Comparative Study of the Electrical Characteristics of Different Photovoltaic Modules in Outdoor Environment

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Abstract—**The electrical characteristics of photovoltaic (PV) modules are affected by solar radiation and module temperature in outdoor environment. It was found that polycrystalline gained a yearly 0.50°C more average module temperature than monocrystalline. Non-crystalline amorphous modules got a yearly 0.83°C more average temperature than thin film modules. The attainment and release of module temperature was related with material properties of PV module technologies. The amorphous module gave 5.7%, 2.7% and 15.0% more yearly average open-circuit voltage than polycrystalline, monocrystalline and thin film modules. Besides that, the thin film modules gave 6.5% and 1.7%, 9.3% and 4.0%, and 11.3% and 8.8% more yearly average normalized short-circuit current and power output than polycrystalline, monocrystalline and thin film modules respectively. It was shown that the maximum annual average open-circuit voltage was given by amorphous modules and maximum short-circuit current and power output by thin film modules during the study period.**

Keywords-climatic conditions; module temperature; IV characteristics

I. Introduction

Solar PV systems produce electricity by converting sunlight directly into electricity. PV modules are normally connected in series and in parallel to produce the desired voltage and current [1-3]. Each PV module is rated under standard test conditions [4-5] and such conditions could not be maintained in outdoor environments [6-7]. The power output (I-V, current-voltage) of modules is influenced by the intensity of solar radiation and module temperature [8]. Module temperature is one of the most important parameters responsible for deteriorating and reducing its power output [8, 9-10]. PV modules give their maximum performance in cold climates and sunny skies rather than cloudy and hot climates [11]. In general, the efficiency of a PV module decreases [12] by 0.2%/ºC-0.5%/ºC rise in ambient temperature beyond nominal cell operating temperature [13]. Authors in [14] concluded that monocrystalline modules were found more efficient than polycrystalline and amorphous in January during high radiation conditions, and amorphous showed higher average performance ratio in low irradiance. Authors in [15] reported that the efficiency of GaAs/Ge cells was 9.47% when they were exposed to the sun light at an air mass of 1.5 and at 26.85°C. Authors in [16] presented the PV systems and net metering in Greece. Authors in [17] improved the efficiency of PV and thermal systems by reducing the solar cell temperature from 51°C to 33°C by increasing wind velocity from 0.5m/s to 3m/s. Authors in [18] stated that the I-V characteristics of PV modules depend on the intensity of solar radiation. Authors in [19] analyzed the climatic data of two different cities namely Nawabshah and Quatta, Pakistan. Authors in [20] analyzed the electrical characteristics of polycrystalline, monocrystalline, amorphous, and thin film PV modules at 8:00, 12:00 and 16:00 hours from April to June 2016, and found that the polycrystalline module performed better than the others. This analysis was performed for a period of only three months, whereas the performance of modules requires to be examined for the entire year. Therefore, this study was conducted to determine the impact of module temperature on the electrical characteristics of PV modules for an entire year.

II. Materials and Methods

Four commercially available PV module technologies were investigated in the climate of Nawabshah, Pakistan. The PV modules were fixed to south at an angle of 12° with respect to the horizon. The experimental setup is shown in Figure 1 and the specifications of the examined PV technologies are given in Table I. The basic climatic variables were measured with the help of a professional weather station HP-2000. The electrical characteristic and module operating temperatures (surface and backside) of each PV module were recorded through Prova-210 and Prova-830. A total of eight k-type thermocouples were used for the recording of modules' temperature. To obtain sufficient outcomes, the data were recorded from November 2015 to October 2016. Furthermore, data loggers were connected with a computer for storing and further analyzing the data [20, 21]. The average module temperature is considered as [20-22]:

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$$T_m = \left(\frac{T_s + T_{bs}}{2} \right) \quad (1)$$

where, T_m is module temperature, T_s and T_{bs} are surface and backside module temperature.

Equation (2) is used to normalize the measured electrical characteristics values (ECVs) of four modules for comparison and performance analysis [14, 20]:

$$Output = \left(\frac{ECVs_{(measured)}}{ECVs_{(STC)}} \right) \times 100 \quad (2)$$

where, STC is the standard test conditions.

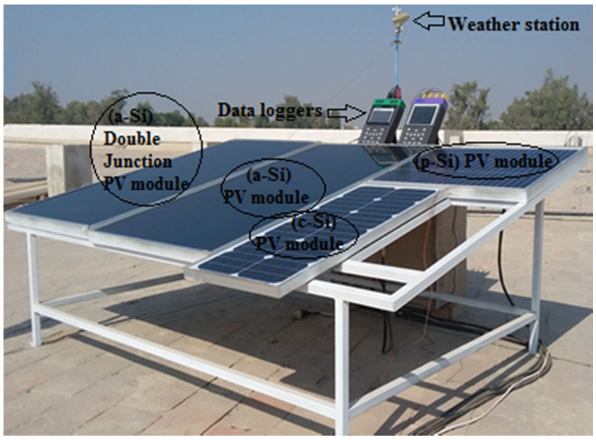

Fig. 1. Experimental setup

TABLE I. ELECTRICAL CHARACTERISTICS OF PV MODULES [20, 21]

Module parameters	Unit	Module Technologies			
		(p-Si)	(m-Si)	(a-Si)	Thin film
Model	--	SUN 40P	SUN 40M	TPS 40	GS 50
V_{oc}	V	43.00	21.50	29.00	62.00
I_{sc}	A	1.29	2.55	2.30	1.42
V_{max}	V	35.00	17.50	18.00	43.00
I_{max}	A	1.14	2.29	2.20	1.17
P_{max}	W	40.00	40.00	40.00	50.00
Area	m^2	0.27	0.24	0.76	0.74

III. RESULTS AND DISCUSSION

A. Basic Climatic Variables

Figure 2 demonstrates the hourly average values of global solar radiation (G_{sr}), ambient temperature (T_a), wind speed (W_v) and relative humidity (R_h). The yearly average values of G_{sr}, T_a, W_v and R_h were found 518.69W/m^2, 30.11ºC, 2.14m/s and 42.66%. It was noted that G_{sr} and T_a were rising from morning until noon, and then were decreasing gradually until the evening. The level of R_h was more when T_a was low, and vice versa. It is deduced that the R_h is inversely proportional to the intensity of G_{sr} and T_a during the study period in outdoor conditions.

B. Operating Module Temperature

The operating temperature of each PV module (T_m) during the study period is illustrated in Figure 3. The average PV module temperatures of polycrystalline, monocrystalline, amorphous and thin film modules were 43.96°C, 43.46°C, 44.38°C, and 43.55°C respectively. In comparison of crystalline modules, polycrystalline gained 0.50°C more yearly average temperature monocrystalline. By matching non-crystalline modules, the amorphous got 0.83°C more yearly average temperature than thin film modules. In general, it was observed that the polycrystalline module warms-up quickly in the morning, before noon, and attains more temperature between 07:00 and 11:00. Amorphous module gains lightly more temperature from 07:00 to 14:00 than the other modules until the evening. Thin film modules reached and released temperature more slowly than the other PV modules. The attainment and release of module temperature is directly related with the material properties of PV module technologies.

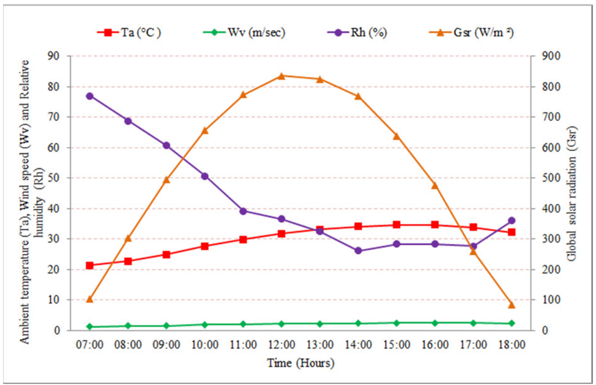

Fig. 2. Yearly hourly average climatic condition

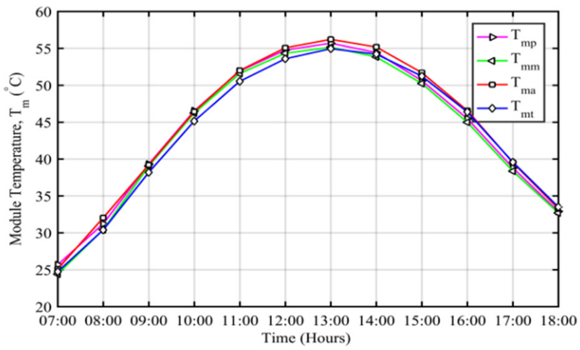

Fig. 3. Hourly average module temperatures.

C. Electrical Characteristics

The electrical characteristics, namely open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), and power output (P) of the four modules were recorded and analyzed. The results of current-voltage (I-V) and power-voltage (P-V) characteristics of polycrystalline are given in Figures 4 and 5. Maximum and minimum hourly average V_{oc} of polycrystalline were reported as 94.00% at 9:00 hours and 66.39% at 18:00 hours. The yearly average V_{oc} was 89.05%. Similarly, maximum and minimum hourly average I_{sc} was found 82.44% at 12:00 and 4.86% at

18:00, and the yearly average I_{sc} was 47.40%. Maximum and minimum hourly average power (P) was 74.87% at 12:00 and 4.27% at 18:00, whereas, the yearly average power output (P) was 43.97%.

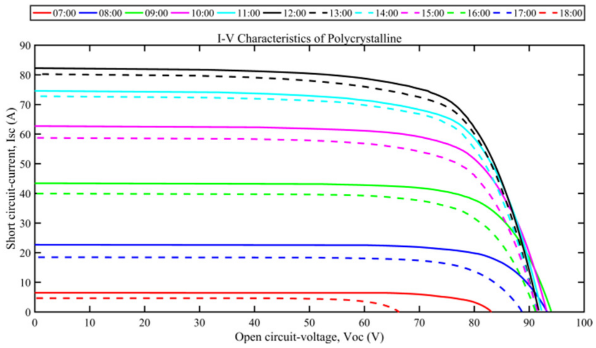

Fig. 4. Current-voltage of the polycrystalline module

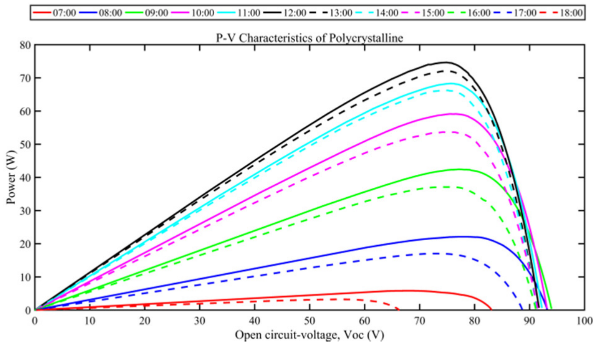

Fig. 5. Power-voltage of the polycrystalline module.

The yearly hourly average recorded values of V_{oc}, I_{sc} and power output of monocrystalline are shown in Figures 6 and 7. Maximum and minimum hourly average V_{oc} of monocrystalline was 96.87% at 09:00 hours and 69.29% at 18:00 hours. The yearly average V_{oc} was 92.07%. Similarly, the maximum and minimum hourly average I_{sc} was 76.71% at 12:00 and 4.20% at 18:00, and the yearly average I_{sc} was 44.57%. Maximum and minimum hourly average power (P) was 69.64% at 12:00 and 3.84% at 18:00. The yearly average power output (P) was 41.61%. The average results of I-V and P-V characteristics of amorphous modules are given in Figures 8 and 9. Maximum and minimum hourly average V_{oc} of amorphous PVs were 100.27% at 09:00 and 68.17% at 18:00. The yearly average V_{oc} was 94.73%. Maximum and minimum hourly average I_{sc} was 74.65% at 12:00 and 3.63% at 18:00, and the yearly average I_{sc} was 42.57%. Maximum and minimum hourly average power (P) was 62.24% at 12:00 and 3.27% at 18:00. The yearly average P output of the amorphous module was 36.79%. The average values of V_{oc}, I_{sc} and P of the thin film module are presented in Figures 10 and 11. Its maximum and minimum hourly average V_{oc} were 85.55% at 09:00 and 54.26% at 18:00. Its yearly average V_{oc} was 79.75%. Maximum and minimum hourly average I_{sc} were 94.75% at 12:00 and 4.24% at 18:00, and the yearly average I_{sc} was 53.85%. Maximum and minimum hourly average P was 78.89% at 12:00 and 3.62% at 18:00. The yearly average P output of the amorphous module was 45.62%.

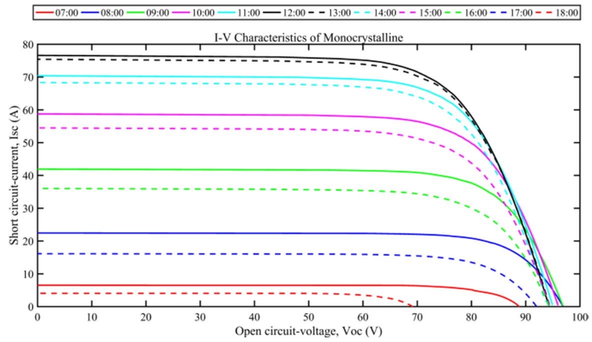

Fig. 6. Current-voltage of the monocrystalline module

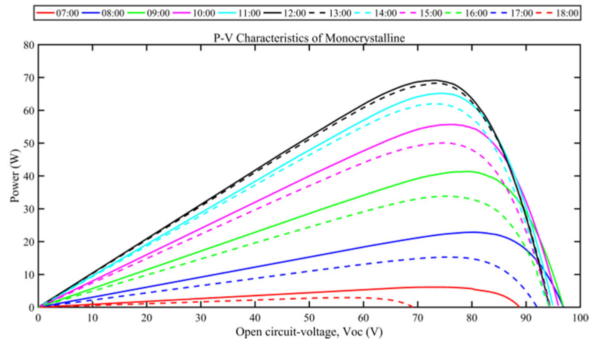

Fig. 7. Power-voltage of the monocrystalline module

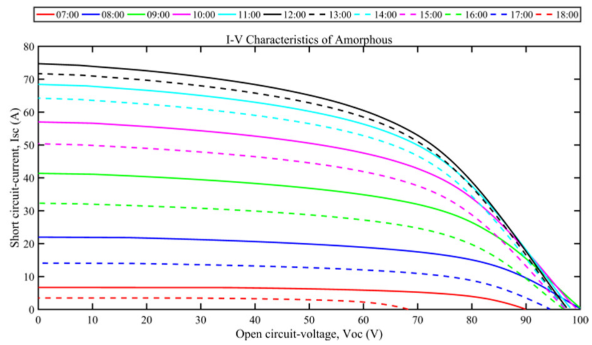

Fig. 8. Current-voltage of the amorphous module

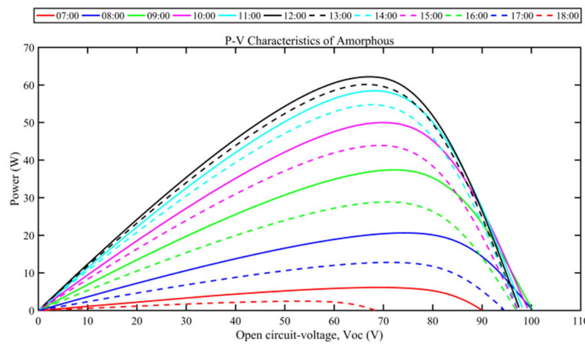

Fig. 9. Power-voltage of the amorphous module

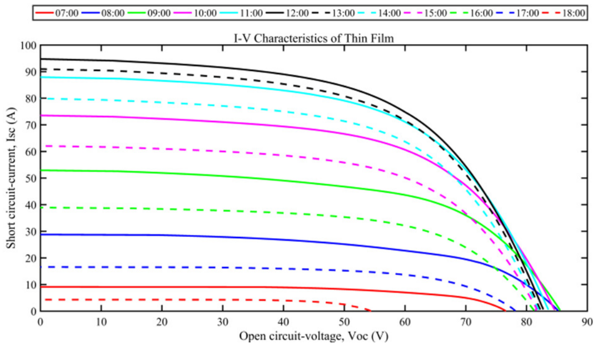

Fig. 10. Current-voltage of the thinfilm module

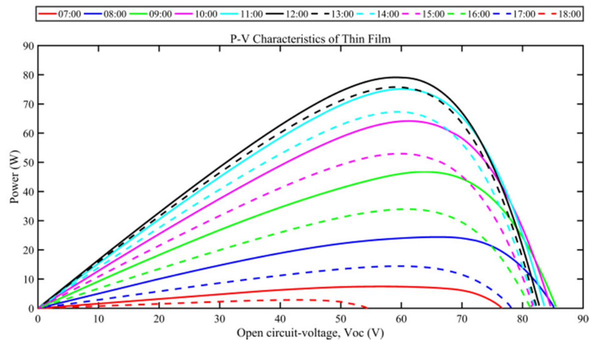

Fig. 11. Power-voltage of the thin film module

It was found that the amorphous PV module gave 5.68%, 2.66% and 14.98% more yearly average V_{oc} than polycrystalline, monocrystalline and thin film modules. Besides that, the thin film PV module gave 6.45% and 1.65%, 9.28% and 4.01%, and 11.28% and 8.83% more yearly average normalized I_{sc} and power output values than polycrystalline, monocrystalline and thin film respectively. Maximum yearly average V_{oc} was noted from amorphous module, and both I_{sc} and P from the thin film module. In general, at higher global solar radiations, each PV module generated more I_{sc} and gave more power output and vice versa. The voltage outputs were found inversely proportional to module and ambient temperature. It was found that V_{oc} was dropping and I_{sc} was slightly increasing when module temperature was rising from standard test conditions.

IV. CONCLUSION

In this research, the electrical characteristics of four commercially available PV module technologies were analyzed in the real climatic conditions of Nawabshah, Pakistan. During the experimental work, the average global solar radiation was 519W/m^2, the ambient temperature was 30.1°C, the wind speed was 2.1m/s, and the relative humidity was 42.7%. Polycrystalline, monocrystalline, amorphous and thin film modules exhibited 44.0°C, 43.5°C, 44.4°C, and 43.6°C average module temperature respectively. Regarding crystalline modules, polycrystalline gained 0.50°C more yearly average temperature than monocrystalline. Regarding non-crystalline modules, the amorphous got 0.83°C more yearly average temperature than thin film. In general, thin film modules accumulated and released temperature slower than the other PV modules. The yearly average V_{oc}, I_{sc} and power output were 89.05%, 47.40% and 43.97% for polycrystalline, 92.07%, 44.57% and 41.61% for monocrystalline, 94.73%, 42.57% and 36.79% for amorphous, and 79.75%, 53.85% and 45.62% for thin film respectively. The amorphous module gave 5.7%, 2.7% and 15.0% more yearly average V_{oc} than polycrystalline, monocrystalline and thin film modules. Besides that, the thin film module gave 6.5% and 1.7%, 9.3% and 4.0%, and 11.3% and 8.8% more yearly average normalized I_{sc} and power output values than polycrystalline, monocrystalline and thin film respectively.

It was concluded that maximum yearly average V_{oc} was given by amorphous and maximum I_{sc} and power output by thin film modules during the study period. All PV modules generated more I_{sc} and gave more power output at higher level of solar radiation. The voltage outputs of the PV modules were found inversely proportional to both module and ambient temperature.

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