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Modeling and Simulation of Prime Solar Photovoltaic Module for Performance Parameter Predictions Using Matlab/Simulink Environment

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ABSTRACT

The model of PV cell converts the solar energy into electrical and provides the I-V and P-V curves for given radiation and temperature as input parameters. For the designers to meet the required specification using virtual rather than physical experiment, modeling and simulation of solar photovoltaic is required. This paper aims at predicting the performance parameter of PV using prime solar photovoltaic module type PS-P310-36. In this study, 8 steps modeling techniques were executed on PV mathematical equations along with electrical parameters obtained from the data sheet of the manufacturer using MATLAB/Simulink environment. In the modeled program, different irradiance (200, 400, 600, 800 and 1000 W/m^2) at constant temperature of 25^{o}C and different temperature (25, 30, 35, 40 and 45^{o}C) at constant irradiance of 1000 W/m^2 under Standard Testing Conditions (STC) were used to obtain I-V and P-V characteristic curves. The simulated models attained optimal value of 308.8 watt under standard testing conditions. Furthermore, the modeled results were compared with the characteristic value of the manufacturer data sheet and maximum relative error percentage of 0.7983% was found. More so, using real metrological data of Maiduguri, Nigeria (irradiance and temperature), the model was used to predict the performance of the PV module. The result showed that March, 2018 has the highest value of power generation of 75.20. This model can be used to predict the behavior of the photovoltaic cells under distinct physical and environmental conditions.

1. INTRODUCTION

Solar energy is a great way of contributing to a cleaner future. This renewable resource is a clean and safe alternative energy solution that can help reduce the production of harmful pollution caused by fossil fuels. Therefore, utilizing solar power can be an excellent way to fight climate change and help reduce homes carbon footprint. Many researchers have developed models that predict the potential of solar energy. For example, Amusat *et al.* (2016) developed empirical models to predict monthly average daily global solar radiation of Maiduguri, Borno State, Nigeria. The model that best fits the data was chosen by comparing regression coefficient of the models. A model was developed by Abdullahi *et al.* (2018) using Gunn Bellan radiation integration in order to assess the potential of the solar radiation for electricity generation in Potiskum, Yobe State, Nigeria. Moreover, Luqman *et al.* (2016) developed a pre-assessment model using single variable and multivariable regression techniques of Angstrom type to evaluate the total solar radiation reaching a horizontal surface in Maiduguri, Borno State, Nigeria.

Using the light and heat of the sun to produce electricity is a major player in the clean energy game. This has benefit over other conventional power generators because the sunlight can be directly converted into electrical energy with the use of smallest photovoltaic (PV) solar cells. Mathematical modeling of PV module for the evaluation of the maximum power produced by a PV generator is very important to size a PV system (Amusat *et al.*, 2020). This is being continuously updated to enable researchers have a better understanding of its workings. The models differ depending on the types of software researchers used such as C-programming, Excel, Matlab, Simulink or the toolboxes they developed and the types of PV used such as Solkar 36W PV Module (Pandiarajan and Ranganath, 2011), Solarex MSX60 PV Module (Kamal *et al.*, 2014) and so on. Nnabuike *et al.* (2017) developed a mathematical model for a single diode PV using MATLAB software program. The simulation was carried out to estimate the electrical characteristic and the power output of the PV panel. The result of the simulation indicated that effect of temperature variation is more on short circuit current than an open circuit voltage which has very small increment.

Kamal *et al.* (2014) developed a mathematical model of a PV to predict the PV cell behavior under different physical and environmental parameters using simulink in MATLAB. The model accepts irradiance and temperature as input variable parameters to give output I – V and P –V characteristics to outline the working principle of PV as well as PV array. Dominique *et al.* (2013) used PV mathematical model to compute five parameters of single diode model. The Matlab script file program used Newton Raphson's method and the results obtained by simulation (short circuit current, open circuit voltage and maximum power) agreed with the parameters given by the manufacturer. Rajaram and Sharma (2015) worked on modeling and simulation of PV using two techniques (P and O and increment conductance methods). The Perturb and Observed (P and O) used algorithm for Maximum Power Point Tracking (MPPT). In the algorithm, the power is directly proportion to the voltage. The process is repeated at each MPP tracking step until the MPP is reached. The increment conductance method used derivative of current with respect to voltage to reach the maximum power point (MPP). Amusat *et al.* (2020) developed mathematical model with MATLAB software and used curve fitting tools to build P-V and I–V characteristic of Solar Module. The developed model used manufacturer data under Standard Testing Conditions to predict the current, voltage and power as well as the maximum current, voltage and power.

There are numerous works in literature based on application of Matlab and its toolboxes. These include; Neural Network (Oumarou *et al.*, 2017; Shodiya *et al.*, 2012), Fuzzy logic (Shodiya *et al.*, 2017) and Simulink (Rajaram and Sharma, 2015). The objectives of this study are to model, simulate and predict the performance of the PV module. Matlab/Simulink software was used because of its inbuilt solar cell blocks rich library. Also, this work makes use of prime solar PV module type PS-P310-36 as a result of its improved output power (Amusat *et al.*, 2020). The input parameters (Open circuit Voltage and Short circuit current) provided by the manufacturer under standard Testing Condition along with solar radiation and temperature were used in the procedure involved in the modeling. The obtained model will serve as a tool for predicting the performance of the PV Module under various environmental conditions.

2. METHODOLOGY

2.1 Materials

The material used for this study is the manufacturer's specification of Prime Solar panel PS-P310-36 under STC as presented in Table 1. The solar irradiance of 200, 400, 600, 800 and $1000W/m^2$, cell temperature of 25, 30, 35, 40 and 45ºC as well as monthly average daily global solar radiation and temperature of Maiduguri, Borno State for the year 2018 were also used.

Table 1: The Technical characteristics of the photovoltaic modules used for the model. (Amusat *et al.*,2020)

Characteristics	Values
Open Circuit Tension (V_{oc}) ,[V]	42.9
Short Circuit Current (I_{sc}) ,[A]	9.31
Maximum Rated Tension (V_{max}) ,[V]	36.3
Maximum Rated Current (I_{max}) ,[A]	8.54
Maximum Power (P_{max}) ,[W]	310

2.2 Methods

The output characteristics of photovoltaic cell depend on the environmental conditions. For any solar cell, the model parameters are function of the irradiance and the temperature value of the site where the panel is placed. In this study, the numerical values of the equivalent circuit are generated from the manufacturer data sheet and used in MATLAB to develop the model. The mathematical equivalent circuit for photovoltaic module in Figure 1 was developed under solar cell block which has inbuilt simulink program. For the modeling and simulation of the photovoltaic cell module type of PS-P310-36, step by step approach was adopted using input parameters (I_{sc} and V_{oc}) provided by the manufacturer alongside under distinct physical and environmental conditions.

2.2.1 Mathematical Modeling of PV Cell

Photovoltaic cell models have long been means of describing photovoltaic cell behavior. The most commonlyusedmodel for predicting energy production in photovoltaic cell is the single diode lumped circ uit model (Dominique *et al.*, 2013). The performance of photovoltaic systems (solar cell/panels), *vis-a-vis*, the output current/voltage curve (I-V curve) and Power/Voltage (P-V curve) are studied using an equivalent circuit model. This equivalent circuit consists of a current source with two resistors, one connected in parallel and the other in series. Based on these electronic components, equations (1-5) were used for the photovoltaic systems (Jobeda and Simon, 2018). Figure 1 shows equivalent circuit of a Photovoltaic with one diode.

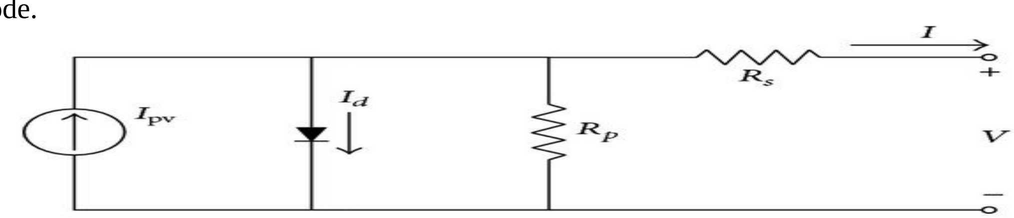


Fig 1: Equivalent Circuit of a Photovoltaic with one diode (Jieming *et al.*, 2013).

The Mathematical equations of PV from Figure (1) used in the program are shown in equations 1 to 5 (Jobeda and Simon, 2018).

$$I_{ph} = \left[I_{sc} + K_i(T_r - T_o) * \left(\frac{S}{1000}\right)\right] \quad (1)$$

$$I_{rs} = \frac{I_{sc}}{\left[exp\left(\frac{qV_{oc}}{N_s AKT}\right) - 1\right]} \quad (2)$$

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

$$\mathrm{I_{pv}} = \mathrm{N_p} * \mathrm{I_{ph}} - \mathrm{N_p} * \mathrm{I_0}\left[\exp\left(\frac{\mathrm{qV_{pv}}}{\mathrm{N_s AKT}}\right) - 1\right] \quad (4)$$

$$P = \mathrm{I_{pv}} * \mathrm{V_{pv}} \quad (5)$$

Where:

I_{ph}: Photocurrent (Ampere)
I_{SC}: Short-circuit current (Ampere)
K_i : Cell„s short-circuit current temperature coefficient (Ampere /Kelvin)
T_o: Cell operating temperature (Kelvin)
T_r: Cell„is reference temperature in degree (Kelvin)
S: Solar irradiance (Watt/meter square)
I_{rs} : reverse saturation current of diode
q: Electron charge (1.602×10^{-19} Coulomb)
V_{oc}: Open circuit voltage (Volt)
N_p: Cells interconnected in parallel (1)
N_s: Cells interconnected in series (36)
A: Ideality factor
k: Boltzmann's constant (1.38 × 10-23 Joule/Kelvin)
T: the temperature of p-n junction
I_{pv}: Output current of a PV module (A)
I_o: PV module saturated current (A)
V_{pv}: Output voltage of a PV module (A)
E_{go}: band gap for silicon

2.2.2 Simulink PV Model

The formulation block modeling of solar PV module is based on equations 1 to 5. These are developed in step by step procedure under MATLAB/Simulink as shown in Figures 2 to 15.

Step1: Figure 2 shows how the input operating temperature was converted from degree Celsius to Kelvin using the block simulink (Vinod *et al.*, 2018). This was embedded in the Figure 3 (Subsystem 1).

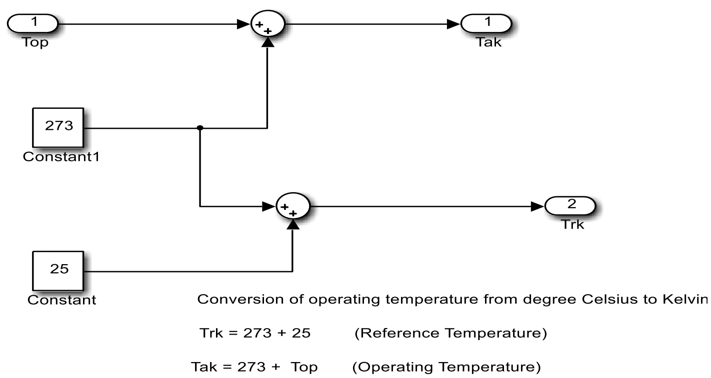


Figure 2: Operating temperature conversion model

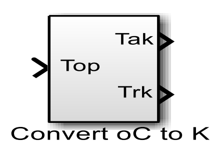


Figure 3: Subsystem 1 of operating temperature conversion model

Step 2: Figure 4 shows the Light generated Photon current of PV Module developed in the MATLAB/Simulink environment (Vinod *et al.*,2018). This Figure was embedded in the subsystem 2 shown in Figure 5.

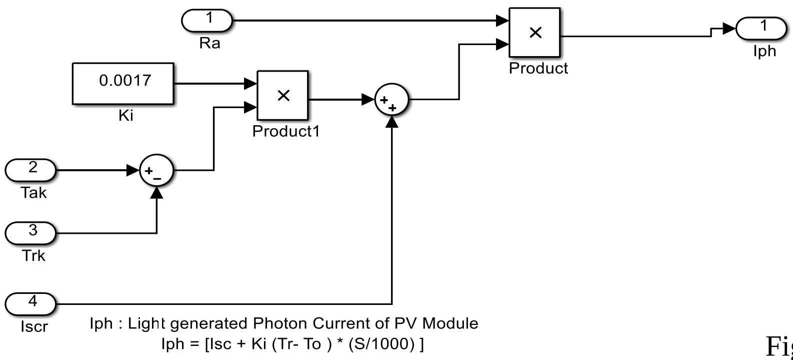


Figure 4: Light generated Photon current of PV Module

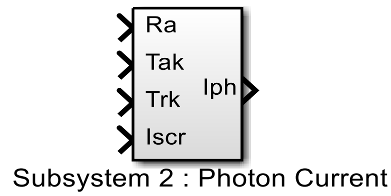


Figure 5: Subsystem 2 of Photon Current

Step 3: The Figures 6 and 7 are both block Simulink of the reversed saturated Model and its subsystem developed in the MATLAB/ Simulink platform (Vinod *et al.*, 2018).

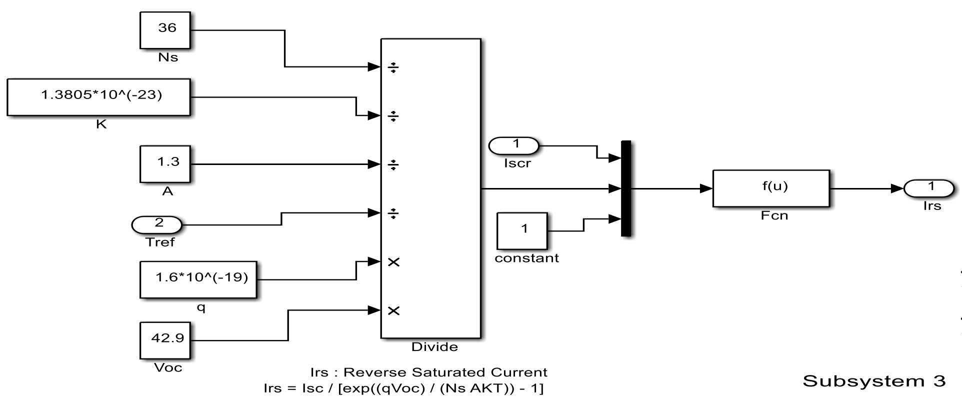


Figure 6: Reverse Saturated Current Model

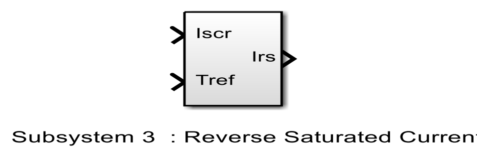
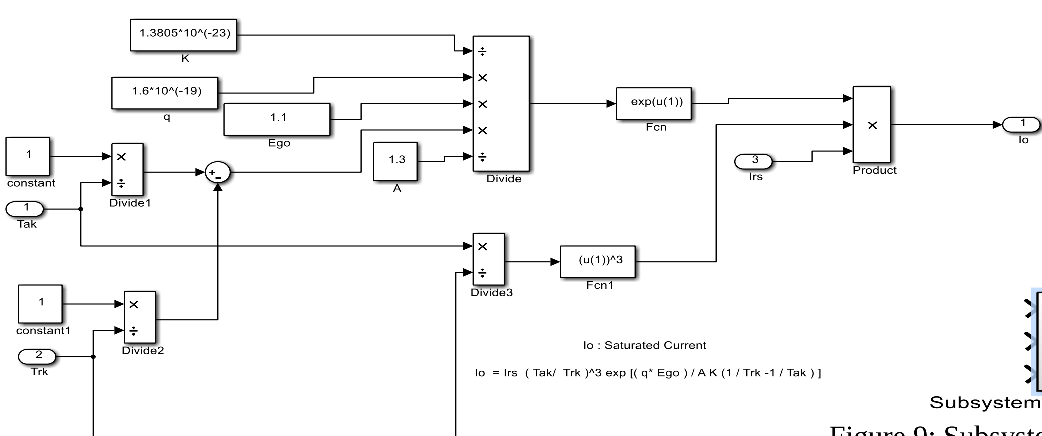


Figure 7: Subsystem 3 of Reverse Saturated Current

Step 4: The Saturated Current model developed was shown in Figure 8. This was embedded in the Figure 9. This used reverse Saturated Current along with energy band gap, electron charge, reference and operating temperature as input parameter (Vinod *et al.*, 2018).



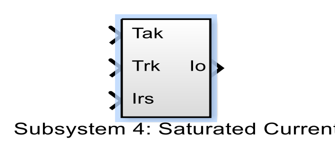


Figure 9: Subsystem 4 of Saturate Current

Figure 8: Saturated Current Model

Step 5: The product model of N_sAKT was shown in Figure 10. It was embedded in the subsystem 5 shown in Figure 11. This product model takes operating temperature in Kelvin (Vinod *et al*., 2018).

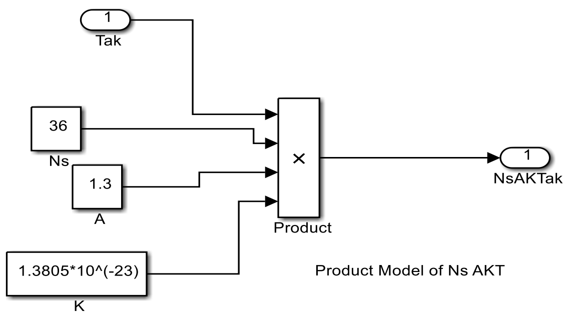


Figure 10: Product Model of N_sAKT

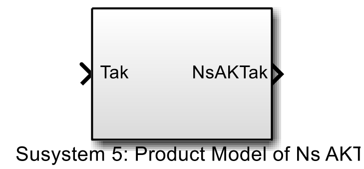


Figure 11: Subsystem 5 of Product Model

Step 6: The output current Model developed in Simulink environment was shown in Figure 12 (Vinod *et al*., 2018). This was embedded in the subsystem 6 in Figure 13.

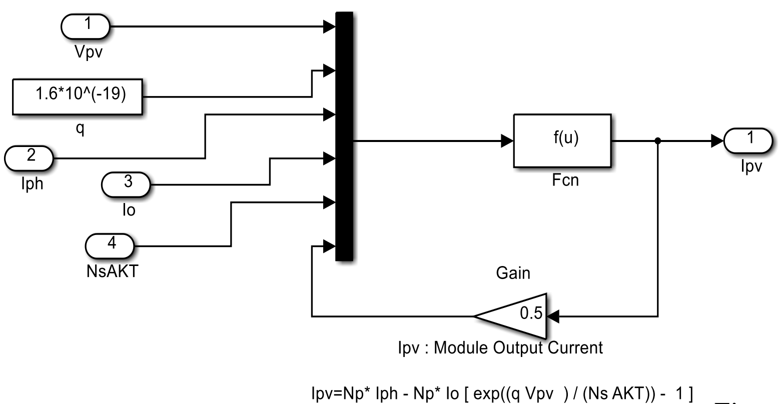


Figure 12: PV Output Current Model

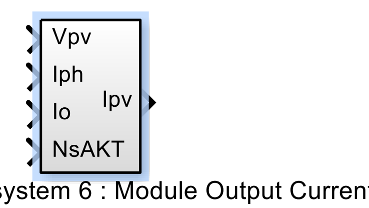


Figure 13: Subsystem 6 of PV Output Current Model

Step 7: Figure 14 contained all the six subsystem models developed in steps 1 to 6 in the simulink environment (Vinod *et al*., 2018).

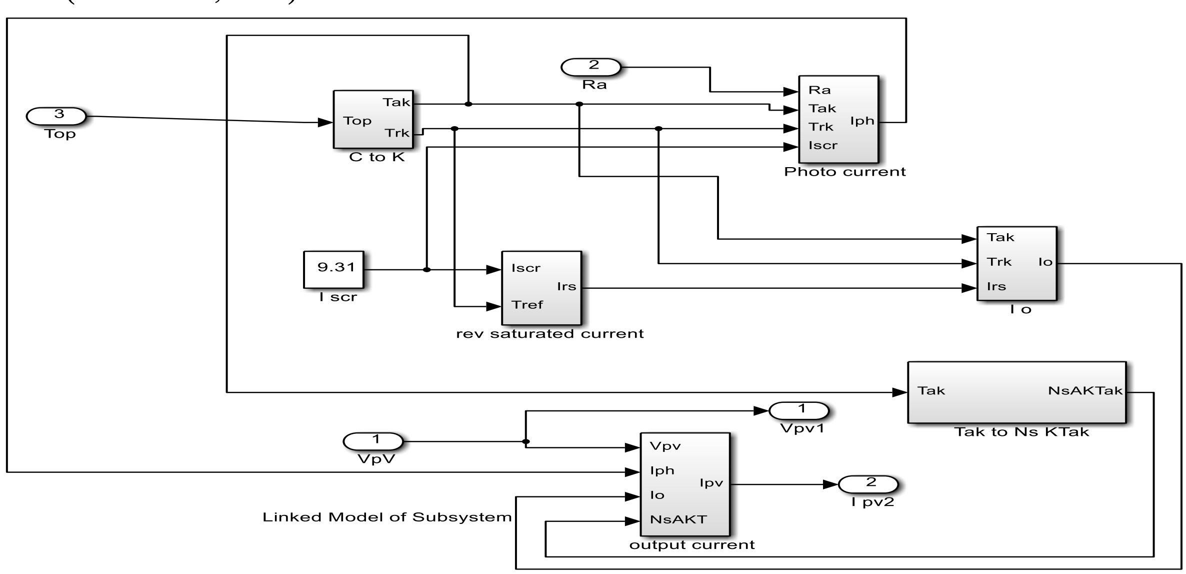


Figure 14: Linked Model of all Subsystems

Step 8: The final PV solar Module Model is shown in Figure 15. This consists of irradiance and temperature as input parameters to give output current and voltage (Vinod *et al.*,2018)

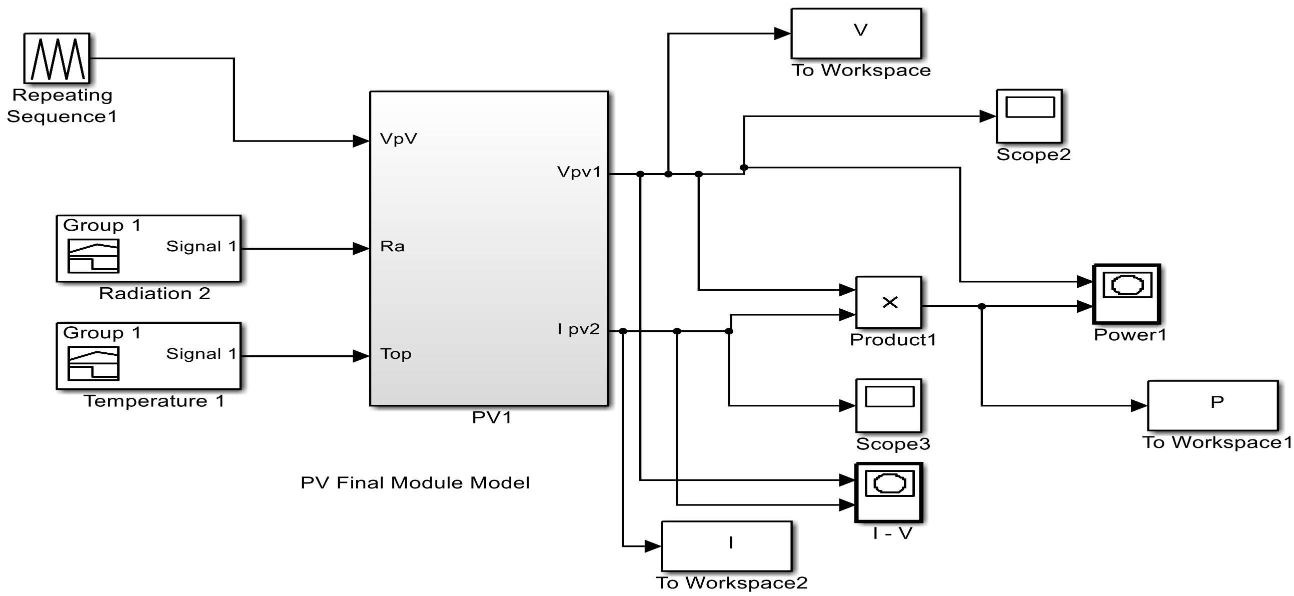


Figure 15: Final PV Model

3. RESULTS AND DISCUSSION

The results of the step by step block Simulink of the PV model were developed based on mathematical equations 1 to 4 (Jobeda and Simon, 2018) and the input parameters obtained from the manufacturer datasheet as provided under the varying intensity of irradiance (200 W/m^2 to 1000 W/m^2) and different temperatures (25^{o}C to 45^{o}C) are shown in Figures 16 to 19. The results for I – V and P - V characteristics of the module showed a good agreement in term of short circuit current, open circuit voltage and maximum power respectively while comparing with manufacturer data sheet.

3.1 Evaluation of Developed Model

The PV model developed is evaluated by comparing with manufacturer data sheet at STC. The conditions were kept at irradiance of 1000 W/m^2, temperature of 25 ^{o}C with 1.5 Air mass (Vinod *et al.*, 2018). The comparison of manufacturer data, simulate values and relative errors are shown in Table 2.

Table 2: Comparison of manufacturer data and simulated model values at STC

Parameters	Manufacturer data	Simulated values	Relative errors (%)
Open Circuit Tension (V_{oc}) ,[V]	42.9	42.9	0.0000
Short Circuit Current (I_{sc}) ,[A]	9.31	9.31	0.0000
Maximum Rated Tension (V_{max}) ,[V]	36.3	34.32	0.7983
Maximum Rated Current (I_{max}) ,[A]	8.54	8.99	0.0527
Maximum Power (P_{max}) ,[W]	310	308.8	0.0039

3.2 Effects of Irradiance and Temperature on the PV Module

The effects of irradiance and temperature on the solar PV model are shown in Figures 16 – 19. Figure 16 shows the I-V output characteristics of PV module for different values of irradiance (200, 400, 600, 800 and 1000 W/m^2) at constant temperature 25^{o}C. The I-V curve shows that the output current is increased with increased in sola r radiation.This shows irradiance have significant effects on short circuit current. The maximum and minimum values of short circuit current are 9.31 A at 1000 W/m^2 and 1.862 A at 200 W/m^2 respectively. It was also observed that current remains the same with increase in voltage up to 34.32V and decrease afterward for each value of irradiance.

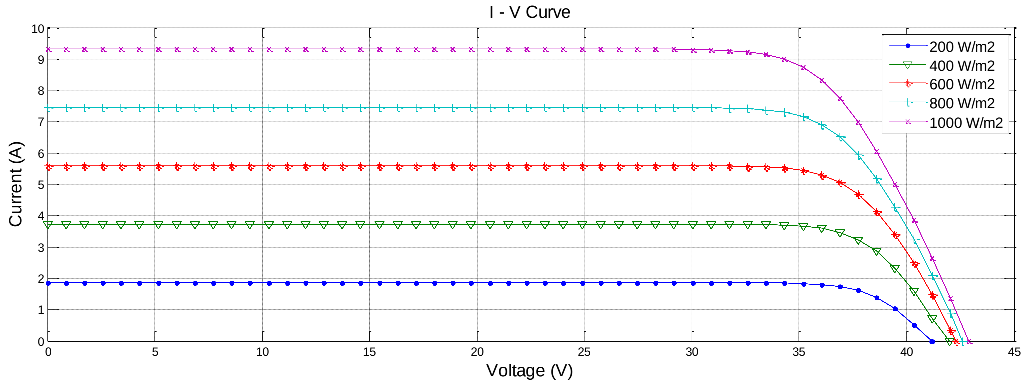


Figure 16: I-V characteristics by varying irradiance

Figure 17 shows the P-V curve of a PV module at different irradiance. The output power of the module is directly proportional to both irradiance and output voltage. This implies that increase in solar radiation leads to increase in output power and voltage which enhances efficiency of the solar panel. Furthermore, there was a 79.03% increase in maximum power when the solar radiation values vary from 200 W/m^2 to 1000 W/m^2 at constant temperature 25^{o}C.

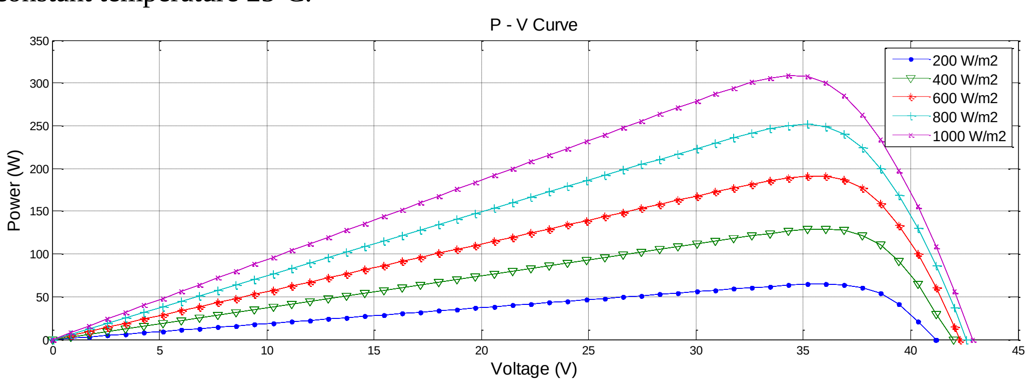


Figure 17: P-V characteristics by varying irradiance

Figure 18 depicts the results for I-V curve of the photovoltaic module under the variation of operating tem perature (25, 30, 35, 40 and 45^{o}C) at constant irradiation level of 1000 W/m^2. The photovoltaic panel generates more power when the operating temperature reduces. This solar PV performance shows inverse relationship with temp erature.The Figure also shows that increase in temperature results into decrease in the open circuit voltage of the PV panel. This increase in temperature has a major impact on the PV module by reducing its volta ge thereby lowering the output power. The maximum and minimum values of open circuit voltage (I_{sc}=0) were 42.9 V at 25^{o}C and 38.0 V at 45^{o}C respectively.

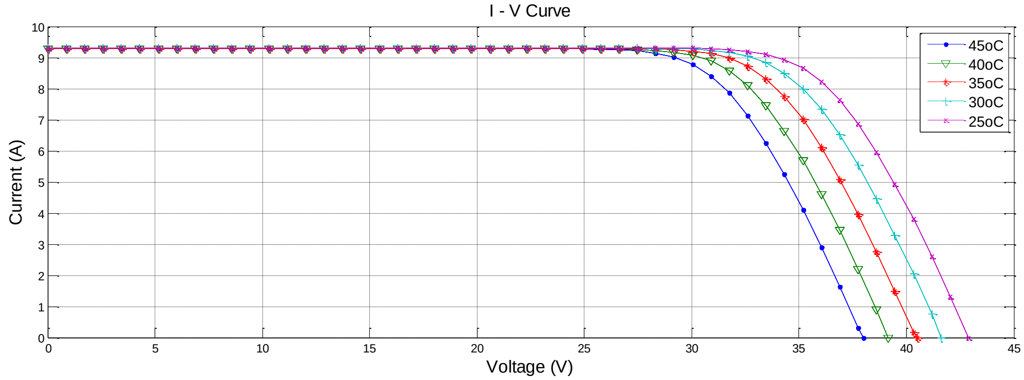


Figure 18: I-V characteristics by varying temperature

Figure 19 depicts the P-V characteristics under constant irradiance of 1000 W/m^2 and varying operating temperature of 25, 30, 35, 40 and 45 ^{o}C respectively. For all the temperature, the power output increase up to the maximum power po ints where they start to decrease sharply. At 45^{o}C the maximum power was 263.6 W and at 25^{o}C the maxi mum power was 306.5 W. The percentage increase in power as the temperature decrease was 13.99%.

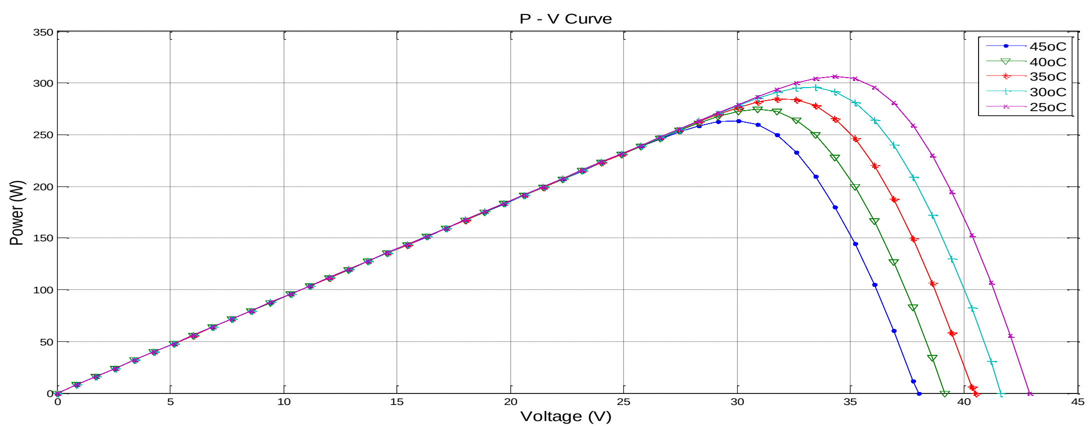


Figure 19: P-V characteristics by varying temperature

3.3 Performance of the PV module in real metrological data

The monthly average values of irradiance and temperature of the Maiduguri collected from Nigerian Metrological Agency, Abuja for the year 2018 is shown in Table 3. This was used as an input parameters (Average values of irradiance and temperature) to evaluate the performance of the developed model. The output values (I_{mp}, V_{mp} and P_{mp}) of the model are also shown in Table 3. The maximum and minimum output power of the model was found to be 51.04 and 75.20 W for the month of August and May respectively. This shows that the PV model's performance decreases or increases in accordance to the values of irradiance and temperature.

To further assess the performance parameter predictions of the developed model, metrological data of Maiduguri, Nigerian from January, 2018 to December, 2018 was used. The values of I – V and P – V characteristic curves of January to December were simulated for solar PV model as shown in Figures 20 to 25. The power output of the PV modeled varied directly under the real metrological data.

Table 3: Solar PV model parameter under real metrological data of the year 2018

Months	Avg. value of G (W/m^2)	Avg. value of temp. (ºC)	I_{mp} (A)	V_{mp} (V)	P_{mp} (W)
January	208.20	31.08	1.8755	36.04	67.58
February	233.90	38.05	2.0791	36.04	74.92
March	234.59	39.11	2.0868	36.04	75.20
April	212.00	41.73	1.8852	36.04	67.93
May	189.37	39.23	1.6815	36.04	60.59
June	165.40	36.97	1.4667	36.04	52.85
July	159.46	33.01	1.4164	36.04	51.04
August	163.67	31.36	1.4751	36.04	53.16
September	172.47	31.47	1.5354	36.04	55.32
October	195.61	37.26	1.7380	36.04	62.63
November	203.17	36.52	1.8102	36.04	65.23
December	210.00	31.64	1.8937	36.04	68.24

Figure 20 depicts the P-V characteristics under the real metrological data for month of January to April. The intensity of the irradiance varies directly with power output and current. The maximum output power was 75.20 W in the month of March and minimum output power was 67.58 W in the month of January. Consequently, Figure 21 depicts the I-V characteristic curve under the real metrological data for the month of January to April. The voltage remains the same for the values of the irradiance. The output current decreases as the value of irradiance decreases. The minimum value of current was 1.8755 A in the month of January. The maximum current (2.0868 A) was attained in the month of March. This is due to the high intensity of the irradiance experience during the month.

Figure 22 depicts the PV characteristics under the real metrological data for the month of May to August. The intensity of the irradiance varies directly with power output and current from May to August. The minimum value of power (51.04 W) was attained in the month of July. This is due to drop in the intensity of the irradiance experience during the month as result of cloud covered and/or heavy rainfall. Figure 23 depicts the I-V characteristic curve under the real metrological data for the month of May to August. The voltage remains the same for the values of the irradiance. The output current decreases as the value of irradiance decreases. The minimum value of current (1.4164 A) was attained in the month of July. This is due to drop in the intensity of the irradiance experience during the month as result of cloud covered and/or heavy rainfall.

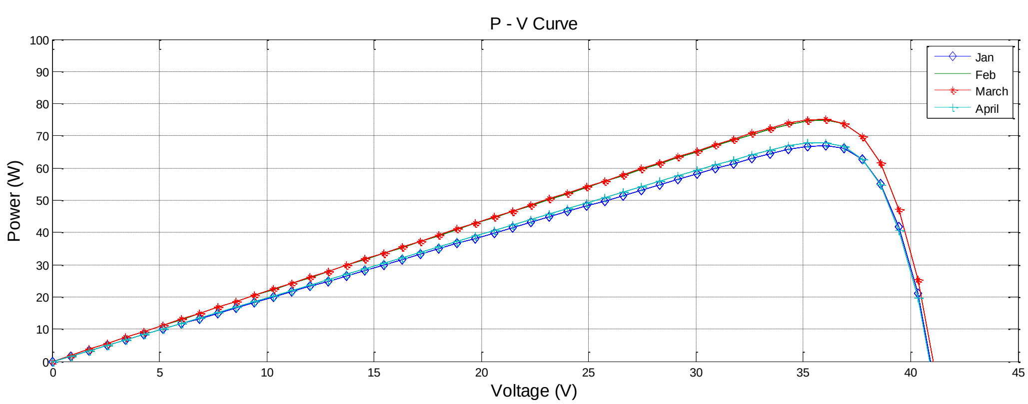


Figure 20: P-V characteristic curve for the month of January to April

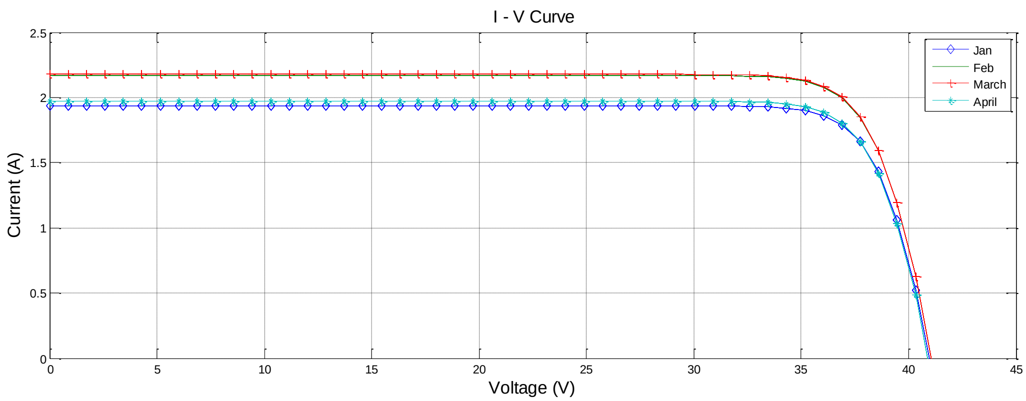


Figure 21: I-V characteristic curve for the month of January to December

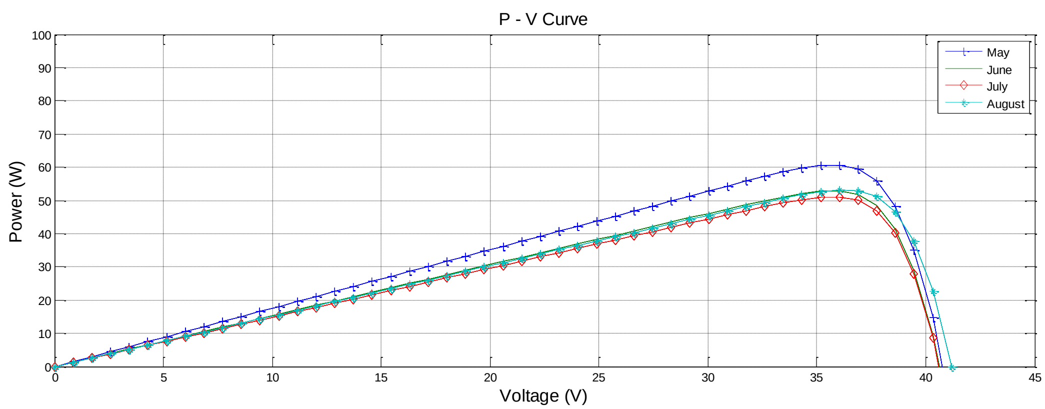


Figure 22: P-V characteristic curve for the month of May to August

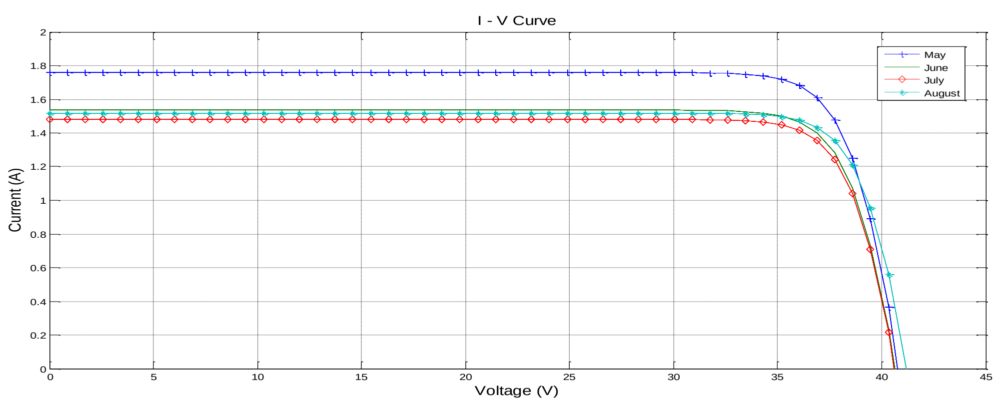


Figure 23: I-V characteristic curve for the month of May to August

Figure 24 depicts the P -V characteristics under the real metrological data for the month of September to December. The intensity of the irradiance is directly proportional to both power output and current. The maximum output power was 68.24 W in the month of December and minimum output power was 55.32 W in the month of December. Figure 25 depicts the I-V characteristic curve under the real metrological data for the month of September to December. The voltage remains the same for the values of the irradiance.

The output current and power increase as the values of irradiance increase from September to December. The minimum and maximum value of current were 1.5354 A and 1.8937 A respectively.

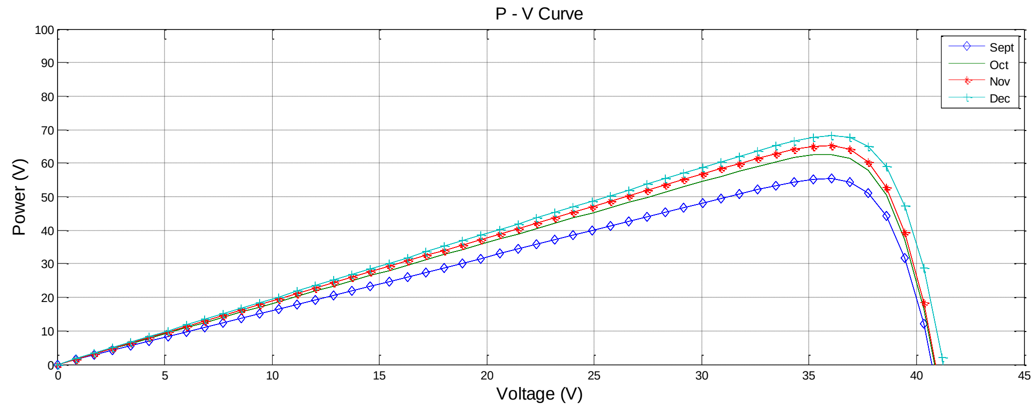


Figure 24: P-V characteristic curve for the month of September to December

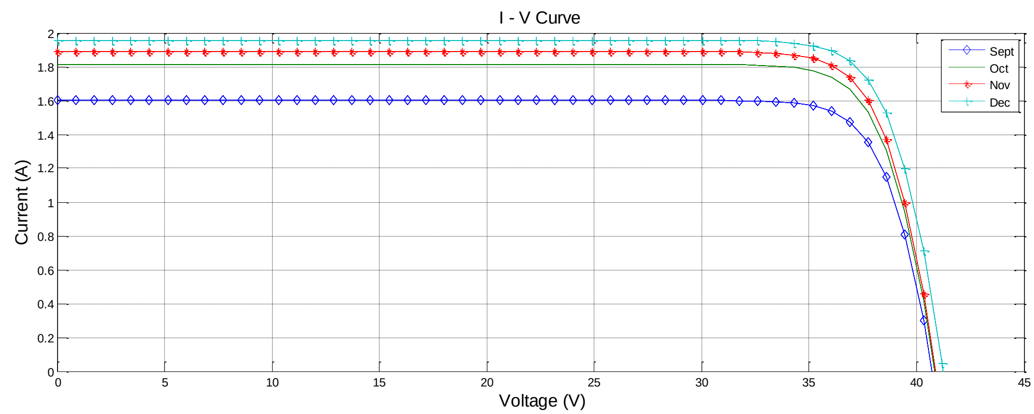


Figure 25: I-V characteristic curve for the month of September to December

4. CONCLUSION

The Prime Solar PV model was developed based on PV mathematical equations, the electrical features of PV provided by the manufacturer and environmental parameters (radiation and temperature). The open circuit I-V and P-V curves were obtained from the simulation of the PV module developed under MATLAB/Simulink environment using step by step approach. The simulated results showed a good agreement when compared with manufacture data. The metrological data of Maiduguri, Nigeria was also used to assess the performance parameter prediction of the developed model. The model can stand as a tool for the designers in the area of PV to test/assess whether the designed specification are met.

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