Grid Connected photovoltaic system based on Chain cell converter Using Simulink

Problem statement

To prove Chain cell converter performance superior when compared with the traditional Pulse width modulation (PWM) inverter and it is quiet suitable for grid connected PV systems

Abstract

Renewable energy resources such as Solar, wind and hydro are pollution free, easily erectable, and limitless so they represent reliable alternatives to conventional energy sources e.g. oil and natural gas. However, the efficiency and the performance of these systems are still under development. Among them, Photovoltaic systems are mostly used as they are light, clean and easily installable. Grid Connected of solar PhotoVoltaic array (collection of PV panels), power conditioner, and controller unit interfaced with the utility grid. The roles of PV array and power conditioner are the same as in the previous case. The controller unit implements MPPT and grid interfacing algorithms and algorithms for monitoring the system status and protection. The controller unit is responsible for the operation of the entire unit. The main advantage of grid connected PV systems over stand-alone PV systems is that there is no wastage of the excess power produced. Chain cell converter is considered to be efficient as compared to Pulse WidthModulation converters due to lower switching losses, modularized circuit layout, reduced voltage rating of the converter switches, reduced EM!. The structure of separatedc sources in chain cell converteris well suited for photovoltaic systems as there will be several separate PV modules in the PV array which can act as an individual dc source. In this work, a single phase multilevel chain cell converter is used to interface the photovoltaic array to a single phase grid at a frequency of 50Hz. Control algorithms are developed for efficient interfacing of the PV system with grid and isolating the PV system from grid under faulty conditions. Digital signal processor TMS320F 2812 is used to implement the control algorithms developed and for the generation of other control signals

Introduction

1.1 Introduction to Solar Photovoltaics

Solar energy has become the most important renewable sources of energy and is gaining increasing popularity to meet the ever increasing global energy demand. The technology of photovoltaics (PV) is essentially concerned with the conversion of the solar energy into suitable electrical energy which can be used directly or stored. The basic element of a PV system is a solar cell. By settling solar cells under the sunlight, they can convert solar energy directly to electricity. This electricity can be modified to any consumer applications such as lighting, water pumping, refrigeration, telecommunications, and so on. Solar cells rely on a quantum-mechanical process known as the “photovoltaic effect” to produce electricity. A typical solar cell consists of a *p-n* junction formed in a semiconductor material similar to a diode. Figure1.1 shows a schematic diagram of the cross section structure through a crystalline solar cell. It consists of a 0.2-0.3 mm thick Môn crystalline or polycrystalline silicon wafer having two layers with different electrical properties formed by doping it with other impurities (e.g., boron and phosphorus). An electric field is established at the junction between the negatively doped (using phosphorus atoms) and the positively doped (using boron atoms) silicon layers. If sunlight impacts the solar cell, the energy from the sunlight (photons) creates free charge carriers, which are separated by the electrical field. An electrical voltage is generated at the external contacts, so that current flows when a load is interfaced. The photocurrent (I_{ph}), which is internally generated in solar cell, is proportional to the radiation intensity.

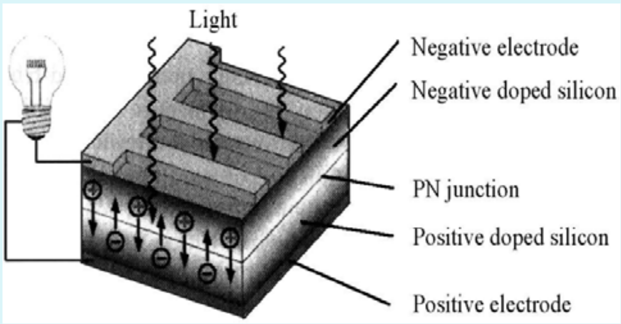

Figure 1.1 Principle of Operation of Solar Cell

1.1.1 Solar Cell

Solar cell is a p-n junction diode of large area (1-100 cm^2), which converts energy of the incident photons into electrical energy. A typical construction of a p-n junction solar cell is shown in *Figure 1.2,* which consists of a shallow p-n junction formed on the surface of a substrate, front ohmic contact grids and a back ohmic contact, and an antireflection coating on the front surface. When a solar cell is exposed to solar spectrum, photons having energy equal to or greater than the band gap (E_g) of the solar cell material, get absorbed and hole and electron pairs are generated, which are collected by the respective terminals. Photon energy in excess of 'E_g' is converted into electrical energy while photon energy less than 'E_g' is either dissipated as heat in the solar cell or transmitted through. The energy band diagram of a p-n junction under illumination is shown in *Figure 1.3* and its ideal equivalent circuit is shown in *Figure 1.4,* where a constant current source is in parallel with a diode. The current source 'I_{ph}' results from the charge carriers excited by solar radiation.

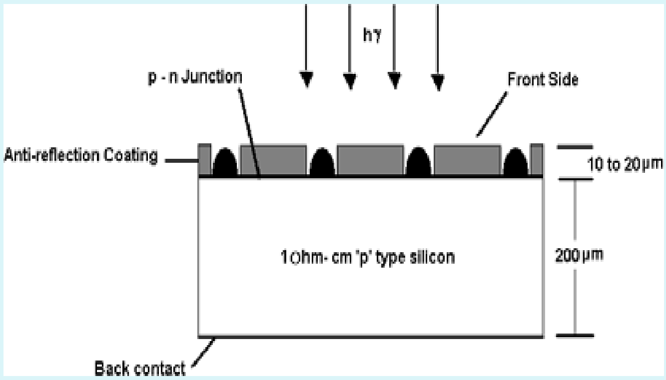

Figure 1.2: Typical construction of a p-n junction solar cell

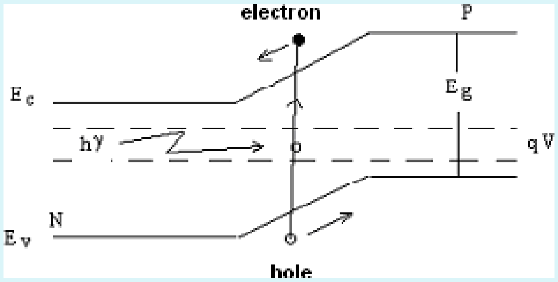

Figure 1.3: Energy band diagram of a p-n junction solar cell under illumination

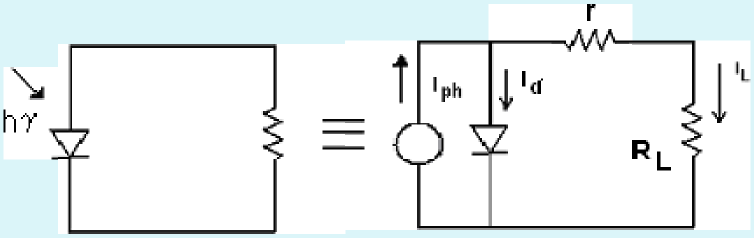

Figure 1.4: Ideal equivalent circuit of a solar cell

1.2 Electrical characteristics of a Solar cell

The ideal current of a p-n junction solar cell under dark condition is given by the current of a semiconductor diode I_d,

$$I_d = I_o \left[e^{\frac{V_d - Ir}{\eta V_T}} - 1 \right]$$

If 'r' is considered negligible, then the above equation becomes

$$I_d = I_o \left[e^{\frac{V_d}{\eta V_T}} - 1 \right]$$

Then the solar current I_L is given by,

$$I_L = I_{ph} - I_d$$

$$I_L = I_{sc} - I_o \left[e^{\frac{V_d}{\eta V_T}} - 1 \right]$$

Where

I_o is reverse saturation current

IL is load current

I_{ph} is photon generated current ~ I_{sc} (short-circuit current of solar cell)

V_d is cell voltage / bias voltage / applied voltage

η is diode factor

r is bulk resistance of the diode (series resistance)

V_T is thermal voltag**e** = kT/q

T is temperature in Kelvin

q is electron charge

k is Boltz Mann constant

1.2.1 I-V Characteristics

The Current-Voltage (I-V) characteristic under illumination is shown in *Figure 1.6*. It shows the cell open circuit voltage (V_{oc}), the short circuit current (I_{sc}), the voltage at maximum power (V_{mp}), the current at maximum power (I_{mp}), and the maximum power point (P_{mp}).

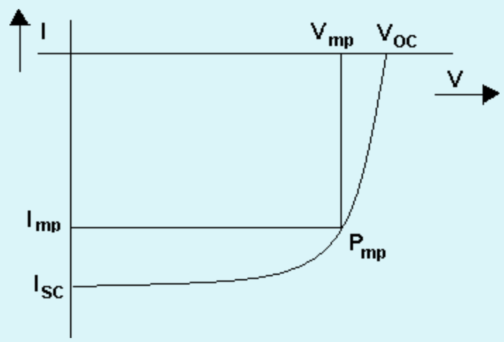

Figure 1.5: I-V characteristics of illuminated solar cell

3. Parameters affecting solar cell static (DC) characteristics

The solar cell static (DC) characteristic is a function of the solar radiation intensity, solar radiation spectrum and cell temperature as follows:-

1. Effect of solar radiation intensity (Insolation)

The cell temperature and spectral distribution of the light are maintained /assumed to be constant. It may be observed from *Figure 1.6* that the open circuit voltage increases marginally with the intensity of the solar radiation and saturates. The short circuit current increase linearly with the intensity of solar radiation, as it is a function of intensity.

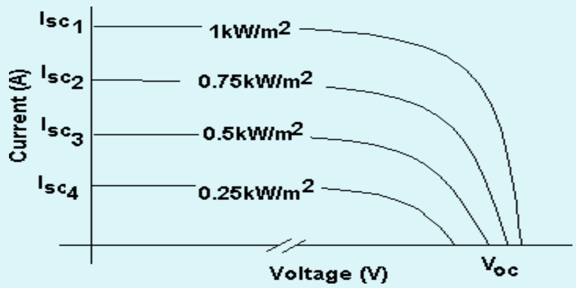

Figure1.6 Effect of intensity

1.3.2. Effect of Temperature

The increase in the cell operating temperature causes a little increase in the cell short circuit current but a significant decrease in the cell voltage. *Figure 1.7* shows the effect of temperature, keeping intensity and spectral distribution of light constant. With increasing solar cell temperature, the entire ‘I-V’ curves shift towards lower voltage at a rate of approximately 2.2 to 2.3mV/°C for silicon solar cell.

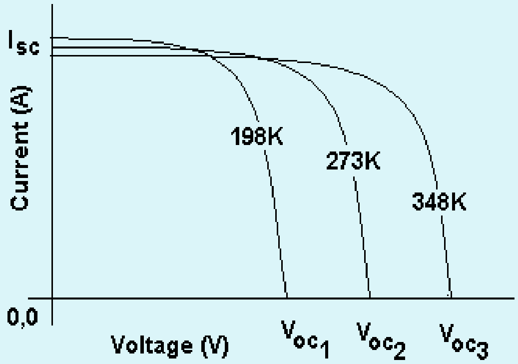

Figure1.7 Effect of temperature

1.4 Photovoltaic Systems

Photovoltaic (PV) systems are two types – 1.Stand alone PV systems and 2.Grid Connected PV systems.

1.4.1 Stand-alone PV systems

A typical stand-alone PV system is shown in Figure 1.8.

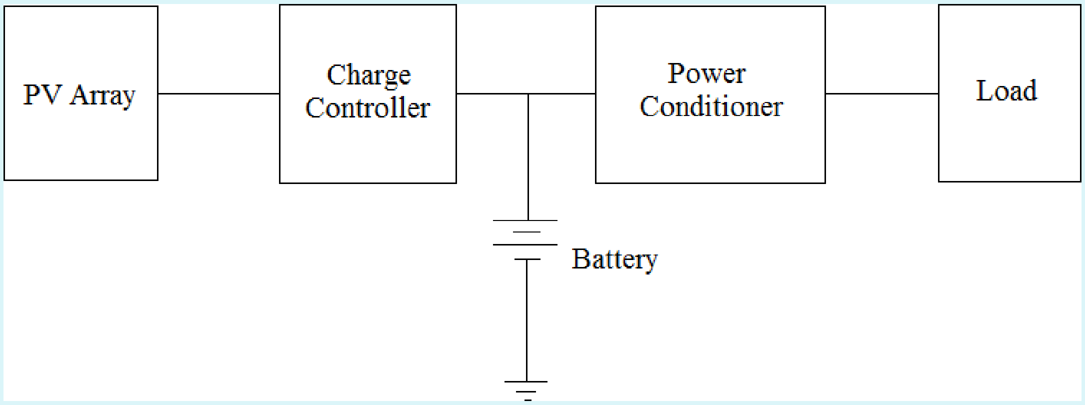

Figure 1.8 Stand-alone PV system

It consists of a photovoltaic/solar panel, a charge controller, a battery and a power conditioner. The elemental unit of the solar panel is a solar cell, several of which are connected in series and parallel to get the desired power at the required voltage. The charge controller interfaces the solar panel with the battery. The charge controller provides the required voltage for battery charging with control and protection. The energy generated from the solar panel is stored in the battery to provide an uninterrupted power to the load through a power conditioner. The power conditioner, transfers the energy stored in the battery to the load in the required form (DC or AC) at the required voltage. The power conditioner can be a DC - DC converter or an inverter or a combination of both. The overall efficiency of the solar power system is the product of the efficiencies of the individual subsystems. The overall system efficiency would be around 10% to 15%. The main disadvantages of this system are: Regular maintenance of the batteries is required which increases the cost and, the excess power produced from the solar panels after the batteries are charged completely is wasted.

1.4.2 Grid Connected PV systems

A typical Grid connected PV system is shown in Figure 1.9.

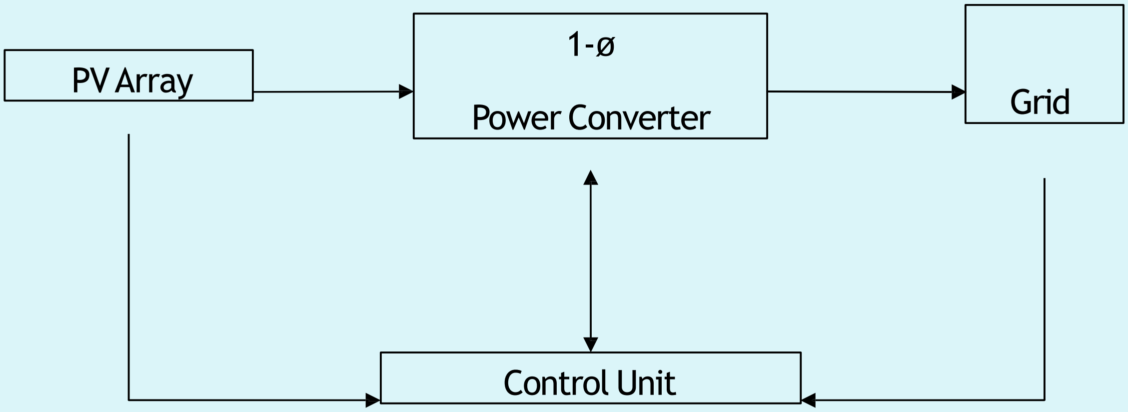

Figure 1.9 Grid connected PV system

It consists of PV array (collection of PV panels), power conditioner, and controller unit interfaced with the utility grid. The roles of PV array and power conditioner are the same as in the previous case. The controller unit implements MPPT and grid interfacing algorithms and algorithms for monitoring the system status and protection. The controller unit is responsible for the operation of the entire unit. The main advantage of grid connected PV systems over stand-alone PV systems is that there is no wastage of the excess power produced.

.The following inference are drawn from the review:

- Multilevel Inverters showed better performance when compared to traditional Pulse Width Modulation (PWM) inverters.
- Among the different topologies of multilevel inverters, Chain cell topology is the best with advantages like having minimum number of components, easier modularization and soft switching.
- None of the systems developed so far have implemented Chain Cell Converter in a grid connected photovoltaic system with complete validation of the control strategies implemented in the system including those of system protection.

Hence it is planned to develop a grid connected photovoltaic system based on the Chain cell converter and validate the control algorithms developed for the system.

Scope of the Present Work

- To develop a MATLAB/SIMULINK based model of a grid connected photovoltaic system based on Chain cell converter.
- Development of various control algorithms for the system and their validation under different conditions such that system protection is ensured.

Approach used to Implementation of grid interfacing algorithm & Report presentation

Chapter 2 gives an overview of the system modeled, detailed operation of the chain cell converter and various control strategies implemented in the system. The models of solar cell, PV array, boost converter, chain cell converter, PWM inverter and the control units are described in chapter 3.

In chapter 4, the results obtained from the simulations carried out using the models developed are presented and discussed in detail.

Approach used

Chapter 2

System Overview

This chapter gives an overview of the system that is to be modeled. The control strategies developed are also discussed. The block diagram of the system is shown Figure 2.1. It consists of PV array, power conditioning unit, and control unit interfaced with grid.

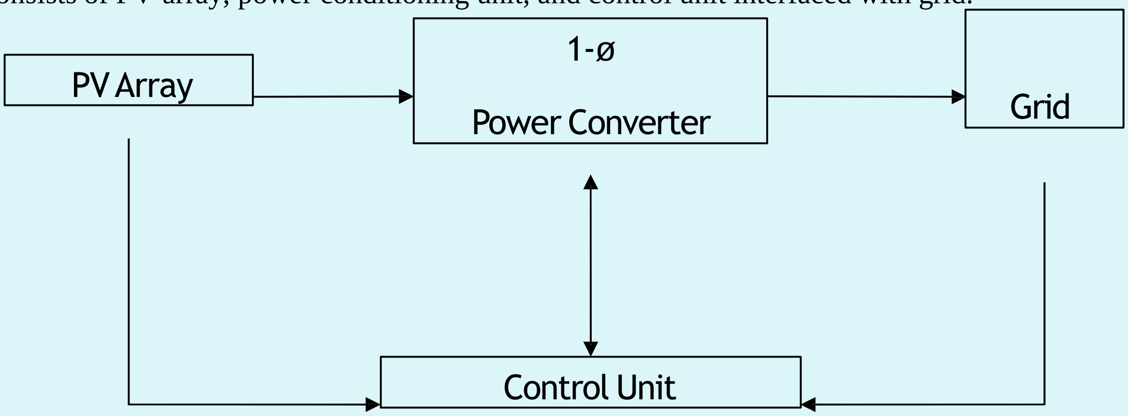

Figure 2.1 Block Diagram of the System

PV Array: It consists of several panels connected in a suitable configuration to give required output dc voltage and current.

Power Conditioning Unit: This unit consists of a dc-dc boost converter and a single phase multilevel chain cell converter. The boost converter boosts the output voltage of the PV array to a suitable voltage based on the maximum power point of the PV array. The chain cell converter generates 230 volts single phase output voltage through an inductance.

Control Unit: The control unit is responsible for the operation of the entire unit. It senses the voltage and current at various points in the system. These are fed to the controller unit to implement MPPT and grid interfacing algorithms and for monitoring the system status. The following algorithms are modeled and validated:

- MPPT algorithm to draw maximum power from PV array,
- Generating firing pulses for the chain cell converter to inject power into the grid,

Approach used (Continued)

- Implementation of grid interfacing algorithm
- Protection of PV system under grid failure conditions

2.1 Power Conditioning Unit

The output voltage of the PV array is usually less than that is required so that an AC voltage of 230 V_{rms} is generated at the inverter output. So the output of the PV array is given to a boost (DC-DC) converter. The MPPT algorithm is usually implemented as a part of the boost converter. The boost converter boosts the output voltage of the PV array to a suitable voltage based on the maximum power point of the PV array. The stabilized output voltage of the boost converter is then given as the input to an inverter to generate AC voltage of 230 V_{rms} and 50 Hz frequency. The inverter that is used in the current system is the Chain cell converter. The details of boost converter and chain cell converter are explained in the following sections.

2.1.1 Boost Converter

In this section the principles of switching power conversion are introduced and details of DC-DC boost converter circuits are discussed. The DC-DC boost converter comes under switched-mode power converters. A switching converter consists of capacitors, an inductor, and a switch in general. All these devices ideally do not consume any power that is the reason for the high efficiencies of switching converters. The switch is realized with a switched mode semiconductor device, usually MOSFET/IGBT. It is switched on and off by driving signals at the gate of the switching device. If the semiconductor device is in the off state, its current is zero and hence its power dissipation is zero. If the device is in the on state, the voltage drop across it will be close to zero and hence the dissipated power will be very small. During the operation of the converter, the switch is operated at constant frequency f_s with an on-time of DT_s, and an off-time of (1-D)* T_s, where T_s is the switching period $1/f_s$, D is the duty ratio of the switch. It is shown in Figure 2.2 and the schematic of boost converter is shown in Figure 2.3.

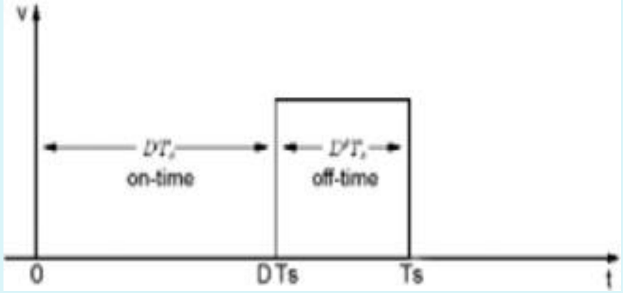

Figure 2.2 Ideal Switch voltage V, Duty ratio D, and switching period T_s

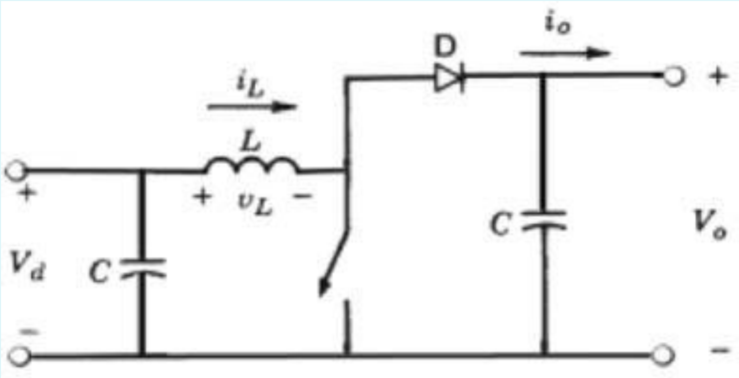

Figure 2.3 DC-DC Boost Converter

The DC-DC converters can have two distinct modes of operation: (1) continuous current conduction and (2) discontinuous current conduction. In continuous mode, inductor current never falls to zero in one switching cycle T_s or at least when the switch or diode is conducting. Whereas in discontinuous conduction mode, the inductor current falls to zero before completing one switching cycle T_s. In practice, a converter may operate in both modes, which have significantly different characteristics.

The Boost Converter, as shown in Figure 2.3 is also known as the step-up converter. As the name implies its typical application is to convert low input-voltage to a high output voltage. During the first time interval DT_s of the switching period T_s, the closed switch connects the input through the inductor to ground and current starts to flow, the current through the inductor increases and the energy stored in the inductor builds up. The diode is reversed biased and hence no inductor current flows through the load, thus isolating the output stage. When the switch is opened in the second time interval $(1-D)*T_s$ of the switching period, the

Approach used (Continued)

output stage receives energy from the inductor as well as from the input. In steady state analysis, the output capacitor is assumed to be large to ensure a constant output voltage $V_o(t) \equiv V_o$. Figure 2.4 shows the operation of the boost converter in the continuous conduction mode where the inductor current $i_L(t) > 0$. When the switch is closed the source voltage V_d is applied across the inductor and the rate of rise of inductor current is dependent on the source voltage V_d and inductance L. This results in a positive voltage across the inductor and is given as,

$$V_L = V_d$$

When the switch is opened, the inductor voltage becomes

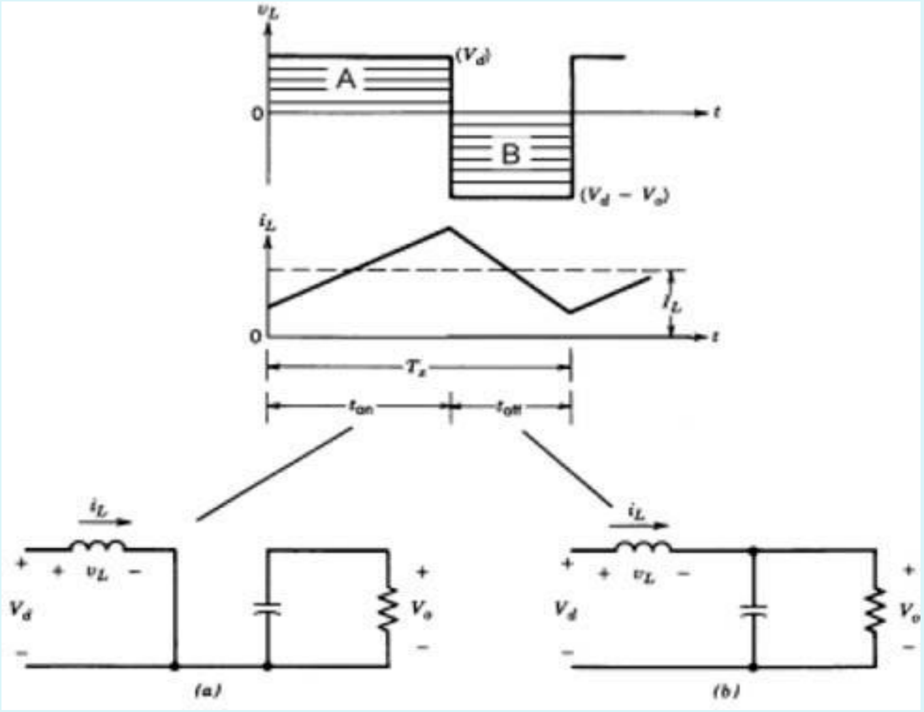

Figure 2.4 Continuous Conduction mode: (a) switch on (b) switch off

Approach used (Continued)

Since in steady state operation, the waveform must repeat from one time period T_s to the next, the integral of the inductor voltage V_L over one time period must be zero. This implies that the areas A and B in Figure 2.4 must be equal. Therefore,

$$Vd * Ton + (Vd - Vo) * Toff = 0$$

Dividing both sides by T_s, and rearranging the terms results to

$$\frac{Vo}{Vd} = \frac{Ts}{Toff} = \frac{1}{1 - D}$$

Hence the voltage transformation ratio of boost converter is given as

$$Vo = \frac{Vd}{1 - D}$$

Assuming the circuit is 100% efficient i.e., the input power (P_d) and output power (P_o) are the same,

$$Vd * Id = Vo * I0$$

Hence,

$$\frac{Io}{Id} = (1 - D)$$

By varying D, the output voltage can be changed and it is always more than V_d. The advantage of this converter is that the input and output current both are continuous. Generally in grid-connected PV systems where the MPPT system is a part, boost converter is utilized to maintain high voltage even if the PV array voltage falls.

2.1.2 Multilevel Converters

Multilevel converters reach high voltage and reduce harmonics by their own structures without transformers. A multilevel converter synthesizes sinusoidal voltage from several levels of voltages obtained from DC voltage of capacitors. The multilevel inverters start from three level inverters. The wave form obtained from a three level converter is a quasi-square wave output. As the number of levels increases, the synthesized output waveform adds more steps, producing a staircase wave which approaches the sinusoidal wave with minimum harmonic distortion. Multilevel converters are of three types:

Diode-Clamp multilevel converter: An *n*-level diode-clamp converter typically consists of $(n-1)/2$ capacitors on the DC bus and produces n levels of voltage. The device voltage stress will be limited to one of the capacitor voltage level, through clamping diodes. Thus, a large number of clamping diodes are required which not only increases the cost but also packing problems. There will be a quadratic increase in the number of clamping diodes with voltage levels.

Flying capacitor based multilevel converter: It solves the excessive diode count problem. The voltage synthesis in a flying capacitor converter is more flexible than a diode clamp converter. However, the number of capacitors required follows a quadratic nature with output voltage levels. The voltage balancing control becomes complicated due to large number of capacitors. This converter requires more number of capacitors than the number of diodes for Diode-Clamp converter.

Chain Cell converter: It is proposed as an alternative to Diode-Clamp multilevel converter and flying capacitor based multilevel converter. Chain Cell converter is discussed in detail in the following section.

2.1.2.1 Chain Cell Converter

The chain cell topology is a type of multilevel inverter. Chain cell converter can synthesize the sinusoidal voltage from several levels of voltages obtained from different dc voltage sources. This mode of using ‘different’ dc sources aptly suits the application of the chain cell converter topology in a Photovoltaic (PV) system as there will be several separate PV modules in the PV array which can act as an individual dc source. Chain cell converter generates an almost sinusoidal waveform with only one switching per cycle. The switching angles are properly chosen such that selected higher harmonics are eliminated and thus the total harmonic distortion (THD) will be minimized. This allows an efficient interface with the utility system. These converters require a series reactance for coupling to the ac system, thus eliminating the heavy, and bulky transformers. It is energy efficient due to less switching losses as compared to Pulse Width Modulation (PWM) inverters. It is cost effective because it does not require phase shifting transformer in multi pulse converters.

Approach used (Continued)

Other advantages of using Chain Cell converter are:

- Compared to other types of multi-level converters like diode clamp model and flying capacitor model, the cascaded inverter model requires least number of components to achieve the same number of voltage levels.
- Modularized circuit layout and packaging are possible because each level has the same structure.
- Soft switching can be used in this structure to avoid bulky and power loss resistor-capacitor-diode snubber circuits.
- The switching frequency is much less compared to that of PWM converters. Hence EMI effects and switching losses are low in multilevel converters.

2.1.2.2 Principle of Operation of Chain Cell Converter

An *N*-level chain cell converter basically consists of *(N-1)/2* full bridge inverters connected in series. Each full bridge inverter is associated with a separate dc source [5, 6, and 7]. The general model of an *N*-level chain cell converter is shown in Figure 2.5(a). Each full bridge inverter is known as a 'Cell' and is shown in Figure 2.5 (b).

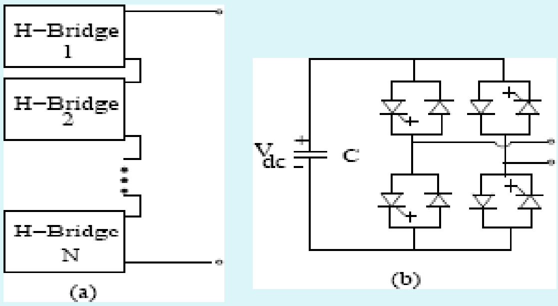

Figure 2.5 (a) General model of a (2N+1)-level Chain Cell Converter. (b) Full bridge inverter

Each bridge has its own capacitor charged with an initial voltage of Vdc. Each full bridge inverter can generate three levels of outputs *viz.*, +Vdc, 0 and −Vdc. As all the full bridge inverters are connected in series, the AC output voltage is synthesized by summing of all full bridge inverter output voltages. The stack of N capacitors produces a (2N+1) level symmetrical voltage waveform which is approximately a sine wave. Figure 2.6 shows the structure of an 11-level chain cell converter and its output voltage waveform in Figure 2.7.

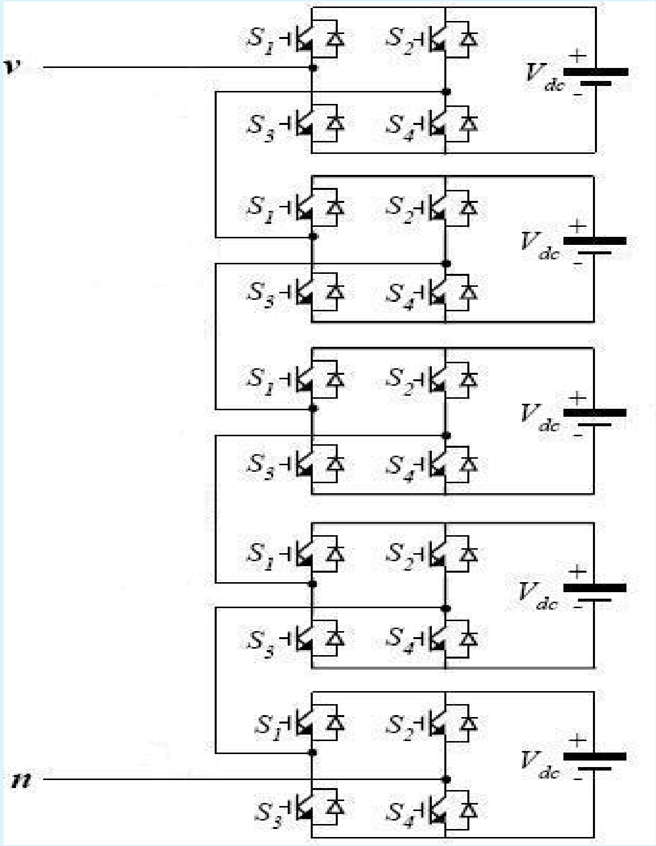

Figure 2.6 Structure of an 11-level chain cell converter

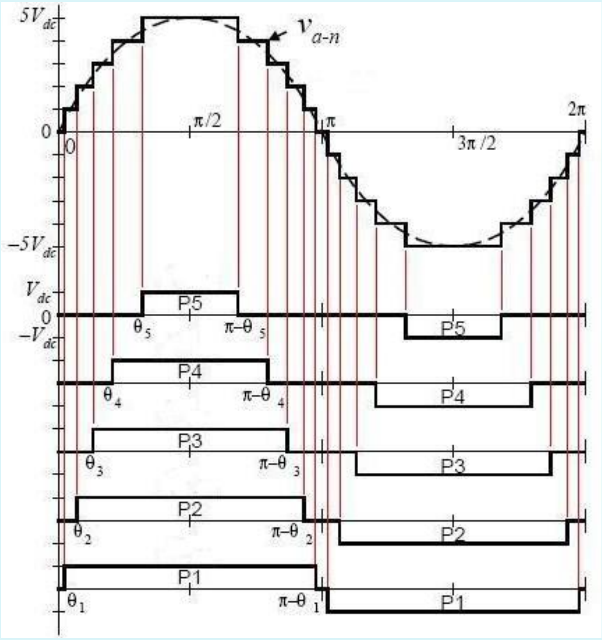

Figure 2.7 Output Waveform of 11-level Chain cell converter

Approach used (Continued)

Because each full bridge inverter produces a pulsating output, the pulse duration of the switches in each full bridge inverter is properly chosen in order to get an approximation of a sine wave. P1, P2, P3, P4, P5 represent the output pulses of the five full bridge inverters shown individually. θ_1 – θ_5 are the corresponding angles at which the firing pulses to the switches of the full bridge inverters are given. Addition of P1-P5 gives the output of the chain cell converter which is shown in the upper part of Figure 2.7.

2. Control Strategies

The following control algorithms are implemented using the Controller unit.

1. MPPT Implementation

The maximum power point tracking (MPPT) in the PV system is implemented using an algorithm based on the linearized relation between the output current and short circuit current of the PV array [4]. This algorithm is not only simple but also efficient.

2. Interfacing with Grid:

The interface model of the grid with the PV system is shown in Figure 2.8**Error! Reference source not found.**.

X_C

V_C V_G

I_C

Figure 2.8: Grid Interface Model

Where, V_C represents the voltage output of the chain cell converter, V_G represents the grid voltage which is taken as reference, in both magnitude and phase, to control the chain cell converter output, X_C represents the interface inductance. The phasor diagram for the above shown interface is shown in Figure 2.9. It follows the relation $V_C = V_G + jX_CI_C$.

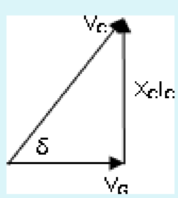

Figure 2.9: Phasor Representation of Grid Interface Model

Approach used (Continued)

Where, δ is the phase angle between V_C and V_G.

The conditions required to inject power into grid are:

- Converter output voltage should be greater than that of the grid voltage.
- Converter output voltage should be leading in phase with respect to the grid voltage.

The control algorithm for the grid interface has the following steps:

- The grid voltage V_G is sensed. The magnitude $|V_G|$ of grid voltage is calculated and is taken for generating the reference voltage for the operation of the chain cell converter.
- A phase shift of δ is calculated based on the magnitude of the converter output voltage V_C. This is done by computing the value of $[\cos^{-1}\{|V_G|/|V_C|\}] = \delta$. This computation is done for every fundamental cycle of 50 Hz.
- This value of δ is used in the generation of firing pulses applied to the switches of the chain cell converter so as to maintain the phase difference of δ between V_C and V_G.
- The current remains in phase with the grid voltage enabling it to inject power at UPF into the grid.

The above algorithm calculates the parameters for every fundamental cycle and provides a safe and very reliable interface with the grid.

2.2.3 Isolation of Grid from PV system Under Faulty Conditions

This control algorithm disconnects the PV system from the grid and turns off all the switches in the power conditioning unit under the following conditions:

- When $|V_C| <= |V_G|$
- Under voltage condition on PV array side because of lack of proper solar irradiance.
- Under short circuit condition.

This works based on the values of various parameters sensed by the control unit.

Tools used

Chapter – 3

Modeling of the System

The modeling of the proposed PV system is done in MATLAB/Simulink environment. The models developed for the PV array (including the model of a solar cell), boost converter, chain cell converter and the control unit based on various control algorithms described in section 2.3 are described in this chapter. In order to compare the performance of chain cell converter and pulse width modulated (PWM) inverter, modeling of PWM inverter is also done. In all the models developed it is assumed that the switches used in the power converters are ideal.

3.1 Modeling a PV array

The modeling of a solar cell is done based on the electrical characteristics of it described in section 1.2. The electrical equivalent of a solar cell is shown below in figure 3.1.

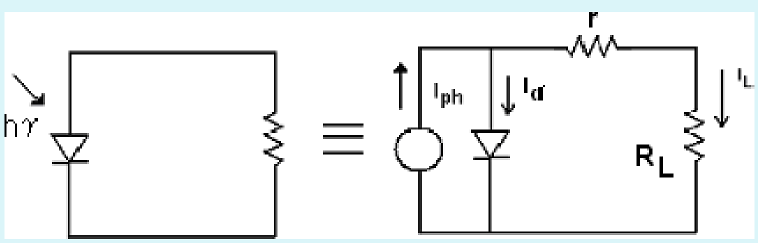

Figure 3.1 Electrical equivalent of a solar cell

The electrical equations of the above electrical circuit are given as follows:

The ideal current of a p-n junction solar cell under dark condition is given by the current of a semiconductor diode I_d,

$$I_d = I_o \quad e^{\frac{7d-Ir}{y7t}} -1 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

If ‘r’ is considered negligible, then equation (3.1) becomes

$$I_d = I_o \left[e^{\frac{7d}{y7t}} - 1 \right] \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

Then the solar current I_L is given by,

$$I_L = I_{ph} - I_d$$

$$I_L = I_{sc} - I_o \left[e^{\frac{7d}{y7t}} - 1 \right] \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

Where

I_o is reverse saturation current

I_L is load current

I_{ph} is photon generated current ~ I_{sc} (short-circuit current of solar cell)

V_d is cell voltage / bias voltage / applied voltage

η is diode factor

r is bulk resistance of the diode (series resistance)

V_T is thermal voltage = kT/q

T is temperature in Kelvin

q is electron charge

k is Boltzmann constant

Hence the current output of a solar cell is given as

$$I_L = I_{sc} - I_o \left[e^{\frac{7d}{y7t}} - 1 \right]$$

The voltage output of the solar cell is nothing but the voltage across the diode which is equal to the cut-in voltage of the same. The equations described above are implemented using the standard blocks of Simulink thus giving the model of a solar cell. The corresponding solar cell model is shown in figure 3.2.

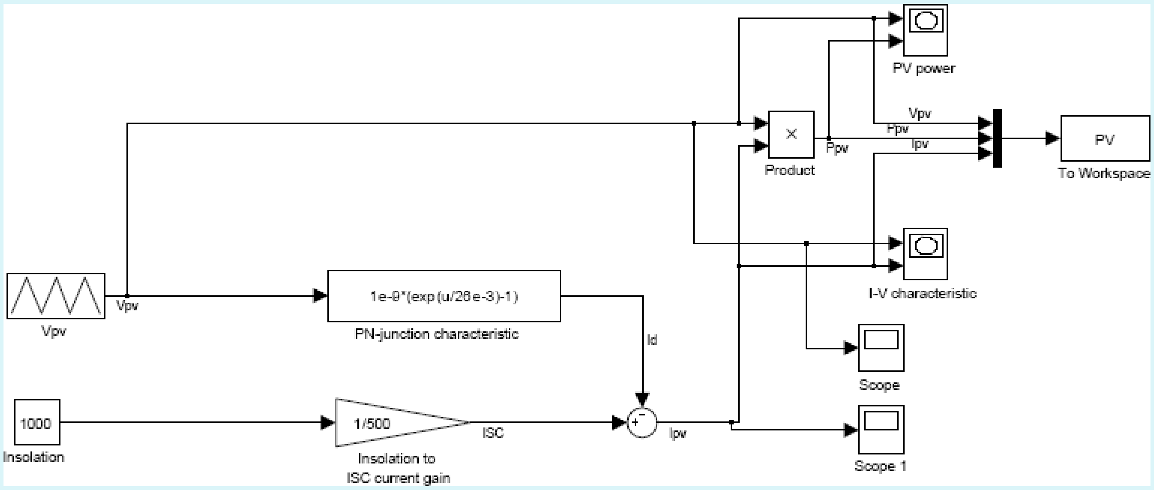

Figure 3.2 Simulink model of a Solar cell

The V-I and P-V characteristics of the solar cell obtained from simulating the above model are shown in figures 3.3 and 3.4 respectively. These characteristics are identical to the V-I and P-V characteristics of the solar cell described in Section 1.3 and hence it can be concluded that the developed model corresponds to a solar cell.

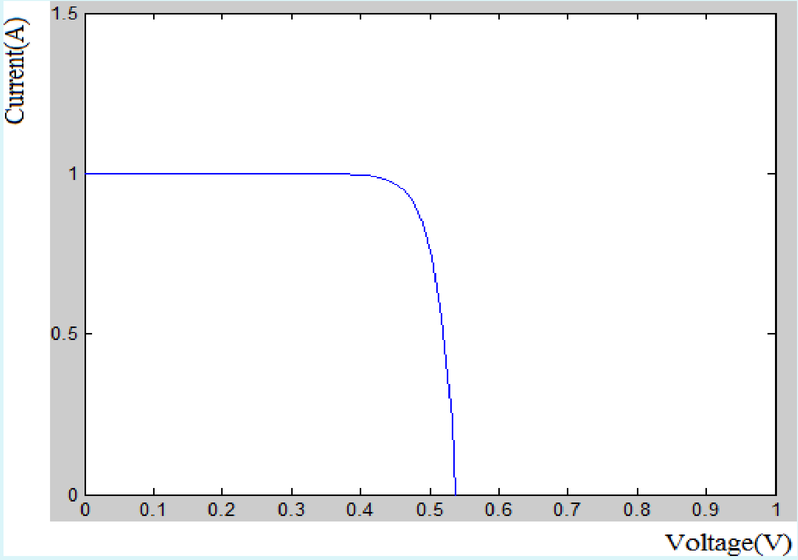

Figure 3.3 I-V characteristics of solar cell (simulation)

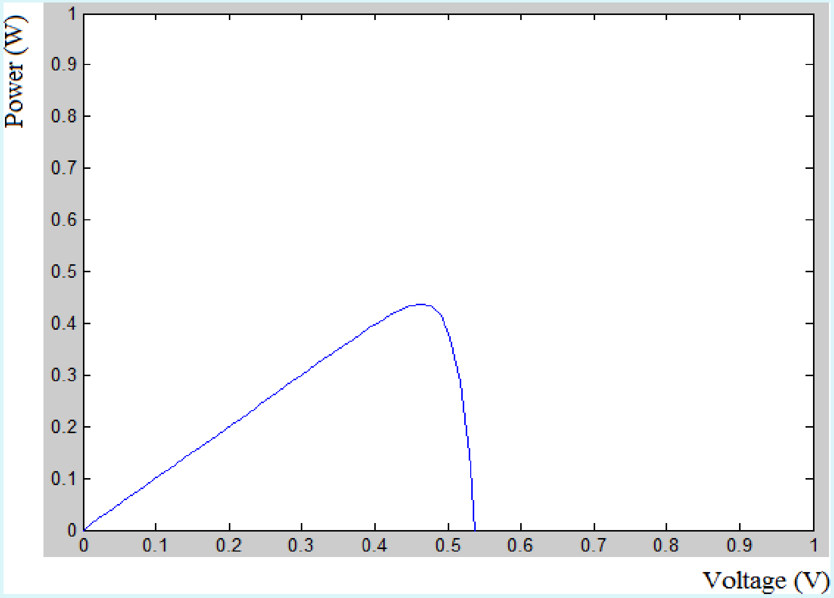

Figure 3.4 P-V characteristics of solar cell (simulation)

A photovoltaic module is modeled using the above solar cell model and is shown in figure 3.5.

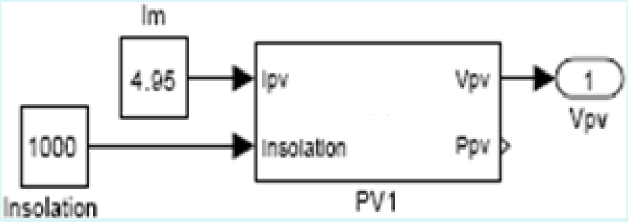

Figure 3.5 Model of a PV Module

The inputs of the module are the reference current value I_m which is equal to the current at MPP and the insolation level. The PV module is modeled such that it gives voltage output of the PV module as its output signal. Each module is modeled to give an output voltage of 17.2V when operating at Maximum Power Point (MPP) and insolation level of 1000 W/m^2. A collection of such modules is done forming the PV array model. Five PV modules are used to form the PV array. The model of the PV array with five voltage outputs is shown in figure 3.6.

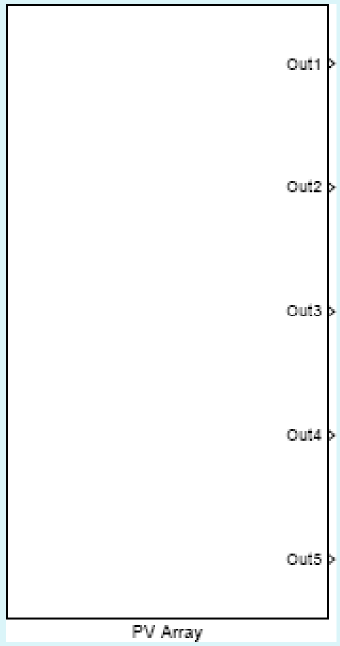

Figure 3.6 Model of a PV Array

The five voltage outputs are given as inputs to five boost converters to step up the voltage to a suitable level.

3.2 Boost Converter Model

The Simulink model of a boost converter is shown in figure 3.7.

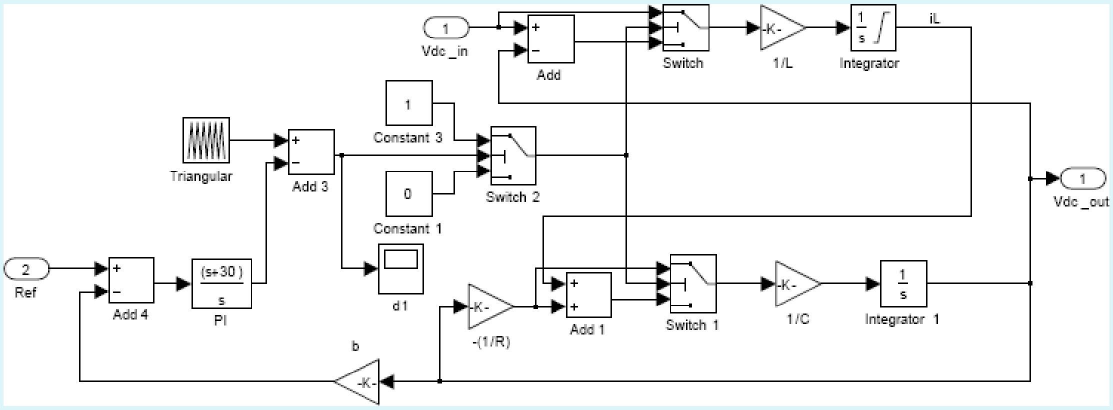

Figure 3.7 Simulink model of a Boost converter

The operation of boost converter is explained in section 2.1.1. The switch in boost converter is operated continuously using a signal of high frequency f_s. The model of the boost converter is designed based on the equations obtained during the ON and OFF states of the switch.

When the switch is ON, the equations governing the boost converter are,

$$iL = \frac{1}{L}\int(Vin)dt$$

$$iC = -\frac{Vo}{R}$$

$$Vo = \frac{1}{C}\int(iC*dt)$$

When the switch is OFF, the equations governing the boost converter are,

$$iL = \frac{1}{L}\int(Vo - Vin)dt$$

$$iC = iL - \frac{Vo}{R}$$

$$= \frac{1}{L}\int(Vo - Vin)dt - \frac{Vo}{R}$$

$$Vo = \frac{1}{C}\int(iC*dt)$$

Where,

Vin = input voltage of boost converter

Vo = output voltage of boost converter

iL = inductor current

iC = capacitor current

L = inductance used in boost converter

C = capacitance used in boost converter

R = load resistance used in boost converter = infinity (open circuit) in the present case because the output of boost converter is given to the inverter instead of a load.

Using the equations mentioned above, the boost converter is modeled as shown in figure 3.7. It is modeled in such a way that it gives a stabilized DC output using a closed-loop that contains the reference value given by the control unit based on the grid voltage magnitude and a PI controller as the main components. The output of this closed loop is the duty cycle D of the switch which in-turn determines the output voltage of the boost converter. Whenever the input voltage is changed the output voltage also changes thus bringing the closed loop operation into action which tries to reduce the gap between the reference and the output voltage. As a result the duty cycle D is changed suitably to give the required output voltage. So by changing the reference value and the feedback gain, desired output voltage is obtained. An example waveform of the output voltage of the boost converter obtained by using the model developed is shown in figure 3.8. Here the feedback gain and reference values are given such that the output is a constant DC voltage of 70 V from an input of around 18V when the switch is operated at a frequency of 10 kHz.

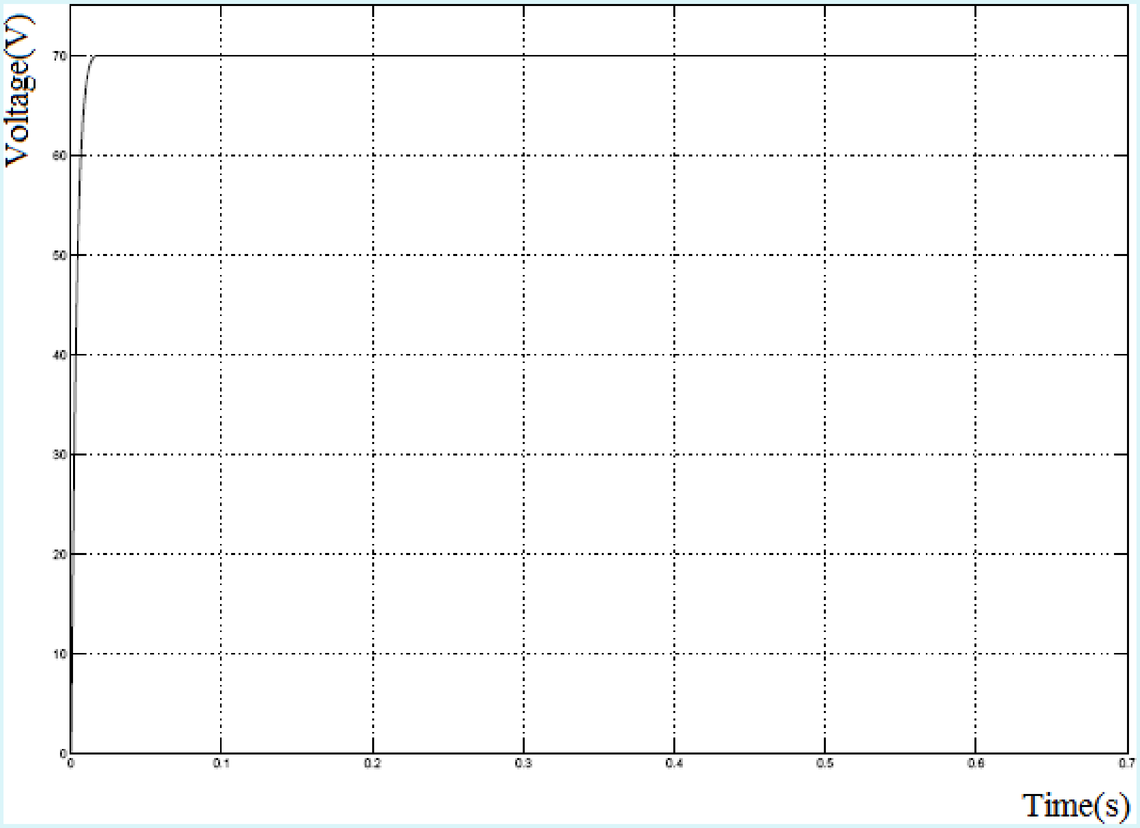

Figure 3.8 Example output waveform of the boost converter.

3.3 Chain Cell Converter Model

The outputs of five PV modules are given to five boost converters. All the outputs of these five boost converters are given to five "cells" of the 11-level chain cell converter to produce AC output voltage of 230 Vrms at 50Hz frequency. The structure and operation of chain cell converter is explained in section 2.2.2. The schematic of an 11-level chain cell converter is shown in figure 3.9.

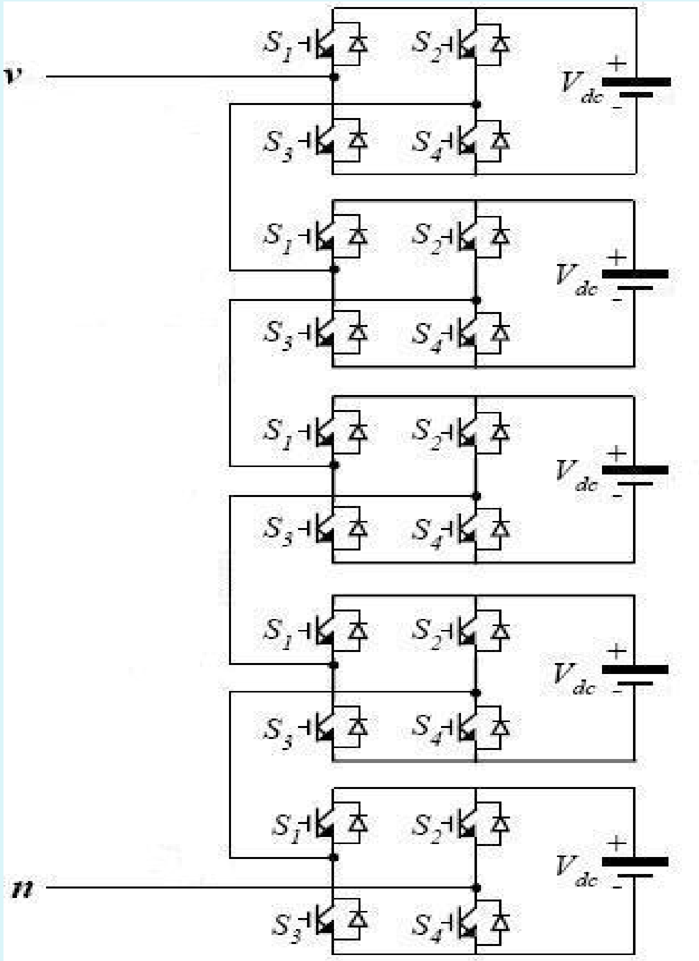

Figure 3.9 Schematic of an 11-level chain cell converter

An 11-level chain cell converter contains five full bridge inverters connected in series. Each full bridge inverter is termed as a 'cell'. So the model of an 11-level chain cell converter is done by first modeling a 'cell'. The model of a cell is shown in figure 3.10.

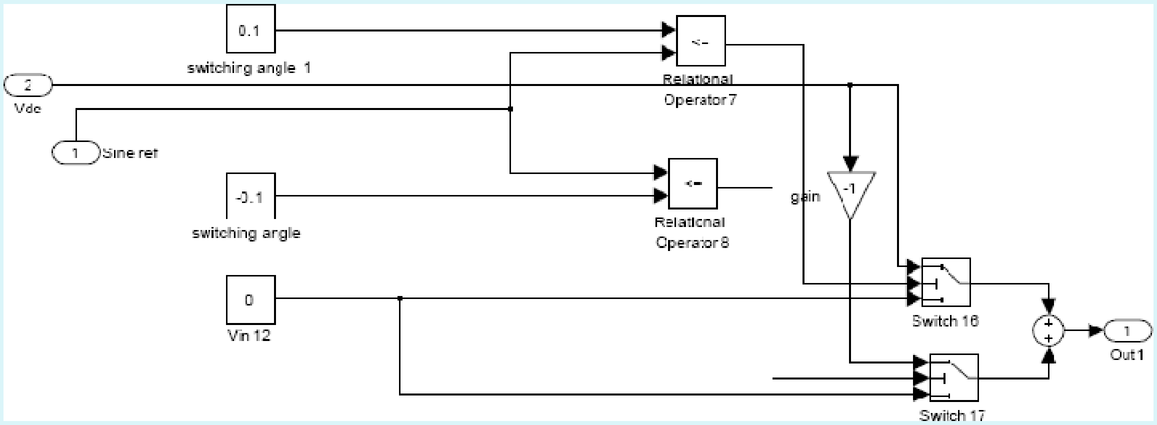

Figure 3.10 Model of a full bridge inverter/cell used in chain cell converter

The model has two inputs and one output. One input is the DC voltage which is the output of the boost converter and the other is the sine wave reference that is used to obtain the pulsating output from the full bridge inverter. The frequency of the output of a full bridge inverter is the same as that of the reference sine wave. Each cell/ full bridge inverter produces a pulsating output that contains three voltage levels +Vdc, 0 and –Vdc where Vdc is the input DC voltage given to each cell. Here the value of Vdc is 70 V. Output pulses from different cells are shown in figure 3.11.

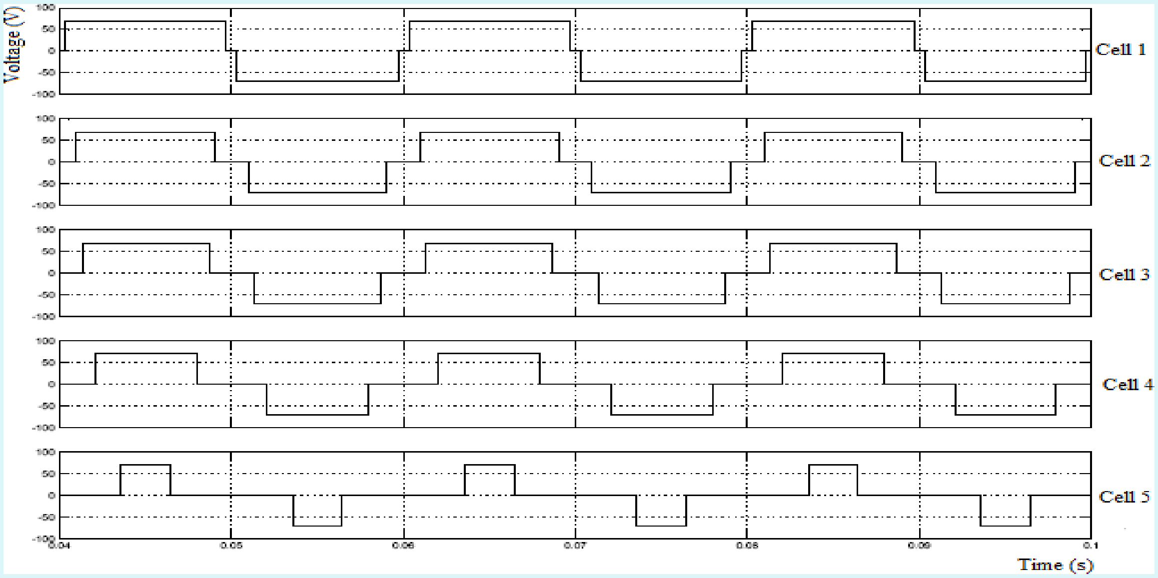

Figure 3.11 Output pulses from 5-cells of the chain cell converter

It can be observed that the frequency of the output pulses of all the cells is same and is equal to 50Hz which is actually the frequency of the sine wave reference given to the cells. So the switches in a chain cell converter are operated at a very low frequency of 50Hz. Because of this the switching losses are very minimal in chain cell converter. The peak values of all the pulses are same but they differ only in their pulse-widths. This is because the switching signals of all the cells are not same. Each cell is given switching signals at a different switching angle with respect to the reference sine wave. Hence each cell gives an output of varied pulse widths. These switching angles are chosen such that when these output pulses are added an approximated sine wave is obtained as the output of the chain cell converter. The basic model of a cell is used to model the chain cell converter as shown in figure 3.12. Five such cells are required for an 11-level chain cell converter.

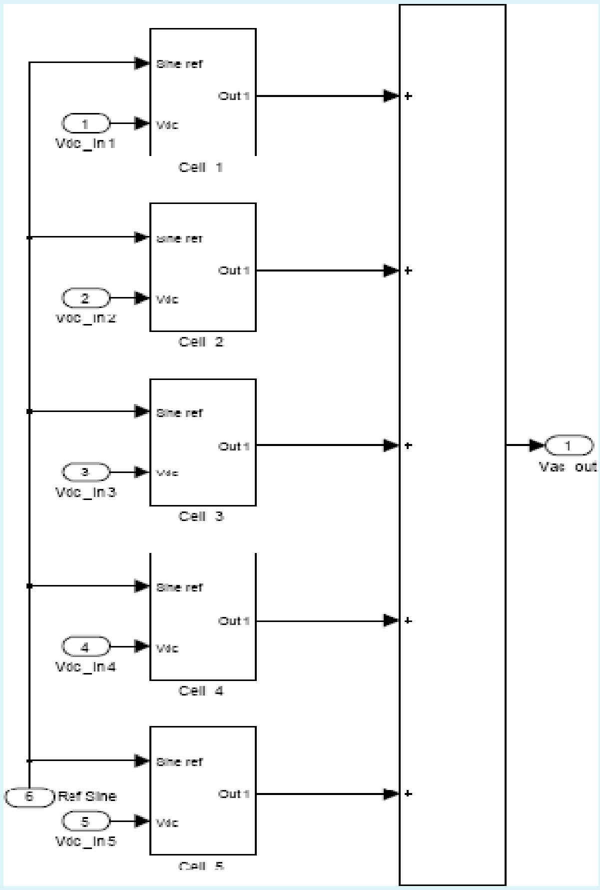

Figure 3.12 11-level chain cell converter model

In order to get an AC output of a frequency equal to that of the reference sine wave, all the cells are given the same reference sine wave. The output of the 11-level chain cell converter is obtained by adding the pulsating outputs of each cell. A typical output waveform of an 11-level chain cell converter is shown in figure 3.13. It can be observed that the output of the chain cell converter in figure 3.11 has 11 levels of voltage *viz.* +5Vdc, +4Vdc, +3 Vdc, +2 Vdc, + Vdc, 0, - Vdc, -2 Vdc, -3 Vdc, -4 Vdc and -5 Vdc (assuming each cell is given a DC input voltage of same magnitude) and hence the name 11-level chain cell converter. Here each cell is given an input of 70V. So the peak of the output voltage is 350V.

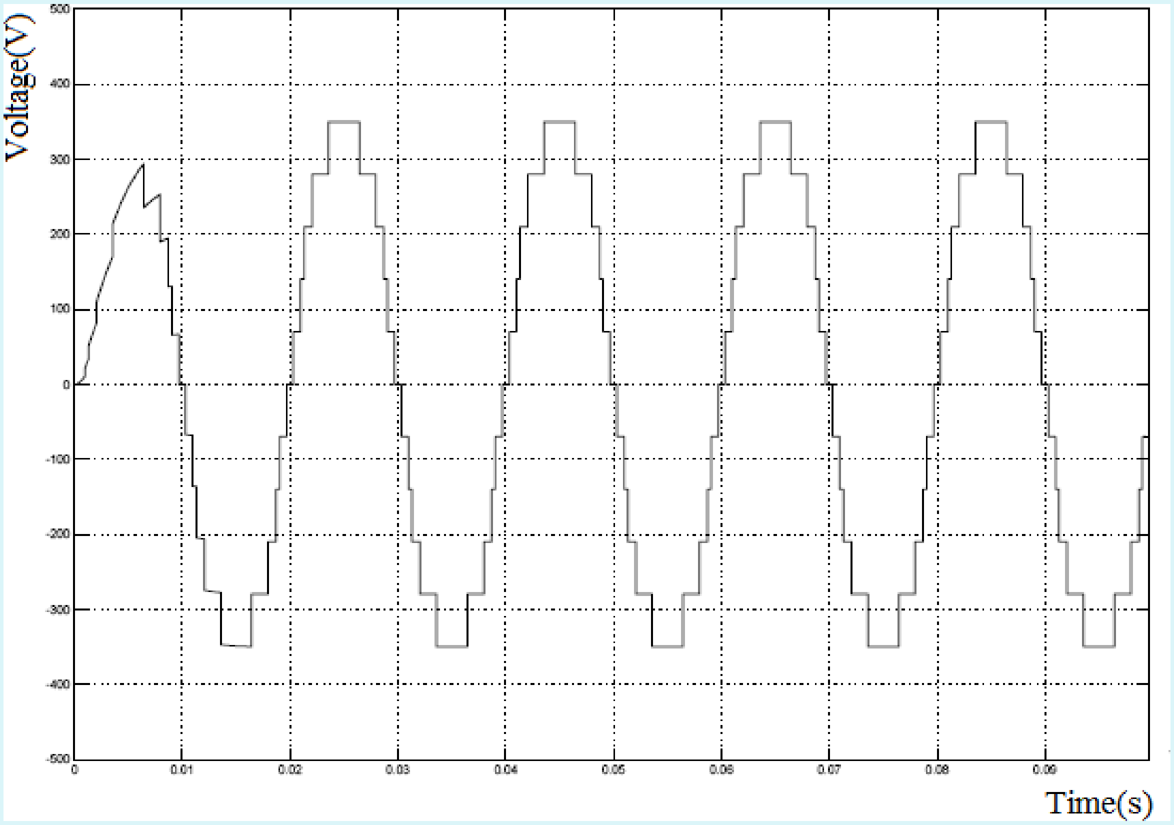

Figure 3.13 Output voltage waveform of an 11-level chain cell converter

3.4 Pulse Width Modulation (PWM) Inverter Model

In order to compare the performance of PWM inverter and chain cell converter, modeling of PWM inverter is done. The Simulink model of a PWM inverter is shown in figure 3.14. A PWM inverter is a full bridge inverter whose switches are operated with pulse width modulated signals generated by comparing a 50 Hz sine wave reference and a high frequency triangular wave. These PWM signals are given to the switches of the full bridge inverter to get a pulsating output as shown in figure 3.15. This pulsating output when passed through a low-pass filter, generally an L-C filter, gives a sine wave output of 50 Hz frequency. The frequency of the output signal depends on the frequency of the sine wave reference used to generate PWM signals. Because sine wave is used as a reference to generate PWM signals the inverter is called as Sine-PWM inverter. The performance of the PWM inverter and chain cell converter are compared in chapter-4.

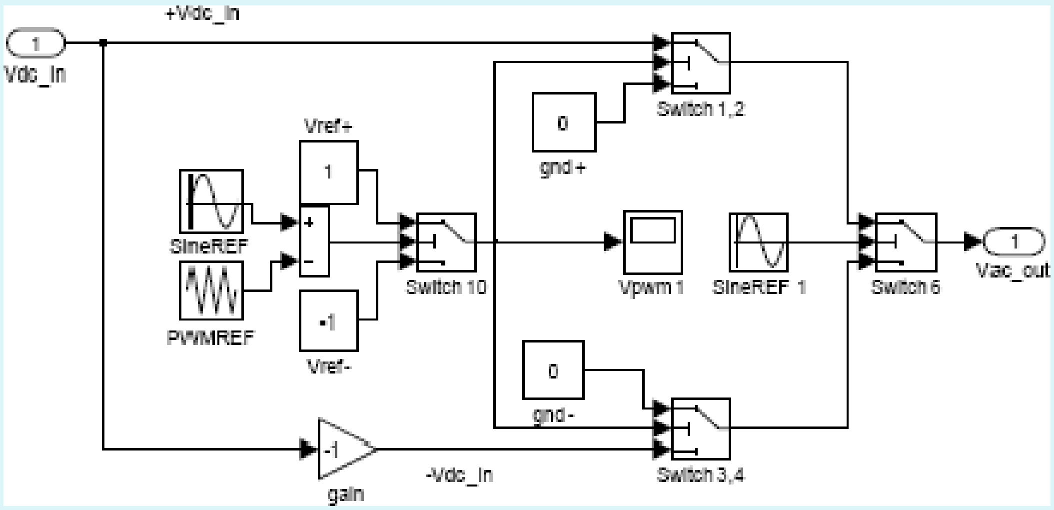

Figure 3.14 PWM Inverter model

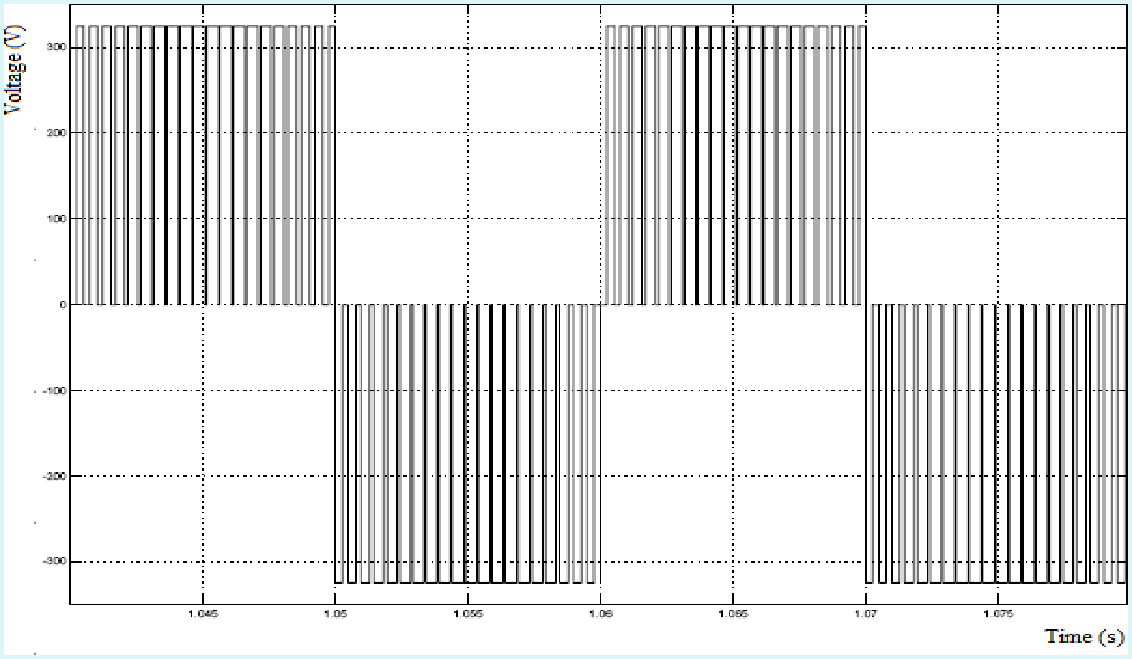

Figure 3.15 PWM Inverter Output voltage waveform

5. Control Unit Model

The control unit is responsible for the operation of the entire system. It implements the following tasks/algorithms:

- Generating reference sine wave for the operation of chain cell converter
- Grid interfacing algorithm
- Protection of the system under the following conditions:
  1. Grid failure conditions i.e., grid voltage drops below a certain value.
  2. When grid voltage exceeds certain threshold value.
  3. Under-voltage condition on the PV array side.
  4. Inverter voltage is less than Grid voltage.

The control unit model is shown in figure 3.16. It has seven inputs and three outputs. The seven inputs include chain cell converter output voltage, grid voltage and five voltage signals of five PV modules. The three output signals are reference value for boost converter on which the output of boost converter depends, reference sine wave for chain cell converter and ON/OFF signal for the switch connecting the system and grid.

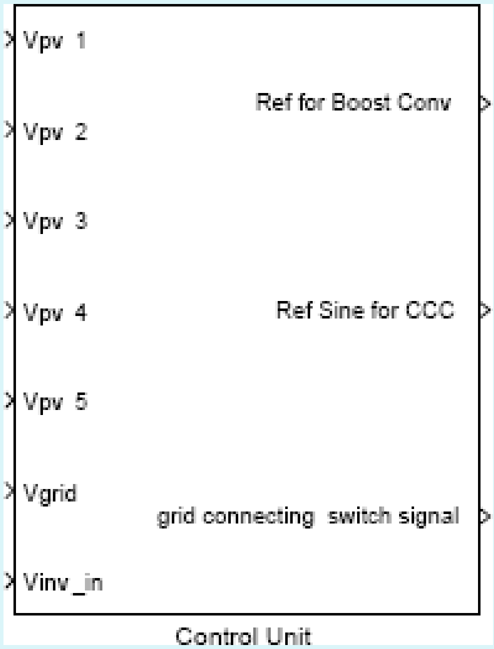

Figure 3.16 Control Unit Model

The chain cell converter output voltage and grid voltage signals are used to generate reference sine wave signals for the operation of chain cell converter and to implement grid interfacing algorithm. The PV module voltage signals are used to “switch off” the system when the PV modules do not give sufficient voltage output during low insolation conditions. The term “switch off” is used in the sense that the signals to all the switches in the power conditioner block are turned off. So during that condition there will be no output from the PV system and it is disconnected from the grid. The algorithm for grid interfacing is explained in section 2.3.2. From the algorithm it is implied that the peak values of chain cell converter output and grid voltage are to be calculated from the corresponding signals. So a peak detector block is modeled for this purpose. The peak detector block is shown in figure 3.17. Also a block that can find the values of inverse- cosine value of the ratio of grid voltage and chain cell converter output voltage is modeled using a look-up table. A transportation delay block is used to introduce some phase difference between the grid voltage and the chain cell converter output voltage which is an important condition to inject power into the grid. The protection system using the seven inputs to the control unit is implemented by comparing the input values with their threshold values and using AND operation between the compare logic outputs for all the inputs, a control signal is generated which decides whether to turn off all the signals given to the switches of the power conditioner and the switch between grid and converter interface. The total internal design of the control unit is shown in figure 3.18. Integrating all the models explained in the previous sections, the total PV system model is shown in figure 3.19.

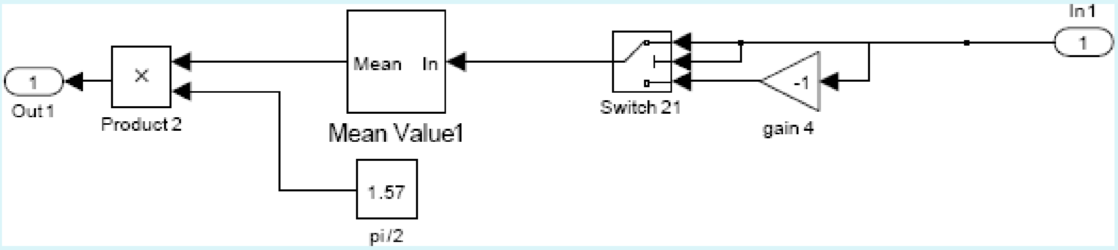

Figure 3.17 Peak Detector Model

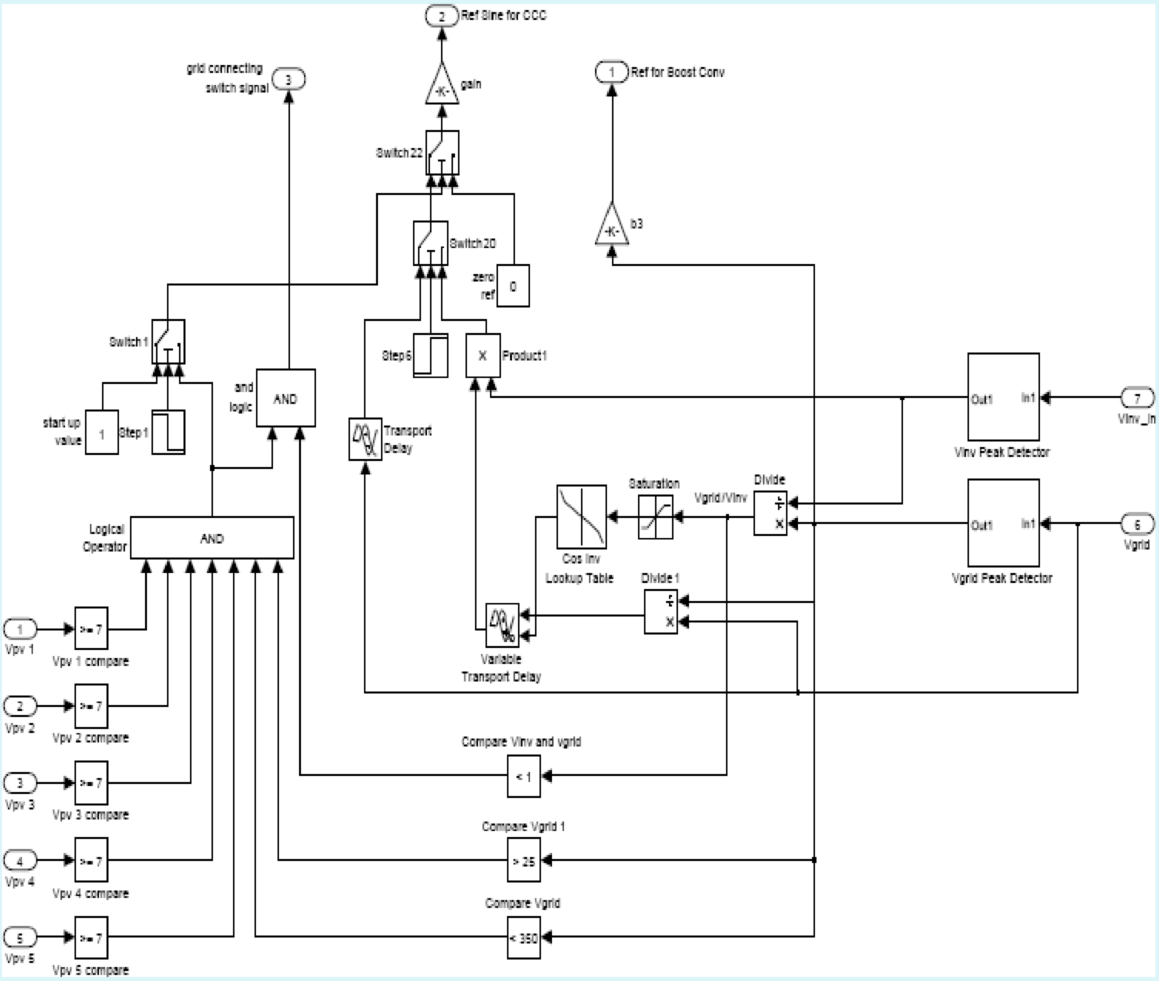

Figure 3.18 Internal Model of the Control Unit

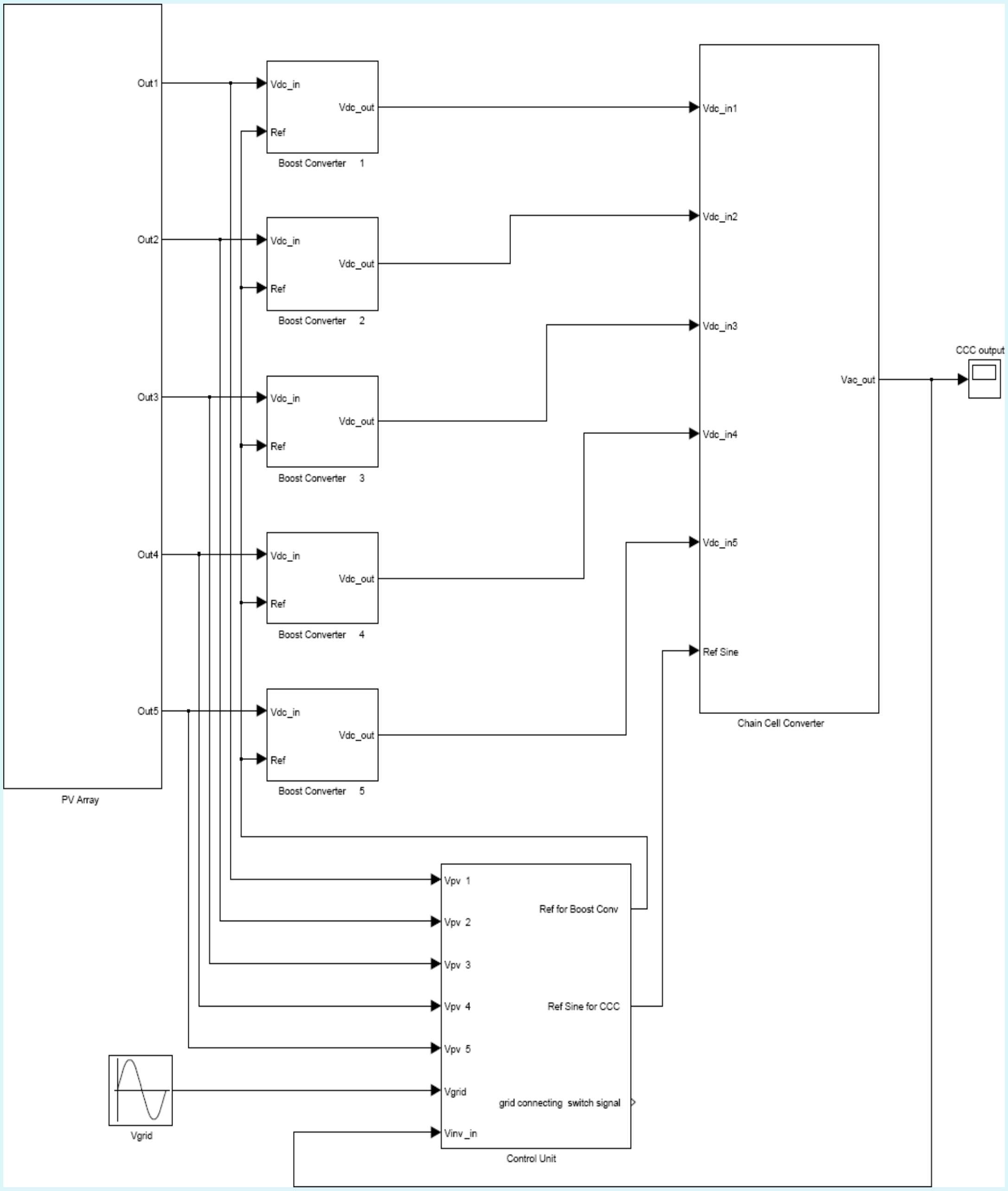

Figure 3.19 Model of the Total PV System

Chapter 4

Results Plotted with Analysis

In this chapter, simulation results obtained using the models are presented and discussed. The performances of PWM inverter and Chain cell converter are compared and discussed first and the performances of various blocks, both individually and as a unit, are discussed using the simulation results in the later part of this section.

4.1 Comparison of PWM Inverter and Chain Cell Converter

The performance of PWM inverter against chain cell converter is compared in Figures 4.1 to 4.6. The output voltages of the PWM inverter and chain cell converter are shown in Figures 4.1 and 4.2 respectively. The odd harmonics (including fundamental) in the outputs of PWM inverter and chain cell converter are shown in Figures 4.3 and 4.4 respectively. It is observed that the 3^{rd} harmonic value is 80V (approx.) in PWM inverter and the same is 20V (approx.) in chain cell converter, which is quite low when compared with the PWM inverter. The total harmonic distortion (THD) of PWM inverter and chain cell converter output voltages are shown in Figures 4.5 and 4.6 respectively. The THD in chain cell converter is 0.1 which is much lower than that of PWM inverter value of 0.63. Hence it is clear that the performance of the chain cell converter is superior to that of the PWM inverter in various aspects of wave shape and harmonic content in their outputs without employing an output LC filter. So the effect of filter in case of chain cell converter is very less when compared with PWM inverter, because the harmonic content is much less in case of chain cell converter. Hence the chain cell converter is quite suitable for grid connected PV systems than the conventional PWM inverters.

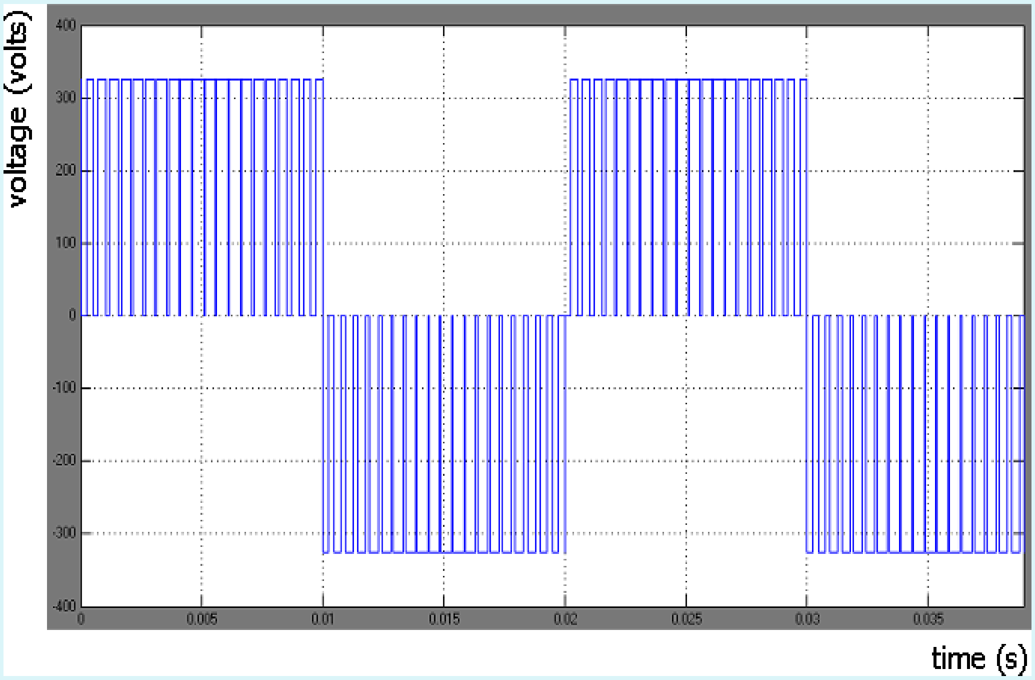

Figure 4.1 PWM inverter output voltage without output filter

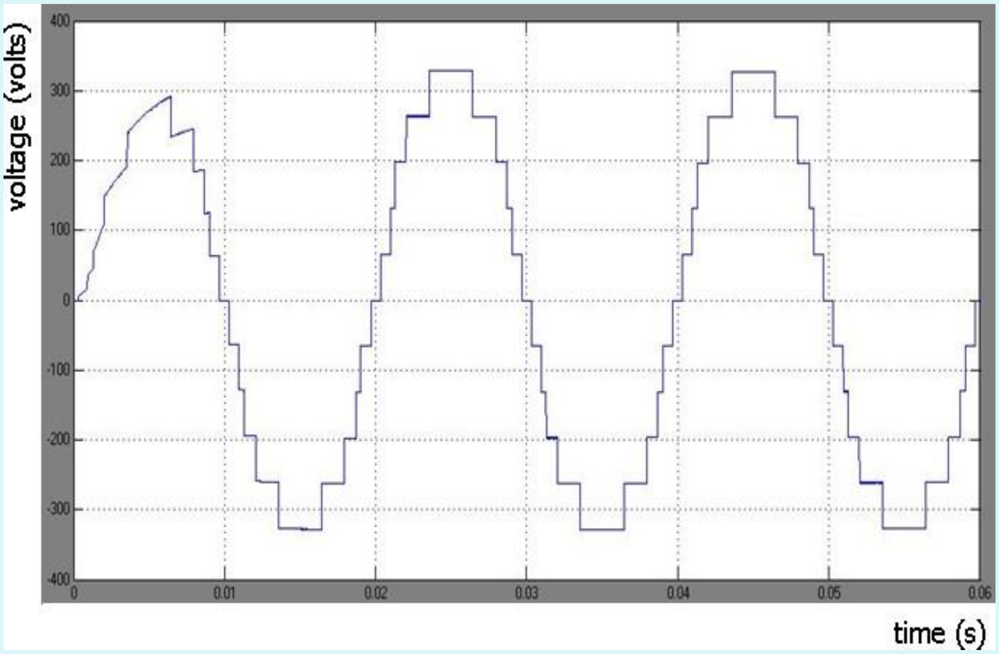

Figure 4.2 Chain cell converter output voltage without output filter

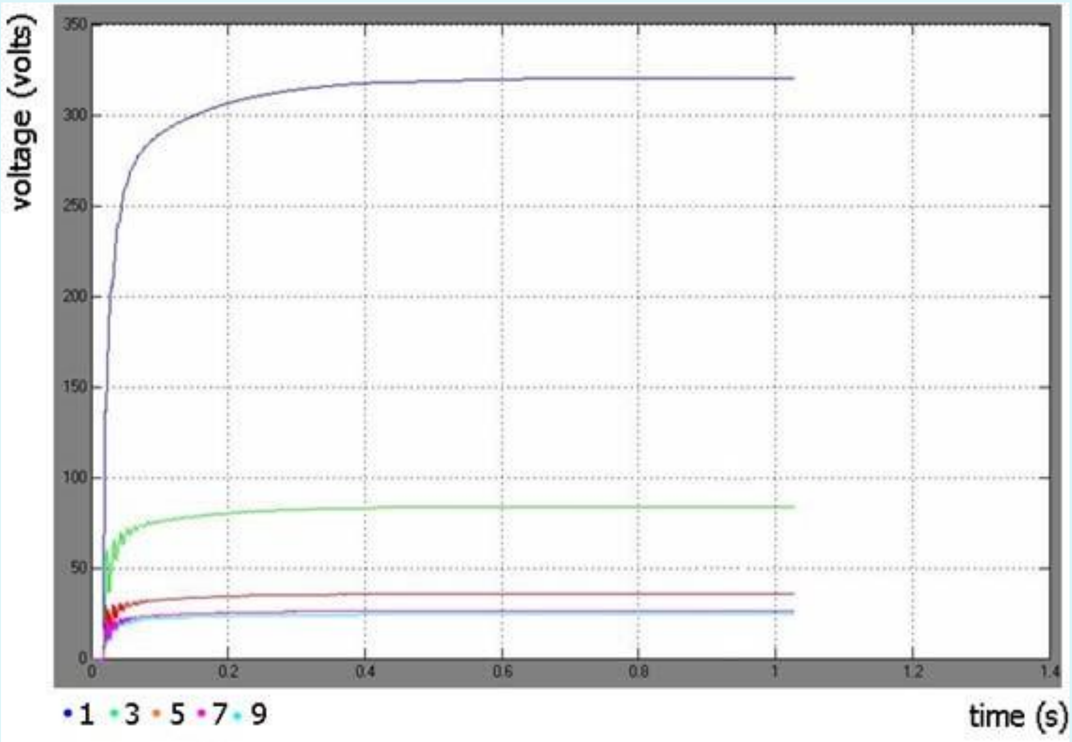

Figure 4.3 Odd harmonics in PWM inverter output without output filter (till 9^{th} harmonic)

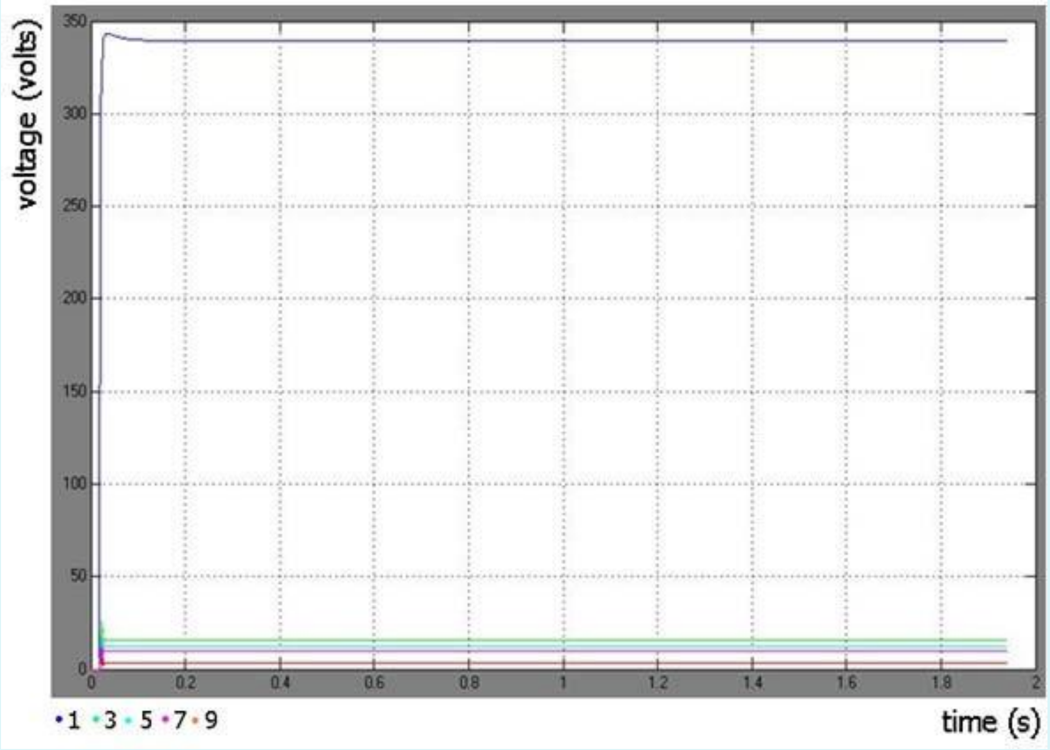

Figure 4.4 Odd harmonics in Chain cell converter output without output filter (till 9^{th} harmonic)

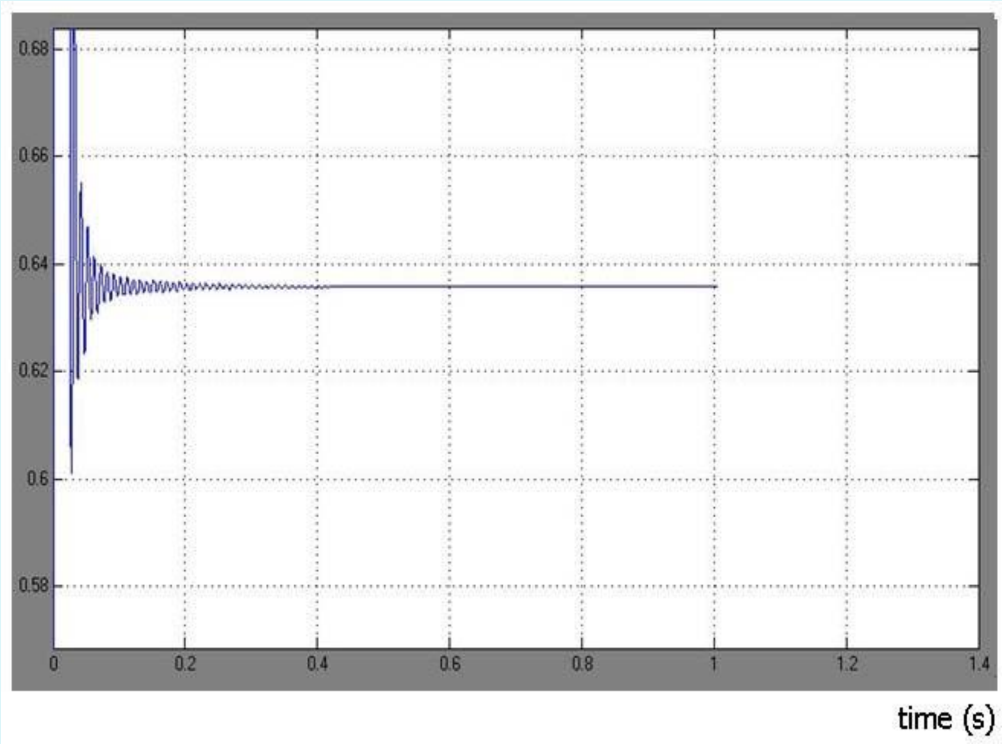

Figure 4.5 Total harmonic distortion in PWM inverter output without output filter

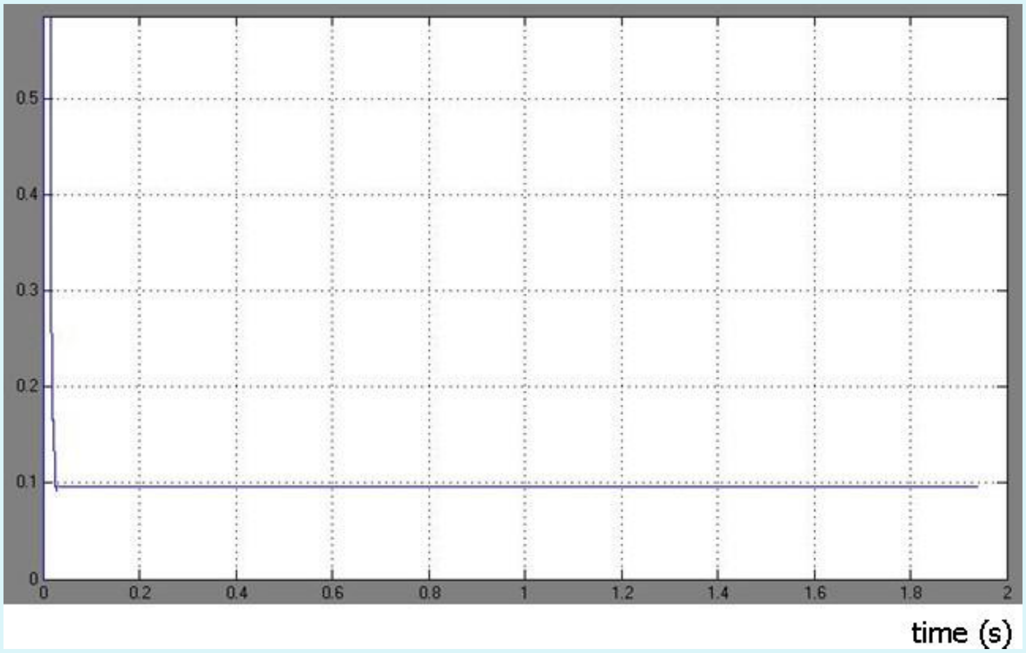

Figure 4.6 Total harmonic distortion in Chain cell converter output without output filter

4.2 Performance of Boost Converter

The performance of boost converter is shown in Figure 4.7. The boost converter gives a stable output voltage of 70V DC. The input to the boost converter in a PV system comes from PV modules whose output voltage changes with solar irradiance levels. So the important aspect in the design of boost converter is that it should give a very stable and constant output in spite of changes in the input voltage. The designed model clearly gave a constant voltage of 70V DC even when the input voltage changes and the same is shown in Figure 4.8. Initially the input voltage is 24V. It has changed to 22V at 0.2 seconds and became 26V at

0.6 seconds. It came back to 24V at 0.7 seconds. In all these stages the output voltage is constant at 70V. Hence the designed model boost converter gave a constant and stable output even when the input has changed.

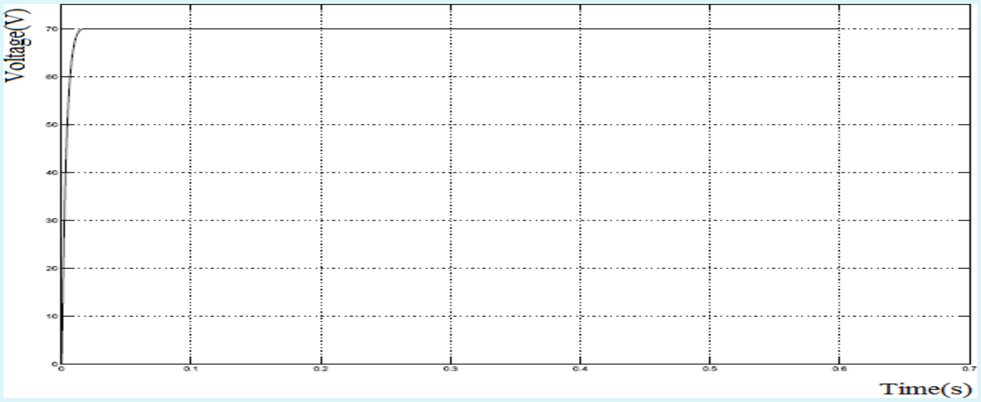

Figure 4.7 Output waveform of the boost converter

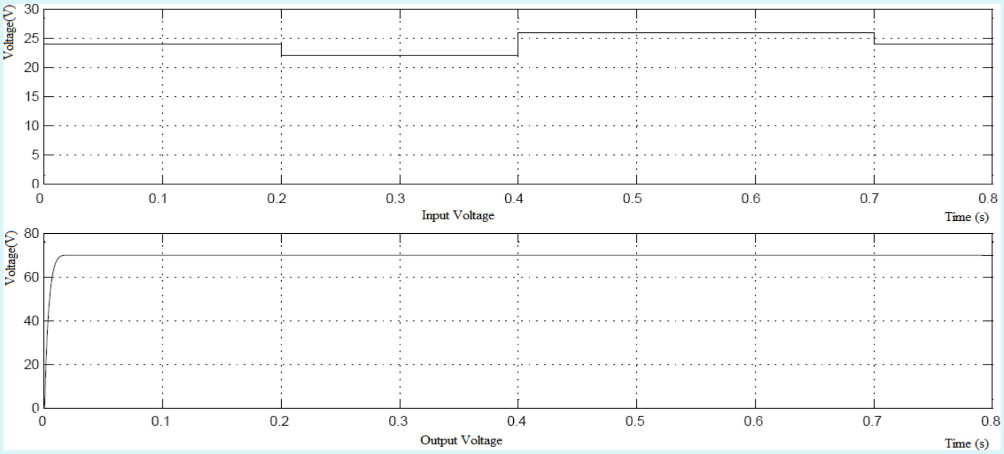

Figure 4.8 Output waveform of the boost converter with changing Input voltage

4.3 Performance of Chain Cell Converter and Control Unit

The 11-level chain cell converter converts the DC input given by the five boost converters to an AC output voltage of near sinusoidal shape and a frequency equal to the grid frequency which is ideally 50 Hz. An important aspect in grid connected PV systems is that the frequency of inverter output voltage must be synchronized with the grid frequency i.e., the inverter output voltage frequency must be equal to the grid frequency and must follow the changes in the grid frequency. For the inverter output to follow the grid frequency, the reference sine wave signal given to the chain cell converter is generated from the grid voltage signal. Because of this the chain cell converter output exactly follows the grid voltage in the aspect of frequency. The reference generation is done by the control unit. The grid frequency is 50Hz, 53Hz and 47Hz in Figures 4.9, 4.10 and 4.11 respectively. It can be clearly observed that the chain cell converter output frequency is exactly following the grid frequency.

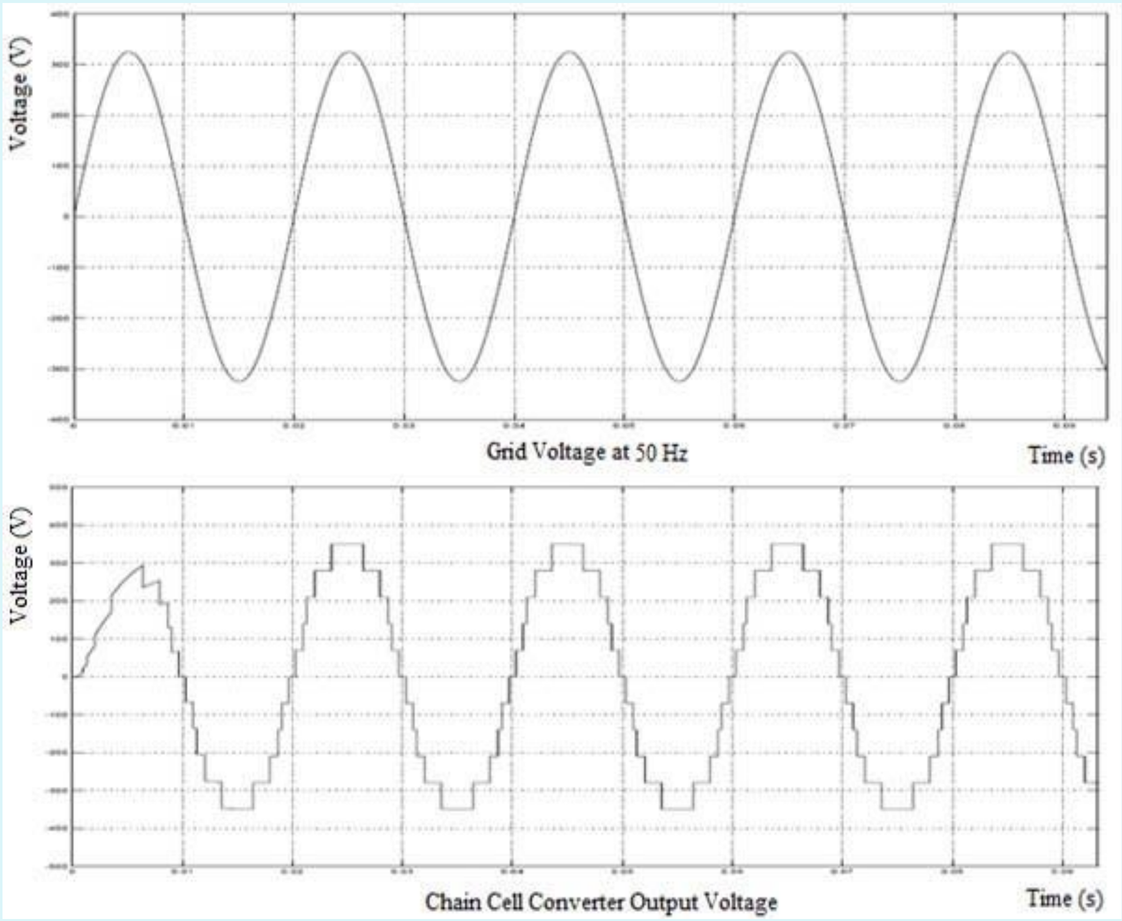

Figure 4.9 Chain cell converter output voltage when grid frequency is 50 Hz

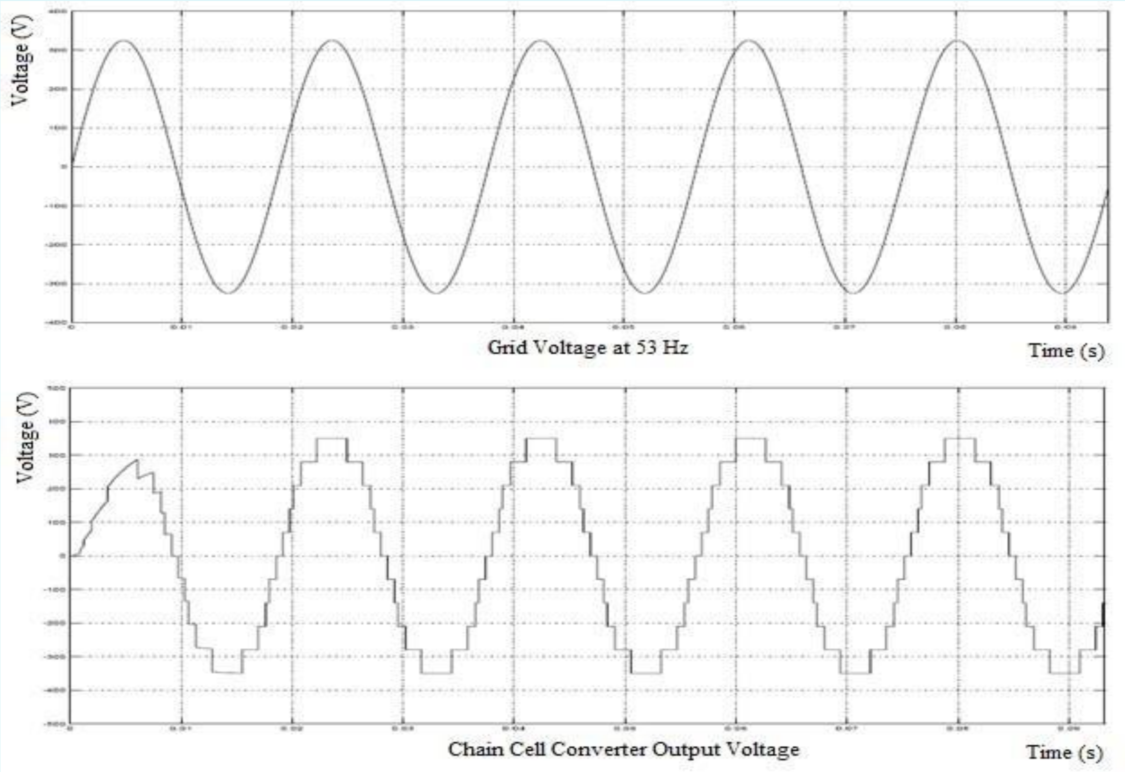

Figure 4.10 Chain cell converter output voltage when grid frequency is 53 Hz

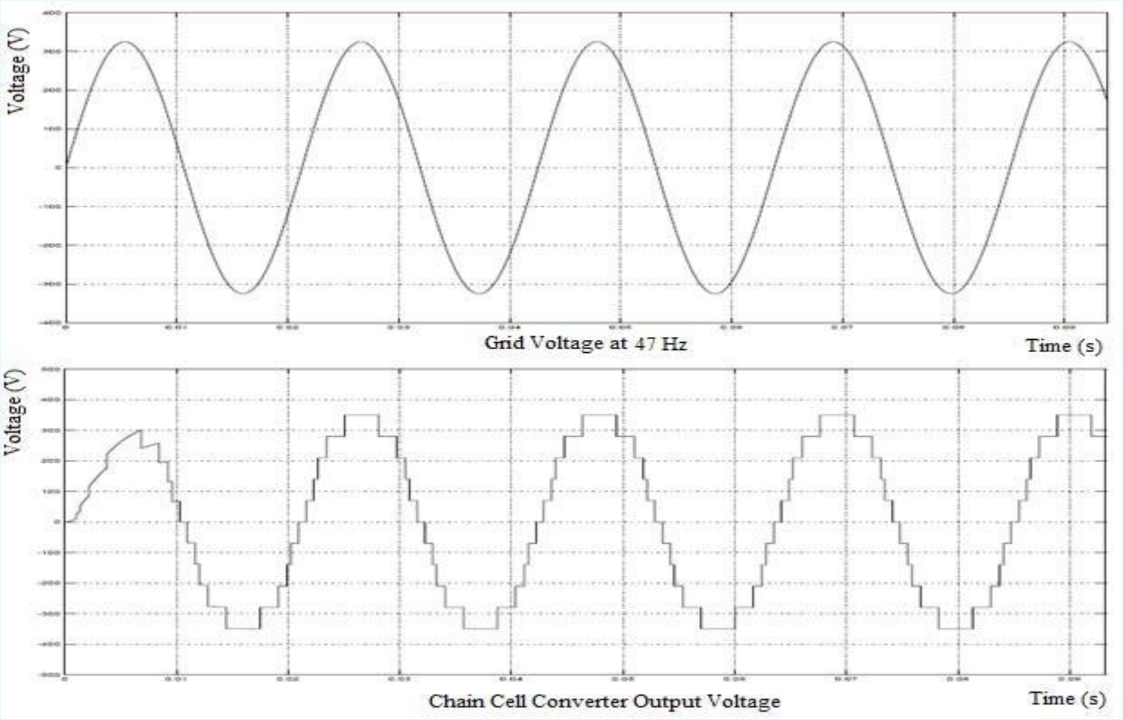

Figure 4.11 Chain cell converter output voltage when grid frequency is 47 Hz

The above simulations are done without introducing any phase difference between the grid voltage and the converter output. The algorithm for grid interfacing is explained in the section 2.3.2. The interface between the converter output and the grid is done using a coupling inductance and is shown in Figure 4.12.

V_C X_C V_G

I_C

Figure 4.12: Grid Interface Model

Where, V_C represents the output voltage of the chain cell converter, V_G represents the grid voltage which is taken as reference, in both magnitude and phase, to control the chain cell converter output, X_C represents the interface inductance. Apart from the coupling inductance shown in the figure 4.12 a switch is also used to close the circuit between converter and grid. The switch is not shown in the figure. The phasor diagram of the interface is shown in Figure 4.13. It follows the relation $V_C = V_G + jX_CI_C$.

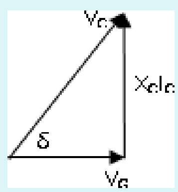

Figure 4.13: Phasor Representation of Grid Interface Model

It is evident that to inject power into grid, converter output voltage must be greater than that of grid voltage and must be leading in phase compared to grid voltage. In order to achieve the phase lead in the converter output, the phase is added to the reference sine wave generated from the grid voltage. The calculation of this phase value is already explained in section 2.3.2. This new reference which has some phase lead is given to the chain cell converter for its operation. One more important condition for injecting power into grid is that the converter output voltage must be greater than that of the grid. The converter output voltage depends on the output of the boost converter. So in order to achieve proper level of voltage at the converter output, the boost converter is modeled to give sufficient DC output. The comparison between the converter output and the grid voltage is shown in Figure 4.14.

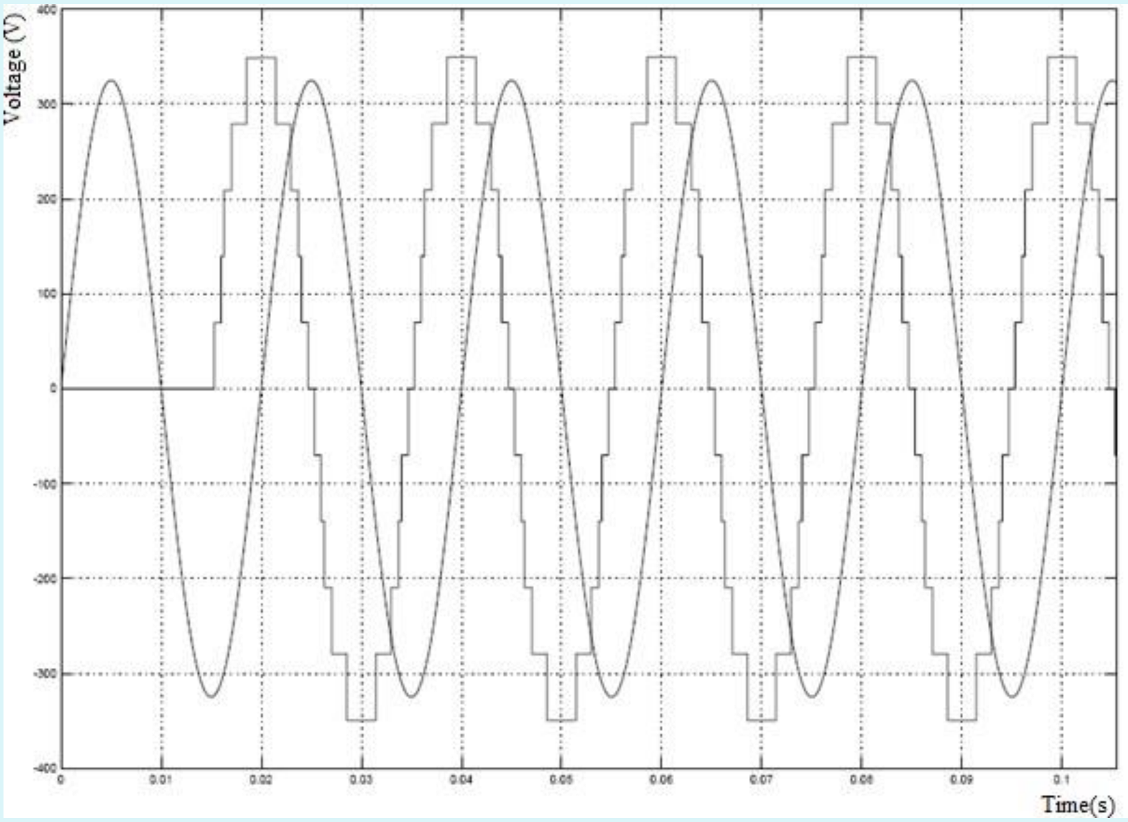

Figure 4.14 Comparison of converter output voltage and the grid voltage

It can be observed that both magnitude and phase of the converter voltage are in accordance with the required conditions of injecting power into grid. Apart from generating proper reference for the operation of chain cell converter, the control unit has to generate other signals for system protection. These signals are generated based on the comparison of PV module voltages, ratio of magnitudes of converter output and grid voltages, and the grid voltage with their corresponding threshold values. The threshold for PV module voltages is fixed as 7V. The reason for this is that, for 7V input, the switch in the boost converter is to be operated at 90% duty cycle, which is the practical limit, to give an output of 70V. So whenever any module gives voltage less than 7V, a signal is generated by the control unit to turn off all the switching signals given to the switches of power converter and the switch that connects the converter and the grid. This is illustrated in Figure 4.15. During time = 0.1 s and 0.2 s, PV module voltage is 5V which is less than the threshold value of 7V. So during that interval the reference sine signal for converter operation is zero and hence the converter output is also zero. At the same time the interface switch between converter and grid is open.

At 0.2 s, when the PV module voltage is more than 7V, the operation is resumed and the switch between grid and converter is closed.

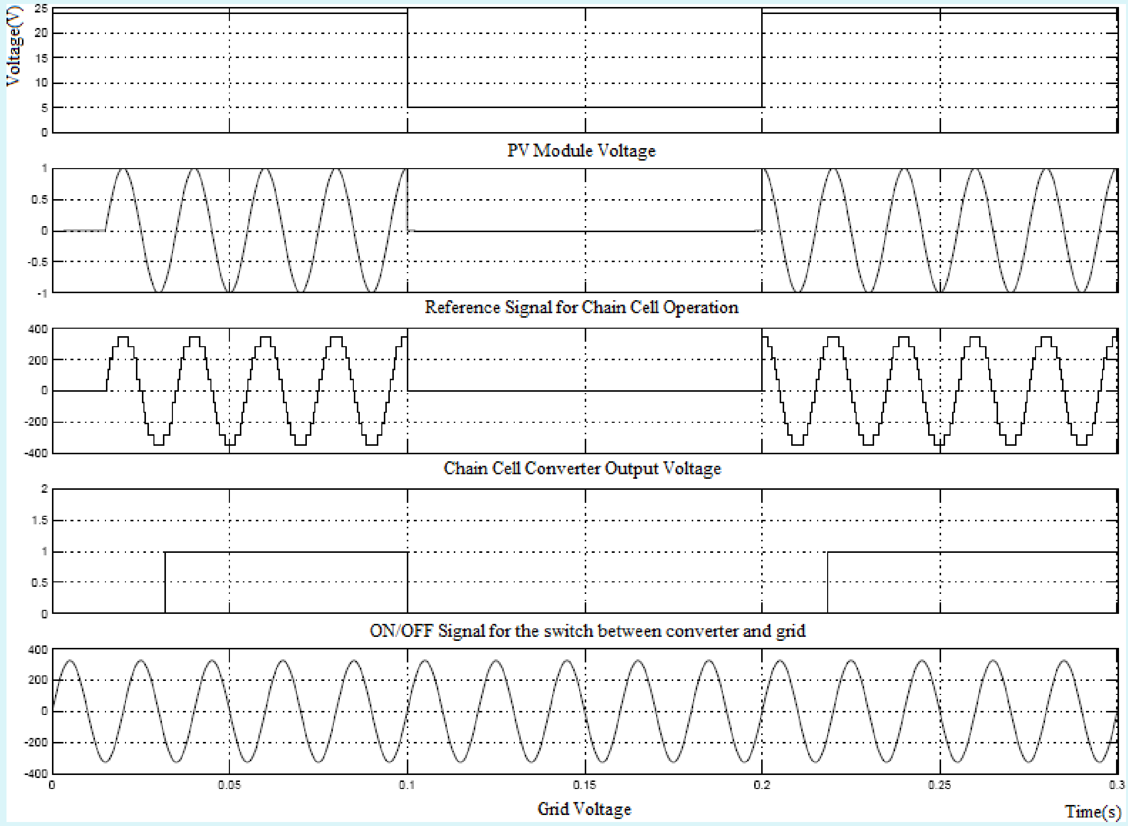

Figure 4.15 Illustration of Control signal generation for system protection when PV module voltage falls below a certain threshold value

Similar action is taken whenever the grid voltage exceeds the converter output voltage and also when grid voltage falls to zero volts i.e. grid failure condition. This is illustrated in figure 4.16

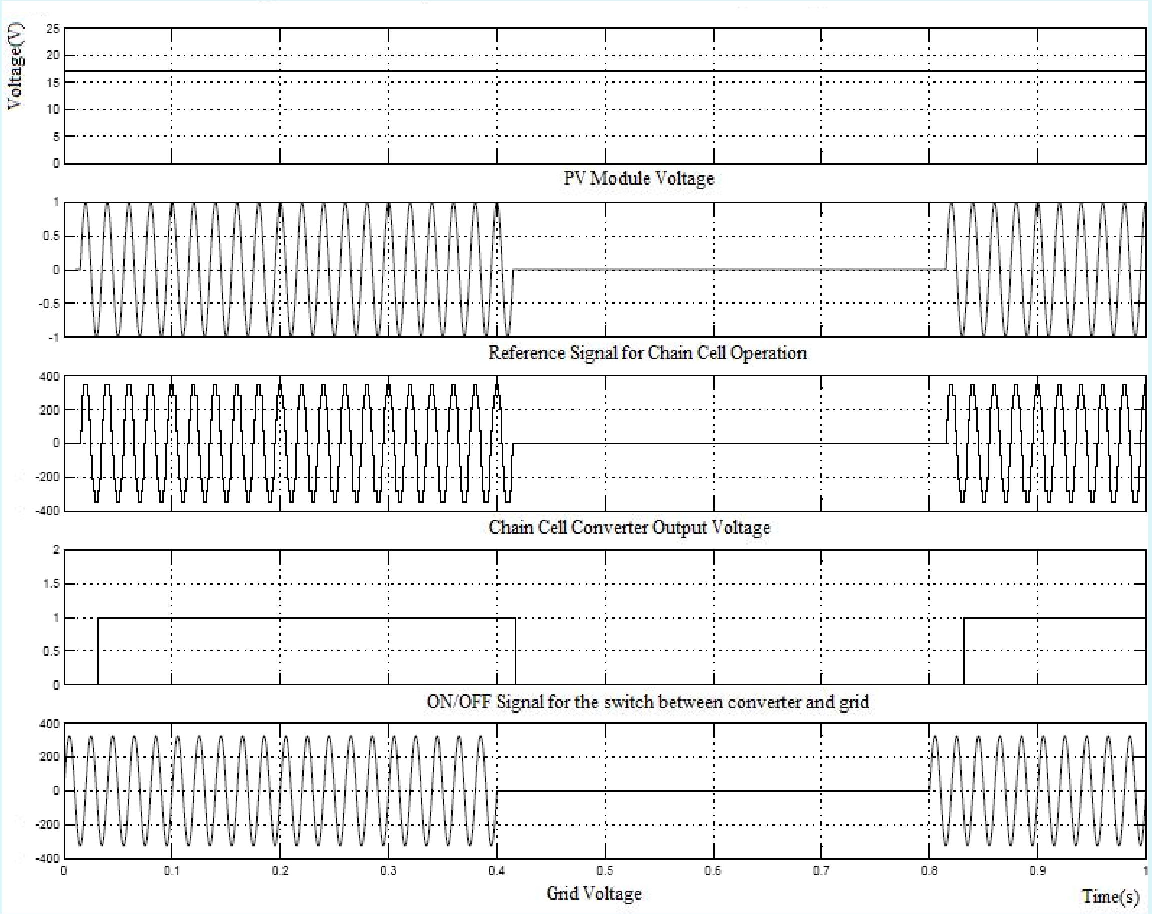

Figure 4.16 Illustration of Control signal generation for system protection when grid voltage falls to zero volts

Hence the designed model of the PV system is working satisfactorily under all possible conditions.


THANK YOU
for your
ATTENTION!