Chapter 3

Modeling of PV based generation for Hybrid power System

3.1 Introduction

A hybrid system is a combination of different RES generations with complimenting nature providing a reliable, stable and efficient operation [129]. The main purpose of such hybrid power systems is to overcome the uncertainty of RES and to make the power supply more consistent. This chapter discusses proposed Hybrid power system, constituting of two RES which is complementing with each other. The two RES being Wind and solar energy is combined into a hybrid system, such system can be proposed for rural electrification which is located at a remote place. Further, the chapter discusses modeling and simulation of different models of PV Cell. An accurate model is selected for analyzing the performance of PV based generation under different loading conditions.

PV Generation consists of PV panels connected in series forming a string, such strings are connected in parallel to form an array to achieve the desired output power from PV generation. The output voltage from the PV are stepped up to the desired DC level using boost converter.

The Wind generation consisting of wind turbine coupled to Permanent Magnet Synchronous Generator (PMSG) whose output voltage is rectified using diode bridge rectifier and stepped up to the desired DC level using boost converter.

The combined DC output of the hybrid system is converted to AC using a VSI. Any harmonics in the DC to AC conversion are minimized using LC filter [130]. This hybrid system can be operated in Stand-alone or Grid integrated mode. To control the AC voltage and frequency of the system a tie-line frequency bias control will be implemented. This requires, mathematical modeling of PV and wind-based generation which helps to understand the dynamic behavior of the two RES under varying environmental and load conditions. The tie-line controller is designed and analyzed on this hybrid system model. In a hybrid power system, the PV based generation is modeled first, followed by wind-based generation system. The following section discusses the PV based generation modeling and analysis.

3.2 PV Based Generation:

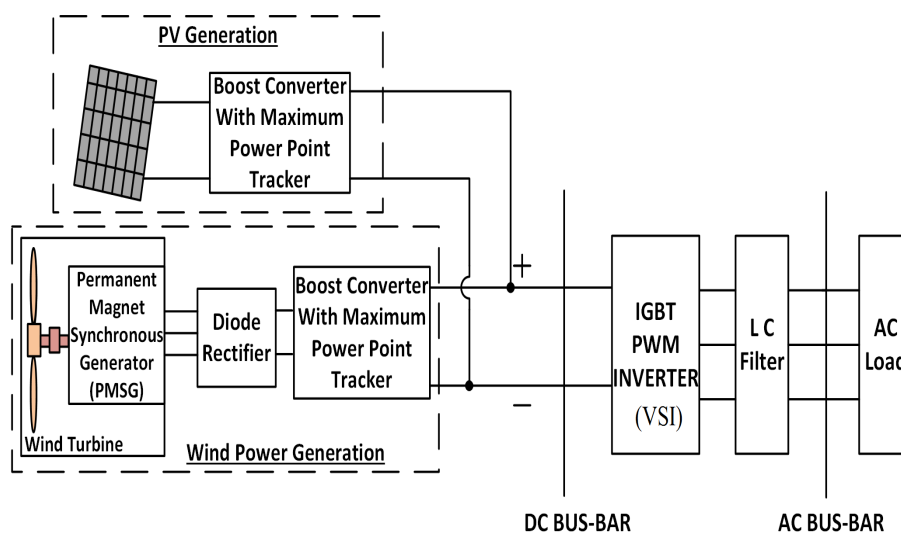The Proposed PV-Wind hybrid power system is shown in Figure 3.1.

FIGURE 3.1: Block diagram of PV-Wind Hybrid Power System.

The basic building blocks of the hybrid power system are

- PV Generation,

- Wind Power Generation,

- Voltage Source Inverter (VSI) i.e. IGBT PWM Inverter

The power from the PV panels is dependent on the solar illumination and operating temperature. Estimating the performance of the PV panel in the real environment with the parameters mentioned in the manufacturer data-sheet of PV panel is a challenge. The electrical parameters of PV panel in the manufacturer data-sheet are computed under standard test conditions i.e. $25^0 C$ and 1000 W/m^2. Before selecting a PV panel it is essential to analyze the performance of PV panel under varying operating temperature from $25^0 C$ to $50^0 C$ and solar irradiation from 1000 W/m^2 to 200 W/m^2 [131].

The performance can be analyzed with a detailed mathematical model of PV module and the power output can be estimated under different solar irradiation levels. Thus modeling of PV cell is vital for PV based generation system and is quite crucial. Mathematical models of PV cells were developed in the MATLAB / Simulink / Simscape environment and simulated to obtain the characteristics of the PV cell models. The mathematical model was simulated to bring out the Power (p) -Voltage (V) and Current (I)-Voltage (V) characteristics under standard and non-uniform conditions. The simulated characteristics of the PV cell models were compared with the Manufacture data-sheet in order to validate the simulated results.

Various researchers have proposed different models for PV cell based on Coding, and equation based design using a single diode and two-diode models. The parameters involved modeling of diode based PV cell are shown in Table 3.1. They can be of form 3, 4 or 5 elements with 4, 5 or 8 parameters respectively involving single or two diodes including series and shunt resistance. Initially, the performance of a single diode model, with 3 element and 4 parameters which are based on diode equations had been studied. The studies were conducted under different solar irradiance levels and effect of a change in series resistance was observed [132–134]. The effect of shunt resistance in the equivalent circuit of single diode PV model with 5 parameters was investigated under different solar irradiation levels [135–137]. In Simscape the

TABLE 3.1: "THE ELEMENTS AND PARAMETERS INVOLVED IN THE DESIGN OF PV CELL"

"3-element" or "4-parameter"		"4- element" or "5- parameter"		"5-element" or "8- parameter"	
"Element"	"Parameter"	"Element"	"Parameter"	"Element"	"Parameter"
"Current" "Source"	"I_{PH}"	"Current" "Source"	"I_{PH}"	"Current" "Source"	"I_{PH}"
"Diode"	"I_D"	"Diode"	"I_D"	2 Diodes	"I_{D1}", "I_{D2}"
	Output current (I)		Output current (I)		Output current (I)
Series Resistance	R_s	Series Resistance	R_s	Series Resistance	R_s
		Shunt Resistance	R_p	Shunt Resistance	R_p

Solar cell is modeled as an equivalent circuit with 5/8 parameters (two diode model). The characteristics of equation based single diode model were studied in [138–140]. Hence a comparative analysis of PV cell developed in Simscape was compared with the PV cell developed in Simulink [141–143]. However, a comparative analysis of the equation based design of PV cell was done using a single diode model only. Further, a comparative analysis of a two-diode model of PV cell is to be investigated.

In order to have an incite of the PV cell modeling, in this section mathematical modeling of diode based PV cell developed in all three different configurations, available in the Solar cell block in Simscape and equation based models of PV cell implemented in Simulink, are studied. Each PV cell is modeled to generate Open Circuit voltage of 0.665 V, Short circuit current of 5.75 A and rated power output of 3 W. The results are compared under Standard Test Conditions (STC) and validated by comparing with the referenced manufacturer data sheet as shown in Table 3.2 [144].

TABLE 3.2: Electrical Parameters of manufacturer Data sheet

"Open Circuit Voltage"	"0.665 V"	"Maximum Power Current"	"5.35 A"
"Short Circuit Current"	"5.75 A"	"Rated Power"	"3.0 W"
"Maximum Power Voltage"	"0.560 V"	"Efficiency"	"20.0 %"
Temperature Co-efficients			
Voltage	-1.9 mV / ^{0} C		
Power	-0.38% / ^{0} C		

3.2.1 Equation Based PV cell modeling

A simplified equivalent circuit model shown in Figure 3.2, a PV array is combination of PV cells in Series / Parallel arrangement.
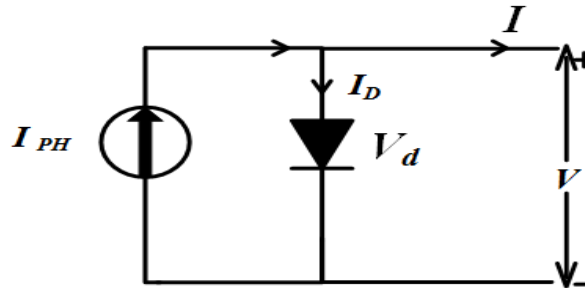

FIGURE 3.2: Electrical equivalent circuit of single diode model.

where

V_D = voltage across diode,

I_D = diode current,

I = output current from PV cell,

I_{PH} = Photo generated current,

V_{oc} = Open Circuit (O/C) voltage, and

I_{sc} = Short Circuit (S/C) current.

The Current (I)-Voltage (V) and Power (P) - Voltage (V) characteristics of PV cell are graphically represented in Figure 3.3. In order to investigate the behavior of a diode based model of PV cell in MATLAB, the equivalent circuit parameters required are V_{oc}, I_{sc}, I_{PH}, V_d, I_D and I.

The Equation based modeling of PV cell is of three types

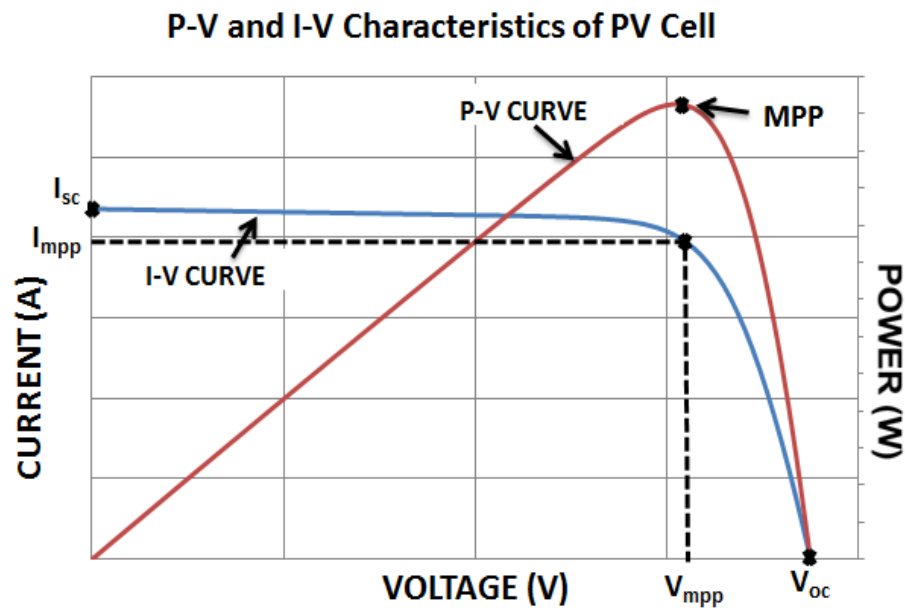1. Single diode model-A "By O/C Voltage and S/C current, 5 parameters",

FIGURE 3.3: P-V and I-V Characteristics of PV cell

2. single diode model-B "By Equivalent circuit parameters, 5 parameter",

3. Two diode model C "By Equivalent circuit parameters, 8 parameter".

Each model is discussed and implemented in the MATLAB/Simulink in the following section.

3.2.1.1 Single diode model-A "By O/C Voltage and S/C current, 5 parameters" :

The ideal single diode model of PV cell as shown in Figure 3.2 is a theoretical model. In order to simulate the characteristics of the PV cell similar to the practical PV cell, the single diode model is modified by adding a contact resistance i.e series resistance (R_s) which signifies the contact resistance between the semiconductor and the terminals, a shunt resistance (R_p) signifies the internal resistance of the source as shown in Figure 3.4.

Thus the electrical equivalent circuit of the PV cell with O. C voltage and S. C current, single diode model with 5 parameter is shown in Figure 3.4. The 5 parameter involved in modeling are V, I_{PH}, I_D, R_s, and R_p [145].
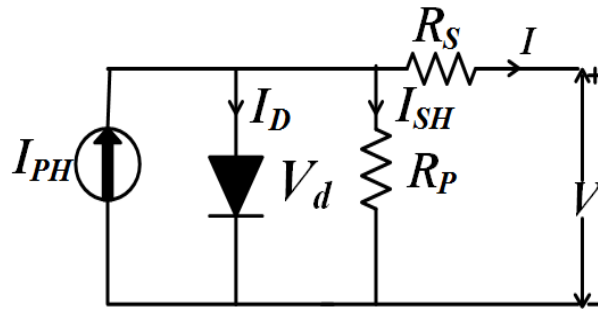
FIGURE 3.4: Electrical equivalent circuit of single diode model.

The output current *I* of PV cell in Figure 3.4 is determined by KCL,

$$I - I_{PH} - I_D - I_{SH} = 0 \tag{3.1}$$

I_{PH} is obtained from solar irradiation level by (3.2)

$$I_{PH} = SolarIrradiation \times \frac{I_{sc}}{1000} \tag{3.2}$$

where 1000 is the standard solar irradiance considered for testing the manufacturer PV cells. The Diode current is

$$I_D = I_s \left[e^{\frac{V_d}{V_T}} - 1 \right] \tag{3.3}$$

where I_s = Reverse Saturation current of diode,

V_T = Thermal Voltage of the diode.

The diode current is re-written as

$$I_D = I_s \left[exp \left(\frac{q \times V}{N \times k \times T} \right) - 1 \right] \tag{3.4}$$

where,

N = diode ideality factor,

V = cell output voltage,

T = junction temperature,

k = Boltzmann constant = 1.38×10^{-23},

q = charge on electron = 1.602×10^{-19} C. From Figure 3.4

$$I_{SH} = \frac{V + (R_s \times I)}{R_p} \tag{3.5}$$

Substituting the values of I_D and I_{SH} in (3.1) the output current from the PV cell is:

$$I = I_{PH} - I_s \left[exp \left(\frac{q \times V}{N \times k \times T} \right) - 1 \right] - \frac{V + (R_s \times I)}{R_p} \tag{3.6}$$

The output voltage of the PV cell is expressed as:

$$V = V_d - R_s I \tag{3.7}$$

The Power output of the PV cell is expressed as:

$$P = V \times I \tag{3.8}$$

The model A represented by (3.1) to (3.8)is implemented in MATLAB, Simulink as shown in Figure 3.5.
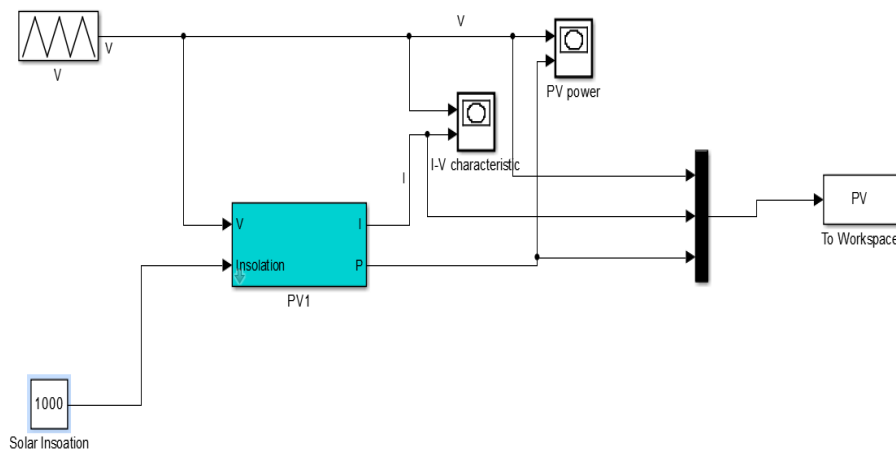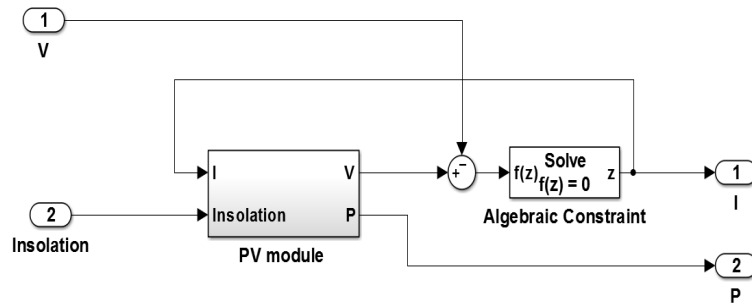

FIGURE 3.5: Simulink implementation of model A.

FIGURE 3.6: Sub-system of the PV1 module in model A.

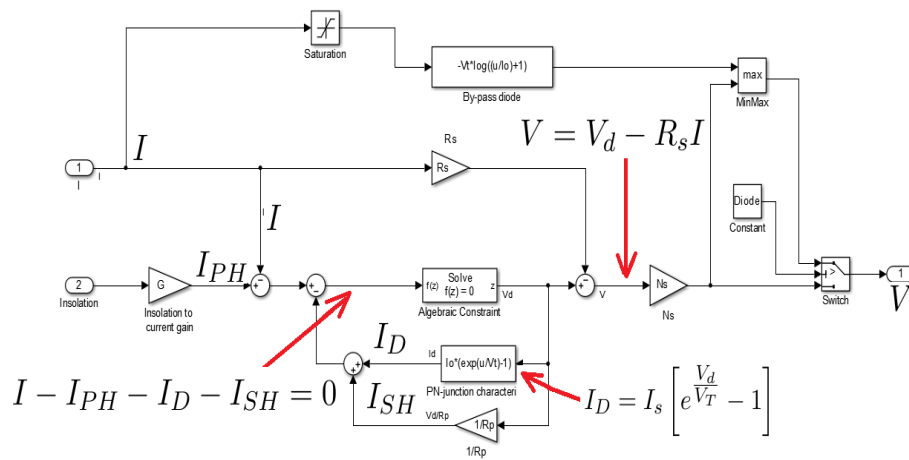The "PV1" sub-system in Figure 3.5 is shown in Figure 3.6. The Figure 3.6 consists of the equation based

FIGURE 3.7: Sub-system implementation of the PV module

implementation of PV cell (3.1)-(3.8) as represented by " PV module ". The voltage computed by the

solving equation is compared with the voltage inputted to generate the current input to the PV cell utilizing

the algebraic solver. This mathematical implementation is done to achieve non-linear characteristics for

PV cell as shown in Figure 3.3. The subsystem implementation of PV module is shown in Figure 3.7.

To simulate the behavior of the PV cell i.e. to plot the I-V and P-V Characteristics similar to the data

sheet, a short circuit and open circuit test on the equation based model is performed. To achieve the task

the voltage is given as in input to the PV cell as [0 0.665V], which are a short circuit and open circuit

voltage from the manufacturer data sheet shown in Table 3.2. The output voltage from this subsystem is

compared with the voltage provided to compute the non-linear value of output Current using Algebraic

Solver as shown in Figure 3.6. The Solar irradiation as input is utilized to compute the Photo-generated

current I_{PH} utilizing (3.2) and is shown in Figure 3.7. Further utilizing the computed I_{PH}, I, I_D, $I_{SH}$and

the output Voltage V of the PV cell is generated.

The change in input Voltage from 0 to 0.665 V, the current computed will be from 5.75 A to 0 A which is the short circuit and open circuit current of the PV cell. The electrical parameters for simulating the model are shown in Figure 3.8 [146].
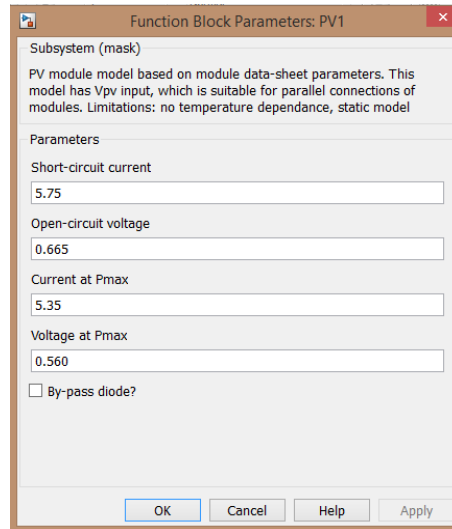
FIGURE 3.8: Block Parameters of PV1 model A

The electrical parameters of the equation based model are computed by initializing the PV1 model in Sub-Mask properties of the PV model in Simulink shown in Figure 3.5 by

N_s = round(V_{oc} /0.61); number of cells in series

V_T = 26e-3; thermal voltage

G = I_{sc}/1000; irradiation to photo generated current gain

V_{mpc} = V_r/N_s; cell voltage at rated MPP

V_{occ} = V_{oc} /N_s; open-circuit voltage

R_{mpp} = V_{mpc}/I_r; cell load resistance at MPP

R_p = 100×V_{occ} /I_{sc}; initial value for R_p

V_d = V_{occ}; initial value for V_d

iterative solution for model parameters: I_o, R_s, R_p

for i=1:10

$I_d = I_{sc}$ - I_r - V_{dm}/R_p; diode current at MPP

$I_s = (I_{sc}$-V_{occ} /R_p)/(exp(V_{occ} /V_T)-1); pn-junction reverse saturation current

$V_d = V_t \times \log(I_d/I_s +1)$; diode voltage at MPP

$R_s = (V_d$-$V_{mpc})/I_r$;

$R_d = (R_{mpp}$ - $R_s) \times R_p/(R_p$-R_{mpp}+$R_s)$; diode incremental resistance at MPP

$I_{dm} = V_T/R_d$; diode current at MPP based on incremental resistance

$R_p = V_d/(I_{sc}$-I_r-$I_{dm})$;

end

The PV cell represented by model A is simulated, the characteristics are discussed in section 3.3.

3.2.1.2 single diode model B "By Equivalent circuit parameters, 5 parameter" :
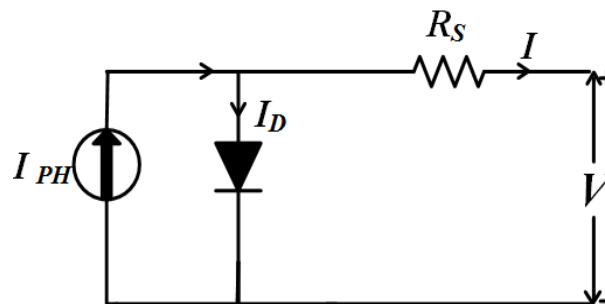

FIGURE 3.9: Simplified equivalent circuit of PV cell.

The adopted model for Equivalent parameter, 5 parameter single diode (model B) is shown in Figure 3.9. It is a 5 parameter single diode model based on V, I_{PH}, I_D, R_s, I in which the shunt resistance is neglected (R_p is infinity) as compared with model A. The output voltage of PV cell is given by (3.9).

$$V = \frac{AkT_c}{q} ln \left(\frac{I_{ph}+I_s-I}{I_s} \right) - (I \times R_s) \tag{3.9}$$

where

T_c = Reference cell operating temperature 20^0 C,

I_s = Reverse saturation current of diode,

Equation (3.9) computes the output voltage of a single solar cell. The Simulink implementation of the (3.9) is shown in Figure 3.10. If the temperature and solar irradiation levels change, the voltage and
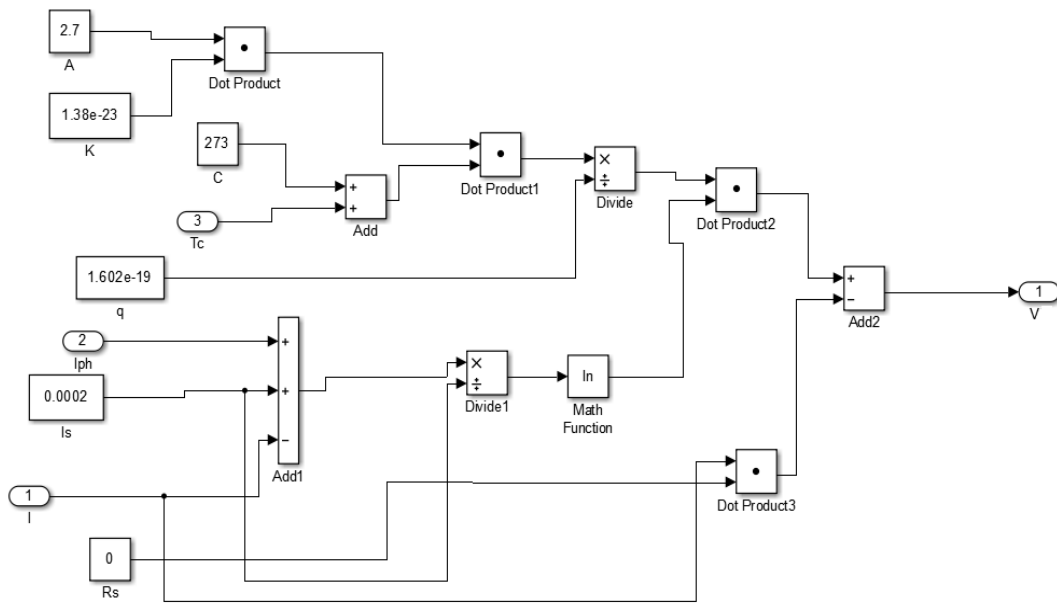

FIGURE 3.10: Implementation of Equation 3.9.

current outputs of the PV array will follow this change. Hence, the effects of the changes in temperature and solar irradiation levels should be included in the PV array model. These effects are represented in the model by the temperature coefficients C_{TV} and C_{TI} for cell output voltage and cell photo-current respectively as in (3.10), (3.11):

$$C_{TV} = 1 + \beta_T (T_a - T_x) \tag{3.10}$$

$$C_{TI} = 1 + \frac{\gamma_T}{S_c} (T_x - T_a) \tag{3.11}$$

where T_a is the ambient temperature during the testing of the cell, T_x is the new or the changed temperature in the field which is used to obtain the modified characteristics of the cell at changed temperature. β_T is the temperature coefficient of the voltage, γ_T is the temperature coefficient of the current these values can be obtained from the manufacturer data sheet [145] and S_c is the solar irradiation at STC.

The change in the temperature ΔT due to the change in the solar irradiation or non-uniform irradiation is given by (3.12)

$$\Delta T = \alpha_s (S_x - S_c) \tag{3.12}$$

where, the constant α_s is the slope of the change in the cell operating temperature with the change in solar irradiation, S_x is the new level or changed solar irradiation.

Thus the change in the operating temperature and in the photo-current due to variation in the solar irradiation level can be expressed via two constants, C_{SV} for PV output voltage and C_{SI} for PV current, which are the correction factors for changes in cell output voltage V and photo-current I_{ph}, respectively and expressed as (3.13), (3.14):

$$C_{SV} = 1 + \beta_T \alpha_s (S_x - S_c) \tag{3.13}$$

$$C_{SI} = 1 + \frac{1}{S_c} (S_x - S_c) \tag{3.14}$$

The final correction factors of the output voltage (C_V) and photo current (C_I) are given by (3.15), (3.16).

$$C_V = C_{TV} \times C_{SV} \tag{3.15}$$

$$C_I = C_{TI} \times C_{SI} \tag{3.16}$$

The equation based implementation of the effect of change in temperature and solar irradiation (3.10)-(3.16) in Simulink is shown in Figure 3.11.

The new values of output voltage (V_c) and output current (I_{phx}) with the early solar irradiation S_x and temperature T_x is expressed as (3.17), (3.18).

$$V_{cx} = C_{TV} \times C_{SV} \times V_c \tag{3.17}$$

$$I_{phx} = C_{TI} \times C_{SI} \times I_{ph} \tag{3.18}$$
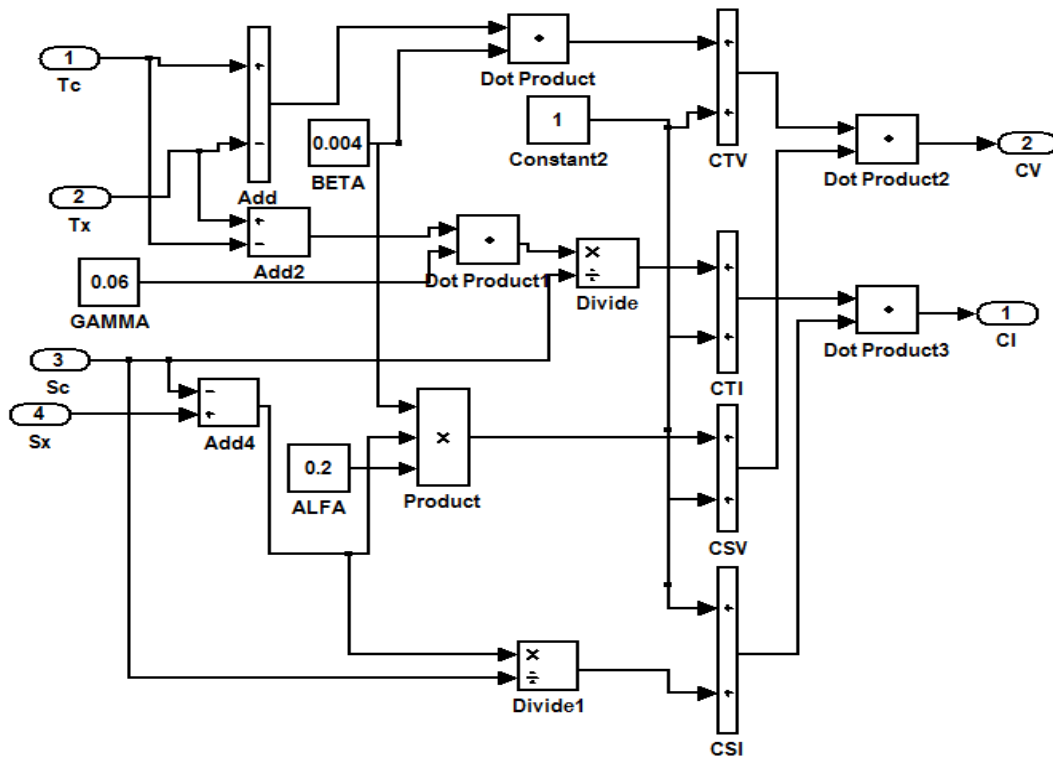
FIGURE 3.11: Implementation of Effect of Temperature and Solar Irradiation.

The Figure 3.12 shows the generated I_{cell} and V_{cell} which are PV cell output current and voltage respectively. These are utilized to compute the PV cell voltage and current as shown in Figure 3.13.
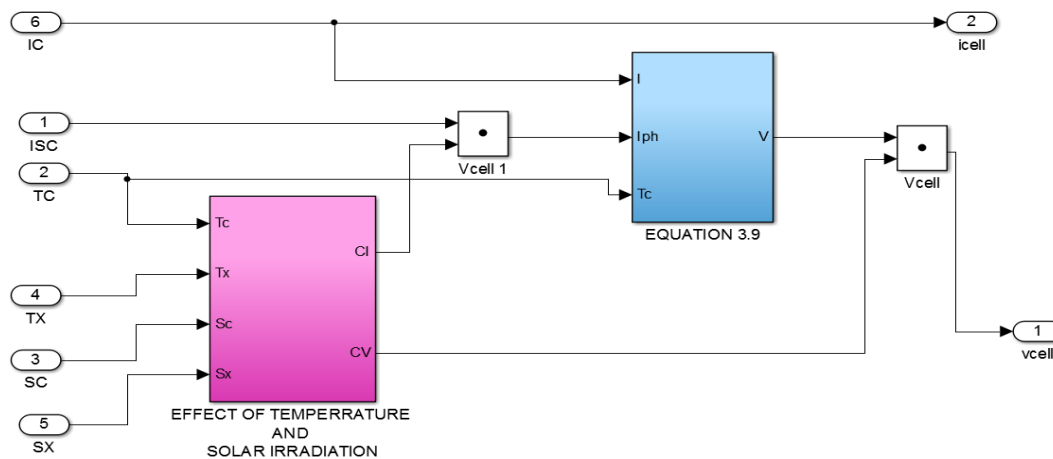

FIGURE 3.12: Implementation of PV cell.

Figure 3.14 shows the Simulink implementation of single diode PV cell by equivalent circuit, 5 parameter model B. The electrical parameters considered for the simulating the model are shown in Table
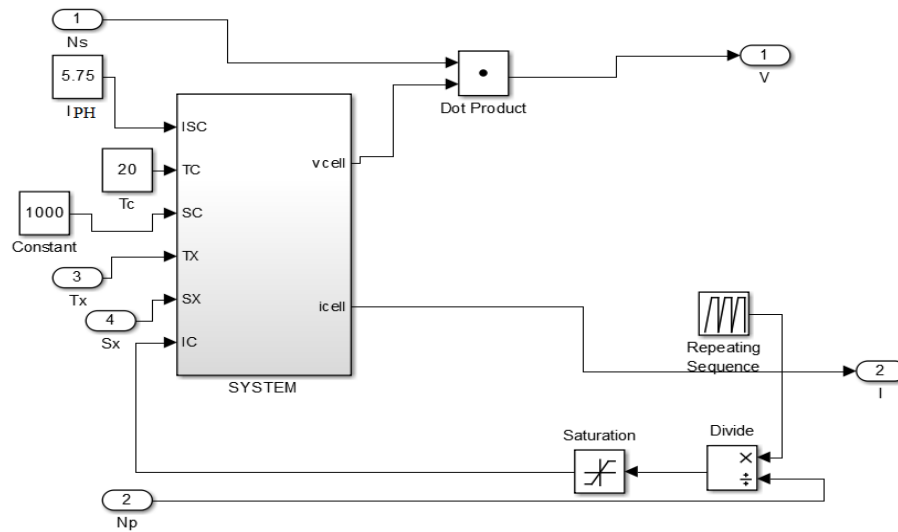
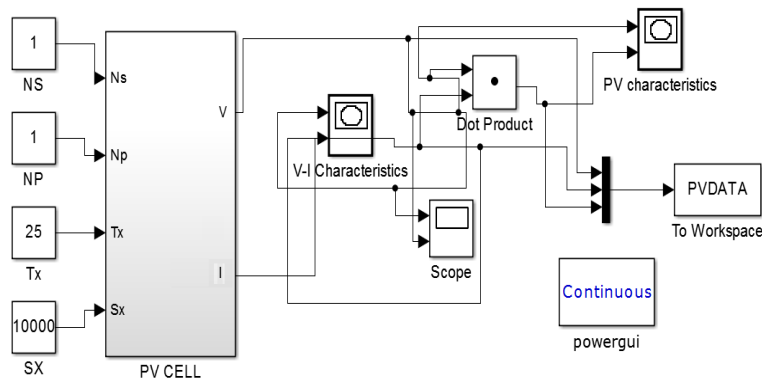FIGURE 3.13: Implementation of PV panel

FIGURE 3.14: Simulink implementation of PV module model B.

3.2 extracted from manufacturer data sheet and the simulated characteristics will be discussed in detail in section 3.3.

3.2.1.3 Two diode model C "By Equivalent circuit parameters, 8 parameter":

The Electrical equivalent circuit of 8 parameter two diode (model C) is shown in Figure 3.15 consisting of Photo-generated current I_{ph}, two diodes D_1, D_2 with diode currents I_{D1}, I_{D2}, Series Resistance R_s, Shunt Resistance R_p, output voltage V and PV current I. In order to incorporate the real time parameters into mathematical modeling and to simulate the real behavior of PV cell similar to practical PV cell is
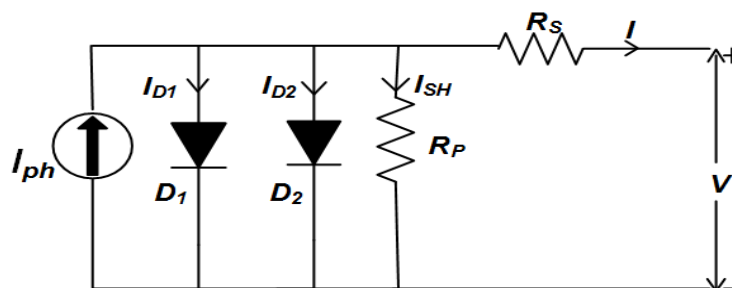
FIGURE 3.15: electrical equivalent of Two-diode model of PV cell.

expressed as:

$$I = I_{ph} - I_{s1}\left[e^{\left(\frac{V+R_s \times I}{N_1 \times V_t}\right)} - 1\right] - I_{s2}\left[e^{\left(\frac{V+R_s \times I}{N_2 \times V_t}\right)} - 1\right] - \frac{V+R_s \times I}{R_p} \tag{3.19}$$

where I_{s1}, I_{s2} are the reverse saturation currents N_1, N_2 are the quality factors of diode D_1, D_2, and V_t is the is the thermal voltage of the module define by (3.20) with N_s being number of cells connected in series.

$$V_t = \frac{N_s \times k \times T}{q} \tag{3.20}$$

Model C of PV cell is implemented in MATLAB, Simulink as shown in Figure 3.16. The subsystem implementation of Two diode model of PV cell is shown in Figure 3.17.
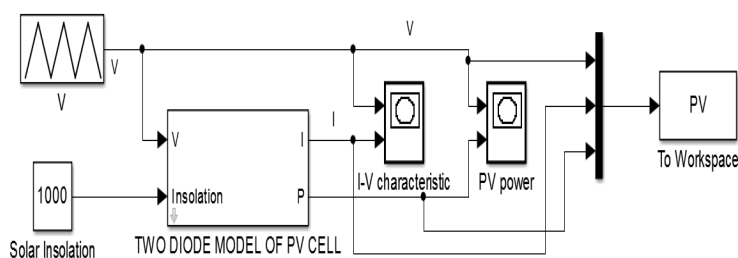

FIGURE 3.16: Simulink implementation of PV cell model C.

The simulated characteristics of Model C PV cell are discussed in detail in the section 3.3. The following subsection discusses the model based implementation of PV cell in Simscape.
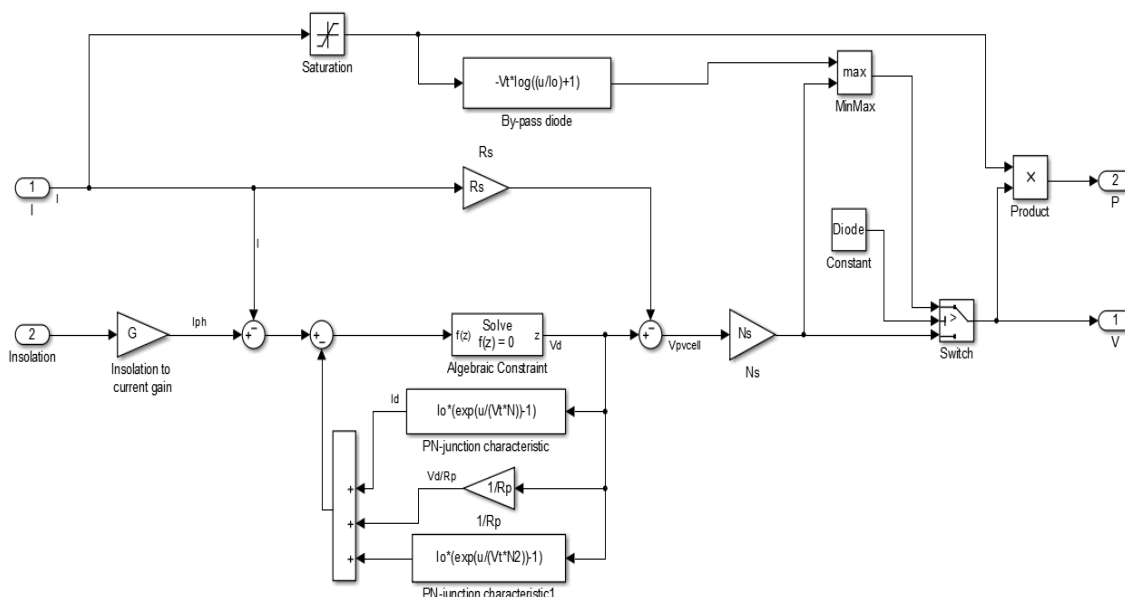
FIGURE 3.17: Subsystem implementation of two-diode model C.

3.2.2 Model Based Implementation Of PV Cell In Simscape:

A solar cell as an energy source is available in the Simscape, Simelectronics library as shown in Figure 3.18. The general equivalent circuit of the solar cell implemented in Simscape is a two diode model as represented in Figure 3.15 whose output current is defined by (3.19).
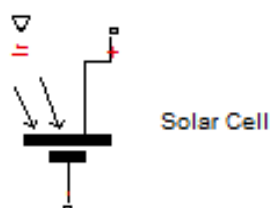

FIGURE 3.18: Solar Cell Block in Simscape/Simelectronics.

This model in Simscape has a provision to appropriately model in different configurations by nullifying few parameters. The necessary configuration with different parameters is chosen by the user from the drop down menu as shown in Figure 3.19.

The different configurations of solar cell block are

- By O/C Voltage and S/C current, 5 parameters single diode in Simscape (model D),
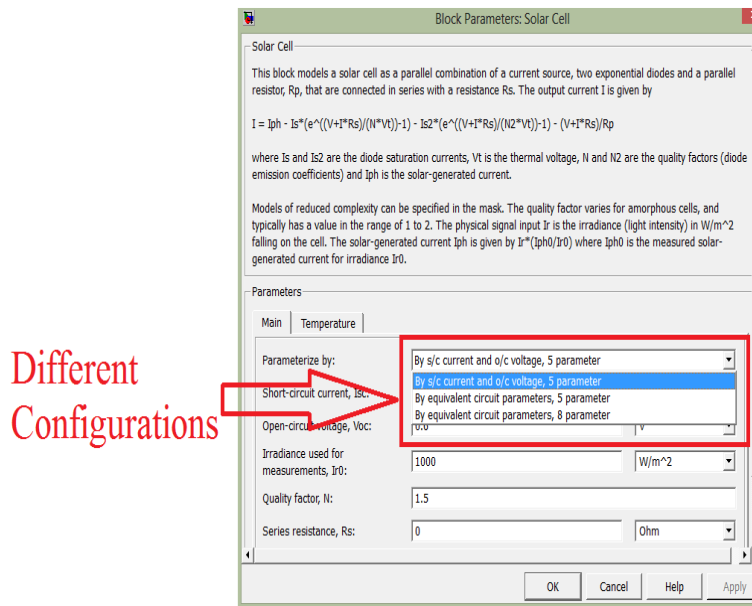
FIGURE 3.19: Block Parameters of Solar Cell in Simscape/Simelectronics.

- By Equivalent circuit parameters, 5 parameters single diode in Simscape (model E), and

- By Equivalent circuit parameters, 8 parameters two diode in Simscape (model F)

3.2.2.1   single diode model D "By O/C Voltage and S/C current, 5 parameters":

On selecting this option the equivalent circuit of the solar cell is as in Figure 3.4. The output current of

the solar cell is given by (3.6). The circuit implementation to simulate the I-V and P-V characteristics of
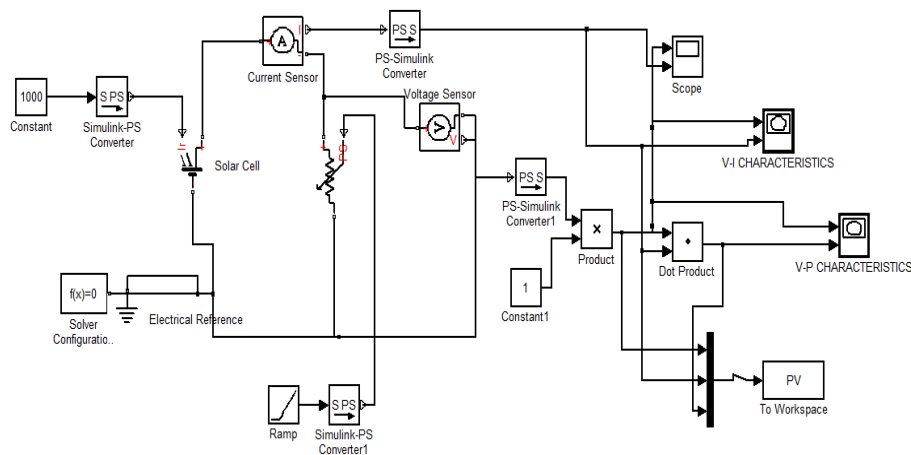

FIGURE 3.20: Solar Cell Model in the Simulink.

the model D is shown in Figure 3.20. The Solar cell is utilized as a source where, the output terminals of

the solar cell are connected to a variable resistor. Using a unit ramp signal as input to variable resistance, the resistance value is varied from zero to maximum value, creating the open circuit and short circuit condition at the terminals of the solar cell. The characteristics of PV cell model D are obtained by utilizing the parameters V_{oc}, I_{sc}, R_s, N, I_s, and Irradiance values from datasheet of the solar cell as shown in Table 3.2 [144]. The I-V characteristics and P-V characteristics of the model D obtained from the simulation will be discussed in the section 3.3.

3.2.2.2   single diode model E "By Equivalent circuit parameters, 5 parameters":

The electrical equivalent of the Solar cell modeled by Equivalent circuit parameters, 5 Parameter single diode is as shown in Figure 3.9. The output voltage of the PV cell of Model E is given by (3.9). The Simulink implementation of PV cell model E is similar to that shown in Figure 3.20. From the block parameters of solar cell the configuration "By Equivalent circuit parameters, 5 parameter" is selected and the electrical parameters of the PV cell are inputted such as $V_{oc} = 0.665$ V, $I_{SC} = 5.75$ A, $W_{mpp} = 3.0$ W etc from data sheet as shown in Table 3.2 [144]. Thus I-V and P-V characteristics of the model E obtained from simulation will be discussed in the section 3.3.

3.2.2.3   two diode model F "By Equivalent circuit parameters, 8 parameter":

On selecting the configuration by equivalent circuit parameters, 8 parameters two diode model F, the electrical equivalent circuit of the solar cell is as shown in Figure 3.15. The output current of the PV cell model F is given by (3.19). To simulate the characteristics of the PV cell a, Simulink implementation of the same is shown in Figure 3.20. The electrical parameters are inputted into the solar cell block are extracted from datasheet. The model is simulated and the characteristics are obtained. The I-V and P-V characteristics of the model F obtained from simulation will be discussed in the section 3.3.

3.2.3 SUNPOWER A-300 SOLAR CELL, MONO CRYSTALLINE SILICON DATA-SHEET

I-V characteristic of the reference solar cell from the data-sheet is shown in Figure3.21. The electrical parameters of the reference PV cell are shown in Table.3.2 [144].
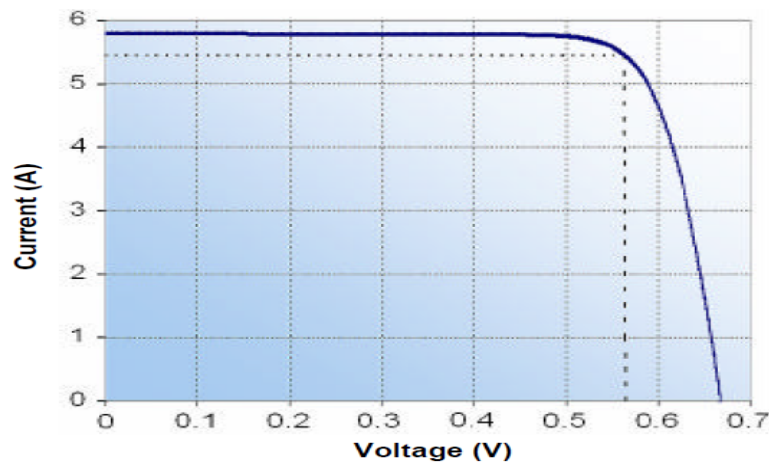

FIGURE 3.21: I-V Characteristics from Data-sheet.

These values from Table 3.2 are substituted in the simulation models and simulated in order to obtain the characteristics similar to that shown in Figure 3.21. In the following section, The simulated results are validated by comparing it with the characteristics from data sheet.

3.3 Comparison of Characteristics of Equation-based and Model-based implementation of PV Cell with real-time data of PV cell extracted from Manufacturer data sheet:

The different configuration of PV cell model implementation by Equation based and model based techniques are

Equation based model:

1. O/C Voltage and S/C current, 5 parameters single diode (model A), as shown in Figure 3.6,

2. By Equivalent circuit parameters, 5 parameters single diode (model B), as shown in Figure 3.14,

3. By Equivalent circuit parameters, 8 parameters two diode (model C), as shown in Figure 3.16

Model based design:

1. By O/C Voltage and S/C current, 5 parameters single diode in Simscape (model D), as shown in Figure 3.20

2. By Equivalent circuit parameters, 5 parameters single diode in Simscape (model E), as shown in Figure 3.20 and

3. By Equivalent circuit parameters, 8 parameters two diode in Simscape (model F), as shown in Figure 3.20

The P-V and I-V characteristics of the different PV cell models considered were simulated and the simulated characteristics are compared with the characteristics obtained from manufacturer data sheet as shown in Figure 3.21 for validation. Similarly, the simulated electrical parameters such as V_{oc}, I_{SC}, V_{mpp}, I_{mpp} etc of all the models of PV cell are compared with real time values of electrical parameters extracted from the manufacturer data sheet which is tabulated in Table 3.2. The comparative study is done to select an accurate mathematical model of PV cell. A comparative analysis of electrical parameters of all the models of PV cell and manufacturer data sheet are tabulated in Table 3.3. The simulation study was conducted under Standard Test Conditions (STC) i.e. 1000 W/m^2 Solar Irradiation and operating temperature of 25^0C.

The simulated P-V and I-V characteristics of the equation based implementation of PV cell models (A, B and C) in Simulink are shown in Figure 3.22, 3.23, 3.24 respectively. The Power-Voltage and Current-Voltage at MPP are marked respectively in the characteristics. The simulated characteristics

TABLE 3.3: SIMULATION RESULTS IN MATLAB/SIMULINK/SIMSCAPE

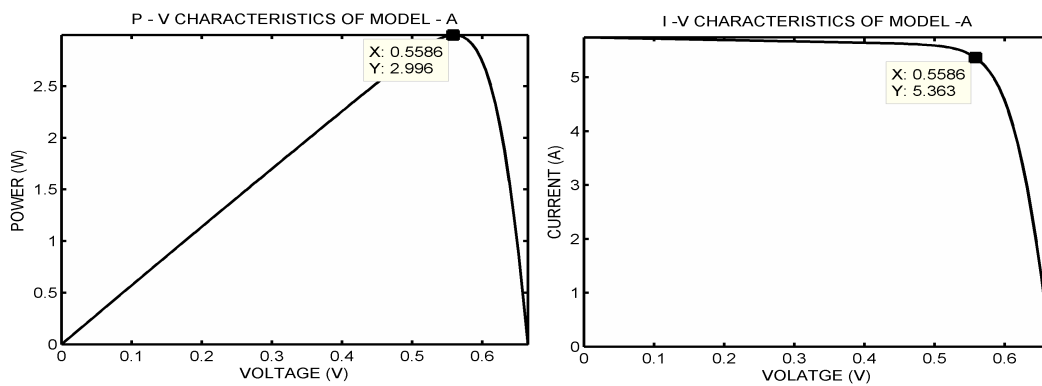| Characteristics	Data-Sheet	Simulink Model			Simscape Model		
	SUN POWER A-300	Model-A	Model-B	Model-C	Model-D	Model-E	Model-F
V_{oc} (V)	**0.665**	0.671	0.685	**0.665**	0.664	0.677	**0.665**
I_{sc} (A)	**5.75**	5.7	5.752	**5.743**	5.75	5.65	**5.75**
W_{mpp} (W)	**3.0**	**2.996**	2.753	**3.008**	3.024	**3.001**	**3.001**
V_{mpp} (V)	**0.560**	**0.559**	0.554	**0.556**	0.571	**0.556**	**0.556**
I_{mpp} (A)	**5.35**	**5.363**	5.061	**5.413**	5.296	5.396	**5.396**
Irradiance (W/m^2)	**1000**	**1000**	1000	**1000**	1000	1000	**1000**
Temperature (^{0}C)	**25**	**25**	25	**25**	25	25	**25**

FIGURE 3.22: "P-V & I-V Characteristics of Model-A (Simulink)".
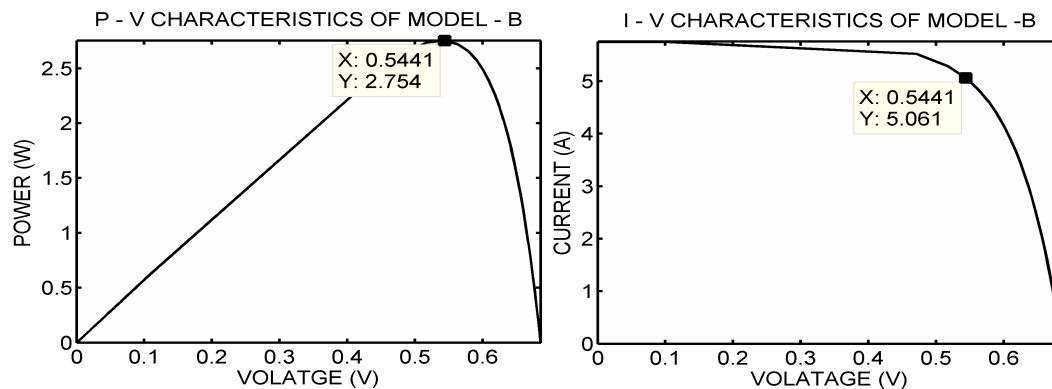

FIGURE 3.23: "P-V & I-V Characteristics of Model-B (Simulink)".

of PV cells are compared with the characteristics obtained from the Data-sheet shown in Figure 3.21.

The I-V characteristics of model- A & C are replicating the reference characteristic and the electrical

parameters such as W_{mpp} are 2.996 W, 3.08 W; V_{mpp} are 0.559 V, 0.556 V; I_{mpp} are 5.363 A, 0.556

A respectively but the characteristics of model B doesn't duplicate the reference characteristics and
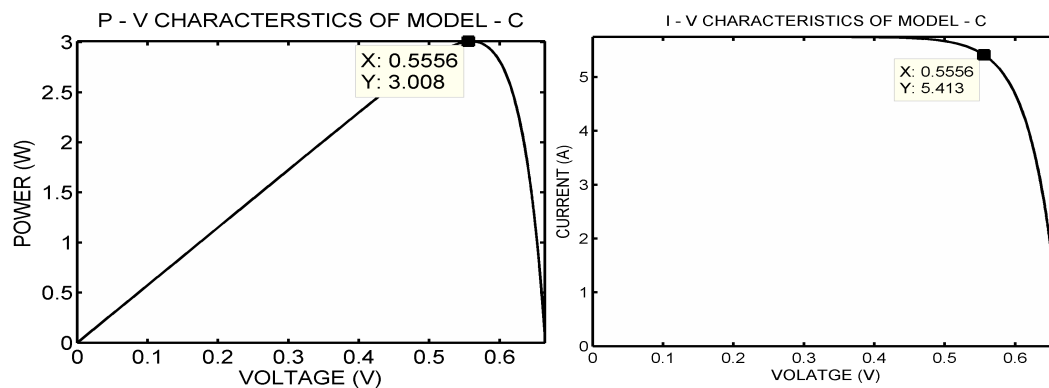
FIGURE 3.24: "P-V & I-V Characteristics of Model-C (Simulink)".

the simulated electrical parameters of this model are 2.753 W, 0.554 V, 5.061 A . Now comparing the

simulated electrical parameters with the electrical parameters extracted from data sheet i.e. W_{mpp} = 3.0

W; V_{mpp}=0.560 V; and I_{mpp}=5.35 A respectively. It can be comprehended that the electrical parameters of

Model A & C produces similar Power, Voltage and Current at MPP as real PV cell. The model B exhibits

a deviated electrical parameters. By comparing the Voltage at open circuit and current at short circuit i.e.

V_{oc} = 0.665 V and I_{SC} = 5.75 A for Models A & C, The Model C has accurate electrical parameters as

compared to Model A which can be comprehended from the comparative analysis tabulation in Table 3.3.

Hence the Model C exhibits accurate characteristics in the equation based implementation of PV cell in

Simulink.

Now comparing the P-V and I-V characteristics of the model based design of diode based PV cell (model

D, E, and F) in Simulink, Simscape i.e. Figure 3.25, 3.26, 3.27 respectively with the Manufacturer data

sheet I-V characteristics i.e. Figure 3.21 it is observed that the I-V characteristics of the model D, E, F

are similar to that of I-V characteristic of Manufacturer data sheet.

Comparing the electrical parameters of the models considering the W_{mpp}= 3.0 W, V_{mpp}=0.560 V and

I_{mpp}=5.35 A from the data sheet as shown in Table.3.3, it is clear that model D produces an output power

of 3.024 W similar to the data sheet. The current at MPP of Model D is 5.296 A which is less than actual

value and voltage at MPP is 0.5711 V which is greater than the actual value. The Power at MPP of Model

D matches exactly but the voltage and current at MPP are not the same values as compared to the data

sheet. Now comparing the electrical parameters of Model E and F, the power produced at MPP i.e. W_{mpp}
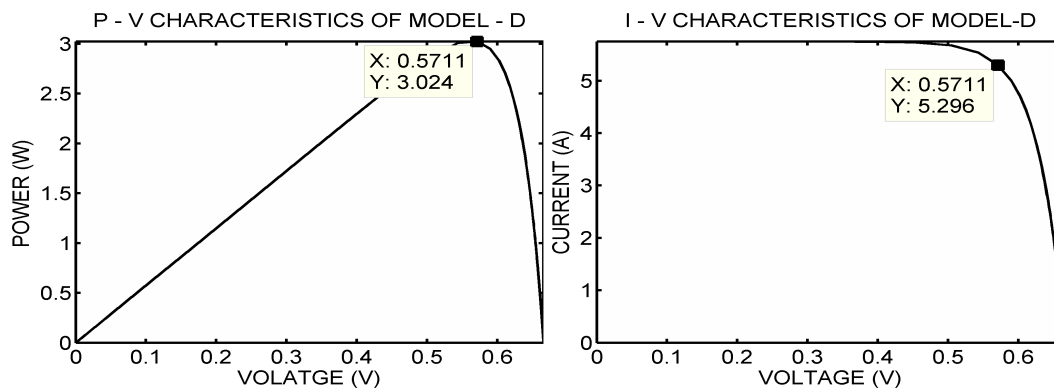
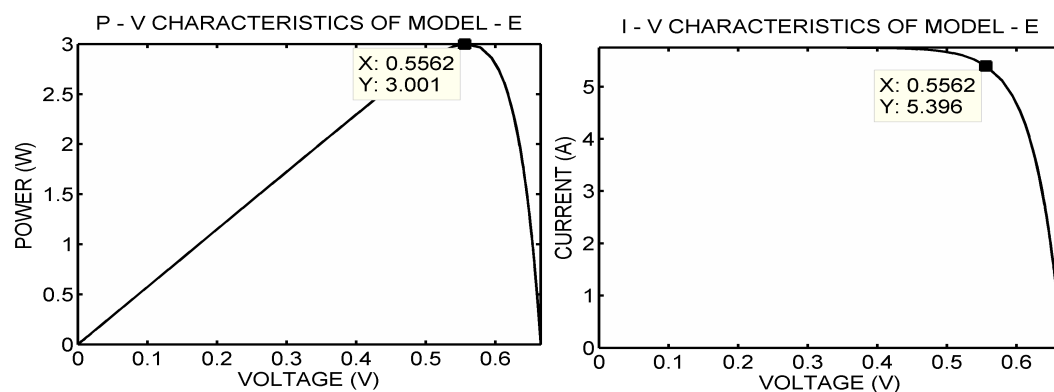**FIGURE 3.25: "P-V & I-V Characteristics of Model-D (Simscape)".**

FIGURE 3.26: "P-V & I-V Characteristics of Model-E (Simscape)".
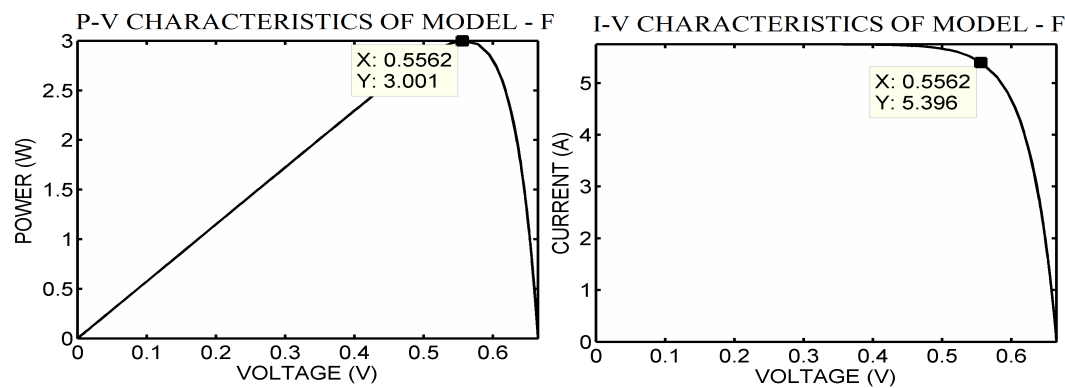
FIGURE 3.27: "P-V & I-V Characteristics of Model-F (Simscape)".

= 3.0 W and voltage and current at MPP are 0.5562 V and 5.396 A respectively. The electrical parameters of Models E, F are similar to the data sheet. In order to get accurate model from Model E and F further electrical parameters are compared such as V_{ov} = 0.665 V and I_{sc} = 5.75 A. The voltage and current at open circuit of Model E are 0.677 V and 5.65 A respectively whereas that of Model F are 0.665 V and 5.75 A. The Model F exhibits an accurate behavior as compared to Model D and F. Hence the Model F exhibits accurate characteristics in the model-based implementation of PV in Simscape.

From the study it is clear that the Simulink, Simscape implementation of PV cell "By Equivalent circuit, 8 parameters two diode model" i.e Models "C" & "F" produces accurate results as compared other model implementation.

It is observed that the diode based model of PV cell by "Equivalent circuit, 8 parameters two diode" implemented by a solar cell from Simscape, Simelectronics library and equation based implementation i.e. Models "C" & "F" produces the output characteristics similar to that of the data sheet. Thereby these models are used as an accurate PV model for developing PV based generation in the hybrid power system.

3.4   Implementation of PV based generation for DC load:

The block diagram of PV based generation is shown in Figure 3.28.
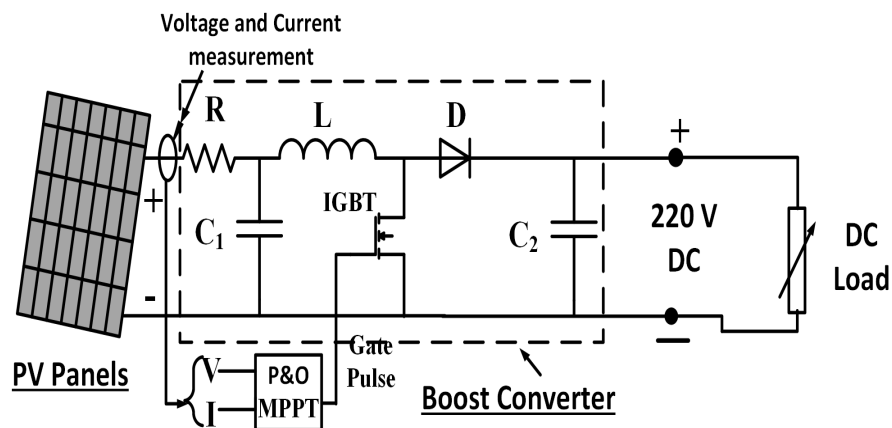

FIGURE 3.28: Block diagram of PV based generation

The basic building blocks of PV based generation are

1. PV Panels,

2. Boost Converter,

3. Maximum Power Point Tracker (MPPT), and

 4. DC Load.

The mathematical model of PV cell selected from the comparative analysis are utilized to implement

PV Panels. The PV cell is connected in series to form PV panel and such PV panels are connected in

series to form a string. The series and the parallel combination of PV panel are known as Array. Such

combinations of PV panels are utilized to generate the required amount of power. The output power of a

PV module is related to ambient temperature and solar irradiation, which are the major components of the

mathematical model of PV cell that affect the accuracy of the simulation. The mathematical model of PV

cell is essential in order to produce accurate Current-Voltage (I-V), Power-Voltage (P-V) characteristics

similar to the manufacturer PV panel. Among the various mathematical models of PV cell studied, a

single diode model of PV cell consisting of short circuit current (I_{sc}), open circuit voltage (V_{oc}) and the

diode ideality factor (N) is a simple model to implement. However, from the study carried out in the

previous sections a two-diode model of PV cell shown to be more accurate and further considered.

The electrical equivalent circuit of a two-diode model of PV cell is shown in Figure 3.15. This electrical

equivalent circuit of PV cell is known to comprise improved accuracy at low irradiation levels which

helps us for more accurate prediction of PV system performance under different environmental conditions

as compared to manufacturer data-sheet [147, 148]. The behavior of the PV cell is investigated under

different solar insolation levels, by calculating the values of Series resistance (R_s), Shunt resistance (R_p)

by iteration method to study the performance of the PV cell.

The equation based implementation of a two-diode model C of PV cell and model-based design of

a two-diode model F of PV cell in Simscape, Simelectronics library in MATLAB are considered for

investigation. The two PV cell models considered are utilized to form PV panel and by selecting optimum

values from manufacturer data-sheet, an accurate output similar to the industrial data-sheet is simulated

and compared. These PV panels are utilized to build PV based generation and simulated for both the

configurations of PV model C and model F. The detailed mathematical modeling of two diode model is

discussed below.

The output current can be obtained by applying Kirchhoff's current law (KCL) to the equivalent circuit shown in Figure 3.15 and governed by (3.21)- (3.24).

$$I = I_{PH} - I_{D1} - I_{D2} - I_{SH} \tag{3.21}$$

$$I_{D1} = I_{s1}\left[exp\left(\frac{q \times V}{N_1 \times k \times T}\right) - 1\right] \tag{3.22}$$

$$I_{D2} = I_{s2}\left[exp\left(\frac{q \times V}{N_2 \times k \times T}\right) - 1\right] \tag{3.23}$$

$$I_{SH} = \frac{V + R_s \times I}{R_p} \tag{3.24}$$

where, I_{s1}, I_{s2} are the reverse saturation currents of the diodes D_1, D_2. The reverse saturation current can be calculated by (3.25)

$$I_s = \frac{\left(I_{sc} - \frac{V_{occ}}{R_p}\right)}{\left(e^{\left[\frac{V_{occ}}{V_t}\right]} - 1\right)} \tag{3.25}$$

Substituting (3.22)-(3.24) in (3.21) we get

$$I_{pv} = I_{PH} - I_{s1}\left[exp\left(\frac{q \times V}{N_1 \times k \times T} - 1\right)\right] - I_{s2}\left[exp\left(\frac{q \times V}{N_2 \times k \times T}\right) - 1\right] - \frac{V + R_s \times I_{pv}}{R_p} \tag{3.26}$$

The (3.26) is the elementary current equation PV cell which represents an ideal source. Practical PV module comprises of different elements that need to be added into the elementary current equation (3.26) such as R_s, R_p. By Re-writing (3.22), (3.23) we have

$$I_{D1} = I_{s1}\left[e\left(\frac{V + R_s \times I}{N_1 \times V_t}\right) - 1\right] \tag{3.27}$$

$$I_{D2} = I_{s2}\left[e\left(\frac{V + R_s \times I}{N_2 \times V_t}\right) - 1\right] \tag{3.28}$$

where, V_t is the thermal voltage of the module and is given by (3.20) and substituting (3.27),(3.28) in (3.26) would derive the final output current of two-diode model of PV cell (3.19) to simulate the

characteristics similar to practical data-sheet. The values of R_s, R_p will vary for different PV panels these

values are computed using iteration method and will be discussed in detail further.

3.4.1 Estimating the Values of R_p and R_s:

The values of R_s and R_p are calculated by iteration. The values of R_p are computed using (3.29) - (3.35).

The computed values of R_s and R_p are used to make the maximum point of the P-V curve simulated to

coincide with the maximum point of the practical P-V curve of the PV module taken from data-sheet.

This can be achieved by iteratively increasing the values of R_s and simultaneously calculating the value of

R_p. Calculation of the values will be stopped when the calculated $P_{max,C}$ equals the $P_{max,D}$ taken from the

data-sheet. Flow chart illustration of the iterative method is shown in Figure 3.29.
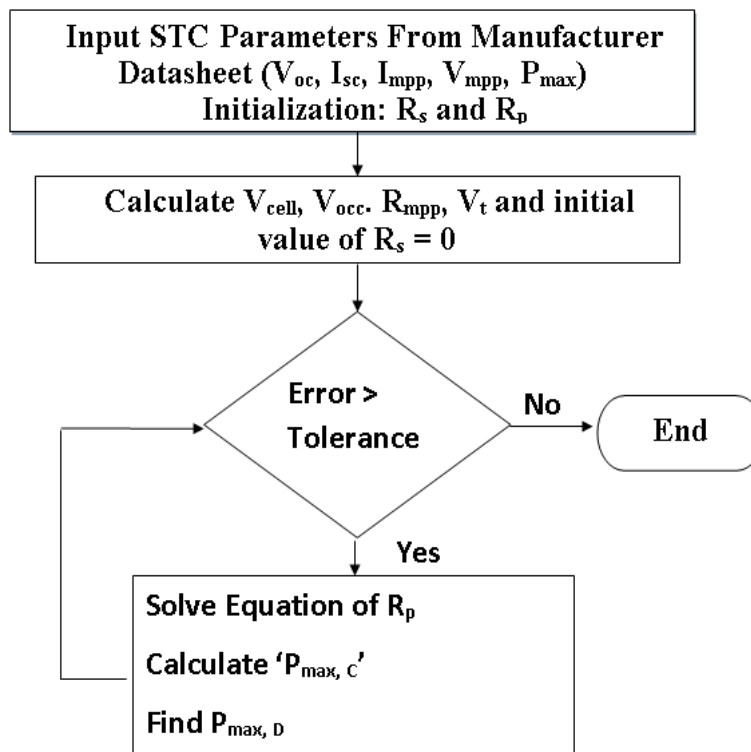

FIGURE 3.29: Flow chart for the iterative Algorithm to calculate Rs and Rp

$$R_s = 0, R_p = \frac{V_{occ}}{I_{sc}} \times 100 \tag{3.29}$$

$$V_{occ} = \frac{V_{oc}}{N_s} \tag{3.30}$$

Voltage across the diode is (3.31)

$$V_d = V_{occc} \tag{3.31}$$

PV cell voltage at P_{max}

$$V_{mc} = \frac{V_{mpp}}{N_s} \tag{3.32}$$

The values of R_s and R_p are computed by (3.33)(3.34)

$$R_s = \frac{V_d - V_{mc}}{I_{mpp}} \tag{3.33}$$

$$R_p = \frac{V_d}{(I_{sc} - I_{mpp} - I_D)} \tag{3.34}$$

$$P_{max,c} = V_{mpp} \times I_{pv} \tag{3.35}$$

The electrical parameters for the simulation of PV panel are extracted from the manufacture data sheet. The electrical parameters and the characteristics of Manufacture data sheet are represented in the following section.

3.4.2 MANUFACTURER DATA SHEET OF PV PANEL:

Sharp NU-E245 (J5) solar panel having P-V & I-V characteristics is shown in Figure 3.30. The model consists of 50 cells of Silicon nitride multi-crystalline silicon cells to generate open circuit voltage of 37.5 V and Short circuit Current of 8.73 A with a power output of 245 W under 1000 W / m^2 solar irradiation and at 25^0 operating temperature. The electrical parameters of the SX 3200 are shown in Table. 3.4. Figure 3.30 shows the I-V and P-V characteristics taken from the data sheet [149]. The following section discusses about PV based generation implementation using two PV cell models selected

TABLE 3.4: ELECTRICAL PARAMETERS OF SHARP NU-E245 (J5) FROM DATA SHEET

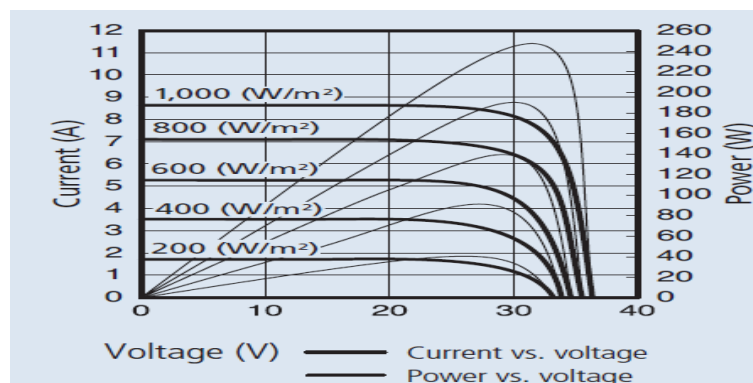| Parameter	Notation	Value
Maximum Power	P_{max}	245 W
Open-Circuit Voltage	V_{oc}	37.5 V
Short-Circuit Current	I_{sc}	8.73 A
Voltage at Maximum Power Point	V_{mpp}	30.5 V
Current at Maximum Power Point	I_{mpp}	8.04 A
efficiency	η_m	14.9
NOCT		47.5
Temp. Co-efficient voltage	αV_{oc}	-130
Temp. Co-efficient Current	αI_{sc}	+0.053
Temp. Co-efficient Power	αP_{max}	-0.485

FIGURE 3.30: characteristics of Sharp NU-E245 (J5) from data sheet

from the comparative study of PV cells. The electrical parameters for simulation are extracted from the manufacturer data sheet as shown in Table 3.4.

3.4.3 Simulation of PV panel in PV based generation:

Figure 3.31 and Figure 3.32 shows the equation based and model based implementation of the Two-diode model PV panel in Simulink and Simscape respectively. The I-V and P-V characteristics under different solar irradiation levels obtained are shown in Figure 3.33 and Figure 3.34. The equivalent circuit parameters of the model are extracted from the manufacturer data sheet as shown in Table 3.4. Comparisons of the electrical parameters obtained at STC from simulation with the electrical parameters
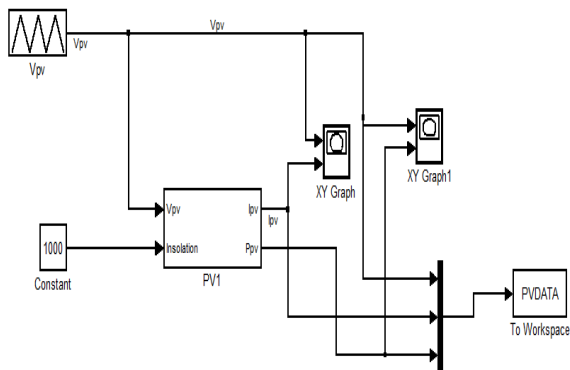
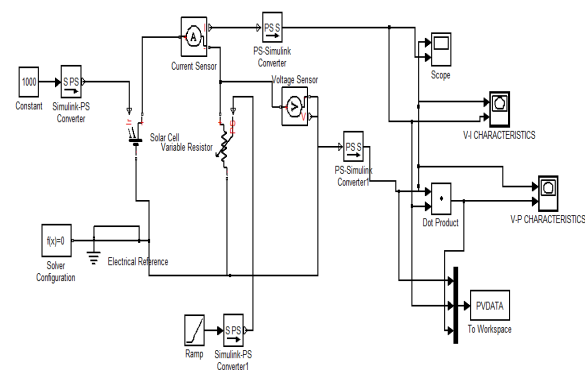FIGURE 3.31: Simulink implementation of Two-diode model of PV panel.

FIGURE 3.32: Simscape implementation of Two-diode model of PV panel.
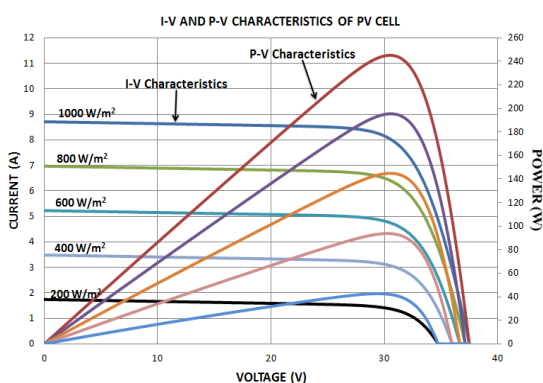

FIGURE 3.33: Characteristics of Two-diode model of PV panel implemented in simulink.
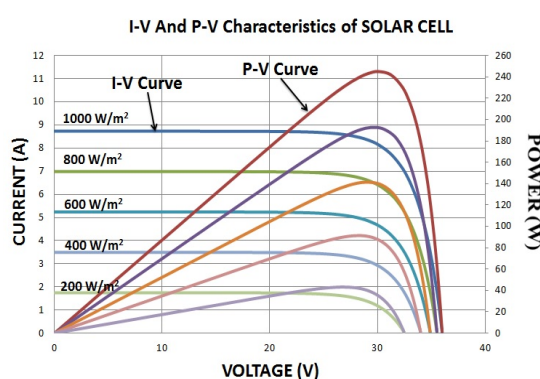

FIGURE 3.34: Characteristics of Two-diode model of PV panel implemented in simscape.

of the manufacturer data-sheet are tabulated in Table 3.5. It can be observed that both the simulated electrical parameters of the PV panel coincide with the manufacturer data-sheet parameters.

TABLE 3.5: Comparing Electrical Parameters of Two PV Panel Models at STC With Manufacturer Data-Sheet

Electrical Parameters	Manufacturer Data-Sheet	Two-diode model of PV cell in Simulink	Two-diode model of PV cell in Simscape
V_{oc}	37.5 V	37.5 V	36.0 V
I_{sc}	8.73 A	8.729 A	8.73 A
P_{max}	245 W	245.06 W	245.09 W
V_{mpp}	30.5 V	30.75 V	30.07 V
I_{mpp}	8.04 A	7.97 A	8.15 A

The output voltage of PV panel is stepped up to the desired level using a boost converter. Modeling of boost converter will be discussed in following section.

3.4.4 DC / DC Boost Converter:

A boost converter is a power electronic device whose output voltage is greater than input DC voltage.

The schematic diagram of the boost converter is shown in Figure 3.35. The boost converter consists of
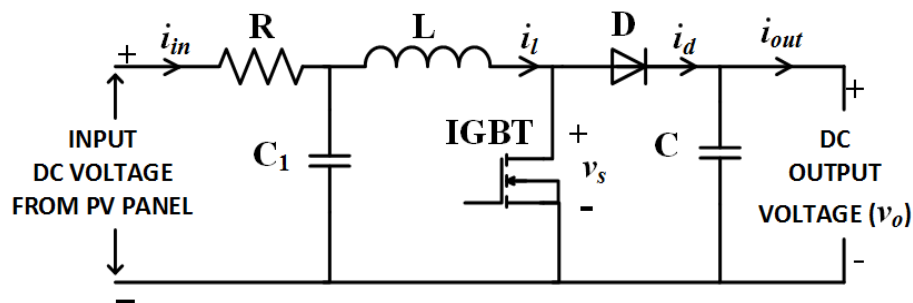

FIGURE 3.35: Schematic of boost converter

power electronic switch (IGBT), a diode D, DC inductor L, filter capacitor C and input capacitance C_1.

When the power electronic switch is triggered, diode D is reverse biased, and the output circuit has

isolated the input. The input DC voltage supplies energy to the inductor L. When the power electronic

switch is turned off, diode D is forward biased, and the energy stored in the L is delivered to the load or

output circuit through the diode. The "output voltage V_o" is the sum of "input voltage V_i" and "inductor

voltage V_L", making the converter output voltage V_o higher than input voltage V_i [150–153],

Operation of boost converter is based on the continuity of the DC current through the inductor i_l and the

operation is divided into two modes

- continuous-current mode (CCM)

- discontinuous-current mode (DCM)

The Figure 3.36 shows the voltage and current waveforms of boost converter operating in CCM. In

steady-state operation of the converter, integral of V_L over T_s essential be zero. This implies that the

average voltage across the inductor L over T_s is zero. Its graphical representation is that the area A_1 in
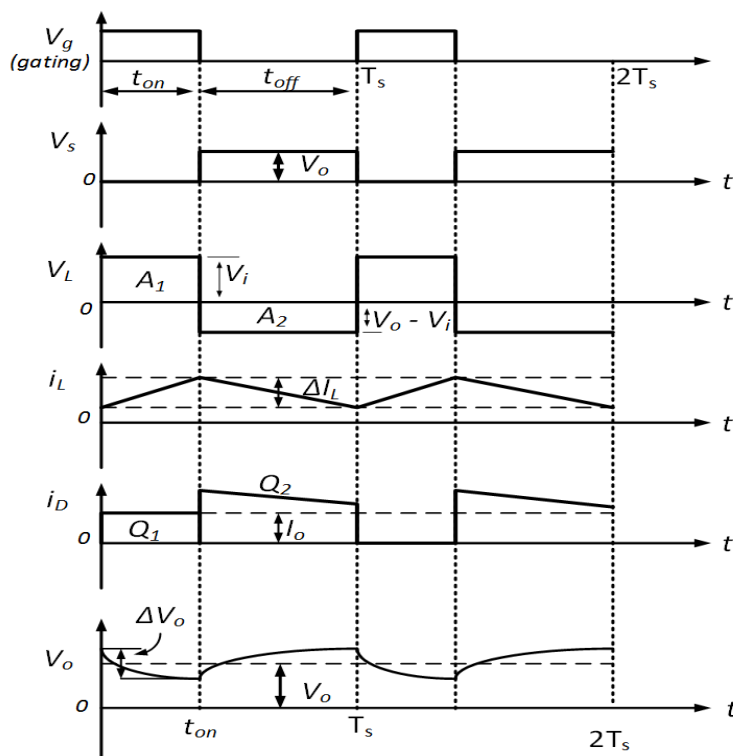
FIGURE 3.36: Waveform of the boost converter operating in CCM.

Figure 3.36 must be of equal area A_2, (3.36)

$$V_i t_{on} = (V_o - V_i) t_{off} \tag{3.36}$$

from which

$$\frac{V_o}{V_i} = \frac{1}{1-D} \qquad for \qquad 0 \leq D \leq 1 \tag{3.37}$$

where D is the duty cycle of the converter, defined by $D = t_{on}/T_s$, T_s is the total switching period, t_{on} and t_{off} are the turn-on and turn-off times of the power electronics switch. The output voltage of the converter is always higher than its input voltage as indicated in (3.37). The relationship between the converter input current I_i and the output current I_o is derived from $V_i I_i = V_o I_o$ from which

$$\frac{I_o}{I_i} = 1 - D \qquad for \qquad 0 \leq D \leq 1 \tag{3.38}$$

To calculate the ripple current in the inductor, $v_L = L\left(\frac{di_L}{dt}\right)$ can be replaced by $\Delta v_L = L\left(\frac{\Delta i_L}{\Delta t}\right)$. The inductor current changes linearly with time. For the t_{off} period in Figure 3.36, the inductor ripple current can be expresses by (3.39)

$$\Delta i_L = \frac{\Delta v_L}{L}\Delta t = \frac{(V_o - V_i)}{L}t_{off} = D(1-D)\frac{V_o T_s}{L} \tag{3.39}$$

The maximum current ripple $\Delta I_{L,max}$ for the boost converter occurs when the duty cycle D is 0.5, at which

$$\Delta I_{L,max} = \frac{V_o T_s}{4L} \tag{3.40}$$

Under light load conditions, the current through the inductor is low, and so the energy stored in the inductor is low during t_{on} and may not be sufficient to maintain current during the t_{ohh} period. Consequently, the inductor current becomes zero before the end of t_{off} period and therefore, becomes discontinuous. The converter thus operates in discontinuous mode. The inductor current at the boundary between the CCM and DCM is given by [154–157](3.41)

$$I_{LB} = D(1-D)\frac{V_o T_s}{2L} = \frac{\Delta i_L}{2} \tag{3.41}$$

The maximum inductor boundary current occurs at D=0.5, which is expressed as

$$I_{LB,max} = \frac{V_o T_s}{8L} \tag{3.42}$$

The boundary output current is :

$$I_{oB} = D(1-D)^2\frac{V_o T_s}{2L} = (1-D)\frac{\Delta i_L}{2} \tag{3.43}$$

and its maximum value occurs at D=1/3, and is evaluated as :

$$I_{oB,max} = \frac{2}{27} \frac{V_o T_s}{L} \tag{3.44}$$

The value of the boost Inductor (L) can be computed as :

$$L = \frac{V_i \times (V_o - V_i)}{\Delta I_L \times f \times V_o} \tag{3.45}$$

where f = switching frequency, ΔI_L = Inductor ripple current and is expressed as

$$\Delta I_L = 0.2 \times i_{out(max)} \times \frac{V_o}{V_i} \tag{3.46}$$

The value of the output capacitance (C) is computed by;

$$C = \frac{I_{o(max) \times D}}{f \times \Delta V_o} \tag{3.47}$$

where $I_{o(max)}$ = maximum output current, D = Duty cycle, f = switching frequency and ΔV_o = desired

output voltage ripple. The peak to peak ripple of output voltage can be calculated by

$$\Delta V_o = \frac{Q_{on}}{c} = \frac{I_o t_{on}}{C} = \frac{V_o D T_s}{RC} \tag{3.48}$$

from which

$$\frac{\Delta V_o}{V_o} = \frac{D T_s}{RC} \tag{3.49}$$

For a given load resistance R and filter capacitor C, the ripple voltage ΔV_o increases with the duty cycle D.

The output voltage transfer function is given by (3.50)

$$\frac{V_o}{V_i} = \frac{1}{1-D} \tag{3.50}$$

The following section will discuss MPPT algorithm for PV based generation.

3.4.5 Maximum Power Point Tracking Algorithm:

The equation and model based implementation of PV panel exhibits non-linear P-V and I-V characteristics under different solar irradiation levels as shown in Figure 3.33, Figure 3.34. To extract maximum power out from the PV generation, it has to be operated at knee of the P-V curve marked as Maximum Power Point (MPP) as represented in Figure 3.37.

1. Off-line Method: The maximum power point is computed based on the various parameters such
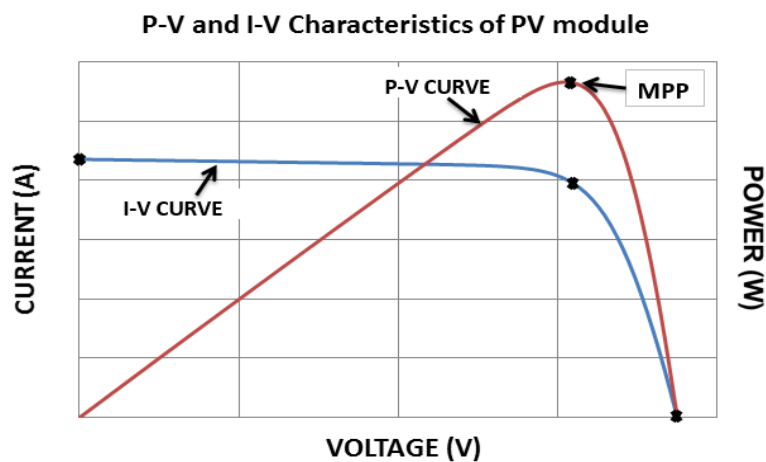

FIGURE 3.37: P-V & I-V characteristics of PV panel

as open circuit voltage, short circuit current, irradiance, current at MPP and voltage at MPP using mathematical modeling. The parameters for MPP tracking are predetermined and tacking algorithm will be designed for that particular PV system based on the predetermination which cannot be applied to other PV system. The computation of MPP is done for specific PV system is the main drawback of the method and few techniques are [158–162]:

- Lookup table method,

- Curve fitting method,

- Fractional OC method,

• Fractional SC method.

From the literature different MPPT techniques with the methodology are tabulated in Table 3.6 [163–178].

TABLE 3.6: Maximum Power Point Tracking Techniques

S NO.	Name Of Technique	Methodology
1	"Curve Fitting Technique"	MPP is the knee point in characteristic of a PV Panel, hence the characteristics are predicte initially in this technique. To predict, is done by off-line computational program. [163].
2	"Fractional Short circuit" "current (FSCI)Technique"	There exits a single operating point (V_{mpp}, I_{mpp}) called MPP at which the power of the panel is maximum at a given environmental conditions. Based on the characteristics, a mathematical relation between I_{mpp} and I_{sc} constructed as I_{mpp} is linearly dependent on I_{sc} by : $I_{mpp} = K_{sc} I_{sc}$ [164].
3	"Fractional Open circuit voltage" "(FOCV) Technique"	In this method, the V_{mpp} can be calculated from the empirical relationship: $V_{mpp} = K_{oc} V_{oc}$. It is observed that the K_{oc} variation is from 0.78 to 0.92 and can be analyzed from different solar illumination and temp. [165].
4	"Look-up Table Technique"	In this method, A table is used to track MPP. The MPP is computed and represented in a tabular form ahead of implementation. [166].
5	Feedback voltage or current Technique	A Current or voltage feedback is utilized to control the output voltage. This method is used in system without battery. [167].
6	"Incremental conductance" "Technique"	The method operates on verifying the change in conductance. [168].
7	"Forced Oscillation Technique"	This method operated by injecting a small-signal sinusoidal perturbation into the switching frequency and comparing the average value. [169].
8	"Ripple Correlation Control" "(RCC) Technique"	The voltage and current ripple produced by the converter are used // to track MPP in this method. [170].
9	"Current Sweep Technique"	In this method a sweep waveform and constant time interval are used tp track MPP. [171].
10	"Estimated Perturb Perturb" "(EPP) Technique"	This method is an outstretch of P and O algorithm.This method has an estimation state between two "Perturbs". [172].
11	"Parasitic Capacitor Technique"	This method is similar to Incremental conductance. The fundamental difference is parasitic junction capacitance is considered. [173].
12	"Load Current / Load Voltage" "Maximization Technique"	If directly connected to the load, operation of the PV array at the MPP cannot be ensured even for a constant load. The main components of the MPPT circuit are its power stage and the controller. As the power stage is realized by means of a switched mode power converter, the control input is the duty cycle [174].
13	"Intelligent MPPT Techniques"	1) Fuzzy logic (FL) based MPPT, 2) Artificial Neural Network (ANN), 3) Particle Swarm Optimization (PSO) etc [175].
14	"Sliding Mode based MPPT" "Technique"	In Inc-Cond technique, ratio of array current and voltage (I/V) term is compared with change in ratio of current and voltage. In this technique the comparison is equated to zero to track MPP [176].
15	"Analytic Based MPPT" "Technique"	This technique is based on observations and experimental results. The open circuit voltage and short circuit current are observed experimentally. Based on the observation values, a ball of small radius is selected for each panel such that MPP is inside the ball. The analytic based MPPT technique is based on the mean value theorem, where, MPP is obtained from the ball using mean value theorem [177].
16	"Hybrid MPPT (HMPPT)" "Technique"	It is found that the P and O technique is the most extensively used in commercial MPPT systems because it is straight forward, accurate, and easy to implement. Its accuracy and tracking time depends on perturbation size. Hence, hybrid control techniques are essential. In a recent proposed hybrid MPPT technique with both P& O and ANN, the perturbation step is continuously approximated by using ANN. Using this technique, on-line MPP tracking is possible [178].

The MPPT techniques are broadly classified into two categories based on the computational techniques utilized to implement the algorithm.

1. Off-line Method

2. On-line Method

2. On-line Method: The Maximum power point is computed without any prior knowledge of the open circuit voltage, short circuit current, irradiance, current at MPP and voltage at MPP. The MPP is tracked

by the algorithm by utilizing the voltage and current samples measured at the output of the PV panel. It overcomes the disadvantage of the off-line method and can be applied to any rating of PV system. The MPP is not predetermined it is computed based on the measured samples at regular intervals. A few techniques involved in MPP tracking are listed below

∗ Perturb & Observe (P & O),

∗ Incremental Conductance,

∗ Current Sweep,

∗ Constant voltage,

∗ Sliding mode based technique.

A Perturb & Observe (P & O) algorithm is selected for MPP tracking. The P & O algorithm is selected on the basis of ease of implementation, robustness, accurate, reliable and efficient way of tracking MPP. Further the implementation of P & O algorithm in MATLAB, Simulink will be studied in detail.

3.4.5.1 Perturb and Observe (P & O) algorithm implementation:

The Perturb and Observe algorithm is widely used MPP tracking algorithm. From the P-V characteristics of the Solar PV panel shown in Figure 3.37 it can be comprehended that power of PV panel increases gradually with the output voltage of PV till it reaches MPP then after the power decreases with the increase in voltage. Hence, exhibiting non-linear characteristics. The controller has to keep the track of MPP by adjusting the output voltage of the PV panel. The flow chart of the P & O algorithm is shown in Figure 3.38 [179–183].

MPP tracking technique: The P & O algorithm initially senses voltage (V_i), Current (I_i) from the PV panel and introduce a perturbation by changing the duty cycle of the boost converter and observes the
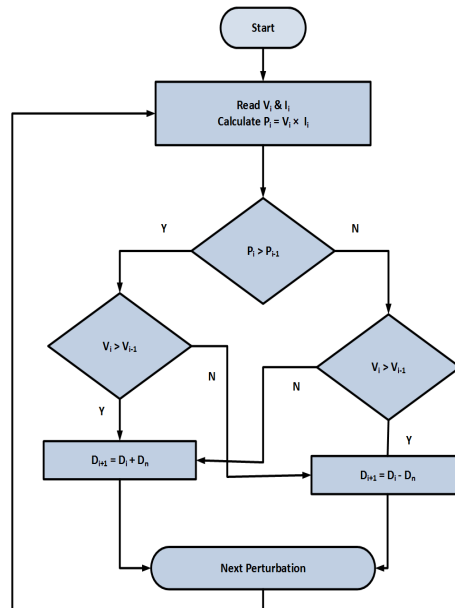
FIGURE 3.38: Flow-chart of P & O algorithm

parameters with the sensing equipment. The power (P_i) is computed for the initial measured (V_i) and

(I_i) and is compared with the power computed after perturbation (P_{i-1}). Depending on the observation

the signal to the boost converter is sent to increment or decrement the duty cycle. The increment and

decrement of duty cycle is based on MPP position and the conditions are tabulated in Table. 3.7.

TABLE 3.7: P & O algorithm MPP tracking technique

Perturbation	Power change	Next Perturbation
"Positive"	"Positive"	"Positive"
"Positive"	"Negative"	"Negative"
"Negative"	"Positive"	"Negative"
"Negative"	"Negative"	"Positive"

The graphical representation of MPP tracking is shown in Figure 3.39

The Simulink implementation of P & O algorithm is shown in Figure 3.40. The Simulink implementation

of PV based generation system incorporating PV Panels, Boost Converter, MPPT algorithm and DC load
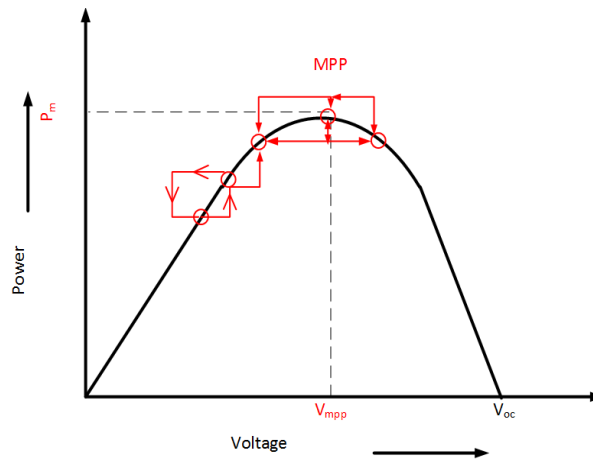
will be analyzed in the following section.

FIGURE 3.39: Graphical representation of MPP tracking of P & O algorithm
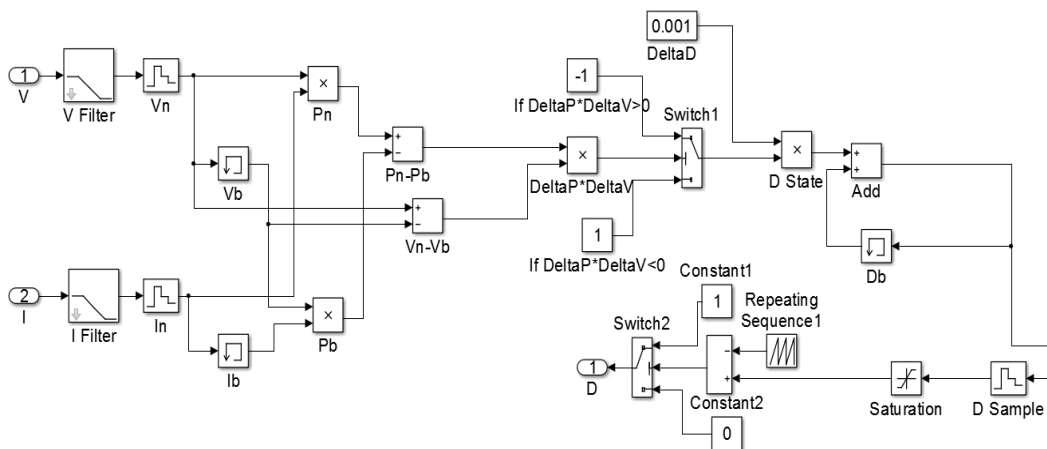

FIGURE 3.40: Simulink implementation of P & O MPP tracking algorithm

3.5   Simulation of PV based Generation:

The two-diode model of PV panel simulated in sub-section 3.4.3 are utilized for implementation of PV based generation. A 220 V, 400 W load is connected to the PV based generation and the performance of the MPPT algorithm are investigated. The Simulink implementation of model based design and equation based design of PV based generation are shown in Figure 3.41, Figure 3.42 respectively. The electrical parameters of the PV panel are extracted from the manufacturer data sheet as shown in Table. 3.5. In-order to drive a load of 400 W two PV panels are connected in series the electrical parameters of PV based generation are tabulated in Table. 3.8.
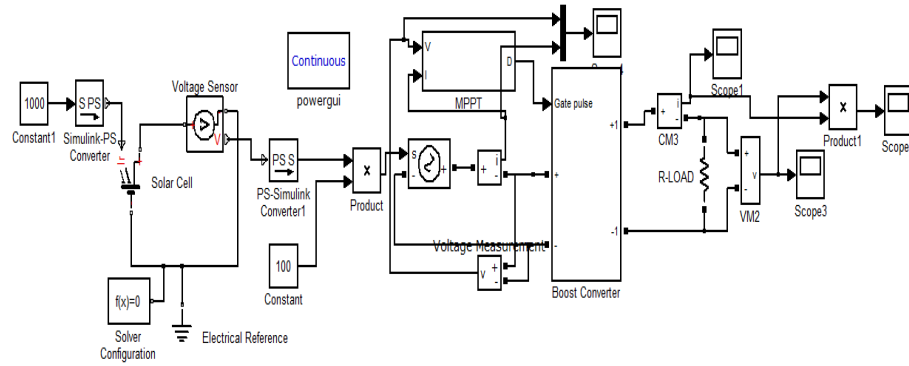
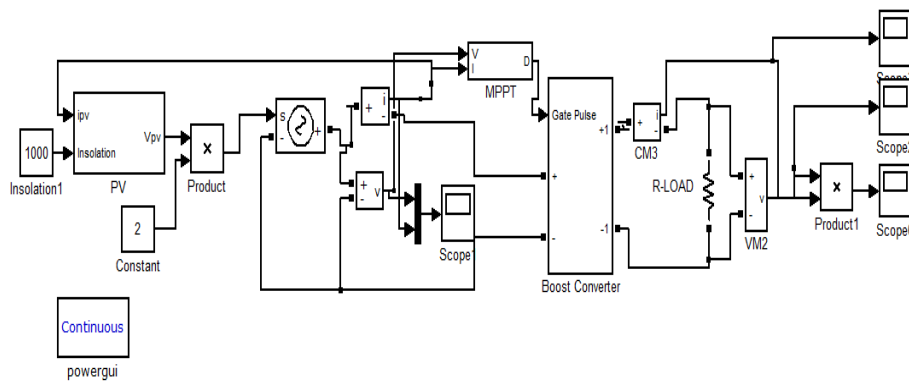FIGURE 3.41: Model based modeling of PV based generation

FIGURE 3.42: Equation based modeling of PV based generation

TABLE 3.8: Electrical Parameters of PV based generation

V_{oc}	65 V
I_{sc}	17. 46 A
V_{mpp}	61 V
I_{mpp}	16.04 A
P_{max}	450 W

The inductor (L) and output capacitor (C) values of DC-DC boost converter computed are 5 mH and 50 μF for V_i = 65 V, V_o = 220 V, ΔI_L = 1 A, ΔV_o = 2 V, $I_{o(max)}$ = 2 A, D = 50% and switching frequency f_s= 10 kHz. The value of input capacitor C_1 = 5000 μF.

A PV based generation represented in Figure 3.28 is built in MATLAB, Simulink as shown in Figure 3.41 using model-based implementation of PV cell utilizing Solar cell block from Simscape. The output from PV panels is interfaced with the boost converter to step up the output voltage of PV panels to desired load voltage. In order to achieve the task P & O algorithm is utilized and Simulink implementation of the same is shown in Figure 3.40.

(A) Simulated Load Voltage

(B) Simulated Load Current

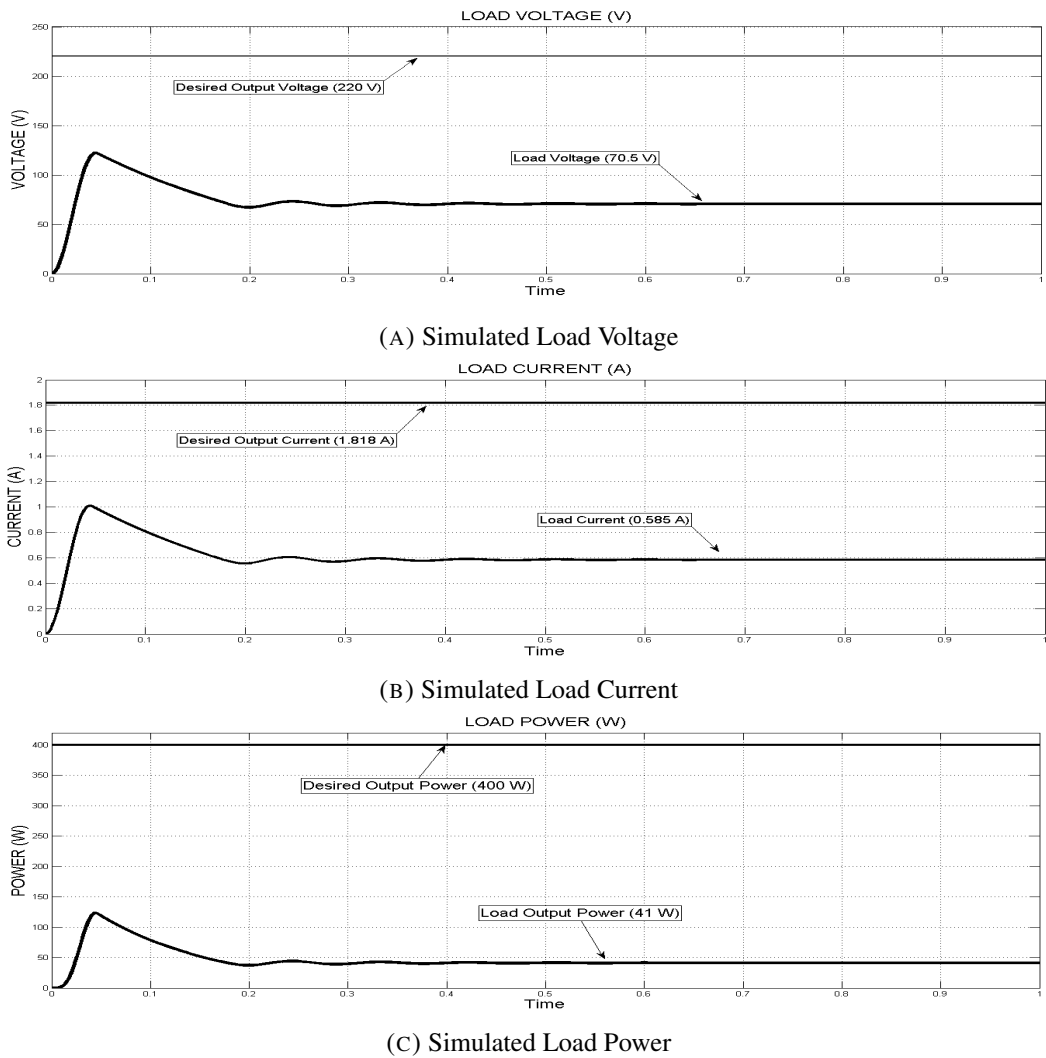

(C) Simulated Load Power

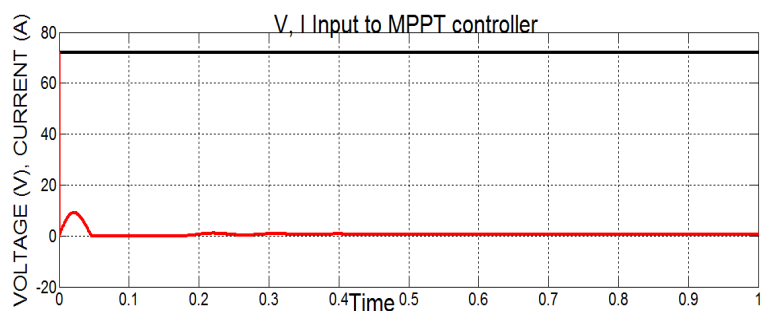FIGURE 3.43: Simulated results of model based model of PV based generation

FIGURE 3.44: Voltage and current samples for MPPT algorithm of Model-based design of PV panel

The inputs to MPPT controller are the voltage and current output of the PV panels which are further utilized to track MPP by controlling the duty cycle of the Boost converter.

The simulation results are shown in Figure 3.43 which gives the voltage across the load, the load current, and power absorbed by the load. voltage-current samples of MPPT are graphically shown in Figure 3.44

respectively.

It is observed from Figure 3.43a that the load voltage settles at 72.05V instead of stepping up to 220V due to which the output current and power for the l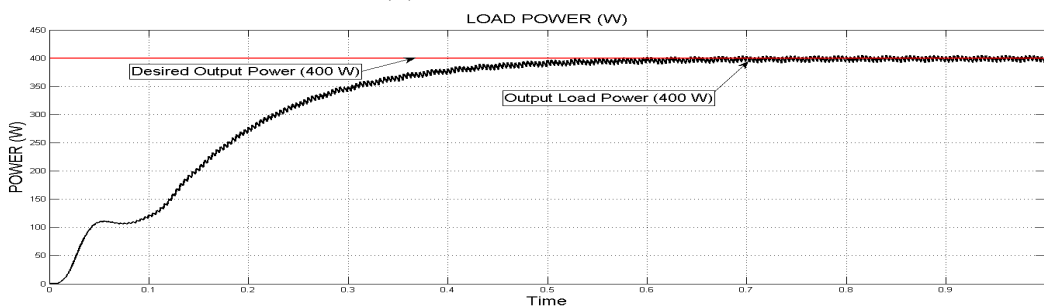oad settles at 0.6A, 40W as seen in Figure 3.43b and 3.43c. Figure 3.44 is the voltage, current sample input to the MPPT controller, which is the output voltage and current of the PV panel. It is observed that the output voltage of PV cell remains constant at 72.05V.
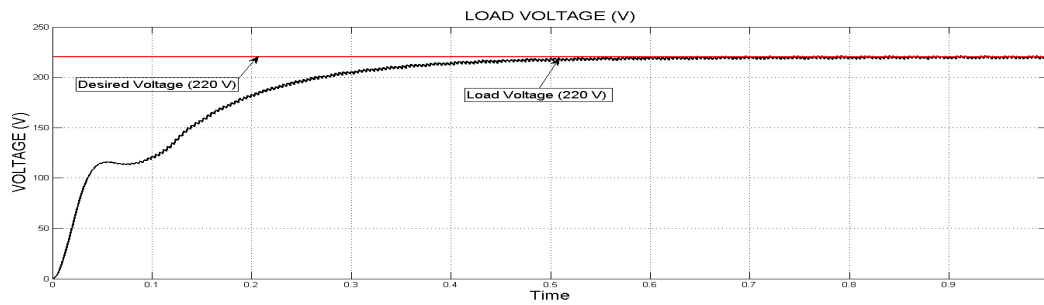
(A) Simulated Load Voltage
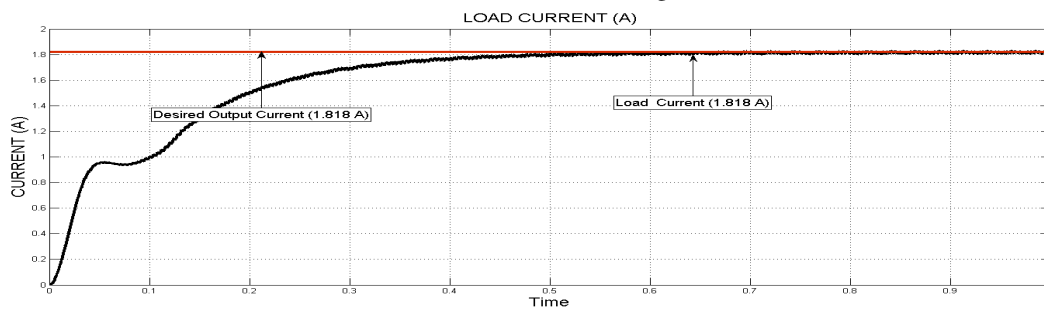
(B) Simulated Load Current

(C) Simulated Load Power

FIGURE 3.45: Simulated results of equation based model of PV based generation

A PV based generation similar to the block diagram as shown in Figure 3.28 is built in MATLAB, Simulink as shown in Figure 3.42 using equation-based implementation of PV cell. The simulation load voltage, current and power of this model are graphically represented in Figure 3.45a, Figure 3.45a and Figure 3.45c. It is observed that the output voltage of the PV system is boosted up to 220V as shown
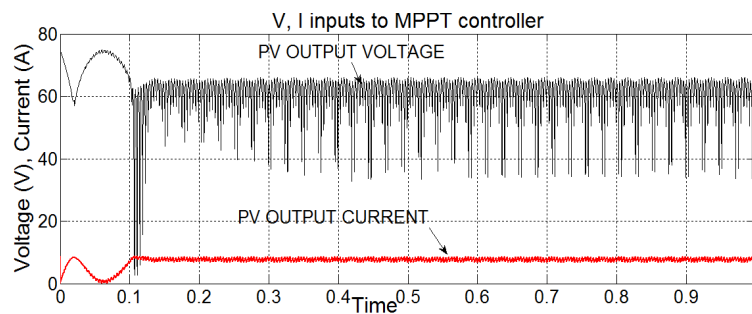
FIGURE 3.46: Voltage and current samples for MPPT algorithm of equation based implementation of PV panel

in Figure 3.45a. The load current of 1.818A is plotted in the Figure 3.45b. The power fed to the load gradually reaches the desired value i.e. 400 W as shown in Figure 3.45c. The load voltage, Current, and power attains steady state value at 0.6 s and maintains the steady state value.

The voltage and current samples inputted to MPPT controller are plotted in Figure 3.46.

The MPPT controller keep track of the V_{mpp}, I_{mpp} such that PV system operates at its maximum power point. This can be clearly observed in Figure 3.46 the operating points are at MPP (61V, 16A) as seen from the electrical parameters of PV generation tabulated in Table. 3.8. The PV based generation system implemented using the equation-based model of the Two-diode model of PV panel built up in Simulink produces the desired operation as compared to the model-based implementation of PV based generation using solar cell block from Simscape, Simelectronics Library in MATLAB.

3.6 Summary:

The main objective of this chapter is to study and investigate PV based generation in the hybrid power system. This chapter summarizes the importance of hybrid power system and installation of the hybrid power system in different parts of the world. Different combinations of RES generation are utilized to form a hybrid power system, such as PV-Wind-battery, wind-diesel generator, PV-Battery-Diesel hybrid installation etc. Further focusing on hybrid installation in India, PV and Wind hybrid power system are selected for the study. This chapter focuses on modeling and simulation of PV based generation.

Investigation of three different models of diode based PV cell model implemented in Simulink and Simscape. A comparative analysis of the characteristic of the models with the manufacturer data sheet characteristics was conducted. Model precision depends on the parameters calculation from the manufacturer data sheet and also by considering the effect of a change in solar irradiation levels and cell operating temperature. The solar cell models considered are a diode based model of PV cell modeled by O/C Voltage & S/C current, 5 parameters single diode model, Equivalent circuit, 5 & 8 parameters single & two diode model.

It is observed that the diode based PV cell model "Equivalent circuit, 8 parameters two diode" implemented by a solar cell from Simscape, Simelectronics library produced the output characteristics similar to that of the data sheet. Thereby this model is used as an accurate PV model for further study.

Performance analysis of a two-diode model of PV cell implemented in MATLAB, Simulink, and Simscape under different irradiance was performed. The simulated I-V and P-V characteristics of both models duplicate the characteristics of the practical PV cell whose values are obtained from the manufacturer data sheet. The Simscape implementation of the Solar cell is available as a source in Simscape, Simelectronics library.

A PV based generation system was implemented in the Simulink using this source block. However, this solar cell block of Simulink, Simscape acts as a constant source instead of displaying the non-linear behavior of the diode based implementation of PV cell. Due to which the input voltage to MPPT controller remains constant. So, the MPPT controller tracks the power with respect to that voltage on the P-V characteristic which is not the desired output. Henceforth the PV based generation implemented using the equation-based design of two-diode PV cell in Simulink has produced desired simulated results. The inputs to the MPPT controller are varying according to the controller action due to which the MPP is being tracked by the MPPT controller to achieve the desired output. It is able to supply the required power to the load at rated voltage. The PV based generation using two-diode model implemented in Simulink can be used for further applications. The other important aspect of the Hybrid power system

is a wind-based generation. The next chapter will discuss the equation based modeling of wind power generation in the Hybrid power system.