Power System Small Signal Stability Analysis for Solar Photovoltaic Power Generation

Major Project Report

Submitted in Partial Fulfillment of the Requirements the Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(Energy System)

By

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MAY 2015

Certificate

This is to certify that the Major Project Report entitled **"Power System Small Signal Stability Analysis for Solar Photovoltaic Power Generation"** submitted by Mr. Akhilesh Panwar (13MEEN01) towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Energy System 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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I, **Akhilesh Panwar**, **(13MEEN01)**, give undertaking that the Major Project entitled ‘‘Power System Small Signal Stability Analysis for Solar Photovoltaic Power Generation” submitted by me, towards the partial fulfilment of the requirements for the degree of Master of Technology in Energy System, Electrical Engineering of 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.

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Acknowledgements

Success of any work depends upon the dedication, sincerity and hard work. It also requires some ingredients such as motivation, guidance, encouragement and time.

With immense pleasure, I would like to present this report on the dissertation work related to **"Power system small signal stability for solar photovoltaic power generation"**. I am very thankful to all those who helped me for the successful completion of the first phase of the dissertation and for providing valuable guidance throughout the project work.

I would first of all like to offer thanks to **Prof. Santosh C. Vora**, Project Guide whose keen interest and excellent knowledge base helped me to finalize the topic of the dissertation work. His constant support, encouragement, and constructive criticism has been invaluable assets through my project work. He has shown keen interest in this dissertation work right from beginning and has been a great motivating factor in outlining the flow of my work.

My sincere thanks and gratitude to **Prof. P. N. Tekwani**, Head of Electrical Engineering Department, Institute of Technology, Nirma University, Ahmedabad for their continual kind words of encouragement and motivation throughout the Dissertation work. I would also like to thank **Dr. K. Kotecha**, Director, Institute of Technology, Nirma University for allowing me to carry out my project work in the institute. I am thankful to Nirma University for providing all kind of required resources.

I am thankful to **Prof. Mihir C. Shah** for his kind help and encouragement in my project work. Also I would like to thank the lab assistants Harshad Patel, Rakesh Patel, Hitesh Makwana, Pratik Jani, for their continuous support during my dissertation work.

Finally, I would like to thank the Almighty, my family members for supporting and encouraging me in all possible ways. I would also like to thank my friends Praful, Megha, Abhishek, Shubham, Chintan, Pawan who have provided continuous encouragement in making this dissertation work successful.

- Akhilesh Panwar

13MEEN01

Abbreviations

AC .... Alternating Current
CR-VSI .... Current Regulated Voltage Source Inverter
CR-CSI .... Current Regulated Current Source Inverter
DC .... Direct Current
PV .... Photovoltaic
IGBT .... Insulated Gate Bipolar Transistor
MPP .... Maximum Power Point
MPPT .... Maximum Power Point Tracker
PLL .... Phase Locked Loop
PWM .... Pulse Width Modulation
SLG .... Single Line to Ground
THD .... Total Harmonic Distortion

Nomenclature

V_{mpp}	Maximum Power Point Voltage	[V]
I_{pv}	Photo Current	[A]
V_{pv}	PV Voltage	[V]
I_d	d axis current	[A]
I_q	q axis current	[A]
V_d	q axis Voltage	[V]
V_q	q axis Voltage	[V]
I_a	a Phase (ϕ) current	[A]
I_b	b Phase (ϕ)current	[A]
I_c	c Phase (ϕ) current	[A]
V_{dc}	DC link Voltage	[V]

Suffix

d	d axis component
q	q axis component
0	0 axis component

Abstract

Government incentives (such as Feed-In Tariffs introduced) created a strong economic impact on individuals to invest in renewable energy sources for power production. Renewable energy sources are trending for power production, because of their relative small size and noiseless operation. Photovoltaic are particularly attractive as a renewable source of energy for distributed power generation. However, there are various concerns associated with photovoltaic modules, such as the impact of their interconnection to the grid because of their generic nature. Solar photovoltaic panels suffer from non-linear behaviour of output. The output of solar PV depends upon the weather conditions, which are not constant. The intermittent nature of weather cause the output to keep on changing. Such intermittent power will have the adverse effect on the power system stability. It is necessary to analyse the solar PV integrated power system stability (small signals stability, transient stability etc.). The proposed work focuses on developing the 3 phase grid connected solar PV system in PSCAD/EMTDC simulation software environment. The system is examined for integration of developed solar PV system. For the proposed work, based upon the simulation result the behaviour of system is examined for various perturbation.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The electrical power system is the largest and complex machine ever developed by mankind. It is quite astonishing that such huge system has operated with a high degree of reliability. The robustness of a system is defined by its ability to operate in an equilibrium state under normal as well as in perturbed condition. In past the main source of power was thermal power station, gas power station etc., as the time passed the trends of power generation is also got changed. Due to rapid industrialisation the energy demand has kept on increasing, causing the fast depletion of available fossil fuels. In order to lower down the dependency on the fossil fuel, renewable source of energy are now used for power generation.

1.1 Background

Rapid industrialisation of developing countries & improvement in living standards cause the larger consumption of energy per capita. It can be infer from the statics shown in the Fig.1.1 of the energy demand/capita of India, there is a phenomenal growth in the energy demand, and which may be even more in near future. As from the fig. 1.1, In the year 1947 the demand was only 16.7 kWh, which shows, the ratio of available fossils fuels for power production to power demand was more but due to rapid neutralisation, there is significant growth in power demand, the ratio has reduced, and will be kept on decreasing with increasing living standards.

In order to maintain the reliability of the existing power system, it is necessary to

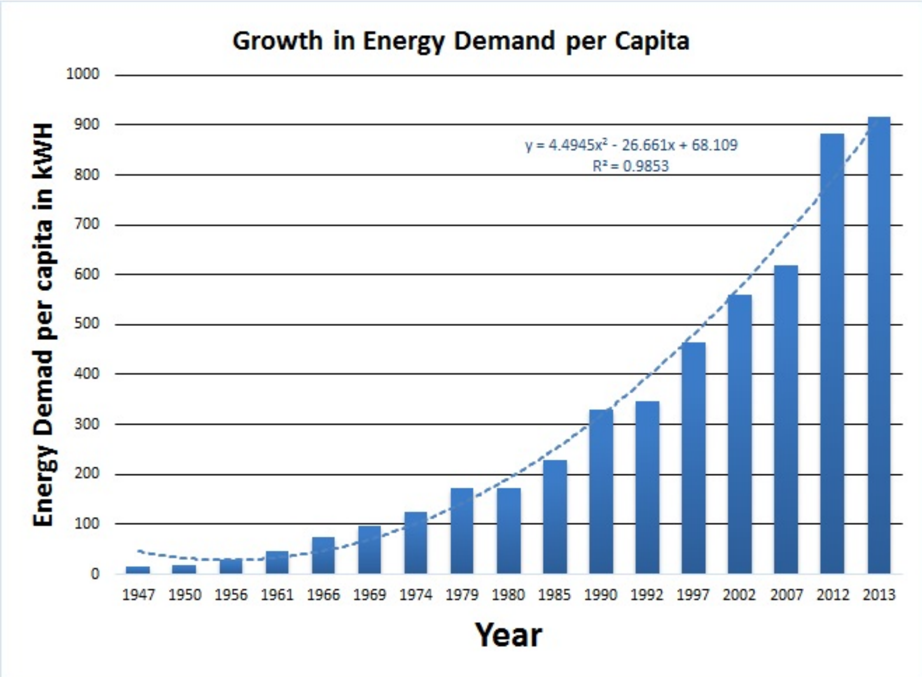

Figure 1.1: Growth in Energy Demand/Capita

have sufficient sources of power so that the demand could be supplied. Fossil fuels are limited source of energy and keep on depleting with increasing energy demand. To lower down the dependency on the fossil fuels, renewable sources trending for power production. This will not only bridge the gap between the supply and demand but also let down the dependency on fossil fuels for power production. Till 31.03.2015 the total installed power plant capacity in India including renewable sources is shown in fig.1.2

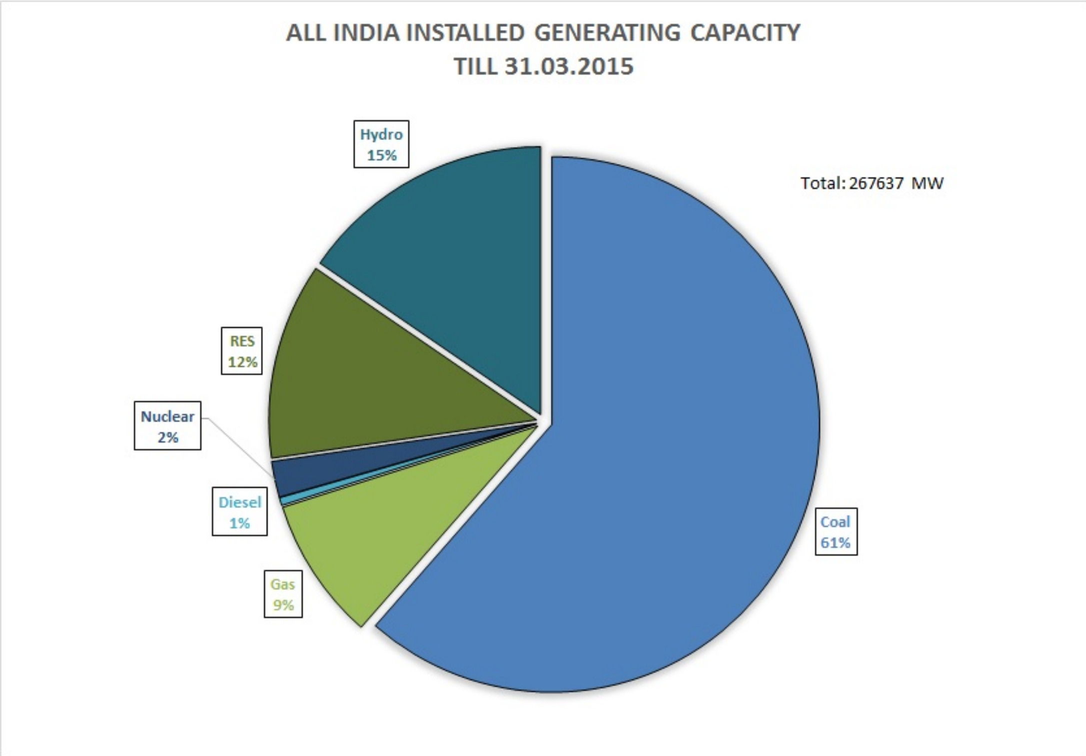

Figure 1.2: Plant capacity of different power generation sources in india

Figure 1.2 shows the present percentage share of different renewable sources for power generation in the total generation capacity of India. It is evident from 1.2 that the percentage share of renewable sources is considerable over other sources like diesel, nuclear. As the source of power has kept on changing the dynamics of the system also getting changed. Previously, there was only synchronous generators to supply the power demand, So system dynamics limited and characterized by the conventional generator only. But, as the sources have changed the system's dynamics also getting changed. So, for such changing scenario it is required to analyzed the system for various perturbation which generally occurs in existing power system [1].

1.2 Literature Survey

Literature survey helped to get the glimpse of the trends in the area of the proposed study. The literature review presents the current state of knowledge and examples of successful developed technology and recent trends in renewable integrated grid system, and emerging trends to improve the reliability of the existing power system. For the proposed work the details of various referred literature are as follows

- **"Impact of high Penetration of Solar Photovoltaic Generation on Power System Small Signal Stability"** [3]. This paper investigate the effect of solar PV on the small signal stability by the help of the modal analysis. Due to non-inertial solar PV it is required to understand the effect of the solar PV on the small signal stability. This paper conclude that the location as well as penetration level have a considerable effect on the system stability. Depending upon the location and penetration, solar PV fed power has a detrimental or incremental effect on the system stability.

- **"Impact of Integration of Solar and Wind Power on Small Signal Stability using Wavelet Transform"**[4].This paper investigates the consequences of integration of renewable sources on power system small signal stability of power system. In this paper author has used IEEE 14 bus system for investing the effect of the wind as well as of solar PV on power system small signal stability. Investigation is done by replacing the conventional generator generation with the solar and wind generation. Eigenvalue analysis is used to compute the frequency and damping factor of oscillatory components. The oscillatory modes are also identified using discrete wavelet transform, a spectral analysis technique [**?**, 4] This paper shows that penetration level has both detrimental and incremental effect on the existing power system.

- **"Small signal stability analysis of large scale variable speed wind turbines integration"**[5]. This paper discusses the effect of the higher wind power penetration on the system small signal stability. This paper focuses on analyzing the small signal stability for large scale variable speed wind turbines with doubly fed induction generator integration. For the analysis purpose two types of small disturbances considered, which are tripping of line & load variations. The boundaries of small signal oscillation are examined for such disturbance with the help of bifurcation analysis. Modal analysis and time domain simulation are carried to analyse the dynamic behaviour for a small disturbance. Paper uses IEEE 14 system for analysis.

- **"Power system small-signal oscillation stability as affected by large scale PV penetration"**[6]. This paper investigates the impact of a large photovoltaic (PV) penetration on power system small signal oscillation stability. A classical model of the of power system is used for the analysis. According to paper investigation, there exists a limit on the penetration level of power fed by solar PV power plant for safer operation of power system. This paper also shows that after a certain operational limit, the PV generation supplies negative damping torque, thus system becomes oscillatory. Based on the analysis carried out in this paper, for safer operation of solar PV integrated power system, the operational limit must be considered.

- **"Investigation of small signal stability of a renewable energy based electricity distribution system"**[7]. Market deregulation and renewable energy sources for power production are gaining significant attention. Therefore the distribution system is facing new challenges. In the presence of power from solar PV, Wind and Biogas plant, the dynamics of the existing power system keep on changing. This paper investigates the small signal stability of distributed power system. The results shows that wind generator dynamics influences the system oscillations to a larger extent and depending upon the penetration level solar PV has a incremental effect on power system small signal oscillation.

- **"PSCAD Simulation of Grid-Tied Photovoltaic Systems and Total Har monic Distortion Analysis"**[8]. For analysing power system behaviour with Solar PV, A simulation model is developed in PSCAD/EMTDC software environment. This paper investigates a performance of grid-tied solar PV system. The developed in the PSCAD consist PV array, DC link capacitor, DC-DC buck converter, three phase six-pulse inverter, AC inductive filter, transformers and a utility grid equivalent model. Inverter in the developed model uses SPWM switching technique. This paper shows the performance of developed model based on the THD analysis.

- **"PSCAD Modules Representing PV Generator"**[9]. NREL U.S. Department of Energy has prepared a grid tied solar PV inverter in PSCAD/EMTDC simulation software environment. Report shows that the developed model operates in synchronism with the grid. To ensure the proper operation of the inverter with grid, Parks's transformation is used to generate the reference signals. This Report also shows the behaviour of PV inverter under fault.

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1.3 Problem Identification

Power system stability (voltage stability, small signal stability, transient stability) deals with the study of power system equilibrium state, under perturb condition of load as well as of the generation. A power system is said to be stable if the interconnected synchronous generators remains in synchronism. Stability of the system is defined as, the ability of power system to control (damp out) the electrochemical oscillation, caused by any perturb condition.
Now a days, the change in the equilibrium state of the system arises due to sudden change in the generation of the integrated renewables sources. This intermittent power output affects the equilibrium state of the system. Solar PV systems are totally different from the conventional generator. Their characteristics are dominated by converters and presence of such system reduces the effective inertia of the system. It is required to investigate the effect of the intermittent power output of solar PV on power system small signal stability.

1.4 Scope of Work

The scope of the presented work focuses on investigating the small signal stability of power system having solar PV as one of the source. For the proposed problem, the work mainly focuses on achieving the following objectives

- To develop solar PV plant with all power electronics circuitry required to integrate it with grid.
- To model the test system for the purpose of analysis in PSCAD/EMTDC software environment.
- To simulate the test system with developed solar PV for different cases.
- To analyse the simulation result for investing the system stability.

1.5 Organisation of Thesis

Work details available in this thesis are sectioned in various chapters. The details are as follows.

- ***Chapter 2***

Chapter 2 gives the brief introduction about, intermittent nature of solar PV generated power & small signal stability. Introduction of simulation tool & strategies of analyzing the developed power system for small signal stability are also given in chapter 2.

- ***Chapter 3***

Chapter 3 focuses on the detailed modelling of centralized grid connected solar in PSCAD/EMTDC software environment. This chapter makes a foundation to analyse the system's stability for various cases.

- ***Chapter 4***

Chapter 4 discusses about the investing the system's stability (small signal stability, transient stability) for various cases, which are high penetration level of PV generated power, change in radiation level, variable load & a single line to ground fault.and related analysis are given in Chapter 4.

- ***Chapter 5***

Conclusion based on the simulated result are given in the Chapter 5.

Chapter 2

Simulation Strategy

Based on the previous discussion, for the requirement of proposed work simulation strategy is adopted, which is given in the following sections.

2.1 Solar PV

Solar photovoltaic cell uses photovoltaic effect to convert the sun energy into electrical energy. The power output from the solar PV cells is mainly governed by the amount of the solar radiation available, temperature, photon energy, cell parameter etc. The requirement of proposed study can be understood from the following figures which shows the effect of temperature and radiation on the solar PV power output. figure

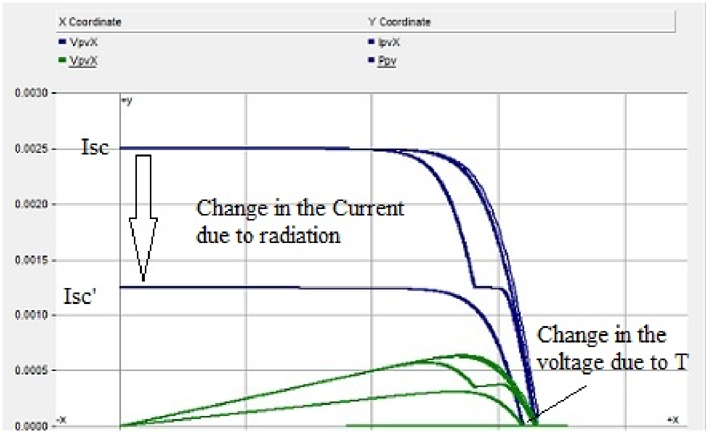

Figure 2.1: Effect of temperature and radiation on solar PV characteristics

As can be seen in fig. 2.1 the optimum voltage moves to the lower values as the temperature increases from 0°C to 75°C. The change in the solar irradiation is more rapid than temperature. The phenomena of the decrement in the power can be understand by the help of the concept of p-n diode. Diode current has a positive temperature coefficient for change in temperature, with increase in the value of the temperature the diode current decreases at the same time it has a negative temperature coefficient for generated voltage, So with increase in the temperature, there is decrement in the voltage that can be observed from the fig. 2.1. As solar irradiation and temperature changes, the P-V curves shift down and to the left, this shifting shows that the power from the solar PV plant depends upon weather condition and due to intermittent weather the power from the plant is intermittent.

2.2 Small Signal Stability

Small-signal stability refers to the ability of a power system to maintain even after being subjected to a small disturbances. Instability may arise in two forms:

- Increase in rotor angle due to insufficient synchronization torque,
- Increase in rotor oscillations amplitude due to insufficient damping torque.

These particular oscillations, when accumulating over certain period of time, not only limit power transfer within the network but, more crucially, could lead to power system breakdown. Thus, it is vital to properly treat the incidents in time. The frequencies and magnitudes of the oscillations under analysis are comparatively small, e.g. in the range of 0.1 to 1.0 Hz for inter-area oscillations and 1.0 to 2.0 Hz for local oscillations, hence the name suggested as 'small-signal' stability. For the purpose of proposed work is to analyze the small signal stability in PSCAD/EMTDC environment. For analysing the system small signal stability, the rotor angle of available machine's and frequency at point of common coupling will be observed.

2.3 Strategy for Analysis

In order to analyze the system stability, grid connected solar PV plant will be developed. The details of modelling of grid connected solar PV plant is given in chapter. After the satisfactory performance of the developed system. Finally a test system will be developed for analysis.

- Different solar radiation levels
- Variable load
- Single line to ground (SLG) fault at one of the generator side

Details of each analysis are given in the chapter 4.

2.4 Simulation Tool

Selection of the software tool mainly based on the requirement of the work. In the proposed work, analysis will be done, considering various steady & transient condition in the system. There are number of software platform available on which the study can be performed. PSCAD/EMTDC simulation software is selected for performing all the simulations.

The main advantage of using PSCAD/EMTDC is that the simulation time requirement is very less with run time parameter variation as one of the major feature of this software. The software itself having the renewable energy sources module like wind,solar PV, So can be used for any analysis.

Chapter 3

Modelling of Grid Connected Solar PV

The solar PV output largely depend upon the solar radiation and ambient temperature. The effect of different radiation level on solar PV output can be analzed by it's non-linear characteristic. Manufacturer used to give the P-V & I-V characteristics for analysing the performance of solar PV module for given input. Various equivalent circuit has been given for analysing the solar PV module, few of them are single diode, double diode equivalent circuit model. The single diode model known as five parameter model is commonly used for analysis. The module of solar PV given in the PSCAD/EMTDC also developed with consideration of single diode equivalent circuit model of solar PV cell. The single diode equivalent circuit model is shown in fig 3.1

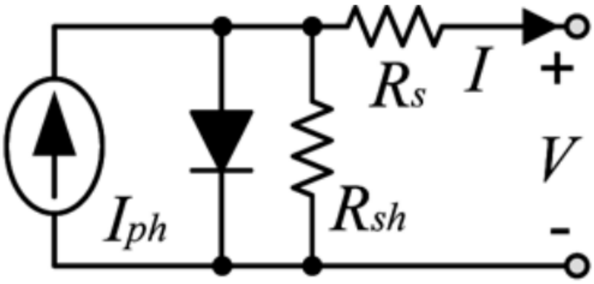

Figure 3.1: Single diode equivalent circuit of PV cell

In fig. 3.1 the value of photo current I_{ph}, open circuit voltage V_{oc} and short circuit current I_{sc} is mainly governed by the following equations

$$I_{ph} = \frac{G}{G_{stc}}(I_{sc} + K_i T) \tag{3.1}$$

$$I = I_{ph} - I_o\left(\exp(\frac{V + IR_s}{V_T}) - 1\right) - \left(\frac{V + IR_s}{R_{sh}}\right) \tag{3.2}$$

In the above equations
I_{ph} is the photo generated current (A)
G is the actual solar radiation (ω/m^2)
G_{stc} is solar radiation available at STC which is $T = 25°C$,$G = 1000\ \omega/m^2$ & at $AM = 1.5$
K_i is temperature coefficient for current (A/K)
I_{sc} is short circuit current (A)
R_s is series resistance considering the effect of lead resistance drop (Ω)
R_{sh} is shunt resistance considering the effect of Shockley red-hall recombination (Ω)
V_T is the thermal voltage (V)
In general the amount of diode saturation current effect is negligible as this is in the range of $e^{(-10)}$ and can be calculated by following equation

$$I_o = \frac{I_{sc} + K_i T}{\exp(\frac{V_{oc}+K_i T}{nV_T} - 1)} \tag{3.3}$$

where
n is the diode ideality factor
$V_o c$ is the open circuit voltage & can be calculated by

$$V_{oc} = \frac{nKT}{q}\ln(\frac{I_{ph}}{I_o} + 1) \tag{3.4}$$

where
q is charge of electron $1.6\times\mathrm{e}^{-19}$ Coloumb
K is Boltzman Constant
Based on the above eq. $3.1 - 3.4$ the capacity of solar PV array is decided. There

are number of solar PV array configuration is available and are selected based on the requirement. They are shown in the fig. 3.2

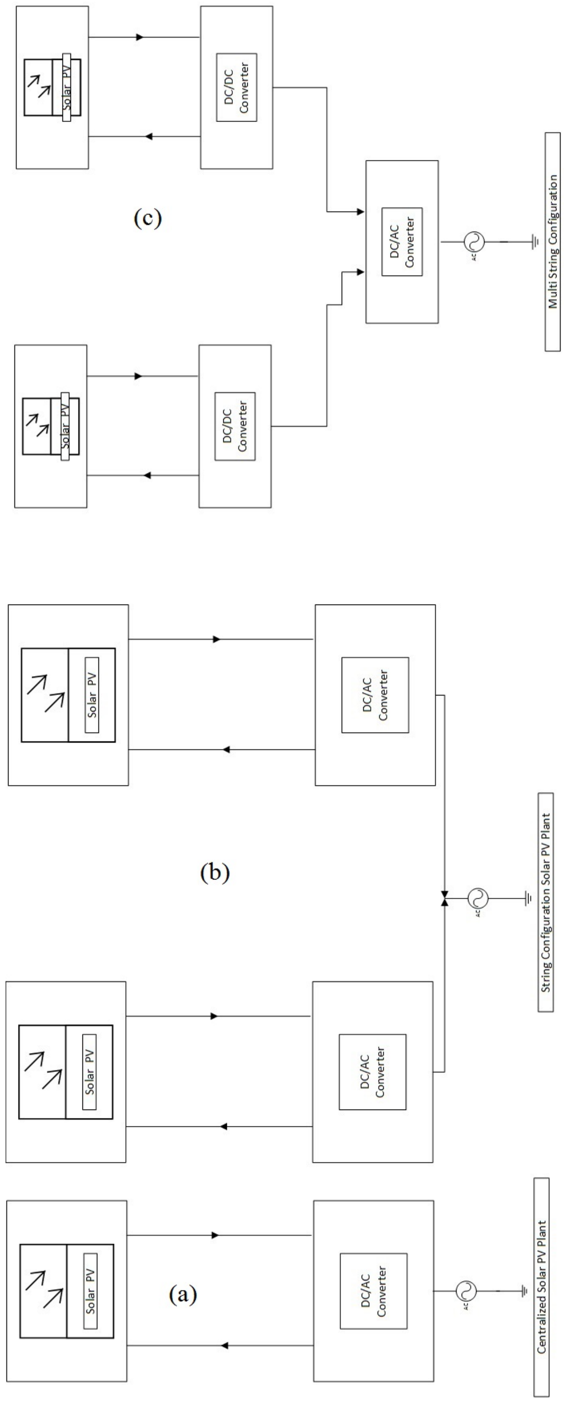

Figure 3.2: Different Configuration to connect PV system into AC main
(a) centralized configuration (b) string configuration (c) multi string configuration

In fig. 3.2 the centralized configuration gives a low cost per watt. The centralized configured solar PV array has adequate capacity to maintain the dc-link voltage. Multi string configuration is generally used, when solar PV has small capacity. In the proposed analysis, the grid connected solar PV is modelled considering centralized configuration.

3.1 Centralized Solar PV System

Typical layout of the centralize configured solar PV system connected to AC mains is shown below

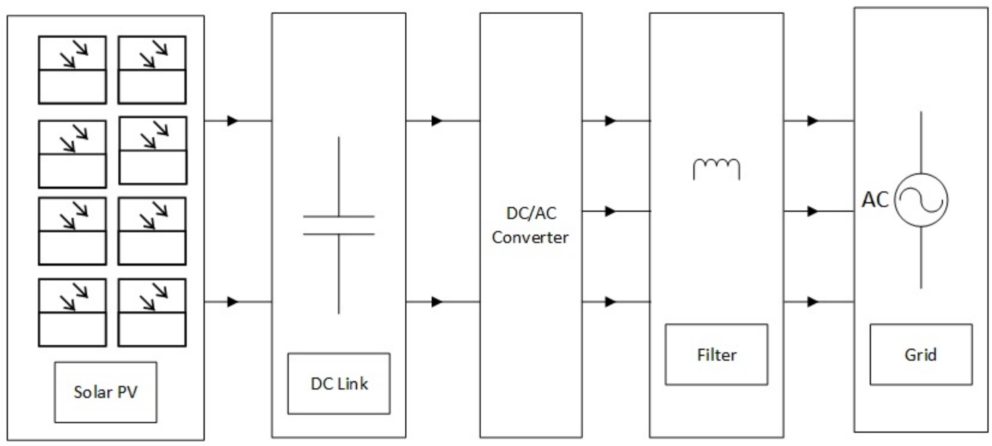

Figure 3.3: Layout of the grid connected solar PV

In the above figure, the dc voltage at the input side is maintained with the help of DC link capacitor. Then it gets converter into AC with the help of inverter. Details of each component used for developing the grid connected solar PV system is given in the following subsections.

3.1.1 DC link

The output voltage & current of solar PV is depend upon the radiation and temperature. For any operating condition, the addition of each module will give the total array voltage. For the successful operation of Inverter, it is required to have constant DC input voltage. To maintain the input side voltage constant, the DC link capacitor is used. By using the large value of DC link capacitor the ripples in the source current can be reduced. In the developed simulation model, the value of capacitor $10000\mu F$ is chosen.

3.2 Inverter

The PV inverter converts the DC into AC quantity, at the same time it decouples the PV from the grid. For large-scale solar PV plant, PV inverter usually comes in three-phase arrangements. The PV inverter consists of three legs of power electronics switches (IGBT,GTO etc.). nti parallel diode is connected across each of the IGBT to allow reverse flow of current.

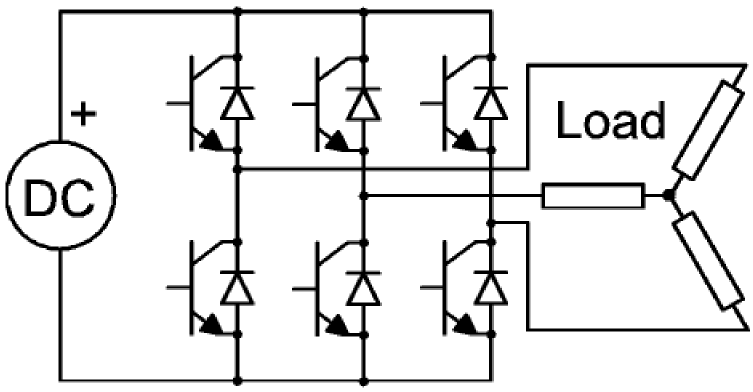

Figure 3.4: Layout of 3ϕ inverter

As shown in figure 3.4 the top switches connect the terminals of phase A, phase B, and phase C to the positive of the DC bus, and the bottom switches connect the phases to the negative of the DC bus.
There are various configuration is available for 3ϕ inverter. Few of them are given below.

- Current Regulated Voltage Source Inverter (CR-VSI),
- Current Regulated Current Source Inverter (CR-CSI),

- *Z* Source Inverter

CR-CSI has better performance compared to CR-VSI. Due to the limitations of CR-VSI and CR-CSI the *Z* source inverter is getting attention [17]. However for proposed work, analysis is done with CR-VSI. The switching of IGBT is done with the help of SPWM technique. The complete control strategy for switching of IGBT's is given in following sub-section.

3.2.1 Control of CR-VSI

Inverter operation is achieved using current controlled inverter, which enables the control over real and reactive power. The real and reactive component is independently controlled [9]. The complete control scheme is given in fig. 3.5

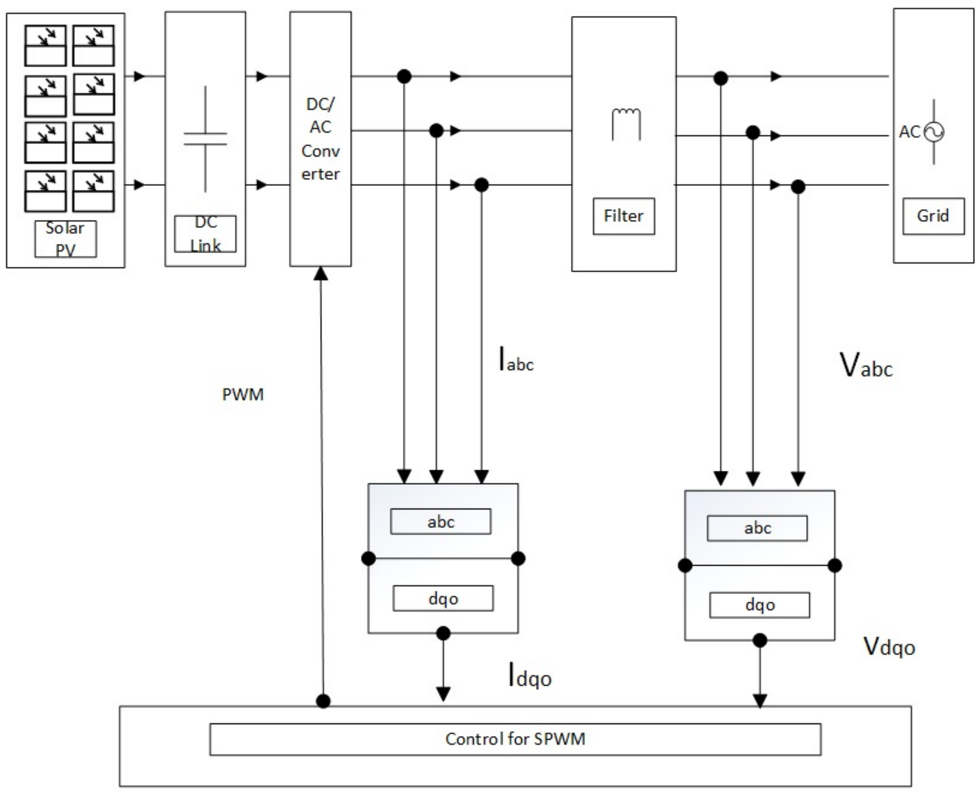

Figure 3.5: Control structure for generating PWM pulses for CR-VSI

For controlling the real and reactive power, voltage & current which are in time domain are sensed from the inverter output side and converted synchronous reference

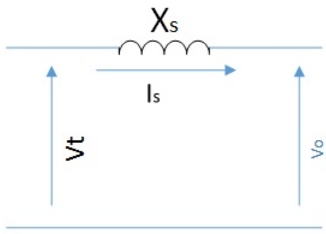

Figure 3.6: Voltage drop occurring at filter impedance

frame.

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\theta & cos(\theta - \frac{2\pi}{3}) & cos(\theta + \frac{2\pi}{3}) \\ -sin\theta & -sin(\theta - \frac{2\pi}{3}) & -sin(\theta + \frac{2\pi}{3}) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.5}$$

Where

θ is the angle at which the grid is operating.

These signals V_d & V_q are sent to the control block. The real and reactive power can be calculated as

$$P = \frac{3}{2}(V_q I_q + V_d I_d) \tag{3.6}$$

$$Q = \frac{3}{2}(V_q I_d - V_d I_q) \tag{3.7}$$

As can be seen in the figure 3.6, A considerable amount of voltage drop occurring at filter impedance. So PV should be capable to generate the voltage which also include the drop occurring across the X_s. The governing equations to generate the required voltage is

$$V_t = V_o + jX_s I_s \tag{3.8}$$

Park's transformation is used to implement the eq. 3.8 in control loop. Park's transformation converts the current and voltage (which are in time domain) to dq axis in synchronous reference frame. In dq axis the voltage drop is included as

$$V_{tq} = V_q + I_d X_s \tag{3.9}$$

$$V_{td} = V_d - I_q X_s \tag{3.10}$$

As given in the eq. 3.9 & 3.10, the signals V_{tq}& V_{td} are again converted back into time domain quantities with the help of inverse Park's transformation.

$$\begin{bmatrix} V_{aref} \\ V_{bref} \\ V_{cref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\theta & -sin(\theta) & \frac{\sqrt{2}}{2} \\ cos(\theta - \frac{2\pi}{3}) & -sin(\theta - \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \\ cos(\theta + \frac{2\pi}{3}) & -sin(\theta + \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} V_{td} \\ V_{tq} \\ V_0 \end{bmatrix} \tag{3.11}$$

The control loop developed in the software environment is shown in fig. 3.7 - 3.8. The d axis reference (I_{dref}) is calculated after comparing the the actual dc link voltage with the reference voltage. Generally, at the place of reference voltage, V$_{mpp}$ is used to extract the maximum power from solar panel. For the unity power factor operation of inverter, the I_{qref} is taken as 0.

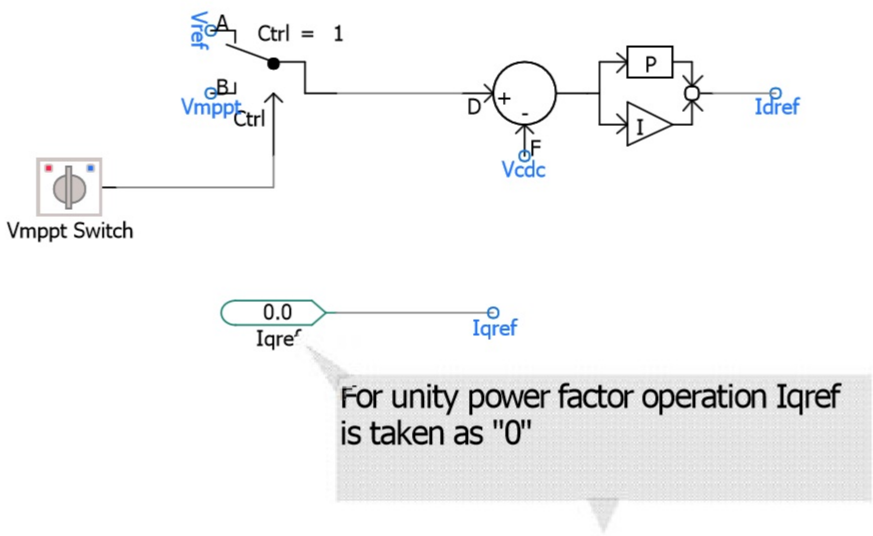

Figure 3.7: I_{dref} & I_{qref} for controlling the real and reactive power

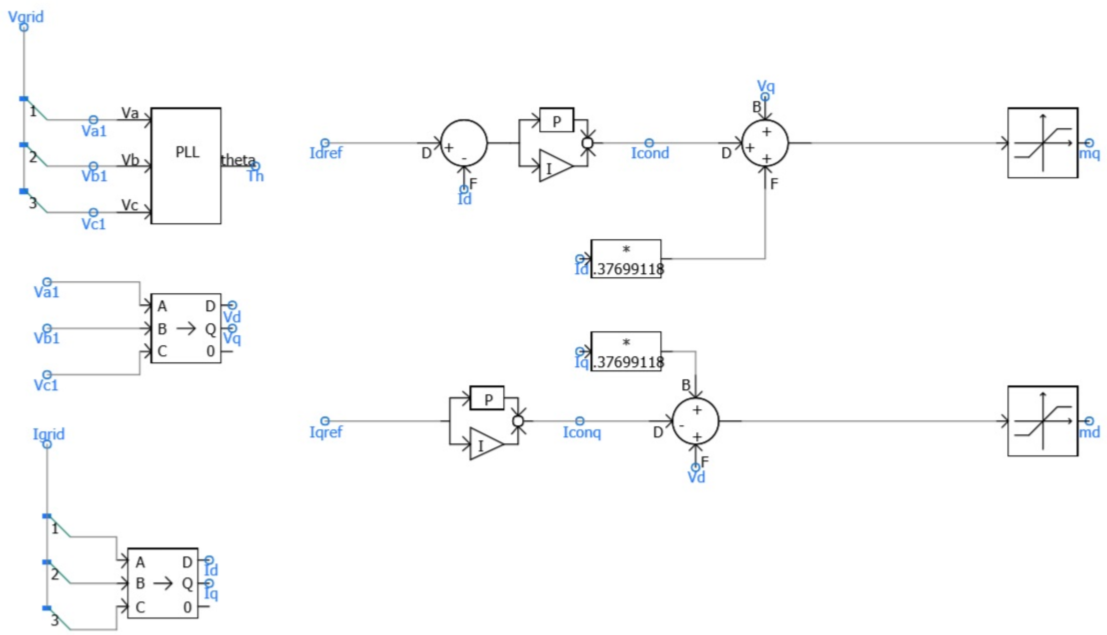

Figure 3.8: Generation of modulated signal after inclusion of voltage drop across filter impedance

These modulated signal as shown in fig. 3.8 (m_d & m_q) are again converted into time domain reference frame with the help of inverse Parks transformation. The converted signal V_{aref},V_{bref} & V_{cref} are used to generate the switching signals for the operation of inverter.

PWM signal are generated by comparing the reference wave V_{aref},V_{bref} & V_{cref} with carrier wave. Carrier wave is generally having the frequency in the range of kHz. Figure 3.9 shows the generation of PWM signals in software environment.

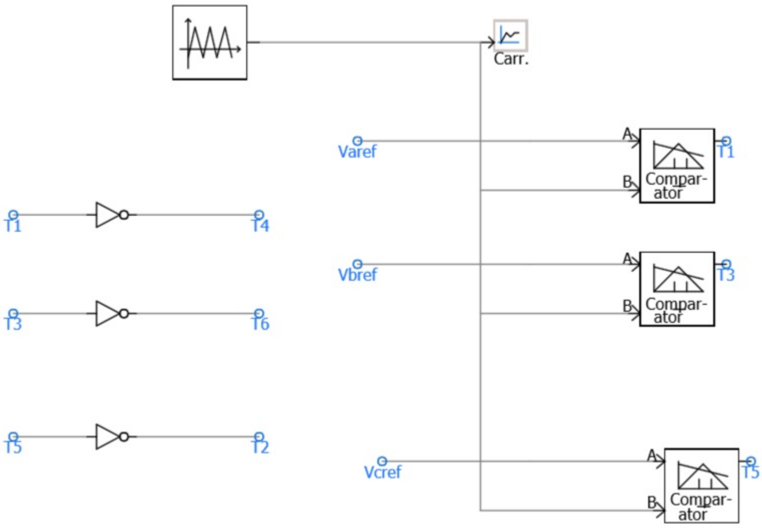

Figure 3.9: Switching signals for inverter IGBT's

3.2.2 Smoothing inductor & transformer

The inductor at the output side of the inverter provides the filtering action. Keeping the higher value of the inductor will lead to the voltage drop across the impedance. Hence, appropriate value of inductor shall be chosen.

Transformer is used to provide the galvanic isolation and at the same time to step up the voltage. Here in the simulation, transformer is used to step up the voltage to 11 kV which is equal to the grid voltage.

3.3 Simulation of 3 Phase grid connected solar PV

Based on the discussion made in the previous section, Modelling of the grid tied solar PV test system is developed. The plot step used for the analysis is 200μsec. The developed model is shown in fig. 3.10

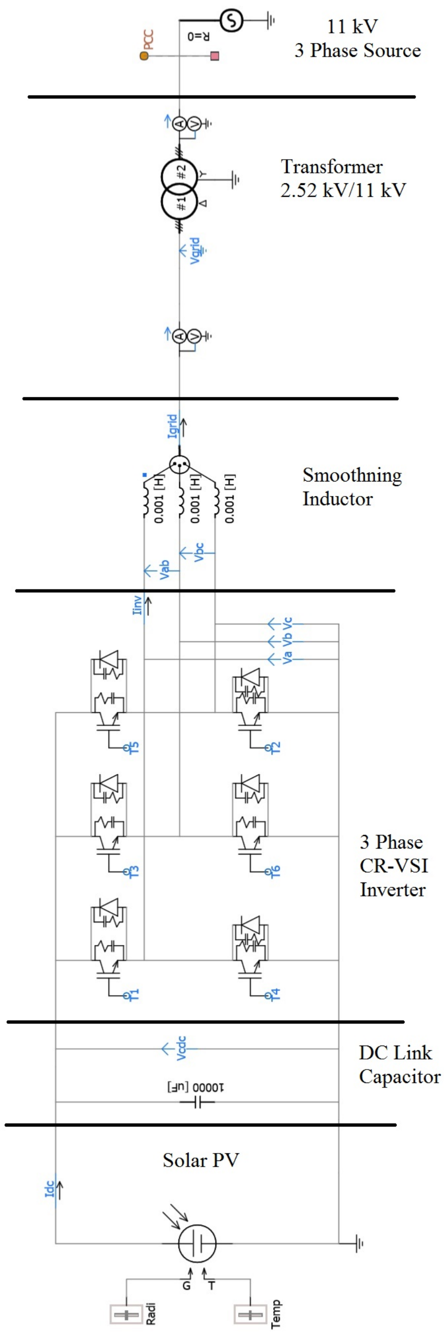

Figure 3.10: 3 phase grid connected solar PV

The solar PV array parameter used for simulation is given in table 3.1.

Table 3.1: Solar PV array parameters

PV Parameter	Value
No. of modules connected in series / array	100
No. of module string in parallel / array	46
No. of cells connected in series / modules	30
No. of string in parallel / module	50
Reference irradiation (ω/m^2)	1000
Reference cell temperature (°C)	25
Effective area (m^2)	.01
Series resistance / cell (Ω)	.02
Shunt Resistance / cell (Ω)	1000
diode ideality factor	1.627
Band gap energy	1.103
Saturation current at reference conditions / cell (A)	$1\mathrm{e}^{-10}$
Short circuit current at reference conditions / cell (A)	2.5
Temperature cofficient of photo current (A/K)	.001

For the above parameters, the simulation results are as follows. The available voltage at the output side of solar PV is shown in fig. 3.11. As shown in figure, DC link capacitor of value $10000\mu F$ is maintaining the output voltage constant.

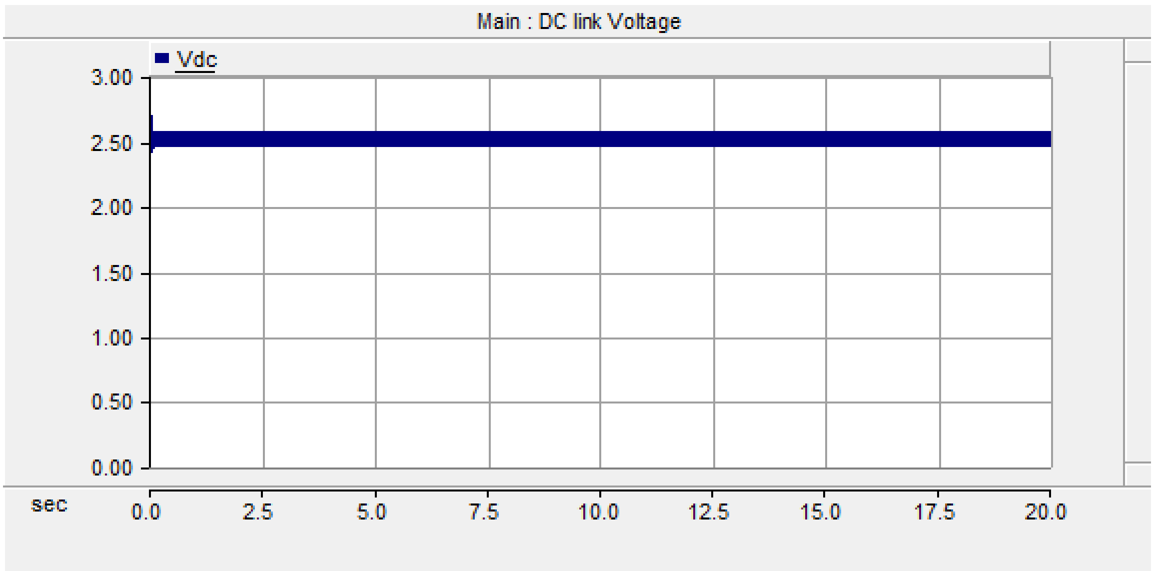

Figure 3.11: DC Link Voltage
X-axis=2.5sec/Div, Y-axis=0.50kV/Div

For the successful operation of the inverter the DC link voltage is required to be constant. Voltage shown in fig. 3.11 is available to the input of inverter.

The closed system described in fig. 3.5 is used to generate the reference waves. Phase locked loop (PLL) is used to fetch the system frequency, required to maintain the synchronisation. Based on the loop structure, the reference voltage is generated with the help of the inverse Park's transformation. The generated reference wave of phase A, B, and C are shown below in figure 3.12

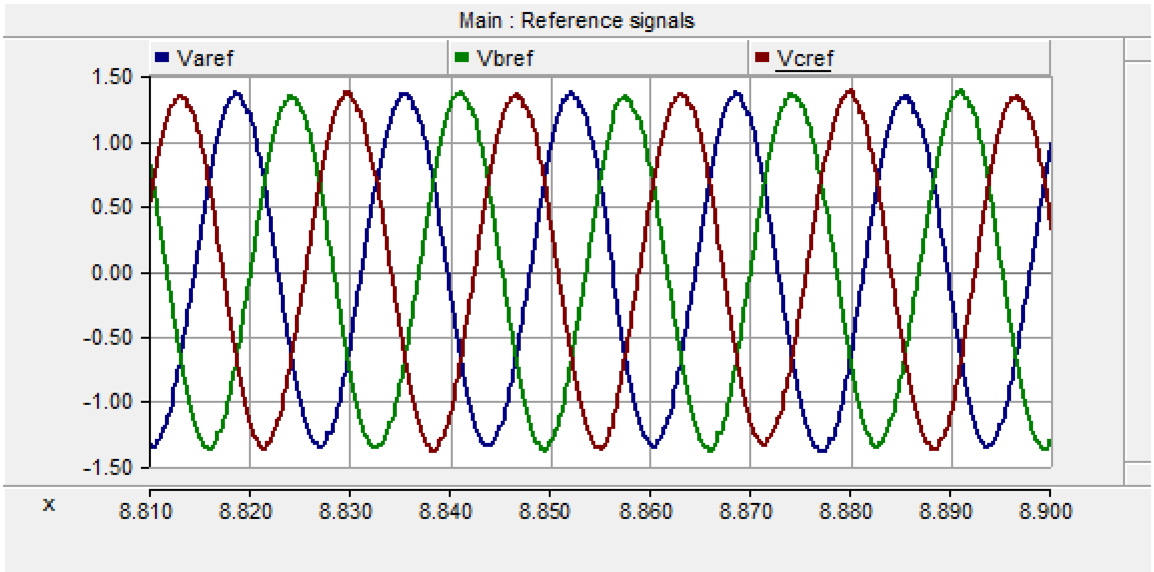

Figure 3.12: Modulated reference signal V_{aref} of phase a
X-axis=0.010sec/Div, Y-axis=0.50/Div

V_{aref}, V_{bref} & V_{cref} as shown in figure 3.12, are compared with the triangular wave of frequency 6 kHz. The comparison of the two signal for generation of switching signals is shown in the figure 3.13

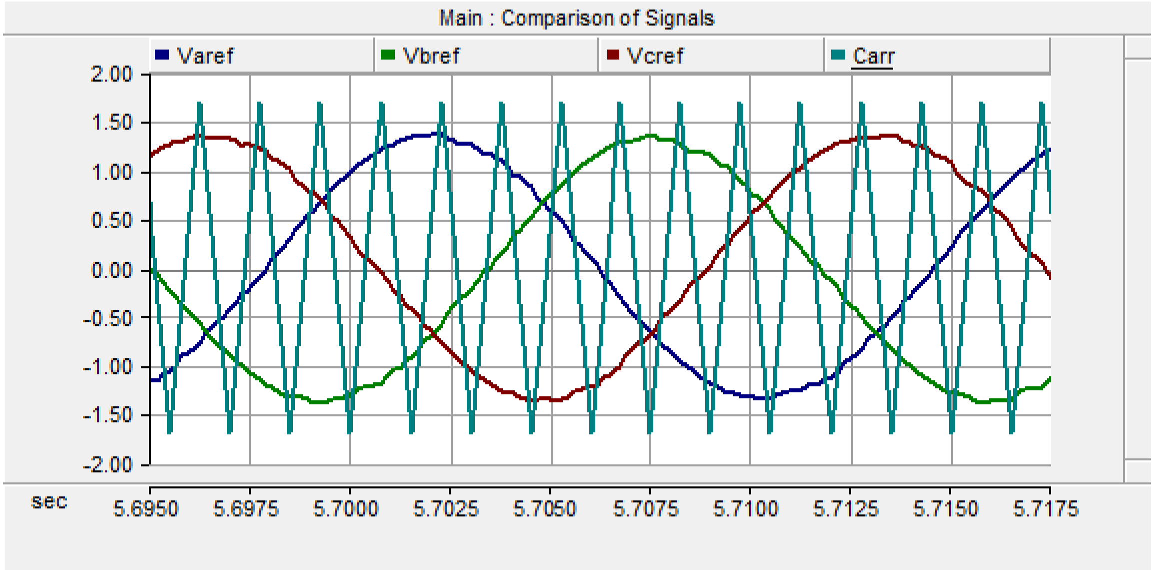

Figure 3.13: Comparison of reference wave and triangular wave
X-axis=0.0025sec/Div, Y-axis=0.50/Div

In figure 3.13 comparison of all the phases are shown. Based on the comparison the triggering signal T_1, T_3 & T_5 are generated. In order to avoid the short circuit of DC bus, two switches of same phase are never be turned on at the same time. Triggering of two switches of a phase is 180° apart. Based on the triggering signal, the output voltage of inverter is shown in fig. 3.14.

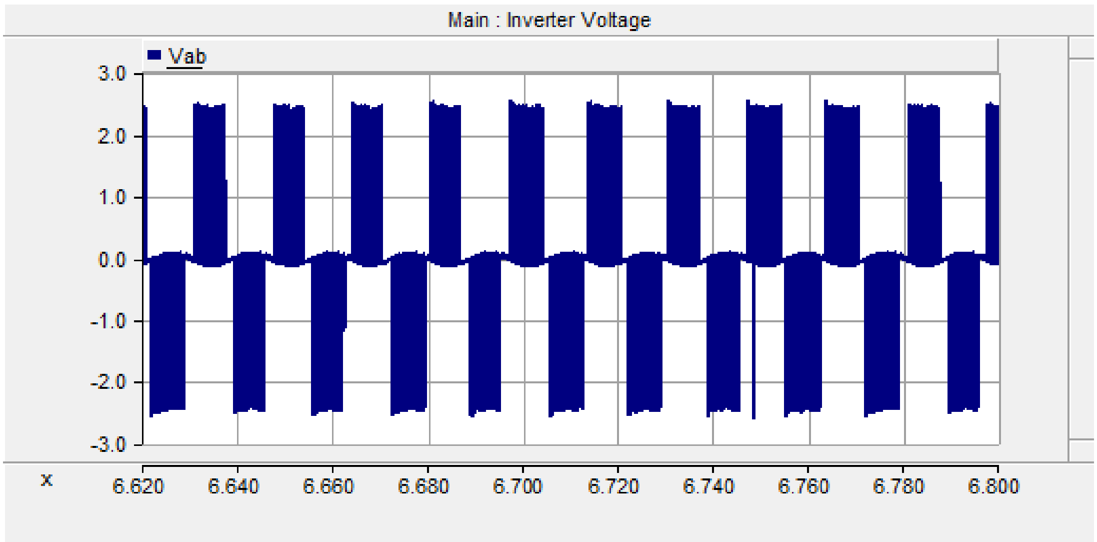

Figure 3.14: Inverter output voltage
X-axis=0.020sec/Div, Y-axis=1kV/Div

The inverter output current is shown in figure 3.15

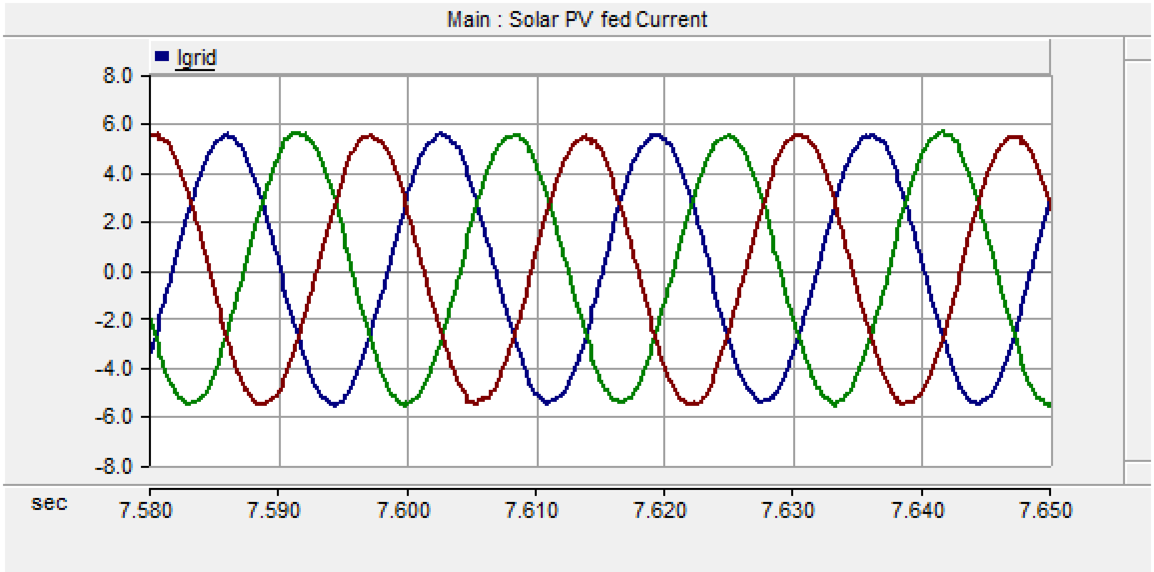

Figure 3.15: Output current of inverter
X-axis=0.010sec/Div, Y-axis=2kA/Div

Total power generated by solar PV is more than the total power available at the point of common coupling (PCC). This is because of the switching losses occurring in the system. The simulated system is a single stage system, so the losses are less compared to the two stage system (DC-DC & DC-AC). The power generated and power available at PCC are shown below 3.16.

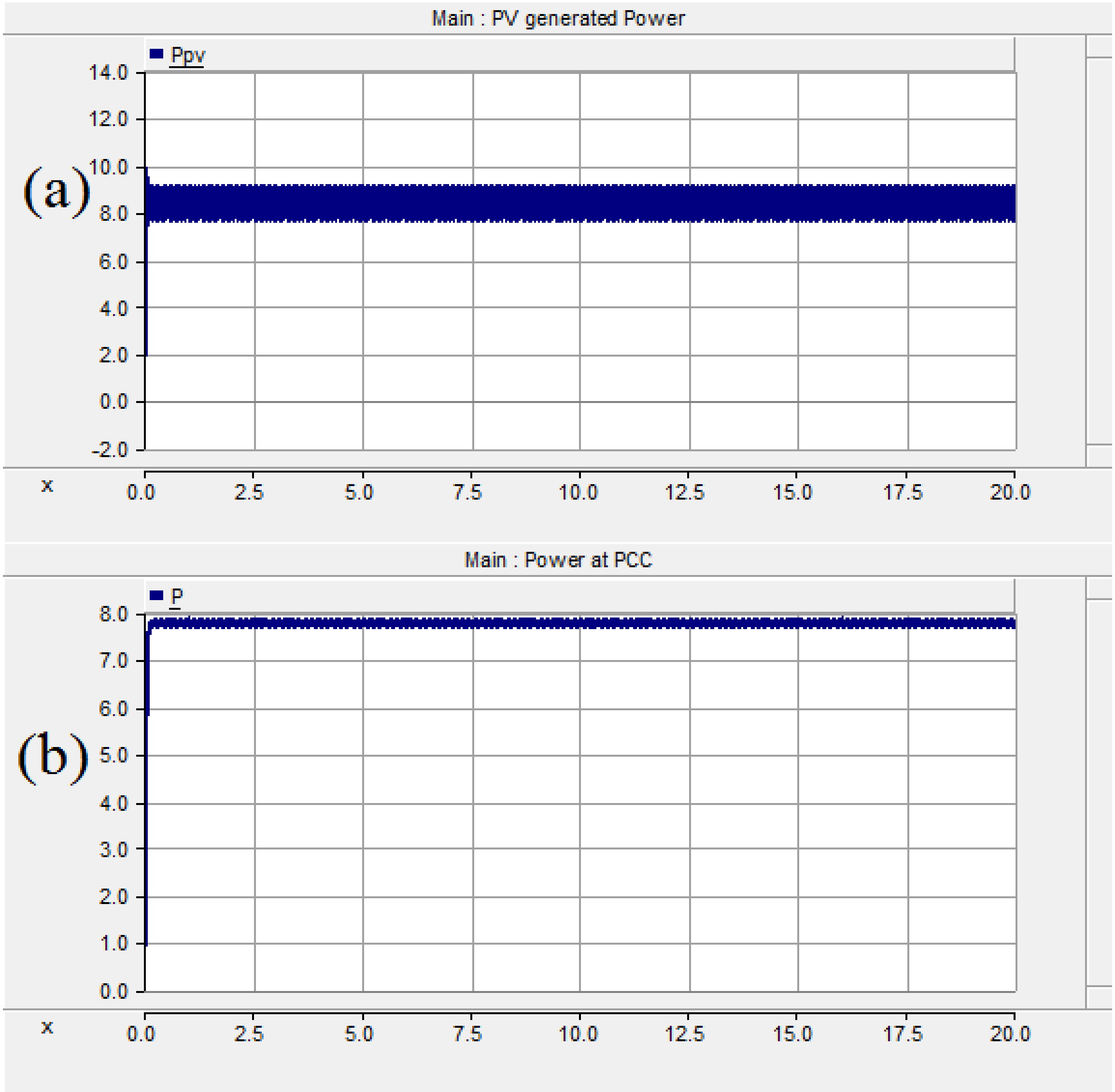

Figure 3.16: (a) Power generated by solar PV (b) Power available at PCC

(a)X-axis=2.5sec/Div, Y-axis=2.0MW/Div
(b)X-axis=2.5sec/Div, Y-axis=1MW/Div

Chapter 4

Stability Analysis of System

For the purpose of analysing the system, A test system is simulated for various cases. The details of simulated system is given in the following sections.

4.1 Test System

In a system to have a relative oscillation more than one machine is required. Test system is developed, in which three generating sources are considered. Two of the generating sources are synchronous generators and Solar PV is considered as the third generating source in the test system. Details of the system is given below.

- Each of the conventional generator is of capacity 6 MVA,
- Inertia constant of one machine is 3.5 Sec. and of the other machine is 1.2 Sec.
- Solar PV is considered of capacity of 8 MW

For analysis, PV penetration level (PV_{glevel}) is considered. The PV penetration (PV_{glevel}) level is defined as the ratio of power generated by the solar PV to the total power generated of the system.

$$PV_{glevel} = \frac{P_{pv}}{P_{total}} \tag{4.1}$$

where

PV_{glevel}= PV penetration level (%),

P_{pv}= Total PV generation (MW),

P_{total}=Total generation (MW)

PV penetration level can also be defined on the basis of the total energy served or the basis of the peak load. With the increase in the penetration of PV power, more power from the conventional generators is displaced. For maintaining the adequate quantity of reactive power in the system conventional generator kept on-line. Typical layout of the system under study is shown below.

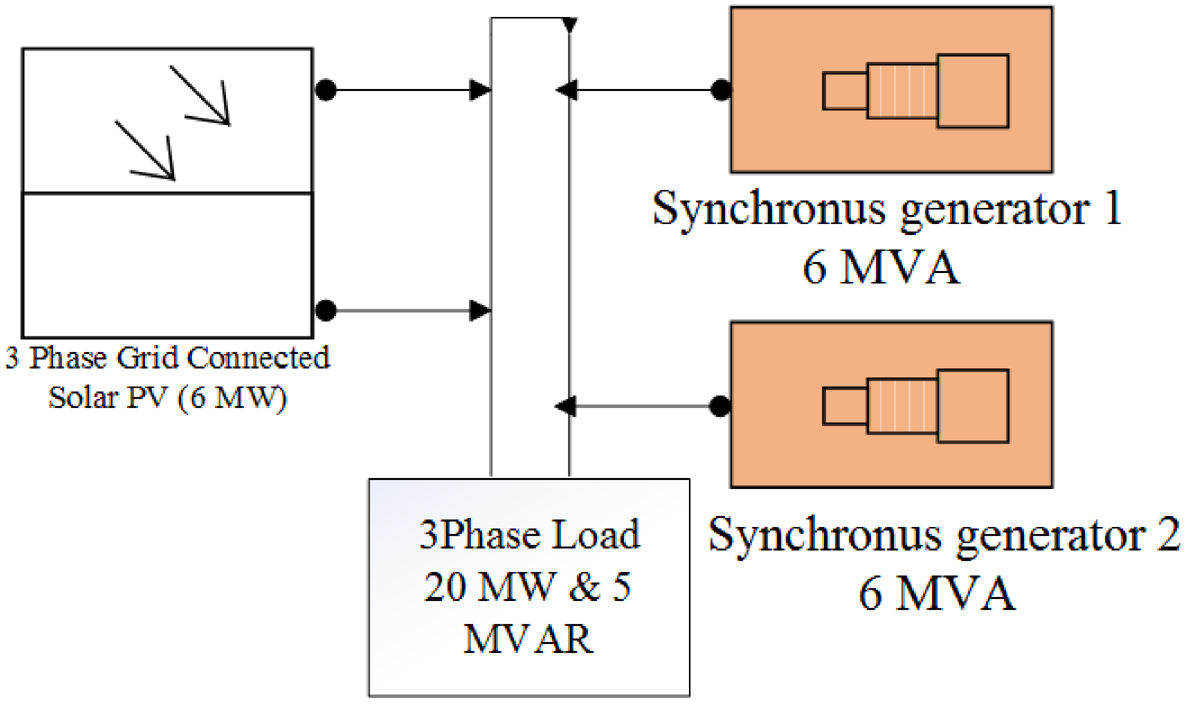

Figure 4.1: Layout of Test System

Test system parameter are as follows

1. Machine:1 has total capacity of 6 MVA with inertia constant of 3.5 Sec.

2. Machine:2 has total capacity of 6 MVA with inertia constant of 1.5 Sec.

3. Solar PV has total capacity of 6 MW.

4. 3ϕ static load on the system is 20 MW and 5 MVAR.

Few cases are considered to analyse the system's small signal stability. These cases considered for the analysis are more general cases and occur in day to day life. The details of each case and the behaviour of system for the particular case is discussed.

4.2 Case:1 Penetration level

The output of the solar PV plant highly depends upon the radiation level. As the weather is intermittent, the power from solar PV varies. As the change in radiation is more rapid then change in temperature, for purpose of analysis the change in radiation is considered. The considered change in radiation level is given below in fig. 4.2.

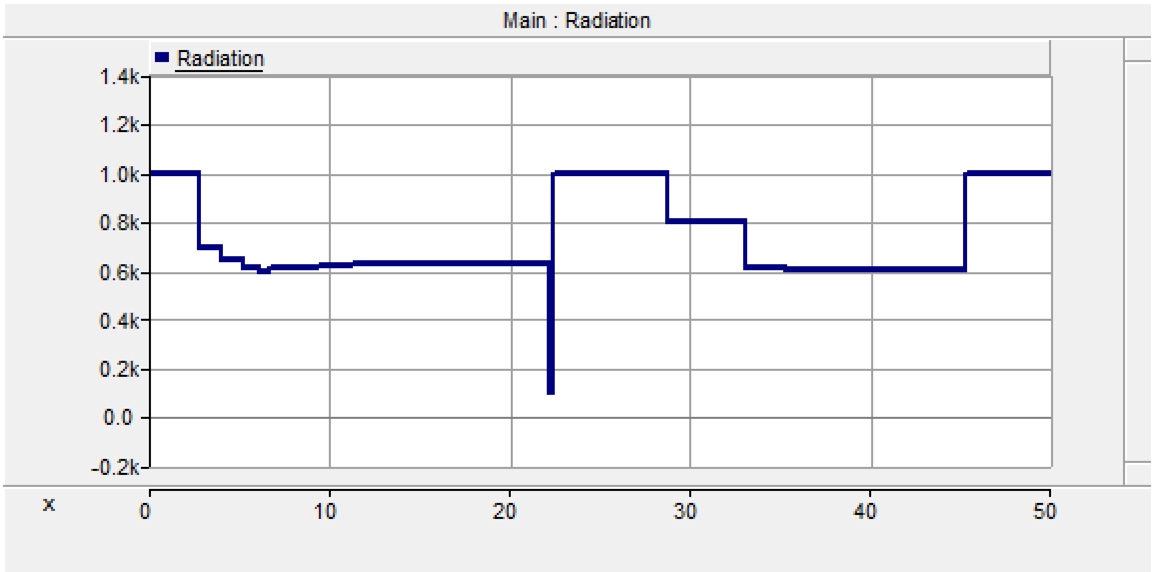

Figure 4.2: Change in Radiation

X-axis=10sec/Div, Y-axis=200 (ω/m^2)/Div

Based on the available radiation level, the solar PV output keeps on changing. The changed solar PV output power is shown below in fig.4.3

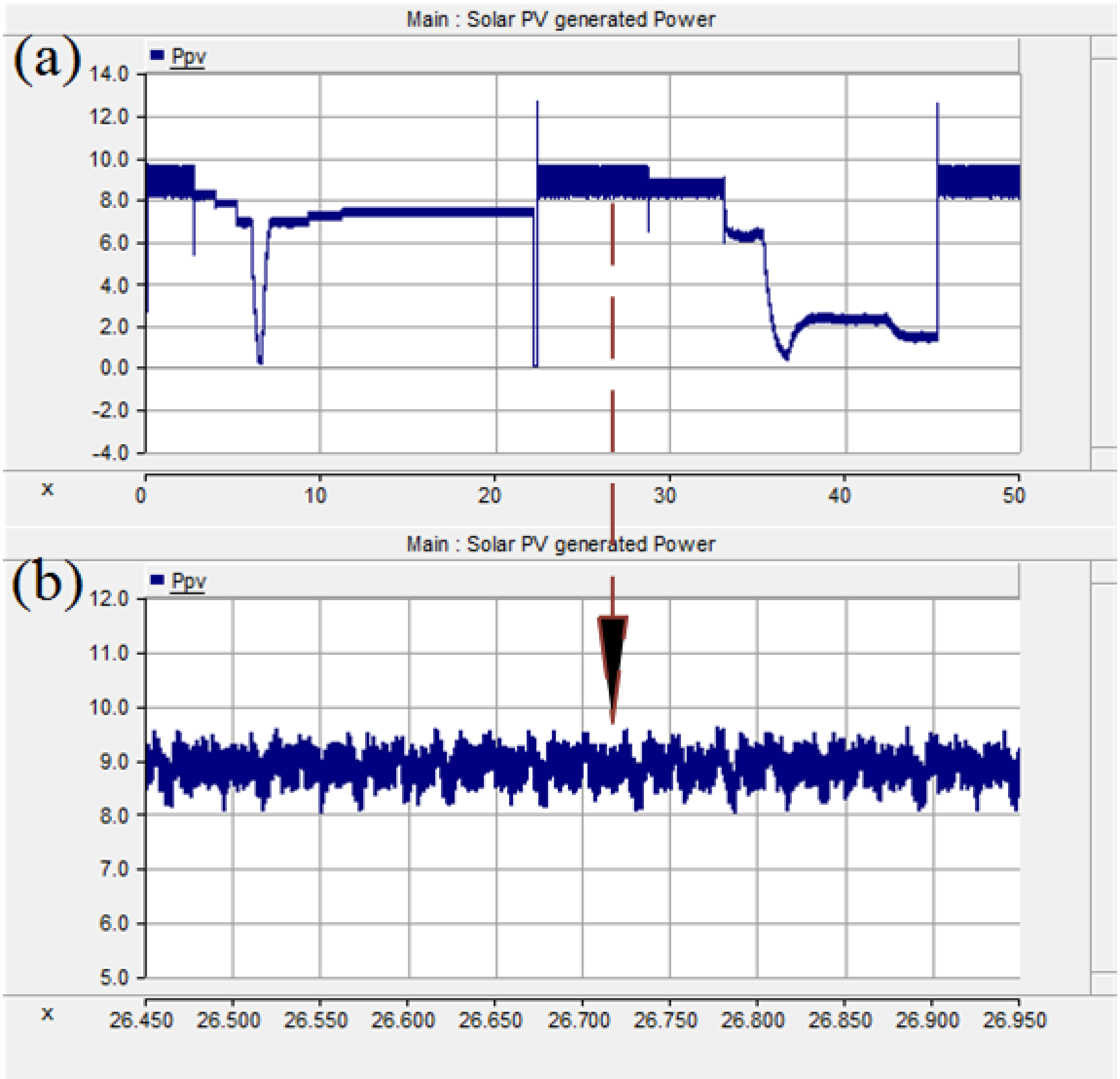

Figure 4.3: Power generated by solar PV

(a)X-axis=10sec/DIv, Y-axis=2MW/Div
(b)X-axis=.050sec/DIv, Y-axis=1MW/Div

The total available power at PCC fed by solar PV is shown below in fig. 4.4.

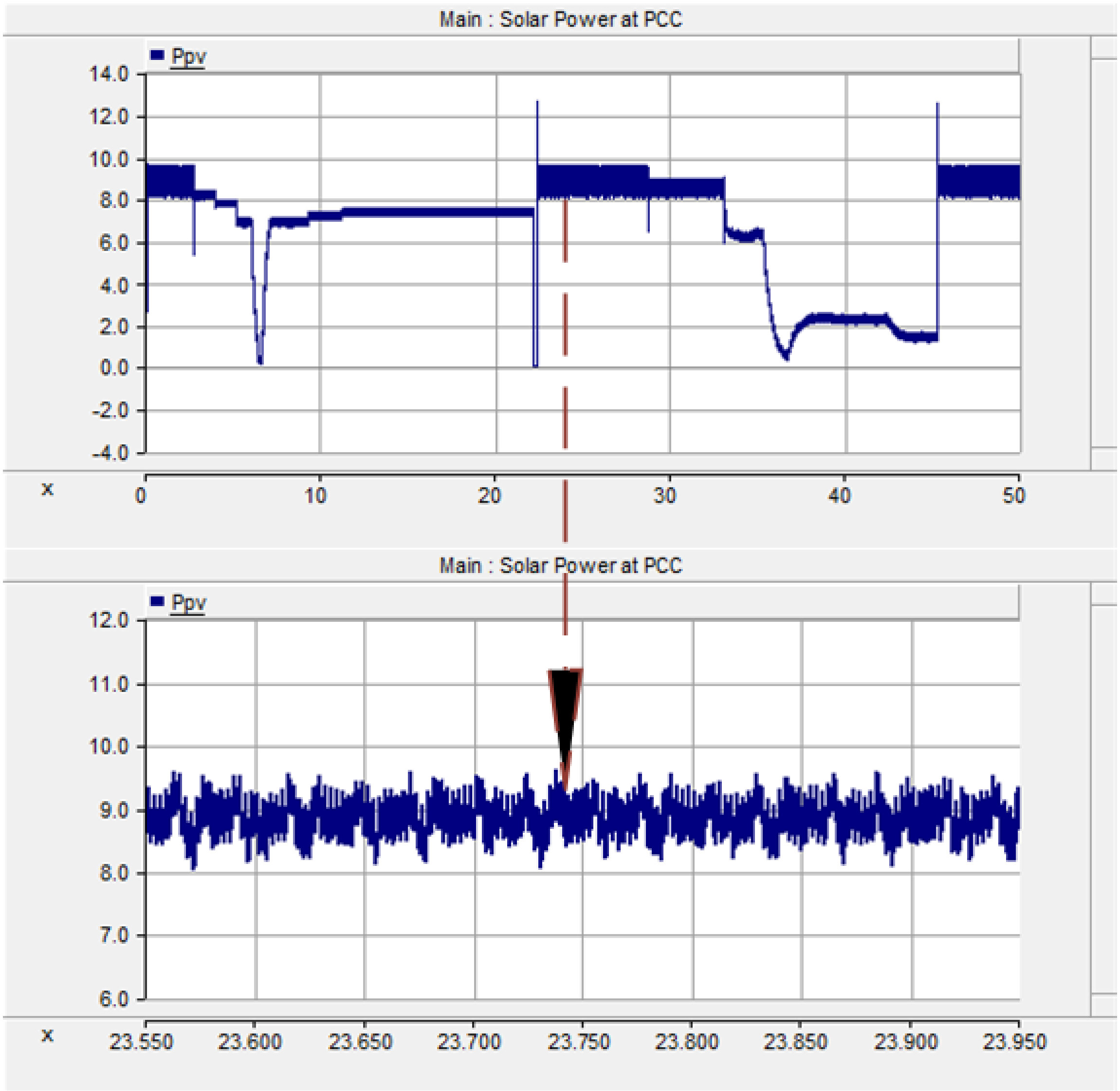

Figure 4.4: Power available at PCC fed by solar PV

(a)X-axis=10sec/Div, Y-axis=2MW/Div
(b)X-axis=.050sec/Div, Y-axis=1MW/Div

In the figure 4.4 power below 0 shows the reversal of the power flow due to insufficient radiation. When power goes negative inverter will not function. As the power from solar PV keep on changing with radiation level, generator made on-line when there is insufficient radiation. In the developed system the two machine shared load based on their respective droop characteristics. For the reduced radiation level, the power generated by synchronous machine's are shown below in fig.4.5

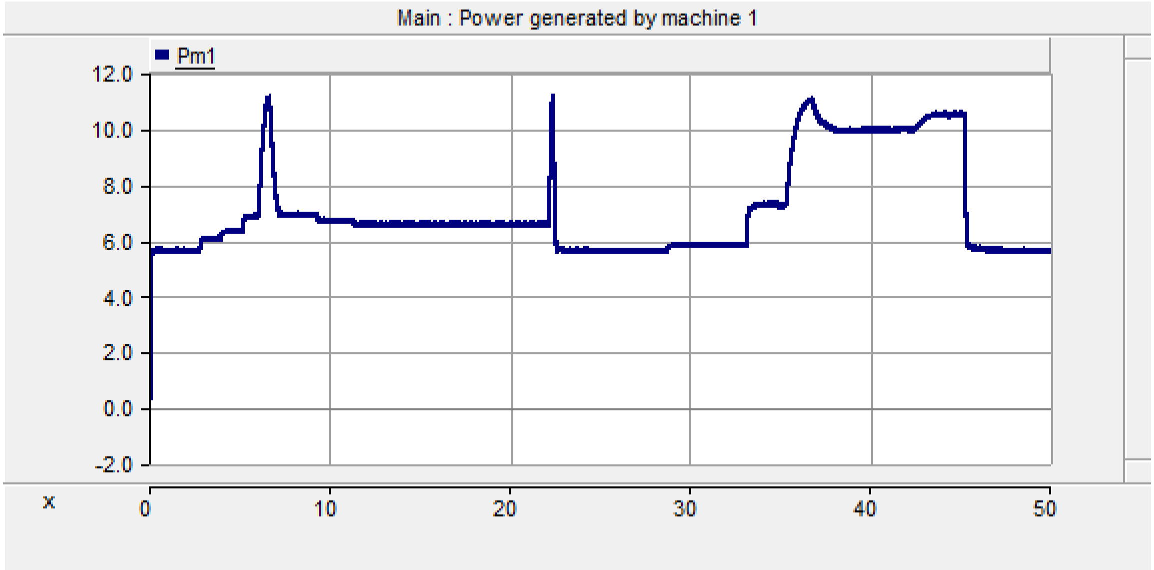

Figure 4.5: Power generated by machine 1
X-axis=10sec/DIv, Y-axis=2MW/Div

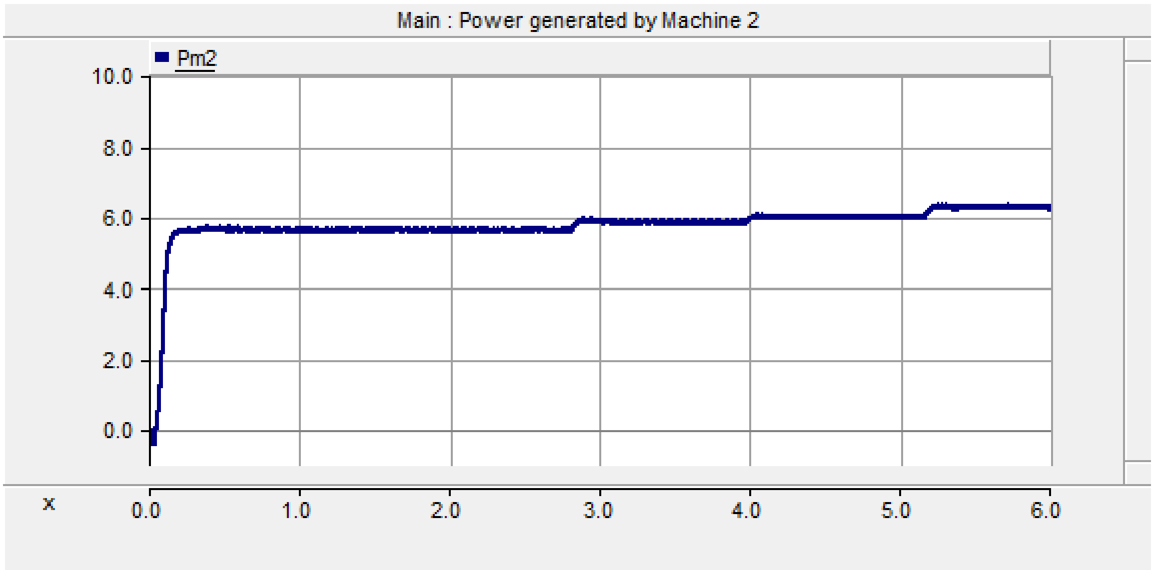

Figure 4.6: Power generated by machine 2
X-axis=1sec/Div, Y-axis=2MW/Div

It can be seen from figure 4.5 & 4.6 that synchronous machine's are balancing available load (after losing the kinetic energy), when the power from the solar PV is not sufficient. For variable power output of solar PV, the variation of rotor angle of each machine is shown below.

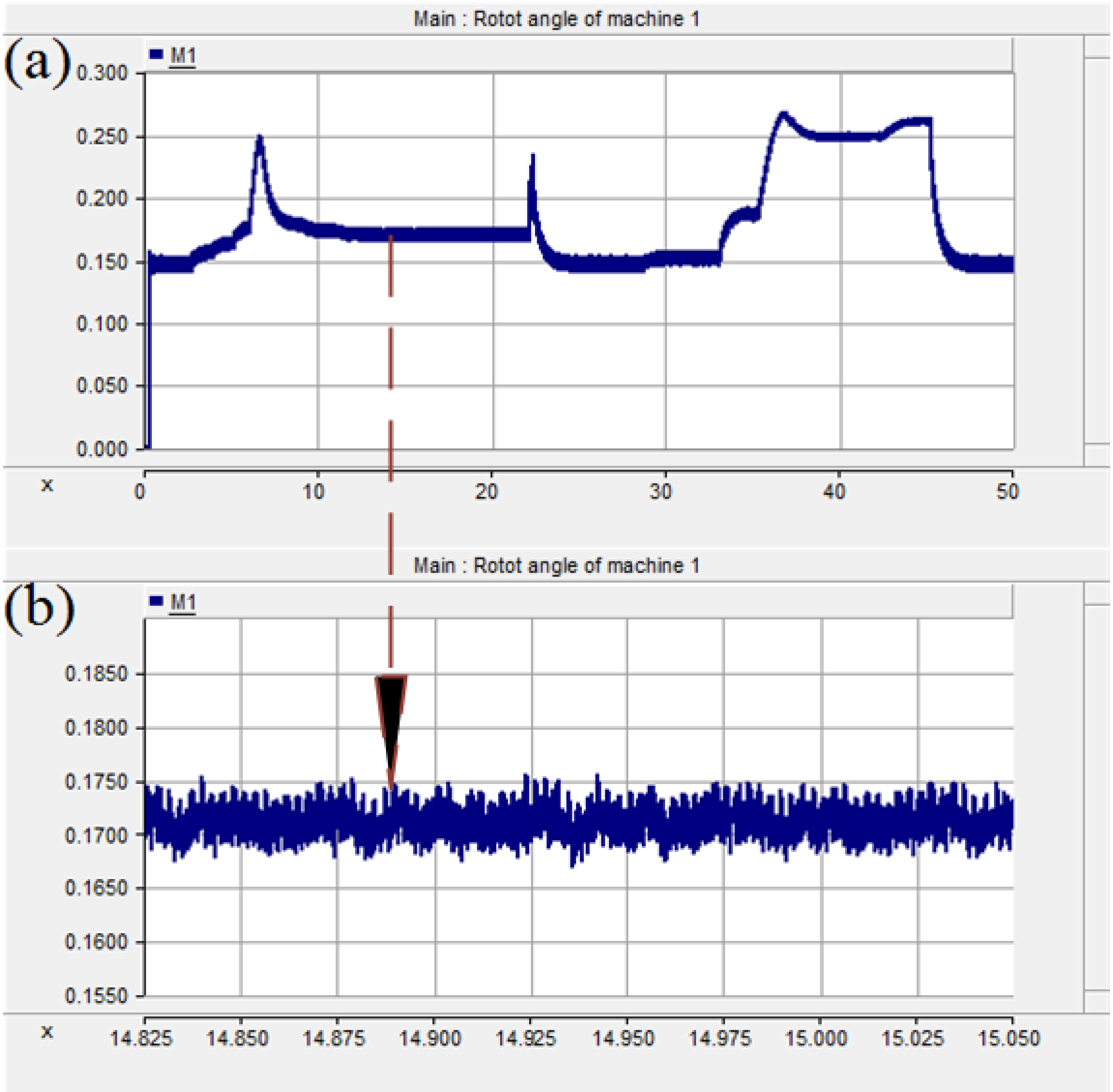

Figure 4.7: Rotor angle of machine 1

(a)X-axis=10sec/Div,Y-axis=.050rad/Div,
(b)X-axis=0.025sec/Div, Y-axis=0.050rad/Div

and of the machine 2 the variation in rotor angle is shown.

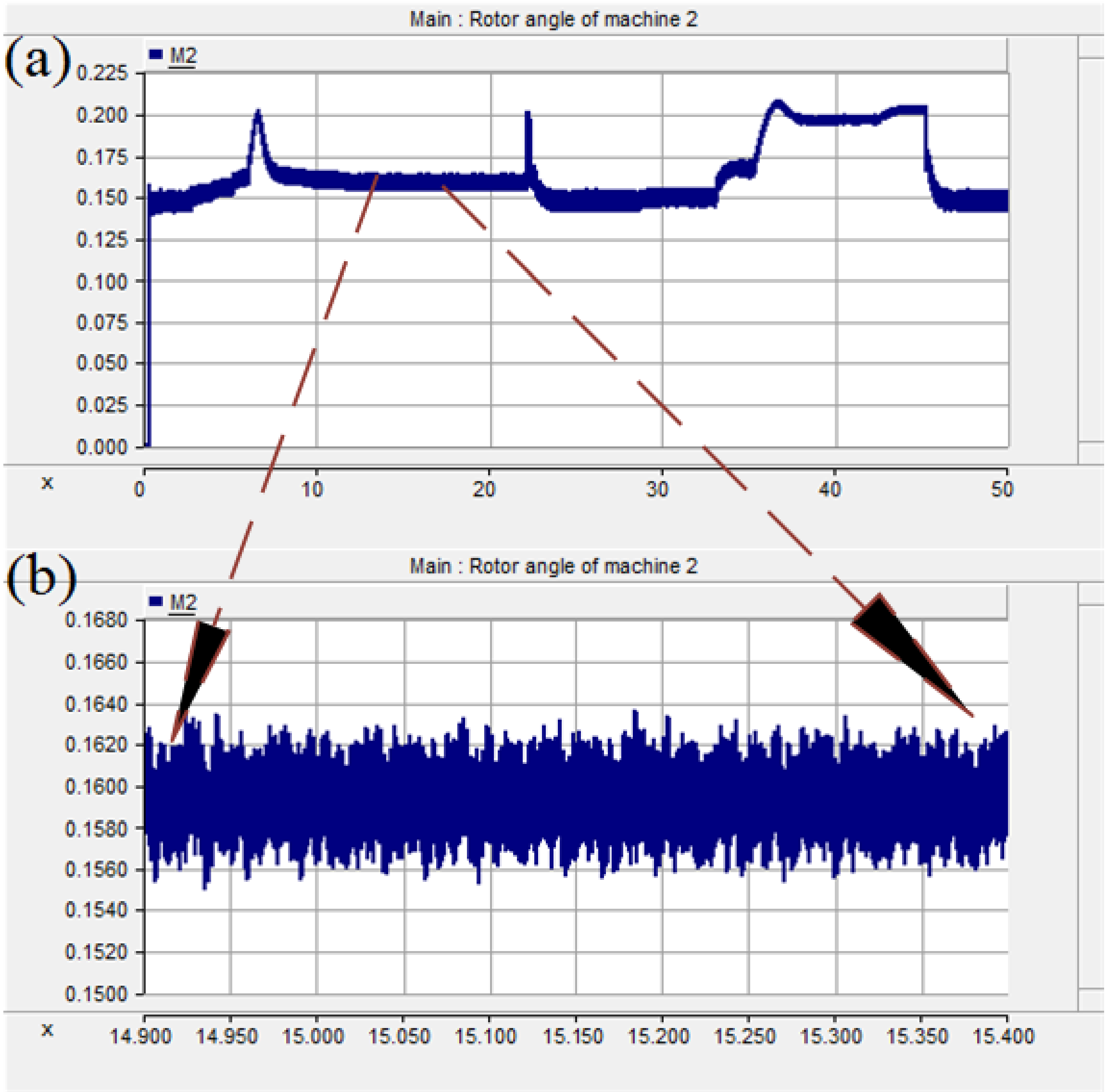

Figure 4.8: Rotor angle of machine 2

(a)X-axis=10sec/Div, Y-axis=0.025rad/Div
(b)X-axis=.050sec/Div, Y-axis=0.020rad/Div

It can be seen from the figure 4.7 & 4.8 that both of the machines are experiencing the continuous oscillations, even when the power from the solar PV is very less. These figures also shows that whenever the radiations fall below a minimum limit, reversal of current take place. For each reversal, current machine is experiencing a huge rotor oscillations. This situation will be more prominent for the case, when the load demand is high and radiations keep on changing.

For simulated system, the frequency at PCC is shown below.

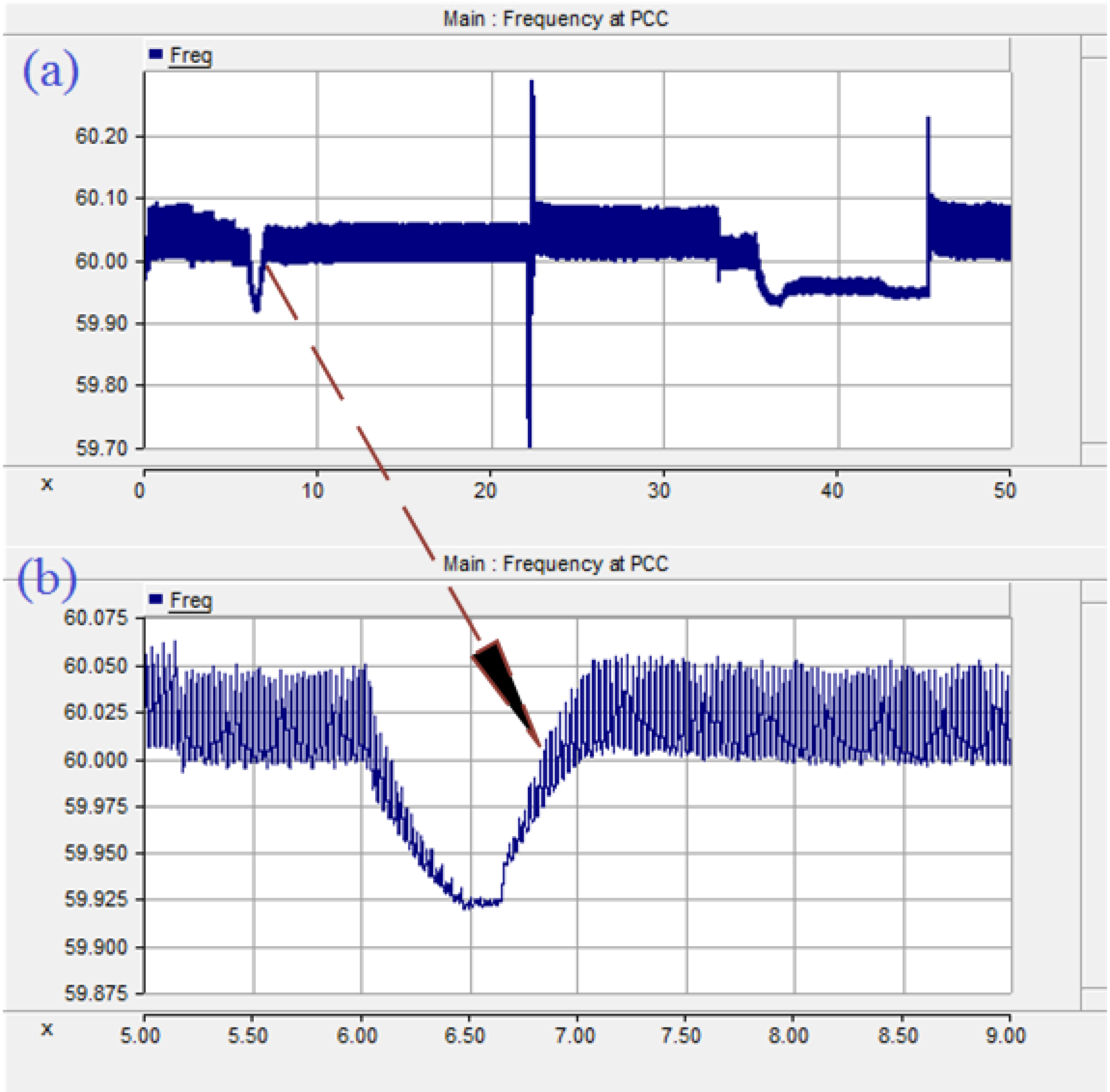

Figure 4.9: Frequency at PCC

(a)X-axis=10sec/Div, Y-axis=0.10Hz/Div
(b)X-axis=.50sec/Div, Y-axis=0.025Hz/Div

It can be observed from the figure 4.9 that the frequency of the system is not maintaining constant. As shown in fig. 4.10, the amplitude of oscillations is depends upon the penetration level. As the penetration level rises, the amplitude of frequency oscillation increases. The increase in the amplitude of oscillation shows that, excess penetration of PV power cause reduction in the damping torque, so rotor of the synchronous generator oscillates.

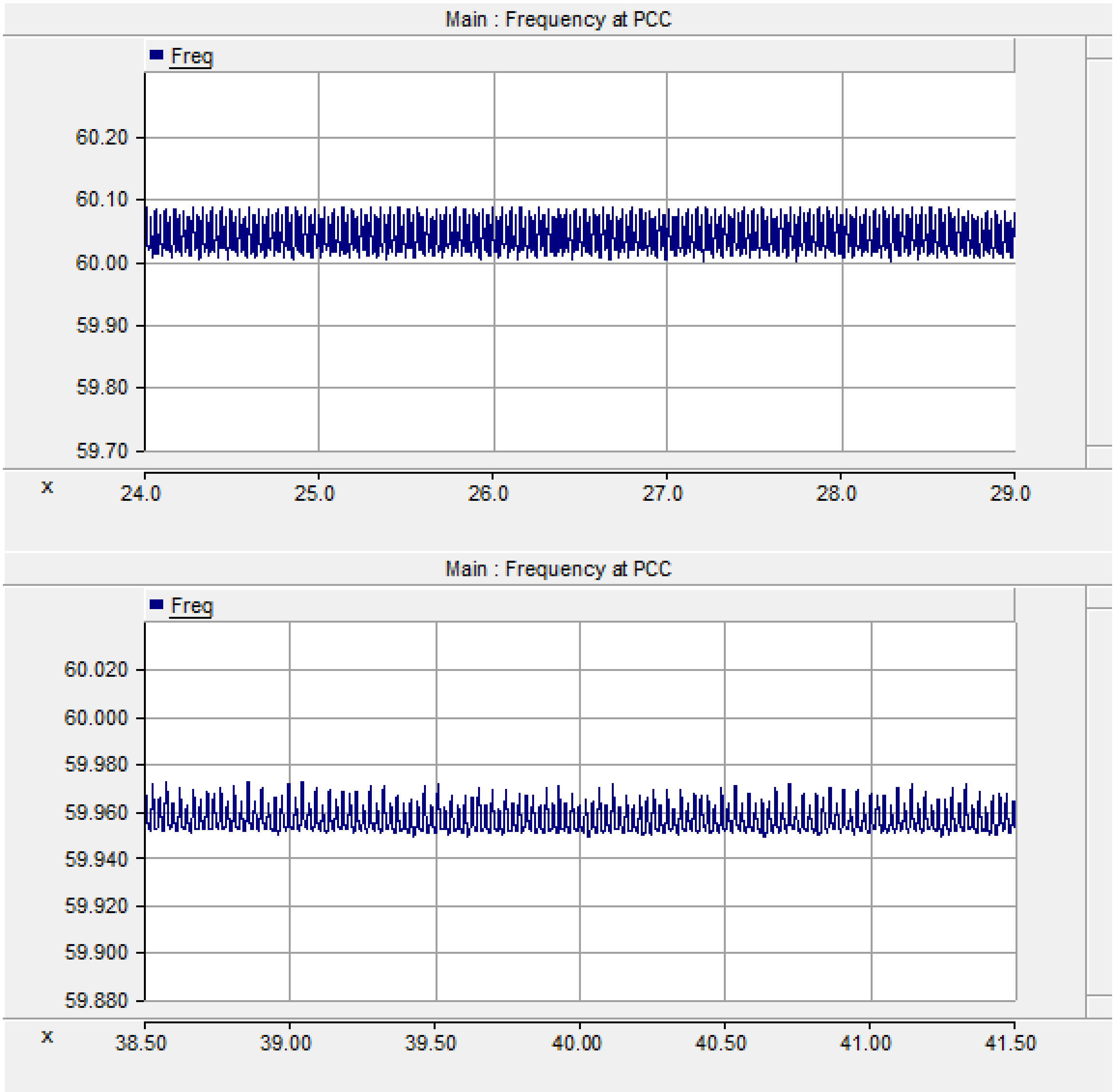

Figure 4.10: Frequency at PCC

(a)X-axis=1sec/Div, Y-axis=0.10Hz/Div
(b)X-axis=.050sec/Div, Y-axis=0.020Hz/Div

4.3 Case:2 Variable load

The next case for analysing the system is varying the load. The solar PV plant has the maximum penetration of 6 MW at 1000 ω/m^2. For this case, static load of the system are 15 MW, 2 MW, 2 MW, 8 MW & 5 $MVAR$. For load variation in the system, two 2 MW loads are removed from the system at 5 $sec.$ and 10 $sec.$, and after 15 $sec.$ the 8 MW load is suddenly applied to the system. The power available at PCC, fed by solar PV is shown in 4.11.

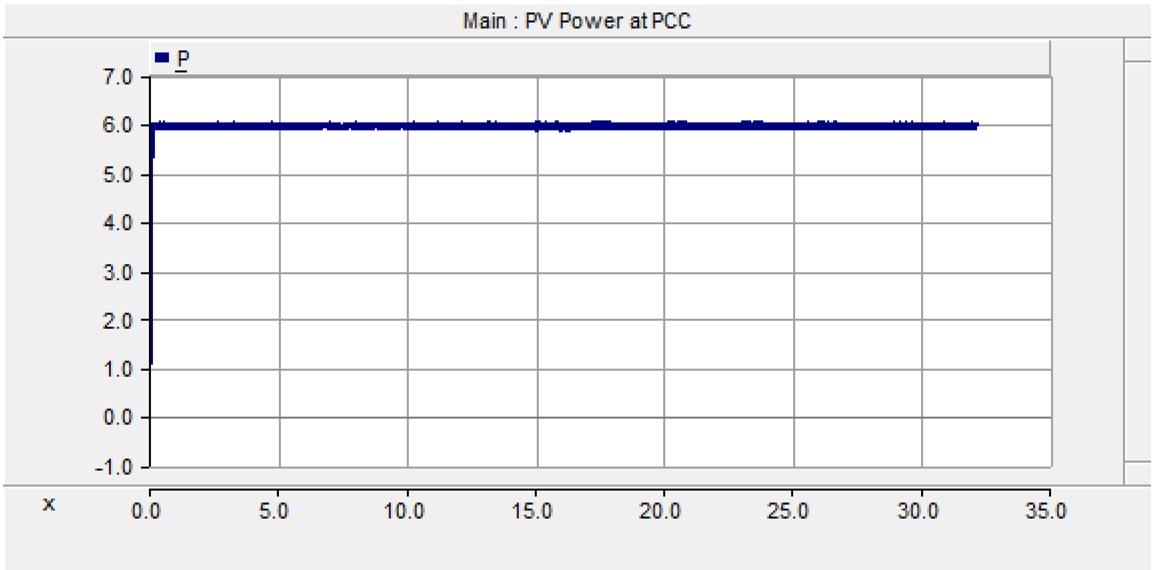

Figure 4.11: Power at PCC

X-axis=5sec/Div, Y-axis=1MW/Div

For analysing the system behaviour, the system is simulated with solar PV and without solar PV. When the system is not having the solar PV, all load is shared by the synchronous machine's. The generated power, deviation of rotor angle & deviation of frequency at PCC for change is load are shown in fig. 4.12,4.14 & 4.16 respectively.

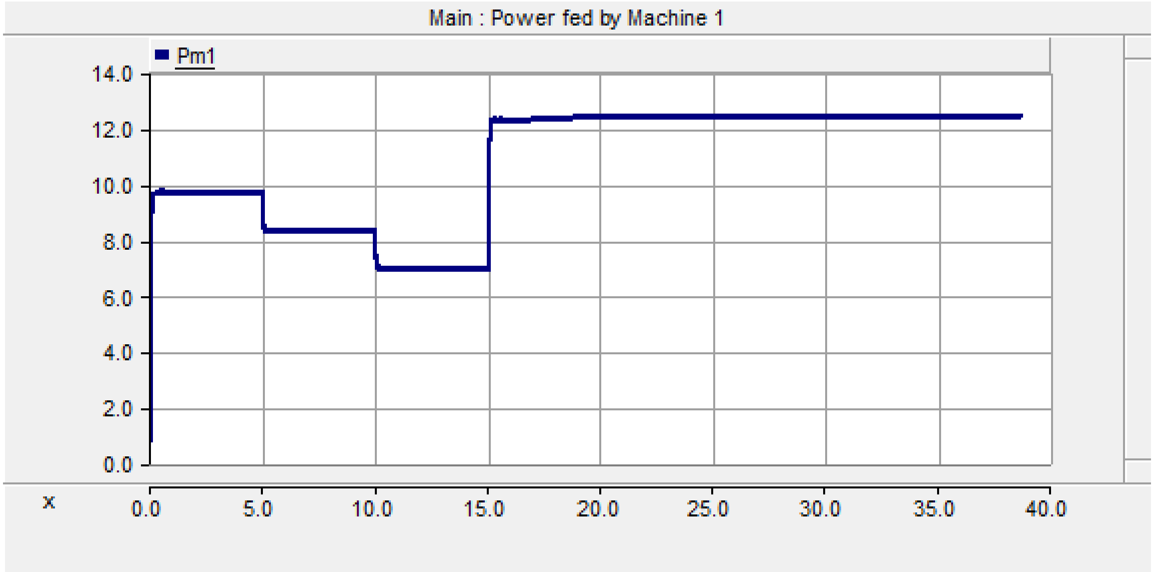

Figure 4.12: Power generated by machine 1

X-axis=5sec/Div, Y-axis=2MW/Div

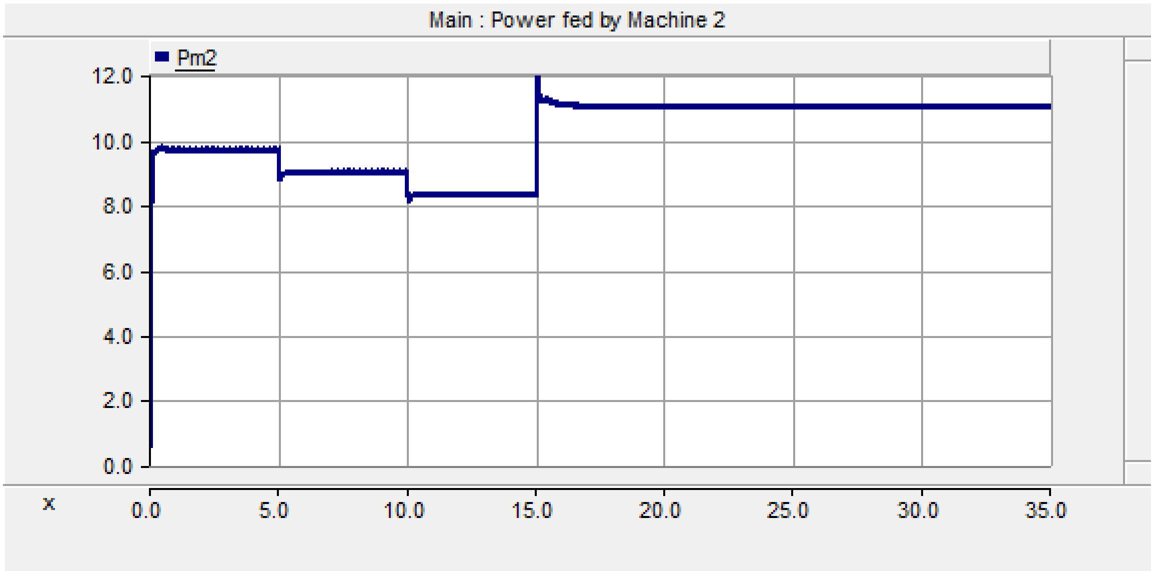

Figure 4.13: Power generated by machine 2

X-axis=5sec/Div, Y-axis=2MW/Div

As the load is changing, the machine output is keep on changing. When system is not having the solar PV the rotor angle of the synchronous machine 1 & 2 are shown in 4.14 & 4.15 respectively.

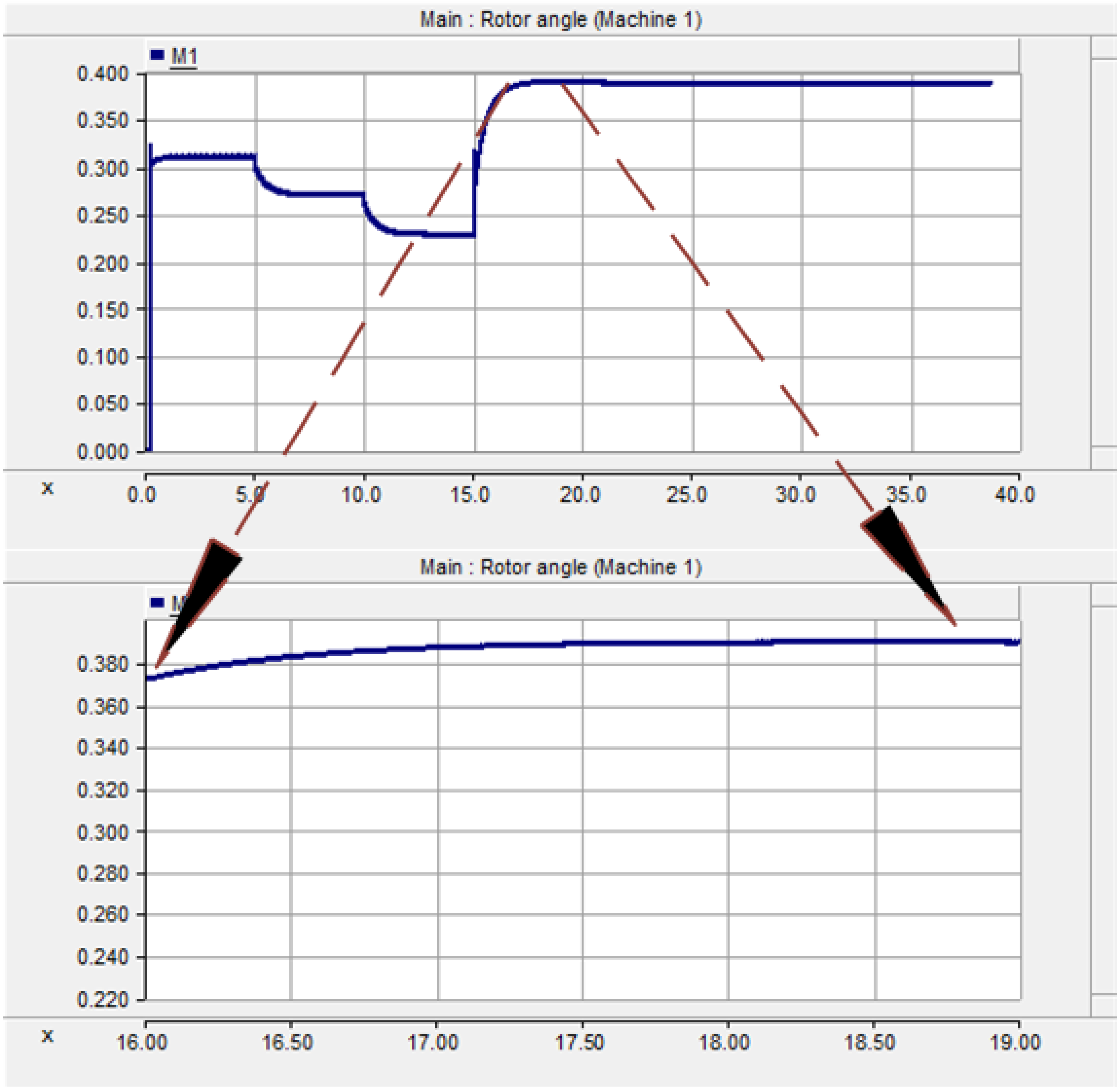

Figure 4.14: Rotor angle of machine 1

(a)X-axis=5sec/Div, Y-axis=0.050rad/Div
(b)X-axis=.50sec/Div, Y-axis=0.020rad/Div

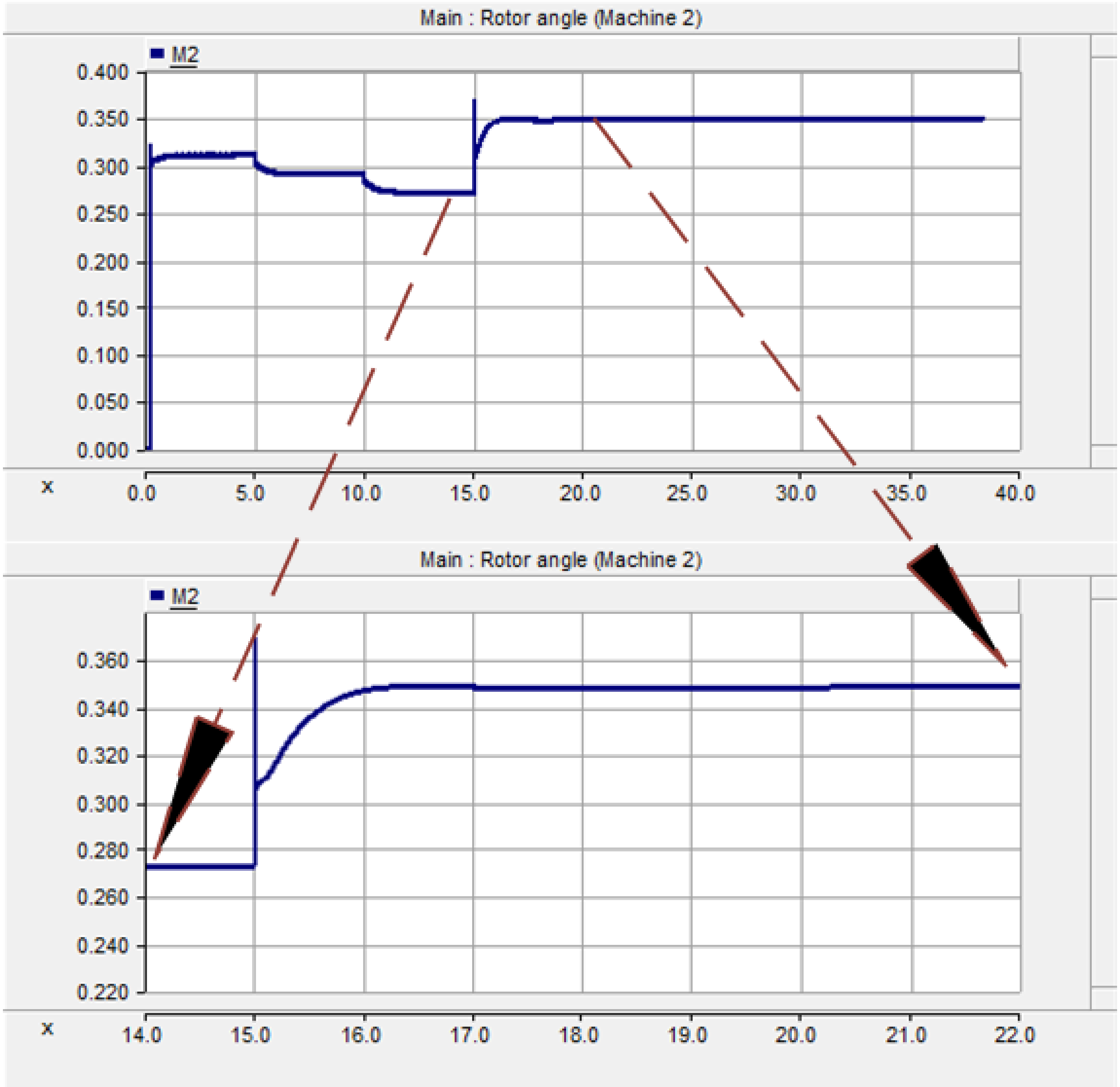

Figure 4.15: Rotor angle of machine 2

(a)X-axis=5sec/Div, Y-axis=0.050rad/Div
(b)X-axis=1sec/Div, Y-axis=0.020rad/Div

It can be observe from the figure 4.14 & 4.15 that in the absence of solar PV, machine is having minimum oscillations. The machine's rotor angle keep on decreasing as the load reduce with negligible oscillation. This shows that the machine is having sufficient damping torque. For the considered case the frequency at PCC for change in load is shown in fig. 4.16.

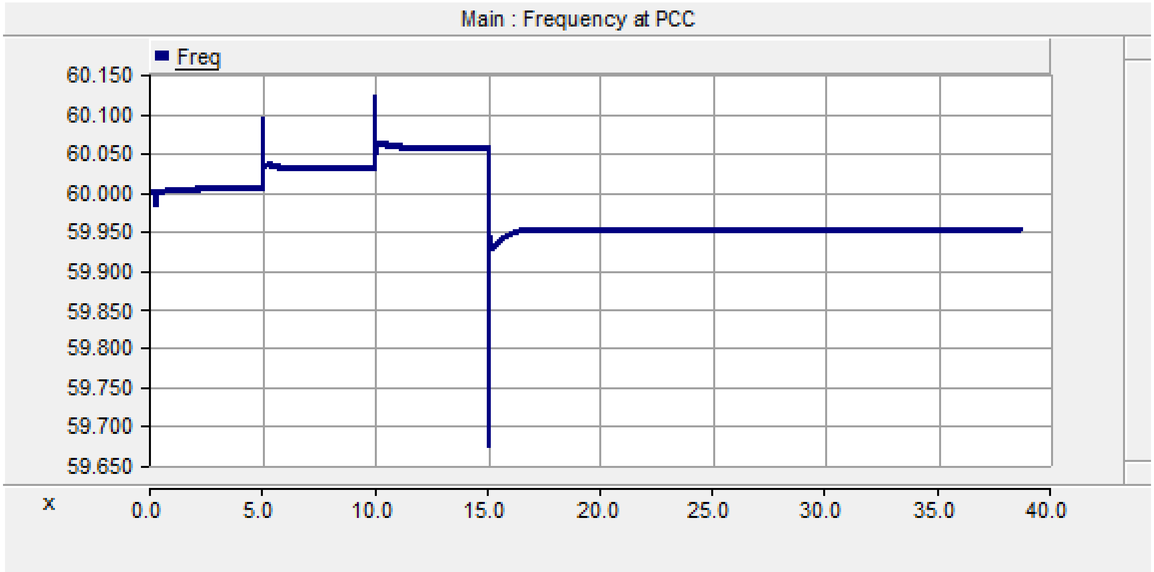

Figure 4.16: Frequency at PCC when load is variable

X-axis=5sec/Div, Y-axis=0.050Hz/Div

The same graphs again plotted with solar PV system. The rotor angle of the machine in presence of solar PV is shown below in fig. 4.17

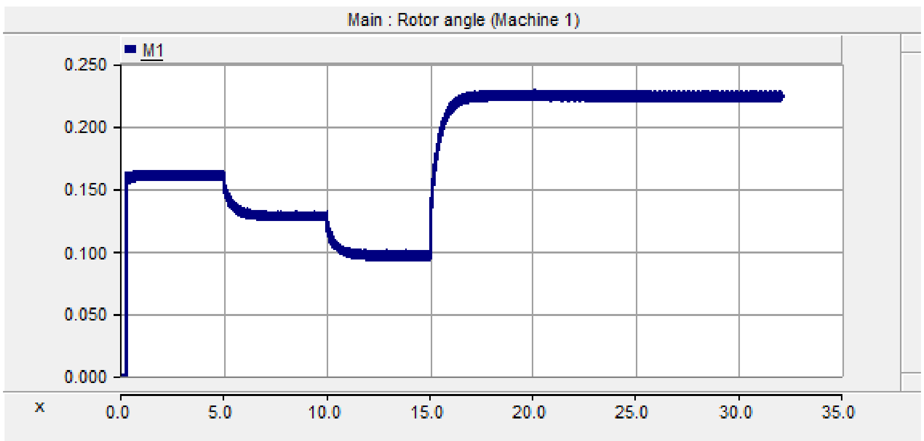

Figure 4.17: Rotor angle of machine 1

X-axis=5sec/Div, Y-axis=0.050rad/Div

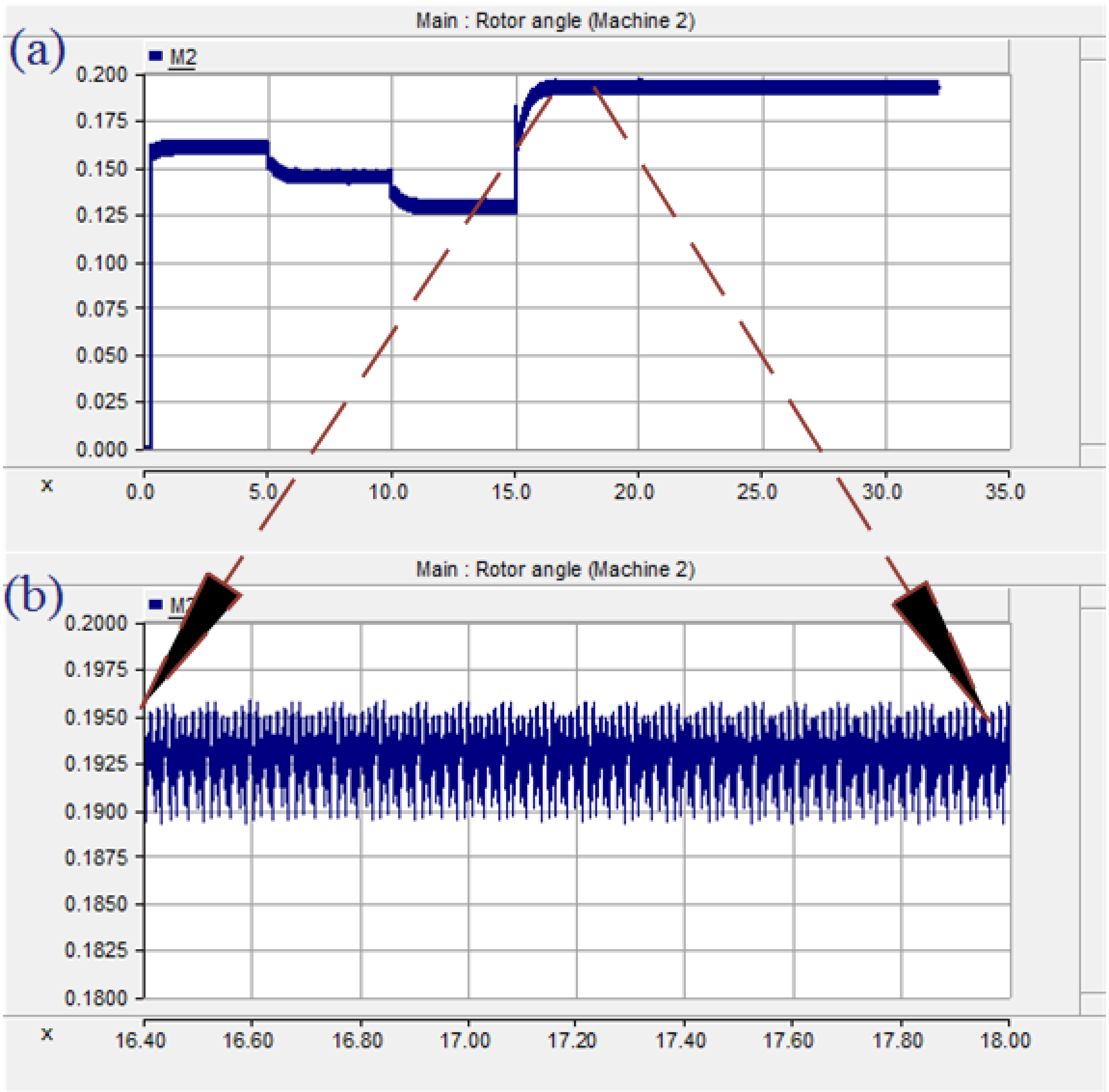

Figure 4.18: Rotor angle of machine 2

(a)X-axis=5sec/Div, Y-axis=0.025rad/Div
(b)X-axis=.20sec/Div, Y-axis=0.025rad/Div

It can be observed that in presence of solar PV, the machine's are having oscillations. In presence of solar PV system, the effect of load variation on generation of power by synchronous machine is shown in fig. 4.19.

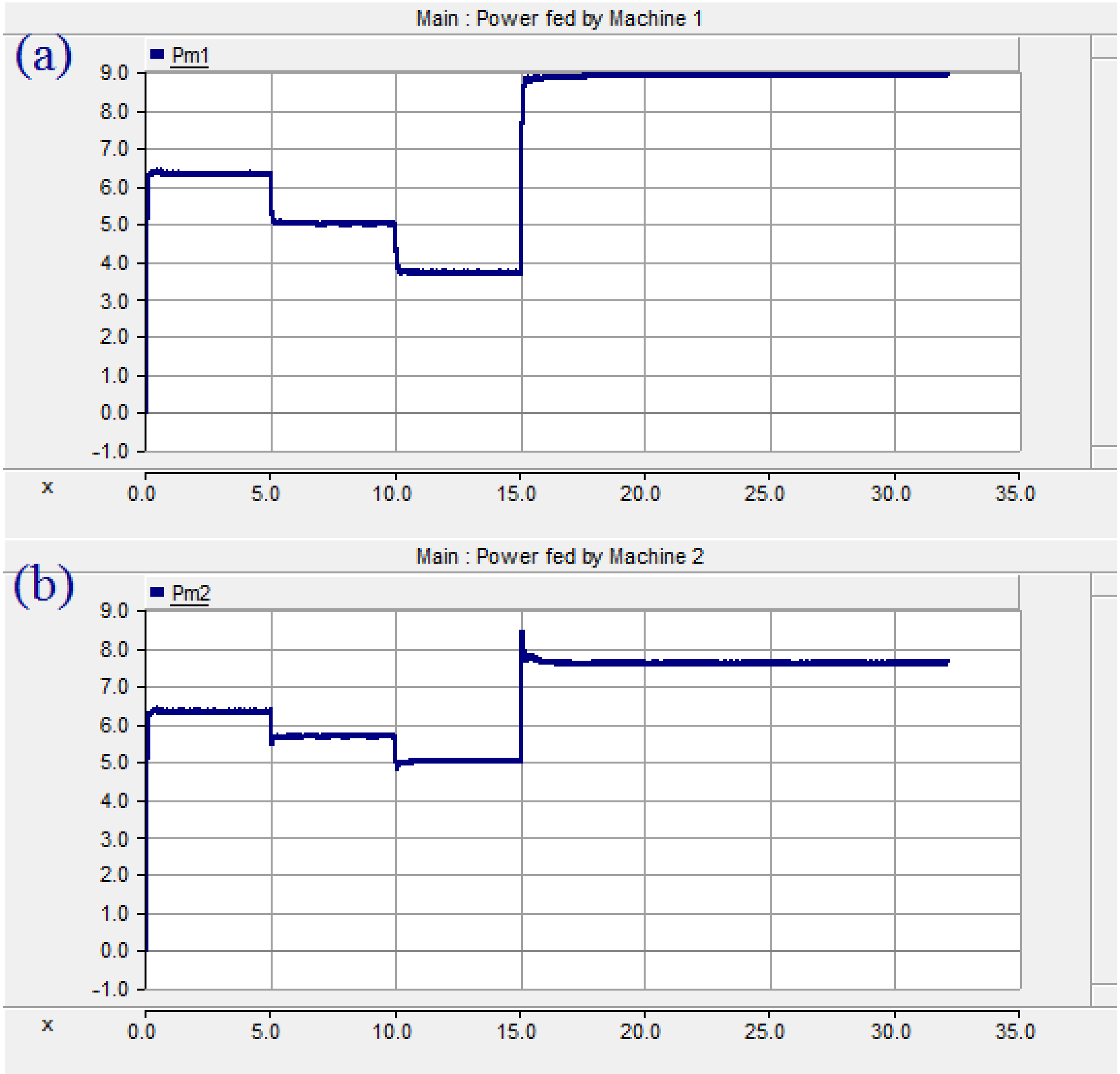

Figure 4.19: Power delivered power machine 1 & machine 2

(a)X-axis=5sec/Div, Y-axis=1MW/Div
(b)X-axis=5sec/Div, Y-axis=1MW/Div

The frequency plot at PCC for changing load is shown in fig. 4.20

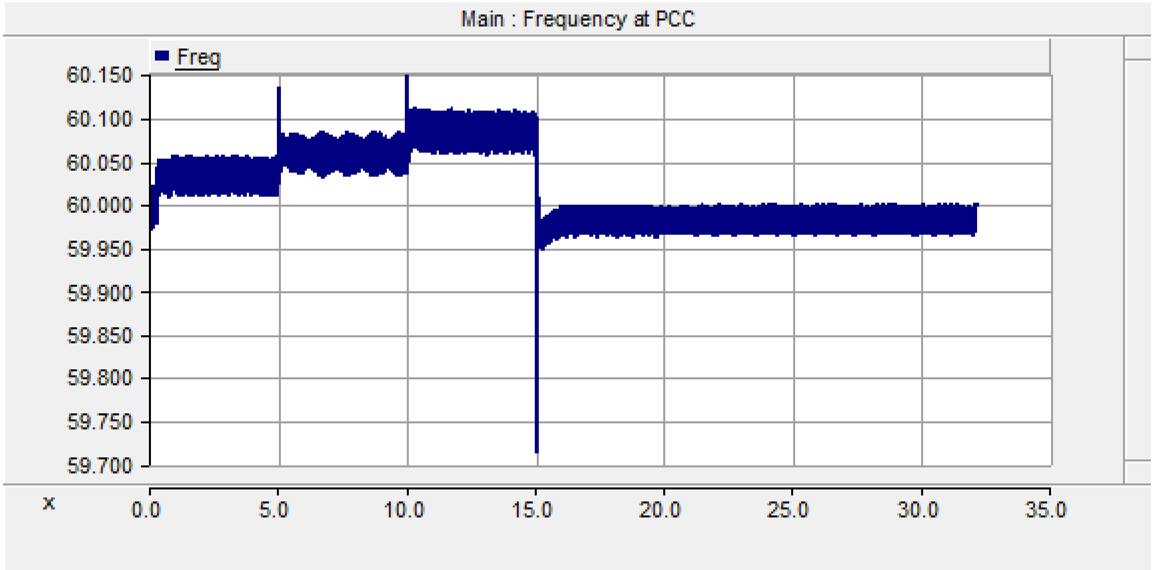

Figure 4.20: Frequency (Hz) at PCC for changing load

X-axis=5sec/Div, Y-axis=0.050Hz/Div

It is evident from the case:1 results, there is a significant reduction in damping torque of the system, which cause continuous rotor angle oscillation. Based on the frequency plot 4.16 & 4.20 possible conclusion can be made about he behaviour of the system, when load is variable. In the presence of solar PV, the reduction in the system inertia can be checked by observing the peaks occurring at transition of load. The solar PV integrated system having higher peak compare to system having only synchronous generators.

4.4 Case:3 Transient stability analysis

A contingency analysis is done for investigating the behaviour of solar PV integrated system under fault condition. The details of analysis is shown in following subsection.

4.4.1 Single line to ground fault

A SLG fault is created at 5 *Sec.* of the duration of .09 *Sec.*. To check the system behaviour, system is simulated without solar PV system and in the next simulation it is simulated with solar PV system. The typical layout of the test system is shown in fig. 4.21.

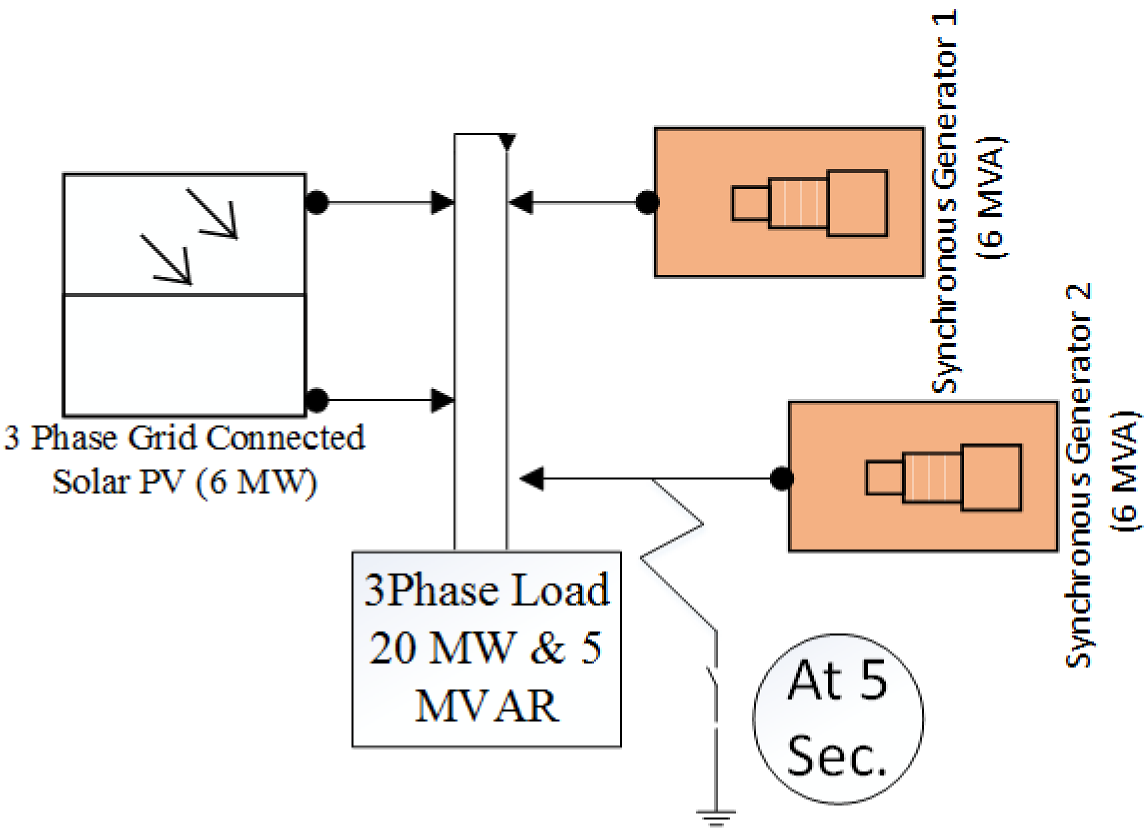

Figure 4.21: Layout of the system for SLG fault study

Based on the figure 4.21 the system is simulated at 200 $\mu Sec.$ plot step. The simulation results of system having no PV power penetration is shown in fig.4.22.

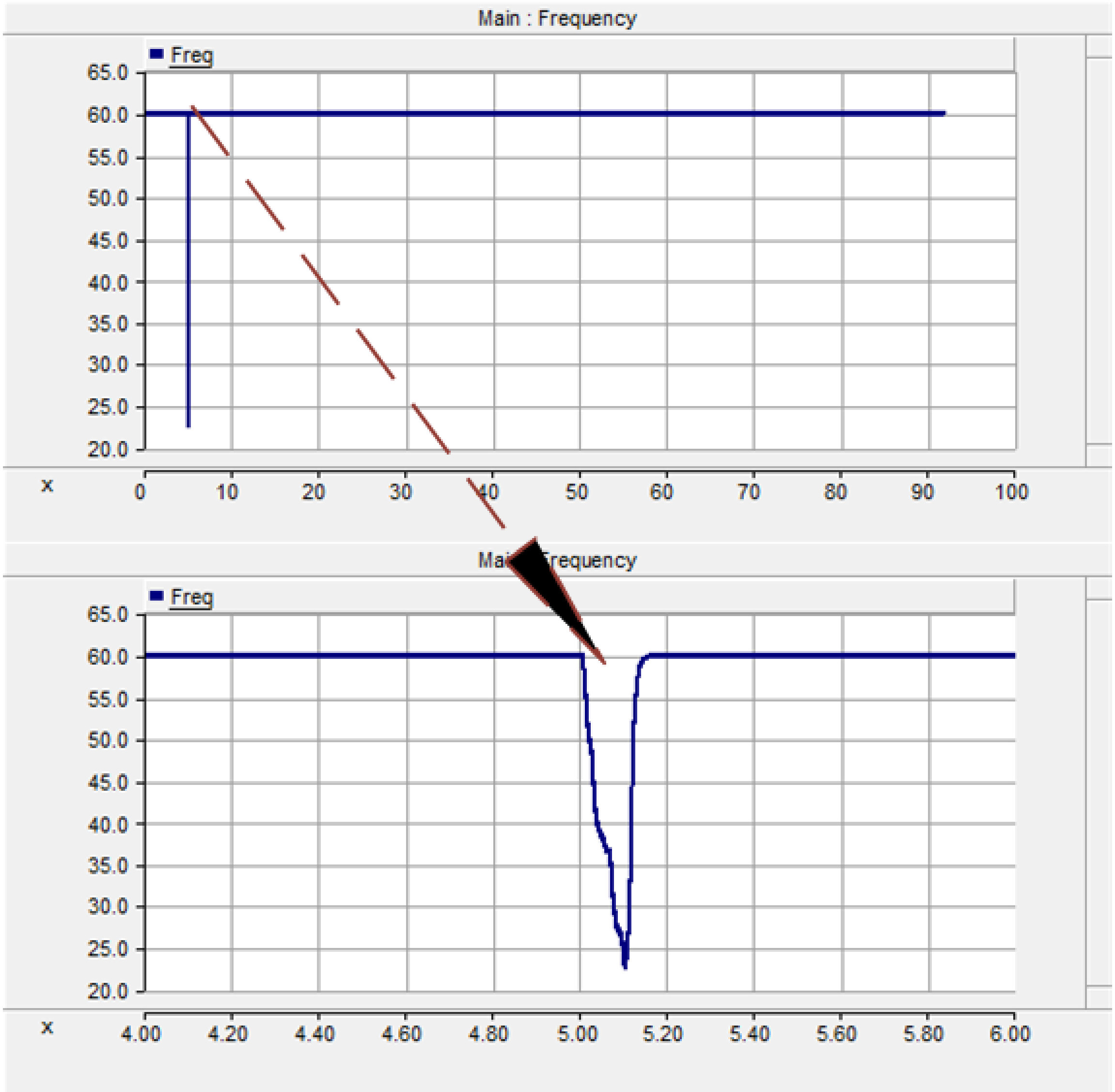

Figure 4.22: Frequency at PCC without solar PV SLG fault

(a)X-axis=10sec/Div, Y-axis=5Hz/Div
(b)X-axis=.20sec/Div, Y-axis=5Hz/Div

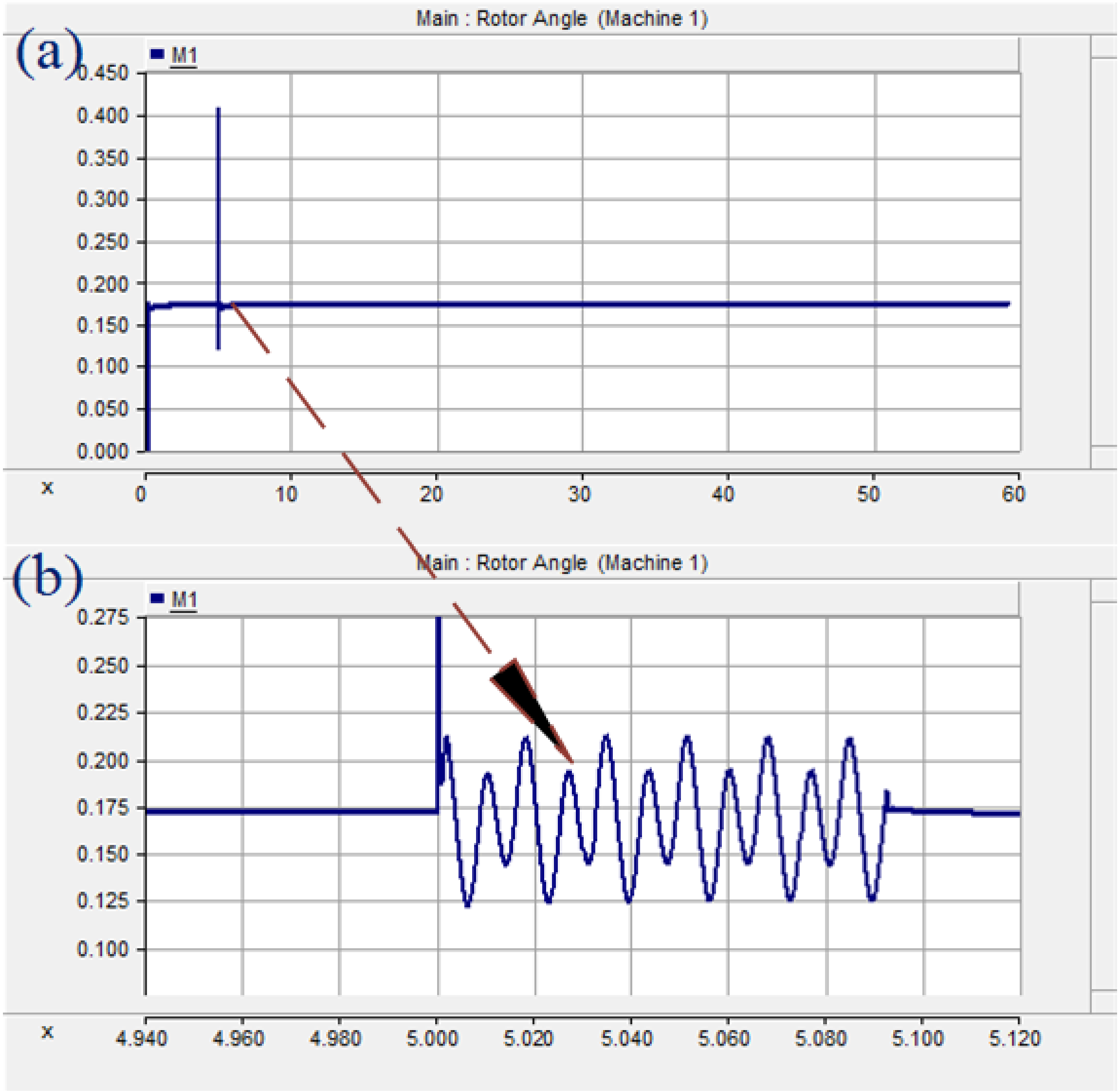

Figure 4.23: Rotor angle oscillations of machine 1 at SLG fault

(a)X-axis=10sec/Div, Y-axis=.050rad/Div
(b)X-axis=.020sec/Div, Y-axis=.025rad/Div

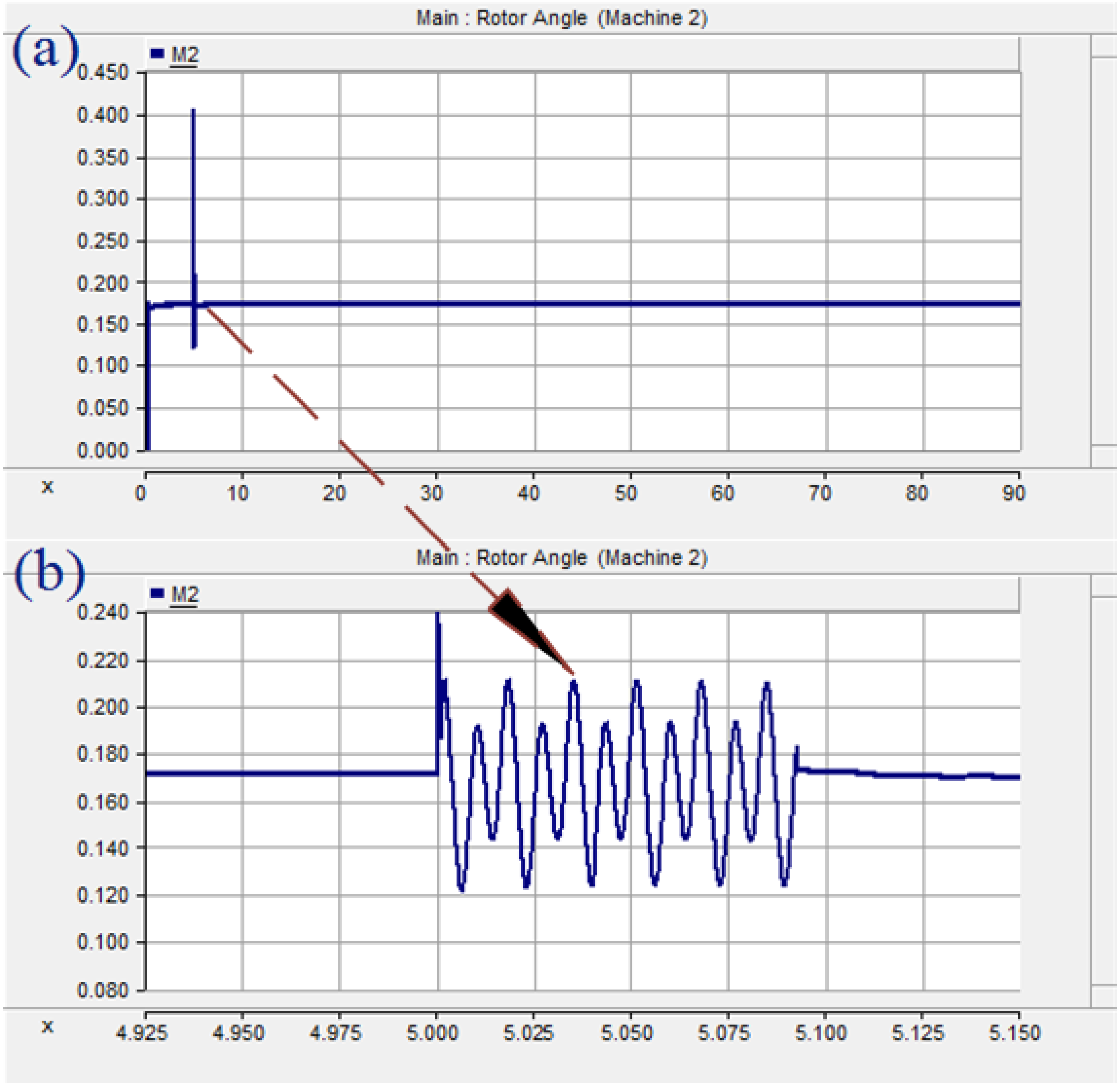

Figure 4.24: Rotor angle oscillations of machine 2 at SLG fault

(a)X-axis=10sec/Div, Y-axis=.050rad/Div
(b)X-axis=.025sec/Div, Y-axis=.020rad/Div

From the figure 4.22, 4.23 & 4.24 at the time of SLG fault, frequency of the system is dropping down to 22 Hz with the rotor angle oscillation of .087 rad of both machine. The graph again plotted for the system with solar PV. The current fed by solar PV at the time of fault is shown in fig. 4.25.

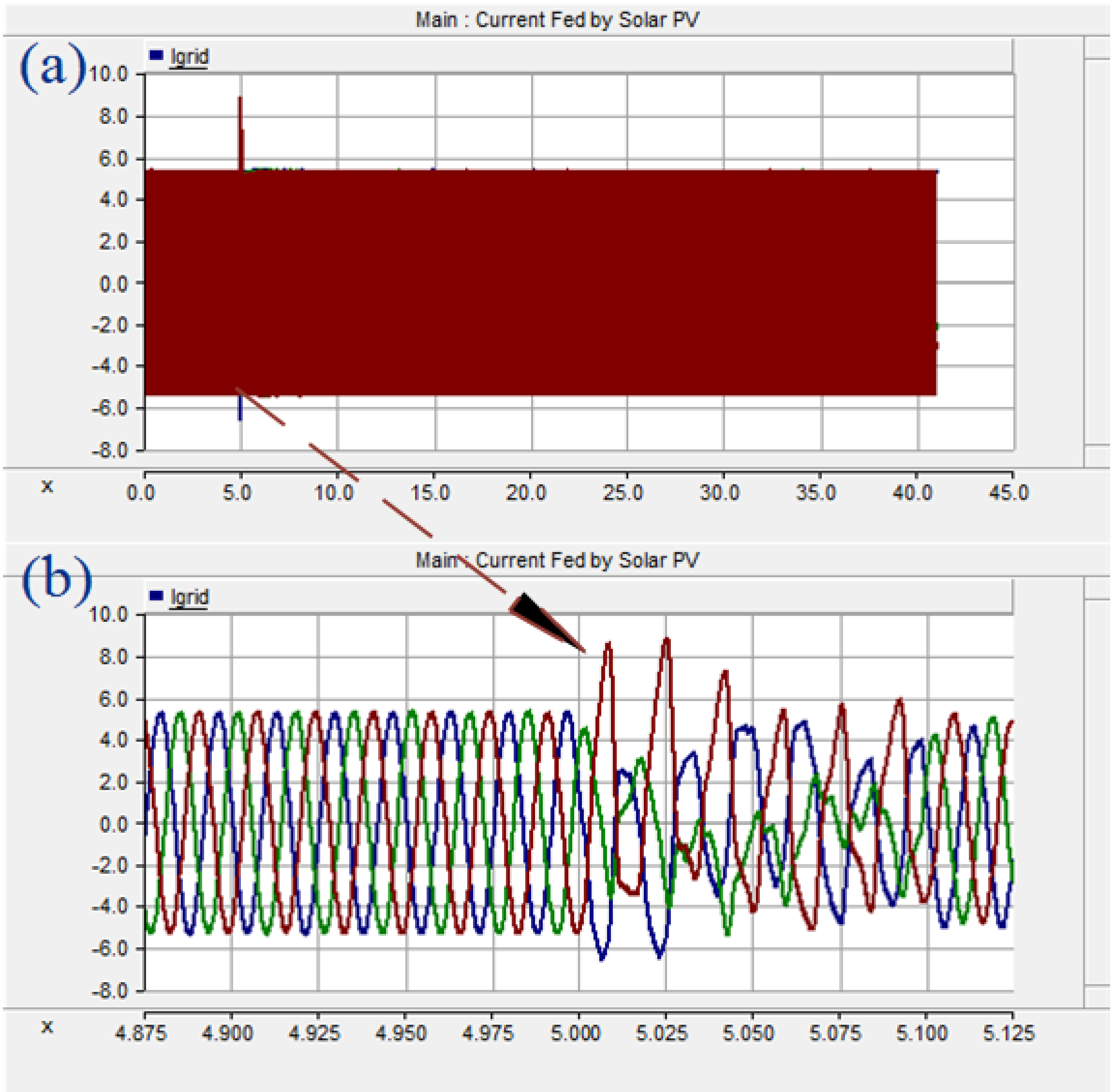

Figure 4.25: Current fed by solar PV at SLG fault

(a)X-axis=5sec/Div, Y-axis=2kA/Div
(b)X-axis=.025sec/Div, Y-axis=2kA/Div

At the time of SLG fault, the system frequency is shown in fig. 4.26.

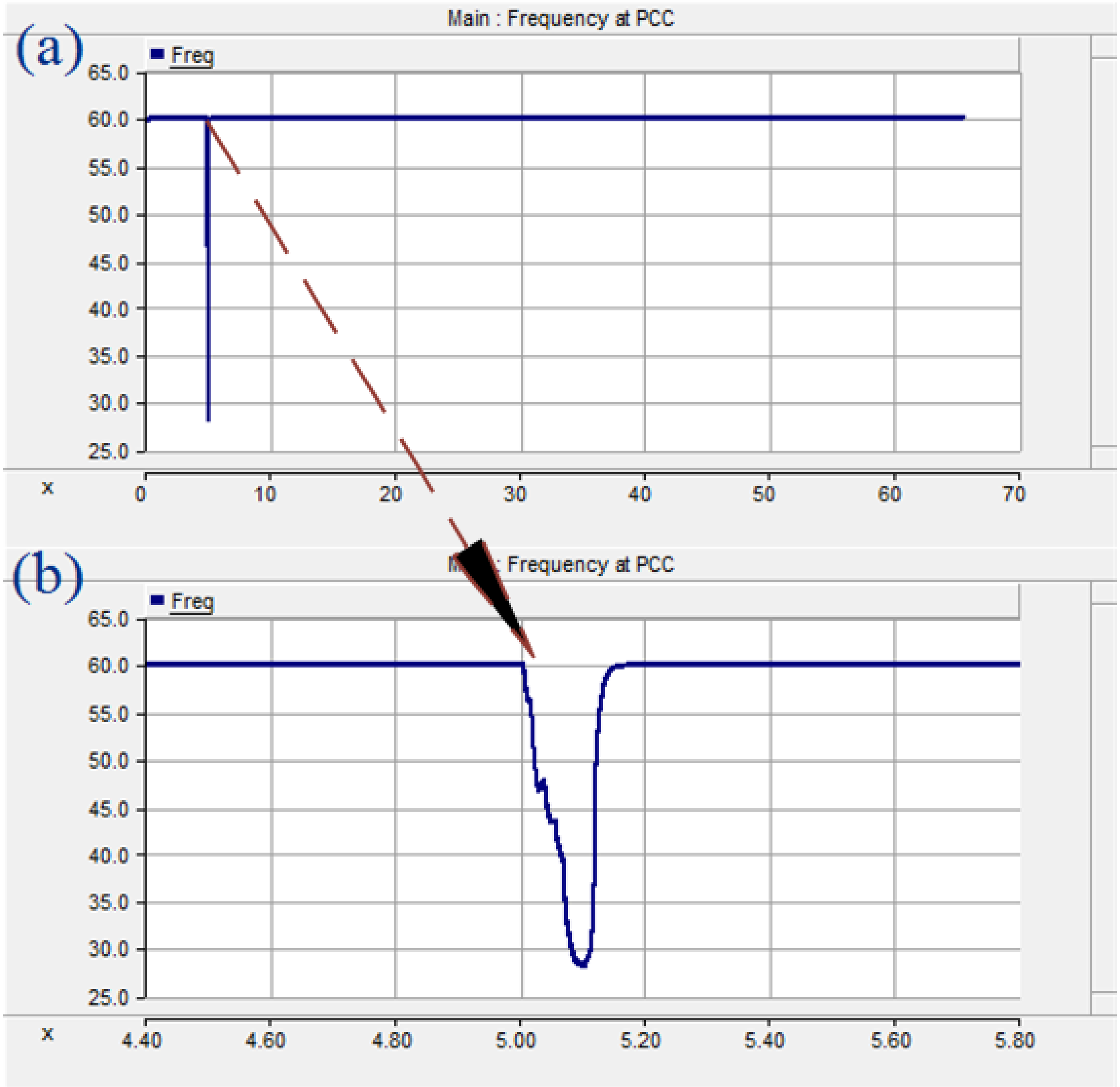

Figure 4.26: Frequency at PCC with solar PV at SLG fault

(a)X-axis=10sec/Div, Y-axis=5Hz/Div
(b)X-axis=.20sec/Div, Y-axis=5Hz/Div

At the time of fault the rotor angle oscillations of machine 1 & machine 2 are shown in fig. 4.27 & 4.27 respectively.

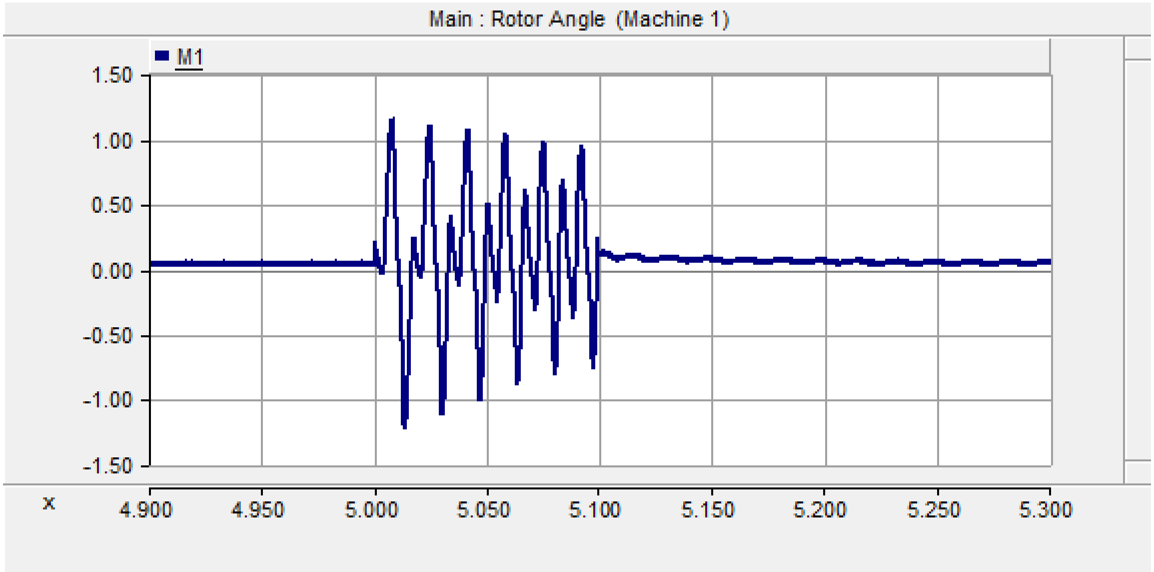

Figure 4.27: Rotor angle machine 1 at SLG fault with solar PV

X-axis=.050sec/Div, Y-axis=.50rad/Div

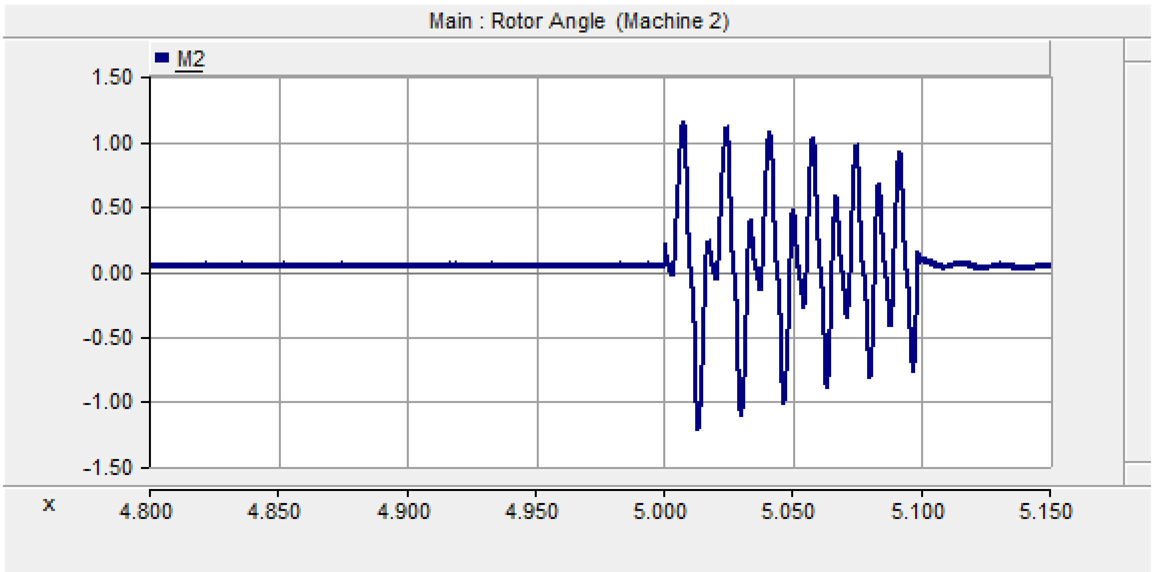

Figure 4.28: Rotor angle of machine 2 at SLG fault with solar PV

X-axis=.050sec/Div, Y-axis=.50rad/Div

As can be observed from fig. 4.23, 4.24, 4.27 & 4.28 that the system experiencing higher rotor oscillation with solar PV, compare to the system having only conventional generator. The possible reason for the higher rotor oscillation is because of the PV power penetration level. Higher penetration level of PV power reduces system inertia. Hence, system becomes more vulnerable and rotor will have larger oscillation at the time of fault. Higher rotor angle deviation will take longer time to settle down.

Chapter 5

Conclusion and Future Scope

Based on the simulation results, the possible conclusion can be made about the stability of the solar PV integrated system.

- Developed grid tied solar PV system can be used to analyze the impact of solar PV on power system stability. In order to fed power from solar PV to grid, it should have capacity more the grid connected in the system, otherwise reverse flow of power will take place & inverter will not function.

- Power system stability greatly influenced by the penetration level. As the penetration level is increasing, system experiences more rotor angle oscillation. For higher penetration level reduces the system inertia, Hence system behaviour becomes oscillatory.

- Reduction of system inertia reduces the damping torque of the system, So solar PV integrated system have higher peaks of frequency for load variation compared to the frequency of the system having no PV power penetration.

- At higher penetration level, for SLG fault synchronous generators of system's experienced higher rotor oscillation compared to the one when system is not having solar PV system.

5.1 Future Scope

The proposed work can be extended for analysing the system performance, which includes

- System stability when system is having PSS,
- Effectiveness of active & passive power filter to reduce the THD,
- Effect of location on solar PV penetration in any reference system,

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Appendix

- Simulation model to analyse the system for changing radiation

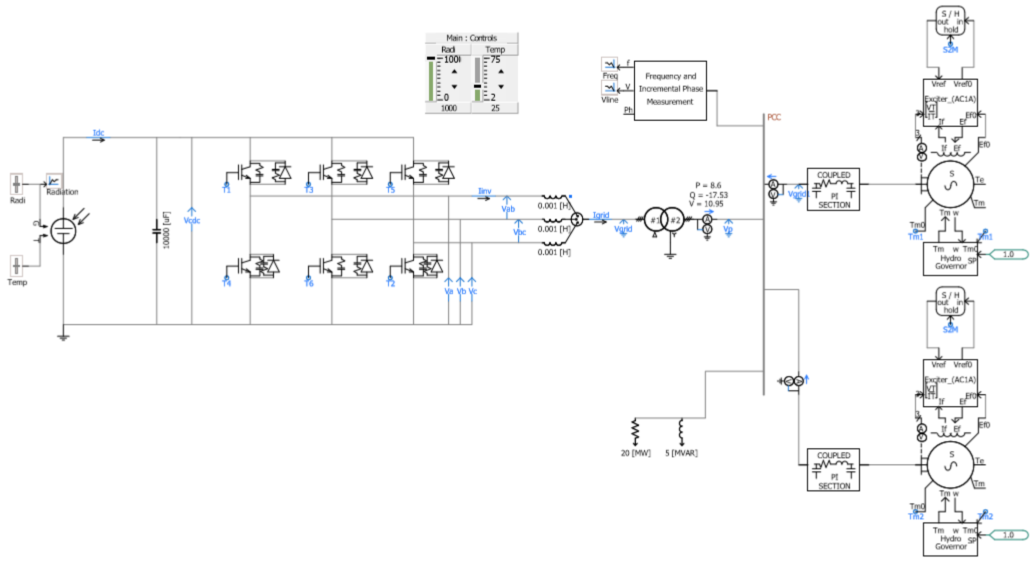

Figure 1: PSCAD model of system under study

- Simulation model to analyse the system for SLG Fault

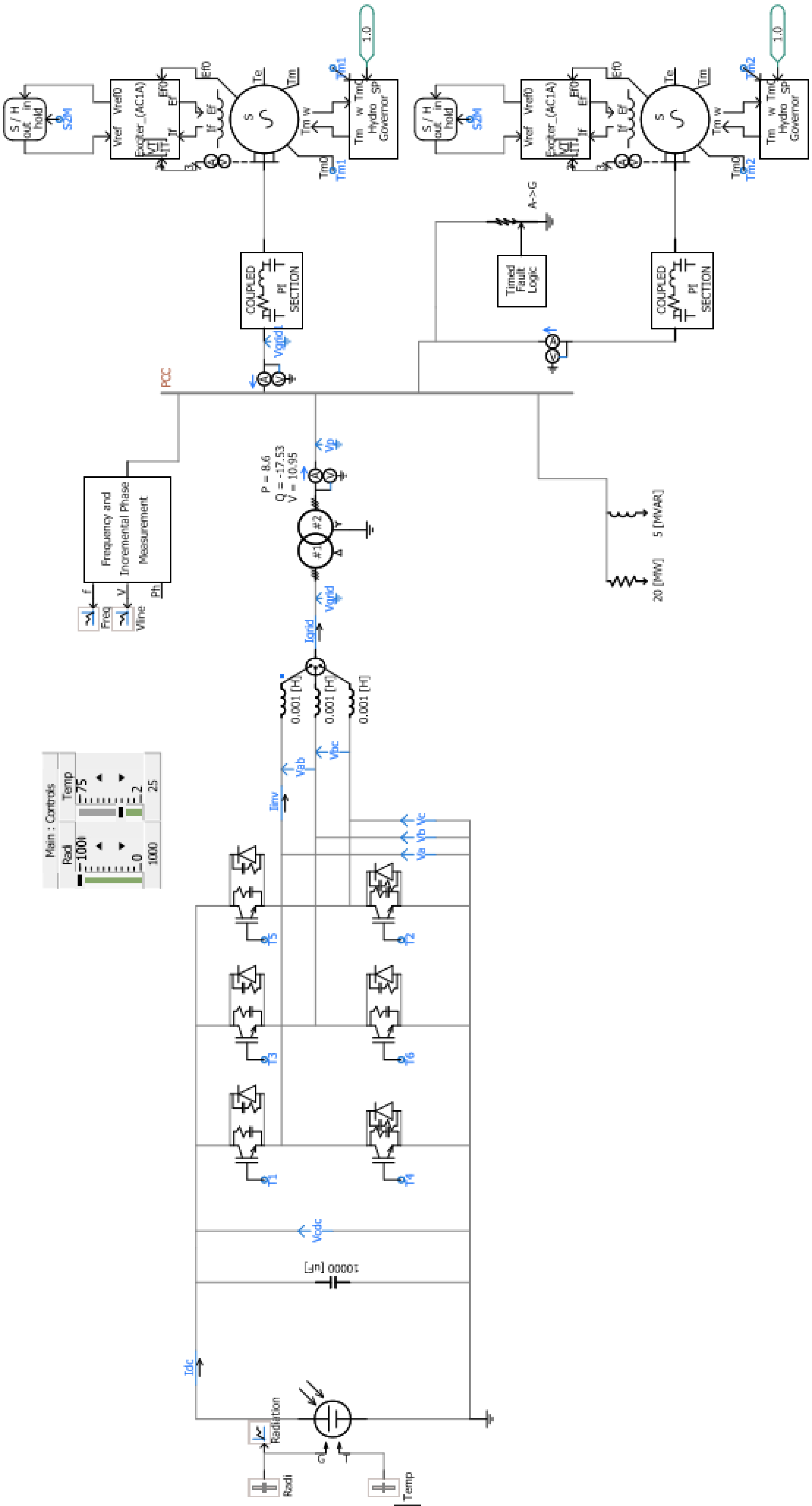

Figure 2: PSCAD model of system under fault study