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Photovoltaic Array Conversion Efficiency and Fill Factor Performances under Varying Intensity of Solar Irradiance

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ABSTRACT

The overall performance of a photovoltaic array varies with varying irradiance and temperature. However, since most locations on earth are characterized by their different microclimatic seasonal conditions typified by respective average seasonal temperatures, it is reasonable to consider the performance of a photovoltaic array under varying irradiance while the temperature is kept at the seasonal average value. With the change in the time of day during each season the power received from the sun by the photovoltaic array changes. Two important performance parameters of the array that are affected by these changes are conversion efficiency and fill factor. The aim of this paper is to present the experimental results of the effects of changing irradiance on these array performance parameters. Although there are well documented efforts on the effects of irradiance 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 irradiance on the fill factor of photovoltaic arrays. In this paper, effort has been made to document clear effects of irradiance on conversion efficiency and fill factor of a photovoltaic array installed at 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 irradiance 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 irradiance and between irradiance and conversion efficiency for all the seasons. The results show that both the conversion efficiency and fill factor of the array have a polynomial relationship with irradiance. The array attains its highest energy conversion efficiency of 13.12% during harmattan, while having a least efficiency of 12.17% during the clear sunny season. Similarly, the PV array attains its highest fill factor of 0.725 during harmattan while having its least fill factor of 0.0.697 during the clear sunny season. Furthermore, the exact empirical polynomial equations relating conversion efficiencies and fill factors of the array have been determined thus making it possible to predict the values of these parameters for any irradiance value during any of the prevailing weather conditions.

Key Words: *Fill Factor, Conversion Efficiency, Irradiance, PV Array Performance Parameters, Microclimatic Weather condition*

1. INTRODUCTION

Conventional energy production from fossil fuels is on the decline in recent times due to the generalized interest in reducing harmful environmental impacts. This is why the development of renewable energy options, like photovoltaic (PV) is gaining prominence. The device used in photovoltaic conversion is called solar cell. When solar irradiance falls on these devices, it is converted directly into dc electricity. A typical solar cell generates only a small amount of power that is not sufficient for any meaningful application. Solar cells are therefore grouped in series and/or parallel to form modules and arrays to meet the desired power requirements. The electrical energy generated by a photovoltaic array depends mainly on the essential properties of the constituent solar cells and on the incoming solar irradiance [1].

Improving PV array conversion efficiency and fill factor is one of the major tasks in controlling the array for enhanced power generation. In order to achieve this, it is necessary to understand the characteristic behaviour of PV arrays with respect to the effects of varying irradiance on the these important performance parameters. The conversion efficiency of a photovoltaic array (η) can be determined by using equation (1) as follows [2]:

$$\eta = \left(\frac{V_{mp}I_{mp}}{GA}\right) x100\% \qquad \dots (1)$$

Where V_{mp}= Maximum power point voltage
V_{mp}= Maximum power point current
G= Irradiance
A= Area of the array

Similarly, the fill factor of the photovoltaic array (FF) can be determined by using equation (2) as follows [2]:

$$FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}} \qquad \dots (2)$$

Where V_{mp}= Open circuit voltage
I_{sc}= Short circuit current

Thus, conversion efficiency and fill factor characterization of a photovoltaic array may be achieved through nonlinear current-voltage (I-V) and power-voltage (P-V) characteristics measurements and plots as function of irradiance and then extracting 'η' and 'FF' from those plots.
In this research work, I-V and P-V measurements and plots were therefore used to obtain exact dependence of conversion efficiency and fill factor on irradiance for the PV array. The measurements covered the 3 major microclimatic weather conditions of harmattan, cloudy and clear sunny seasons. Regression analysis was then performed on the data to obtain empirical relationships between fill factor and irradiance and between irradiance and conversion efficiency for all the seasons.

2. EXPERIMENTAL SETUP AND PROCEDURE

Fig. 1 indicates the layout of the various devices as connected in the experimental setup. The procedure and list of materials used in the experiment are presented in sequel.

2.1 Experimental Procedure

The following experimental procedure was adopted and used to extract the necessary data for characterizing the conversion efficiency and fill factor performance parameters of the photovoltaic array [3]:

- The PV array is first shaded and then cooled or heated up to the seasonal average temperature.
- The PV array is then un-shaded and exposed to normal solar irradiance.
- Quickly take Current and Voltage measurements as a function of solar irradiance while keeping the PV array temperature at seasonal average. Do this for all seasonal average temperatures.
- Plot I-V curves as a function of solar irradiance for all seasons and extract: $V_{oc}^{A}, I_{sc}^{A}, V_{mp}^{A}, I_{mp}^{A}, P_{mp}^{A}$
- Use equations (1) and (2) to compute and plot conversion efficiencies and fill factors as function of irradiance

2.2 Materials

The following materials are required for the experimental setup:

1. Photovoltaic array consisting of 5 M55 Siemens modules.
2. 1 CM6B Pyranometer for direct solar irradiance measurement.
3. 1 Digital Ammeter
4. 2 Digital Voltmeters
5. Connecting wires and leads
6. Decade box containing various resistive loads
7. Data logger
8. Laptop

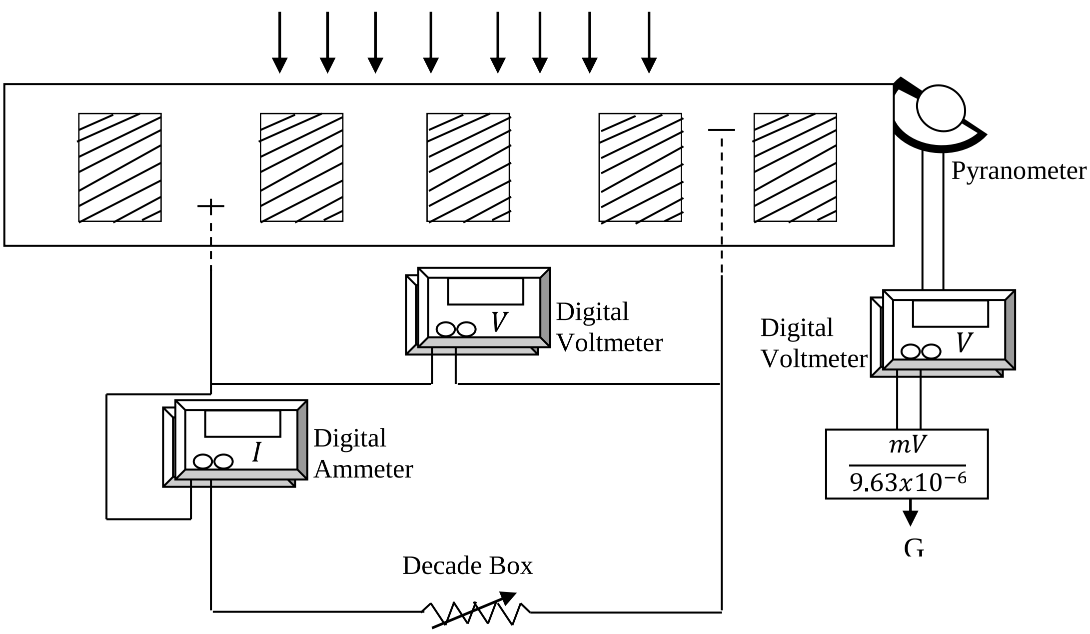

Figure 1: Experimental Setup for I-V and P-V Data Recording

3. RESULTS OF EFFECTS OF IRRADIANCE ON PV ARRAY CONVERSION EFFICIENCY

The effects of irradiance on the array conversion efficiency (η^A) for the three microclimatic seasons of harmattan, cloudy and clear sunny are clearly depicted in Figs. 2, 3 and 4 respectively. With the temperature held at the experimentally determined seasonal average value of 29^0C, 38^0C and 46^0C for harmattan, cloudy and clear sunny seasons respectively [4], I-V and P-V data readings were taken at times when the irradiance values were at different values of 200 W/m^2 to 900 W/m^2 (at increments of 100 W/m^2). This was replicated for every micro-climatic seasonal average temperature condition at the experimental PV site. The huge data acquired in respect of I-V and P-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 empirical equations relating the PV array energy conversion efficiency to irradiance for each of the three seasons are presented in Table 1. The result shows that the PV array has higher energy conversion efficiency of 13.12% during the harmattan season during which the seasonal average temperature is 29^0C. The least energy conversion efficiency of the array is 12.17% and is during the clear sunny season when the average seasonal temperature is 46ºC. These results compare favourably well with those obtained in [5] in which the effects of temperature on PV array conversion efficiency were investigated. For comparative purposes, the combined plot of the conversion efficiency variations as function of irradiance for the three microclimatic seasons is indicated in Fig. 5.

4. RESULTS OF EFFECTS OF IRRADIANCE ON PV ARRAY FILL FACTOR

The effects of irradiance on the PV array Fill Factor (FF^A) for harmattan, cloudy and clear sunny seasons are depicted in Figs. 6, 7 and 8 respectively. As described in the previous section, the huge data acquired in respect of I-V and P-V characteristics of the array and entered into excel as database was used to determine different seasonal values of P_{mp}^A, V_{oc}^A and I_{sc}^A that are needed to compute the array fill factor. The PV array fill factors as function of irradiance are then computed for each of the microclimatic seasons and appropriately plotted. From these plots, the empirical equations relating the PV array Fill Factor to irradiance for each of the three seasons were determined and the summary is presented in Table 2. The result shows that the PV array has its highest Fill Factor of 0.725 during the harmattan season during which the seasonal average temperature is 29^0C. The least Fill Factor of the array is 0.697 which occurs during the clear sunny season when the average seasonal temperature is 46^0C. Interestingly, these results also compare favourably well with those obtained in [5] in which the effects of temperature on PV array fill factor were investigated. For comparative purposes, the combined plot of the fill factor variations for the three microclimatic seasons is indicated in Fig. 9.

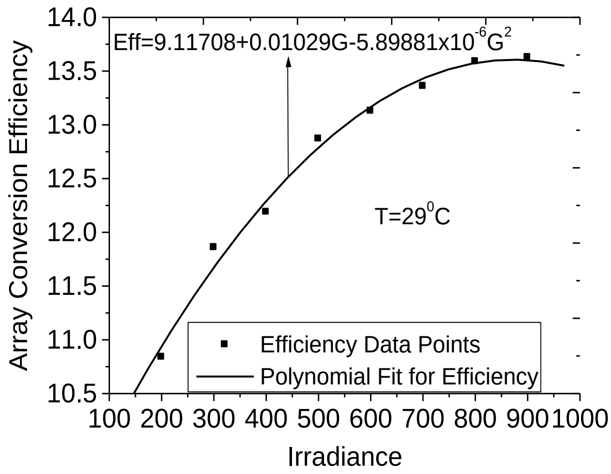

Figure 2: Array Conversion Efficiency as Function of Irradiance at Harmattan Season Average

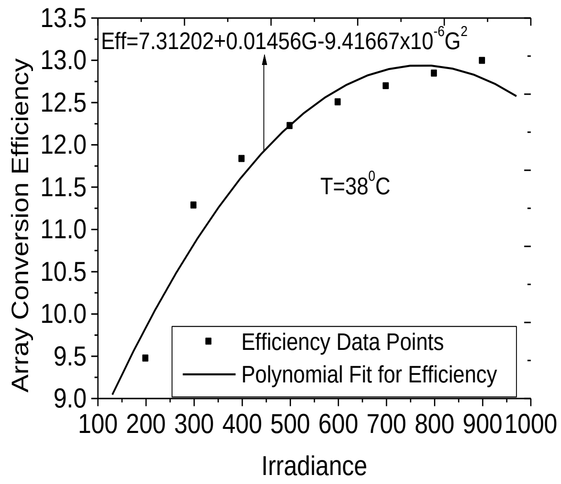

Figure 3: Array Conversion Efficiency as Function of Irradiance at Cloudy Season Average

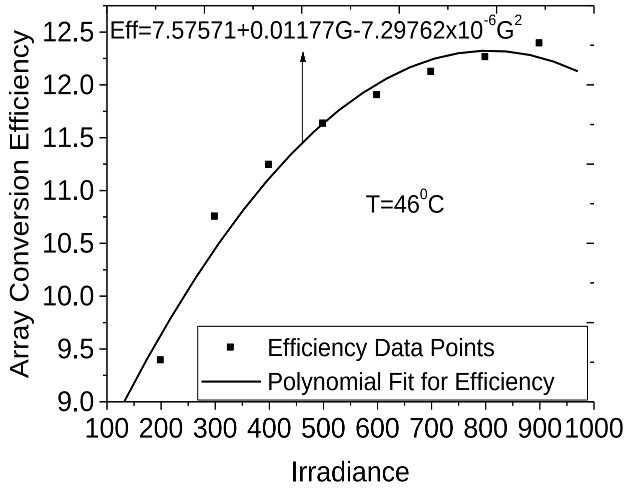

Figure 4: Array Conversion Efficiency as Function of Irradiance at Clear Sunny Season Average

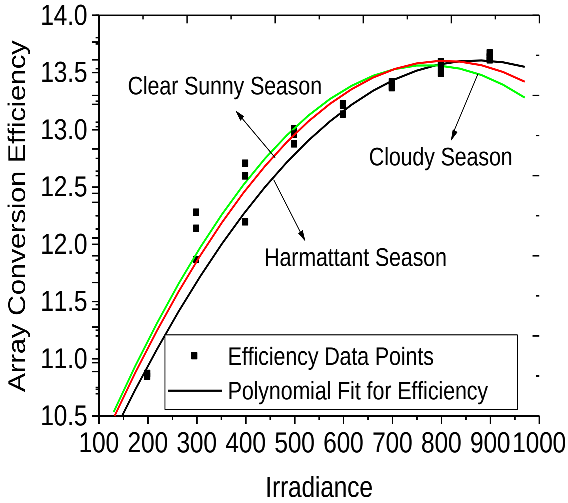

Figure 5: Combined Array Conversion Efficiency as Function of Irradiance at Harmattan, Cloudy and Clear Sunny Season Average Temperatures

Table 1: Summary of Results of Effects of Irradiance on PV Array Conversion Efficiency

Weather Condition	Empirical Equation
Harmattan Season (T=29^{0}C)	$\eta^A = 9.11708 + 0.01029G - 5.89881x10^{-6}G^2$
Cloudy Season (T=38^{0}C)	$\eta^A = 7.31202 + 0.01456G - 9.41667x10^{-6}G^2$
Clear Sunny Season (T=46^{0}C)	$\eta^A = 7.57571 + 0.01177G - 7.29762x10^{-6}G^2$

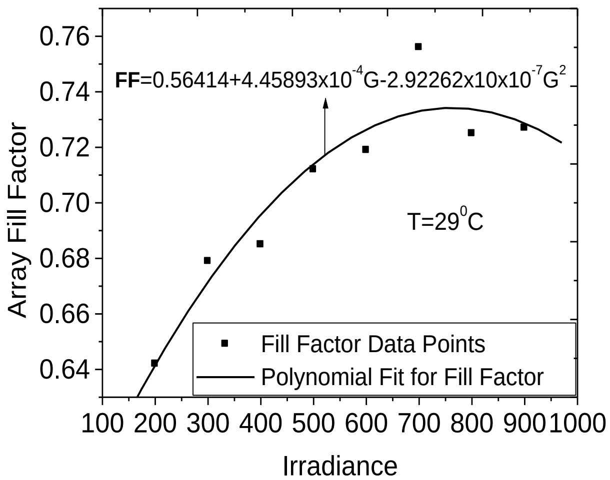

Figure 6 Array Fill Factor as Function of Irradiance at Harmattan Season Average Temperatures

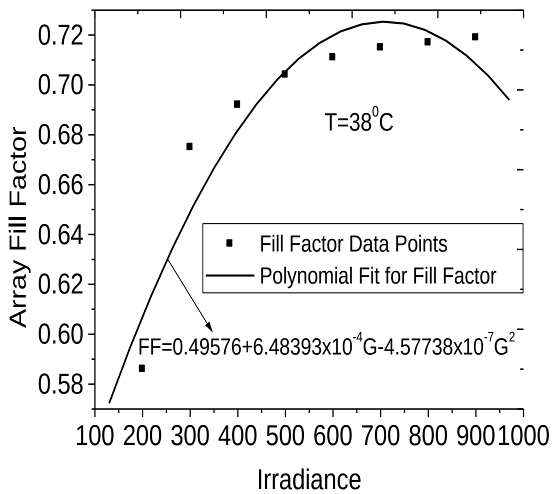

Figure 7 Array Fill Factor as Function of Irradiance at Cloudy Season Average

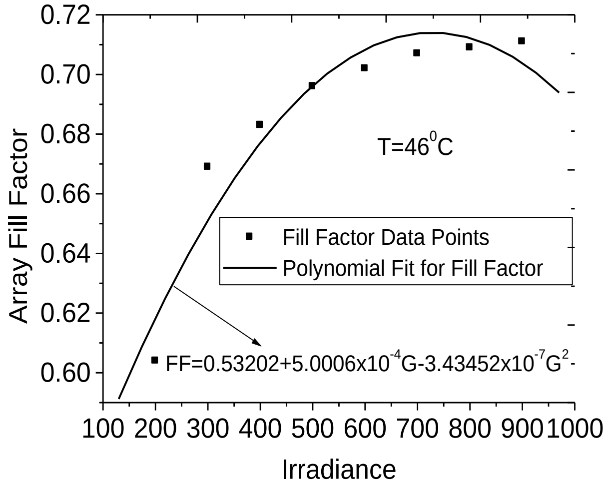

Figure 8 Array Fill Factor as Function of Irradiance at Clear Sunny Season Average

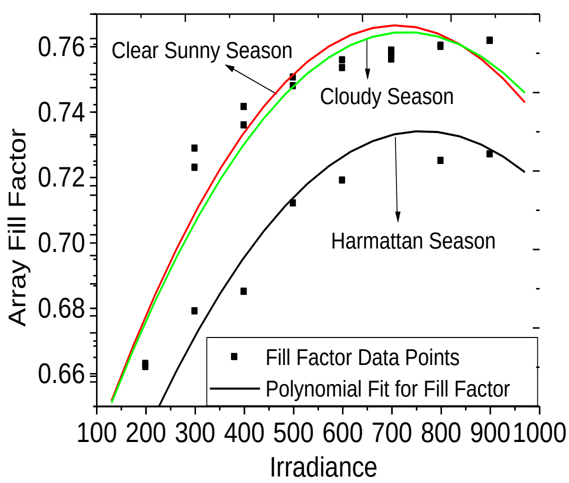

Figure 9: Combined Array Fill Factor as Function of Irradiance at Harmattan, Cloudy and Clear Sunny Season Average Temperatures

Table 2: Summary of Results of Effects of Irradiance on PV Array Fill Factor

Weather Condition	Empirical Equation
Harmattan Season (T=29⁰C)	$FF^A = 0.56414 + 4.45893x10^{-4}G - 2.92262x10^{-7}G^2$
Cloudy Season (T=38⁰C)	$FF^A = 0.49576 + 6.48393x10^{-4} - 4.57738x10^{-7}G^2$
Clear Sunny Season (T=46⁰C)	$FF^A = 0.53202 + 5.0006x10^{-4}G - 3.43452x10^{-7}G^2$

5. CONCLUSION

The effects of irradiance on the 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 conversion efficiency and fill factor during harmattan which is the coolest season of the year in the locality. However, the 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 conversion efficiency and fill factor have a second order polynomial fit to irradiance.

Conversion efficiency and fill factor values obtained compare favourably well with those obtained in a similar study published in [5] in which the effects temperature on these array performance parameters were investigated. Empirical equations relating these important parameters of the array to irradiance have also been carefully extracted and tabulated.

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