# Modeling of a Detailed Photovoltaic Generation System for EMT-Type Simulation

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*Abstract--* **This article presents a detailed three-phase grid connected PV model which includes important control systems required for EMT-type simulation. A one diode model for the PV array is used to simulate environmental constraints such as solar irradiation. A detailed control system including dc voltage control, inner current control, MPPT and PWM control are implemented in order to simulate the model during steady state and dynamic conditions. The PV model is merged with a simple distribution network to investigate the PV's interaction with the AC grid. Several simulation scenarios are presented in order to validate the performance of the model.**

*Index Terms--* **Photovoltaic systems, maximum power point tracking, EMT simulation**

## I. INTRODUCTION

Funded by the European Commission's FP7 program (7th Framework Programme for Research and Technological Development), the IDE4L (Ideal Grid for All) project has recently started to develop a system of distribution network automation, information technology systems and applications for network management [1]. The project consists of several work packages to accommodate different parts of network management. To assess the quality and relative advantages of the developed methods, there is a need to develop a reference grid model that includes the active components such as DER (Distributed Energy Recourses) and DES (Distributed Storage systems). The distribution grid model will be then combined together with external controllers and a co-simulation of communication networks to carry out real-time hardware-in-the-loop simulation studies using OPAL-RT's technologies.

Among different types of DERs', PV generation is becoming more relevant due to its high growth in recent years. According to a report of EPIA 2012 [2], for the second year in a row, PV was the number one new source of electricity installed in Europe. Internationally, 31.4 GW of PV generation was installed in 2012 and it could reach up to 84 GW under specific policy driven scenarios. These statistics foretell the importance of PV in future power systems and thus, detailed models of the PV system are needed for

different types of system studies. For EMT-type studies, including real-time simulation, the model should contain PV controls, i.e. Maximum Power Point Tracker (MPPT), inverter controllers and others. Although some PV models are available in the literature [3] [4][5], these models do not provide a fully integrated and detailed model for EMT-type and real time simulation, therefore they did not fulfill the requirements for the studies in the IDE4L project. Hence, there was a need to develop a detailed PV model which could be used for EMT-type system studies in real time using OPAL-RT's technologies, which in turn requires to develop the model using MATLAB/Simulink.

This paper presents modeling details of a three-phase grid connected PV system developed by the authors. It includes the PV array model, which represent the (VI characteristics) of a basic PV cell. It incorporates the effect of changing the environmental conditions (i.e. solar irradiation and temperature) on the PV output power .This model is equipped with several control systems which are required for a grid connected PV system. The model is integrated into a simple distribution system containing static and dynamic loads. The system's dynamic behavior is simulated for some scenarios to demonstrate the performance of the PV model.

The reminder of this paper is organized as follows. In Section II the detailed structure of the PV model is explained. Each subsection of Section II elaborates on modeling details of different components of the PV model. In Section III, different case studies are presented together with analysis of simulation results. In Section IV conclusions and future work are summarized.

## II. STRUCTURE OF THE PV SYSTEM

The PV system is comprised by a PV array, inverter and control system. The dc voltage and current are measured from dc link and are given to Maximum Power Point Control (MPPT) Control. It provides a reference dc voltage $Vdc_{ref}$ to the main control system. The PV array produces DC power which is converted to AC power via a three phase inverter. The output of the inverter gives AC power which is in turn filtered into a sinusoidal output using an LC filter [5]. The PV system is connected with an AC network at medium voltage level via a step up transformer. Output load current and

voltage are measured at the Point of Common Coupling (PCC) and then fed back as inputs to the control system. Fig 1 shows an overview of the PV system. All parameters of the model are shown in the Appendix.
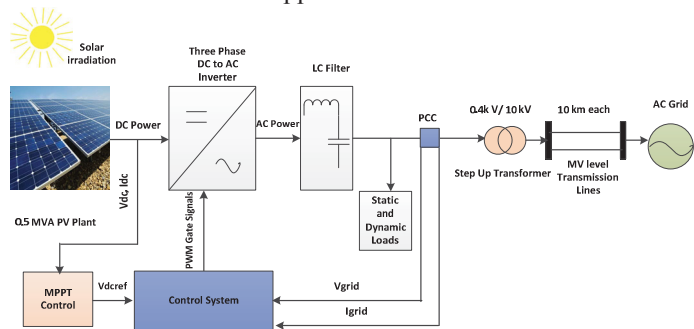


Fig. 1.  PV System Overview

## A. PV Array

A one diode model is used to represent one PV cell in the PV array. The total output current for the PV cell can be calculated by taking a difference between the photo electric current ($I_{ph}$) and the diode current ($I_D$) as shown in Fig 2. The output current of the PV cell ($I$), can be calculated from (1) by applying a known voltage ($V$) at its terminal as follows.

$$I = I_{ph} - I_D = I_{ph} - I_0 \exp\left(\frac{V + I R_s}{V_t}\right) \qquad (1)$$

where, $I_{ph}$ is the photoelectric current, is $I_D$ the diode current, $I_0$ is the dark current, $R_s$ is the series resistance shows losses due to poor conductivity in the solar cell and $V_t$ is the thermal voltage.

Using the method described in [6], short circuit and open circuit conditions are applied on (1), which gives $I_{ph}$ and $I_0$ respectively

$$I_{ph} = I_{sc} \qquad (2)$$

$$I_0 = \frac{I_{sct}}{\exp\left(\frac{V_{oct}}{V_t}\right)} \qquad (3)$$

The remaining unknown quantities in (1) ($V_t$ and $R_s$) are calculated, method described in [6].

The output of a PV cell depends upon the ambient temperature and solar irradiation. The PV array does not operate on Standard Test Conditions (STC) during normal operation [7]. Therefore, in order to calculate the voltage and current under different operating conditions, the correctionfactors $K_I$ and $K_V$ are incorporated in expressions (4) to (7).

The short circuit current ($I_{sc}$) of the PV cell is represented by a linear function of irradiation and temperature. According to (4) and (5) it can be estimated as

$$I_{sct} = I_{sc1}\left(1 + \frac{K_I}{100}(T - T_{ref})\right) \qquad (4)$$

$$I_{sc} = I_{sct}\left(\frac{E}{E_{stc}}\right) \qquad (5)$$

where, $I_{sct}$ is the short circuit current which is only temperature dependent, and $I_{sc}$ is the short circuit current which is dependent on both irradiation and temperature.
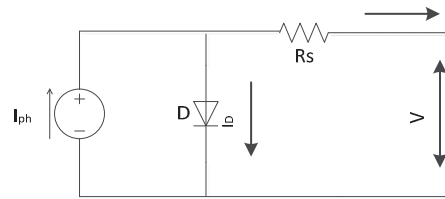


Fig. 2.  One Diode PV cell

The open circuit voltage ($V_{oc}$) can be expressed as a linear function of temperature and irradiation. According to (6) and (7) it can be estimated as

$$V_{oct} = V_{oc} + (K_V(T - T_{ref})) \qquad (6)$$

$$V_{oc} = V_{oct}\left(\frac{\ln E}{\ln E_{stc}}\right) \qquad (7)$$

Similarly, $V_{oct}$ is the open circuit voltage which is only temperature dependent and $V_{oc}$ is the open circuit voltage which is dependent on both irradiation and temperature.

The remaining terms in (4)-(7) are defined as follows: $T_{ref}$ is temperature at the STC (25 C), is $I_{sc1}$ the short circuit current at STC, $V_{oc1}$ is the open circuit voltage at STC, $I$ is irradiation at the output, $E_{stc}$ is irradiation at STC (1000 W/m²) and $T$ .is temperature at the output.

## B. PV Inverter

A three bridge two level voltage source inverter (6 pulse configuration) is used. This inverter takes the dc voltage ($V_{dc}$) as voltage input, while 6 gate pulses (generated by the control systems) as a control input to provide three phase sinusoidal voltage to the AC side ($V_{abc}$). The details of the control systems are explained in detail below. The Simulink /SimPowerSystemslibrary block "Universal Bridge" is used in this model, which is a detailed switching model of the inverter.
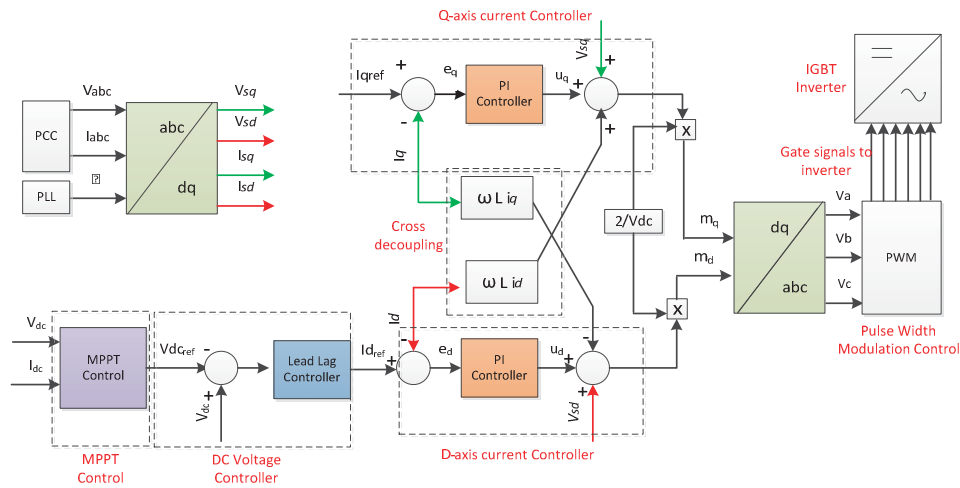
Fig. 3. PV Control Systems

## C. Filters

The three phase unfiltered output of the PV inverter contains high frequency harmonics. Harmonics are filtered via LC filter which gives a sinusoidal output to the grid.

## D. Control System

The control systems of the PV system consist of: dc voltage controller, inner current controller, MPPT controller and PWM signal generator. Three phase sinusoidal voltage and current from the PCC are measured and given as inputs to the control systems.

These three phase voltages and currents are converted into the *dq*-frame. Dc voltage and dc current are taken as input to the MPPT control which gives the *d*-axis reference current. An inner current controller compares the reference grid currents ($id_{ref}$ & $iq_{ref}$) with the *dq* frame component of the actual grid currents ($i_d$ & $i_q$). These comparisons provide modulating switching signals ($m_d$ & $m_q$) which are further converted to gate pulse signals to the PV inverter using the PWM generator. The detailed control system is shown in Fig. 3.

The space phasor variables are projected into the *dq*-frame. A Phase Locked Loop (PLL) regulates $v_{sq}$ to zero in order to synchronize space phasors with the *dq* frame variables. By doing so, active and reactive power can be controlled as follows

$$P = \frac{3}{2} v_{sd} i_d \quad (8) \quad Q = -\frac{3}{2} v_{sd} i_q \quad (9)$$

The main objective of this type of control is that both active and reactive power can be independently controlled. Active power can be controlled by regulating $i_d$ and similarly reactive power can be controlled by controlling $i_q$.

## a. Phased Locked Loop

The three phase sinusoidal signals at the AC side of PV inverter are varied with time at the grid frequency $\omega_0$. The *dq* frame variables also vary with time, which is not desirable as these control signals should be time invariant. Therefore, using a PLL, the angular velocity of *dq* frame variable $\omega$ is matched with the grid angular frequency $\omega_0$. Then, the control variable becomes synchronized with the grid and can be used for control actions.

## b. Dc Voltage Control

Dc link voltage control is realized by simply measuring the dc voltage ($V_{dc}$) from the dc link and compared it with a dc voltage reference ($Vdc_{ref}$). The dc voltage reference can be either calculated on the basis of MPPT control or can be a given constant voltage. This error is the input to a lead-lag controller that regulates $V_{dc}$ such that actual dc voltage should follow the reference dc voltage. Dc voltage control is shown in Fig. 3 (left bottom). The transfer function of the lead-lag controller is given by

$$FV_{dc}(s) = K_{dc} \left( \frac{1}{s} \frac{1 + T_1 s}{1 + T_2 s} \right) \quad (10)$$

where, $K_{dc}$, is the gain of lead-lag compensator and $T_1$ and $T_2$ are time constants of the lead –lag compensator.

## c. Current Control Scheme

A current control scheme is implemented to ensure that $i_d$ and $i_q$ follow their references, $id_{ref}$ and $iq_{ref}$. $Id_{ref}$ is generated by the dc voltage controller, while $iq_{ref}$ is a given constant. This type of current control improves the protection of VSC against overload and external faults [8]. This scheme is implemented using (11) and (12).

$$L \frac{di_d}{dt} = -R i_d + L \omega i_q + \frac{V_{dc}}{2} m_d - v_{sd} \quad (11)$$

$$L \frac{di_q}{dt} = -R i_q + L\omega i_d + \frac{V_{dc}}{2} m_q - v_{sq} \qquad (12)$$

In (11) and (12), $i_d$ and $i_q$ are state variables, $m_d$ and $m_q$ are control inputs and $v_{sd}$ and $v_{sq}$ are the disturbance inputs. Due to the factor $L\omega$, the dynamics of the *dq* axis are coupled and nonlinear. In order to decouple them, the following two control laws are deduced to find $m_d$ and $m_q$ .[8]

$$m_d = \frac{2}{V_{dc}} \left( u_d - L\omega i_q + v_{sd} \right) \qquad (13)$$

$$m_q = \frac{2}{V_{dc}} \left( u_q - L\omega i_d + v_{sq} \right) \qquad (14)$$

In (13) and (14), two new additional control inputs are generated, i.e. $u_d$ and $u_q$ . Substituting the expressions of $m_d$ and $m_q$ from (13) and (14) into (11) and (12) gives the following

$$L \frac{di_d}{dt} = -R i_d + u_d \quad (15) \quad L \frac{di_q}{dt} = -R i_q + u_q$$
$$(16)$$

Expressions (15) and (16) show that $i_d$ and $i_q$ can be independently controlled by controlling $u_d$ and $u_q$ respectively.

The implementation of (13) and (14) is shown in Fig 3. The control inputs ( $e_d = id_{ref} - i_d$ ) & ( $e_q = iq_{ref} - i_q$ ) are given to their respective compensators (PI controllers). These two compensators are identical and are represented by (17).

$$k_d(s) = k_q(s) = \frac{k_p s + k_i}{s} \qquad (17)$$

where, $k_p$ and $k_i$ are proportional and integral gains respectively. The current controllers finally give modulating signals $m_d$ and $m_q$, which are fed to the PWM control.

*d. PWM Control*
The terminal voltage of the inverter is controllable through PWM modulation. Hence, by controlling these modulating signals the output voltage can be controlled. Therefore, modulating signals $m_d$ and $m_q$ in the *dq* reference frame are converted back to the abc reference frame as $m_a$ , $m_b$ and $m_c$ which correspond to the three phase sinusoidal voltage reference signals ( $V_a$ , $V_b$ and $V_c$ ). Three phase reference signals ( $V_{abc}$ ) are compared with a triangular carrier signal using a pulse width modulation scheme to provide the final gate pulse control signals to the inverter.

*e. MPPT Control*
Maximum Power Point Tracking (MPPT) control is applied in order to ensure maximum output power. The output power of the PV array can be controlled by regulating the dc link voltage. Perturb and Observe (P & O) is a widely used MPPT technique and was implemented in this work [9]. The method perturbs the dc link voltage, if the power increases by increasing the voltage (dP/dV >0), the voltage continues to increase to reach the maximum power point (MPP). Whereas, if dP/dV <0, the voltage will be decreased to reach MPP in order to maximize the power.
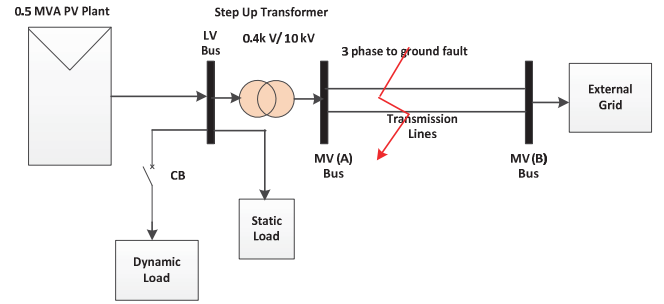


Fig. 4. Simulation Setup

III. CASE STUDIES AND SIMULATION RESULTS

In this section the system shown in Fig. 4 is simulated using SimPowerSystems to investigate the steady state and dynamic behavior of the PV in a power system. Various case studies are analyzed in order to show the dynamic response and stability of the PV model. The model is equipped with an ARTEMIS block in order to provide numerical stability, and will also allow in the future to use this model for real time simulation. ARTEMIS improves the computation speed while preserving accuracy [10].

The simulation setup is made by incorporating the PV panel model into a basic distribution grid. The PV array is connected to a low voltage AC bus at 0.4 kV. Both static and dynamic loads are also connected to this bus. A step up transformer boosts this low voltage to a medium voltage of 10 kV. Then it is connected to a strong grid via two parallel short transmission lines.

*A. Case Study 1: Steady-State Operation*
The steady state operation corresponds to an irradiation of 1000 W/m$^2$ and a temperature of 25º C. Under these conditions the response of the PV system is shown in Fig. 5. At the beginning of the simulation, the dc voltage goes up to 1.05 p.u. due to initialization issues but system reaches to a stable steady state at *t* = 0.5 sec.
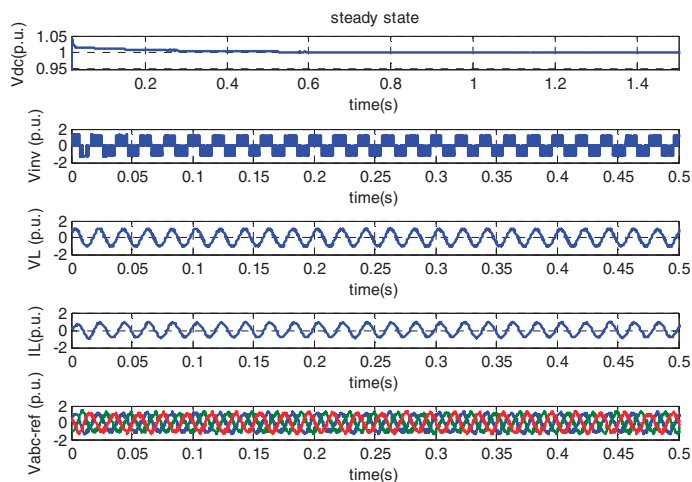
Fig. 5. Steady State operation of PV Model

## B. Case Study 2: Response to Irradiation Changes

In this scenario solar irradiation is reduced to 50% in the form of a step change at time $t = 2$ sec and is brought back to its rated value at time $t = 3$ sec as shown in Fig. 6.

Without MPPT Control, the decrease in irradiation causes the dc voltage to decrease quickly. The dc voltage returns to its steady state value quickly due to the dc voltage control action. However, when the MPPT Control is enabled dc voltage is readjusted to find a new operating point which maximizes the output power. The dc voltage settles quickly for both cases (with and without MPPT), when irradiation is brought back to its original value at $t = 3$ sec. This can be observed in the middle subplot of Fig. 6.

When solar irradiation reduces to 50%, the PV current, and hence PV power, reduces with almost the same percentage. The bottom subplot of Fig. 6 shows that the PV power is reduced to 0.47 p.u., thus following the irradiation step change.

## C. Case Study 3: Assessment of MPPT Control

In order to maximize the PV power in case an environmental disturbance occurs (irradiation change in this case), the dc voltage should be regulated. This is done through the MPPT control. In the bottom subplot of Figure 6, the small figure on the right hand side (zoomed in view of power variation) shows a comparison of the PV power output, with and without MPPT control for a decrease of solar irradiation from 1000 w/m$^2$ to 500 w/m$^2$ at $t = 2$ sec.

The comparison shows that with MPPT control 0.0067 p.u. of additional output power is produced. The rated power of PV array is 448840 Watts; therefore additional 3007.23 Watts are produced. This shows the benefit of MPPT control.

## D. Case Study 4: Three phase to ground fault

A three phase to ground fault is applied on the short transmission lines at $t = 2$ sec and removed at $t = 2.2$ sec as shown in Fig. 4. The dc voltage of the PV system increases to its open circuit voltage with short circuit. When the fault is removed the controls stabilize the dc voltage at $t = 3.5$ sec. This is shown in Fig. 7.

The active power becomes zero during short circuit fault; because the AC voltage at the LV bus goes to zero. As soon as fault is removed at $t = 2.2$ sec, the active power and AC voltage come back to their steady state values. This is shown in Fig. 7.
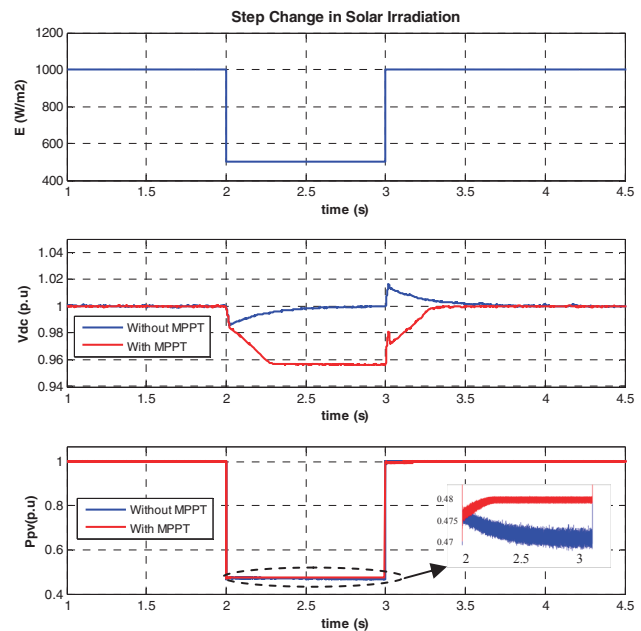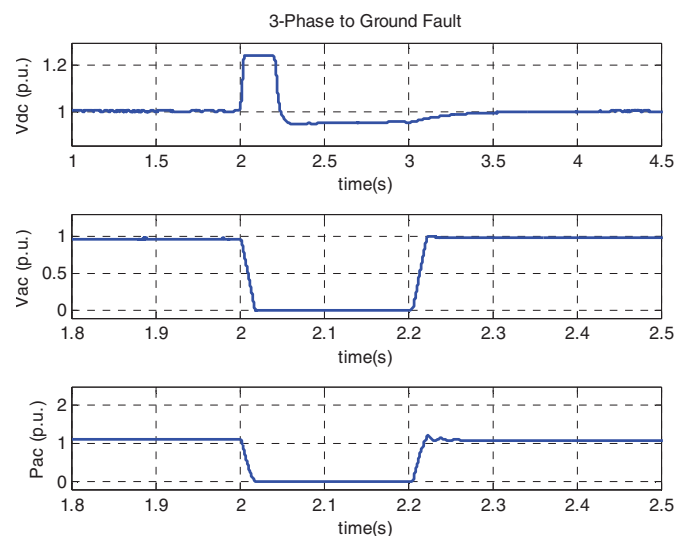


Fig. 6. Step Change in Solar Irradiation



Fig. 7. Three phase to ground fault

## IV. CONCLUSIONS AND FUTURE WORK

This paper presents a comprehensive model of a grid connected photovoltaic system suitable for electromagnetic transient real time studies. The model was developed using MATLAB/Simulink/SimPowerSystems. Modeling details of the PV array and control systems were presented. The model shows the good performance and stability in steady state and under different perturbations.

This PV model is appropriate for investigating PV interactions with the AC grid and it may be used for real time simulation applications. For this purpose, the model needs to

be prepared for real time execution which requires to equip the model with specific Simulink libraries required for compilation in eMegaSim Opal RT's simulator. This future work will be carried out in future stages of the FP7 IDE4L project.

## ACKNOWLEDGMENT

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APPENDIX
PV SYSTEM PARAMETERS

| System Parameters | Value | System Parameters | Value |
|---|---|---|---|
| Rated PV Power, $S_{pv}$ | 0.5 MVA | Temperature at STC,Tref | 25 C |
| DC link voltage, $V_{dc}$ | 700 V | Correction factor | 0.0004 |
| Inverter AC voltage (line-line), $V_{ac}$ | 400 V | current, KI | -0.0039 |
| DC link Capacitance, C | 0.0172 F | Correction factor voltage,KV | 1000 |
| Transformer voltage ratio | 0.4/10kV | Irradiance at STC , ESTC | W/m2 |
| Grid Frequency, f | | | 20 |
| Filter capacitor, $C_f$ | 50 Hz | nSerialModules Number | 140 |
| Filter inductor $L_f$ | 10 μF | nParallelModules Number | |
| PWM frequency, $f_{PWM}$ | 0.9m H | | |
| PV Array | 2 kHz | Controllers | 15796 |
| Short circuit current, Isc1 | 5 A | Dc voltage lead lag compensator gain, $K_{dc}$ | 1.7 |
| Open circuit voltageVoc1 | 43.8 V | Current Controller proportional gain, $K_p$ | 0.002 |
| Current at MPP , Impp0 | 4.58 A | Current Controller integral gain $K_i$ | 0.2323 |
| Voltage at MPP, Vmpp0 | 35 V | Time constant,$T_1$ Time constant,$T_2$ | 0.0010 |