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PERFORMANCE EVALUATION OF ELECTRICAL CHARACTERISTICS OF BIFACIAL HALF-CUT PERC MONOCRYSTALLINE PV MODULES UNDER OUTDOOR CONDITIONS IN NAWABSHAH CITY

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Abstract

Electrical characteristics of both front and rearside of bifacial photovoltaic modules are normally examined at standard test conditions and rarely at outdoor environments. This work was carried out to inspect the electrical properties (front and rearside) of bifacial half-cut PERC mono-crystalline photovoltaic modules in Nawabshah city's opened environment. This study measured the PV module's power output (P), open-circuit voltage (Voc), short-circuit current (Isc), maximum voltages (Vmax), maximum current (Imax). Weather parameters included global solar radiation (Ir), ambient temperature (Ta), wind speed (Ws), and relative humidity (Rh). A light meter (HD-2302) was used to measure the amount of global solar radiation that struck the site's horizontal surface, while PROVA AVM-05 was used to record the ambient temperature (Ta), wind speed (Ws), and relative humidity (Rh). Also via the PV analyzer PROVA-1101, the electrical properties of the PV modules both (front and rear) sides were recorded from 09:00 to 16:00 hours at an interval of 15-minutes. The average Ir, Ta, Ws and Rh were found 842.4W/m^2, 29.7°C, 3.0m/sec and 46.0%respectively during study period. The PV module's average Pmax, including both the front and back sides, was 334.6W, with the rearside alone producing 27.6W. It is established form the study that the front side produced around 91% of output power and the rest is contributed by its back-side during analysis period at the same operational and environmental conditions.

INTRODUCTION

Energy is backbone of economic growth and sustainable development through the fossil fuels like coal, oil, and natural gas could be one way or can be obtained from hydro, solar, wind, biomass, geothermal or other alternative sources [1]. Nevertheless the primary source of greenhouse gases and the ultimate driver of global warming is fossil fuels. On the other hand, as a result of global population growth and industrial advancements, energy demand is progressively increasing. The nations are concentrating on raising the proportion of renewable resources in the overall energy demand in order toward effectively address this scenario. It was expected that system might be expended to 1220 GWs for using renewable energy resources through 2024[2,3]. Besides the solar energy systems technologies are more reliable, environmental friendly, reliable as well as sustainable than other renewable energy sources. One way to produce electrical energy is by Photovoltaic or solar thermal systems. The photovoltaic system is simpler way to generate electrical energy as compare to solar thermal systems also the Photovoltaic systems are very easy to maintain and provide consumers with direct electricity. Solar photovoltaic technologies are more preferred [4, 5]. However, the amount of solar radiations that the solar modules receive directly affects their performance, and mounting techniques, Ws, Ta, and Rh also have an indirect impact [6–8]. Pakistan is one of the world's most populous and developing nations. To continue developing and to address the issue of energy safety, it needs a steady supply of energy. The nation is currently experiencing a severe energy crisis, with 10 to 12 hours of darkness per day [4,5]. There is electricity shortfall in Pakistan is about to 51,765 GWh [9, 10]. Thankfully, Pakistan receives a lot of sunlight, It is a desirable alternative for delivering power to remote areas where it is challenging to extend transmission lines from the national grid [11].

PV modules electrical characteristics are evaluated under STC are maintained at covered environment by keeping the PV modules planetary solar radiations at 1000W/m^2, temperature at 25°C, as well as the air mass of 1.5 by the manufacturers [12, 13].The marketable efficiency of PV modules like poly-crystalline, mono-crystalline and amorphous are 12-13%, 14-15% and 6-7% at STC[14]. Their power output can also be decreased by various operational conditions, weather parameters, and geographical conditions [12,15,16]. The electrical properties of PV modules are negatively impacted by ambient temperature by 0.2% to 0.5%/°C above the nominal cell operating temperature [17, 18]. Additionally with advanced technology Passivated Emitter Rear Cells (PERC) were produced in place of silicon based technologies by PV industries which are expected to account for 45–60% of the market by 2027 [20, 21]. According to the passivation layers deposited, PERC technology has a reported efficiency of about 22% [22]. Additionally, it has been reported that bifacial PV modules can increase system efficiency (5-25%) compared to monofacial counterparts. Author's [22, 23-27], reported that their actual contribution is still questionable due to influence of geographical, environmental and operational parameters and its configuration. It is still unknown that, how much percentage of power output can be obtained from the backside of bifacial modules at a particular location. Although, these modules are proved to be more beneficial at snowy conditions yet their performance in hottest environments is to be ascertained [28, 29], Even through hypothetical the Bifacial modules having more advantages in snowy conditions, little is known about how well they work and what their backside energy gain is high in hot environmental and outdoor conditions. Additionally the efficiency of PV modules was predicted using various empirical efficiency models. The reason for this investigation is the erratic nature of environmental factors that may affect the electrical properties of PV modules and adjust their performance. The purpose of this research work is to investigate the electrical properties of half-cut bifacial PERC monocrystalline PV modules' front and rear sides in outdoor environmental settings. Additionally, it aims to determine the bifacial modules' rear side energy gain in relation to their front side. Furthermore, the study explores the suitability of existing models for accurately forecasting the performance of such modules under these environmental conditions. In order to determine the power output of the rear side of the bifacial module in comparison to the front side, this study was carried out in Nawabshah city, to examine the electrical properties (front and back) of bifacial half-cut PERC modules in one of Pakistan's hottest location [30].

1. MATERIALS AND METHODS

Two PERC half-cut monocrystalline bifacial photovoltaic modules were used in this research investigation, compass, metal stand and structure for measuring the weather parameters, the light meter and weather station were utilized, For assessing electrical characteristics of photovoltaic modules, The both modules were acquired with the same specifications, and their attributes were evaluated as stated in Table1.

The system was installed over the Energy Systems Engineering's departmental buildings at QUEST, Nawabshah, and orientation towards true south at a 26° slope angle horizontal. One module was covered from the front and opened from the rear side to examine its rear side performance, while another PV module was left open on both sides to view its combined electrical characteristics. Using a professional weather station (HP-2000), weather parameters like Ir (W/m^2), Ta (^{o}C), Ws (m/sec), and Rh (%) were measured as shown in Figure 1. The PV Analyzer (PROVA-1011) was used to measure the electrical characteristics of each PV module, specifically the Voc, Isc, Vmax, Imax, and Pmax output. PV modules were connected to the computers and data loggers in order to store and analyze the data.

2.1 Photovoltaic modules

Both monocrystalline bifacial modules were of same specifications employed for determining their electrical characteristics and power output by keeping these at various environmental and operational conditions as given in Table 1. The rated power of both bifacial modules was 545W at standard test conditions (STC). When the modules are rated at solar radiation of 1000W/m^2, ambient temperature (T_a) of 25^{o}C and air mass of 1.5 m/s are referred to as STC. In addition to the two bifacial modules.

Selected PV Module technologies: Monocrystalline Bifacial Half-Cut		
Manufacturer		JA SOLAR
Model	--	JAM72530-545/MR
Open circuit voltages (Voc)	V	49.60
Short circuit current (Isc)	A	13.86
Rated Voltages (Vmax)	V	41.64
Rated Current (Imax)	A	12.97
Rated Power (Pmax)	W	545
Open circuit voltage tolerance	%	±2
Short circuit current tolerance	%	±4
Power production tolerance	%	±3
Testing condition	STC	STC
PV module area	m^2	

Table. 1. Electrical features of PV Modules

2.2 Experimental setup

Compass was used to place the photovoltaic modules at the required slope and orientation. It shows the direction of any location with respect to true north. The angles markings in degrees shown on the compass, as north corresponds to zero, east 90, south 180, and west 270 degree. These degrees can be used to affix the module at the desired orientation and slope. The materials used for metal stand were metal rods, screws, frame, bars, nuts and bolts etc. The metal stand was made by welding and jointing the pieces of sheets and rods in the Mechanical Engineering Workshop. The every reading was taken between 9:00 and 16:00 Pakistan Standard Time, with a 15-minute break in between the data collection.

2.3 Electrical characteristics of bifacial modules at outdoor conditions

In this section, methodology for electrical characteristics, namely, V_{oc} , I_{sc} , V_{max} , I_{max} and P_{max} output of total (front + rear side) versus only rear side of bifacial module was discussed. The coefficient of correlation for data set of both modules was determined.

Least square method was adopted for best fit model to determine how different parameters relate to the data that was observed. A variety of models, including polynomial, Fourier, Gaussian, power, exponential, sum of sine, and other custom functions, were tested using the MATLAB curve fitting toolbox. On the basis of goodness of fit, the best possible model was selected for prediction of power output of modules.

Data of front and rear side (total) of one module and only rear side of the other module was taken by fixing the modules at same level above the ground surface. Rear side of both modules was being made open for incoming diffuse (reflected) radiation. Front side of the other module was being covered by a wooden material to block the direct radiation hitting the surface of the module. The modules are fixed at optimum tilt angle (slope) with that of location latitude as shown in Figure 1. Finally, the contribution of rear side with respect to total power output of bifacial module was determined.

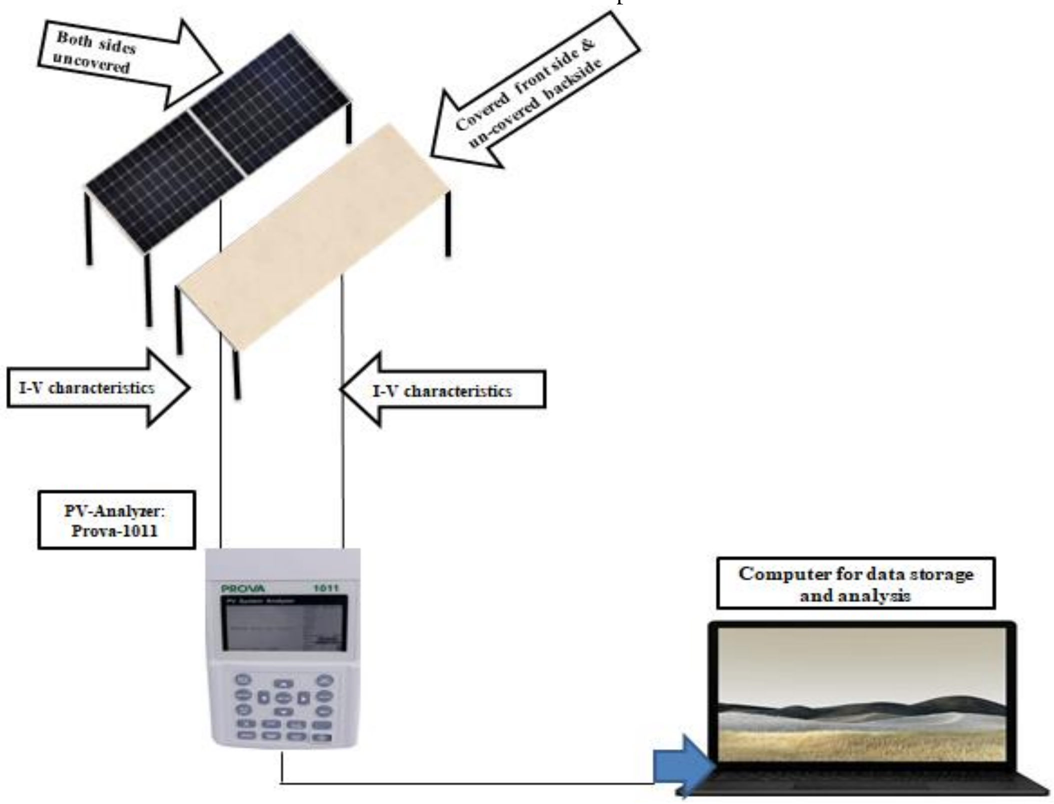

Figure 1. Electrical characteristics of bifacial solar photovoltaic modules: uncovered front and rear sides and covered front side or uncovered rear side

2. RESULTS AND DISCUSSION

3.1. Calibration of photovoltaic modules

Two bifacial photovoltaic modules were purchased with similar specifications and then installed and studied for performance analysis at outdoor conditions. Although, these both modules were rated at standard test conditions by the manufacturers, yet for verification and validation, their electrical characteristics (P_{max}, I_{max}, V_{max}, V_{oc} and I_{sc}) are investigated at real outdoor conditions. The analysis of one module, PV-1 and other module PV-2 was carried out to calibrate their electrical characteristics with each other and find out their percentage error before fixing out PV-1 without any adjustment and other module PV-2 with changes in operational parameters. PV-1 gave average power of 185W and PV-2 184W during calibration period. PV-1 gave 0.8% more power output than PV-2 as shown in Figure 2.

In general, the percentage error was found less than one percent, thus was considered negligible and ignored during subsequent analysis. The error between both modules was quite less in early and late hours of the day and slightly more during midday. However, overall percentage error between both examined modules is less than one percent, which was considered as negligible and overlooked in upcoming parameter evaluations.

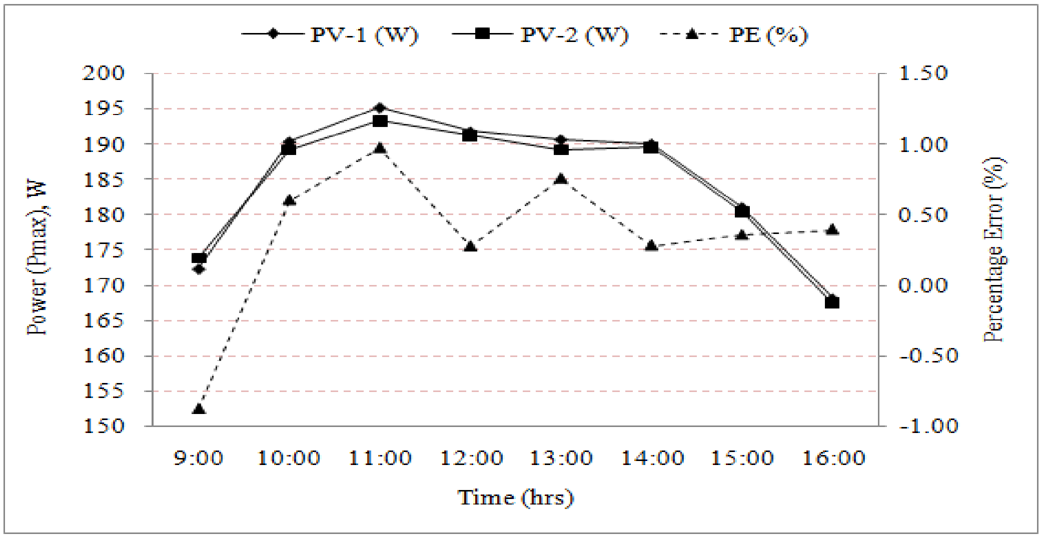

Figure 2: Percentage error between bifacial photovoltaic modules

3. Power output of bifacial modules at outdoor conditions

This section includes the results of power output of total (front + rear side) of one module versus only rear side of other bifacial module, their correlation between each other and percentage change in their average maximum power output. A time-dependent model for the bifacial module's power output along with determination of percentage error between the fitted model and observed data is given.

3.1. Weather parameters during the analysis of bifacial photovoltaic modules

The hourly average measured weather parameters like G_{rad} (W/m^2), T_a (°C), R_h (%), W_s (m/sec) and T_c (°C) are presented in Figure 3.

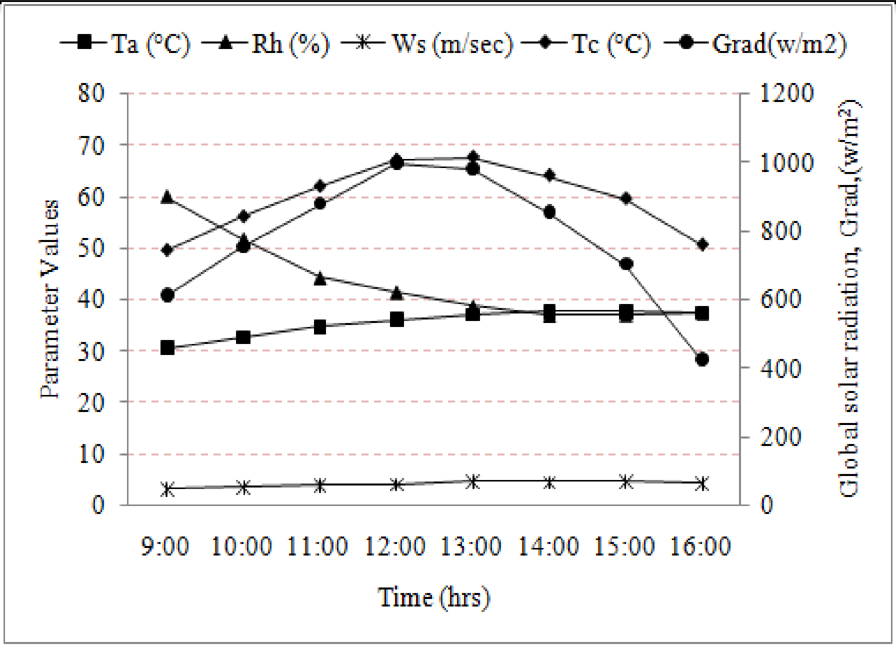

Figure 3. Weather parameters during analysis of bifacial photovoltaic modules

The maximum values of G_{rad}, T_a, R_h, W_s and T_c were noted 996W/m^2, 37.68°C, 59.88%, 4.47m/sec and 67.46°C during the analysis of bifacial photovoltaic modules with monofacial photovoltaic module. Whereas, the minimum values were recorded 422.38W/m^2, 30.45°C, 36.84%, 3.0m/sec and 49.39°C. Moreover, the average weather parameters like G_{rad}, T_a, R_h, W

3.2. Bifacial PV modules' Open circuit voltages and Short circuit currents (front and rear sides) in comparison to the rear side

The hourly average measured open circuit voltages and short circuit current of examined modules are presented in Figure 4. The maximum, minimum and average values of open circuit voltages (V_{oc}) of bifacial PV module (front and rear side) were recorded 44.9, 44.4 and 44.8V, and rear side bifacial module produced 44.9, 41.4 and 41.8V.

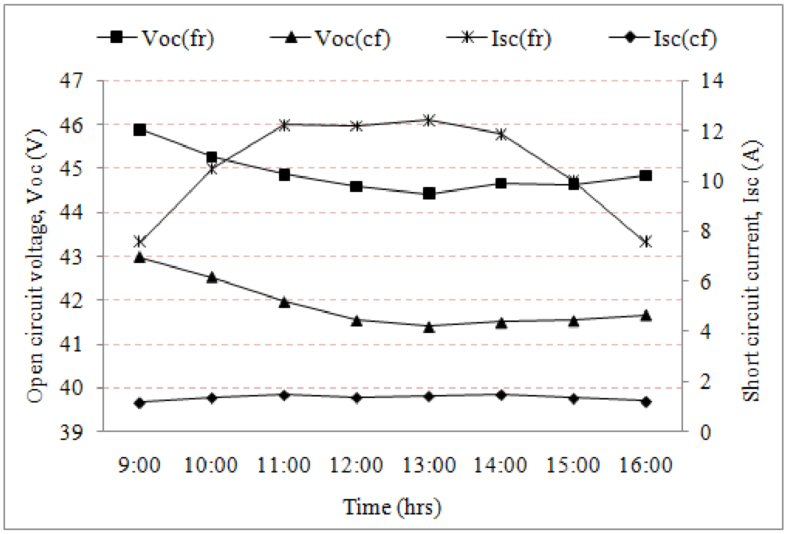

Figure 4: Comparing the short circuit current (Isc) and open circuit voltage (Voc) of the front and rear side Bifacial PV modules to the rear side Bifacial PV module

Whereas, the maximum, minimum and average short circuit current (I_{sc}) of bifacial PV module (front plus back side) was recorded 12.5, 7.6 and 10.9A, and rear side bifacial PV module generates 1.5, 1.2 and 1.4A respectively. It was noted from results that bifacial PV module (front and rear side) gave 3V (7%) and 9.5A (87.15 %%) more average Voc and Isc than rear side bifacial PV module. It is clear that rear side bifacial PV module produced approximately 12% short circuit current during analysis period.

3.3. Maximum voltages and current of Bifacial PV Modules

The hourly average maximum voltages (Vmax) and maximum current (I_{max}) of examined PV modules are display in Figure 5. The maximum, minimum and average values of voltages of bifacial PV module (front and rear side) were recorded 41.0, 36.3 and 37.6V, and rear side bifacial module produced 36.4, 34.5 and 35.2V.

Whereas, the maximum, minimum and average current of bifacial PV module (front plus back side) was recorded 10.5, 6.5 and 8.9A, and rear side bifacial PV module generates 0.87, 0.65 and 0.79A respectively. It was noted from results that bifacial PV module (front and rear side) gave 2.4V and 8.11A more V_{max} and I_{max} than rear side bifacial PV module. It is clear that rear side bifacial PV module produced approximately 0.79A maximum current during examined time.

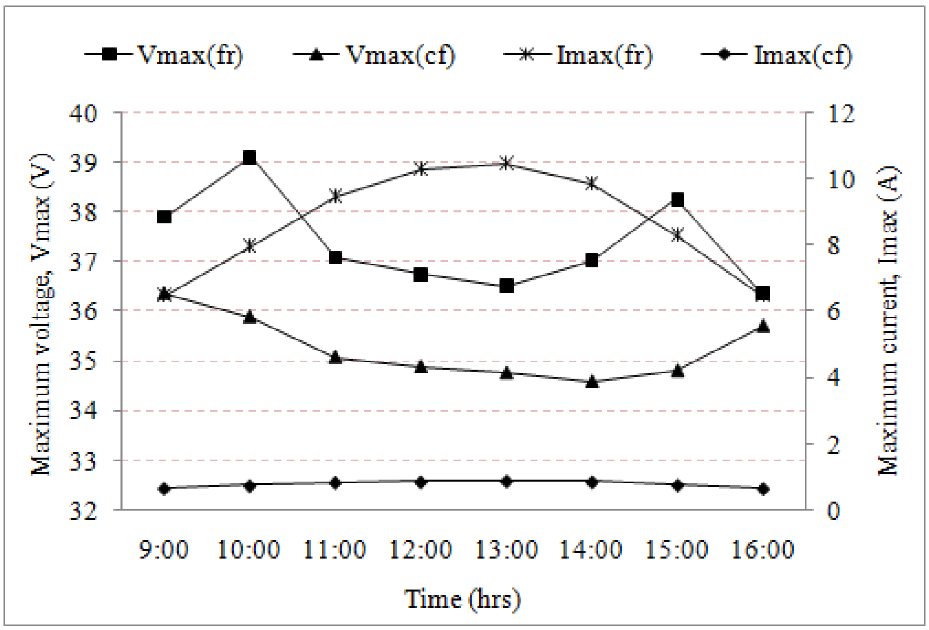

Figure 5: Maximum voltage (Vmax) and current (I max) of Bifacial PV modules (front and rear side) versus Bifacial PV module (rear side)

3.4. Power output of total (front + rear side) versus only rear side of bifacial module

The correlation between the average maximum powersof one bifacial module (both front plus rear side) against other bifacial module (rear side only) with respect to time was found 0.9880. It was observed that the values of coefficient of correlation between these were very close to each other. The comparison of average maximum power output of bifacial module front plus rear side and rear side only are illustrated in Figure 6. It is found that minimum average power output from the both front plus rear side of bifacial module was around 240 W at 1600 hours and maximum average at 1300 hours with 380W. The trend for rear side of module regarding average power out was same as that of both front plus rear side. However, the rear side of the bifacial module gave an average power output of around 30W. It is discovered from the analysis that as solar radiation was increasing the average power out of the modules was increasing and vice versa. The contribution of the bifacial module's rear side was found directly proportional to the front plus rear side of the module. It means that during noon hours share was found increasing due to higher availability of solar radiation.

The percentage change in the average maximum power output of front plus rear side versus rear side only of bifacial module are shown in Figure 7. Average minimum percentage change of average maximum power output from both front plus rear side versus rear side only with respect to time was noted in early (at 0900) and late hours (at 1600) of the day with around change of 10%, while small change was noted during noon with approximately 7%. The rear side gave 8.5% power of total (front plus rear) side of bifacial module. It is discovered that rear side of the module might perform better during higher solar radiation and temperature periods (around noon) compared to morning and evening.

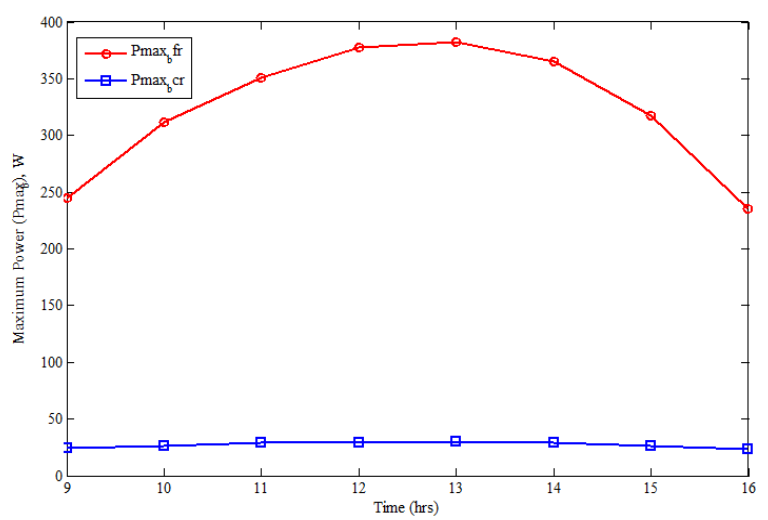

Figure 6. Comparison of maximum power output of bifacial module front side plus rear side versus rear side with respect to time

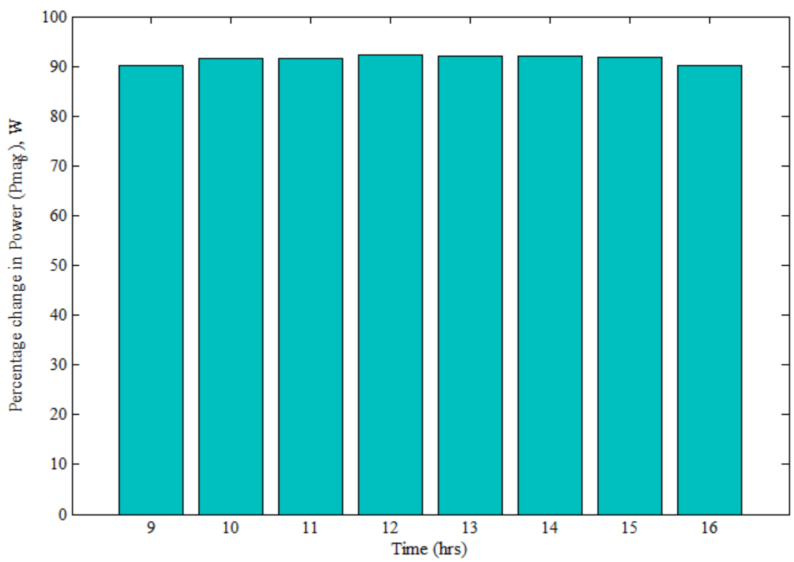

Figure 7. Percentage change in the maximum power output of bifacial module when the front plus rear side versus rear side

3.5. Time dependent model of power output of bifacial module with its front plus rear versus rear side

Curve fitted power output model of bifacial module with its total (front plus rear sides) versus rear side only is shown in Figure 8. A time dependent curve fitted model for bifacial modules with respect to its total (front plus rear sides) against rear side only is given in Equation1.

$$\begin{aligned} Pmax_{bcr}(Pmax_{bfr}) = &-6.481\times10^{8} + 8.631\times10^{8}\cos(0.0001581 Pmax_{bfr}) \\ & 4.188\times10^{7}\sin(0.0001581 Pmax_{bfr}) - \\ & 2.15\times10^{8}\cos(0.0001581 Pmax_{bfr}) - \\ & 2.092\times10^{7}\sin(0.0001581 Pmax_{bfr}) \end{aligned}$$

(1)

Equation (1) is a fitted model, which shows the relationship between the maximum power outputs of front plus rear side versus rear side only. This is a Fourier type nonlinear model. Its goodness of fit parameters, like SSE were noted as 0.6593, R-square 0.987, Adjusted R-square 0.9544 and RMSE 0.5742.

When comparing the developed curve fitted models of the bifacial module with the observed data in Figure 9 which shows that the percentage error between the total (front plus rear side) to rear side. It was discovered that the percentage error was less than ± 1.5%, which is actually very small. At midday, the average maximum error was recorded at ±1.5, but in the early hours of the day, the error was negligible at ≤0.5.

The ratio function between the bifacial modules' front and rear power outputs is displayed in Equation (2). The antecedent in the ratio function is the number that is being divided, and the consequent is the term that is being divided. This function can be used for comparison purposes and provides information about the amount of time that one quantity is equal to another. The ratio is the number that can be used to express one quantity as a fraction of another. It should be mentioned that two numbers in a ratio can only be compared if they have the same unit.

$$\frac{Pmax_{bcr}}{Pmax_{bfr}} = \left(\frac{\begin{aligned} &-6.481\times10^{8} + 8.631\times10^{8}\cos(0.0001581 Pmax_{bfr}) \\ & 4.188\times10^{7}\sin(0.0001581 Pmax_{bfr}) - \\ & 2.15\times10^{8}\cos(0.0001581 Pmax_{bfr}) - \\ & 2.092\times10^{7}\sin(0.0001581 Pmax_{bfr}) \end{aligned}}{Pmax_{bfr}} \right) \quad (2)$$

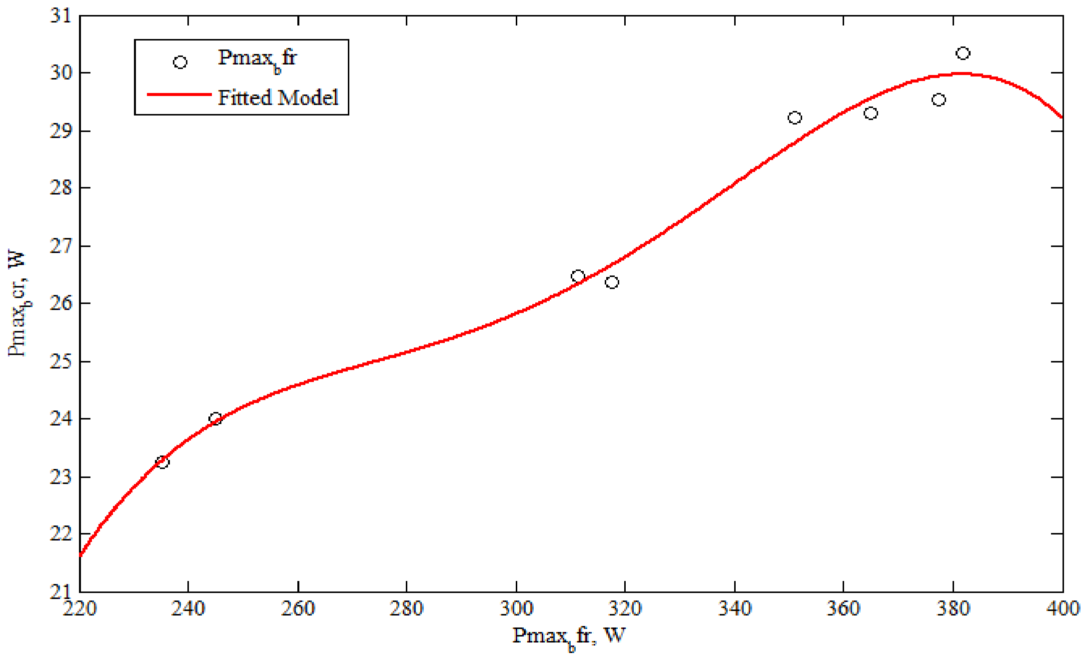

Figure 8. Curve fitting model for maximum power outputs of front plus rear side versus rear side

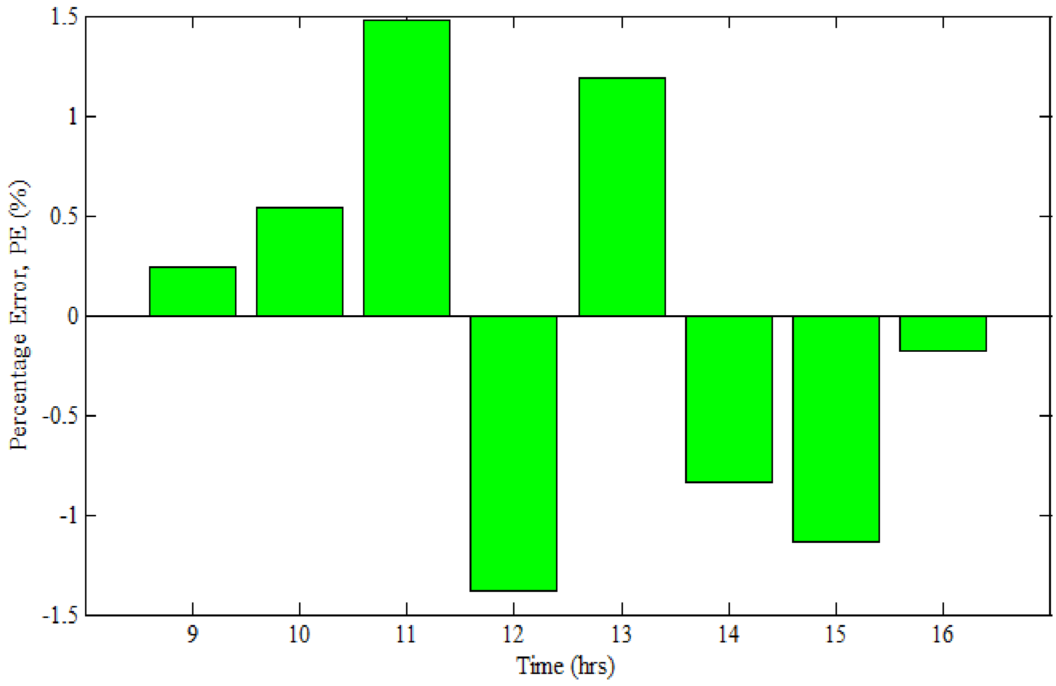

Figure 9. Percentage error between the developed model and its total versus rear side power output with the observed data

4. CONCLUSIONS

5. Both selected bifacial photovoltaic modules studied were calibrated with each other by verifying their electrical characteristics using error analysis and found lees than one percentage error. The contribution of rear side of bifacial module in the early hours of the day was 10% and around noon 7% of the total (front plus rear side). It is discovered that rear side of the module might perform better during lower solar radiation and temperature periods

(around noon) compared midday. Whereas, the time dependent model for of bifacial module with its total against rear side power output was a Fourier type nonlinear model and displayed overall percentage error of ± 1.5 and less than 0.5 percentage in the early hours of the day.

The average Ir, Ta, Rh, Ws and module temperature were found 842.4W/m^2, 29.7°C, 46.0% and 3.1m/sec and 54°C respectively during study period. In contrary to the weather parameters, the average Voc of PV module (front plus back side) was 44.8V and only backside 41.8V.It is noted that Voc was not profoundly affected by the amount of Ir. The average Isc of PV module (front plus back side) was noted as 10.9A and only backside was 1.4A. The Isc was decreased by 87.6%. Thus, there was loss of Isc as well as power. Only the rearside of the PV module produced 27.6W, while the average maximum power output (Pmax) of the front and rear sides was 334.6W. It should be noted that the module's rear side power output only accounted for 8.25% of the total power generated. The study's findings, which are consistent with previous findings published by other researchers, indicate that the rearside of the bifacial module contributes only about 9% of the total power produced by the bifacial PERC photovoltaic module in outdoor conditions in Nawabshah city.

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