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Experimental Determination of Photovoltaic Array Model Parameters

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ABSTRACT

This paper aims at determining the model parameters of a photovoltaic array installed at the Faculty of Engineering and Engineering Technology of Abubakar Tafawa Balewa University Bauchi, Nigeria. The mathematical model of the photovoltaic array is first deduced from the electrical equivalent circuit of the solar cell. The model parameters are essential in order to be able to evaluate the performance of the Photovoltaic (PV) array under all operating conditions. The popular method for determining the model parameters is to rely on the manufacturer's datasheet specification as model input. This approach will not yield very accurate model parameters because it is not representative of the actual field performance of the array. An alternative and more accurate method for the determination of model parameters is presented in this paper. It involves getting the model input specification from measured data rather than relying on the manufacture's datasheet. Measured data for sunny, cloudy and Harmattan conditions has been obtained and used to completely specify and determine the PV array model parameters.

Key Words:*Solar Cell, Pv Array, Model Parameters, Experimental Determination, Measured Data, Operating Conditions*

1. INTRODUCTION

There are numerous reasons for the recent increase in the use of photovoltaic energy option. The most important reason is the fact that conventional and non-renewable energy sources are exhaustible and that they are becoming more and more expensive. Another important issue is the impact of the energy technologies on the environment. It is well known that the burning of fossil fuel is responsible for both air pollution and greenhouse effects. Furthermore, nuclear energy option is not always recommended because it is afflicted with a possible danger and the problem of nuclear waste storage. In contrast to these, the advantage of the photovoltaic generated energy is apparent. It is a clean energy technology that can generate electricity on-site where it is needed, avoiding transport losses and requiring little or no maintenance. There are currently many programmes that are designed to support projects aimed at providing utilities with access and familiarity with photovoltaic energy technologies. For these reasons, it is mandatory to improve the know-how and skills in this promising renewable energy field.

The determination of the characteristics of a photovoltaic array is a pre-requisite for designing and sizing a photovoltaic power supply. This is why we are interested in modeling a photovoltaic array. The knowledge of the model parameters is essential in evaluating the PV array behavior under all operating conditions. Unfortunately however, the manufacturers give just the electrical features of the PV array under Standard Test Conditions (STC). This explains the recent focus on the identification of the unknown parameters of a PV array to reflect actual field operating conditions.
In this paper, a model based on the single diode electrical equivalent circuit of the solar cell is used to deduce the model of the PV array under test. The parameters of the array model are then determined using experimental data that was taken to represent the actual field array performance for dry, cloudy, and Harmattan weather conditions. The obtained values are then compared with those determined using the Manufacturers provided data. The paper presents in detail the equations of the array and a brief statement on the method used to determine the parameter values.

2. MODELING THE PHOTOVOLTAIC ARRAY

A photovoltaic (PV) array is a large interconnection of solar cells which convert solar radiation into electricity. The basic component of a PV array is therefore the solar (photovoltaic) cell. Multiple cells are connected in series and parallel to form solar panels or modules, which are sold commercially and are generally suitable only for small scale load applications. In order to generate enough power for relatively large scale commercial power applications, solar modules are connected in series and parallel to create the required power.
Due to this modular nature of the PV array, its mathematical model can be deduced from the solar cell model as described in the following sections:

2.1 Non-ideal Solar Cell Model

Fig. 1 shows the equivalent circuit of the practical (non-ideal) solar cell [1]. The basic solar cell equation after applying Kirchhoff's current law to nodes '**a**' and '**b**' is given in equation (1) as:

$$\mathrm{I} = \mathrm{I_{pv}} - \mathrm{I_d} - \mathrm{I_p} \quad (1)$$

It is obvious from Fig. 1 that the shunt current, I_p is given by equation (2) as follows:

$$I_p = \frac{V+IR_s}{R_p} \quad (2)$$

Furthermore, from the theory of a p-n junction diode [6], the diode current, I_d may be expressed as in equation (3).

$$I_d = I_0\left\{e^{\frac{q(V+IR_s)}{nkT_c}} - 1\right\} \quad (3)$$

Substituting equations (2) and (3) into equation (1) results in equation (4) as follows:

$$I = I_{pv} - I_0\left\{e^{\frac{q(V+IR_s)}{nkT_c}} - 1\right\} - \frac{V+IR_s}{R_p} \quad (4)$$

Where I_{pv}= the generated photon current that depends on solar radiation.
I_0= the temperature depended diode saturation current.
I_p= the solar cell leakage current.
R_p= the parallel resistance that represents the internal losses across the diode.
R_s = joule losses.
V = solar cell output voltage.
I = solar cell terminal current.
N = diode idealizing factor.
K = Boltzmann's constant.
T_c = solar cell absolute temperature.
q = electronic charge.

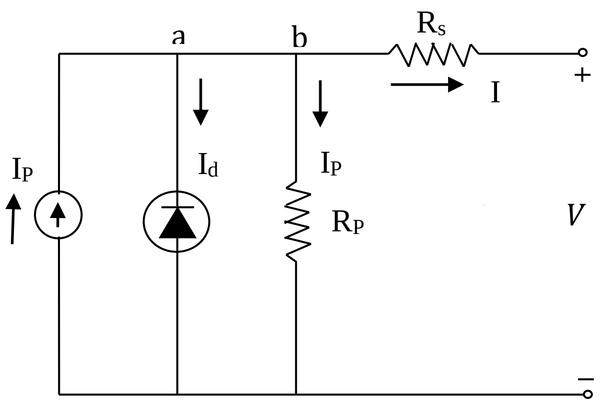

Figure 1: Equivalent Electrical Circuit of a Non-ideal Solar Cell

A solar cell is normally characterized by the following specifications:

- **Short circuit current (I_{sc}):** it is the greatest value of current generated by a solar cell. It is produced under short circuit condition when $V = 0$. Generally $I_{sc} = I_{pv}$.
- **Open circuit voltage (V_{oc}):** it is the voltage drop across the diode, when it is traversed by the photocurrent I_{pv} (i.e. $I_d = I_{pv}$) when the generated current is $I = 0$. It reflects the voltage of the cell at night and can be mathematically expressed as in equation (5).

$$V_{oc} = \frac{nkT_c}{q} \ln\left(\frac{I_{pv}}{I_0}\right) = nV_t \ln\left(\frac{I_{pv}}{I_0}\right) \quad (5)$$

Where $V_t = \frac{nkT_c}{q}$ = thermal voltage.

- **Maximum power point (MPP):** this is the operating point (V_{max}, I_{max}) at which the power dissipated in the resistive load is maximum. i.e. $P_{max} = I_{max} * V_{max}$.
- **Maximum efficiency (η):** this is the ratio of the maximum power and the incident light power. It is mathematically expressed by equation (6) as:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{max}*V_{max}}{A*G_{in}} \quad (6)$$

Where G_{in}= incident solar radiation and
A = solar cell area.

- **Fill Factor (FF):** this is the ratio of the maximum power that can be delivered to the load and the product of I_{sc} and V_{oc}. It is expressed mathematically as in equation (7).

$$FF = \frac{P_{max}}{I_{sc}*V_{oc}} = \frac{I_{max}*V_{max}}{I_{sc}*V_{oc}} \quad (7)$$

The Fill Factor is a measure of the real I-V characteristics. Its value is higher than 0.7 for good cells.

2.2 Module Model

Solar cells are normally grouped into 'modules', which are encapsulated with various materials to protect the cells and the electrical connections from the environment. A typical photovoltaic module is composed of a series and parallel connection of solar cells. While a variety of connection schemes exist for a multitude of applications, a common scheme for PV modules is a connection of 36 or 72 cells in series.

In general, modules supplied by manufacturers may be considered as consisting of C_p parallel branches, each with C_s solar cells in series [2] as shown in Fig. 2.

The model for the PV module is obtained by replacing each cell in Fig.2 by its equivalent circuit of Fig.1. It can then be easily shown that the PV module's current I^M under arbitrary operating conditions can be described by equation (8) as:

$$I^M = I_{pv}^M - I_0^M\left\{e^{\frac{q(V^M+I^M R_s^M)}{nkT_c}} - 1\right\} - \frac{V^M+I^M R_s^M}{R_p^M} \quad (8)$$

Where $I_{pv}^M = C_p I_{pv}$ = module generated photon current.
$I_0^M = C_p I_0$ = temperature dependent module saturation current.
$I^M = C_p I$ = module terminal current.
$V^M = C_s V$ = module output voltage.

$R_s^M = \frac{C_s}{C_p} R_s$ = module series resistance.

$R_p^M = \frac{C_s}{C_p} R_p$ = module parallel resistance.

2.3 Array Model

A photovoltaic array is composed of series and parallel connection of solar modules. The number of modules connected in series and parallel is based on the voltage requirements of the system and the desired power output of the array.

The desired array size is selected by first connecting a number of modules in series string to give the correct voltage requirement. Thereafter, additional strings of the same number of modules may be added to increase the current production and therefore the power capability of the array.

Fig.3 (a) shows an array composed of M_s modules in series. For this type of array connection, it is apparent that the output voltage is increased proportionately to M_s while the output current remains unchanged. Similarly, the equivalent series and parallel resistances are directly proportional to the number of modules (M_s).

Fig.3 (b) shows an array composed of M_p modules in parallel. In this type of array connection, there is an increased output current proportional to M_p and the output voltage is unchanged. Similarly, the equivalent series and parallel resistances are inversely proportional to the number of parallel modules, M_p

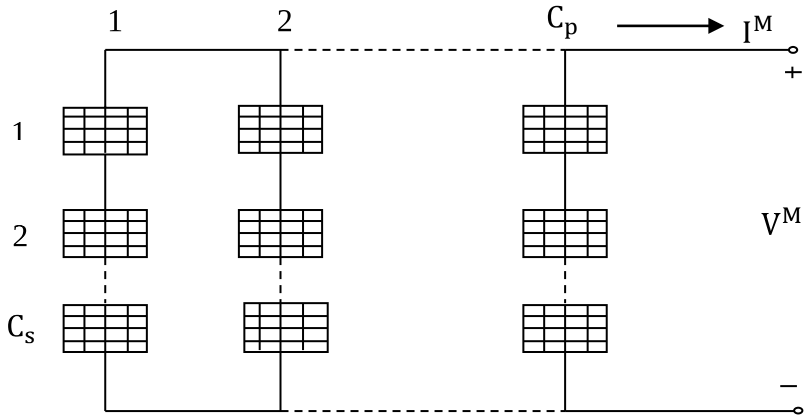

Figure 2: A typical PV Module consisting of C_p parallel branches,each with C_s Solar Cells, in series.

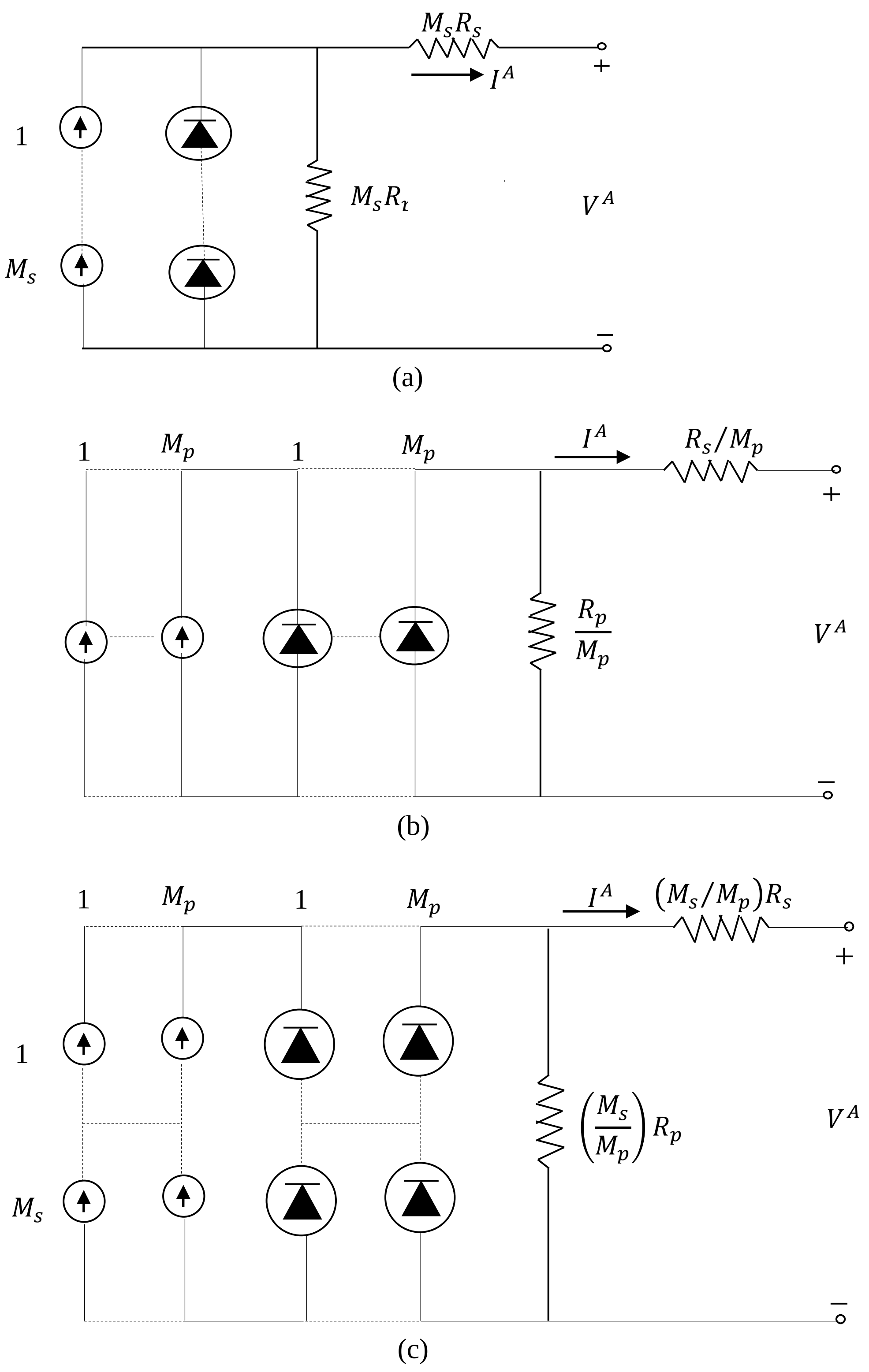

Fig. 3 (a): Array of M_s modules in series, (b) Array of M_p modules in parallel, (c) Array of $M_s x M_p$ Modules connected in series and parallel.

Fig.3(c) shows a photovoltaic array composed of $M_s x M_p$ modules connected in series and parallel. For an array with this type of module connection, the following I-V equation (9) describing its performance can be easily deduced:

$$I^A = I_{pv}^A - I_0^A \left\{ e^{\frac{q\left(V^A + I^A R_s^A\right)}{nkT_c}} - 1 \right\} - \frac{V^A + I^A R_s^A}{R_p^A} \quad (9)$$

Where $I_{pv}^A = M_p I_{pv}^M = M_p C_p I_{pv}$ = array generated photon current.

$I_0^A = M_p I_0^M = M_p C_p I_0$ = temperature dependent array saturation current.

$I^A = M_p I^M = M_p C_p I$ = array terminalurrent.

$V^A = M_s V^M = M_s C_s V$ = array output voltage.

$R_s^A = \frac{M_s}{M_p} R_s^M = \frac{M_s}{M_p} \frac{C_s}{C_p} R_s$ = array series resistance.

$R_p^A = \frac{M_s}{M_p} R_p^M = \frac{M_s}{M_p} \frac{C_s}{C_p} R_p$ = array parallel resistance.

3. PV ARRAY DESCRIPTION AND DATA COLLECTION

The photovoltaic array that is being characterized is installed at the Faculty of Engineering and Engineering Technology of Abubakar Tafawa Balewa University, Bauchi, Nigeria. It consists of ten 53 watts polycrystalline Kyocera solar modules. The ten modules are however, connected into two separate but identical sub-array systems. Each sub-array consists of five modules connected in parallel with a total rated power of 265 watts. Each module in the array system contains 36 solar cells connected in series. Both sub-arrays are fixed and tilted towards the south at an angle of 30 degrees.

3.1 Data Collection

Solar radiation, cell temperature and current/voltage data for the PV array was measured for a total of 30 days spread over a period of 1 year (starting from August 2009 to August 2010). The 12 months of the 1 year period were divided into 3 seasons within which 10 days of data measurements/collection was carried-out for each season.

In this seasonal division, **Rainy season** consists of the months August 2009, September 2009, June 2010 and July 2010**;** **Harmattan season** consists of the months October 2009, November 2009, December 2009 and January 2010**;** **Dry season** consists of the months February 2010, March 2010, April 2010 and May 2010. Within the Rainy season, readings were taken on ten selected cloudy days. Similarly, readings were taken on ten selected extremely dusty days within the Harmattan season, while ten clear and sunny days were selected for the Dry season. Radiation data was then averaged for **clear sunny**, **cloudy** and **Harmattan** days resulting in three seasonal average radiation data sets. Similarly, cell temperature and current/voltage measurements were averaged for each weather condition.

4. PV ARRAY MODEL PARAMETERS IDENTIFICATION PROCESS

From the PV array equation (9), there are five unknown model parameters that need to be determined. They are: $I_{pv}^A, I_0^A, n, R_s^A$, and R_p^A. However, in order to determine the values of these parameters, the following module specification information that is normally supplied by manufacturers is needed as input [3]:

- Short circuit current (I_{sc})
- Open circuit voltage (V_{oc})
- Maximum power point current (I_{mp})
- Maximum power point voltage (V_{mp})
- Slope of the module's I-V curve at short circuit point ($\frac{dI}{dV}$ $_{V=0}$)

Sections (4.1) and (4.2) explain the procedure for determining the values for the five unknown parameters using information from the manufacturers' datasheet and the measured data respectively.

4.1 Determination of Model Parameters from Data Sheet Values

The procedure to numerically determine the PV array model parameters using the module's datasheet information is well documented by [4]. The method involves finding five independent equations involving the five unknown parameters by using the datasheet information. The five systems of equations are then solved simultaneously using Newton's numerical method to determine the model parameters. Thereafter the resultant current/voltage equation gives a continuous analytical expression of current as a function of voltage, at a reference irradiance and cell temperature. Under new values of irradiance and cell temperature, the values of some of the parameters will change appropriately and therefore need to be updated for each set of new conditions.

4.2 Determination of Model Parameters Based on Measurements

The current/voltage (I-V) characteristic is the basic descriptor of the photovoltaic array. The measured current and voltage data is plotted between the short circuit current point (I_{sc}) – where the array produces maximum current and zero voltage, and the open circuit voltage point (V_{oc}) – where the array produces maximum voltage and zero current. This is then followed by the plot of the power/voltage (P-V) curve. From these curves, the following array specifications can be easily determined:

- I_{sc}^A - Array short circuit current.
- V_{oc}^A - Array open circuit voltage.
- V_{mp}^A - Array maximum power point voltage.

- I_{mp}^{A} - Array maximum power point current.
- P_{mp}^{A} - Array maximum power.
- R_{s}^{A} - Array series resistance.
- R_{p}^{A} - Array parallel resistance.

These new set of array field specifications are then used to determine the actual field performance model parameters for different sets of radiation and temperature values representative of the three weather conditions (rainy, dry and Harmattan).

5. EXPERIMENTAL RESULTS

In this section, field measurements and photovoltaic array performance results are presented for different climatic conditions at the site of the experimental photovoltaic array test rig. More specifically, long-term solar field measurements carried out at the site of the experimental photovoltaic array for all micro-climatic conditions, typified by harmattan, cloudy and clear sunny seasons, have been pre-processed statistically and plotted. Specifically, results of seasonal solar irradiance and temperature variations, PV array seasonal average I-V & P-V curves and the determined model parameter values are presented hereunder.

5.1 Results of Seasonal Solar Irradiance and Temperature Variations

The solar irradiance data has been processed for the three micro-climatic conditions viz.: Harmattan, Cloudy and Clear Sunny days; thereby resulting into three seasonal solar irradiance databases. Also, the temperature measurements were similarly processed for each micro-weather condition. The processed solar irradiance and temperature databases in, Excel, Origin and MATLAB environments have been plotted against time of day (hours) and offered in Figs. 4 – 9 for the three micro-climatic conditions. The min-max and average plot of the daily variation of solar irradiance and temperature against time for Clear Sunny days are depicted in Figs. 4 and 5, respectively. Similarly the average daily variation of solar irradiance and temperature plots versus time of day for Cloudy days are shown in Figs. 6 and 7, while those for Harmattan days are portrayed in Figs. 8 and 9. For completeness each plot also incorporates the min-max values for each hour. The import of the min-max is to convey at a glance the extent of variability of solar irradiance and temperatures over the sampled days for each micro-climatic condition.

In addition, fairly comprehensive statistical characterizations of midday solar irradiance and temperatures for the three seasons are summarized in Table 1. Note that the statistical information is based on all midday data with the highest solar irradiances and temperatures.

It is obvious from Table 1 that the average solar radiation and temperature for Clear Sunny, Cloudy and Harmattan days at the PV site are 950.8w/m^2 & 46^{0}C, 600w/m^2 & 38^{0}C and 586.7w/m^2 & 29^{0}C respectively

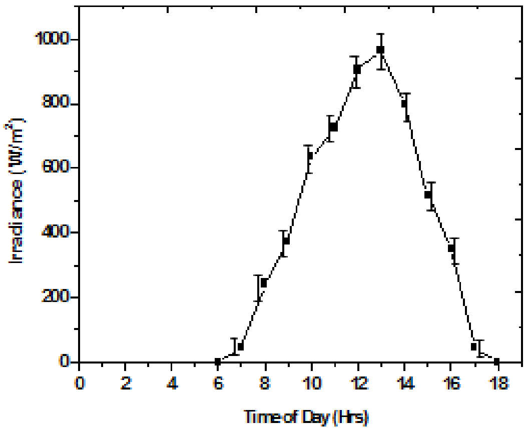

Figure 4: Plot of Irradiance versus Time of Day for Clear Sunny Days

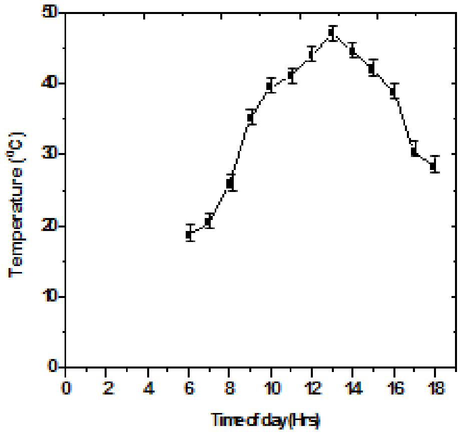

Figure 5: Plot of Temperature versus Time of Day for Clear Sunny Days

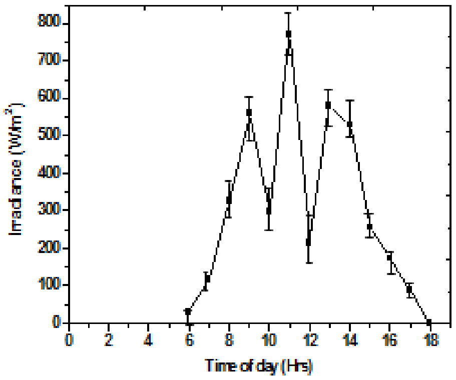

Figure 6: Plot of Irradiance versus Time of Day for Cloudy Days

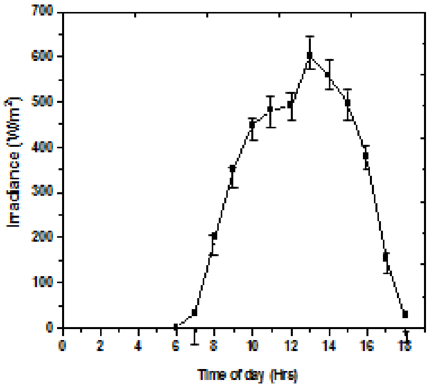

Figure 8: Plot of Irradiance versus Time of Day for Harmattan Days

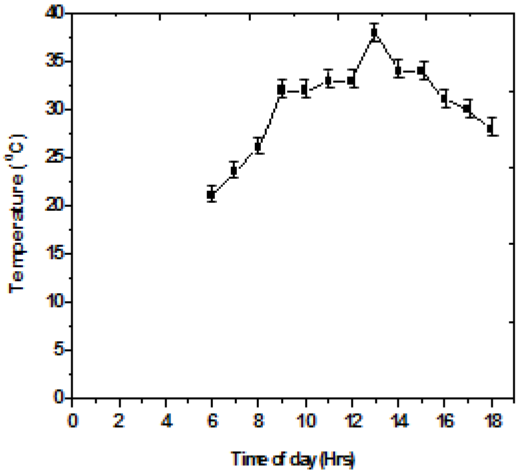

Figure 7: Plot of Temperature versus Time of Day for Cloudy Days

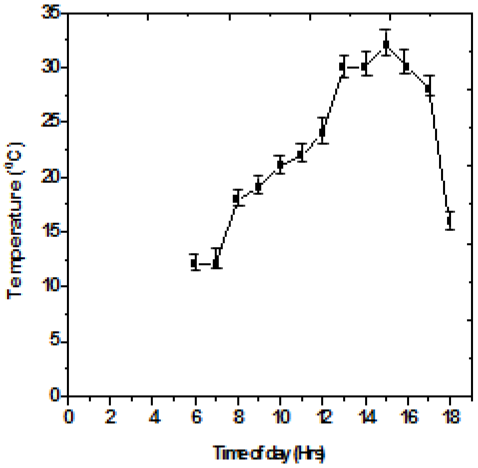

Figure 9: Plot of Temperature versus Time of Day for Harmattan Days

Table 1: Summary of Statistical Characterizations of Solar Irradiance and Temperature for the Observed Micro-climatic Seasons at Experimental PV Site

PV Measured Parameters	Statistical Information	Micro-climatic Seasons		
		Harmattan	Cloudy	Clear Sunny
Solar Irradiance (W/m^2)	Maximum	605	608	965.4
	Average	586.7	600	950.8
	Minimum	560	590	927.3
	Median	565.75	592.5	950.5
	Mode	592	598	950.4
Temperature (^{0}C)	Maximum	30	39.5	50
	Average	29	38	46
	Minimum	26.5	36	40.4
	Median	30.5	37.5	45.5
	Mode	30	38.5	45

5.2. Results of Field Data based PV Array Seasonal Average I-V and P-V Curves

The fairly large database created in excel was sorted according to each season. The data for each season was further processed to remove bad data points and subsequently weighted to evolve representative I-V curve characteristics for various seasons. The seasonal average I-V curves for clear sunny, cloudy and harmattan seasons so determined from field measurements are plotted in Figs. 10, 11 and 12, respectively. These figures constitute the benchmark I-V curves against which the PV array model parameter values are to be compared. The comparison of benchmark I-V characteristic curves for the three micro-climatic conditions all plotted on common axis for comparative purpose is shown in Fig. 13. Furthermore, the P-V curves for the three micro-climatic seasons plotted, using common axes, are depicted in Fig. 14.

5.3 Determined PV Array Model Parameter Values

The numerical solution of the PV array nonlinear equations was determined via Newton-Raphson technique for each average micro-climatic condition to give the desired model parameter values. These parameter values obtained in respect of the two analytic models (Datasheet and Measurement based) for each PV site climatic condition average irradiance and temperature are presented in Table 2.

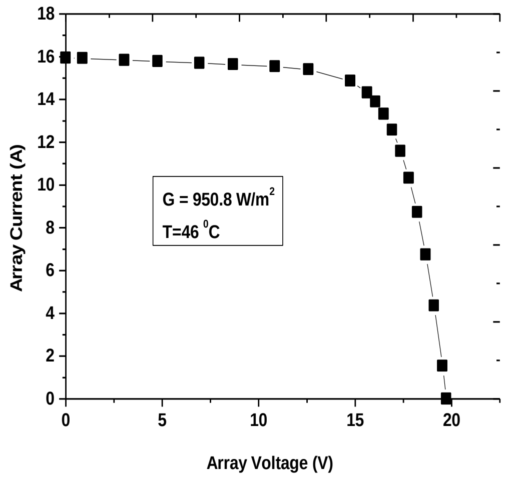

Figure 10: Seasonal Average Current versus Voltage Curve for Clear Sunny Season

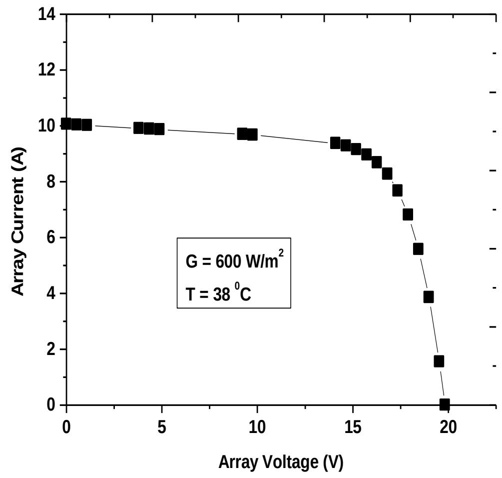

Figure 11: Seasonal Average Current versus Voltage Curve for Cloudy Season

6. CONCLUSION

The mathematical model the photovoltaic array installed at the Faculty of Engineering and Engineering Technology of Abubakar Tafawa Balewa University, Bauchi in Nigeria has been developed from the equivalent electrical circuit of the solar cell. The solar radiation, temperature, and Current/voltage measured data for selected clear sunny, cloudy and harmattan days has been obtained and plotted. From the obtained plots, the photovoltaic array can be completely specified. The PV array specifications can then be used as input to the model in determining its unknown parameters. In line with this, the PV array measurement based model parameters have been determined. The parameter values obtained do not only compare favourably well with those obtained through the use of the Manufacturers' datasheet, but are considered to be more accurate because they represent the actual field performance of the PV array.

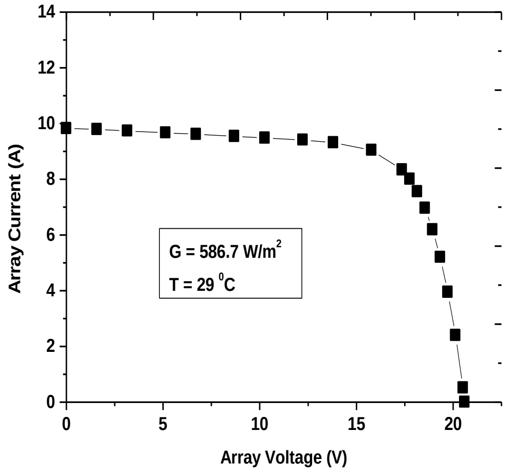

Figure 12: Seasonal Average Current versus Voltage Curve for Harmattan Season

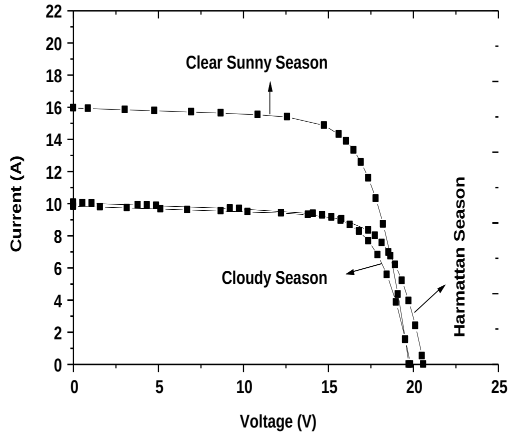

Figure 13: Seasonal Average I-V Curves for Harmattan, Cloudy and Clear Sunny Seasons.

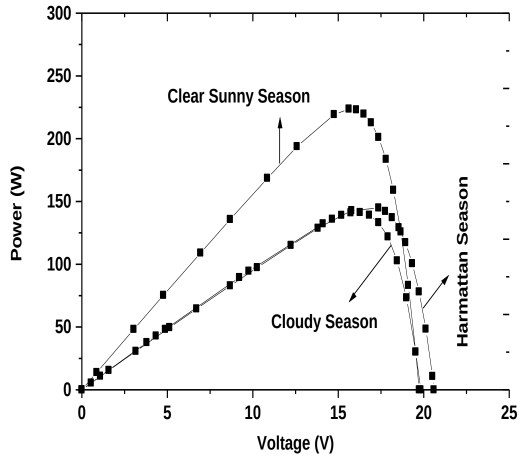

Figure 14: Seasonal Average P-V Curves for Harmattan, Cloudy and Clear Sunny Seasons.

Table 2: Determined PV Array Parameter Values per Climatic Condition

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Analytical Model Based on	Model Parameters	Parameter Values per Climatic Condition Harmattan+	Cloudy*	Clear Sunny**
Manufacturer's Datasheet	n	1.3	1.3	1.3
	$I_{pv}^{A}(A)$	16.777	16.774	16.771
	$I_{o}^{A}(A)$	1.1×10^{-6}	1.5×10^{-6}	1.5×10^{-6}
	$R_{s}^{A}(\Omega)$	0.047	0.043	0.039
	$R_{p}^{A}(\Omega)$	28.536	29.949	31.296
Field Measurement	n	1.56	1.56	1.56
	$I_{pv}^{A}(A)$	9.842	10.062	15.973
	$I_{o}^{A}(A)$	1.06×10^{-6}	2.0×10^{-6}	4.0×10^{-6}
	$R_{s}^{A}\Omega)$	0.042	0.047	0.046
	$R_{p}^{A}(\Omega)$	29.082	29.081	29.073

Average season Solar Irradiance = 586.7 W/m^2 & Average Seasonal Temperature = 29 °C

*: Average season Solar Irradiance = 600.0 W/m^2 & Average Seasonal Temperature = 38 °C

**: Average season Solar Irradiance = 950.8 W/m^2 & Average Seasonal Temperature = 46 °C

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