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ELECTRICAL PARAMETERS ESTIMATION OF SOLAR PHOTOVOLTAIC MODULE

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ABSTRACT

Environmental Weather conditions such as ambient temperature and solar irradiance have significant impact on predicting I-V and P-V characteristics of solar PV modules. Electrical parameters of solar PV modules at site of installation differ from those provided by the manufacturer due to variation in environmental conditions such as solar irradiance and ambient temperature. This paper estimates electrical parameters of a monocrystalline solar photovoltaic module (SW 250) with respect to Maiduguri weather conditions. A simple one-diode mathematical model was implemented using MATLAB script which predicts the I-V and P-V characteristics of the solar PV module based on Local Operating Conditions (LOC) i.e Maiduguri environmental weather conditions. Simulation results confirmed that electrical parameters at LOC differ slightly with that provided by the manufacturer at Standard Test Conditions (STC) and Nominal Operating Cell Temperatures (NOCT). The results show that the short circuit current and the peak current at LOC are 8.7% and 9.5% less than that at NOCT respectively, while the open circuit voltage and the peak voltage at LOC differed by 15% and 7.5% to that at NOCT respectively. The maximum power at LOC is 17.5% less than that provided by the manufacturer at NOCT. Thus the photovoltaic module exhibited good performance in the region under study.

Keywords- *Photovoltaic module, short circuit current, irradiance, temperature, open circuit voltage*

INTRODUCTION

Renewable energy sources are gaining more interest in recent years. Solar Photovoltaic (PV) technology is one of the renewable energy generation systems that have enormous potential and can provide suitable solution for domestic power requirements. It offers several advantages such as minimal maintenance requirement and free environmental pollution. Solar Photovoltaic system can be used for a wide range of electrical energy requirements, including; solar home systems, water pumping, refrigeration, telecommunications etc. These applications have positive social and economic impact on the lives of individual users, business and communities. Solar cells are devices that convert photons into electric potential in a PN silicon junction (or other material). It generates voltage in the range of 0.5 to 0.8 volts depending on cell technology been used. Light of certain wavelengths is able to ionize the atoms in the silicon and the internal field produced by the junction separates some of the positive charges (holes) from the negative charges (electrons) within the PV device. The holes are swept into the p-layer and the electrons are swept into n-layer. Although these opposite charges are attracted to each other, most of them can only recombine by passing through an external circuit outside the material because of the internal potential energy barrier. [1]. The current–voltage (I–V) characteristic of the solar cell describes its electrical performance. These I–V characteristics are determined by parameters such as diode saturation current, diode ideal factor, photo generated current, series, and shunt resistance. These parameters depend, in turn, on the solar cell structure, material properties and operating conditions [2]. The most important electrical characteristics of a PV module are the short-circuit current I_{sc}, open-circuit voltage V_{oc},, the fill factor FF and the maximum power output P_{max},. Electrical output of a single cell is usually insufficient for most applications. Therefore, the individual solar cells must be connected together to give the appropriate current and voltage levels and they must also be protected from damage by the environment in which they operate. There are two basic connection methods: series connection as shown in Fig 1., in which the top contact of each cell is connected to the bottom contact of the next cell in the sequence, and parallel connection as shown in Fig 2., in which all the top contacts are connected together, as are all the bottom contacts. In both cases, this results in just two electrical connection points for the group of cells. The current output of the series string is equivalent to the current of a single cell, but the voltage output is increased, being an addition of the voltages from all the cells in the string. In the parallel connection, the current from the cell group is equivalent to the addition of the current from each cell, but the voltage remains equivalent to that of a single cell.

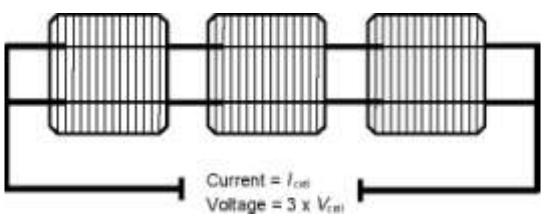


Fig 1: Cells Connected in Series

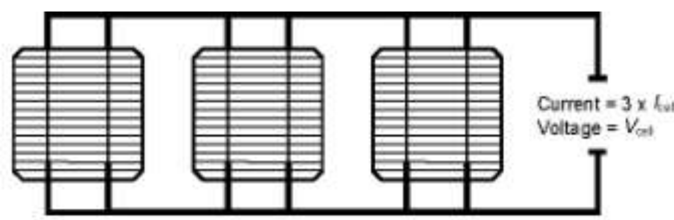


Fig 2: Cells Connected in Parallel

This electrically connected environmentally protected unit is usually termed a photovoltaic module. The electrical output of the module depends on the size and number of cells, their electrical interconnection, and, of course, on the environmental conditions to which the module is exposed. There are essentially three different types of PV modules, Crystalline Silicon, Amorphous Silicon and other Thin Film technology PV Panels. Crystalline Silicon modules are the oldest, most reliable and highly efficient PV modules in the market today. Crystalline modules can be further divided into Mono-Crystalline and Poly-Crystalline modules. Solar PV module can be used alone or connected in an electrical circuit with other similar modules to form a photovoltaic array. Knowledge of PV Module electrical parameters is essential to predetermine the behaviour of the modules subjected to various weather conditions. There have been various papers on effect of environmental factors on PV module performance. Francisco [3] estimated electrical behaviour of solar cell with respect to changes on environmental parameters. Similarly, Ibrahim in [4] investigated the performance and parameters of photovoltaic single crystalline silicon (Si) solar cell at different conditions of solar irradiance and tilt angle while Ghoneim et al. [5] investigated the effects of temperature and radiation intensity on the performance parameters of amorphous hydrogenated silicon (a-Si:H) photovoltaic module.

On the other hand Kerr and Cuevas [6] presented a new technique that can determine the current–voltage (I–V) characteristics of PV modules based on measuring the open-circuit voltage (Voc) as a function of a light intensity. Likewise, Christopher et al. [7] examined the performance of PV model based on actual measured parameters to accurately predict PV system energy production. Chegaar and Mialhe [8] examined the effects of global and diffuse solar radiation incident on solar cells using a spectral transmittance model for varying atmospheric conditions on the site of Algiers. Alonso and Garcia[9] compared performance of different module designs and the influence of module temperature on system predictions based on NOCT. Environmental Weather conditions such as ambient temperature and solar irradiance have significant impact on predicting I-V and P-V characteristics of solar panels. However, electrical parameters of solar PV modules at site of installation differ from those provided by the manufacturer under Standard Test Conditions (STC) and Nominal Operating Cell Temperatures (NOCT) conditions due to variation in environmental weather conditions such as solar irradiance and ambient temperature. This paper estimates electrical parameters and predict I-V, P-V characteristics of a monocrystalline solar photovoltaic (PV) module with respect to Maiduguri weather conditions. A simple one-diode mathematical model is used to estimate electrical parameters of a solar PV module and predict the I-V and P-V characteristics of the PV panel.

METHODOLOGY

A simple one-diode model is derived from the physics of the p-n junction to describe the electrical characteristics of solar cell. When there is no light present to generate any current, the PV cell behaves like a diode i.e. a p-n junction. It produces neither a current nor a voltage. However, if it is connected to an external supply it generates an current I_s, called diode saturation current or dark current . As the intensity of incident light increases, current is generated by the PV cell. The equivalent circuit of the model which consists of a photo current, a diode, a parallel resistor R_p expressing a leakage current, and a series resistor R_s describing an internal resistance to the current flow is shown in Fig 3.

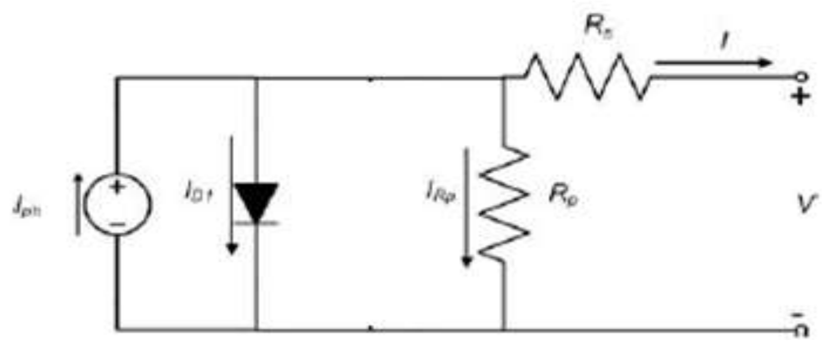


Fig 3: Equivalent Circuit of one-diode Model of a Solar Cell,

Using Kirchhoff's first law, the terminal current of the cell is:

$$I = I_{ph} - I_{sat}\left\{\exp^{\frac{q(V+IR_s)}{nkT}} - 1\right\} - \frac{V+IR_s}{R_p} \quad (1)$$

Where n is an ideal factor, q is the elementary charge of value 1.6x10^{-19} Coulombs, k is a Boltzmann's constant of value 1.38x10^{-23} J/K, $\mathrm{I_{sat}}$is the diode saturation current, $\mathrm{I_{ph}}$ is the light-generated current which is directly proportional to the light falling on the cell i.e solar irradiance G, linearly related to cell temperature T, and depends on the materials used and fabrication processes.

The photo generated current is given as:

$$\mathrm{I_{ph}} = \mathrm{I_{sc}^*}\left(\frac{\mathrm{G}}{\mathrm{G^*}}\right)(1 + \mathrm{K_o}(\mathrm{T} - \mathrm{T^*}))$$

(2)

Where $\mathrm{I_{sc}^*}$, $\mathrm{G^*}$, $\mathrm{T^*}$ are the cell's short-circuit current , solar irradiance and cell's temperature at Standard Test Conditions (STC) respectively. $\mathrm{K_o}$ is the cell's short-circuit current temperature coefficient.

$$\mathrm{K_o} = \frac{\mathrm{I_{sc(T_1)}} - \mathrm{I_{sc}^*}}{\mathrm{T_1} - \mathrm{T^*}}$$

(3)

On the other hand, the cell's saturation current varies with the cell temperature, which is described as

$$\mathrm{I_{sat}} = \frac{\mathrm{I_{sc}^*}\left(\frac{\mathrm{T}}{\mathrm{T^*}}\right)^{\left(\frac{3}{\mathrm{n}}\right)} \exp\left[\frac{-\mathrm{qE_G}}{\mathrm{nk}}\left(\frac{1}{\mathrm{T}} - \frac{1}{\mathrm{T^*}}\right)\right]}{\exp\left(\frac{\mathrm{qV_{oc}^*}}{\mathrm{nkT^*}}\right) - 1}$$

(4)

Where $\mathrm{E_G}$ is the band-gap energy of the semiconductor used in the cell. Band gap of silicon is 1.12eV and that of germanium 0.66eV [10].The saturation current $\mathrm{I_{sat}}$ depends on the diffusion coefficient of electrons and holes and is highly sensitive to temperature changes. The saturation current at reference temperature $\mathrm{T^*}$ is given as:

$$\mathrm{I_{sat}^*} = \frac{\mathrm{I_{sc}^*}}{e^{\frac{\mathrm{qV_{oc}^*}}{\mathrm{nkT^*}}} - 1}$$

(5)

Series resistance inside each cell is :

$$\mathrm{R_s} = -\left[\left.\frac{\mathrm{dV}}{\mathrm{dI}}\right|_{\mathrm{V=V_{oc}}} + \frac{1}{\mathrm{X_V}}\right]$$

(6)

$$X_v = I_{sat}^* \cdot \frac{q}{nkT} e^{\frac{qV_{oc}}{nkT}} - \frac{1}{X_V}$$

(7)

Short circuit current is the greatest value of the current generated by a cell. It is produce by the short circuit conditions i.e V=0. Since normally $\mathrm{I_{ph}} >> \mathrm{I_{sat}}$ and ignoring the small diode and ground-leakage currents under zero-terminal voltage, the short-circuit current $\mathrm{I_{sc}}$ is approximately equal to the photocurrent $\mathrm{I_{ph}}$.

$$\mathrm{I_{sc}} = \mathrm{I_{ph}}$$

(8)

Open circuit voltage correspond to the voltage drop across the diode (p-n junction), when it is transverse by the photocurrent I_{ph}, namely when the generated currents $I = 0$. It reflects the voltage of the cell in the night and it can be mathematically expressed as:

$$V_{oc} = V_t \ln\left(\frac{I_{ph}}{I_{sat}}\right)$$

(9)

Where V_t is the thermal voltage [8]

$$V_t = \frac{nkT}{q}$$

(10)

The temperature of solar cell T significantly affects the output power of a solar module and it depends exclusively on the irradiation G and on the ambient temperature T_a, according to the equation:

$$T = T_a + \beta G$$

(11)

Where β is a constant given as

$$\beta = \frac{T^{*} - T_1}{G^{*}}$$

(12)

Solar PV Module

In most commercial PV products, PV cells are generally connected in series configuration to form a PV module in order to obtain adequate working voltage. PV modules are then arranged in series-parallel structure to achieve desired power output.

Let N_s and N_p be the number of cells in series and in parallel in one PV module respectively. The output voltage V_p and current I_p of the module are given by:

$$V_p = N_s \,.\, V$$

(13)

$$I_p = N_p \,.\, I$$

(14)

The maximum power can be expressed as

$$P_{max} = V_{max} \quad I_{max} = \gamma V_{oc}\, I_{sc}$$

(15)

where V_{max} and I_{max} are terminal voltage and output current of PV module at Maximum Power Point (MPP), and γ is the cell Fill Factor (FF) which is the ratio of the maximum power that can be delivered to the load and the product of V_{oc} and I_{sc}.

$$FF = \frac{P_{max}}{V_{oc} I_{sc}} = \frac{I_{max} V_{max}}{V_{oc} I_{sc}}$$

(16)

Module efficiency η is

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{max} V_{max}}{P_{in}}$$

(17)

Where P_{in} is the incident power,

$$P_{in} = E * A$$
(18)

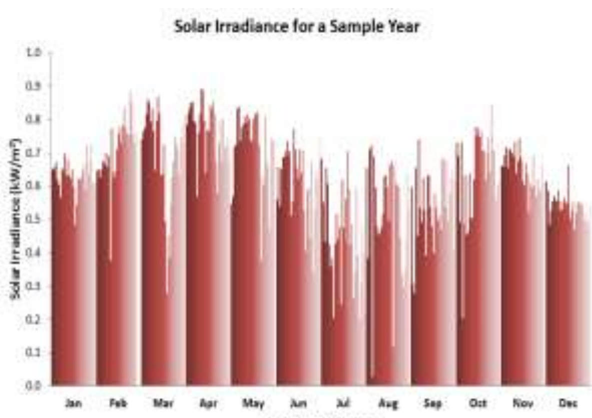
Where E is the plane of array irradiance of the incident light in [kW/m] and A is the surface area of the solar cell including the frames in meters. Energy that can be generated from the unit area of the module is given as the product of the efficiency of the module and the average daily radiation at that location.

$$Em = \eta * \varphi$$
(19)

Where Em is the Electricity generated in kWh/m^2/day, η is the module efficiency, φ is the average daily radiation in kWh/m^2/day.

RESULTS AND DISCUSSION

The SW 250 PV module was chosen for the estimation of electrical parameters due to its wide applications in developing countries such as Nigeria. The module provides 226 watt of nominal maximum power, and has 60 series connected monocrystalline silicon cells. The model of the PV module was implemented using a MATLAB program. Newton-Raphson method is used to solve systems of nonlinear equations i.e enq(1), eqn(7). The model electrical parameters(currents, voltages and power) are estimated using temperature and irradiance obtained from Nigerian Meteorological Department for Maiduguri metropolis which has relatively higher daily insolation ranging from 5kWh/m^2/day to 7kWh/m^2/day and higher solar altitude throughout the year, the average solar radiation is about 550 W/m^2. The data covered mainly twelve months (January to December) of the year 2010. Fig. 4 shows an annual solar irradiance for the year 2010. The figure shows that average daily insolation varies largely with periods. The sunniest month in the year which is April gets average insolation of 0.8kW/m^2, about 37.5% more than the least sunny month in the year i.e August which received average insolation of 0.5kW/m^2 . Also the average insolation throughout the year is about 0.6kW/m^2. Fig. 5 shows annual ambient temperature for the year 2010. The figure reveals that month of April has the highest average temperature of about 43^{o}C while month of August has the lowest average temperature of about 31^{o}C which is 38.7% less than the highest average temperature. The average temperature of the year is 37^{o}C, about 48% more than the temperature at STC.



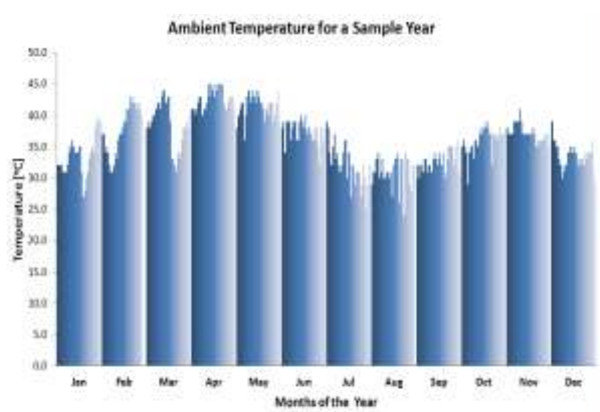


Fig 4: Annual Solar Irradiance Vs Months **Fig 5: Annual Ambient Temperature Vs Months**

Fig 6 and Fig 7 show I-V and P-V curves of the module under three different operating conditions (STC, NOCT and LOC). It is observed that module's short circuit current at LOC differed significantly with short current at STC which was provided by the manufacturer. Short circuit current at LOC is 1.4 times less than short circuit current at STC but the voltage remains almost the same. The least sunny month received nearly 11 times less power than the theoretical peak value at STC. It is also observed that there's a very large difference between the power at STC quoted in the datasheets and the true average power output of a solar panel at the site of installation. This indicates that irradiance has insignificant effect on the output current than the output voltage. This means that generation of electron-hole pair in the photovoltaic module which leads to increase in the mobility within the p-n junction increases current of the module. This indicates that module power is directly dependant on the amount of solar irradiation striking the surface of the PV module. It is also observed that power generated by the module is strongly dependant on location and local weather conditions.

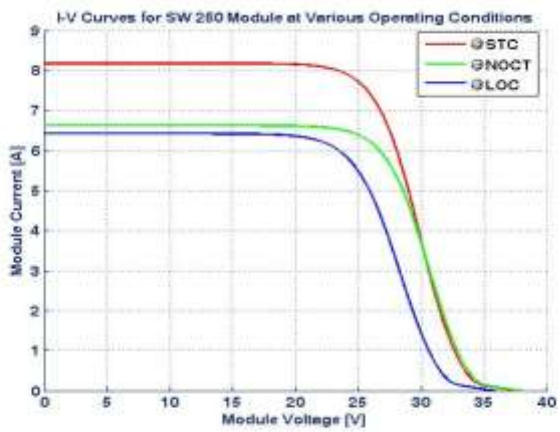


Fig 6: I – V Curves of SW 250 Module at Various Operating Conditions

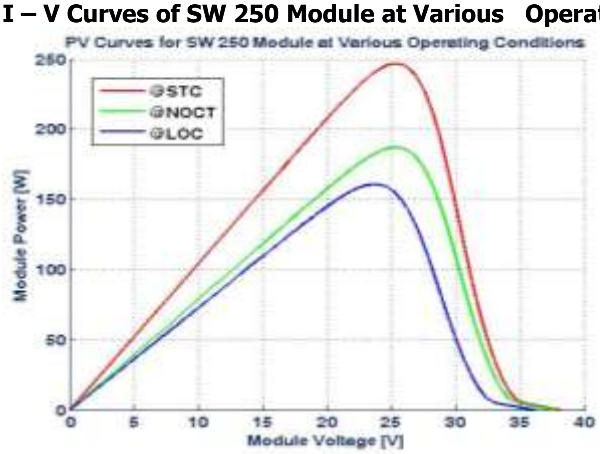


Fig 7: P – V Curves for SW 250 Module at Various Operating Conditions.

Fig 8 shows electrical parameters of SW 250 Solar PV module at LOC. The results show that P_{max} at LOC is about 17.5 % less than the maximum power at NOCT. Similarly, V_{oc}, I_p and I_{sc} at LOC are 7.5% , 9.5% and 8.7% respectively less than that at NOCT. This indicates that environment conditions significantly influence electrical parameters of a Solar PV module. The electrical parameters of SW 250 Solar Module for the three operating conditions are shown in table 1.

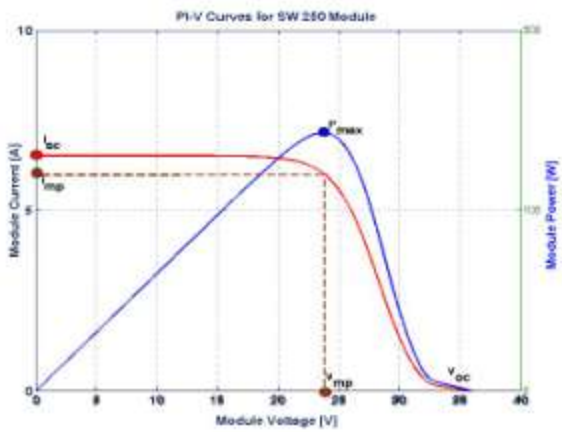


Fig 8: Electrical Parameters of SW 250 Solar Module

Table 1: Electrical Parameters of SW 250 at various operating conditions

SW 250 Monocrystalline SunModule Parameters				
Electrical Parameters		***STC G = 1000 W/M^2 T= 25^{o}C [11]***	***NOCT G = 800 W/M^2 T = 20^{o}C [11]***	***LOC G = 550 W/M^2 T = 37^{o}C***
Maximum Power	P_{mp}	250 W	183.3 W	151.2 W
Voltage @ V_{mp}	V_{mp}	31.1 V	28.5 V	24.2 V
Current @ i_{mp}	I_{mp}	8.05 A	6.44 A	5.83 A
Open circuit Voltage	*Voc*	37.8 V	34.6 V	32 V
Short circuit Current	*Isc*	8.28 A	6.68 A	6.1 A

CONCLUSION

A simple one-diode mathematical model was implemented using MATLAB script which predicts the I-V and P-V characteristics of the solar PV module based on Local Operating Conditions (LOC). Simulation results show that electrical parameters of solar PV modules at site of installation differ from those provided by the manufacturer due to variation in environmental conditions such as solar irradiance and ambient temperature

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