IPEC Journal of Science & Technology Vol. 01 (02), Oct. 2022

ISSN: 2583-3286(Online)

Analysis of Photovoltaic Generator Using MATLAB-Simulink

Shilpa Gupta, Sadaf Naqvi

Department of Electrical and Electronics Engineering, Inderprastha Engineering College, Ghaziabad, India

Abstract: **A nonlinear controller-based MPPT scheme is proposed here to minimize the error amongst the intended array voltage under changing temperature and radiation by changeable duty cycle of the switching converter. The dynamic behaviour of the test scheme is evaluated using the describing function method, which linearizes a nonlinear element using harmonic approximation. In the MATLAB-Simulink environment, a generic model of photovoltaic array is designed according to empirical equation of the photovoltaic (PV) cell taking solar insolation and cell temperature into account. PV systems have non-linear output response. The suggested model helps developers achieve accuracy and speed in PV system simulation.**

Keywords **— Describing function, Generalized model, MATLAB- Simulink, Photovoltaic array, Robust control, Renewable energy.**

I. INTRODUCTION

In current times, the average rate of world primary power utilization has augmented to about 78.47 Btu (AEO 2012). Additionally, the ecological effects on usage of the conventional sources have been disintegrative with the environmental concerns like pollution, global warming, excessive greenhouse effect etc. Because of these problems and our declining supply of petroleum, finding sustainable alternatives is becoming foremost urgent. Perhaps, the greatest challenge is in devising a sustainable future, which relies on convergence and regulation of sources of renewable power in grid distributed generation. Generation of power regionally at distribution voltage level by using non-conventional energy sources like, solar photo-voltaic cells, wind power, biogas, and fuel cell is known as distributed generation (DG).

Among renewable energy solar power is a vast and ultimate source of energy. If used in appropriate way, it has a capacity to achieve numerous energies demand of the world. The power from the sun captured by earth is approximately 3,850,000 exajoules (EJ)[1]. This data, which is thousands of times greater than the current usage, enables ever more studies in the areas of solar energy allowing the world's current and future electricity requirements to be met. As a result, despite the greater investment fabrication price and reduced transfer effectiveness of the PV system, the rapidly higher oil prices make solar energy an inevitably sustainable power supply with possibly long benefits.

A photovoltaic module is the basic energy transformation component of a PV generating system. The main variables upon which performance characteristics of a PV module depend are solar irradiance, heat flux, and output voltage.

Date of Submission: 01 June 2022, Accepted on 30 September 2022

Corresponding Author: Shilpa Gupta
(Email: shilpa.gupta@ipec.org.in)

Even though PV systems have nonlinear characteristics, it is critical to model them for maximum power point tracking (MPPT) design and simulation in Photovoltaic systems implementation areas. Throughout the last quarter century, numerical PV designs for modeling have been developed [2-5]. Almost all well-developed Photovoltaic designs define the V-I and P-V attributes, which are primarily affected by solar irradiance, cell temperature, and load voltage. A numerous comprehensive subsystem electronics modeling software packages are now widely used in the configuration and advancement of power electronics application domains. Moreover, the MATLAB-Simulink program contains wind farm frameworks but still no Photovoltaic model for incorporation with existing electronics simulation tools. As a result, it is hard to model and investigate the standardized simulations of a Photovoltaic array. So, a generalized simulation model for Photovoltaic cell, module and array in MATLAB-Simulink environment is developed. This suggested basic prototype that will plot P-V as well as V-I contours for almost any specimen and various diode ideality factor. As a result, the said prototype is known as a generalized model for projecting contours for photovoltaic systems.

II. PHOTOVOLATICSYSTEM MODELLING

A. Basics of PV Module

PV cell is a semiconductor device whose junction is subjected to light. To reduce costs and maximize efficiency, the photovoltaic cell's P-N junction is manufactured from several types of semiconductor materials using various manufacturing techniques. The solar cell comprises of a Boron doped P type substrate to which Phosphorous atoms are added using high temperature diffusion method in direction to form the P-N Junction Figure 1.For various application domains, the industry offers a variety of Photo voltaic materials, including single crystal, poly - crystalline, and amorphous silicon, as well as compound thin film materials. Thin film solar cells are manufactured from $CuInSe_2$, CdS, CdTe, Cu_2S, InP. Among these the $CuInSe_2$ solar cells have excellent stability. A potential barrier is formed at the junction to prevent charge carriers, such as electrons and holes, from moving. The incidence of light on

ISSN: 2583-3286(Online)

the cell produces electron-hole pairs in the depletion layer. Charges are produced whenever the incident photon's energy is adequate to disassociate the semiconductor's covalent electrons—this effect is dependent on the semiconductor material and the wavelength of the sun's radiation. Because of the electrostatic potential at the interface, electrons and holes are detached in different directions. Such free charged particles are accumulated at the terminals of the photovoltaic array. When a cell's terminal is connected to an external load, electrons flow through it, causing current to flow in the circuit. A solar cell is a current source for an external circuit that is connected to it.

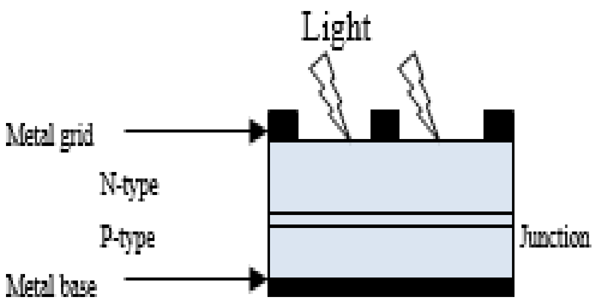

Figure 1. : Physical Structure of Solar Cell

B. Mathematical model of PV module

According to physical model and output characteristic of Solar cell, mathematical model. Solar cell is actually a PN junction, which characteristic is similar to diodes characteristic. The several parameters of the solar cell are modeled as in Figure 2. When solar cell is illuminated, electron-holes movement results electric fields and photocurrent (I_L). The current source generates the photocurrent I_L, which is proportional to the solar irradiation. This current (I_L) continues to flow without externally applied voltage. And this current is termed as short circuit current (I_{sc}).

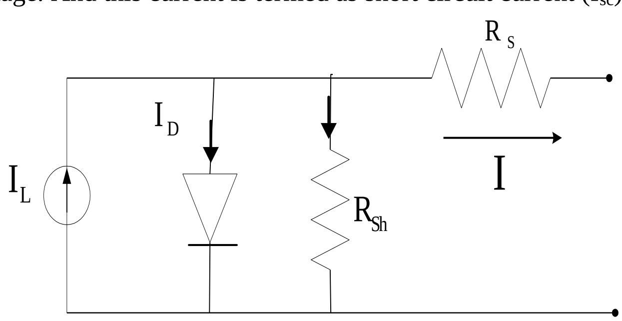

Figure 2.: Equivalent Circuit of PV Module

The equations that describe I-V characteristics of the solar cell based on simple equivalent circuit in figure. 2 are given below-

$$I_L = I_D + I_{sh} + I \quad (1)$$

$$I_D = I_0 \left(e^{\frac{q(V+IR_S)}{KTA}} \right) - 1 \quad (2)$$

Hence,
I =

$$I_L - I_0 \left(e^{\frac{q(V+IR_S)}{KTA}} \right) - \frac{V+IR_s}{R_{sh}} \quad (3)$$

where, I_0 is cell saturation current

I is cell current (A).
q is charge of electron = $1.6\text{x}10^{-19}$ (coil).
K is Boltzmann constant (J/K) (i.e., $1.38\text{x}10^{-23}$ J/K)
T is cell temperature (K).
I_L is light generated current (A).
Io is diode saturation current.
R_S, R_{Sh} are cell series and shunt resistance (ohms).
V is cell output voltage (V).
A is an ideal factor depend on PV technology (2.5)

Because a typical PV cell generates less than 2W at 0.6 V, the cells must be linked in series-parallel on a panel to generate significant energy. A Photovoltaic array is a collection of Photovoltaic modules that are linked up in series and parallel circuits to produce the desired current and voltage. Figure 3 depicts the schematic diagram for the solar module, which is configured in N_P parallel and N_S series. The array's terminal equation for current and voltage is as follows [6-9].
Equation (3) can be written as

$$I = N_p I_L - N_p I_0 \left(e^{\frac{q\left(\frac{V}{N_s}+\frac{IR_S}{N_p}\right)}{KTA}} - 1 \right) - \frac{\left(\frac{V}{N_s}+\frac{IR_S}{N_p}\right)}{R_{sh}} \quad (4)$$

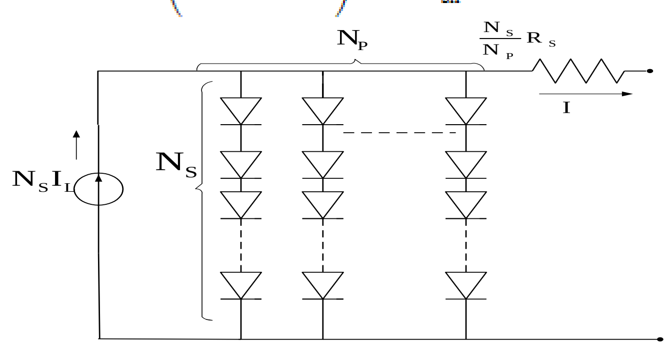

Figure 3. :A generalized model of solar cell module.

In fact, the PV efficiency is sensitive to small change in R_S but insensitive to variation in R_{Sh}. For a Photovoltaic module, the series resistance appears to be significant, while the shunt down resistance approaches infinity, implying that the module is open. In order to obtain an adequate working voltage, most commercial PV products connect PV cells in series to form a PV module. Photovoltaic cells are then connected in a series-parallel

ISSN: 2583-3286(Online)

configuration to achieve the optimal energy output. It can be shown that N_S =1 and N_P = 1 for a PV cell, N_P and N_S: series number of cells for a PV module, and N_S and N_P: series-parallel number for a PV array [10-12]. The mathematical equation of generalized model can be described as

$$I = N_p I_L - N_p I_0 \left(e^{\frac{q\left(\frac{V}{N_S}+\frac{IR_S}{N_P}\right)}{KTA}} - 1 \right) \quad (5)$$

The most simplified model [6] of generalized PV module is shown in Figure 3 and described by the equation (5).

III. EFFECT OF VARYING SOLAR IRRADIATION AND CELL TEMPERATURE

The photocurrent I_L depends on the solar irradiation and the cell's working temperature which is expressed as

$$I_L = [I_{sc} + K_i(T - 298)] \frac{\beta}{1000} \quad (6)$$

Here, Isc is short circuit current

K_i is cell's short circuit current temperature coefficient (i.e., 0.0017 A/°C)

β is solar radiation (W/m^2)

The most important parameters widely used for describing the cell electrical performance is the open-circuit voltage V_{oc} and the short- circuit current I_{sc}. The aforementioned equations are implicit and nonlinear; therefore, it is difficult to arrive at an analytical solution for a set of model parameters at a specific temperature and irradiance [13-15]. Since generally $I_L >> I_0$ and ignoring the small diode and ground leakage current under short circuit terminal. So, the short circuit current I_{sc} is approximately equal to the solar current I_L, i.e.

$$I_L = I_{sc} \quad (7)$$

The cell saturation current I_0 varies with the cell current which can be relate by equation given below

The voltage V is considered varying from 0 to open circuit voltage V_{oc} corresponding to the variation in current from short circuit current I_{sc} to 0 A. Figure 8 shows the V-I & P-V curve for the values provided by manufacturer and with the variation in solar insolation level at a constant cell temperature of 25 degrees respectively.

$$I_0 = I_{rs} \left(\frac{T}{298}\right)^3 e^{\frac{qE_G\left(\frac{1}{298}-\frac{1}{T}\right)}{KA}} \quad (8)$$

where,

I_{rs} is cells reverse saturation current at a 25°C

E_G is band gap energy of the semiconductor

On the other hand, the V_{OC} parameter is obtained by assuming the output current is zero. Given the PV open-circuit voltage V_{OC} at reference temperature and ignoring the shunt-leakage current, the reverse saturation current at the reference temperature can be approximately obtain as

$$I_{rs} = \frac{I_{sc}}{\left(\frac{T}{298}\right)^3 e^{\frac{qE_G\left(\frac{1}{298}-\frac{1}{T}\right)}{KA}}} \quad (9)$$

IV. GENERALIZED PV MODEL BUILDING AND SIMULATION

A general model of solar cell built in MATLAB SIMULINK environment according to equations (3), (4) and (6)-(9) is shown in Figure 4.

The subsystem of masked PV module is shown in Figure 5. This subsystem block contains functional block for (8) and (9). These functional blocks are connected to build the final model of Photovoltaic system. These equations represent the effects of the temperature and solar irradiation as two variables.

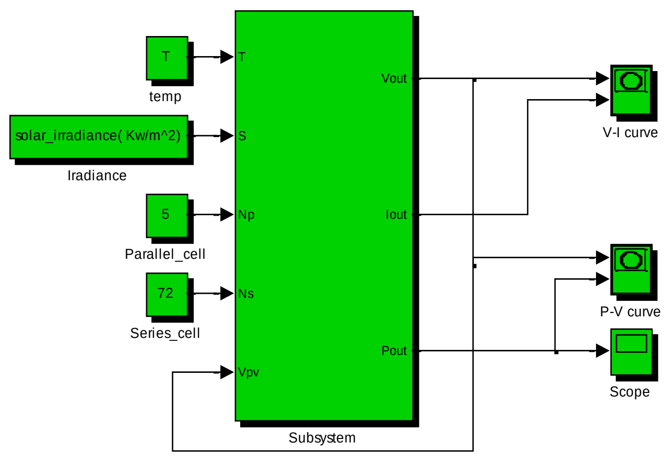

Figure 4. : Masked Simulink model of PV panel

It can be seen that the short circuit current as well as the power increases with the increase in insolation level, while very little change in the open-circuit voltage. The V-I and P-V characteristics of photovoltaic array with effect of different values of solar irradiation and cell temperature is shown in Fig 6-8. These curves of proposed generic model show the dynamic behavior of solar module.

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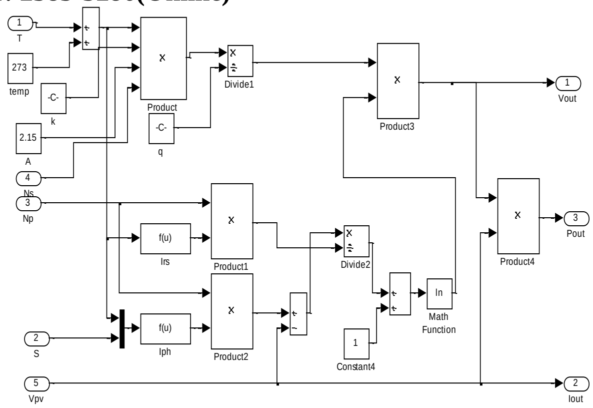

Figure 5. :Subsystem of PV Module

For example, the BP Solar SX l90 module is taken from the NREL System Advisor Model. The manufacturer specified data of BP Solar SX 190 modules are given in Table 1. Here NOCT denotes the nominal operating cell temperature at irradiance of 1000 W/m^{2}with an AM 1.5 spectrum at 25 ^{0}C.

TABLE I
PARAMETERS OF BP SOLAR SX3190 MODULE

Parameter	Values
Short circuit current (I_{sc})	8.51A
Open circuit Voltage (V_{oc})	30.6 V
Maxim power(P_{max})	190 W
NOCT	42±2% ^{0}C
I_0	1.06e-6 A
N_S	3
N_p	55

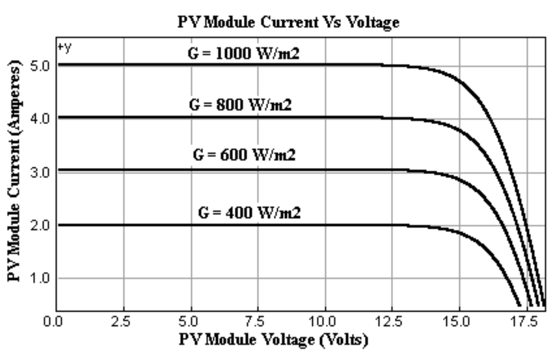

Figure 6.: PV cell characteristics of for different weather conditions

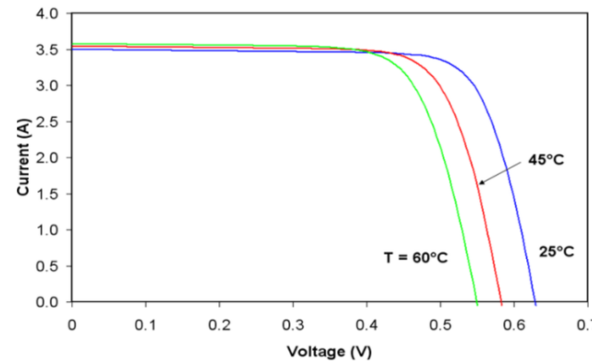

Figure 7.: Source Voltage, source current and tracking current

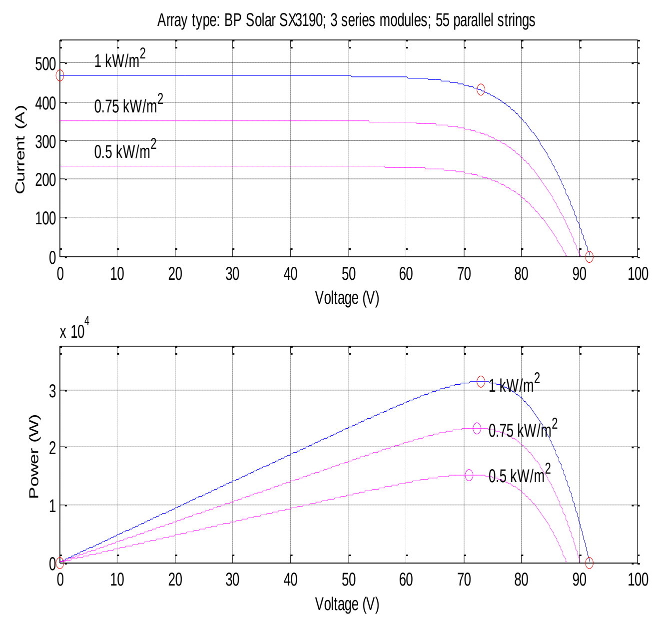

Figure 8.: I-V & P-V curve of PV Array

V. CONCLUSION

The dynamic characteristics of the Photovoltaic cell, Module and Array are obtained at MATLAB Simulink platform for different values of insolation as well as different values of cell temperature. The results show the dynamic characteristics and effectiveness of the solar system in consideration of change of weather conditions as well as change in temperature and aging of the PV cell. It is found that output characteristics of Simulink model are matching with the theoretical characteristics.This model is simple and user-friendly for study a Photovoltaic generator in the framework of the SimPowerSystems MATLAB/Simulink toolbox in the area of solar power conversion systems. The developed method and simulation

ISSN: 2583-3286(Online)

models for parameter extraction of photovoltaic module is useful for power electronic designer to design an accurate and fast simulation model of solar photovoltaic system emphasis to grid and of standalone systems. It will helpful for parameter extraction of photovoltaic module is useful as some of parameters may get change due to use in field because of change of weather conditions as well as change dust, humidity, temperature and aging.

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