Transient Stability Analysis of Grid Connected Photovoltaic System

Major Project Report

Submitted in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING
(Electrical Power Systems)

By

Jatin K. Mistry
13MEEE27

DEPARTMENT OF ELECTRICAL ENGINEERING
INSTITUTE OF TECHNOLOGY
NIRMA UNIVERSITY
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Undertaking For Originality of the Work

I, **Jatin Mistry (Roll No:13MEEE27)**, give undertaking that the Major Project en-titled **"Transient Stability Analysis of Grid Connected Photovoltaic System"** submitted by me,towards the partial fulfillment of the requirement for the degree of Master of Technology in Electrical Power System, Electrical Engineering, under Institute of Technology, Nirma University, Ahmedabad is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere,it will result in severe disciplinary action.

....

Signature of Student

Date:

Place:Ahmedabad

Endorsed By:

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Project Guide

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Ahmedabad

Certificate

This is to certify that the Major Project Report entitled **"Transient Stability Analysis of Grid Connected Photovoltaic System"** submitted by **Mr.Jatin K. Mistry(Roll No: 13MEEE27)** towards the partial fulfillment of the requirements for the award of Degree of Master of Technology (Electrical Engineering) in the field of Electrical Power Systems of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Success comes in step's. To achieve success not only researcher contributes his efforts but there are many more people who helps researcher in achieving his goal. I take opportunity to express my gratitude to the people who have been there in successful completion of this project.

I would first acknowledge my Guide**Prof. Vihang M. Dholakiya**, Asst. Professor, Institute of Technology, Nirma University. I thank him for his continuous efforts, co-operation, support and encouragement. I thank him for giving me guidance and motivation at every level of the project. Without his efforts and advise this project would not be materialized.

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Jatin K. Mistry
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Abstract

In late years, lack of adequate transmission capacity, limitation in constructing new transmission lines, growing demand of customers and emerging electricity market have contributed to the use of Distributed generation, in the form of small or large DG. Many of the DG are renewable sources of electric generation and thus helps in mitigation of the adverse environmental impacts. Solar Energy is one of the major alternative sources of vitality. There has been a considerable addition of electricity generation from solar energy conversion system in later years.

Most of the photovoltaic plants are grid connected. The solar array at different insolation level has been materialized. To achieve maximum power an circuit has been developed in order to trace the maximum power of the system. The process of extracting the maximum power from the terminal voltage is called maximum power tracking (MPPT). In this thesis, a high rated power array(600MW) have been considered for integration at the 3-phase lines of 220kV, using two stage configuration (DC-DC boost converter and DC-AC converter). The DC-DC converter has been used to boost the voltage and ensuring the MPPT of the PV array.

The controllers for grid connected photovoltaic have been developed using PI method. As the system is grid connected there are many chances of occurring faults in the system, transient faults are likely to occur in the system. The GCPS transient response to grid faults and varying atmospheric condition has been materialized. A grid connected photovoltaic system with its transient analysis has been carried out in PSCAD X4(v4.5.1) software and analysis of the same is carried out.

Nomenclature

V_m .... Maximum Voltage, Volts

I_m .... Maximum Current, Amperes

P_m .... Maximum Power, Watt

R_s .... Series Resistance Ω

R_{sh} .... Shunt Resistance Ω

I_{ph} .... Short Circuit Current, Amperes

I_{sat} .... Saturation Current, Amperes

I_{sato} .... Saturation Current at STC

I_d .... Diode Current, Amperes

q .... Electronic Charge, C

N_s .... Number of cells in series

N_p .... Number of cells in parallel

E_{gap} .... Energy of Band gap, eV

K .... Boltzmann's constant, J/K

T .... Cell Operating Temperature, K

T_r .... Reference Cell Temperature, K

T_{amb} .... Ambient Operating Cell Temperature ^0C

S .... Solar Irradiance, W/m^2

V_{com} .... Voltage to compensate temperature, Volts

Abbreviation

GCPS .... Grid Connected Power System
STC .... Standard Test Condition
PSCAD .... Power System Computer Aided Design
PV .... Photovoltaic
DG .... Distributed Generation
T & D .... Transmission and Distribution
NOCT .... Nominal Operating Cell Temperature
MPP .... Maximum Power Point
MPPT .... Maximum Power Point Tracking
IC .... Incremental Conductance
P & O .... Perturb and Observe
IGBT .... Insulated Gate Bipolar Transistor

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Chapter 1

Introduction

1.1 Background

Power system engineering is a huge part of electrical technology. It is chiefly concerned with production of electrical force, transmission from sending to receiving terminal as per consumer requirement, with minimum losses. The ability at the consumer end is frequently submitted to changes due to the variation of load or due to disturbances induced within the duration of transmission line. For this case, the term power system stability is of utmost importance in this field, and is employed to determine the ability of the of the system to cause back its operation to steady state condition within minimum possible time after having undergone some kind of transience or disturbance in the occupation.

Stability limit is another factor that is taken into consideration. The stability limit is defined as the maximum power passed through a given period or it is an arrangement during which is subjected to line disturbance of faulty flow of power. The stability of a system refers to the ability of a system to revert back to its steady state when subjected to a disorder. A generator is synchronized with a bus when both of them have the same frequency, electric potential and phase sequence. Likewise, in distributed generating stations like PV is connected we need to have same frequency, electric potential and phase sequence in order to make the system in stable status.

We can hence determine the power system stability as the power of the power scheme to return to steady state without losing synchronism. Usually power system stability is categorized into:

- Steady State Stability
- Transient Stability
- Dynamic Stability

1.1.1 Transient Stability of Power System

Transient stability of a power system refers to the ability of the system to reach a stable condition following a large disturbance in the network condition. All cases related to large changes in the system like sudden application or removal of the load, switching operations, line faults or loss due to excitation the transient stability of the system come into play. Transient stability deals with the ability of the system to come back into synchronism following a disturbance. Hence, transient stability of the system is the maximum power flow through the network without loss of stability following through short time disturbance. The thesis mainly deals with the transient analysis of grid connected photovoltaic system. When the distributed generation is connected to the existing network it will possess many advantages, but on the other hand it will have many upsets.

1.2 Literature Survey

The literature survey is carried out on different topology of converter and inverter. The prime importance of the survey is to come across different techniques used in grid integration.

- In paper titled as "Design of Photovoltaic Solar Cell Model for stand-alone Renewable System" [2] authored by **Martin Galad** and **Pavol Spanik** discuss the simple mathematical model that describes properties of the photo voltaic solar cell. The paper aims to model PV solar cell and module. Proposed model is verified using the MATLAB software.

- Paper [3] authored by **Weidong Xiao**, **William G. Dunford** and **Antoine Capel**. The paper discuss the novel modelling process, mathematical description of current and voltage are represented by non-linear equations hence difficult to solve. Computer simulation model demonstrates the cell output features in relevance of environmental change and irradiance. There are three types of photovoltaic panels of different material CIS thin film, multi-crystalline silicon and mono crystalline silicon are evaluated.

- In [4] authored by **Mohamed Azab**, circuit based model of photovoltaic array (PV) suitable for simulation studies of solar power systems is proposed. The model is prepared using the Piecewise Linear model. The obtained results of both uniform and mismatched PVs prove the validity of the proposed model to simulate the non-linear behaviour of photovoltaic array not only to understand the operation of PV systems but also to design a proper maximum power point tracker to extract the maximum possible power from the photovoltaic array.

- In [5] authored by **Abdulrahman Y. Kalbat**, presents the grid tied photovoltaic system, which is explained in PSCAD software and harmonic analysis of the system is presented.

- In [6] author **S.Jayachandra Naidu** explains the modeling and control of grid type photovoltaic system. Modeling of photovoltaic system is done through the piece wise linear model and controlling the firing pulse of the IGBT Parks transformation is explained.

- In [7] authored by **Gazi Md. Saeedul Islam**, **Ahmed Al-Durra**, **S.M. Muyeen** and **Junji Tamura** presented a new robust control strategy to improve the steady-state and transient stabilities of a grid connected large scale photovoltaic(PV) system. The proposed control scheme helps in quick voltage recovery against different symmetrical and unsymmetrical faults and ensure a good DC link over voltage protection. With proposed model grid side recovery voltage is fast and DC link over-voltage is very small which is required to avoid the shutdown of the system during fault condition.

- In “Modeling and analysis of a PV Grid-Tied Smart inverters’s support functions” [10] authored by **Benjamin Anders Johnson** explains design, modeling and analysis of grid tied photovoltaic system. The analysis is done through the PSCAD software and harmonic analysis is performed and analyzed. Firing scheme of Inverter is explained properly.

1.3 Problem Identification

Grid integrated PV system , runs normally when there is no fault, but when the fault occurs system is likely become unstable. Such unstable condition will effect the synchronization. The parameter such as voltage, current and frequency are effected. The problem which might occur and effect the system stability are L-L faults, 3L-G faults etc. This problems are tried to explained in the project.

1.4 Objective and Scope

The objective of the project is to perform transient stability analysis of the Grid Connected Photovoltaic System (GCPS). Fault such as L-G faults and 3L-G are aimed to and performance evaluation under such transient situation is targeted. In order to achieve objective scope of work would be:

- Literature survey.
- Rating of the PV array is decided. Design of boost converter in order to provide constant DC link voltage to the inverter.
- Selection of triggering scheme for inverter.
- System would first run in normal condition and then a transient is created for e.g. Fault, voltage sag/swell. and analysis of system is done.

1.5 Outline of Thesis

The work carried out is assembled in different chapters.

- **Chapter 1** includes introduction to project and aim of the project. It includes literature survey, problem identification and scope of the work.

- **Chapter 2** discusses the introduction of distributed generation and photovoltaic system as a distributed source of generation. Basic structure of PV array has been explained and its simulation in PSCAD environment has been done.

- **Chapter 3** will discuss about the stages of P-V integration with grid. The stage include DC-DC converter with MPPT, DC link capacitor and then inverter. This chapter mainly deals with the DC-DC boost converter and maximum power tracking algorithm. The Maximum power has been traced at different solar radiation is shown using PSCAD software.

- **Chapter 4** discusses about the inverter topology. Necessity of PLL is explained. Simulation results under faulted condition are materialized using PSCAD software.

- **Chapter 5** Conclusion and future scope

Chapter 2

Photovoltaic System

2.1 Introduction

With increase in the large demand of electricity, there is a need of many distribution station which are working in parallel or stay connected with the main generating station. This distribution system are mostly photovoltaic systems, wind turbines, fuel cells and many more. There are many advantages of using distributed generation, they are; Flexibility, Improved Reliability, reduce loading of T and D losses etc. On other hand distribution generation has many problems, they are:

- Capital cost of the system.
- Bi-directional flow of power will create voltage instability.
- Effect on system stability and quality of power to customers.

Due to above disadvantages there is need to do transient study of the system. The photovoltaic system is explained in this chapter.
The Photovoltaic based solar system generates electrical energy, when certain semiconductor material exposed to illumination. It is one of the most important renewable source as it is fresh, contamination free, inexhaustible, and can be controlled with minimal variable cost. Due to rapid growth in semiconductors and power electronics technologies, the PV system is earning interest in electrical power applications.

2.2 Basic Structure of PV module

An individual cell produces only 0.5 V, it will be a rare application in which just a single cell is of any use. A PV module consist of a string of N_s number of cells in series and N_p such in parallel. Several PV module can be wired in series to further increase the voltage, and in parallel to increase current to get a PV array. Arrays are made up of some combination of series and parallel modules to increase the power output. A typical configuration of photovoltaic cell, module, and array as shown in figure 2.1.

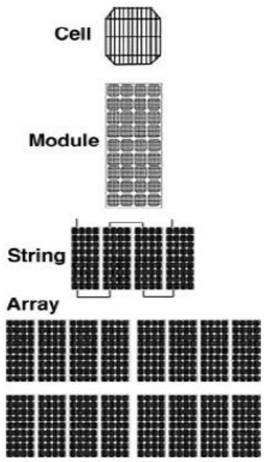

Figure 2.1: Structure of PV module

An equivalent circuit of solar (PV) module having N_s number of cells in series and N_p such string in parallel is shown in figure 2.2 and the mathematical equation relating the module current to the module voltage can be written as,

$$I_{sm} = N_p I_{ph} - N_p I_{sat}\{exp[\frac{q}{AKT}(\frac{V_{sm}}{N_s} + \frac{I_{sm}R_s}{N_p})] - 1\} - \frac{N_p}{R_{sh}}(\frac{V_{sm}}{N_s} + \frac{I_{sm}R_s}{N_p}) \quad (2.1)$$

2.2.1 Equivalent Circuit Model of PV Cell

There are several ways to model PV cell, module, or array for simulation. PV cell model can be coded through advance software. The simplified equivalent circuit of a PV cell can be obtained by a current source in parallel with a diode as shown in

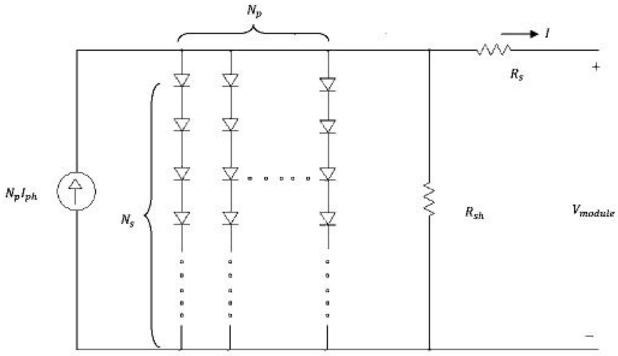

Figure 2.2: Solar Module(N_s - series cells and N_p - Parallel Cell)

figure 2.3. A better equivalent circuit will include a series resistance R_s and a parallel resistance R_{sh} as shown in figure 2.4. Series resistance R_s represents the contact resistance associated with the bond between the cell and its wire leads, and resistance of semi-conductor, which leads to voltage loss of PV cell. R_{sh} is representative of the cell leakage current.

In figures 2.3 & 2.4, I is the output current of the PV cell, V is the output voltage, R_s is the series resistance, R_{sh} is the shunt resistance, I_{ph} is the light generated current, I_d is the diode current and I_{sh} is the leakage current. Voltage and Current equations for the equivalent circuit of the PV cell, are as below.

$$I = I_{ph} - I_d - I_{sh} \tag{2.2}$$

$$I = I_{ph} - I_{sat}\{exp[\frac{q}{AKT}(V + IR_s)] - 1\} - \frac{V + IR_s}{R_{sh}} \tag{2.3}$$

$$I_{sat} = I_{sato}\{\frac{T}{T_r}\}^3 exp[\frac{qE_{gap}}{KA}(\frac{1}{T_r} - \frac{1}{T})] \tag{2.4}$$

Here,

I_{sat} is the diode reverse saturation current(A)

I_{sato} is I_{sat} at Standard Test Condition (S=1000 W/m^2)

I_{ph} is the light generated current or short circuit current (A)

q is the electronic charge (1.6022 x 10^{-19} C)

A is the dimensionless deviation factor from the ideal p-n junction diode (=1 $\sim$ 5)

K is the Boltzmann's contant (1.3807 x 10^{-23} J/K)

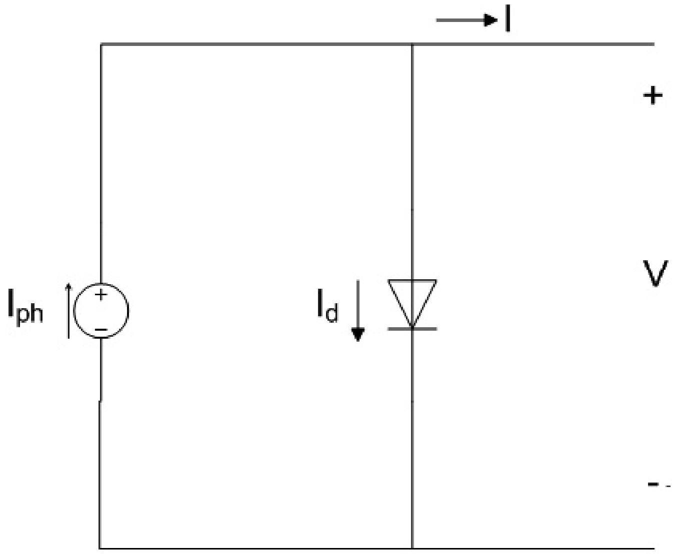

Figure 2.3: Simplified equivalent circuit of a PV cell

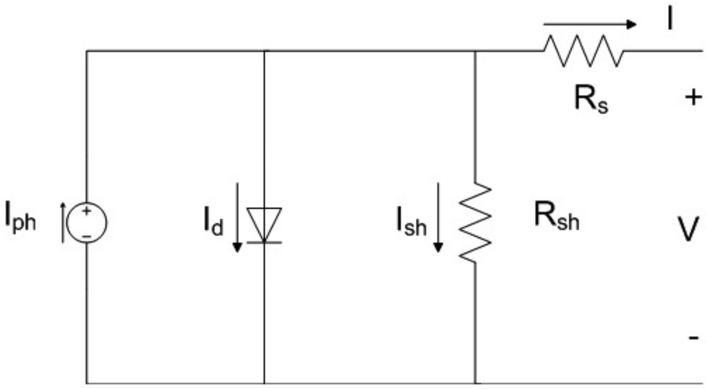

Figure 2.4: Equivalent circuit of PV cell

T is the cell operating temperature (K)

T_r is the reference cell temperature(K)

E_{gap} is the Energy of the Band gap(for Silicon E_{gap} = 1.1eV)

2.3 Impact of Temperature and Insolation on PV Cell Characteristics

PV array characteristics (voltage and current) depends upon the solar insolation level and cell operating temperature. Short circuit current I_{ph}, is directly proportional to the insolation. As insolation drops short circuit current also drops, and frailty versa. Decreasing insolation also reduces the open circuit voltage V_{oc}, but it follows algorithmic relationship that results in a relatively small change in V_{oc}. As the cell temperature increases, the open-circuit voltage decreases substantially, while the short circuit current increases only slightly. Hence, photovoltaic can perform better on cold, clear days than hot ones. For crystalline silicon cells, V_{oc} drops by about 0.37% for each ^{0}C increases in temperature and I_{ph} increases by approximately 0.05% per ^0C [1]. Cell temperature depends on the ambient temperature of the atmosphere and insolation as given in the equation below.

$$T = T_{amb} + (\frac{NOCT - 20}{800})S \tag{2.5}$$

where,
S is solar irradiance and
T_{amb} is ambient atmospheric temperature.
NOCT stands for Nominal Operating Cell Temperature.

The effect of solar irradiance and temperature on PV array characteristics are given in the following equations.

$$I_{ph} = I_{sso}\{1 + k_i(T - T_r)\}\frac{S}{1000} \tag{2.6}$$

$$V_{oc} = V_{ocact}\{1 - k_v(T - T_r)\} = V_{ocact} - V_{com} \tag{2.7}$$

where,
I_{sso} is short circuit current
V_{ocact} is PV module open circuit voltage at Standard Test Condition (STC) at a cell operating temperature of 25^{0}C solar irradiation of 1000 W/m^2
V_{com} is voltage to compensate the effect of the temperature.
k_i(0.0005/^{0}C) and k_v(0.0037/^{0}C) are temperature co-efficient for the short circuit current and open circuit voltage respectively [1].

2.4 P-V system Sizing

2.4.1 Implementation of PV array in PSCAD

In latest version of PSCAD library both Solar panel component and Maximum power point tracking block are present, Dr. A. D. Rajapakse developed both of these components [9].The solar panel model includes all PV cell characteristics mathematically describe in previous section. The model of PV and MPPT block used in PSCAD is as shown in figure 2.5 below.

The Solar panel component will include different component parameter they are P-V

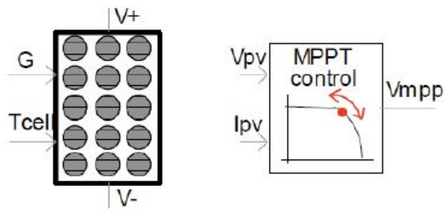

Figure 2.5: Solar Panel and MPPT Block

cell and P-V array parameters, as shown in Table2.1.Cell parameters are taken default. Moving to solar array parameters default values number of cell in series/parallel in each module, the reference solar radiation, and the cell temperature is kept unchanged.Parameters that needed to be determined for this system were the number of modules connected in series/parallel for each array.The output power of single module is approximately 650W. The solar panel we required is of 620MW hence, number of modules connected in series per array is 1200 and number of modules string parallel per array is 700, which is approximately giving the output of 600MW. I-V and P-V curves of solar array at STC (1000W/m^2 and 25 ^{0}C)is as shown in figure 2.6.

Table 2.1: PV cell parameters and array parameters

Effective area per cell(m^2)	0.01
Series resistance per cell (Ω)	0.02
Shunt resistance per cell (Ω)	1000
Diode ideality factor	1.5
Band gap energy (eV)	1.103
Number of modules connected in series per array	1200
Number of modules strings connected in parallel per array	700
Number of cells connected in series per module	108
Number of cells strings connected in parallel per module	4
Reference irradiation (W/m^2)	1000
Reference cell temperature (^{0}C)	25

The below figures 2.7 and 2.8 are at different solar insolation(S) at 600W/m^2 and 800W/m^2 respectively. From the graph it has been seen that power level as well as voltage has been reduced. For different irradiations the maximum power of the panel is different, an MPPT is developed in order to track maximum power at different radiation which will be explained in next chapter.

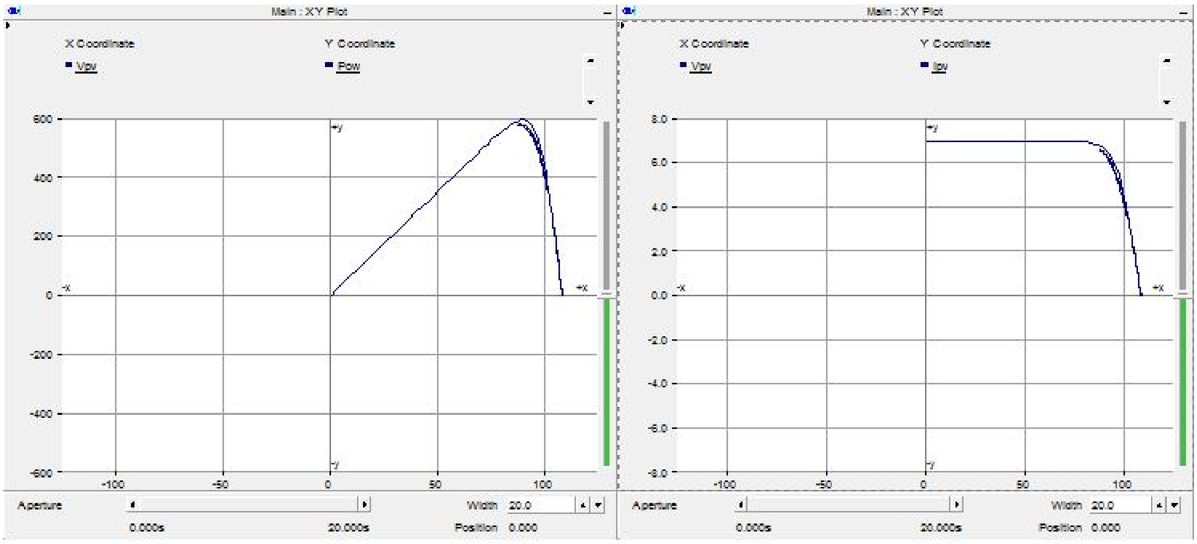

Figure 2.6: PSCAD results of I-V and P-V curve at STC

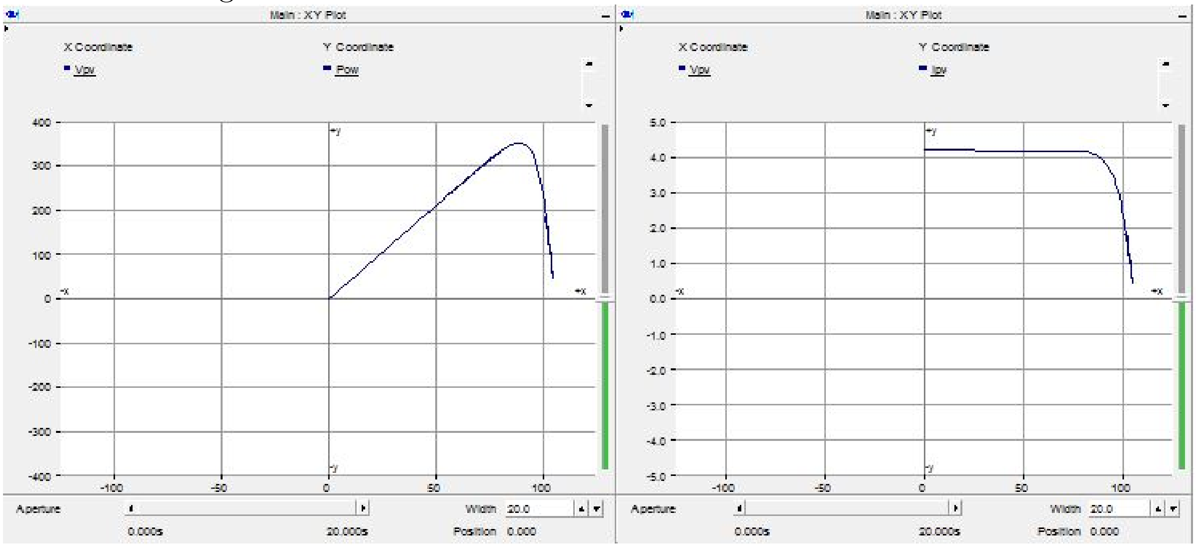

Figure 2.7: PSCAD results of I-V and P-V for S=600 W/m^2

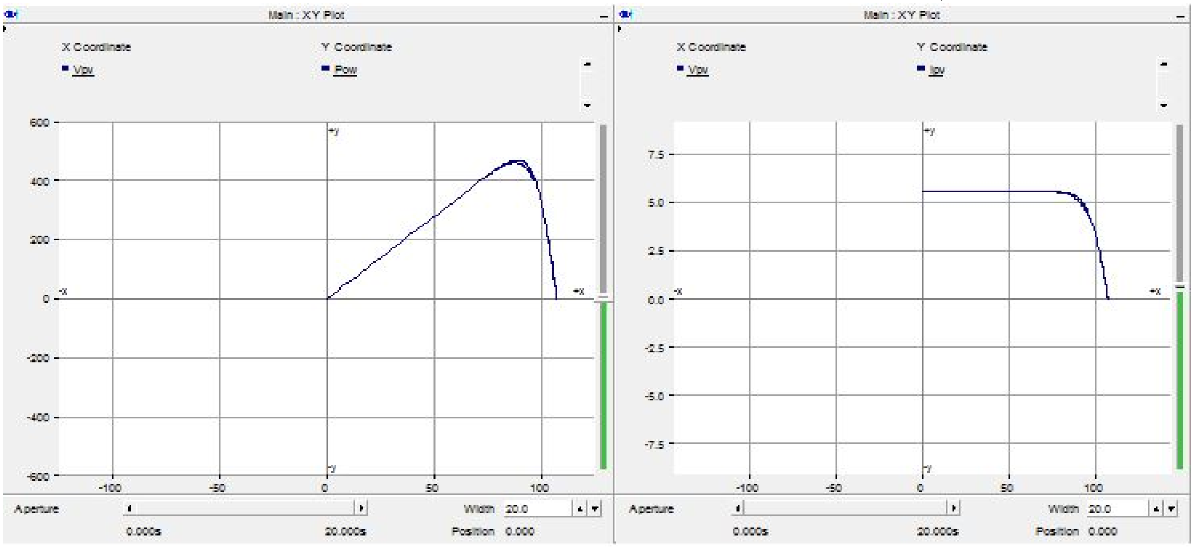

Figure 2.8: PSCAD results of I-V and P-V for S=800W/m^2

Chapter 3

Grid Connected P-V system

Grid Connected system means, the distributed system connected to existing generating station in order to improve reliability, to reduce T & D losses is called grid connected system. When the photovoltaic system is connected to the grid we say it Grid Connected Photovoltaic System(GCPS).

3.1 System Description

The GCPS system has stages of power flow, in order to supply power to the grid. The system consist of PV arrays, DC-DC converter with MPPT tracking, DC link Capacitor and inverter. The PV array description is explained in the above chapter. This chapter will deals with DC-DC boost converter design and control, DC link capacitor and tracking of maximum power at different level of insolation's using MPPT block in PSCAD software.

3.2 DC-DC Boost Converter

The modern electronic system requires high quality, small in size, light-weight, reliable and efficient power supplies. Linear power regulators whose principle of operation are based on voltage or current divider are inefficient. The function of DC-DC converter are:

- To provide constant voltage to inverter.

- To provide isolation between the input source and load.
- In this thesis we have used in order to provide a constant voltage against variation of irradiation.

As PWM converters are have advantages so this converters is used in this work. Advantage of using PWM converters are :

- Include low component cost and high efficiency.
- constant frequency operation and simple to control.
- commercial availability of integrated circuit controller and ability to achieve high conversion ratio for both step up and step down application.

Disadvantages of PWM DC-DC converters is that cause turn-on and turn-off losses in semiconductor devices. Rectangular waveforms also generate electromagnetic interferences.
There are main two different types of converters used according to the application. They are as follows:

- Buck Converter(Step down DC-DC converter)
- Boost Converter(Step up DC-DC converter)

3.2.1 Boost Converter

The step up DC-DC converter, commonly known as boost converter, as shown in figure 3.1. It consist of dc input voltage source V_in, controllable switch S, diode D, filter inductor L, filter capacitor C_o, V_o is output voltage.

3.2.2 Design of Boost Converter

The equivalent circuit if a boost converter is as shown in figure 3.1. The design of boost converter, value of L and C is evaluated in this section. A capacitor C_{in} is connected across the PV source in order to bypass the ripple current and to make the output voltage stiff. As PV system is grid connected it has been assumed that

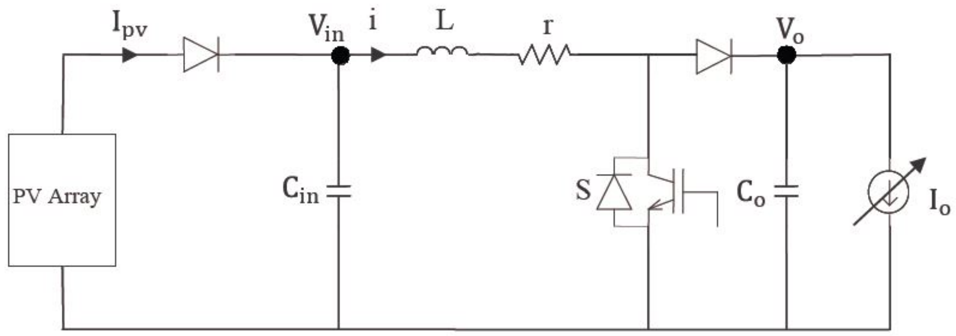

Figure 3.1: Boost converter

Table 3.1: Specification of DC-DC Boost Converter

Specification	600MW PV Array
Input Voltage (V_{in})	80kV
Output Voltage (V_o)	150kV
Inductor Current Ripple (Δ/I)	$\leq$10%
Input Voltage Ripple ($\Delta v_{in}/V_{in}$)	$\leq$1%
Output Voltage Ripple($\Delta v_o/V_o$)	$\leq$1%

output of boost converter is replaced by equivalent resistive load. It is also assumed that inverter injects power to grid at unity power factor. Here PV array of 600MW is used in this work for integration with three phase grid. The component of the boost converter are required to be selected according to specification of the PV array.

3.2.3 Specification of the Boost Converter

As discuss in the above chapter for 600 MW PV array the maximum power output is at 80kV. Hence, the input voltage of the boost converter is taken as 80kV. The output DC link voltage of 600 MW is maintained at 150kV. So output of the boost converter will 150kV. The inductor current ripple is set to be less than 10%, whereas the input voltage and output voltage ripple is set to be less than 1%. IGBT has been used in this work. The switching frequency of IGBT is normally less than 50kHz. In this work, the switching frequency f_s is chosen as 30kHz. Hence, the switching period T_s is equal to 33.33μsec. The specification of the boost converter is given in the Table3.1.

3.2.4 Design of Inductor

The equivalent resistive load of the boost converter, at rated operating point is:

$$R = \frac{{V_o}^2}{P} = \frac{(150kV)^2}{600MW} = 37.5\Omega \tag{3.1}$$

The rated duty ratio is:

$$D = 1 - \frac{V_{in}}{V_o} = 1 - \frac{80}{150} = 0.4667 \tag{3.2}$$

Here, in this work D is taken as 0.50 for better performance. The rated input inductor current can be obtained as:

$$I = \frac{V_{in}}{(1-D)^2 R} = 7.5kAmp \tag{3.3}$$

Based on the requirement specified for the inductor ripple current, we can get:

$$\frac{\Delta i}{I} = \frac{D(1-D)^2 T_s R}{L} \leq 10\% \tag{3.4}$$

Hence,

$$L \geq 10D(1-D)^2 RT_s \geq 3.12mH \tag{3.5}$$

In this work L is chosen as 200mH.

3.2.5 Design of DC link Capacitor

The output voltage ripple restricted to be $\leq$1%. Hence, C_o can be calculated as following.

$$\frac{\Delta v_o}{V_o} = \frac{D}{RC_o f_s} \leq 1\% \tag{3.6}$$

$$C_o \geq \frac{D}{0.01 R f_s} \geq 44.44\mu F \tag{3.7}$$

In this work C_o is selected as 1000μF.

3.3 DC link Capacitor

DC link capacitor is of the upmost importance as it serves three very important functions.

- It minimize the voltage ripple across the PV terminals and which results in a ripple of the output power.
- The capacitor acts as a sink and source every half cycle to help create a balance of power on the DC bus.
- The capacitor is the source for reactive power generation.

3.4 Maximum Power Point Algorithm

As discussed earlier characteristics of the P-V panel is non-linear, hence it greatly depends on the voltage in which it is operating. In order to fully use any solar system, the potential difference across the solar panel terminals needs to be monitored and controlled in such a way that it is always at the maximum power point voltage.
The two most commonly used and studied control algorithms for maximum power point tracking (MPPT) are:

- Perturb and Observe (P and O)
- The Incremental Conductance (IC) methods.

The P and O method calculates the current output power of the solar panel. From this it perturbs the terminal potential difference of the solar panel by incrementing or decrementing it and compares the new calculated output power to the previously estimated one. If the raw value is bigger, then the terminal voltage remains in the way it was incremented or decremented. The algorithm operates in this manner until the maximum power point (MPP) is reached. Nevertheless, the drawback to this method is that once the MPP is reached it continues to oscillate around this period. An attempt to prepare this is to create the voltage perturbation smaller but this results in slower reaction to rapidly changing atmospheric conditions. The IC method was created in order to provide a more dependable alternative to the P and O method. The basic concept of how the IC algorithm finds the MPP is based along the position of the power curve for a solar cell. At the MPP the slope of the power curve is zero, to the left of the MPP the slope is positive, and to the right of the MPP the slope is negative.

By sampling the current and voltage of the solar cell and computing the incremental and instantaneous conductances the MPP voltage can be determined. A detailed flow chart explaining the functioning of the algorithm step by step is shown in figure 3.2

The two main factors for this design choice was the IC methods has ability to better

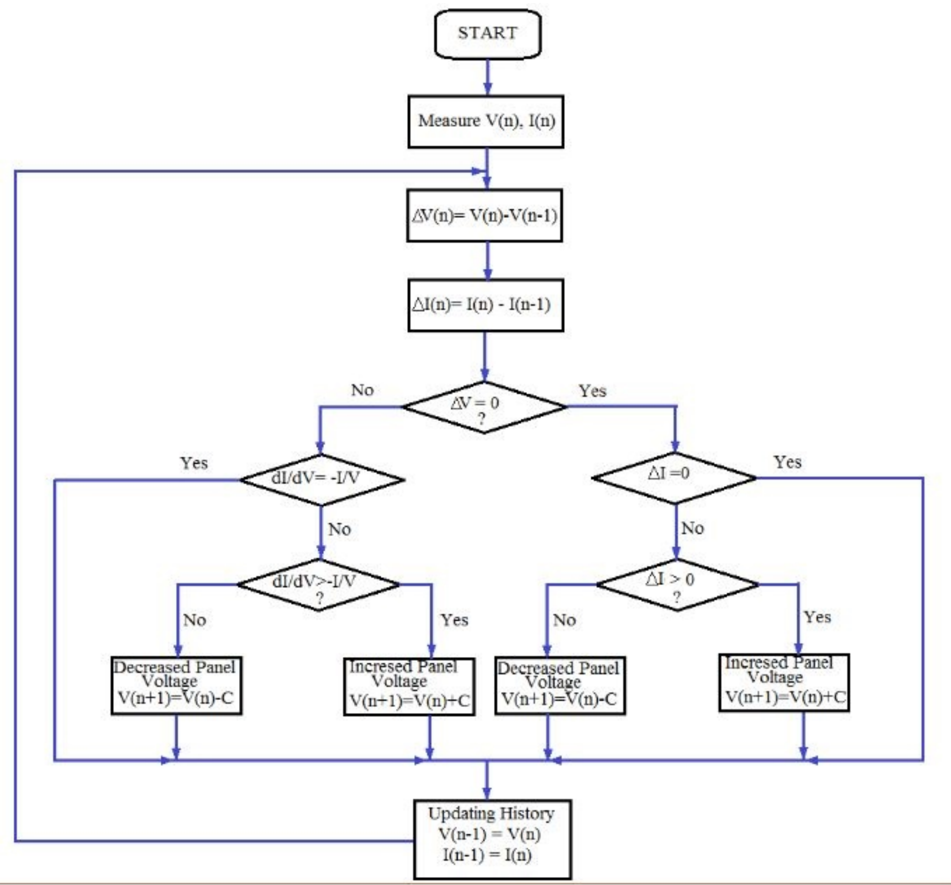

Figure 3.2: Flow Chart for Incremental and conductance algorithm

adapt to rapidly changing weather conditions and its ability to find the MPP without oscillating around it.

3.4.1 Boost Converter with MPPT in PSCAD

The above circuit is implemented in PSCAD software as shown in figure 3.3. The voltage generated from solar module is step-up with the help of boost-converter. In order to switch on and off the IGBT, control circuit is developed and firing pulse are generated using MPPT block as shown in figure 3.4 3.5. The output of boost as shown in figure3.6. Tracking of maximum power at different insolation level has shown in the figure 3.7.

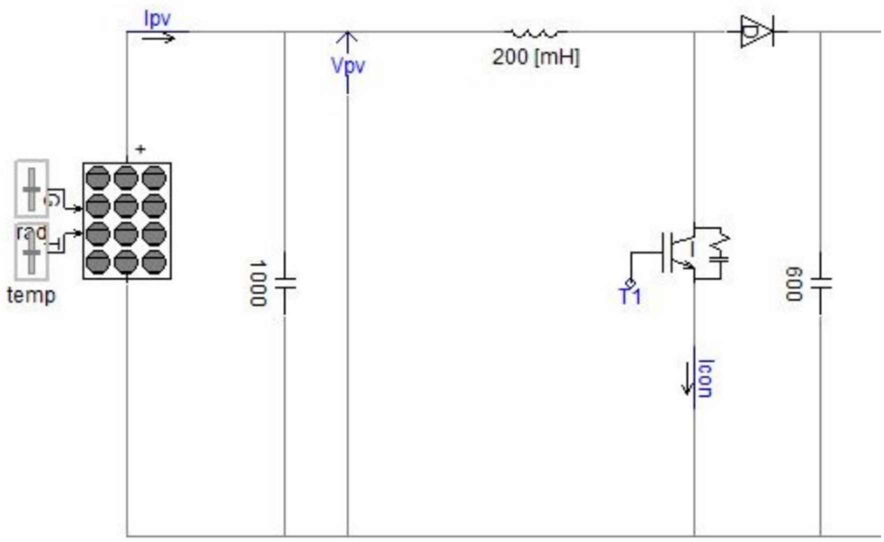

Figure 3.3: PV module with Boost converter

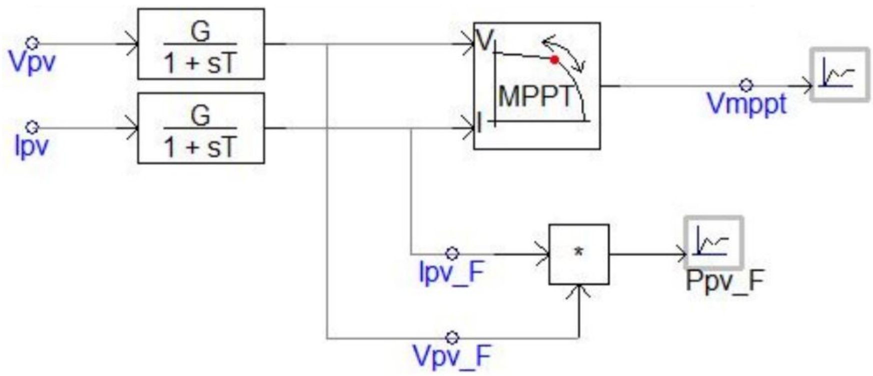

Figure 3.4: MPPT for maximum power

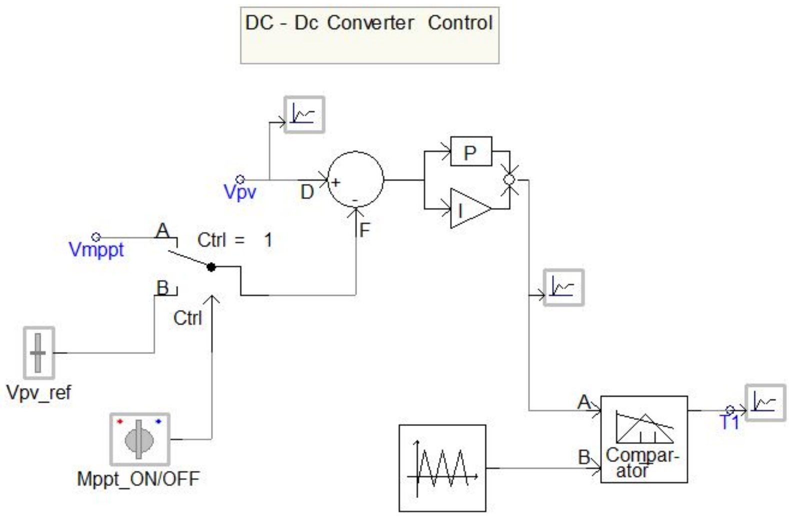

Figure 3.5: Control circuit for boost converter

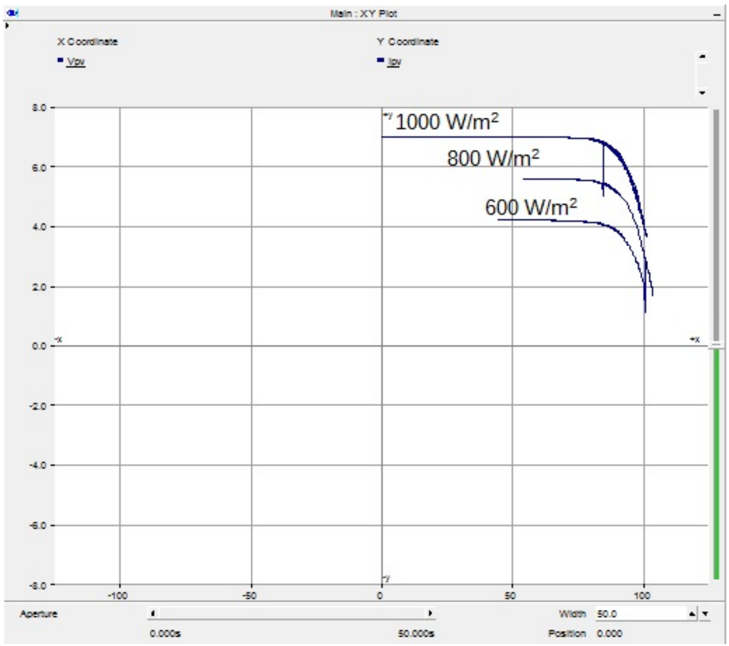

Figure 3.6: I-V curve at different insolation's S=1000W/m^2,800W/m^2,600W/m^2

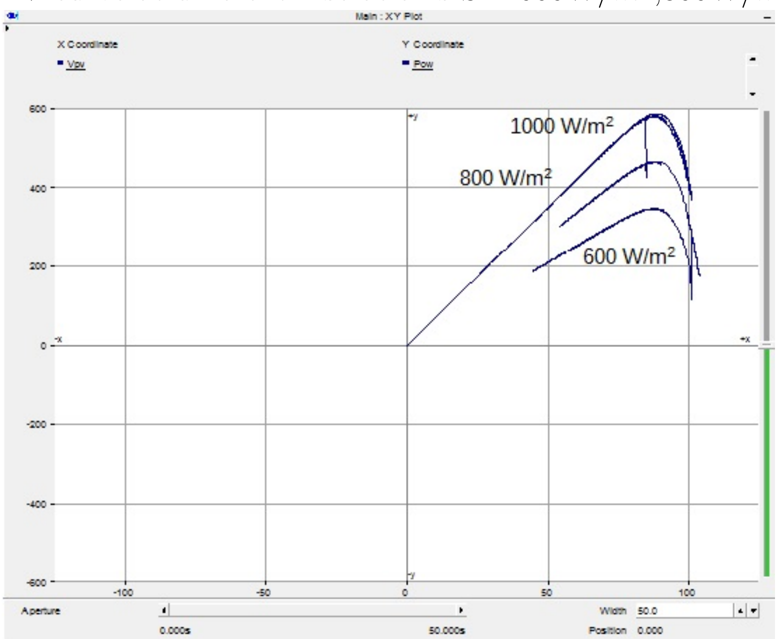

Figure 3.7: P-V curve at different insolation's S=1000W/m^2,800W/m^2,600W/m^2

Chapter 4

Integration of Photovoltaic System with Power Grid

Single machine connected to a large system through transmission lines. Because of the size of the system to which the machine is supplying the power there will be no change in the voltage and frequency, such a voltage source of constant voltage and frequency is called infinite bus. In this chapter integration of P-V system with infinite bus system is materialized.

4.1 Inverter Topology

The PV array can be integrated with 3-ph network using DC/DC converter and three phase voltage inverter. The inverter is responsible for following things.

- Control Active Power supplied to grid.
- Control DC link Voltage.
- Ensure high quality of injected power
- Grid Synchronization

The switches, which are used to chop the DC voltage, were chosen to be Insulated-Gate Bipolar Transistors (IGBTs).They are quite similar to power transistors except for one major improvement.Power transistors require a current to be applied at the gate in order to force the transistor to conduct while IGBTs require a voltage at the gate terminal.This advancement allows the IGBT to be controlled by an applied gate voltage, with minimal current flow, which gives them the ability to switch much faster than the current driven power transistors.IGBTs also have much higher voltage (6500V) and current (2400A) ratings then other switching devices.These characteristics make them optimal for high-power high frequency applications such as a voltage source inverter.

4.2 Generating Gate Signals for IGBT

The AC output waveforms shape and quality is directly related to how the conduction intervals of the switches are controlled. Methods for controlling the switches range from simple to complex. The method chosen for this application was unipolar sinusoidal pulse width modulation (SPWM). This control technique is very well known and was used because it allows the control of three very important output waveform variables. These three variables are the phase, magnitude, and frequency of the generated AC waveform whose importance will be discussed in a later section.
SPWM is a control technique that requires three reference sinusoidal waveforms for three phase operation of the same frequency as the desired output waveform and one high frequency triangle waveform known as the carrier signal. The signal deciding when the appropriate switch should conduct or remain off is determined by comparing the magnitudes of the sinusoidal and triangle waveforms. Between the comparing logic and the gate terminal of the IGBT is a driving circuit providing the necessary voltage and power to operate the switch.

4.3 Controlling of Inverter

Controlling the inverter is important task, in this thesis synchronous reference frame control is chosen. The control strategy involves two control loops, the first the internal current loop, which will regulate the grid current and the external voltage control loop, which control dc link voltage. The dc link voltage controller is designed for balancing the power flow in the system. In this thesis, a synchronous reference frame control is chosen. It is also called as *dq* control. It uses a reference frame transformation module, $abc \longrightarrow dqo$, to transform the grid current and voltage waveforms into a reference frame that rotates synchronously with the grid voltage so that control variable becomes dc values. Thus, filtering and controlling can be achieved. PLL has been used in order to extract phase angle of the grid voltages. In this chapter need of PLL, Inverter control filter design and performance of inverter under external faults has been explained.

4.4 Phase Locked Loop(PLL)

The Phase Locked loop is a control system who generates the phase angle of the input signal. Here we deal with the phase angle of grid, hence in order to deal find phase angle PLL has been applied.

4.4.1 Necessity of PLL

Phase angle and amplitude of the utility voltage vector are basic information for aa increasing number of grid connected VSIs. Some of the information are not measured directly so there are special means to extract them. A SRF approach based PLL is used in the work. The phase angle is estimated from the angular frequency of the grid voltages. The objective is to compute an accurate estimate phase angle (θ^*) of the actual phase angle(θ) of the grid voltage. The accuracy of the estimation is indicated by the estimation error ($\Delta\theta$).

$$\Delta\theta = \theta^* - \theta \tag{4.1}$$

4.4.2 Synchronous Reference Frame(SRF)PLL

The SRF will include two transformation levels of the voltage signals as shown in figure 4.1.

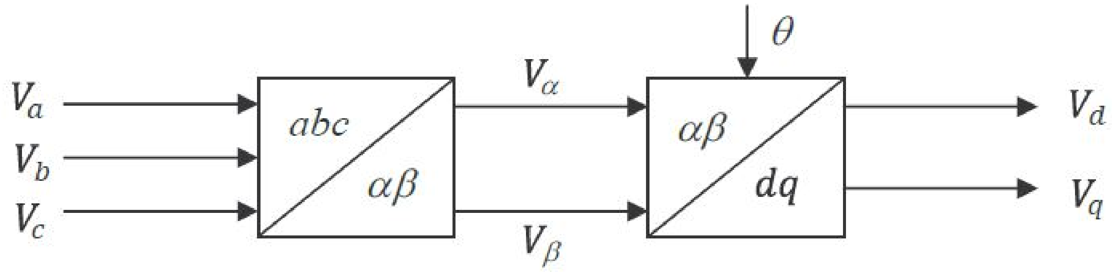

Figure 4.1: Synchronous Reference Frame Transformation

The voltage of the network can be represented as:

$$V_a = V_m \cos \omega_{grid} t \tag{4.2}$$

$$V_b = V_m \cos(\omega_{grid} t - 2\pi/3) \tag{4.3}$$

$$V_c = V_m \cos(\omega_{grid} t + 2\pi/3) \tag{4.4}$$

Here, ω $_{grid}$ t=θ_{grid}

Applying Clarke's transformation to equations 4.2, 4.3and4.4 to transform from $abc \rightarrow \alpha\beta$.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{4.5}$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = V_m \begin{bmatrix} \cos\theta_{grid} \\ \sin\theta_{grid} \end{bmatrix} \tag{4.6}$$

Applying Park's transformation to equation 4.6 to transform from $\alpha\beta \rightarrow dq$.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = K_s^e \times \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \times \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{4.7}$$

$$V_d = V_m \cos(\theta_{grid} - \theta) \tag{4.8}$$

$$V_q = V_m \sin(\theta_{grid} - \theta) \tag{4.9}$$

From equation 4.9 if θ is controlled to θ_{grid}, then the synchronization is achieved. This will shows that inverter output signals has the same frequency and phase of the grid. Then,

$$V_d = V_m \tag{4.10}$$

$$V_q = 0 \tag{4.11}$$

If it is assumed that the phase difference θ_{grid}-θ is very small, then

$$\sin(\theta grid - \theta) \cong \theta grid - \theta \tag{4.12}$$

From equations 4.9 and 4.12,

$$V_q = V_m(\theta_{grid} - \theta) \tag{4.13}$$

The angular frequency of PLL system can be represented as,

$$\omega = \frac{d\theta}{dt} = G_c V_q \tag{4.14}$$

Where, G_c is Controller (a PI controller).
Hence, the PLL frequency ω and phase angle θ can track utility frequency ω_{grid} and phase angle θ_{grid}, respectively, by properly designing the controller G_c.

4.5 Filter Design

[A.]Inductor Calculation

The switching frequency considered is f_s = 10kHz. The PV array is of 600MW used for integration with 220kV line, 50Hz there phase network, the RMS value of the rated fundamental current in each line is 11kAmp at STC. Therefore, peak value of current is 15.55kAmp. In this thesis peak ripple current has been assumed to be 2.8% of the rated current, which is approximately will be 0.4354kAmp.
Here,m_a= 0.75,

$$V_a = 0.75\frac{V_{dc}}{2} \tag{4.15}$$

Impedance at switching frequency is given as,

$$Z_{f_s} = 2\pi f_s L = \frac{V_a}{I_{ripple}} \tag{4.16}$$

From the above equations, L value is calculated as 3.3mH.

[B.] Capacitor Calculation

Equation used to calculate capacitance is:

$$F = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{4.17}$$

For eliminating the 11^{th} harmonics capacitor is selected with the value of 40 μF.

4.6 Simulation In PSCAD

The full circuit diagram is shown in figure 4.2.

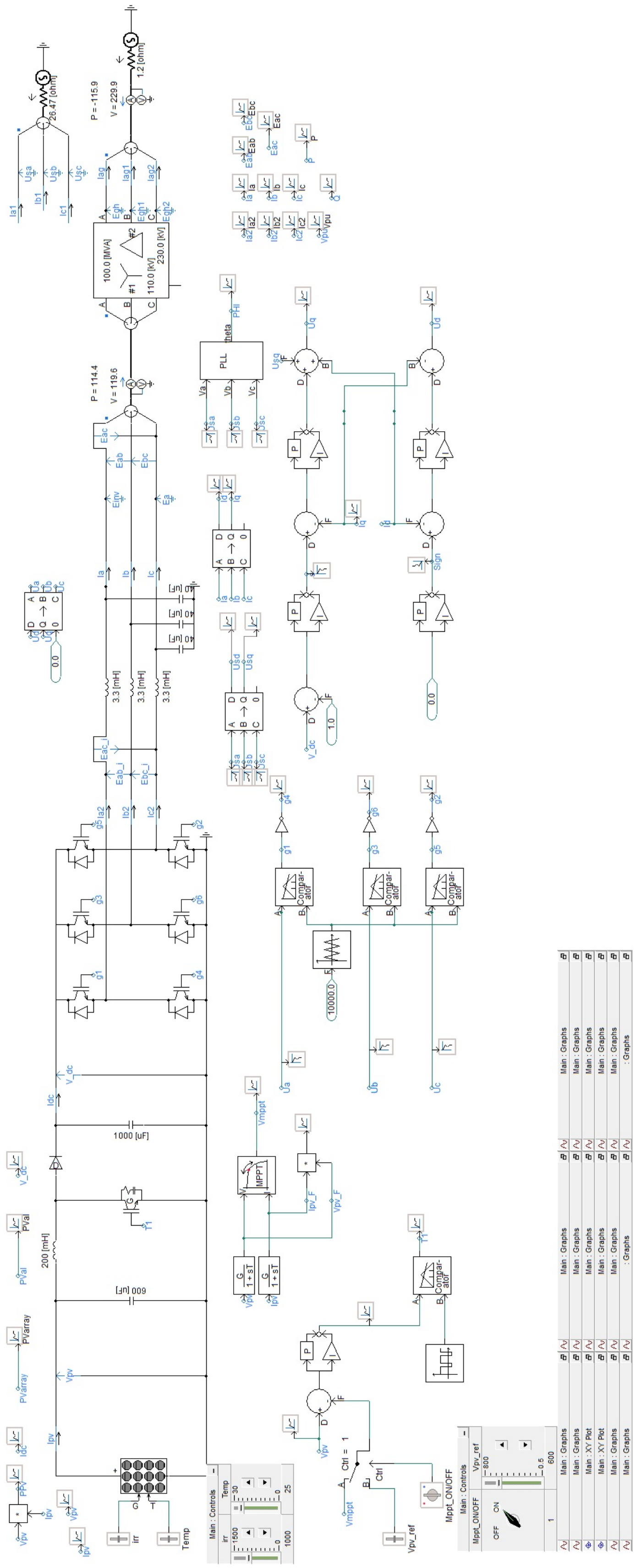

Figure 4.2: 3-phase grid connected photovoltaic system

4.6.1 Results At STC

The below figures 4.3, 4.4, 4.6, 4.7, 4.9 and 4.8 shows the output of d-q axis voltages, power from panel, inverter voltage(unfiltered and filtered), DC link voltage and Power to Grid respectively at normal operating condition. From the figures 4.4 and 4.9 it can be concluded that the system is giving average output power to grid 160MW and from the panel the out power is 182.68 MW. Hence the system efficiency is 87.5%.

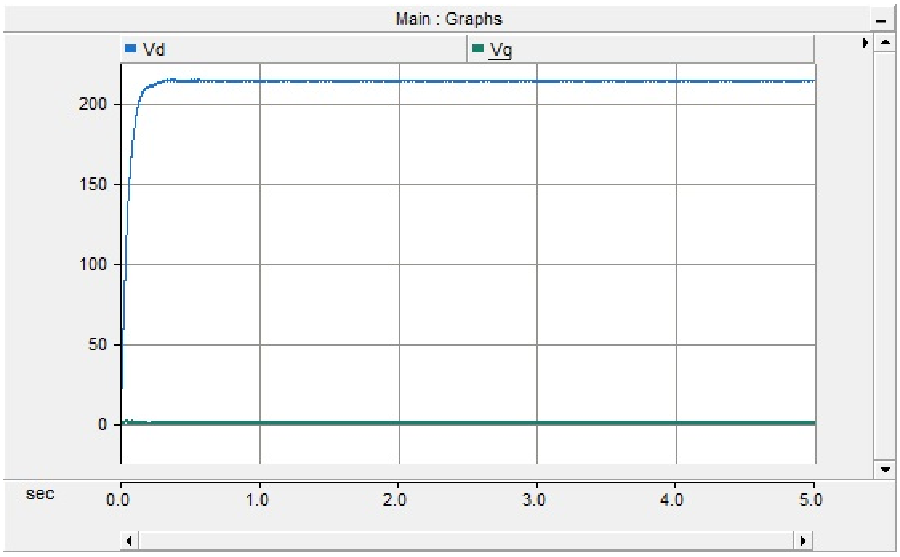

Figure 4.3: d-axis and q-axis voltages

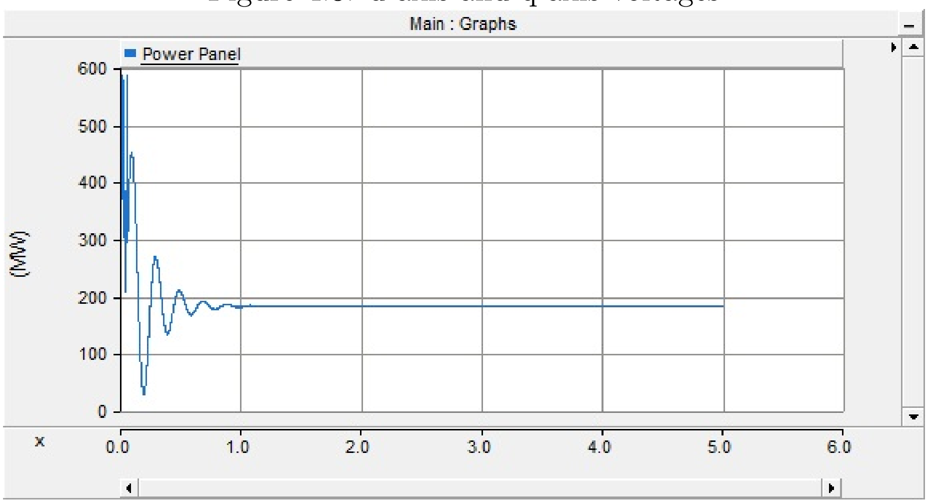

Figure 4.4: Output power from Solar panel

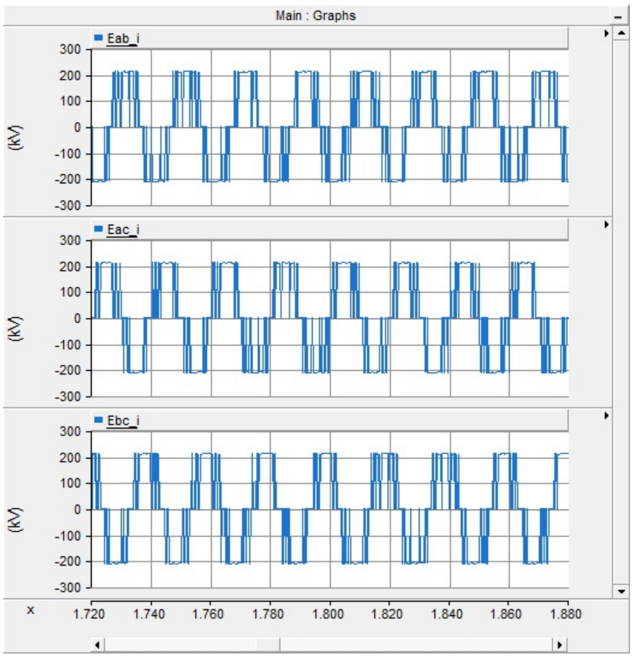

Figure 4.5: Output Voltage of Inverter(Unfiltered)

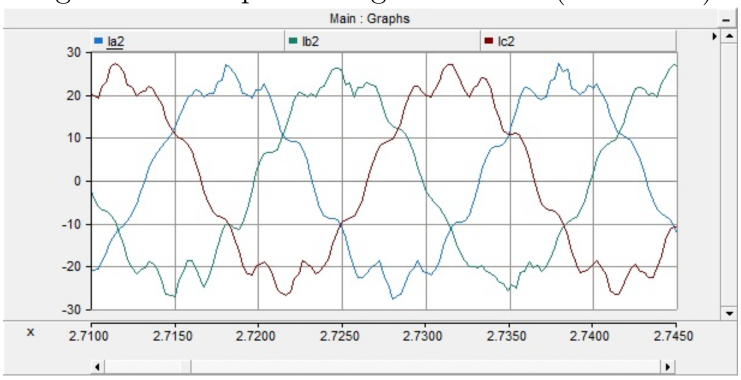

Figure 4.6: Output Current of Inverter(Unfiltered)

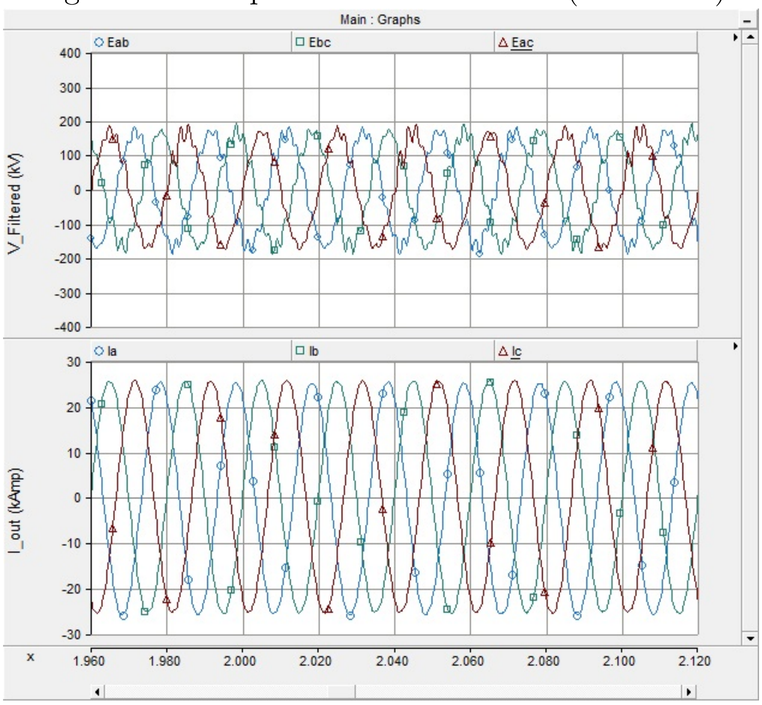

Figure 4.7: Output Voltage and Current

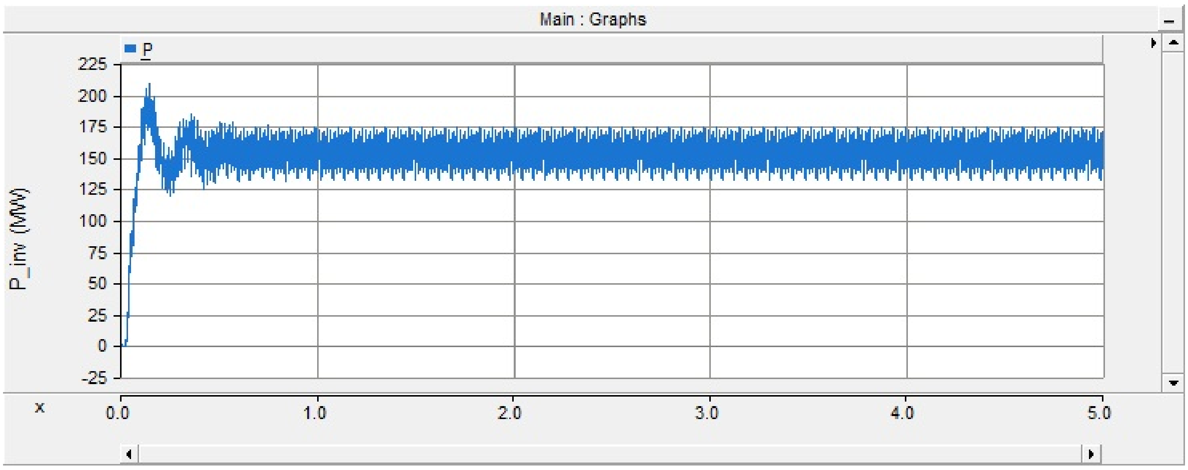

Figure 4.8: Power to Grid

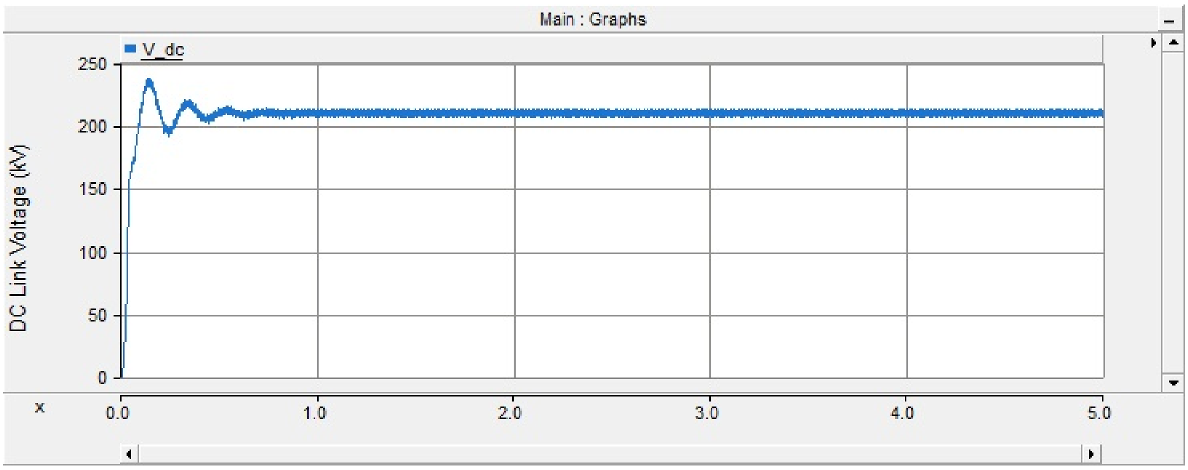

Figure 4.9: DC link Voltage

4.7 Performance of 3-ph grid connected PV system under grid faults

In most of the power grids, the most common type of faults is a line to ground fault and the most severe type is three phase short circuit faults. The grid connected photovoltaic system transient response have been simulated. The GCPS is assumed to operating at STC and faults is created assuming 1Ω resistance. The faults are applied at 1.5s and is lasted till 0.5s and than it was cleared. The fault was cleared at 2.00s.

4.7.1 Single phase to Ground Fault

Case A. Fault on Inverter Side

Figure 4.10 represents the circuit diagram of 3-ph GCPS under single line to ground fault. In this case fault is applied on phase A. Figure 4.11 shows the impact of fault on the inverter. During the fault, the voltages of all phase gets disturbed. So, there is an imbalance in the grid currents as shown in the figure 4.12.From figure 4.12 is observed that the GCPS remains stable in presence of fault, and successfully arrives to its normal position as fault is cleared. The disturbance in PV system output power in turn causes disturbances in DC link voltage V_{dc} as shown in figure 4.14. The three phase grid connected system under faulted condition is shown in the figure 4.10.

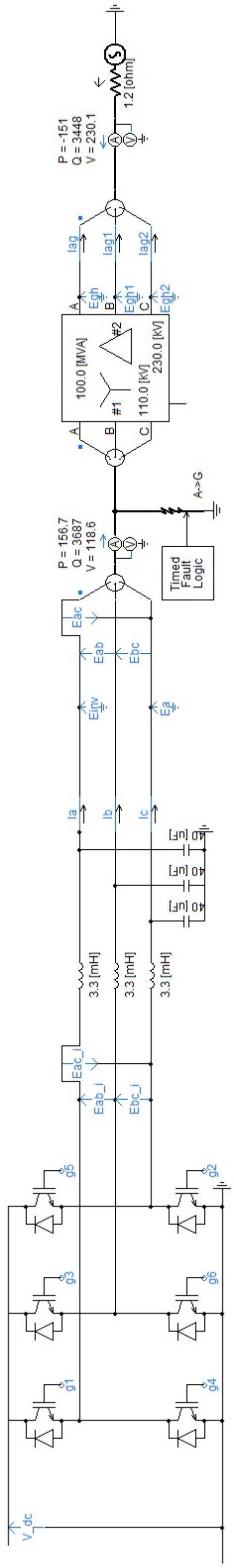

Figure 4.10: 3-phase GCPS under single line to ground fault(Inverter side)

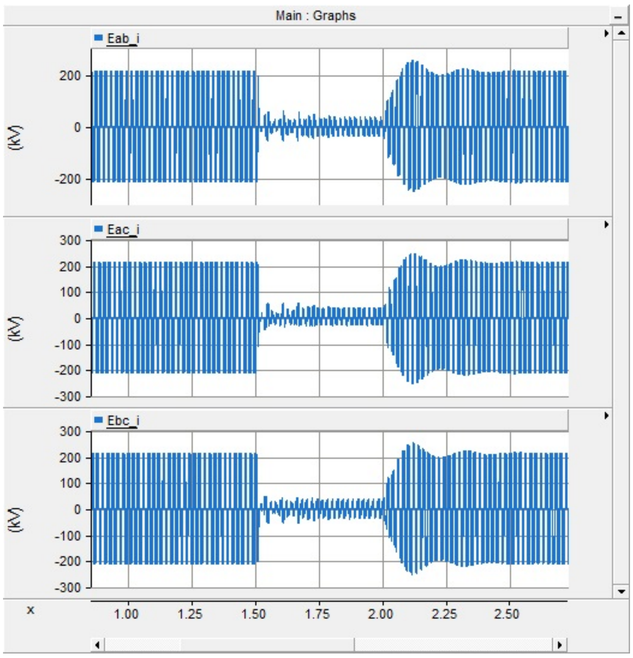

Figure 4.11: unfiltered voltage response to single line to ground fault (for t=1.5s to 2.0s)

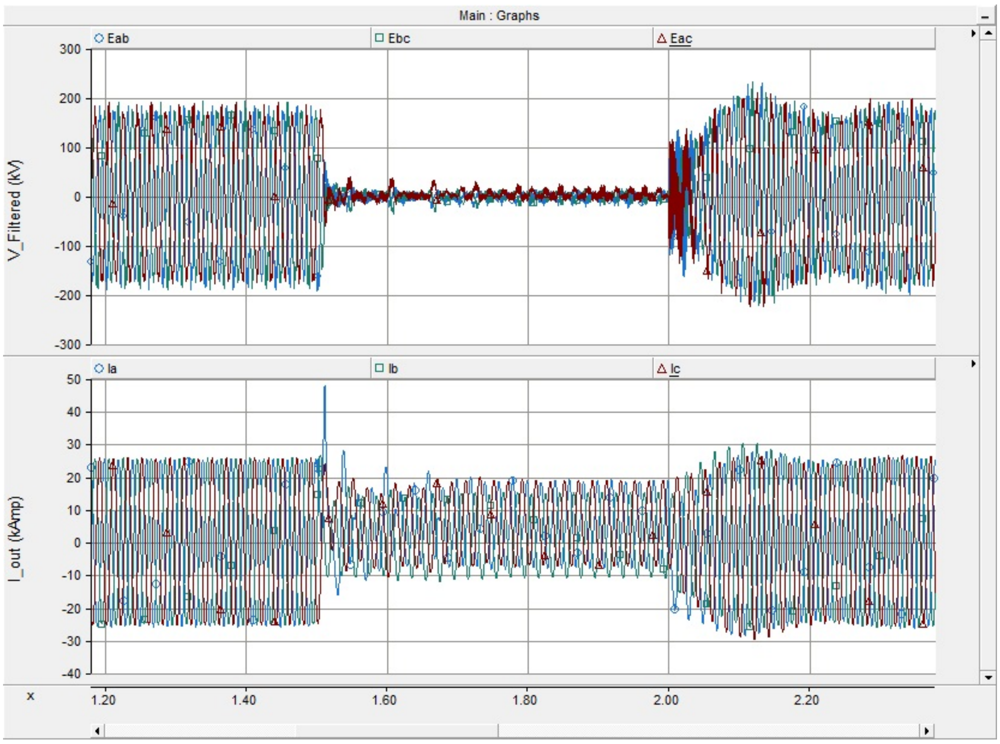

Figure 4.12: Filtered voltage response to single line to ground fault (for t=1.5s to 2.0s)

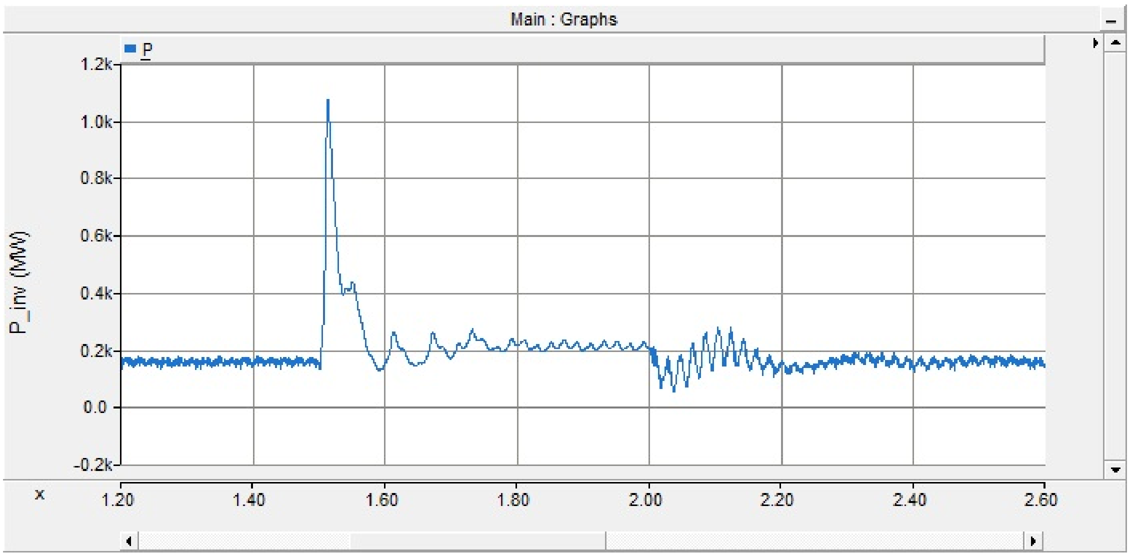

Figure 4.13: Output power response to single line to ground fault (for t=1.5s to 2.0s)

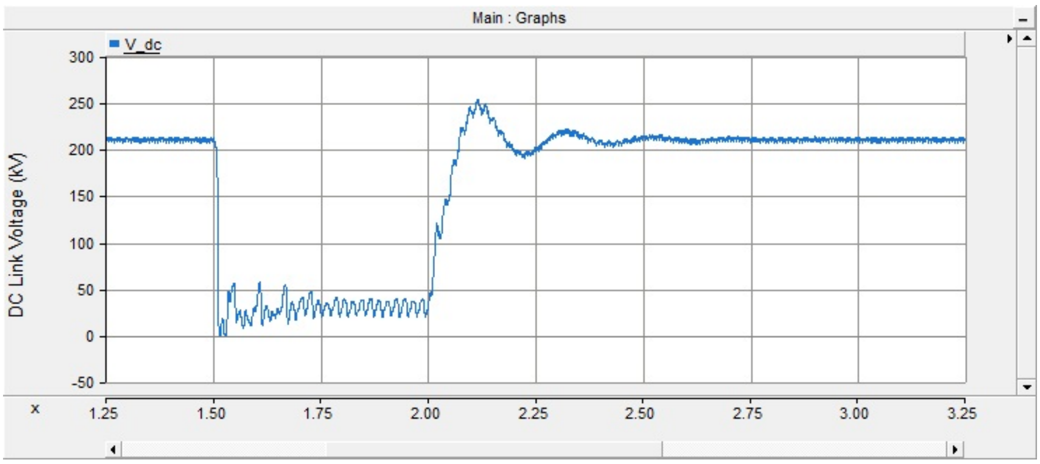

Figure 4.14: DC link voltage to single line to ground fault (for t=1.5s to 2.0s)

Case B. Fault on Grid Side

Figure 4.15 shows a 1-ph ground fault on the grid side. The fault is applied at 1.5sec and was cleared at 2.00sec. The fault lasted for 0.5sec on phase A. From the analysis it was seen that grid voltages and grid current gets fluctuated and there is severe rise in current and drop in voltage of phase A as shown in figures 4.16 and 4.17. Figure 4.18 shows that the power coming from the grid is negative initially, which indicates the P-V panel is supplying power to the grid. At the time of the fault, the power coming from the grid has become positive which indicates the grid is supplying power to the fault. After clearance of the fault, the P-V panel starts supplying power to the grid.

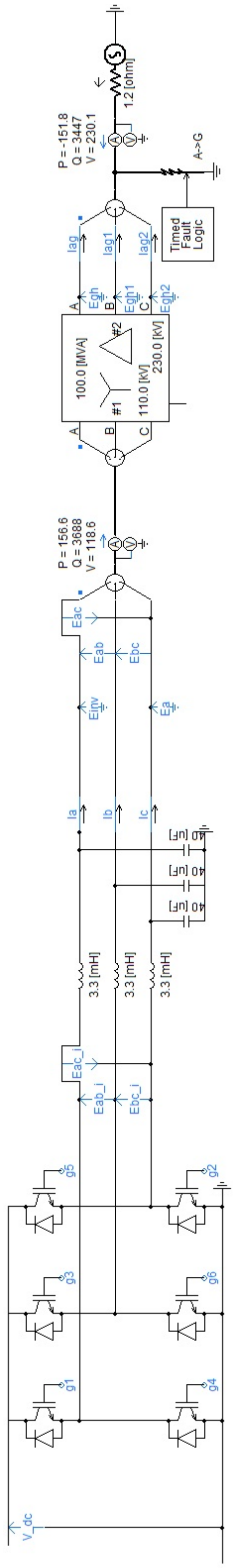

Figure 4.15: 3-phase GCPS under single line to ground fault(Grid Side)

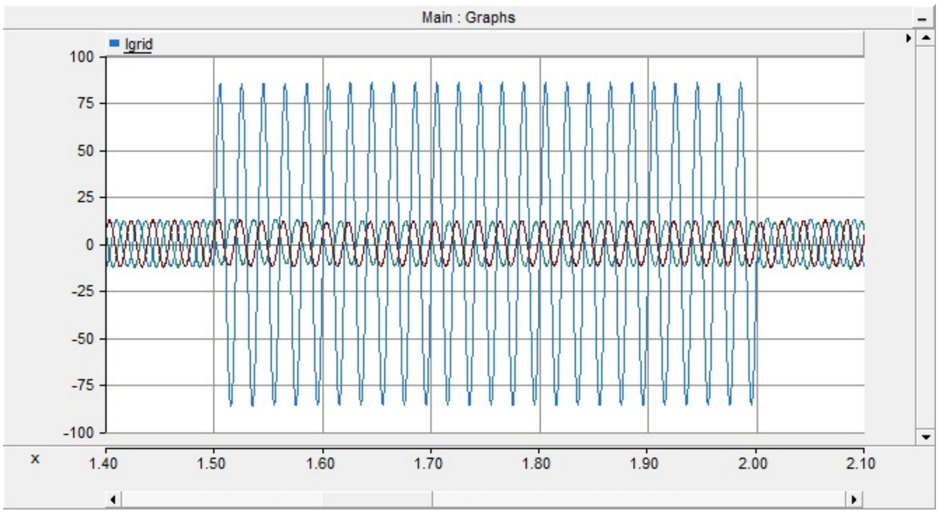

Figure 4.16: Current response under fault condition (for t=1.5s to 2.0s)

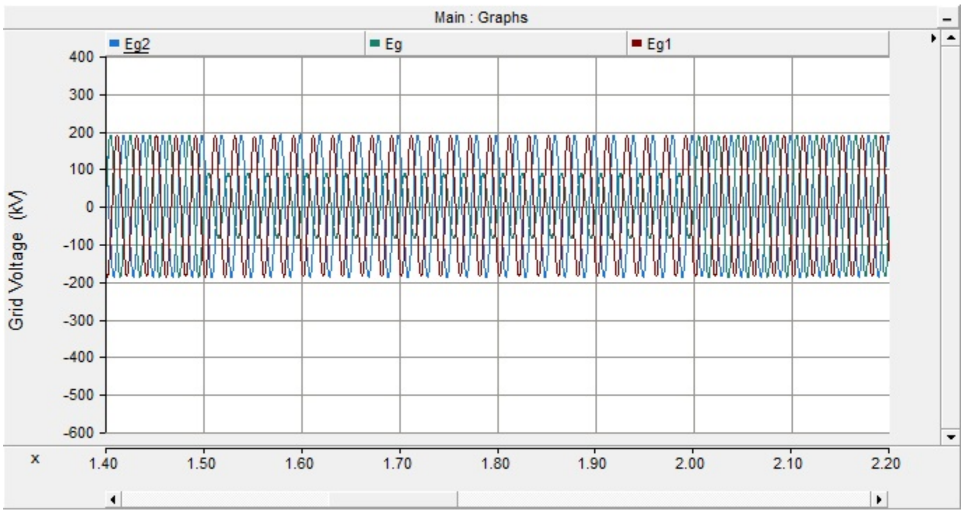

Figure 4.17: Voltage response under fault condition (for t=1.5s to 2.0s)

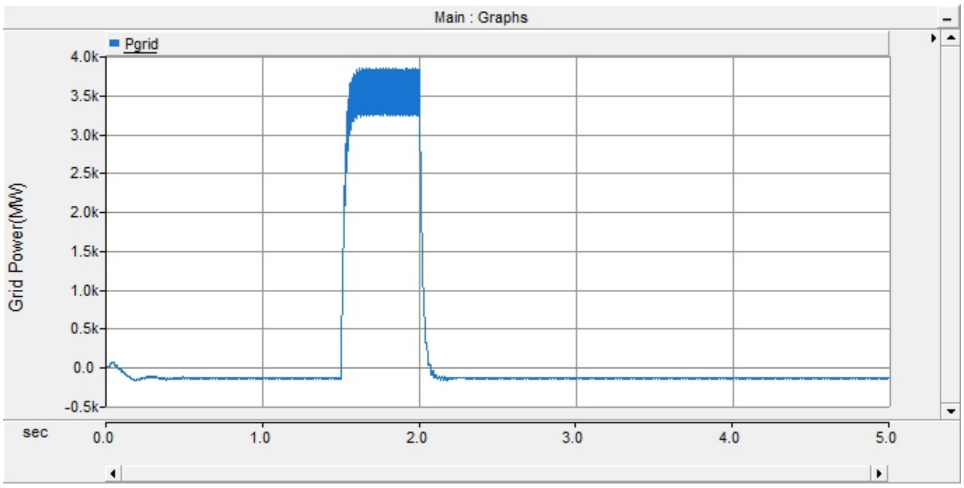

Figure 4.18: Grid Power response under faulted condition (for t=1.5s to 2.0s)

Figure 4.19, shows the output power of the inverter. The output power of inverter will decreases and will try to maintain the power level, as the fault is cleared the power comes back to its normal state. Due to power fluctuation there is fluctuation in DC link voltage as shown in the figure 4.20.

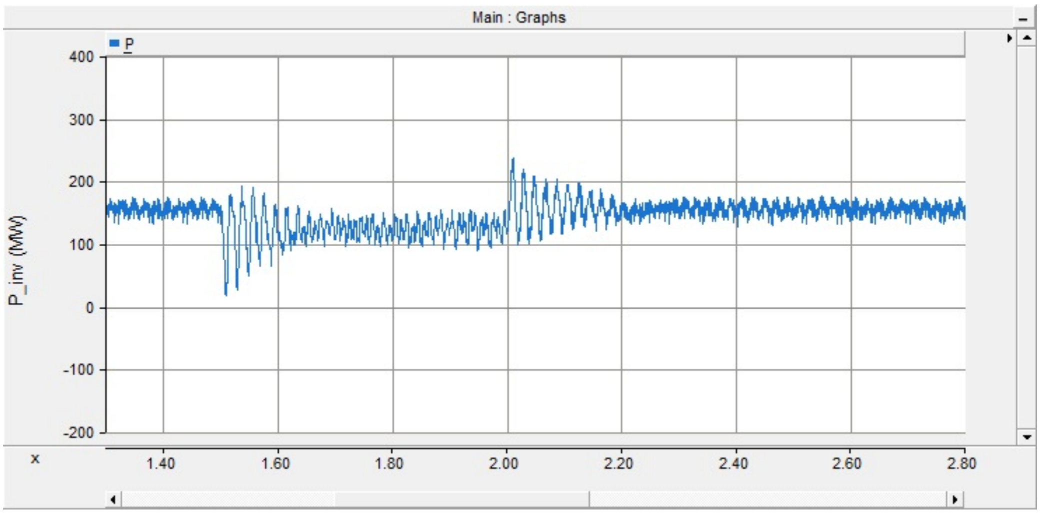

Figure 4.19: Inverter power response under faulted condition (for t=1.5s to 2.0s)

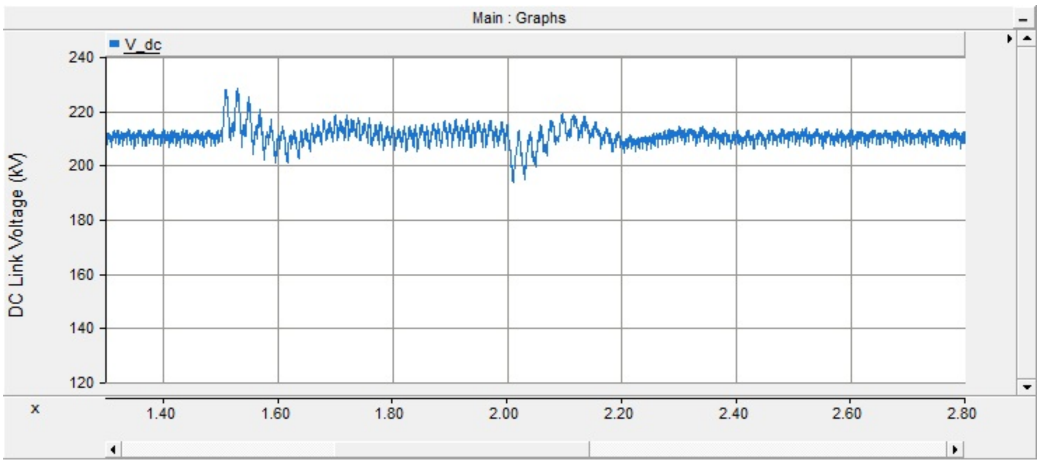

Figure 4.20: DC link voltage response under faulted condition (for t=1.5s to 2.0s)

4.7.2 Three phase to Ground Fault

Case A Inverter Side Fault

Figure 4.23, voltage and current response of GCPS under three phase to ground fault. From the figure 4.23 the output voltage drops due to the fault resistance. The fault resistance is taken as 1Ω. During the application of fault the fault current decreases, the controller will try to maintain the current, after the clearance of fault the system comes back in normal position. The unfiltered voltage response is shown in figure 4.22.The three phase grid connected system under faulted condition is shown in the figure 4.21.

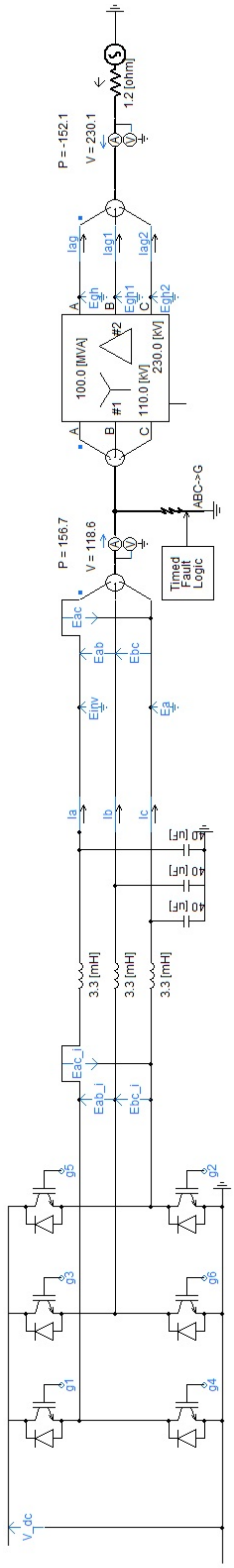

Figure 4.21: 3-phase GCPS under 3-line to ground fault(Inverter side)

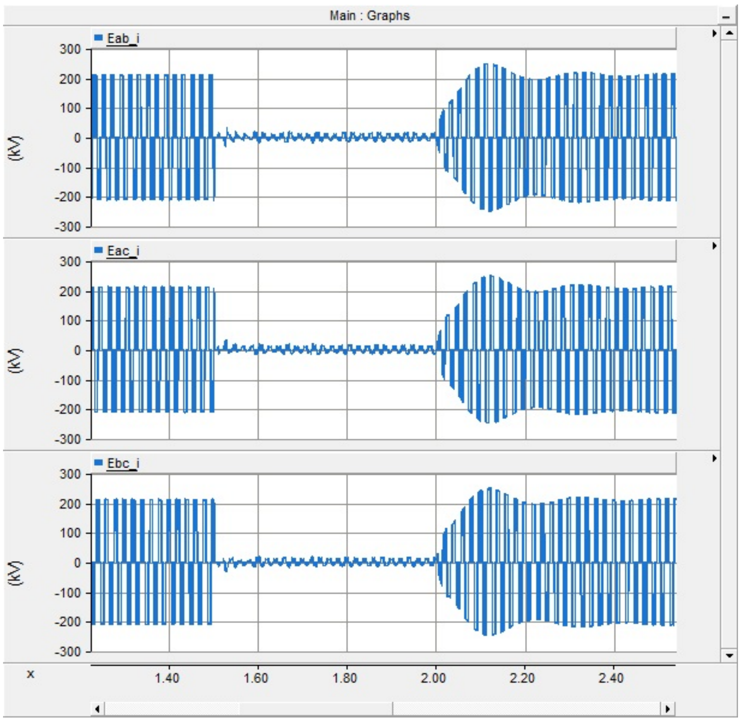

Figure 4.22: Voltage(Unfiltered)response under 3-phase to ground fault(for t=1.5s to 2.0s)

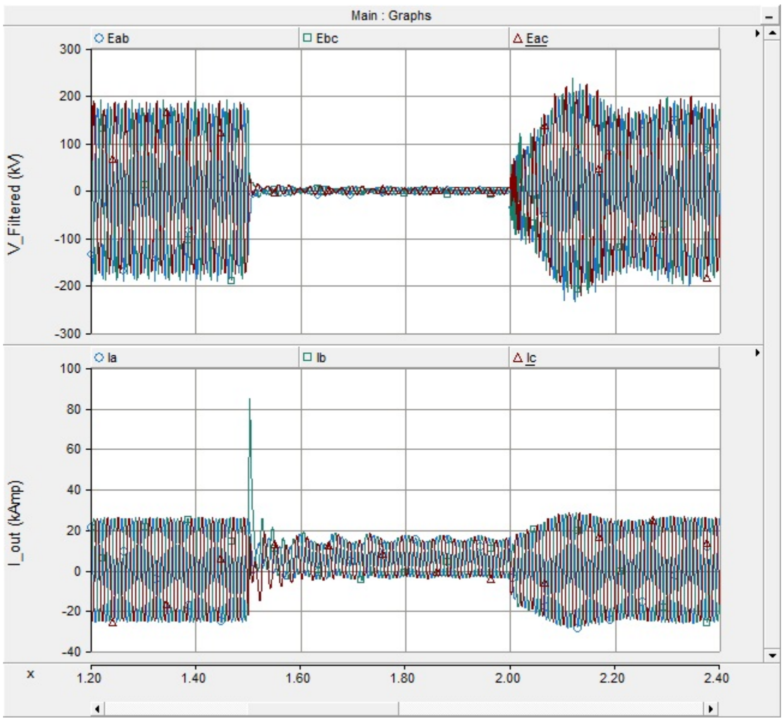

Figure 4.23: Voltage and Current response under 3-phase to ground fault(for t=1.5s to 2.0s)

The DC link voltage is also drop due to the fault as shown in the figure 4.24. The power produced by the inverter will increase in sudden and then the power of the system will drop due to drop in the voltage as shown in figure 4.25.

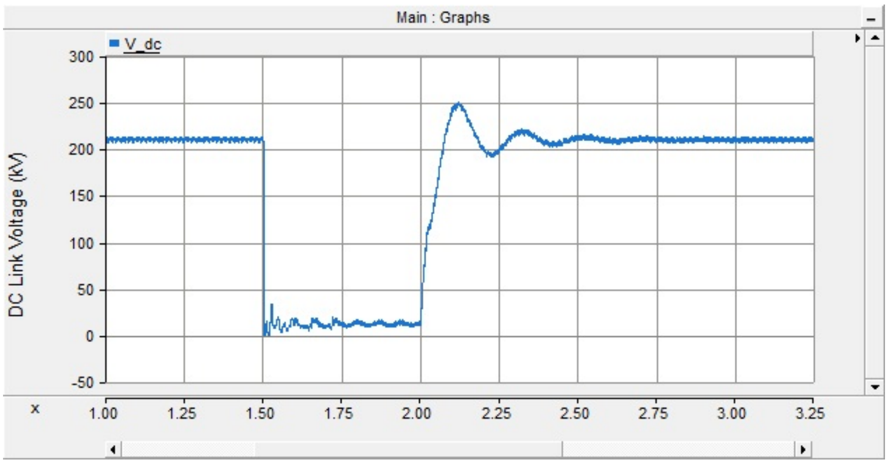

Figure 4.24: DC link voltage response under 3-phase to ground fault(for t=1.5s to 2.0s)

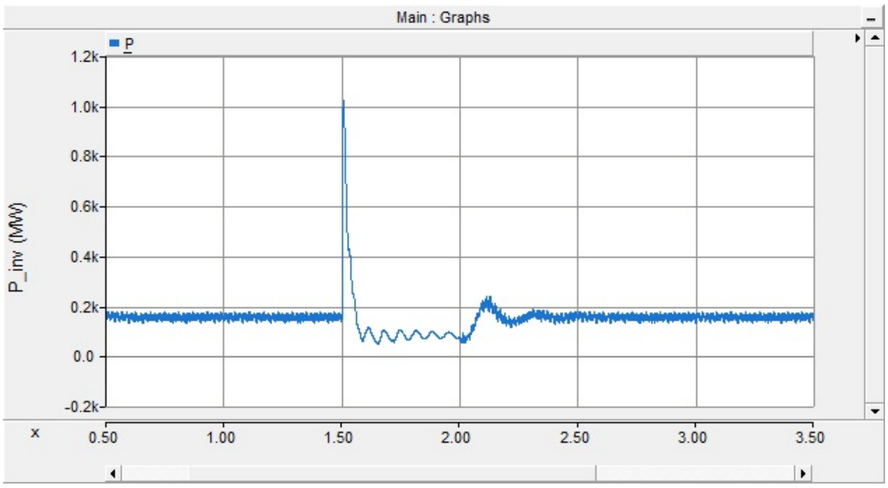

Figure 4.25: Inverter Power response under 3-phase to ground fault(for t=1.5s to 2.0s)

Case B Grid Side Fault

Figure 4.26, shows circuit setup for 3-ph to ground fault on grid side. The fault applied at 1.5sec and is cleared at 2.0sec. The grid voltages are dropped down and grid current rises 10 times the normal current. The circuit will come back to its original state as the fault is cleared. The figure 4.27 and 4.28 shows the voltage and current response under faulted condition respectively.

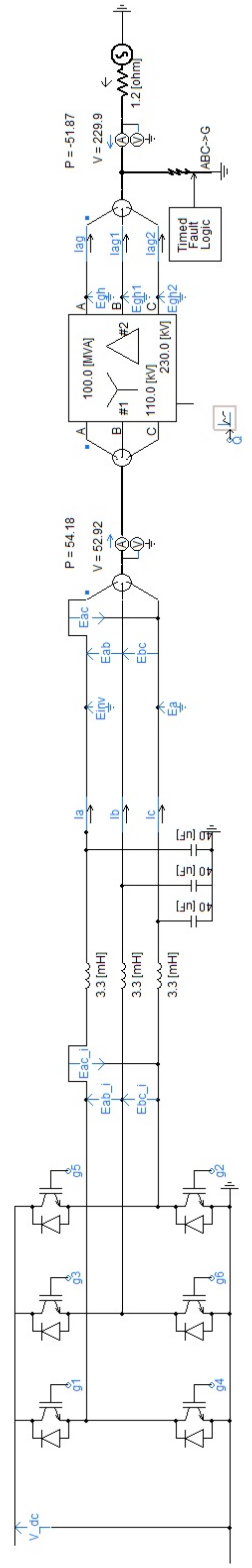

Figure 4.26: 3-phase GCPS under 3-line to ground fault(Grid side)

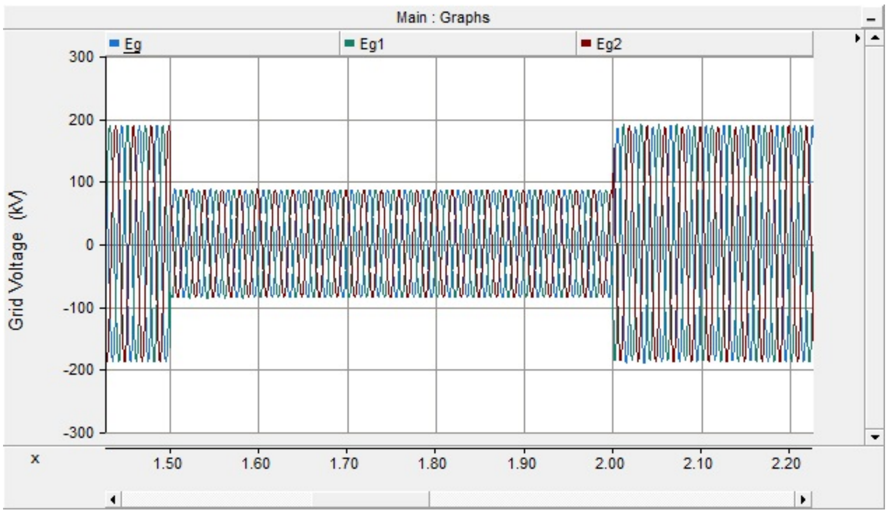

Figure 4.27: Current response under fault condition (for t=1.5s to 2.0s)

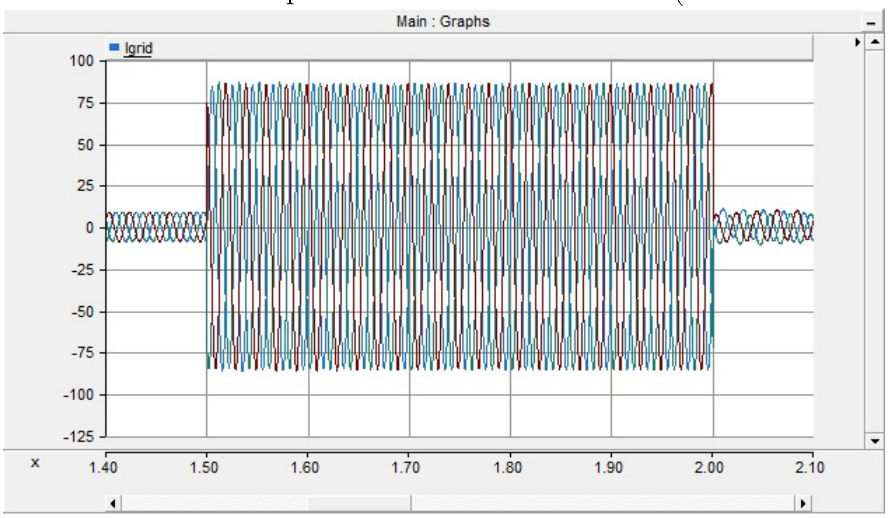

Figure 4.28: Voltage response under fault condition (for t=1.5s to 2.0s)

Figure 4.29, shows the power of inverter response to 3-ph to ground fault. From the figure it is clearly observed that the power of the inverter drops down and as the fault is cleared the system will try to recover its steady state position. As there is fluctuation in inverter power, DC link voltage also gets affected. The DC link voltage will try to achieve its steady state value as the fault is cleared as shown in figure 4.30.

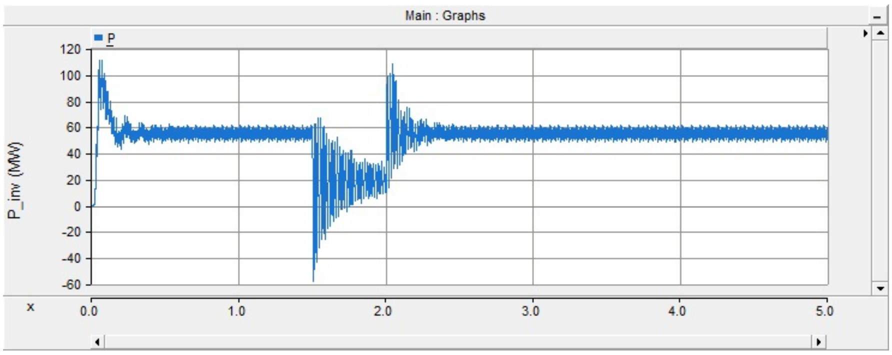

Figure 4.29: Inverter power response under 3L-G fault condition (for t=1.5s to 2.0s)

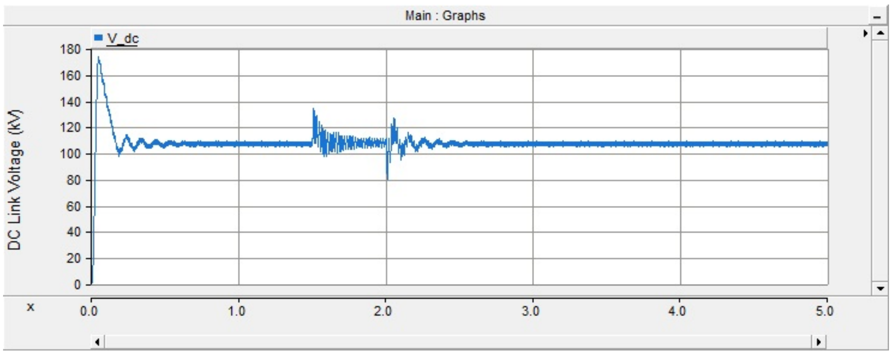

Figure 4.30: DC link voltage response under 3L-G fault condition (for t=1.5s to 2.0s)

4.8 Response of Power at different Solar Irradiations

As the solar irradiation is decreases there is drop in power output from the panel which is materialized in this section and is shown in figure 4.31. Due to irradiation decreases there is an impact on DC link voltage and on inverter output voltage, current and power as shown in figure 4.32, 4.33 and 4.34 respectively.

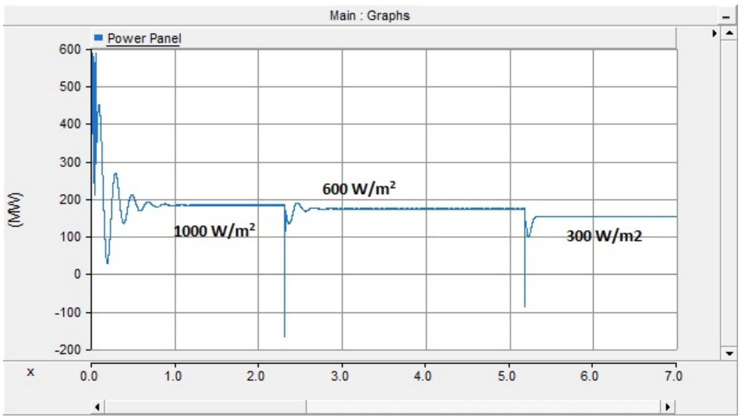

Figure 4.31: Solar Panel Output at different irradiation

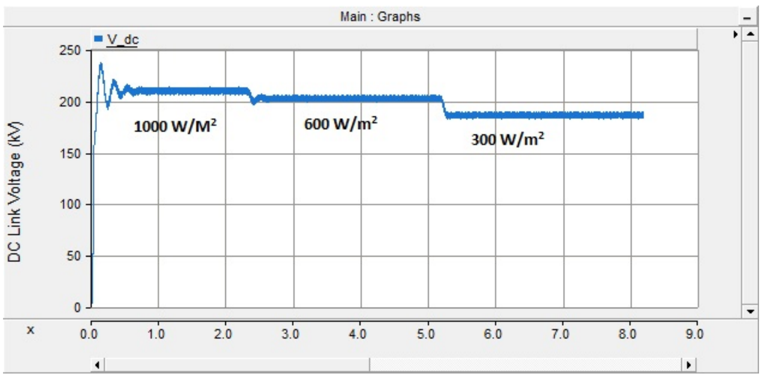

Figure 4.32: DC link voltage at different irradiation's S=1000 W/m^2,600 W/m^2 and 300 W/m^2

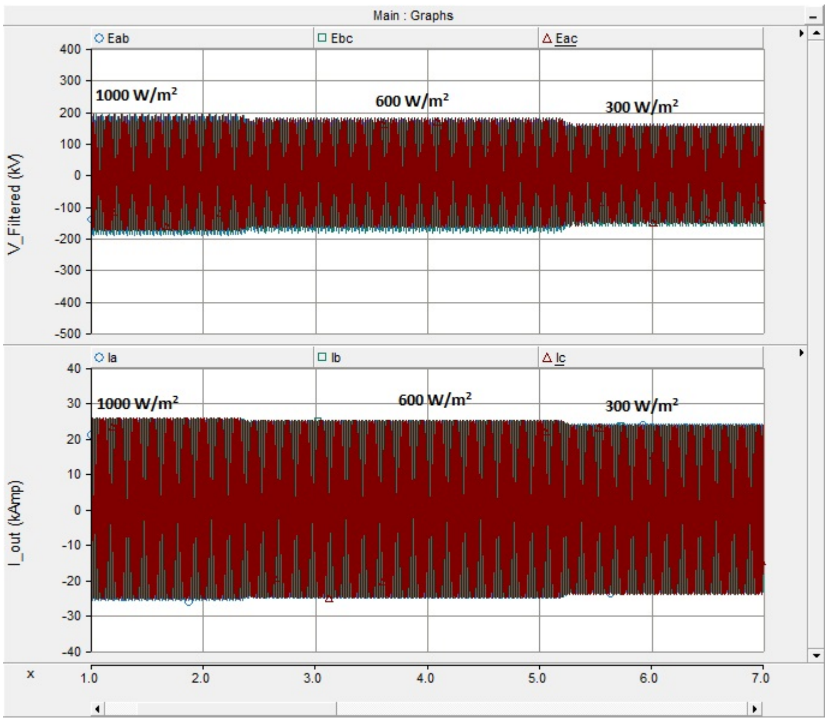

Figure 4.33: Inverter voltage and current at different irradiation's S=1000 W/m^2,600 W/m^2 and 300 W/m^2

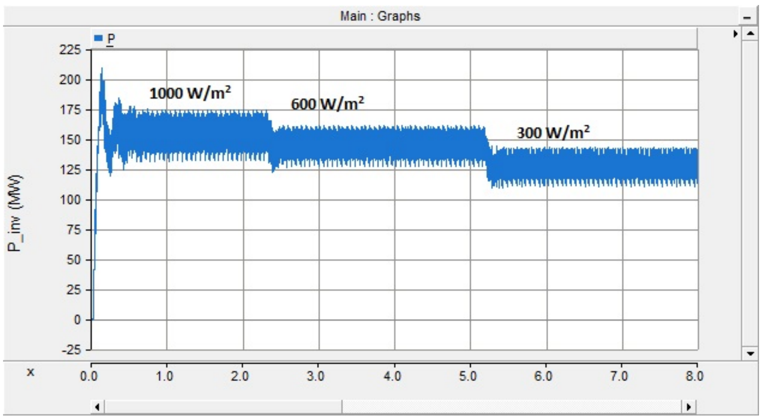

Figure 4.34: Inverter output power at different irradiation's S=1000 W/m^2,600 W/m^2 and 300 W/m^2

Chapter 5

Conclusion and Future Scope

Distributed generations, specially based on Renewable Energy Source, are being installed in electrical power system due to increase demands in the customers. Among various RES technology, solar energy is one of the leading free electricity production. The recent development in late years had let to more reliable and efficient in grid connected PV system. Proper simulation is required to be carried out. In order to require the better results proper parameters have to be calculated with rating and protection system. So it becomes important to study the system in transient condition such as faults and voltage variation.

This thesis have related to issues related to the same. The GCPS have been developed in PSCAD software. The main contributions to this thesis are:

- PV system sizing calculation has been carried out which includes number of modules required to be connected in series and parallel and number of arrays and cells to be included for typical power generation capacity.
- It also includes boost converter design which is specifically responsible for real power control.
- MPPT performance has been evaluated under different atmospheric conditions.
- Current control loop and DC link voltage voltage loop are tested for various transient condition.

- A control strategy for voltage and current is based on decoupling concept using dqo transformation.
- PLL block has been used and performance of the same has been evaluated in different transient condition. It has been observed that it is giving satisfactory performance and retrieve the synchronization after removal of perturbation.
- Several perturbed transient conditions such as L-G and 3L-G faults at PCC are considered. This result in drastic change in DC link voltage and power injected to grid. Perturbed phase or phases are developing unbalance situation which results into large power draw from grid
- Under different irradiation condition or cloud parsing situation the performance of GCPS has been evaluated and it has been noticed that it does not losses it synchronization but produces power in accordance to available irradiation successfully.

5.1 Future Scope

- The same system can be tested for multi-machine power system and impact of large PV penetration under transient conditions can be evaluated in terms of stability of power system.
- Different technique for transient stability enhancement can be implemented with proper system consideration and design.

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