iJET EXPLORE International Journal of Engineering & Technology
CENTRE OF PROFESSIONAL RESEARCH PUBLICATIONS
ISSN 2049-3444

International Journal of Engineering and Technology Volume 5 No. 1, January, 2015

Effects of Temperature on Photovoltaic Array Conversion Efficiency and Fill Factor

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ABSTRACT

This paper presents the results of an in-depth study on the effects of temperature on photovoltaic array conversion efficiency and fill factor. Although there are well documented efforts on the effects of temperature on photovoltaic cell and module efficiencies, such efforts have not been extended to a complete array size. Although photovoltaic cell or module efficiency values may be analytically scaled to obtain corresponding array size values, this approach is not accurate due to obvious mismatch considerations. Furthermore, there are limited studies on the effect of temperature on the fill factor of photovoltaic arrays. In this paper, effort has been made to document clear effects of temperature on both conversion efficiency and fill factor of a photovoltaic array installed in the Faculty of Engineering and Engineering Technology of Abubakar Tafawa Balewa University, Bauchi, Nigeria. Measurements were carried out to obtain exact dependence of conversion efficiency and fill factor on temperature for the PV array. The measurements covered the 3 major microclimatic weather conditions of harmattan, cloudy and clear sunny seasons. Regression analysis is then performed on the data to obtain empirical relationships between fill factor and temperature and between temperature and conversion efficiency for all the seasons. The results show that the PV array has its highest energy conversion efficiency of 13.14% during harmattan, while having a least efficiency of 12.43% during the clear sunny season. Similarly, the PV array exhibits its highest fill factor of 0.756 during harmattan while having its least fill factor of 0.708 during the clear sunny season. Furthermore, the conversion efficiency of the array drops by $7356x10^{-5}$% $7262x10^{-5}$% and $7427x10^{-5}$% during harmattan, cloudy and clear sunny seasons respectively for every 1^{o}C rise in temperature while its fill factor drops by $116x10^{-5}$, $109x10^{-5}$ and $116x10^{-5}$ during harmattan, cloudy and clear sunny seasons respectively for every 1^{o}C rise in temperature.

Key Words:*Photovoltaic Array, Fill Factor, Conversion Efficiency, Temperature Effect, Stand-Alone*

1. INTRODUCTION

The concern for fossil fuels depletion and non-polluting ways of energy production is generally responsible for the rapid increase in the production and demand of photovoltaic cells. It has been established that photovoltaic (PV) power represents one of the most promising renewable energy in the world [1]. Unfortunately however, the use of photovoltaic energy is confronted by two main obstacles, which are:

- High initial cost and
- Very low PV cell conversion efficiency

The major concern of researchers over the years has been to find ways of increasing PV cell efficiency, since higher efficiency will translate to lower cost/watt of PV energy.
Technically, improving PV cell conversion efficiency can be achieved through any of the following four ways:

1. Researching and developing more efficient solar cells
2. Using Maximum Power Point Tracking (MPPT) methods
3. Optimal orientation of the PV panel
4. Reducing the operating temperature of the PV cell

Most PV cells generate a voltage of approximately 0.5 Volts and a current, which depends on the solar irradiance and geometry of the cell [2]. It is a well known fact that, by connecting these cells in series and parallel it is possible to build up modules that can generate power sufficient enough for most stand-alone applications. The module is then used alone or connected electrically with other similar modules to form a photovoltaic array. The exact configuration of the array depends on the current and voltage requirements of the load.
In this paper, we explore the effects of temperature on photovoltaic array performance. The experimental approach normally adopted by researchers on this issue is limited to PV cell or module level. The results obtained at these levels are then analytically extended to the array level. The disadvantage of this approach is that well known problems of mismatch are ignored. Furthermore, most of the experimental results on the dependence of PV cell conversion efficiency on temperature that have been reported are based on ideal standard rated condition (SRC). Such results are not accurate because they are not based on the actual field operating conditions of installed PV arrays.
It is more realistic and therefore more accurate to determine the conversion efficiency and fill factor performance of a PV cell by considering the complete array that is subjected to the actual microclimatic conditions of the site. Tests have therefore, been carried out on the installed array for periods spreading over harmattan, cloudy and clear sunny weather

conditions. Using the test data, the variations of the array fill factor and conversion efficiency with temperature have been determined and plotted. Empirical equations relating these array parameters to temperature have also been established.

2. PV ARRAY CONVERSION EFFICIENCY AND FILL FACTOR

Several parameters are used to characterize the performance of a photovoltaic array. The most important of these parameters include maximum power point power (P_{mp}), energy conversion efficiency and fill factor. A graphic illustration of the physical meaning of these parameters is presented in Fig. 1. The maximum power point power is the product of maximum array current (I^A_{mp}) and the maximum voltage (V^A_{mp}) at the point where the power out of the array is greatest. This point is located at the 'knee' of the I-V curve as illustrated. The definition of Conversion efficiency and fill factor of the array with reference to Fig. 1 are now presented in sequel.

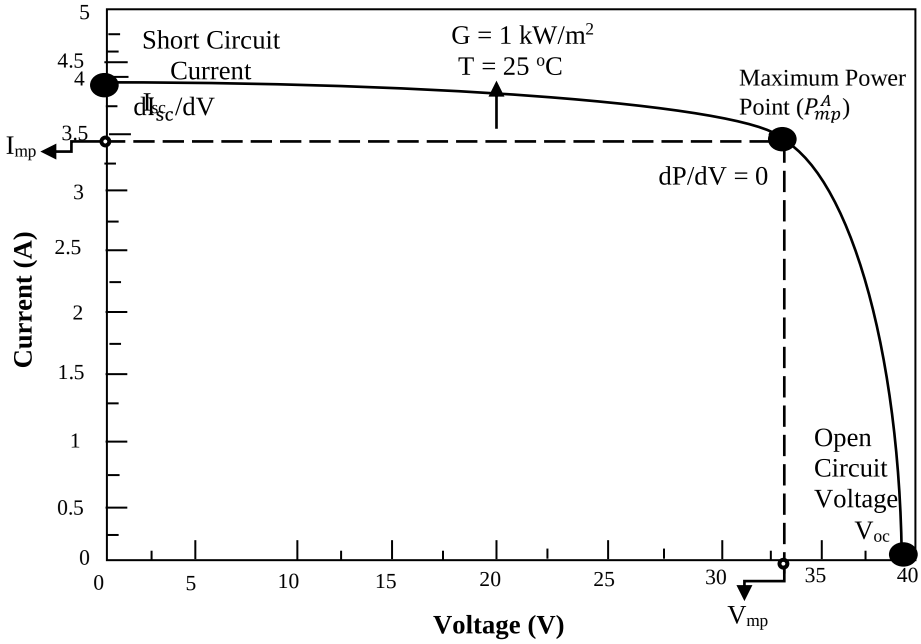

Fig. 1: location of points of interest needed for calculating Energy conversion efficiency and fill factor of an array

2.1 Conversion Efficiency

PV array efficiency is the most commonly used parameter to compare the performance of one PV array to another. It is defined as the ratio of the electrical output of an array to the incident energy in the form of sunlight. Thus the energy conversion efficiency of the array is the percentage of the solar energy to which the array is exposed that is converted into electrical energy. This is computed by dividing the array's power output at its maximum power point by the input solar irradiance and the surface area of the array as expressed in equation (1).

$$\eta^A = \frac{P^A_{mp}}{G x A^A} \qquad (1)$$

Where η^A = PV array energy conversion efficiency
P^A_{mp} = Maximum power point power of the array
G = Solar irradiance incident on the array
A^A = PV array cross-sectional area

Conventionally, PV array efficiency is not measured directly. Instead, it is the solar cell efficiency that is first measured under standard rated conditions (SRC) at temperature and irradiance of 25°C and 1000 W/m^2 respectively. Thereafter, the obtained cell efficiency value is then appropriately scaled to match the array size and actual operating conditions of temperature and solar irradiance.

In this paper, measurements were carried-out directly on the array and under its actual field operating conditions. From the obtained data, a more realistic conversion efficiency of the array is then determined for the microclimatic weather conditions of the site. The variation of the array energy conversion efficiency for each of the weather conditions is determined and plotted as portrayed by the results obtained hereunder.

2.2 PV Array Fill Factor

Another important parameter that defines the characteristics of a PV array is the Fill Factor (FF^A). It is a key parameter in evaluating the operating performance of PV arrays. The Fill Factor is defined as the available power at the maximum power point (P^A_{mp}) divided by the product of the open circuit voltage (V_{oc}) and the short circuit current (I_{sc}) as expressed in equation (2).

$$FF^A = \frac{P^A_{mp}}{V_{oc} x I_{sc}} \qquad (2)$$

The Fill Factor is directly affected by the values of the array's series and parallel resistances. Increasing the parallel resistance of the array (R_p^A) and decreasing its series resistance (R_s^A) will lead to a higher Fill Factor, thus

resulting in greater efficiency and bringing the array's output power closer to its theoretical maximum [3]. The ideal array has a Fill factor equal to 1. However losses due to series and parallel resistances lower this ideal value. A large Fill Factor is desirable and corresponds to an I-V sweep that is squarer. With reference to equations (1) and (2), the PV array energy conversion efficiency and Fill Factor are related by equation (3) as:

$$\eta^A = \frac{V_{oc} x I_{sc} x FF^A}{G x A^A} \qquad (3)$$

3. EXPERIMENTAL PHOTOVOLTAIC ARRAY USED AS TEST RIG

The experimental photovoltaic array installed at the School of Engineering, ATBU Bauchi as shown in Fig. 2 is used as test rig in this research work. The PV array comprises five M55 Siemens modules connected in parallel with rated maximum voltage of 17.4 V and maximum power rating of 265 Watts. The photovoltaic array is of fixed orientation at optimally determined inclination angle facing southward for all year round maximum solar energy harvest and at a location devoid of overcasts from nearby trees and buildings.

4. EXPERIMENTAL SETUP

The critical equipment required in the overall experimental setup is a pyranometer for solar irradiance measurement as shown in Fig. 3. All other measuring instruments utilized are of digital variety so as to secure the desired accuracy in the field data acquisitions. Provisions have been made for both manual and automatic data measurement capabilities including pragmatic PV array cooling arrangement.

Fig. 2: experimental photovoltaic array (built from m55 siemens modules)

Fig. 3: pyranometer (model no.: cm6b) for Direct solar radiation measurements

5. MEASUREMENT EQUIPMENT

The measurement requirements in this work are critical in the attainment of the goal embarked upon in the research work. The choice of equipment for the various measurements has been given due and careful consideration. In what follows, the various equipment facilities used are briefly described from the standpoints of their accuracies, specifications and calibration needs for all the measurement tasks.

5.1 Pyranometer

A pyranometer essentially generates voltage signal from thermopile detectors which is directly proportional to the incident solar irradiance. Most high quality pyranometers measure the total irradiance irrespective of the wavelengths in the solar spectrum and at all incident angles. The pyranometer, model No: CM6B, used in this research work for the measurement of direct solar irradiance is also capable of measuring horizontal component of solar irradiance. The calibration of the pyranometer involves specification of its conversion factor to enable direct mapping of the generated voltage output, normally in millivolts range, into its corresponding solar irradiance expressed in W/m^2. With respect to the model of pyranometer used, its representative conversion factor as specified by the manufacturer is $9.63\ x10^{-6}\ V/Wm^{-2}$. This is however contingent on regular cleaning of the convex glass of the pyranometer to be dust free and ensuring its firm attachment to the PV array rack.

5.2 Digital Multimeters

The desirability for uninterrupted measurements throughout the measurement period engendered reliance on manual measurements of the needed field data to enable PV array energy conversion efficiency and fill factor characterizations. The main measuring instruments required are essentially dedicated multimeters of various selectable ranges for current and voltage measurements. In order to achieve the desired measurement accuracies, fluke digital multimeters are chosen for hourly measurements of PV open circuit voltages and short circuit currents as well as solar irradiance. Except for the tedium of manual measurements and data logging into logbook, the desired measurement accuracies need not be compromised. Of course, automatic data acquisition system (DAS) configured for the same purpose is naturally preferred with manual measurement arrangement as substitute in the event of DAS mal-operation particularly in a developing research environment characterized by paucity in such equipment stock.

5.3 *Thermocouples/Digital Thermometers*

There is the need to monitor PV temperatures at strategically selected locations to build the required credible database. The measurement of temperature can be accomplished by using thermocouples. The most popular thermocouple for PV temperature measurement is the k-type configured from dissimilar wires comprising chromel and alumel which is appropriately calibrated for specific temperature range of interest. The thermocouple based temperature measurement is easily adaptable to DAS setup. It is also possible to manually monitor PV array operating temperatures at specific nodes using readily available hand held digital thermometers of superior quality than achieved through thermocouples. Digital thermometers of +/- 0.05^{o}C accuracy and temperature range of 0 to 100 ^{o}C are available for manual measurements of PV temperatures at selected nodes.

5.4 Multi-channel Data Logger

The data logger available is delta T logger model DL2e built by Cambridge Researchers and specifically configured for solar data acquisition. It is equipped with 64 channels having calibrated sensors for voltage, current and temperature measurements. The logger sampling rate is of the order of few milliseconds and sufficiently fast for the solar data acquisition tasks. With the data logger connected to the desktop computer, all the data acquired can be stored for subsequent preprocessing and analysis. The flexibility of the DAS is clearly evident most especially its programmable capabilities to acquire the relevant PV data sequentially with minimum human intervention. It is noteworthy that the implementation of DAS can be adversely affected by unreliable power supply with the attendant problem of considerable data loss. For this reason, manual field measurements are almost always unavoidable during power supply outages.

5.5 Variable Resistive Load

The use of electronic load has become the standard approach of characterizing the power of PV array with high accuracy. However for lack of its availability, suitably rated variable decade resistor box has been devised in this experimental setup to secure I-V curve for the PV array at constant solar irradiance, G and temperature, T_{cell}. The variable decade resistor box has the capability to sweep at discrete steps from short circuit to very near open circuit condition with corresponding PV current and voltage measured at each load point. The variable decade resistor load can be replaced by variable rheostat of rated current capacity and resistive value.

5.6 PV Cooling Arrangement

This experimental setup has incorporated a pragmatic cooling arrangement aimed at rapidly cooling the PV array to preset temperature level via conduction and forced convection processes. In this cooling arrangement, a thin layer of heat extractor/shade bearing embedded capillary pipe system is tightly overlaid on the entire PV array surface. Chilled water from reservoir tank (serving as coolant) is then circulated through the heat extractor to remove the heat trapped by the PV array. Temperature sensors at carefully selected nodes on the PV array surface are relied upon to monitor and confirm the attainment of the desired PV operating temperature level. Upon attainment of the set PV array temperature, preferably lower than the ambient temperature, the cooling arrangement is then removed to un-shade the PV array and necessary measurements can then be conducted as quickly as possible for every incremental rise in array temperature. Other pragmatic cooling and shading arrangements such as installation of hybridized solar collector or/and use of a pre-cooled shading/heat absorbing material could also be adopted [4] and [5].

6. RESULTS OF EFFECTS OF TEMPERATURE ON PV ARRAY ENERGY CONVERSION EFFICIENCY

Figs. 4 to 6, clearly portray the effects of temperature on the array energy conversion efficiency for the three microclimatic seasons of harmattan, cloudy and clear sunny respectively.

With the solar irradiance held at the experimentally determined average value of 586.7 W/m^2, 600 W/m^2 and 950.8 W/m^2 for harmattan, cloudy and clear sunny seasons respectively [6], the PV temperature was allowed to rise from 25^{o}C to 65^{o}C at incremental step of 5^{o}C with I-V curve data generations carried out at every step increment. This was replicated for every micro-climatic condition at the experimental PV site. The huge data acquired in respect of I-V characteristics were subsequently entered into excel as database from which different seasonal values of P_{mp}^{A} needed to compute the array conversion efficiencies were determined. A summary of the equations relating the PV array energy conversion efficiency to temperature for each of the three seasons and temperature sensitivities of the efficiencies are presented in Table 1. The result shows that the PV array has higher energy conversion efficiency of 13.14% during the harmattan season during which the seasonal average temperature is 29^{o}C. The least energy conversion efficiency of the array is 12.43% and is during the clear sunny season when the average seasonal temperature is 46^{o}C. For comparative purposes, the combined plot of the efficiency variations for the three microclimatic seasons is indicated in Fig. 7.

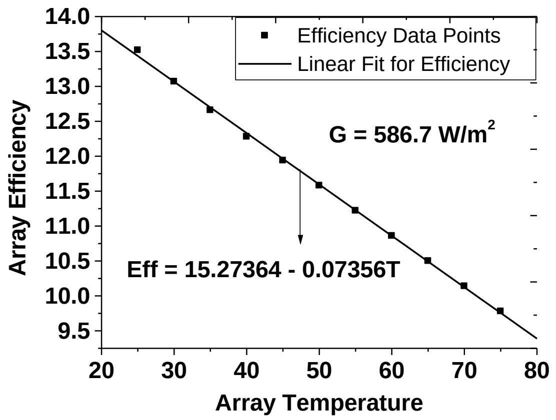

Fig. 4: array energy conversion efficiency as function of temperature at harmattan season average irradiance

7. RESULTS OF EFFECTS OF TEMPERATURE ON PV ARRAY FILL FACTOR

Figs. 8 to 10 indicate the effects of Temperature on the PV array Fill Factor for harmattan, cloudy and clear sunny seasons respectively. As described in the previous section, the huge data acquired in respect of I-V characteristics and entered into excel as database was used to determined different seasonal values of P_{mp}^{A}, V_{oc}^{A} and I_{sc}^{A} needed to compute the array fill factor were determined. A summary of the equations relating the PV array Fill Factor to temperature for each of the three seasons and temperature sensitivities of the Fill Factors are presented in Table 2. The result shows that the PV array has higher Fill Factor of 0.757 during the harmattan season during which the seasonal average temperature is 29^{o}C. The least Fill Factor of the array is 0.708 during the clear sunny season when the average seasonal temperature is 46^{o}C. The seasonal average temperature for harmattan, cloudy and clear sunny seasons was experimentally determined to be 29^{o}C, 38^{o}C and 46^{o}C respectively [6]. For comparative purposes, the combined plot of the fill factor variations for the three microclimatic seasons is indicated in Fig. 11.

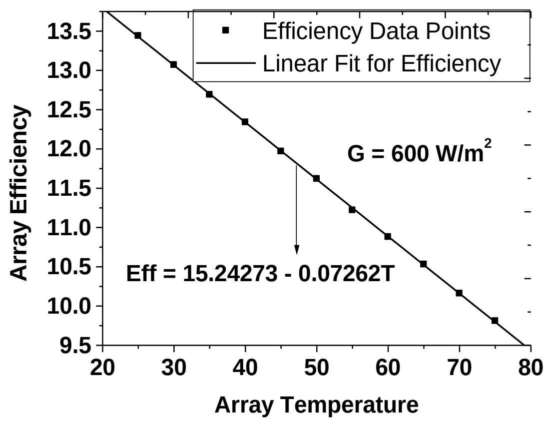

Fig. 5: array energy conversion efficiency as function of temperature at cloudy season average irradiance

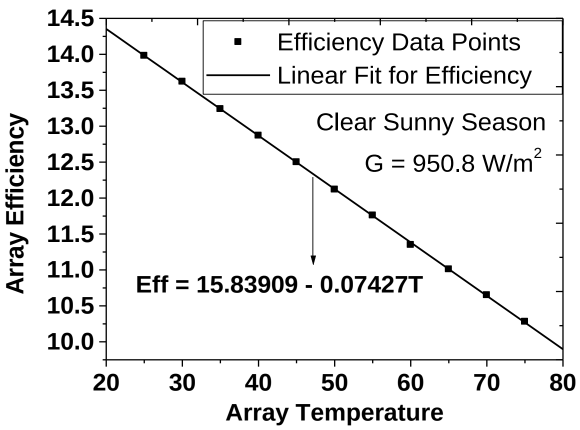

Fig. 6: array energy conversion efficiency as function of temperature at clear sunny season average irradiance

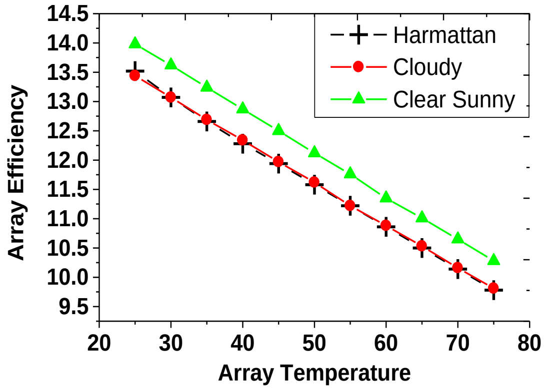

Fig. 7: combined array conversion efficiencies as function of temperature at harmattan, cloudy and clear sunny season average irradiances

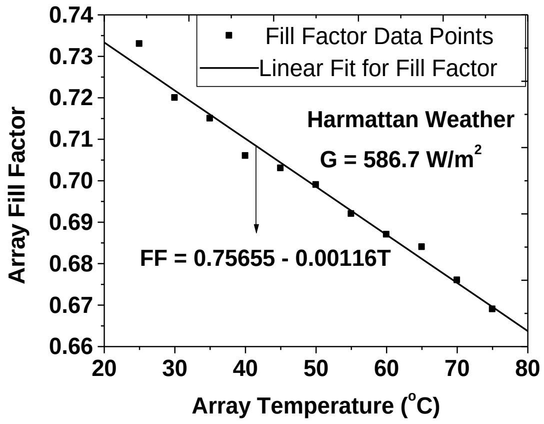

Fig. 8: array fill factor as function of temperature at harmattan season average irradiance

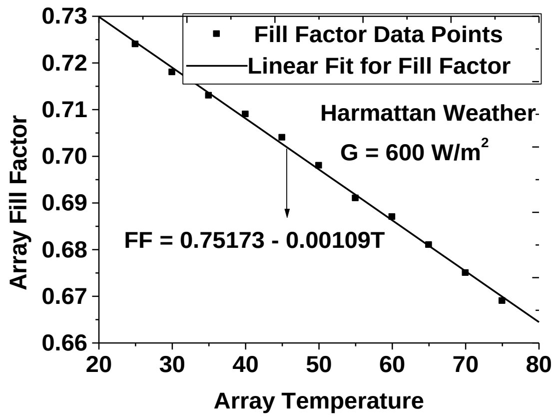

Fig. 9: array fill factor as function of temperature at cloudy season average irradiance

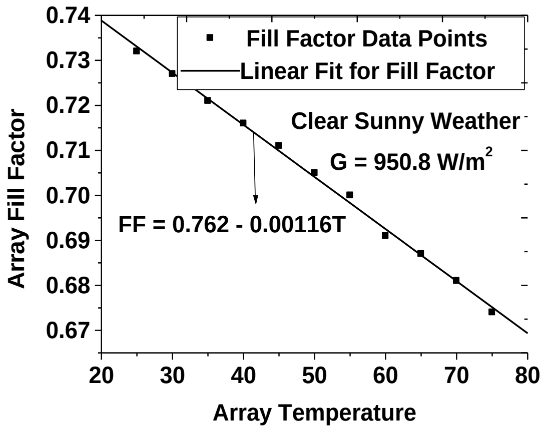

Fig. 10: array fill factor as function of temperature at clear sunny season average irradiance

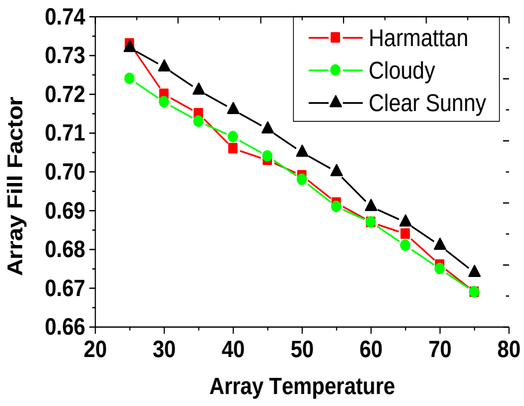

Fig. 11: combined array fill factors as function of temperature at harmattan, cloudy and clear sunny season average irradiances

TABLE 1: SUMMARY OF RESULTS OF EFFECTS OF TEMPERATURE ON PV ARRAY CONVERSION EFFICIENCY

Weather Condition	Empirical Equation	R^2	Temperature Coefficient
Harmattan Season (G=586.7 W/m²)	$\eta^A = 15.27364 - 0.07356T$	0.99956	-7.356% /ºC
Cloudy Season (G=600 W/m²)	$\eta^A = 15.24273 - 0.07262T$	0.99995	-7.262% /ºC
Clear Sunny Season (G=950.8 W/m²)	$\eta^A = 15.83909 - 0.07427T$	0.99995	-7.427% /ºC

TABLE 2: SUMMARY OF RESULTS OF EFFECTS OF TEMPERATURE ON PV ARRAY FILL FACTOR

Weather Condition	Empirical Equation	R^2	Temperature Coefficient
Harmattan Season (G=586.7 W/m²)	$FF^A = 0.75655 - 0.00116T$	0.99168	-0.00116 /ºC
Cloudy Season (G=600 W/m²)	$FF^A = 0.75173 - 0.00109T$	0.99895	-0.00109 /ºC
Clear Sunny Season (G=950.8 W/m²)	$FF^A = 0.762 - 0.00116T$	0.99863	-0.00116 /ºC

8. CONCLUSION

The effects of temperature on the energy conversion efficiency and fill factor of a PV array installed at the Faculty of Engineering and Engineering Technology of Abubakar Tafawa Balewa University, Bauchi were investigated. The results show that the array has its highest energy conversion efficiency and fill factor during harmattan which is the coolest season of the year in the locality. However, the energy conversion efficiency and fill factor of the PV array are found to be lowest during the hottest season of clear sunny, despite the harvestable high solar irradiance during this season. Also worthy of the note is the fact that both energy conversion efficiency and fill factor are proportional to temperature.

The temperature coefficients of both the energy conversion efficiency and the fill factor of the PV array have been determined. Finally, empirical equations relating these important parameters of the array to temperature have also been carefully extracted and tabulated.

REFERENCES

[1] Hamrouni, N., Jraidi, M. and Cherif, A. 'Solar Radiation and Ambient Temperature Effects on the Performance of PV Pumping System', Revue des Energies Renouvelables, Vol. 11 No. 1, pp. 95 – 106, 2008.

[2] Halme, J. "Design Considerations of Photovoltaic Systems." Sixth International Summer
a. School on Solar Energy. Workshop 4, 283-316. 2000.

[3] Jenny Nelson. 'The Physics of Solar Cells', Imperial College Press. ISBN 978-1-86094-340-9, 2003.

[4] King, D. L. (1997). Photovoltaic Module and Array Performance Characterization Methods for All System Operating Conditions. *Research Publication of Photovoltaic System R and D Department*, MS0752. Sandia National Laboratories, Albuquerque. NM 87185.

[5] King, D., Kratochvil, J. and Boyson, W. (1997). Temperature Coefficients for PV Modules and Arrays: Measurement Methods, Difficulties, and Results. *26th PV Specialists Conference*. pp1183-1186.

[6] Guda, H. A. "Improved Modeling and Simulation of a Stand-Alone Experimental Photovoltaic Array for Different Climatic Conditions of Bauchi Locality". Unpublished doctoral dissertation, Abubakar Tafawa Balewa University, Bauchi, Nigeria. 2012.