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Nonlinear Matlab/Simulink-Based Mathematical Modeling of Solar Photovoltaic Modules for Power Generation

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Abstract:

Solar photovoltaic (PV) arrays comprised of modules are the most important power conversion elements of solar PV-generating systems. Because of the nonlinear characteristics of the solar PV array, determining its operating curves under various operating conditions is a laborious and expensive process. To overcome these barriers, engineers have updated multiple engineering software platforms, including Matlab and Simulink, to incorporate standardized and simplified solar panel designs. Nevertheless, these models are unsuitable for implementation in hybrid energy systems due to their intuitive nature and the need to manually adjust specific system parameters. Consequently, this article outlines a systematic process for simulating photovoltaic cells, modules, and arrays utilizing Matlab and Simulink. The reference model utilised is a 100-watt solar panel. Additionally, the operational characteristics of PV arrays under a broad spectrum of physical parameters and operating conditions are investigated. The simulation investigation is conducted for three distinct weather scenario conditions: cloudless days, days with moderate clouds, and days with heavy overcast conditions. When solar irradiation falls from 1 KW/m2 to 100 W/m2, the resulting voltage, current, and output power all decrease. The output power and voltage increase slightly as the temperature decreases, but the output current from solar PV panels remains approximately constant. The I-V and P-V curves of the solar photovoltaic module are significantly influenced when the shunt resistance changes from 1000 Ω to 0.1 Ω, resulting in a noticeable decrease in power output.

Keywords: Solar PV system, MATLAB , Simulink, Output Power, Series Resistance.

1. INTRODUCTION

Many believe that solar power will one day eliminate humanity's need for fossil fuels. The ideal renewable resource to combat the energy crisis is the sun's free, abundant radioactivity that reaches the Earth's surface. The sun always gives forth more energy than we need. The amount of energy that the sun radiates in only one minute is enough to power a whole year. This means that the amount of energy radiated in only one day is equivalent to the energy needed by the entire human population for 27 years. Because of its proximity to the equator and its status as the world's seventh-largest country, India experiences abundant sun radiation all year round. For around 300 sunny days a year, solar power is accessible across the nation, even in more remote places.

Numerous studies aimed at improving solar cell materials have examined the efficiency of SPV systems. Norshahirah Mohamad Saidi et al. (2021) developed a dye-sensitized solar cell (GPE-TBP3). In this experiment, the DSSC adopting GPE-TBP3 attained the maximum power conversion efficiency of 8.1% under 100 mW cm^{-2} light irradiation. According to Mohamed Mousa et al. (2021), a tandem cell that makes use of MAPbI3/CIGS could have a high-power conversion efficiency. The efficiency of the suggested MAPbI3/CIGS tandem cell, as determined by simulation findings, is a mere 30.5%. The efficiency is enhanced by substituting CIGS with GeTe in the bottom subcell to 35.9%. The conversion of the top subcell of MAPbI3 to MAPbI3xClx results in a 41.73% increase in efficiency. In 2020, W. Abdelaziz et al. conducted an experiment analysis comparing the proposed GBHJ's performance with other bulk heterojunction and bi-layer solar PV cells. The modeling findings show that BHJ has a collecting efficiency of 96.71% and GBHJ has an energy conversion efficiency of 11.15%. Manish Kumar and his team (2020) produced the lead-free organic-inorganic perovskite known as formamidinium tin iodide by synthesis. The device has a higher PCE of 19.08%, a voltage when no current is flowing (V_{oc}) of 1.81 V, a measure of how well it utilises available power (fill factor) of 33.72% and a measure of the current it can produce when there is no voltage of 31.20 mA/cm^2. A study showed by Ahsan S. M. and Hassan Khan (2019) evaluated the efficiency of thin-film solar panels composed of c-Si and CdTe under low-light circumstances. By conducting experimental comparisons, it was determined that CdTe solar panels generated 1.09% more energy than c-Si solar panels. Mabrouk Adouane et al. (2020) conducted a comprehensive assessment and comparison of eight distinct solar modules in the challenging environment of Kuwait. The results indicate that heterojunction solar panels outperform monocrystalline and polycrystalline silicon solar modules.

Ramadan et al. (2022) presented a novel solar photovoltaic (PV) model that incorporates Hunter-Prey Optimisation (HPO) and three diode models (TDM). The efficacy and accuracy of the techniques used to estimate parameters for different solar panels working in various conditions, provided by the HPO and WHO, are evaluated by simulation studies and statistical analysis. Hussein et al. (2022) conducted a comprehensive study into the optical, electrical, and thermal characteristics of various solar panel models. In their research, Mahmoud El-Dabah and his team (2021) developed a method based on artificial ecosystem optimisation to find the nine secret parameters in a triple-diode solar PV model. Hosseini et al. (2018) enhanced the technique for modelling solar photovoltaic (PV) modules by integrating the parameter extraction approach with the single-diode model. The modelling methodology relies on the utilisation of analytical equations and empirical data derived from the single-diode solar PV model. The model analyses the consequences of the spectrum and the performance of solar PV modules. As a result, we achieved a satisfactory comprehension of the photovoltaics' performance in actual outdoor environments. The study conducted by Et-Torabi et al. (2018) investigated and evaluated the efficacy of single-diode and two -diode models in solar cell performance. This study studies the parameters derived from analytical procedures for two-diode models and the numerical techniques employed for one-diode models. The analysis has revealed the necessity for new mathematical models to tackle the substantial disparities between the Voc area and the existing models. We employ the equations within the MATLAB/Simulink framework and assess the effectiveness and accuracy of the improved mathematical models by comparing the produced data with experimental data. Multiple authors, including Chayut Tubniyom et al. (2018), Hussein et al. (2022), Mirza Qutab Baig et al. (2019), and others, have extensively documented the procedure of simulating solar photovoltaic (PV) panels using a single diode. Abdul Qayoom Jakhrani and his colleagues (2014) developed a mathematical model for solar panels that improves accuracy by combining analytical and numerical methodologies. Zainal Salam et al. (2010) proposed an improved two-diode model that reduces the computation time and the number of unknown parameters and approximated values for the series resistor and shunt resistor. Marcelo Gradella Villalva et al. (2009) introduced a direct and effective approach for fitting the mathematical model without relying on any underlying assumptions.

2. PROPOSED METHODOLOGY

TYPES OF MODELLING OF SOLAR CELL

Based on the photovoltaic effect, a Solar cell changes sun irradiance into electrical energy which produces clean energy. Essentially, the behavior of a solar cell can be represented electrically in five ways for analyzing various processes that modify the PN junction's characteristics. In practice, a substantial quantity of solar photovoltaic cells are interconnected in parallel and series to produce the essential output power at the terminal voltage and current specifications, thereby satisfying the load's power demands. Various electrical parameters of the following five commonly used models available in the literature are recorded in Table 1.

Table 1 Types of Modelling of Solar Cell

Name of the Solar PV Model	No. of Parameters	Parameters	Description
Ideal Solar PV Model with Three Parameters	3	N, I_d, I_{ph}	N- Ideality factor I_d - Reverse saturation current I_{ph}- Photocurrent
Single-Diode Solar PV Model with Four Parameters	4	N, I_d, I_{ph}, R_{se}	N- Ideality factor I_d - Reverse saturation current I_{ph}- The Photocurrent R_{se} - Series resistance
Single-Diode Solar PV Model with Five Parameters	5	N, I_d, I_{ph}, R_{se}, R_{sh}	N- Ideality factor I_{ph}- Photocurrent R_{se} - Series Resistance I_d – Diode Reverse saturation current R_{sh} - Shunt Resistance
Two-Diode Solar PV Model with Seven Parameters	7	N_1, N_2, I_{d1}, I_{d2}, I_{ph}, R_{se}, R_{sh}	I_{d1} - Diode D1 reverse saturation current I_{ph}- Photocurrent N_1- Ideality factor of D1 I_{d2} – Diode D2 reverse saturation current R_{se} - Series resistance N_2- Ideality factor of D2 R_{sh} - Shunt resistance
Three-Diode Solar PV Model with Nine Parameters	9	N_1, N_2, N_3, I_{d1}, I_{d2}, I_{d3}, I_{ph}, R_{se}, R_{sh}	N_1- Ideality factor of D1 I_{d1} – D1 Diode reverse saturation current I_{ph}- Photocurrent N_2- Ideality factor of D2 I_{d2} – Diode D2 reverse saturation current R_{se} - Series resistance N_3- Ideality factor of D3 R_{sh} - Shunt resistance I_{d3} – D3 Diode reverse saturation current

2.1 Ideal Solar PV Model with Three Parameters

It is clear, from Table 1, that the parameters N, I_d and I_{ph} are the vital parameter which are common to all five models. The first step of analysis is developing a mathematical model by assuming ideal conditions. For this ideal solar PV model with three parameters, the ideal model is developed by using Equation (1) and is represented in Figure 1. The charge transport mechanisms and the internal resistances of the semiconducting material are ignored in this model for ideal conditions.

$$I = I_{Ph} - I_d * (e^{\left(q*V/_{N*T*N_s*k_B}\right)} - 1) \quad (1)$$

Where,

- I -Solar Panel Output Current

- q - Charge on an electron
- k_B - Boltzmann constant
- V- voltage output
- T - Cell temperature in K
- N_s - Quantity of solar cells in series connection
  - N=1 to 2 for real diode
  - N=1 for an ideal diode

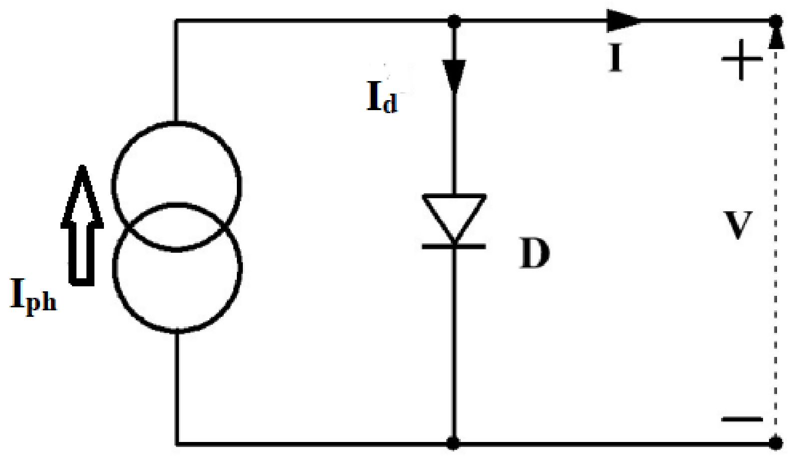

Figure 1 Model Equivalent Circuit for a Three-Parameter Single-Diode Solar PV

2.2 Single-Diode Solar PV Model with Four Parameters

The presence of parasitic resistance cannot be ignored in a practical model, hence, the Single-Diode Solar PV Model with Four Parameters model represented by Equation (2) is modeled by the load R_{se} which is coupled in series with the solar PV panel.

As a result, the mathematical model of solar cells incorporates the characteristics that express non-idealities as parasitic resistances. Equation (2) depicts a mathematical model of a solar cell with four non-measurable parameters: R_{se}, I_{ph}, I_{os}, and N. Figure 2 depicts the circuit that is equivalent to a Single-diode solar PV model, consisting of Four Parameters.

$$I = I_{Ph} - I_d * [e^{\left(q*(V+I*R_{se})/_{N*T*N_s*k_B}\right)} - 1] \qquad (2)$$

Where,

- I -Solar Panel Output Current
- I_{ph}- Photocurrent
- V- Output voltage
- q - Charge on an electron
- I_d - Diode Reverse saturation current
- R_{se} – Series resistance
- N_s - Number of solar cells in series
- T - Cell temperature in K

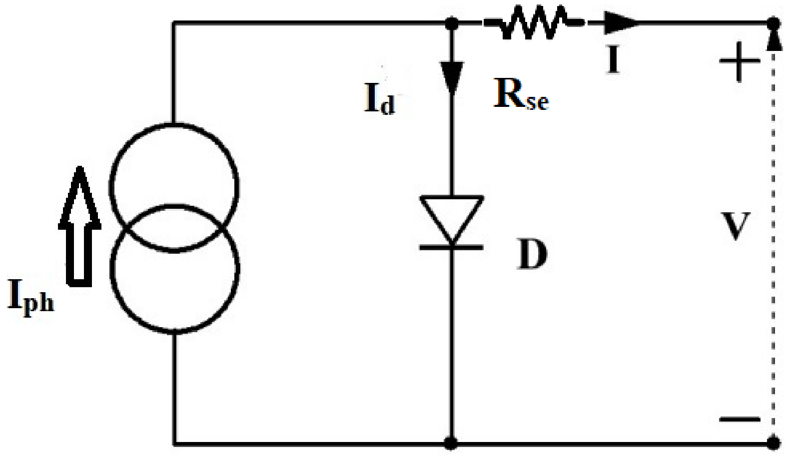

Figure 2 Model Equivalent Circuit for a Four-Parameter Single-Diode Solar PV Cell

2.3. Single-Diode Solar PV Model with Five Parameters

Typically, in all solar PV models, leakage current is a significant factor that cannot be overlooked. The corresponding mathematical model is illustrated in Figure 3.To account for this, it is represented by a parasitic shunt resistance 'Rsh' connected in parallel.

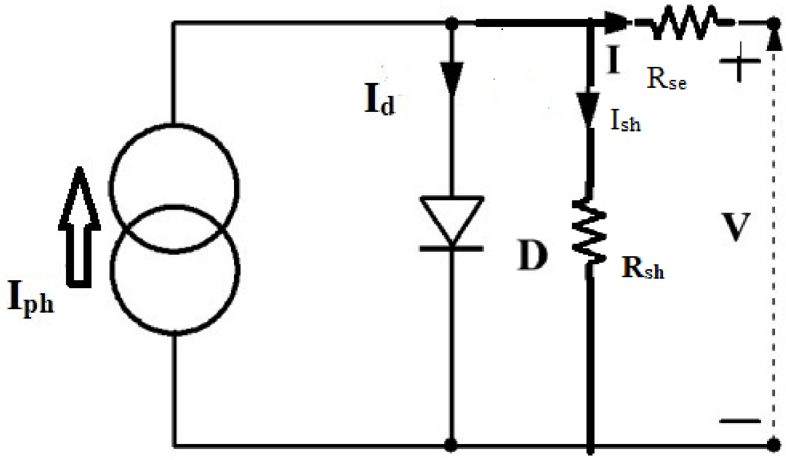

Figure 3 Equivalent Circuit of Five Parameters Single-Diode Solar PV Model

$$I = I_{Ph} - I_d * \left[e^{\left(q*(V+I*R_{se})/_{N*T*N_s*k_B}\right)} - 1\right] - \frac{(V+I*R_{se})}{R_{sh}} \qquad (3)$$

Where,

- I -Solar Panel Output Current
- I_d - Diode reverse saturation current
- k_B - Boltzmann constant
- q - Charge on an electron
- R_{sh} – Shunt resistance
- T - Cell temperature in K
- R_{se} – Series resistance

2.4 Seven Parameters Two-Diode Solar PV Cell

While recombinating the carrier, the solar PV model incurs some power losses due to the recombination process in the surface region and in the vicinity of the junction space. To mitigate these losses, photovoltaic modules must incorporate two exponential diode junctions.

The saturation current in a semiconductor junction (PN junction) is denoted by the variable 'Ios,' which is the sum of the contributions from charge diffusion and recombine in the space charge layer. In the space charge layer, the diffusion and recombination of current are represented by two components similar to Shockley diodes: 'Iod' for charge diffusion and 'Iog' for charge recombination. These two currents are linked to two diodes, respectively. Equation (4) provides a mathematical representation of the solar PV module, specifically illustrating the various elements of the saturation current in a PN junction. Figure 4 illustrates the circuit that corresponds to the mathematical model provided in Equation (4).

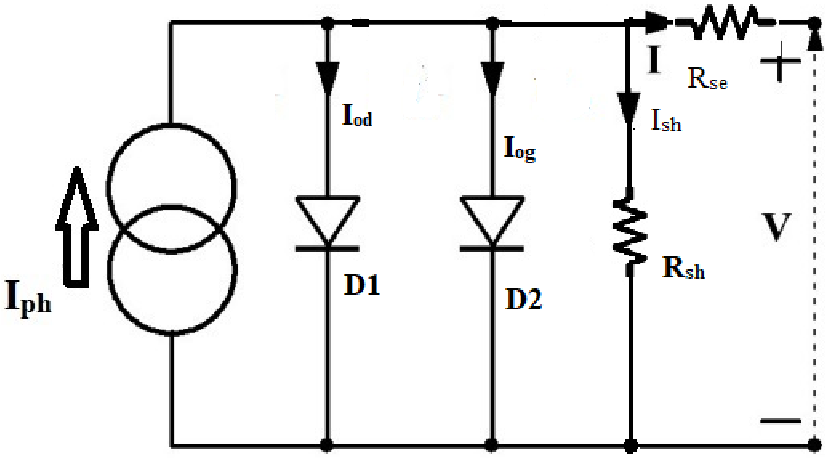

Figure 4 Equivalent Circuit of Seven Parameters Two-Diode Solar PV Cell

$$I = I_{Ph} - I_{od} * \left[e^{\left(q*(V+I*R_{se})/N_1*T*N_s*k_B\right)} - 1\right] - I_{Og} * \left[e^{\left(q*(V+I*R_{se})/N_2*T*N_s*k_B\right)} - 1\right] - \frac{(V+I*R_{se})}{R_{sh}} \quad (4)$$

Where,

- I -Solar Panel Output Current
- N_s - Number of solar cells in series
- q - Charge on an electron
- I_{ph}- Photocurrent
- V- Output voltage of the solar PV model

2.5 Nine Parameters Three-Diode Solar PV Cell

The I-V characteristic can be perfectly adapted using seven parameters two-diode solar PV model; but, if the solar PV cells are smaller in size, the I-V characteristics cannot be precisely matched. In the two-diode model, the leakage current of the PN junction due to enhanced recombination of minority charge carriers through the surface of the peripheral regions, which is omitted in earlier models. As a result, the 3rd diode with a diode ideality factor of two is incorporated into the solar PV model to account for peripheral leakage current caused by increased minority carrier recombination. Figure 2.5 shows the mathematical system of a three-diode solar PV cell with unknown parameters 'I_{ph}', 'I_{leak}', 'I_{od}', 'r', 'I_{og}', 'R_{s1}', 'R_p', 'R_{s2}', and 'R_{sh}' which is described in Equation (5).

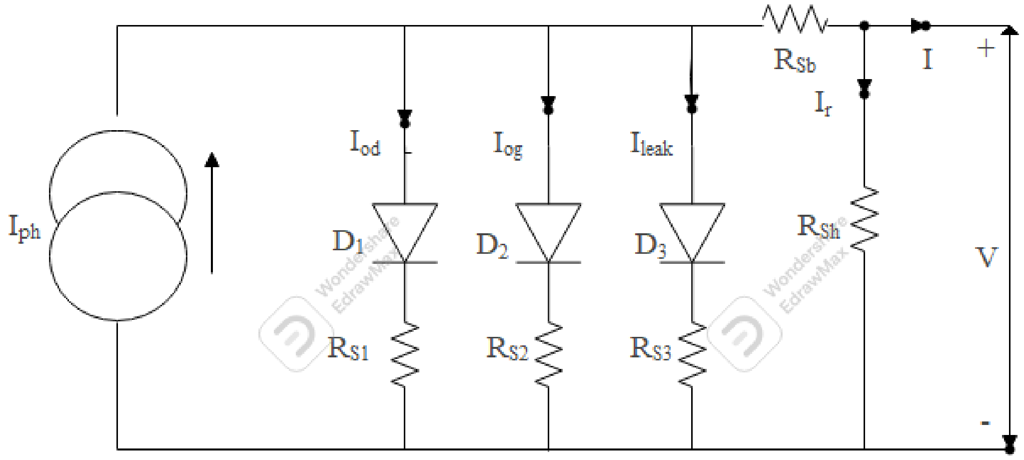

Figure 5 Equivalent Circuit of Three Diode Solar PV Model with Nine Parameters

$$I = I_{Ph} - I_{od} * \left[e^{\left(q*(V+I*R_{se})/_{N_1*T*N_s*k_B}\right)} - 1\right] - I_{Og} * \left[e^{\left(q*(V+I*R_{se})/_{N_2*T*N_s*k_B}\right)} - 1\right] - I_{leak} * \left[e^{\left(q*(V+I*R_{se})/_{N_3*T*N_s*k_B}\right)} - 1\right] - \frac{(V+I*R_{se})}{R_{sh}} \qquad (5)$$

Where,

- I -Solar Panel Output Current
- I_{ph}- Photocurrent
- V- Output voltage of the solar PV model
- R_{sh} – Shunt resistance
- T - Cell temperature in K
- R_{se} – Series resistance

As a result, the three-diode solar cell with the nine-Parameters model isn't used in this study. Villalva *et al.* (2009) found that the single-diode solar PV model perfectly fits with parameter adjustments and provides significant enhancements for effective research investigations incorporating controls in solar PV systems. Furthermore, the single diode with the four-Parameters model is less accurate than the single diode solar cell with five Parameters model, hence the same is not used in this study. Furthermore, the two-diode solar PV cell with the seven-parameters model is more complex and requires more computations than the single-diode solar PV cell with the five-parameters model, hence it is not included in this work. The double-diode model is reduced to a single-diode model by reasonably omitting charge recombination in the space charge region, which significantly decreases computation time and simplifies parameter adjustment in the model.

Moreover, the single-diode model can be scaled up appropriately in such a way that it provides a good way to design power electronic circuits often used to simulate the solar PV power generating model, as well as necessary controls for optimally extracting energy from solar PV cells, and thus the single-diode solar cell with five Parameters model is utilized in the investigation proposed in this thesis.

3. PERFORMANCE ANALYSIS OF SINGLE-DIODE FIVE PARAMETER SOLAR PV PANEL USING MATLAB

A solar PV system is constructed in the MATLAB SIMSCAPE software for the intended experiment, utilising the datasheet provided by the module manufacturer (Table 2). Figure 6 illustrates the MATLAB model utilised to construct the proposed solar PV power producing system. The P-V and I-V curves of the solar PV model under consideration are comprehensively examined across a spectrum of solar irradiation levels, series resistances, solar cell temperatures, and diode ideality factors.

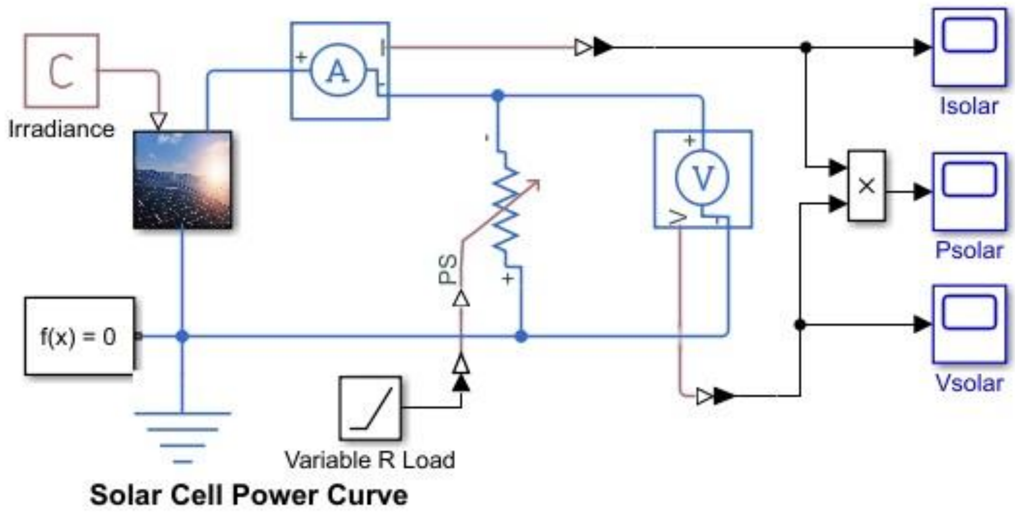

Figure 6 MATLAB Simulation Model of Solar PV System

Table 2 Datasheet of 100 W Polycrystalline Solar PV Modules

Electrical Parameters		Mechanical and Thermal Parameters	
P_{mpp} in W	100	L: Length x W: Width x T: Thickness (cm)	115 x 67.5 x 3.5
Open Circuit Voltage :V_{oc} in V	21.97	Weight	10.15 kg
Short Circuit Current: I_{sc} in A	6.07	Solar Cells per Module / Arrangement	36 / (9*4)
V_{mp} in V	17.46	α (%/ºC)	0.068
I_{mp} in A	5.73	ß (%/ºC)	-0.294
Module Efficiency	12.88	γ (%/ºC)	-0.384

3.1 Electrical Parameters of Solar PV Module under STC

Figure 7 demonstrates the current-voltage curve of the simulated solar photovoltaic (PV) model, whereas Figure 8 represents the power-voltage curve. The solar panel undergoes testing using standard parameters (Irradiation 1 KW/m^2, an air mass value of 1.5, and a solar cell temperature of 25 °C) , which consists of V_{oc} - 21.97 V, I_{sc} - 6.07 A, and solar power output of 100 W. Thus, the accuracy of the modelling system has been validated by comparison with the experimental setup and specifications.

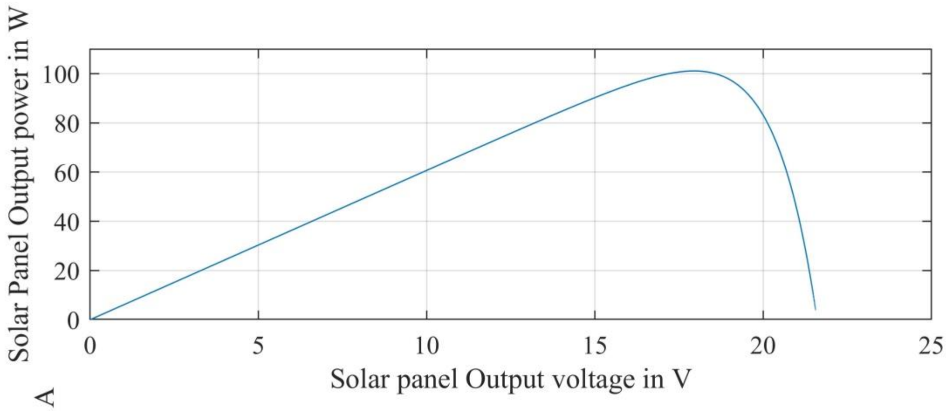

Figure 7 P-V Curve of Solar PV Panel at Standard Test Condition

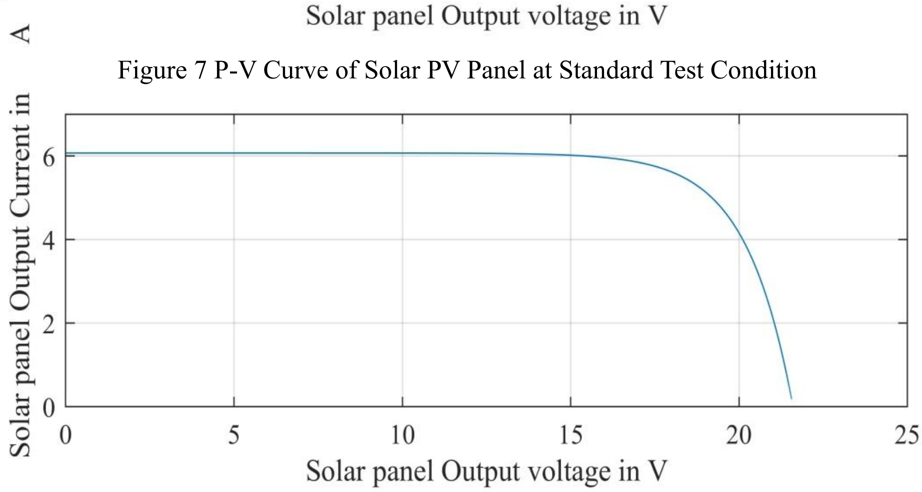

Figure 8 I-V Curve of Solar PV Panel at Standard Test Condition

3.2 Influence of Sun Irradiation on Electrical Parameters of Solar PV Panel

The term "irradiance" refers to the power density of solar radiation received at a particular location on Earth, expressed in W/m^2. On the contrary, irradiation functions as a measure of the concentration of solar energy. The I-V and P-V curves of the solar panel are affected comparably by the variations in solar irradiance that happen during the day. As solar irradiance increases, the short-circuit current and open-circuit voltage also increase, causing an alteration of the maximum power point. The P-V and I-V characteristics of the solar photovoltaic (PV) system are depicted in Figure 9 and Figure 10, respectively, under varying solar irradiance conditions of 1 KW/m^2, 0.8 KW/m^2, 0.6 KW/m^2, 0.4 KW/m^2, and 0.2 KW/m^2.

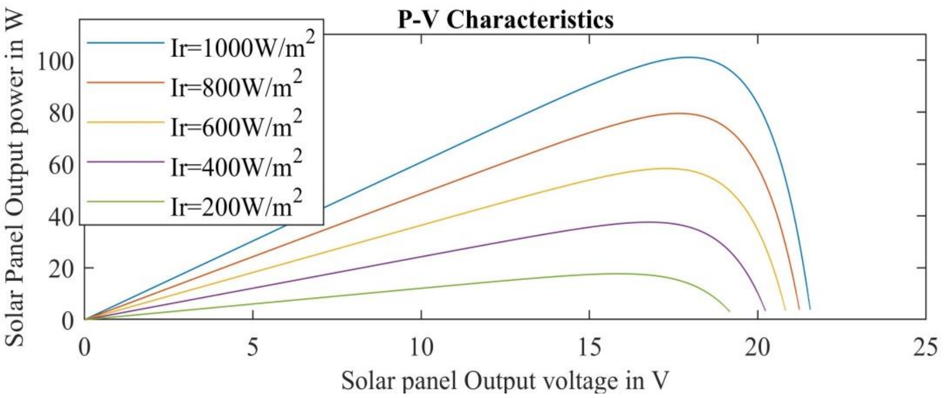

Figure 9 P-V Curves of Solar PV System under Various Solar Irradiation

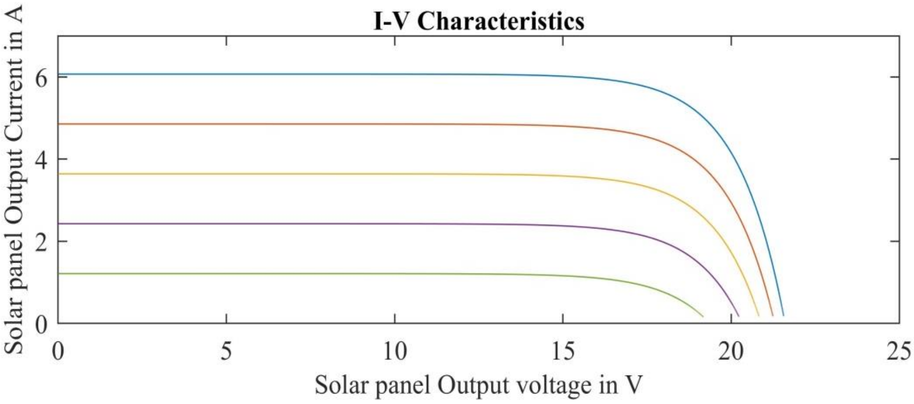

Figure 10 I-V Curves of Solar Module under Various Solar Irradiation

3.3 Influence of Solar Cell Temperature on Electrical Parameters of Solar PV Panel

An additional critical factor that impacts the efficiency of solar cells is thermal energy, also known as temperature. The rate of photon production increases in parallel with the temperature, resulting in a rapid surge of reverse saturation current and a subsequent narrowing of the band gap. Consequently, substantial fluctuations occur in solar output voltage while minimal fluctuations occur in solar output current. As temperature rises by one degree, the output voltage of the solar cell decreases by 2.2 mv. Consequently, solar cells operate most efficiently during frigid, sunny days as opposed to hot, sunny days. Ita-V and P-V The solar photovoltaic system's characteristics at various temperatures—50 °C, 40 °C, 30 °C, 35 °C, and 25 °C—are illustrated in Figure 11 and Figure 12. The graph illustrates that the voltage of the solar array is significantly impacted by temperature. Due to the reduction in voltage, power output rises as the temperature decreases but decreases as the temperature rises.

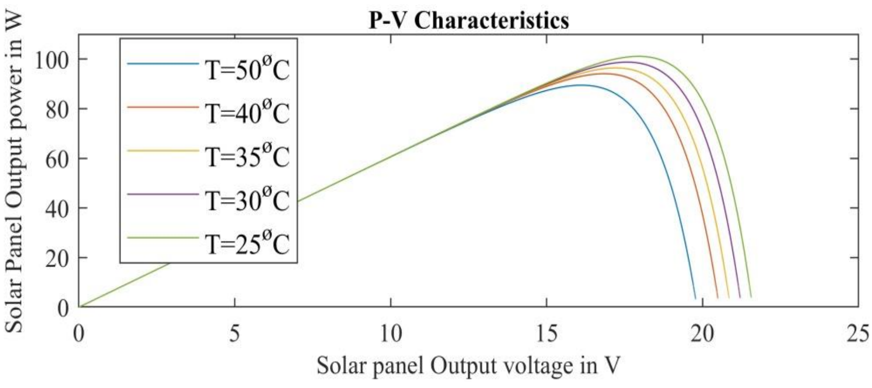

Figure 11 P-V Curves of Solar PV Panels at Various Temperatures

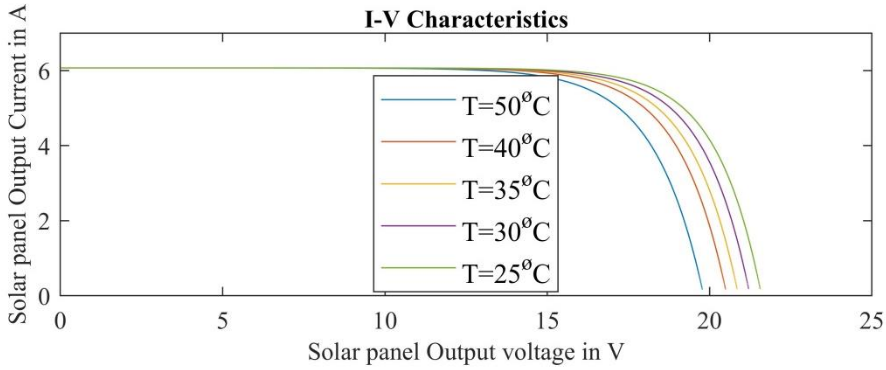

Figure 12 I-V Curves of Solar PV Panels at Various Temperatures

3.4 Influence of Series Resistance on Electrical Parameters of Solar PV Panel

The series resistance associated with the model has a major impact on power development. It is observed that, at high-intensity levels, the voltage drop occurs, and the series resistance is high, thereby causing the reduction in the maximum power. Figure 13 displays the P-V characteristics of the photovoltaic system at different series resistance values, whereas Figure 14 shows the I-V characteristics.

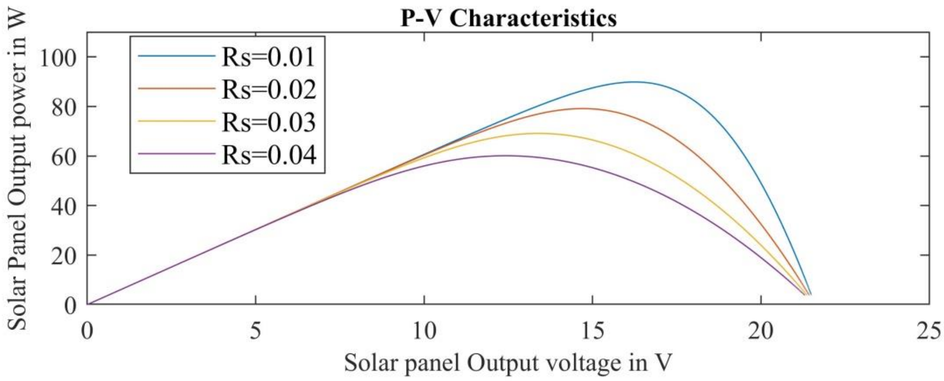

Figure 13 I-V Characteristics of Solar PV Panel at Various Series Resistance.

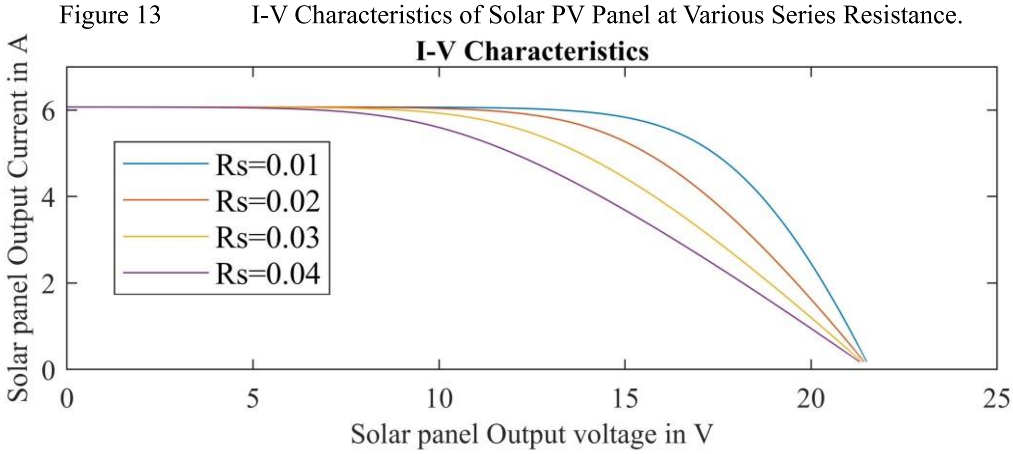

Figure 14 I-V Characteristics of Solar PV System at Various Series Resistance

3.5 Influence of Diode Ideality Factor on Electrical Parameters of Solar PV Panel

In a single-diode solar panel with the five-Parameters model, the ideal diode ideality factor N is often one. However, in this study, the solar PV array is modeled for varies values of

N ranging from 1 to 1.75 under standard testing conditions. The electrical characteristics demonstrate that the output around the ideal value of N is close to the maximum power rating in the datasheet, however, there is a considerable loss of power below the ideality factor value of one. Figure 15 displays the P-V characteristics of the solar photovoltaic system for different values of N, whereas Figure 16 shows the I-V characteristics.

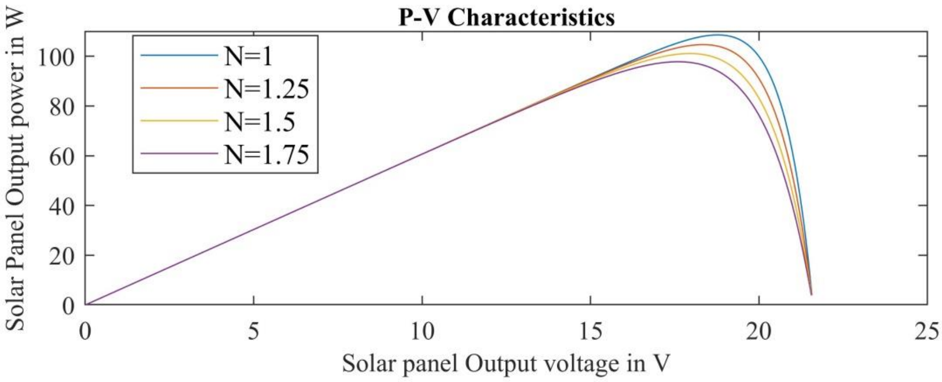

Figure 15 P-V Characteristics of Solar PV System at Various N

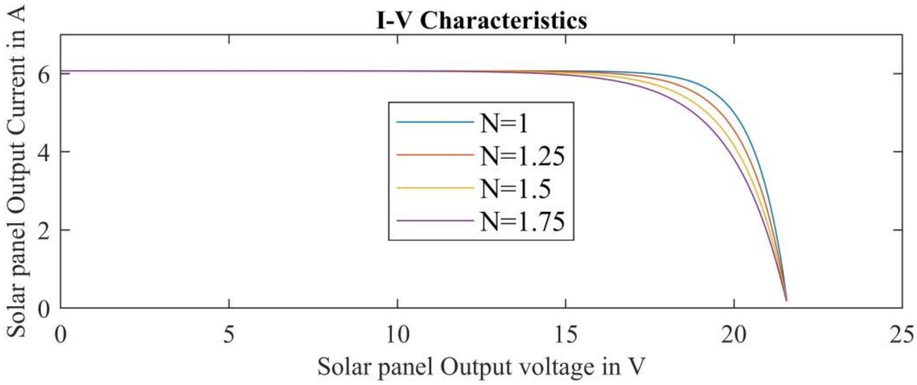

Figure 16 I-V Characteristics of Solar PV System at Various N

4. CONCLUSION

The single-diode five Parameters solar PV module with series and shunt resistance is designed and simulated using MATLAB software. In comparison with the two and three-diode models, the above model contains all the essential ohmic losses in the operation and is also less complicated. The solar PV model is then simulated under various solar irradiance, temperature, series resistances, and diode ideality factor. When simulated with the derived five parameters, the electrical performance of the solar PV array is very near to the rated values. since the study focuses on addressing power loss owing to quickly changing atmospheric conditions, the characteristics that has a substantial influence on the power output in relation to the conditions indicated above is narrowed down. In comparison to the other electrical parameters involved, solar irradiance and solar panel temperature are having a significant impact on output power and hence will be given more attention in the following chapters as the investigation progresses. Detailed performance analyses of the impact of solar irradiance and temperature on the single-diode five parameter solar panel model is carried out along with experimentation validation of the simulation study.

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