary according to the instantaneous power demand. The power active or reactive power consumption of the consumer's loads will vary according to the voltage supplied by the grid. The reactive power control uses the nominal grid voltage to provide a quadrature current for regulating the voltage at the PCC as shown in Figure 3.4 .

CHAPTER 4 SIMULATION AND RESULTS

4.1 Simulation Overview

The simulations of the grid tie system was done in Simulink using the Simscape library as shown in Figure 4.1.

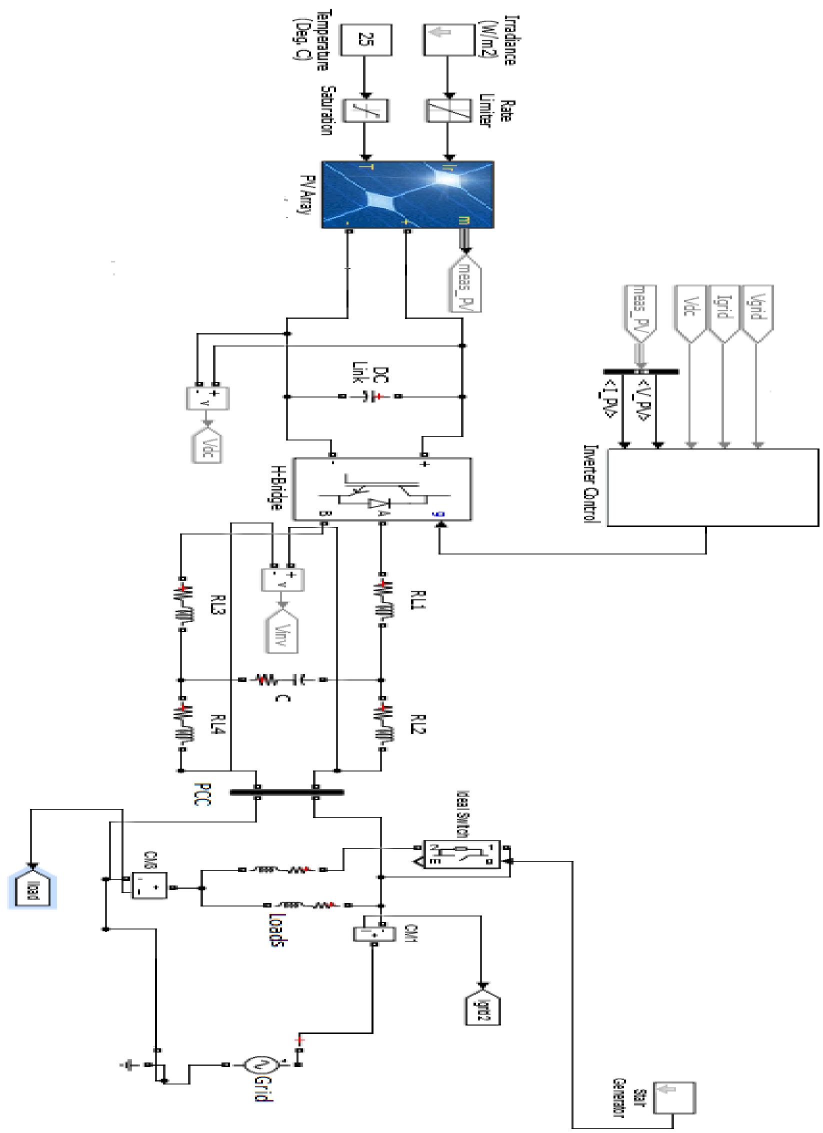

Figure 4.1 Simulated system in Simulink

The PV converter system is expected to supply both active and reactive power to supply to the grid. The specifications for each modules are given in table 4.1, 4.2 and 4.3

Table 4.1 System Configuration

Nominal grid voltage, V_g	240V rms
Grid frequency	60 Hz
Rated inverter current, I	8.5 A rms
Switching frequency, fsw	4 kHz
DC-link voltage	435V
Rated Inverter power	3.5 kVA
Percentage DC-link ripple	5 %

Table 4.2 LCL Filter parameters

Lin(mH)	Lg (mH)	C (uF)	Rg(Ohms)	Rd(Ohms)	Rin(ohms)
2.2	0.022	7.5	0.008	1.5	0.008

.

Table 4.3 Inverter Controller gains

PI regulator gain for active power control	[kp ki]= [13 205]
PI regulator gain for reactive power control	[kp ki]=[35 550]
PI regulator gain for current regulator	[kp ki]= [0.17 6.4]

Allowing of a ripple of 5 percent yield, the DC link capacitor C, at the inverter input can be calculated using equation 2.4 as

C = 3.5 kW /2(377 rad/s). (430*21.5) = 502.08 μF.

4.2 PV Module

The outputs of the PV system are plotted in Figure 4.2-4.4. From Figure 4.2, it can be seen that the PV output voltage tracks its reference voltage. At 0.4s, the irradiance of the PV was changed to 1000W/m^2 from 300W/m^2. The mean of the PV output voltage was plotted because the output voltage of the PV has ripple and it was minimized by the capacitor used for the DC link voltage. The ripple in the PV output voltage was less than 3.5 percent of its mean value.

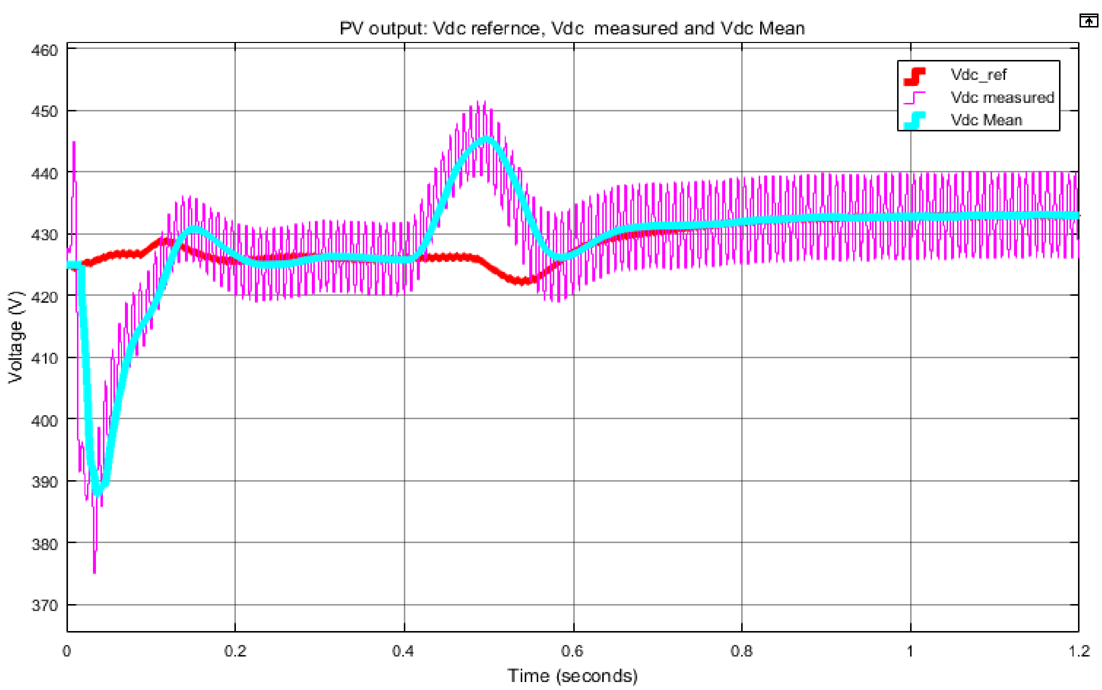

Figure 4.2 Measured and reference output voltage of the PV

In Figure 4.3, the current flowing from the PV output and current flowing through the PV diode current can be seen. With an irradiance of 300W/m^2 till 0.4s and 1000W/m^2, the current through the PV ramps up from 2.2A to 8 A. It can be deduced from the plot that the PV diode current is a percentage of the PV output current.

From Figure 4.4, the output power of the PV was plotted, with irradiance from 300W/m^2 to 1000W/m^2, the PV average power was measured and can be concluded that the PV voltage and current are proportional to its output power. The PV output current is proportional to the irradiance. From the results, the PV output power is directly proportional to the irradiance while the power is indirectly related to the temperature of the PV.

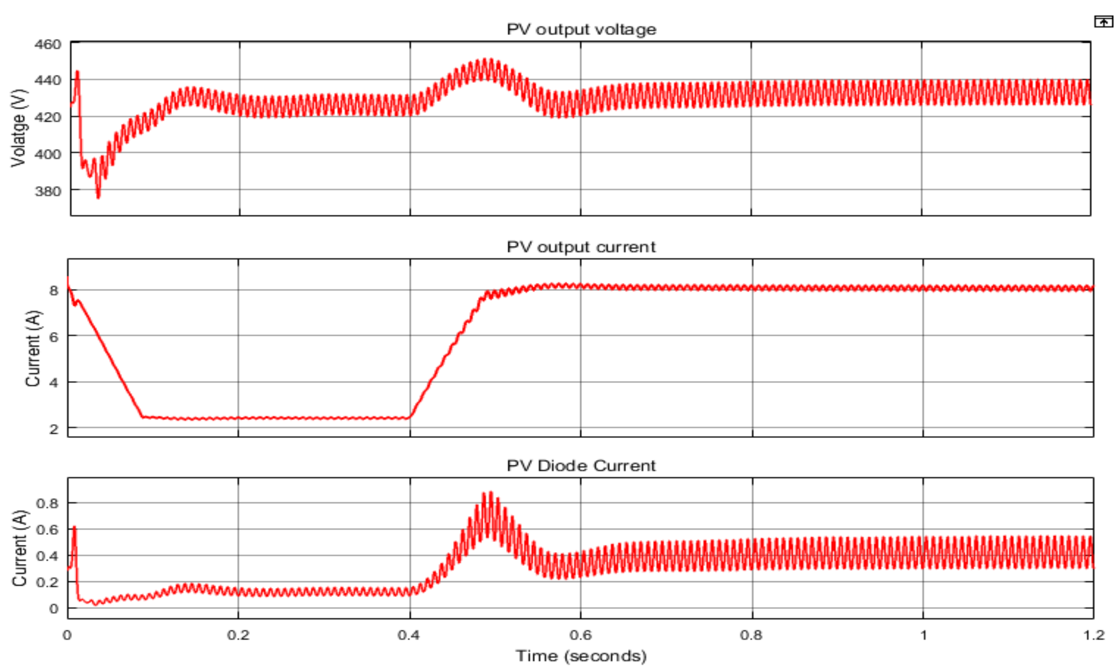

Figure 4.3 PV output voltage, PV current and PV diode current

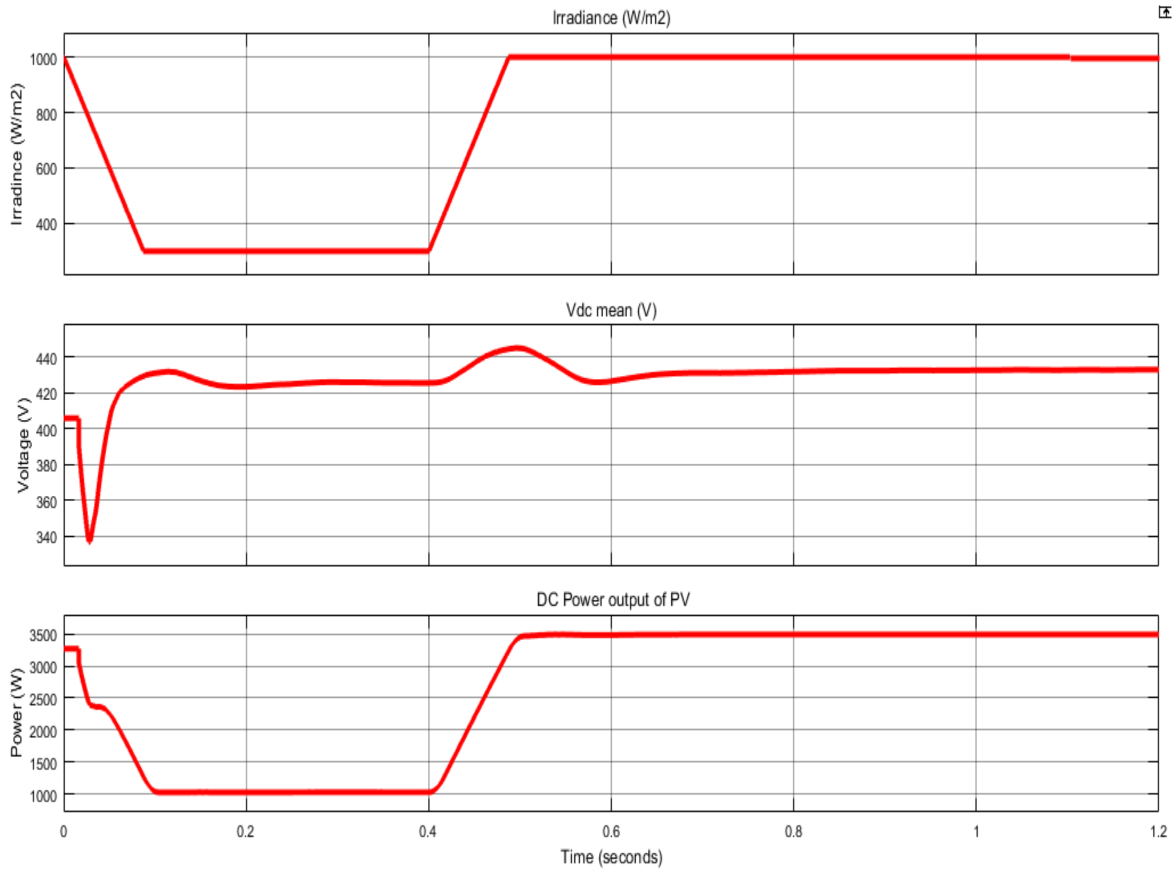

Figure 4.4 Irradiance of PV from changing from 30 to 100 percent of 1000 W/m^2 at 0.4s, PV output power

4.3 Inverter System

The output voltage of the inverter was filtered through the LCL filter, the filtered output voltage was plotted in Figure 4.5. The plot shows that the voltage is sinusoidal with no harmonics or noise components in the signal. The quadrature and direct signal components of the voltage at the point of common coupling were plotted in per unit in Figure 4.6. The quadrature component is zero as expected from the design of the system where it was used as a reference in the *dq* frame for the PLL. And a magnitude of 1 for V_d corresponds to the output voltage of 240Vrms.

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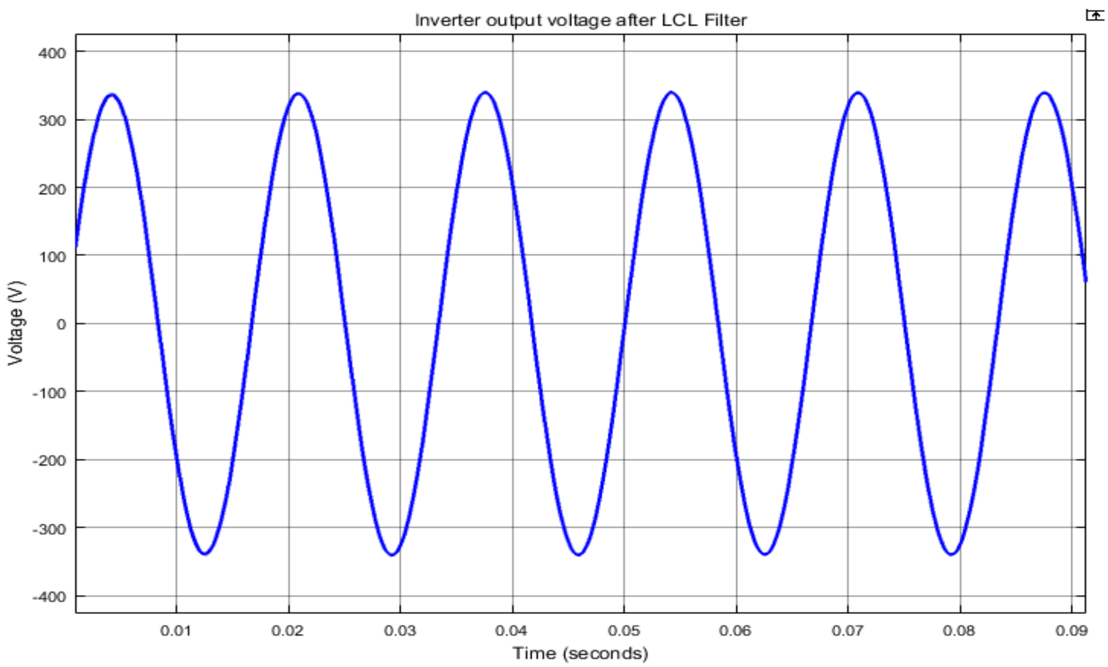

Figure 4.5 Inverter output voltage after LCL filter

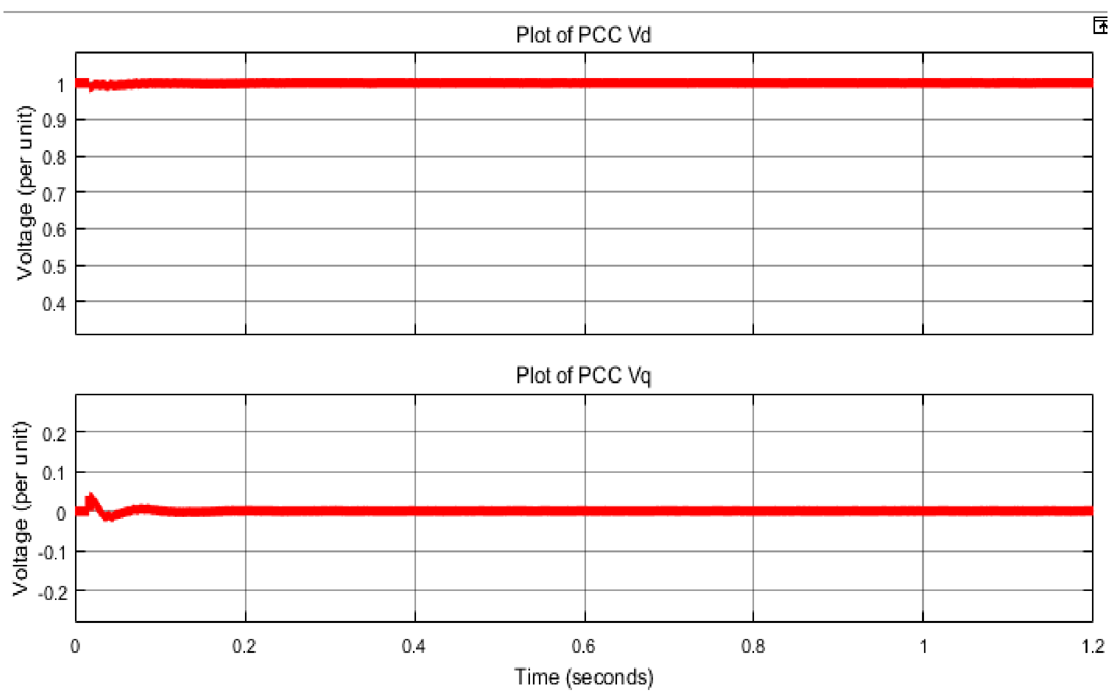

Figure 4.6 Decoupled point of coupling (PCC) voltage into direct and quadrature components

Before the controller was turned on, it can be seen in Figure 4.7 that the inverter was supplying active power to a resistive load and supplying excess active power to the grid. Since both load current and inverter current are in phase and the grid current at 180 degree phase shift with the load and inverter voltages, it can be deduced that the grid is absorbing active power while the inverter is supplying active power.

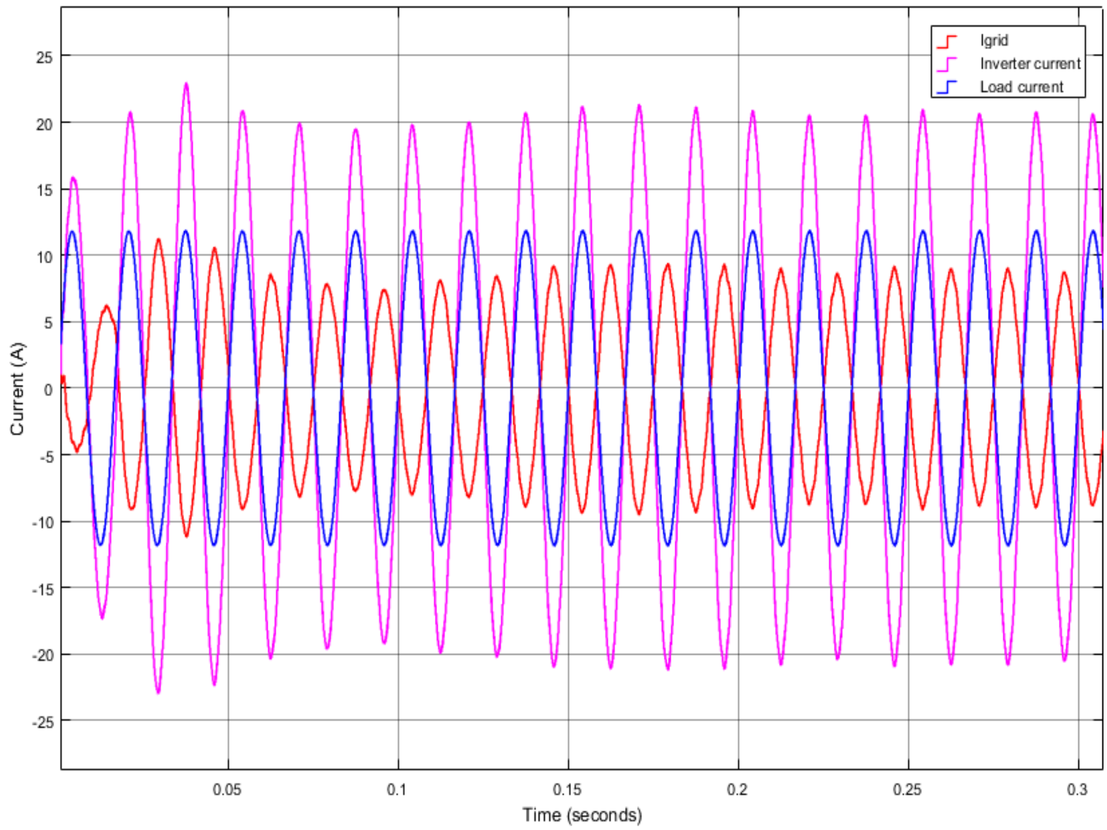

Figure 4.7 Inverter current, grid current and load current of 2000W load with no reactive power support

In Figure 4.8, a step load change was applied to the system increasing the load from 2000W to 5000W at 0.15s. Since the inverter is only capable of supplying power of 3500VA, the grid then started supplying the extra power needed to the resistive load. After stepping the load, the grid current, inverter and the load were all in phase which concludes that the grid was supplying the deficit active power to the load.

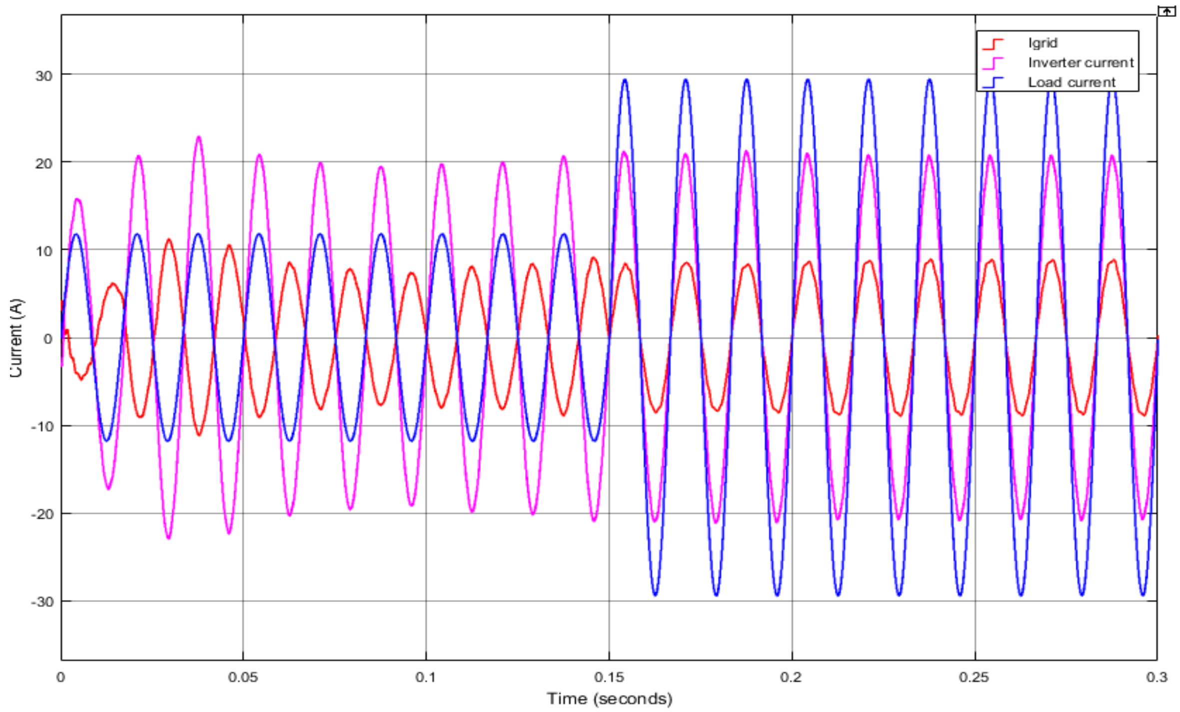

Figure 4.8 Inverter current, grid current and load current of a load step from 2000W to 5000Wat 0.15s

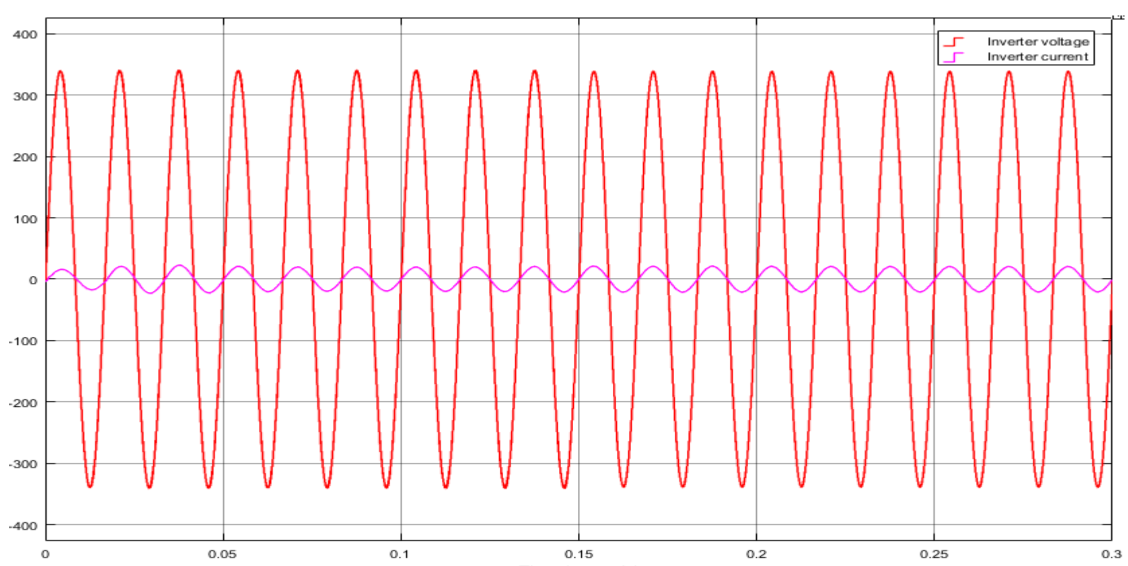

Figure 4.9 Inverter voltage and current in phase for 5000W load

Figure 4.9 shows that the inverter voltage and current are in phase when the inverter is supplying active power to the load at the point of common coupling. The currents from the grid, inverter and load are plotted in Figure 4.10 with reactive power support.

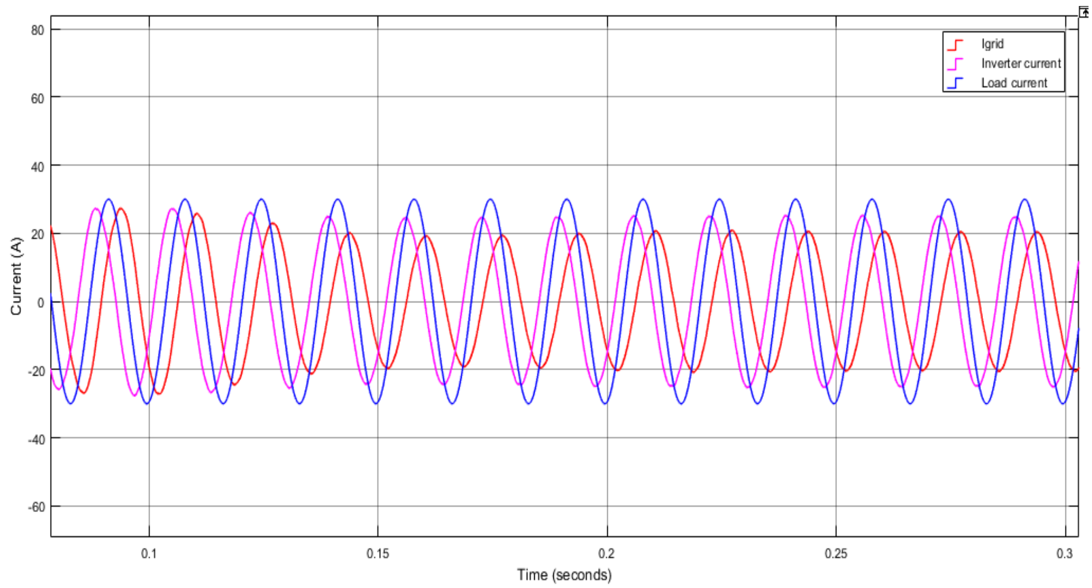

Figure 4.10 Grid current, load current and inverter current of 1000W + 5000VAR with reactive power support from inverter

When a negative quadrature reference current is generated from the inverter control system, the inverter behaves as a capacitor, thus producing reactive power. It compensates reactive power at the grid due to excess inductive loads. In Figure 4.11, the direct and quadrature currents can be seen tracking its reference when a load of 1000W and 5000VAR. The quadrature components being a non-zero magnitude, shows that the inverter is supplying reactive power to the grid. Figure 4.12 shows the inverter voltage and current with a phase shift, this indicates that power is supplied to an inductive load in the system.

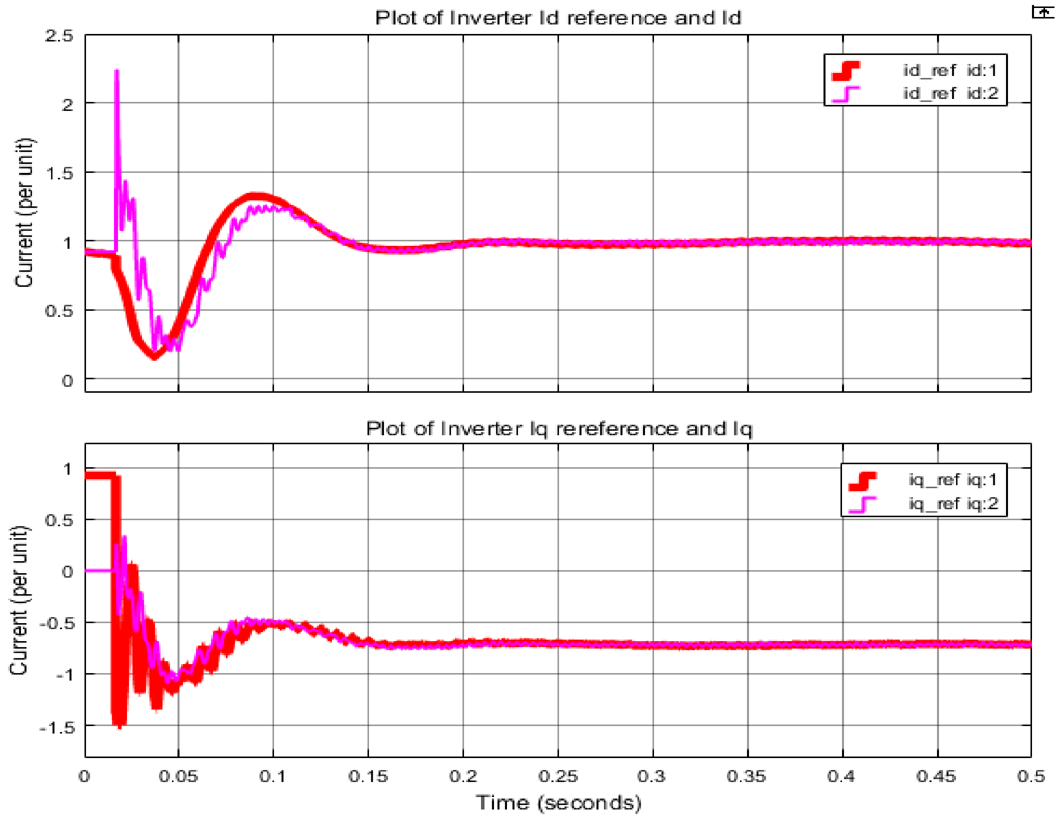

Figure 4.11 Inverter direct and quadrature current for active power and reactive power compensation load of 1000W and 5000VAR

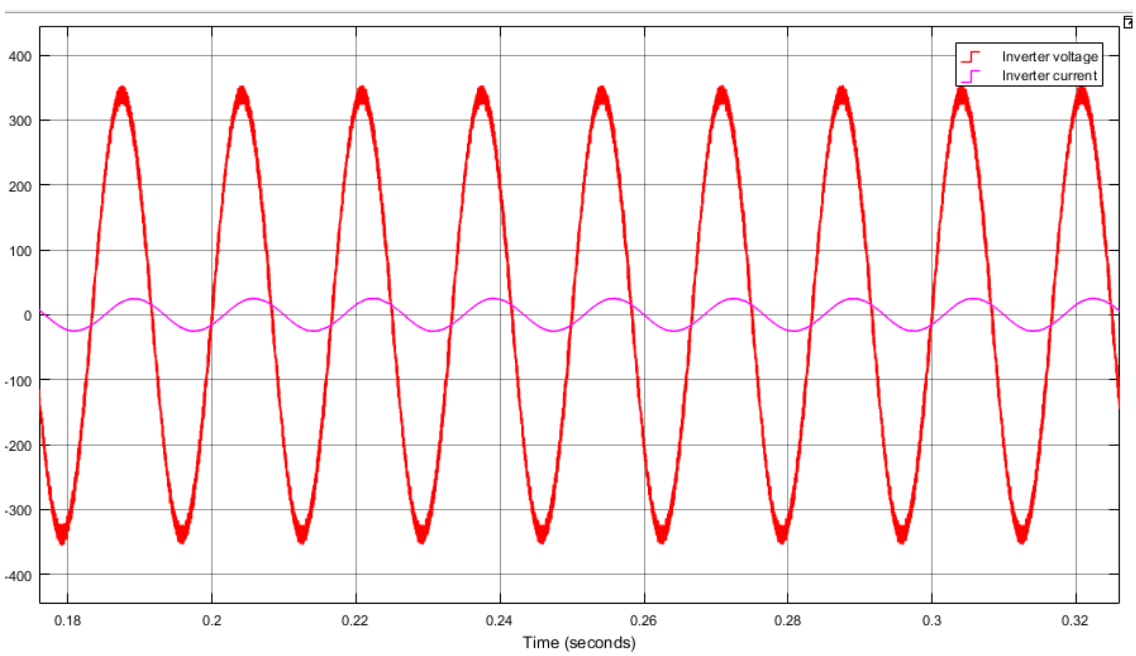

Figure 4.12 Inverter voltage and current showing a phase shift for reactive power support

To support reactive power in the grid, the voltage at the point of common coupling needs to be stiff so that the voltage does not sag due to the large inductive load being connected to the grid. In Figure 4.13 and 4.14, the RMS voltage at the PCC was plotted with a step load of 1000W + 15000VAR from 0s to 0.5s and 1000W +15000VAR from 0.5s to 1s.

Figure 4.13, shows the plot of the RMS voltage at PCC with the step load without the reactive power support from the inverter. It can be seen that the PCC voltage sags from 240Vrms to 238Vrms and at 0.5s to 231Vrms respectively for the two loads.

In Figure 4.14, the reactive power controller was used and PCC voltage for the two loads settled at 240Vrms and 236Vrms respectively. The voltage at PCC sags down but rises after the reactive power controller supported the high VAR load demand after with both loads. It can be seen that the controller improved the voltage profile at PCC in Figure 4.14 compared to when the controller was off in Figure 4.13.

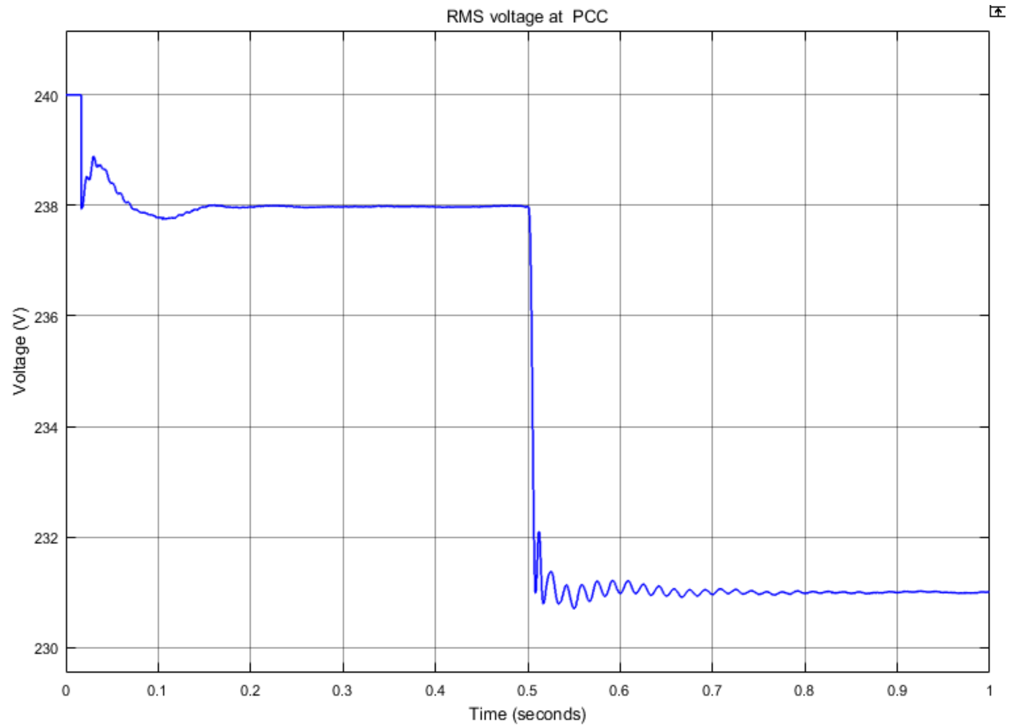

Figure 4.13 RMS Voltage at PCC for load step from 1000W+5000VAR to 1000W +15000VAR without reactive power support

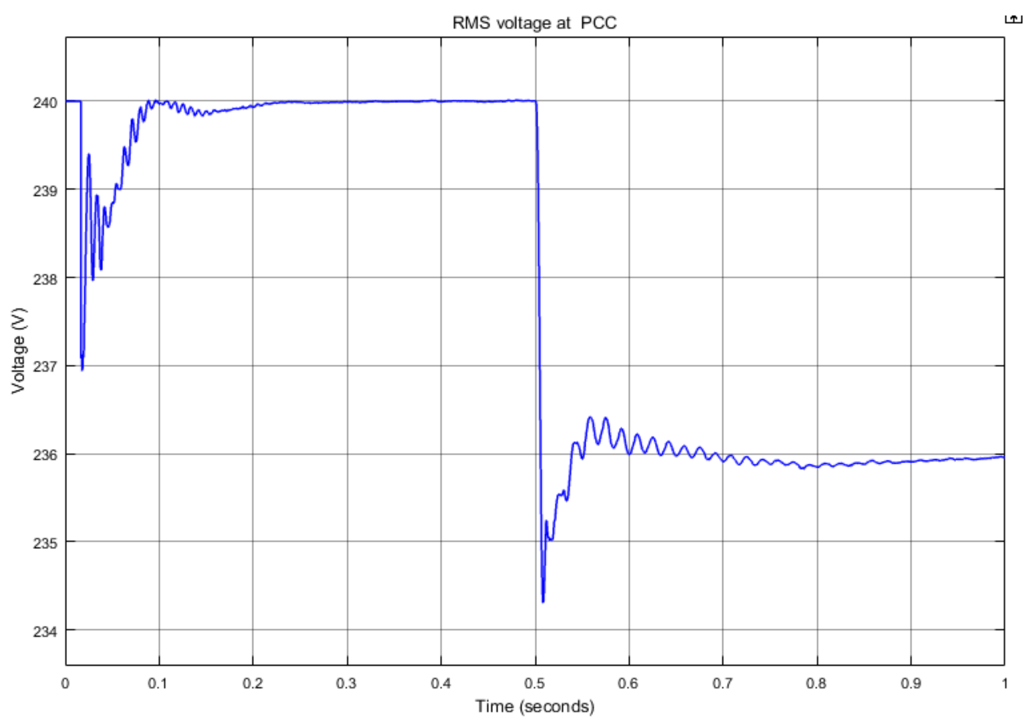

Figure 4.14 RMS Voltage at PCC for load step from 1000W+5000VAR to 1000W+15000VAR with reactive power support

CHAPTER 5 CONCLUSION AND FUTURE WORK

5.1 Conclusion

In Chapter 2, different single phase PWM switching schemes and their advantage in single phase converter applications were discussed. The carrier and reference signal for the inverter were also described.

In Chapter 3, the common method for determining the real and reactive components of an AC parameter was discussed with a focus on applications of the method to single phase converters. After the transformation step of the AC parameters, the current and voltage feedback signals become time-invariant components separated in the *dq* frame. The control system for the inverter uses of a current loop and an outer voltage loop. The coupling terms between active and reactive power are decoupled within the controller which provided an alternative approach of a *d-q* controller. Therefore, active and reactive power reference changes are not inducing transient changes in each other because the system is now completely decoupled. The synchronous rotating frame controller yields enhancements in the applications single-phase grid tie inverter reactive power compensation by injecting reference quadrature current to produce reactive power.

Chapter 4 presents the measured outputs of the PV, the inverter and its controller outputs, and the grid parameters when the controller was supplying active power for a resistive load and reactive power when there was a reactive load demand in the system.

From the system design, it can be concluded that PI controllers are best suited even for grids in which the values of grid voltage and grid frequency are changing during the operation. From the step change in the load power, the references continued to track their desired parameters which proves that a PI controller was suitably in this application. This controller can be applied in residential PV application to support the reactive power at the grid. The proposed controller will improve the power quality at the consumer side of the grid by making the voltage at the point of coupling closer to nominal value. Inverters with reactive power support capabilities will be of great importance to grid tie energy sources with the ability to minimize blackouts.

5.2 Future Work

This thesis was proposed for applications in single phase inverters, but applications of the control technique used in this thesis can be further investigated in 3-phase inverter systems and multi-level inverters. Also, additional designs can be include in the inverter control system with an adaptive control approach for the inverter, to be able to regulate the grid voltage within a specified range of the nominal grid voltage.

REFERENCES

[1] American Public Power Association, “Distributed Generation,” *An Overview of Recent Policy and Market Development*, Washington, D.C., Nov. 2013.

[2] T. Brekken, A. Yokochi, A. Jouanne, Z. Yen, H. Hapke and D. Halamay, "Optimal energy storage sizing and control for wind power applications," *IEEE Trans. Sustain. Energy*, vol. 2, pp. 69-77, Aug. 2010.

[3] A. Panda, M. Pathak and S. Srivastava, "Grid tie inverter control for rooftop photovoltaic system," in *2012 IEEE Fifth Power India Conference*, Murthal, 2012, pp. 1-6.

[4] K. Cheng, X. Luo, C. Lee, "Reactive power control of grid tie inverter to enhance the stability of Power Grid," in *2014 IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems*, 2014, pp. 1-8.

[5] P. Kundur, N. Balu, M. Lauby, "Power system stability and control," McGraw-Hilll Education, 1994.

[6] S. Eftekharnejad, V. Vital, G. Heydt, "Impact of increased penetration of photovoltaic generation on power systems, " IEEE Transactions on Power Systems, Vol. 28, No 2, pp. 893-901, May 2013.

[7] F. Blaabjerg, R. Teodorescu, M. Liserre and A. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398-1409, 2006.

[8] R. Wandhare, V. Agarwal, "Reactive power capacity enhancement of PV-Grid system to increase PV penetration level in smart grid scenario," IEEE Transactions on Smart Grid, vol. 5, pp. 1845-1854, July 2014.

[9] A. Canova, L. Giaccone, F. Spertino, and M. Tartaglia, "Electrical impact of photovoltaic plant in distributed network, " IEEE Trans. Ind. Appl., vol. 24, no. 1, pp. 341–347, Feb. 2009.

[10] R. Wandhare and V. Agarwal, "A photovoltaic power control algorithm covering complete range," *2013 IEEE 39th Photovoltaic Specialists Conference (PVSC)*, Tampa, FL, 2013.

[11] R. Wandhare and V. Agarwal, "Precise active and reactive power control of the PV-DGS integrated with weak grid to increase PV penetration," *2014 IEEE 40th Photovoltaic Specialist Conference (PVSC)*, Denver, CO, 2014.

[12] O. Robles, J. Jimenez and J. Ramirez, "Single-phase bidirectional high frequency link photovoltaic inverter with reactive power compensation function," *2015 IEEE Workshop on Power Electronics and Power Quality Applications (PEPQA)*, 2015.

[13] J. Chew, A. Gupta and M. Yap, "Performance of ABR flow control in ATM networks," *Proceedings of ICICS, 1997 International Conference on Information, Communications and Signal Processing. Theme: Trends in Information Systems Engineering and Wireless Multimedia Communications*.

[14] R. Wandhare, S. Thale and V. Agarwal, "Design of a photovoltaic power conditioning system for hierarchical control of a microgrid," *2014 IEEE 40th Photovoltaic Specialist Conference (PVSC)*, 2014.

[15] S. Jena, B. Babu, G. Mishra and A. Naik, "Reactive power compensation in inverter-interfaced distributed generation," *2011 International Conference on Energy, Automation and Signal*, 2011.

[16] B. Crowhurst, E. El-Saadany, L. Chaar and L. Lamont, "Single-phase grid-tie inverter control using DQ transform for active and reactive load power compensation," *2010 IEEE International Conference on Power and Energy*, 2010.

[17] O. Ochoa Robles, J. Jimenez and J. Ramirez,"Reactive Power Compensation in a photovoltaic grid tie system, using a single-phase bidirectional high frequency link converter," *IEEE Latin America Transactions*, vol. 14, no. 4, pp. 1816-1821, 2016.

[18] North American Electric Reliability Council, "Technical analysis of the August 14, 2003, Blackout: what happened, why, and what did we learn?" Princeton, NJ, July 2014.

[19] V. Abri, "Relationship between the paper covering thickness of the electrode and the development of the surface flashover at impulse voltages," *ICSD'98. Proceedings of the 1998 IEEE 6th International Conference on Conduction and Breakdown in Solid Dielectrics, 1998*.

[20] D. Hart, "Inverters" in *Power electronics*. New York: McGraw-Hill, 2011, ch. 8, pp. 331-386.

[21] S. Sharma, "Single Phase *d-q* Transformation using as indirect control method for shunt active power filter," *IJERGS,* vol. 2, 2014.

[22] S. Monfared, J. Guerrero and M. Joorabian, "A D-Q synchronous frame controller for single-phase inverters,"*2011 2nd Power Electronics, Drive Systems and Technologies Conference*, Tehran, 2011.