Simulation and Performance Study of Photovoltaic (PV) Module in Varied Operating Conditions

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Abstract— The Photovoltaic (PV) systems are trending in power sector area due to their eco-friendly nature. This article emphasizes on constructing a PV module, based on individual diode type and simulating it in MATLAB/SIMULINK. The performance of the module for changing conditions of radiation, temperature, series resistance and ideality factor are explored. The influence of these parameters on the Maximum Power output, Efficiency and Fill Factor are studied for Solkar 36W PV module.

Key words: PV Cell Modeling, PV Characteristics, Efficiency, Fill Factor, Matlab/Simulink

I. INTRODUCTION

At present, adopting green technologies like solar energy has become mandatory due to scarcity of fossil fuels and the emission of carbon products from the conventional energy production methods [1]-[2]. India is the third largest carbon dioxide emitting country [3]. Hence to reduce global warming and environmental pollution, development of eco-friendly technology is essential. Even though numerous renewable energy technologies are available, solar energy is widely used due to its noiseless operation, abundant availability and portability, less maintenance cost, zero fuel cost and nil emission of toxic gases. It is reported in [4] that, an electrical energy of 500,000 terawatt-hour (Twh) can be harvested from the energy of the Sun, received in Indian soil, with PV modules of 10% efficiency. Further it is estimated by International Energy Agency that, 45% of the total energy requirements of the world, will be met through solar power generation in 2050.

The task of obtaining electrical energy from light energy in a single stage is performed by the Photovoltaic (PV) cell. Operating a PV panel at higher efficiency all the times is the most important challenge faced by the PV system engineers. Mathematical modeling is a means by which the equivalent circuit of a PV module is specified by its governing equations. A 36W PV module of Solkar make is chosen as the reference model. Then its equations are realized through Matlab/Simulink. This paper gives a detailed study on the simulation of a PV module and provides a wide knowledge about the various factors affecting the behavior of the PV module.

The fundamental equations concerned with equivalent circuit of PV module are dealt in Section 2. The basic factors influencing the solar cell behavior are addressed in section 3. Realization of the constructed model in Matlab is dealt in Section 4. A thorough investigation of simulated results is made in Section 5, from which the impact of various factors on its performance characteristics is studied. Finally, the article comes out with conclusion in Section 6.

II. EQUIVALENT CIRCUIT

The equivalent circuit pertaining to single diode model is depicted in Fig. 1 [5]-[6]. Since this model balances between accuracy and simplicity, it is preferred by several authors [7]. The mathematical relations pertaining to this model are given by (1)-(4) [8].

$$I_{ph} = [I_{scr} + K_i(T - 298)] * \frac{G}{1000} \quad (1)$$

$$I_{rs} = I_{scr} / [\exp(qV_{oc} / N_s KAT) - 1] \quad (2)$$

$$I_o = I_{rs}\left[\frac{T}{T_r}\right]^3 \exp[\frac{q * E_{go}}{AK}\left\{\frac{1}{T_r} - \frac{1}{T}\right\}] \quad (3)$$

$$I_{PV} = N_P * I_{ph} - N_P * I_o[\exp\left\{\frac{q * (V_{PV} + I_{PV} R_s)}{N_s AKT}\right\} - 1] \quad (4)$$

Where Vpv = VOC, NP = 1 and NS = 36. ‘Vpv’ and ‘Ipv’ are the output voltage and current of the PV module in Volts and Amps respectively. ‘Tr’ (=298K) and ‘T’ are the reference and module operating temperatures in Kelvin. The generated current due to incident light is represented by ‘Iph’ in Amps.

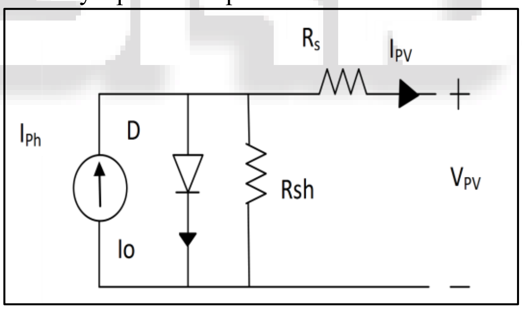


Fig. 1: Equivalent Circuit of a PV Cell using One Diode Model

The saturation current of the PV module is denoted by ‘Io’ whose unit is also in Amps. ‘A’ denotes the ideality factor and ‘K’ signifies the Boltzman constant (=1.3805X10-23 J/k). The Electron charge (=1.6X10-19 C) is labeled by ‘q’. The series and shunt resistances in ohms are given by ‘Rs’ and ‘Rsh’ respectively. Since Rsh is ideally infinite, it is neglected in this paper. ‘Iscr’ (=2.55A) is the PV module short circuit current at 25°C and 1000 W/m2. The intensity of solar radiation is denoted by ‘G’ in W/m2. ‘Ki’ (=0.0017 A/°C) signifies the short circuit current temperature coefficient at Iscr. The energy band gap is indicated by ‘Ego’ (=1.1 eV for silicon). ‘Ns’ and ‘Np’ are used to specify the number of series and parallel connected cells respectively.

III. SOLAR CELL CHARACTERISTICS

The predominant factors in determining the behavior of the solar energy source are as follows [9].

A. Short Circuit Current, Isc

Short circuiting the PV terminals results in fall of voltage to zero; whereas its current rises to maximum. This current is called as Short circuit current (ISC). Its unit is usually in mA/cm2.

B. Open Circuit Voltage, V_{oc}

Open circuiting the PV terminals leads to fall in current to zero; but its voltage rises to peak value known as open circuit voltage (V_{OC}). Its unit is either mV or V.

C. Fill Factor, FF

The division of maximum power by ideal power is known as Fill Factor (FF). It is associated with the resistive losses of a solar cell. It will be in the range of 0.8 to 1 for superior cells. The FF value quantifies the perfection of the square shape of the I-V curve. It is expressed by (5).

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \quad (5)$$

D. Efficiency, η

Expressing the utmost generated PV power as a fraction of input power is known as Efficiency (η). The input power is the power of solar radiation. Efficiency is mathematically given by (6).

$$\eta = \frac{V_m I_m}{P_{rad}} = \frac{V_{oc} . I_{sc} . FF}{P_{rad}} \quad (6)$$

IV. SIMULATED MODEL

The specifications of the simulated Solkar make 36W PV module are given in Table I [8].

Rated Power	37.08W
Voltage at Maximum Power (V_{mp})	16.56V
Current at Maximum Power (I_{mp})	2.25A
Open Circuit Voltage (V_{oc})	21.24V
Short Circuit Current (Iscr)	2.55A
Total number of series connected cells(N_s)	36
Total number of parallel connected cells(N_p)	1

Table 1: Specifications of Simulated Pv Module [8]

Note: The electrical specifications are under STC of radiance 1000W/m2, AM 1.5 and cell temperature of 25°C.

The circuit for realizing (1) – (4) are developed using Matlab/simulink software and simulated. The simulated model is shown in Fig. 2.

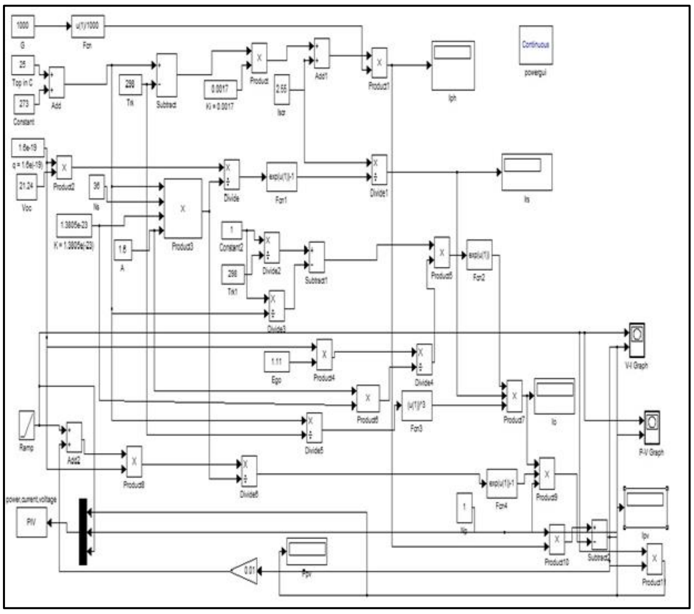


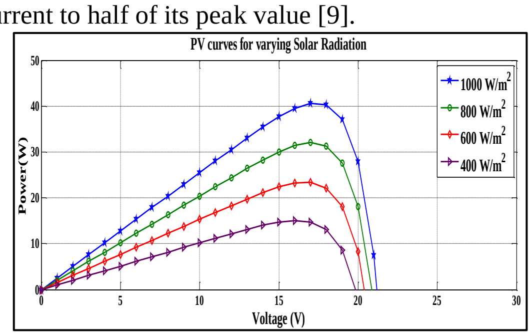
Fig. 2

V. SIMULATED RESULTS

The detailed study on the simulated characteristics of PV cell for changing conditions like radiation, temperature, series resistance and ideality factor are as follows:

A. Radiation Effects

The simulated results for changing radiations of 1000 W/m2, 800 W/m2, 600 W/m2 and 400 W/m2 are illustrated in Fig. 3. A constant cell temperature of 25°C, Series resistance of 0.05Ω, and ideality factor of 1.6 are chosen for simulation. It can be viewed that there exists a linear relation between the output power and radiation because, both the module voltage and current shoot up for rise in radiation. Consequently, it results in the improvement of efficiency of the energy source. Module current is linearly dependent on radiation whereas module voltage is a logarithmic function of it [9]. A maximum power of 40.5W, 32.5W, 23W and 15W are generated at 1000 W/m2, 800 W/m2, 600 W/m2, 400 W/m2 respectively. It can be observed that voltage pertaining to maximum power differs by 0.5V as radiations are increased. Hence this difference is not prominent for a large change in radiation intensity [9]. The module current of 2.55A at 1000W/m2 is found to be decreasing to 1.55 A at 600 W/m2. Hence it is apparent that a reduction in radiation to half of its maximum value leads to reduction of its current to half of its peak value [9].



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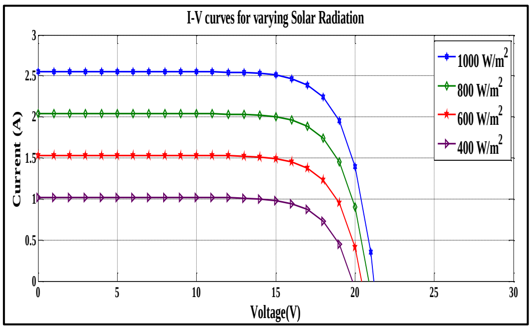


(b)

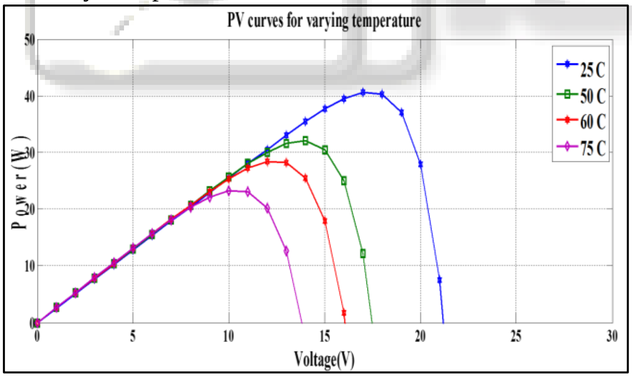
Fig. 3: PV & IV Curves for Varying Radiations

B. Temperature Effects

The simulation is carried out for 25°C, 50°C, 60°C and 75°C with constant radiation of 1000W/m^2. A value of 0.05Ω and 1.6 are chosen for series resistance and ideality factor respectively. The P-V and I-V curves under this condition are given in Fig. 4.

As the temperature is increased from 25°C to 75°C in suitable steps, the module current is found to rise from 2.55A to2.7A. But this rise in short circuit current due to reduction of band gap of silicon with increase in temperature is not prominent [9]. At the same time, the open circuit voltage is observed to be 21.2V, 17.5V, 16V and 13.9V for 25°C, 50°C, 60°C and 75°C respectively.

Hence it is vivid that, when the temperature shoots up, there will be fall in the open circuit voltage of about 3V, which has been caused due to rise in carrier recombination rate [9]. Further it is explicit that, the open circuit voltage reduces significantly for rise in temperature whereas the rise in short circuit current is not prominent. Consequently, the efficiency droops.



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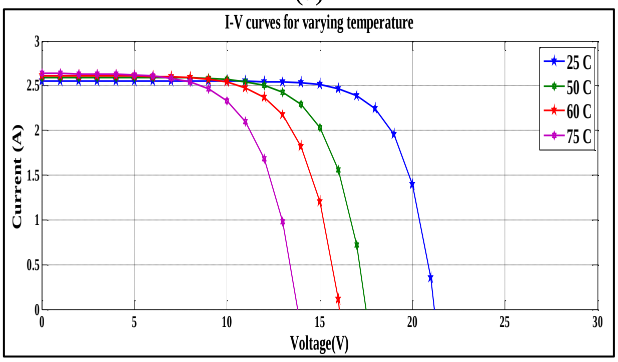

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Fig. 4: PV & IV Curves for Varying Temperature

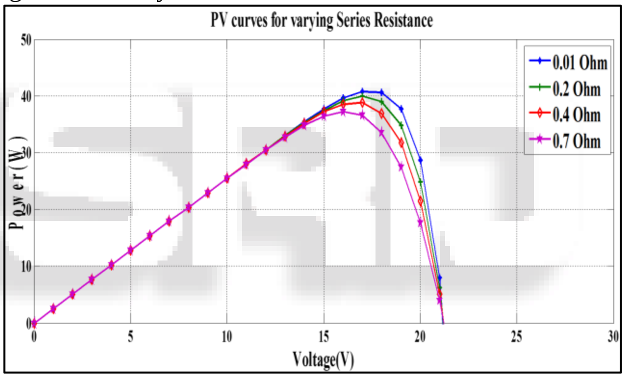
C. Effects of Series Resistance, Rs

Series resistance has its impact on Fill Factor and efficiency of the PV cell. It signifies the ohmic resistance offered by various components in the current path. The expression for series resistance is given by (7) [10].

$$R_s < 0.1\frac{V_{oc}}{I_{sc}} \tag{7}$$

Hence for the chosen PV module, its value is calculated to be less than 0.8Ω by using (7). Four values of series resistances are chosen for the simulation namely 0.01Ω, 0.2Ω, 0.4Ω and 0.7Ω. Fig. 5 elucidates the P-V and I-V curves for changing series resistance.

From the resultant I-V curve, it is inferred that the series resistance has not altered the two points namely: the open circuit voltage Voc and Short circuit current Isc. But at the same time, the steepness with which the curves roll off changes. The deviation of the I-V curve from the square shape for increase in series resistance is also revealed from the obtained results. Since the rise in series resistance is reflected in fall of Fill factor, it leads to decline in efficiency. Further it is ensured from the P-V curve that, a reduction in the power output occurs for large value of series resistance. Therefore, low series resistance results in higher efficiency.



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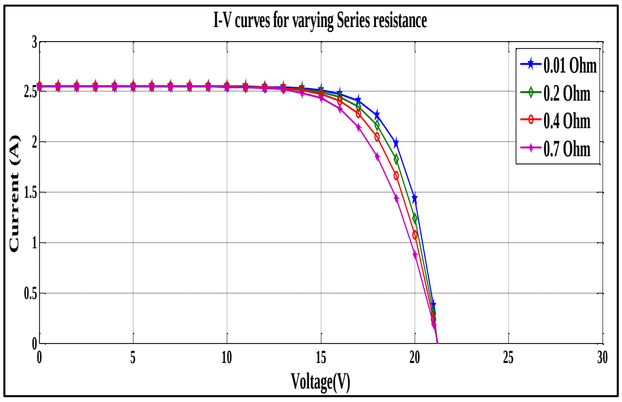

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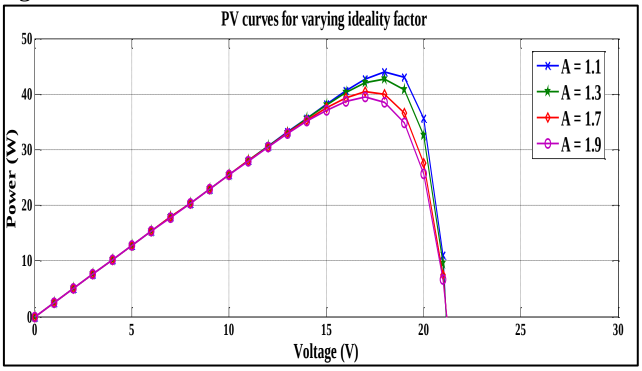
Fig. 5: PV & IV Curves for varying Series Resistance

D. Effects of Ideality factor, A

Ideality factor signifies the ideal behaviour of the diode [11]. For silicon cells, its value can be from 1 to 2 [12]. The simulation of the PV module at constant radiation of 1000W/m2 and temperature of 25°C is carried out for the following four values of ideality factor namely 1.1, 1.3, 1.7

and 1.9. The resultant characteristic curves are shown in Fig. 6.



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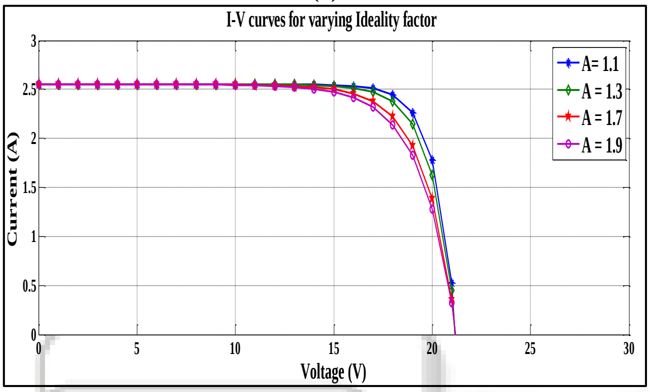

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Fig. 6: PV & IV Curves for varying Ideality factor

From the I-V curve it is clear that, increase in the ideality factor does not change the two points namely Voc and Isc but change in slope of the curves are noted. It is inferred that the amount of power produced declines with increase in ideality factor and hence the efficiency reduces.

E. Effects of Series Resistance on Maximum Power

The maximum power values obtained from simulation, for various values of series resistance are given in Table II.

R_S (Ω)	P_m (W)
0.01	41
0.2	40
0.4	39
0.7	37.5

Table 2: Specifications of Simulated Pv Module

The relation that exists between maximum power and series resistance is shown in Fig. 7.

It is observed that the maximum power value drops for increase in series resistance. It has negative slope. Consequently, efficiency decreases for increase in series resistance

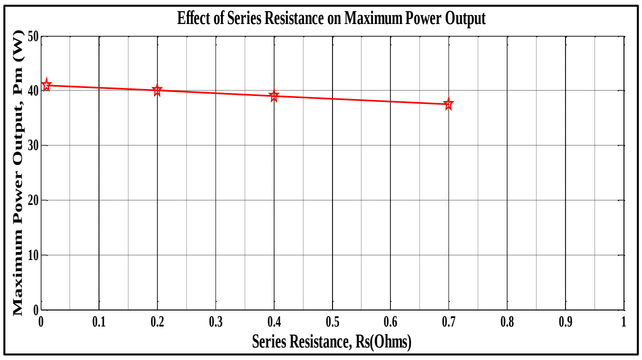

Fig. 7: Effect of Series resistance on Maximum Power

F. Effects of Radiation on Maximum Power

The simulated values of maximum power obtained for changing radiations are listed in Table III. The graph of Maximum power versus Radiation is shown in Fig. 8.

G (W/m^2)	P_m (W)
1000	40.5
800	32.5
600	23
400	15

Table 3: Maximum Power (Pm) Vs Radiation (G)

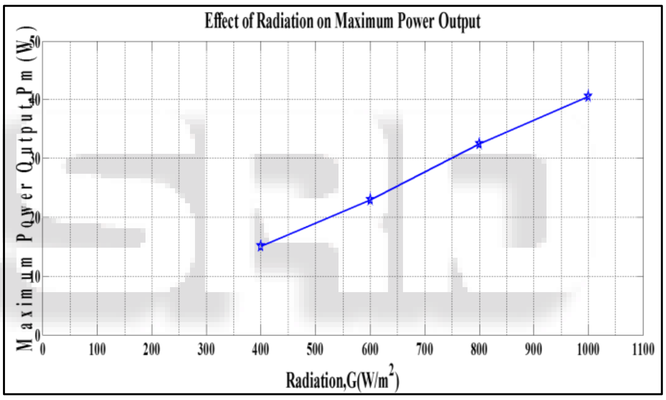

Fig. 8: Effect of Radiation on Maximum Power

It is vivid that a linear relation exists between Maximum power and Radiation. It has positive slope. Hence efficiency increases for rise in radiation.

G. Effects of Radiation on Fill Factor

From Table III, the Fill Factor values at different radiation intensities are calculated using (5) and are listed in Table IV. A graph of Fill factor versus Radiation is given in Fig. 9.

G (W/m^2)	FF
1000	0.747
800	0.6
600	0.424
400	0.276

Table 4: Fill Factor (Ff) Vs. Radiation (G)

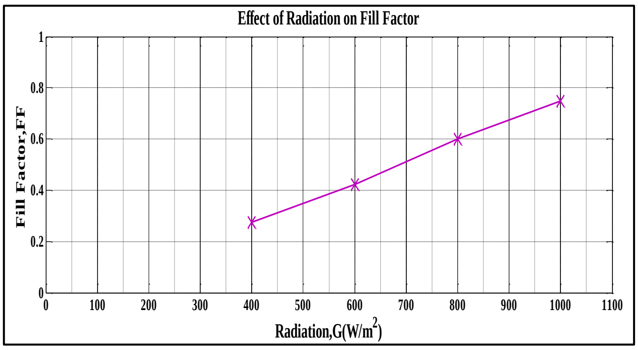

Fig. 9: Effect of Radiation on Fill Factor

It is observed that as radiation increases, Fill Factor also increases and hence it has positive slope. For low values of Fill Factor, the shape of the I-V curves deviates from square. Fill Factor is usually linked with resistive losses in a solar cell. For high values of radiation, Fill Factor is more and hence the efficiency will be more.

H. Effects of Series Resistance on Fill Factor

From the simulated characteristics for varied Series resistance, the Fill Factor values are calculated using (5) and are given in Table V. A graph of Fill Factor Versus Series Resistance is depicted in Fig. 10.

It is explicit from the obtained results that, the Series resistance and Fill Factor are inversely proportional to each other. For low values of series resistance, Fill Factor is observed to be more which results in high value of efficiency.

R_s (Ω)	FF
0.01	0.756
0.2	0.738
0.4	0.72
0.7	0.69

Table 5: Fill Factor (Ff) Vs Series Resistance (Rs)

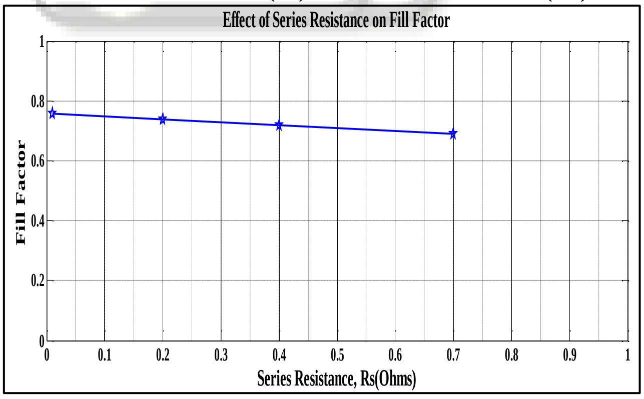

Fig. 10: Effect of Series Resistance on Fill Factor

VI. Conclusion

Adequate knowledge in the performance of solar cells for different operating conditions will help the PV system designers to achieve maximum efficiency at all situations. Choosing appropriate PV parameter values yields utmost output from the available energy source.

The response of 36W Solkar PV module is explored deeply in this article by simulating it in the MATLAB/SIMULINK platform. Simulation is executed by choosing different sets of values for the PV parameters and its corresponding P-V and I-V responses are analyzed.

From the obtained results it is obvious that maximum power extraction is made from the PV source for large values of insolation. At the same time, the energy source yields low output for high module temperature. Also it is inferred that low values of series resistance and ideality factor will improve the performance of the energy source.

Hence this article provides exemplary knowledge about the choice of parameters for achieving efficient operation of the PV system. This paper will be a stepping stone for the researchers in the field of solar energy systems.

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