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Outdoor Performance Characterization of Multi-Crystalline Silicon Solar Module

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Abstract: The performance parameters of solar modules are characterized under Standard Test Conditions (STC). However, solar modules when deployed outdoor results in the output that differs from its output obtained at STC, due to the influence of various environmental factors, leading to confusion in deciding the appropriate electrical components and loads used for Solar Photovoltaic (SPV) power plant. In view of the above, Outdoor performance characterization of the multi-crystalline silicon solar module was studied. Daily solar illumination data were measured using an optical Pyranometer and analyzed together with the module output power. Blow of air mass was found very active at the site. Stable voltage output and dynamic current outputs were recorded. The average module efficiency of ~10 and 9.5% were obtained for the high and low illumination days, respectively. However, the integrated daily efficiency was found as 9.8% irrespective of the variation in solar illumination. Percentage of variations between the solar illumination and its associated current output under the blow of air mass were not found matching. Higher blow of air mass and its associated reduction in the solar insolation condition found yielding higher current output than the expected.

Key words: Solar module, air mass, insolation, efficiency, illumination, daily efficiency

INTRODUCTION

Recently, Solar Photovoltaic (SPV) technology is gaining popularity due to the reasons that the cost of the conventional source of energy and their demand is rising (Dupraz *et al*., 2011; Panwar *et al*., 2011). Also, SPV technology oriented electrical conversion, handling and management technologies are well developed and the cost is becoming affordable (Albuquerque *et al*., 2010; Patrao *et al*., 2011; Vivar *et al*., 2012; Sharaf *et al*., 2000; Valdes *et al*., 2012; Menti *et al*., 2011; Hassaine *et al*., 2009; Welch and Venayagamoorthy, 2010; Parthasarathy *et al*., 2011). Even then, further improvements are awaited in terms of SPV-power system efficiencies. Currently, the system efficiencies are found lingering between 9~12% (Eltawil and Zhao, 2010). Therefore, various approaches were made to improve the system efficiencies, reliability in operation, life time etc., (Patrao *et al*., 2011; Menti *et al*., 2011; Chekired *et al*., 2011; Firat and Beyene, 2012; Su *et al*., 2012; Gautam and Kaushika, 2002; He *et al*., 2012). However, so far, those approaches were found resulting incomparable results with their laboratory predictions (Eltawil and Zhao, 2010). The direct exposure of the solar photovoltaic modules to the sunlight results in the outputs that differs from its outputs obtained under standard test conditions (STC) (Kurnik *et al*., 2011). In detail, the outdoor solar insolation flux is found dynamically varying with the time as well as with the blow of air mass (Su *et al*., 2012; Nakada *et al*., 2010; Minemoto *et al*., 2009), the conversion efficiency is found variable with respect to the illumination intensity (Reich *et al*., 2009; Huld *et al*., 2010), the UV illumination present in the outdoor spectrum were found imposing material degradations to the EVA (Kempe, 2010), the environmental effects like: humidity, stray light, UV lighting, temperature, etc., were found playing effective role in the degradation of module interconnects, development of defects, etc., (Firat and Beyene, 2012; Skoczek *et al*., 2009). Hence, in total, the aforementioned factors were found resulting in performance degradation in SPV systems (Huld *et al*., 2010; Skoczek *et al*., 2009; Khan *et al*., 2010; Stamenic *et al*., 2004). It is reported that the 20 years of exposure to the outdoor sunlight leads to performance losses of 1.9~2.8% on crystalline Silicon SPV systems and 0.7~1.4% on the poly-crystalline SPV systems (Ishii *et al*., 2011). Apart from degradations, it is impossible to quantify exactly the output rate or even define the daily output capacity of the solar module and

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as a consequence there are confusions over its utility. Particularly the confusion mounts over the establishment of relation between the designed capacities to the deliverable capacities. This anomaly is solely generated by the blow of air mass which is different for different geographical locations based on its climate induced compositions (Krishnan *et al*., 2009; Akhmad *et al*., 1997). To address this problem, direct outdoor monitoring, estimation of solar irradiance and clearness index, direct measurements under outdoor conditions are proposed (Nakada *et al*., 2010; Sanchez *et al*., 2011; Katsumata *et al*., 2011; Minemoto *et al*., 2007a). On the other hand, the cost of SPV system is estimated from module efficiency, module cost, land cost, array construction and installation cost as well as the site dependent solar insolation as discussed (Kamel and Muhlbauer, 1984). Nevertheless, the payback period is only depending on the electricity produced by the SPV power system (Garcia-Valverde *et al*., 2009) and thus the payback period should be clearly determined to promote the attraction towards SPV power plant business. Moreover, it is also essential to have an idea about the output characteristics of the SPV power plants in order to decide appropriate electrical components and loads.

Consequently, it is clear that the test results of solar modules obtained at STC fails to reveal the realistic output capabilities and characteristics of them when deployed outdoor. Therefore, widespread usage of the STC results for the field performance assessment misleads the predictions of output power and the output characteristics. In view of the above, this study was conducted to analyze the outdoor performance characteristics of a solar module of 5 W in power together with an installed optical Pyranometer. The solar spectral irradiance, module output current, module output voltage, module output power and module efficiency were analyzed for different outdoor illumination conditions.

MATERIALS AND METHODS

Outdoor performance measurement of SPV module was conducted at the Pondicherry University campus, Puducherry, India (Latitude: 12.0107° and Longitude: 79.856°). Multi-crystalline silicon solar module of 5 W containing 18 cells of 25 cm^2 (12.5×2 cm^2) in series (450 cm^2), processed using standard industrial module making process by Maharishi Solar Technologies Pvt. Ltd., India was employed for this study. An optical Pyranometer was installed with computer controlled data acquisition system at the measurement site and used to collect the spectral irradiance data. The output characteristics of the solar module tested at AM 1.5 STC is shown in the data sheet (Table 1). Measurements were carried out using high precision Agilent table-top multi-meters for the entire duration of the days from Sun-rise to Sun-set. Among the measured data, the data obtained for two different days: 15th of September 2011 (15DS11) and 2nd of December 2011 (02DD11) and their corresponding solar illumination data were selected for further analysis.

Table 1: Multi crystalline silicon SPV module data sheet at STC

Specifications	Values
Open circuit voltage (V)	10.50
Short circuit current (A)	0.73
Maximum voltage (V)	8.20
Maximum current (A)	0.61
Maximum power (W)	5.00
Fill factor (%)	65.20

The important parameters that are needed to characterize the performance of the solar module are solar irradiance (P_{irr}), open circuit voltage (V_{oc}), short circuit current (I_{sc}), output power (P_{od}) and efficiency (η_{mod}). The module output current, module output voltage and solar spectral irradiance were directly measured and used further to obtain the output power, efficiencies by following the standard procedures.

The output power (P_{od}) of a solar module can be obtained from their measured V_{oc} and I_{sc} values by multiplying with its Fill-Factor (FF) as reported (Maiti *et al*., 2010):

$$P_{od} = V_{oc}\times I_{sc}\times FF \qquad (1)$$

On the other hand, in general the power produced by a solar module (P_{od}) is dependent of the active area of the module (A_{act}), module efficiency (η_{mod}) and the solar irradiance (P_{irr}) as defined (Kamel and Muhlbauer, 1984):

$$P_{od} = A_{act}\times\eta_{mod}\times P_{irr} \qquad (2)$$

The outdoor efficiency was further calculated using the following relation:

$$\eta_{mod} = P_{od}/(P_{irr}\times A_{act}) \qquad (3)$$

where, the active area of the module (A_{act}) is 450×10^{-4} m^2.

RESULTS AND DISCUSSION

Different days have different solar insolation profile. However, days that received better average profile of solar insolation with high (15DS11) and low (02DD11) illumination intensities were considered for analysis. Figure 1 shows the plot of global solar irradiance data obtained from Pyranometer for entire duration of the days of 15DS11 and 02DD11 which reveal that the solar irradiance is affected by the blow of air mass. The disturbances were found both in the morning as well as in the afternoon hours. This may be related to the blow of air mass from land-to-sea and sea-to-land driven by the temperature differences. It can be observed that the peak irradiation intensity of 15DS11 is ~ 950 and 02DD11 is ~817 W m^{-2}, respectively.

Figure 2 shows the plot of the recorded output current (I_{sc}) and output voltage (V_{oc}) with respect to the time duration of the days 15DS11 and 02DD11, respectively. It is worth to note that the profile of the output current (I_{sc}) is exactly falling with the profile of the solar irradiance as presented in Fig. 1. The increase and decrease of solar irradiance in morning and evening generates proportional free electrons in the solar module that leads to almost linear increase and decrease in the output current, respectively that may be identified in the figure. While, the module output voltage was found getting steeply build up in the morning and attains saturated value of ~9.3 V (15DS11) for a period of duration of ~7.5 h and ~9.15 V (02DD11) for a period of duration of ~7.3 h, respectively, above 40% of illumination level with respect to STC value (1000 W m^{-2}). The peak output currents of 0.71 A and 0.68 A were measured for the peak illuminations of both the days of ~950 and ~ 817 W m^{-2}, respectively. The measured I_{sc} values of both the days are falling with 97.26 and 93.15%, respectively with respect to the STC value (0.73 A). On the other hand, their respective solar irradiances were found as 95 and 81.7%, respectively to the STC illumination. From this, it is noticeable that the relatively lower percentage of light received under the influence of the blow of air mass yields higher percentage of current output (02DD11) than its linear dependence. This inconsistency in the correlation between the illumination and the current yield reveals that the module receives more active photons during the heavy float of air mass. This fact of the observation of higher current output at lower illumination intensity is found supported by the report which stated the presence of higher density blue photons in the outdoor light than in the STC AM 1.5 spectrum (Katsumata *et al*., 2011; Minemoto *et al*., 2007b).

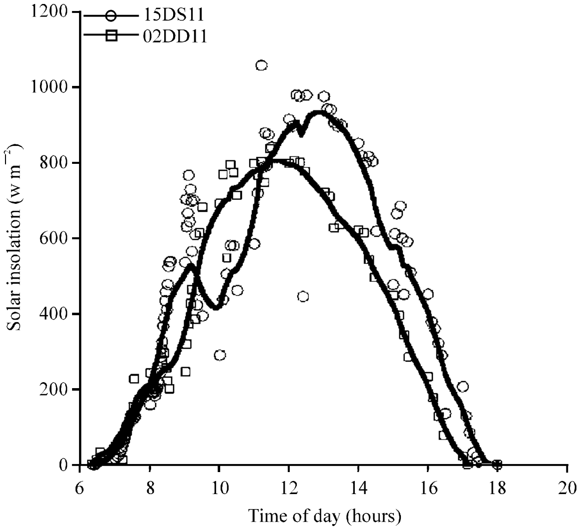

Fig. 1: Global solar spectral irradiance data for entire duration of the days of 15DS11 and 02DD11

In addition to the above, it can be sighted from Fig. 2 that the output voltage builds up primarily before

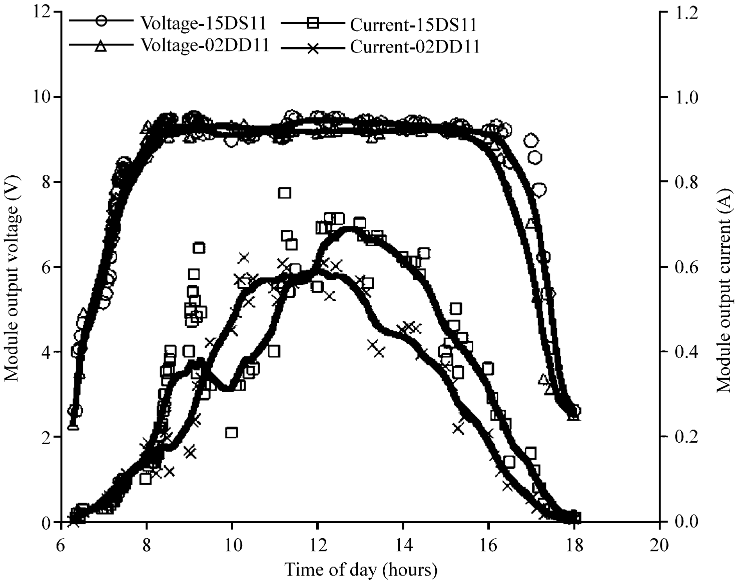

Fig. 2: Module output voltage (V_{oc}) and output current (I_{sc}) with respect to the time duration of the days 15DS11 and 02DD11

the current output at low illumination condition. As module position is fixed, it is not directly facing the sun and hence the insolation falls with wide angle of incidence boosting the reflection losses. As a consequence, the current generation may be dominantly influenced only by the weak diffused light than the direct light. Hence, there may be a quasi-static dynamism in the build-up of V_{oc}.

This visible build-up of voltage with respect to the increase in illumination level is also an indication of the presence high resistive material across the junction. It was reported that the V_{oc} of the $n^{+}p$ solar cell rises slowly when there is high resistive material that elucidate difference between the quasi-Fermi potentials of the two active space charge regions in the solar cell (Fossum and Lindholm, 1977).

Meanwhile, it was also reported that the solar cells having high density of trap states due to the multi-crystalline structure can result in an additional voltage build-up at low illumination intensities (Khan *et al*., 2010). Therefore we may state that the visible voltage build-up at low illumination level may be due to the presence of non-uniform doping in the multi-crystalline solar cells due to the impact of its grain boundaries as discussed (Halder and Williams, 1983). This situation of voltage build-up or voltage drop was found either in the early hours of the day or in the late evening hours of the day, whenever the light injection levels are falling less than 20% of its STC value as observable from the Fig. 2.

From the Fig. 2, the saturated mean values of V_{oc} were found as 9.3 and 9.15 V for those days of 15DS11 and 02DD11, respectively. This voltage saturation was found stable for the durations of 8:00 and 7:30 h, respectively. These differently observable values of saturated V_{oc} with respect to the solar illumination states that the V_{oc} saturation requires critical illumination intensity as stated earlier. Moreover, it was also interestingly noted from the Fig. 2 that the timely short fall of illumination after the establishment of saturated V_{oc} did not impose any major drop in V_{oc}. On this basis, we may imply that the dynamic fall in outdoor illumination intensity due to the dynamic movement of air mass may not be effective to the cut-off voltage of inverter operation in the case of SPV power system.

Figure 3 shows the plots of module output power (P_{od}) with respect to the time duration of the days 15DS11 and 02DD11 obtained using the Eq. 1. It was observed that the 5 W capacity module results in the total output powers of 221.6 and 112.8 watts, respectively which are equivalent to the 3.6936 and 1.88 W h day^{-1}.

The comparative analysis of the Fig. 2 and 3, further implies that there are two types of output performances exist from the module deployed under outdoor illumination. They are: (1) the stabilized voltage output above certain illumination level and (2) The fluctuating power output with respect to the solar illumination of the entire days. It is reported that this dynamic change in output power pumps in harmonic distortion in the power distribution system and depreciate the power quality (Hengsritawat *et al*., 2012). Thus, we can state that the observed air mass induced output fluctuations as shown in Fig. 3 drives the development of harmonics and the consequent power depreciation. Meanwhile, the shown stable output voltage in Fig. 2 also indicates that the outdoor deployed SPV module is able to provide the operational voltage stability index (V_{si}) for further system integration (Charkravorty and Das, 2001).

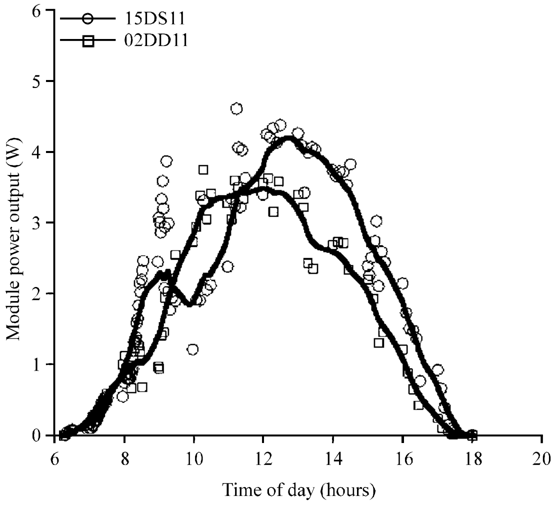

Fig. 3: Module output power (P_{od}) with respect to the time duration of the days 15DS11 and 02DD11

Figure 4a and b present the plot of efficiency versus the time duration of the days 15DS11 and 02DD11, respectively. Figure 4a and b clearly indicate that the average efficiency varies with the growing hours of the days. The average efficiency for the day 15DS11 is ~10% (Fig. 4a) with the variable values found between the lowest of ~6.95% (early hours) to the highest value of ~13.47% (late hours) with fluctuations. Similarly, the average efficiency of 02DD11 is ~9.5% (Fig. 4b) with minimum and maximum values of ~5.2% (early hours) to ~13% (late hours), respectively. Overall, it may be noticed from Fig. 4a and b that the module efficiency is increasing with the time duration of the day. Normally, at an outdoor exposure of modules, the increase in illumination intensity was found resulting an increase in module efficiency (Firat and Beyene, 2012; Eikelboom and Reinders, 1997). In the present case, the result is in analogous to the reports until noon hours but differs for after the noon as shown in both Fig. 4a and b. This observation of dual

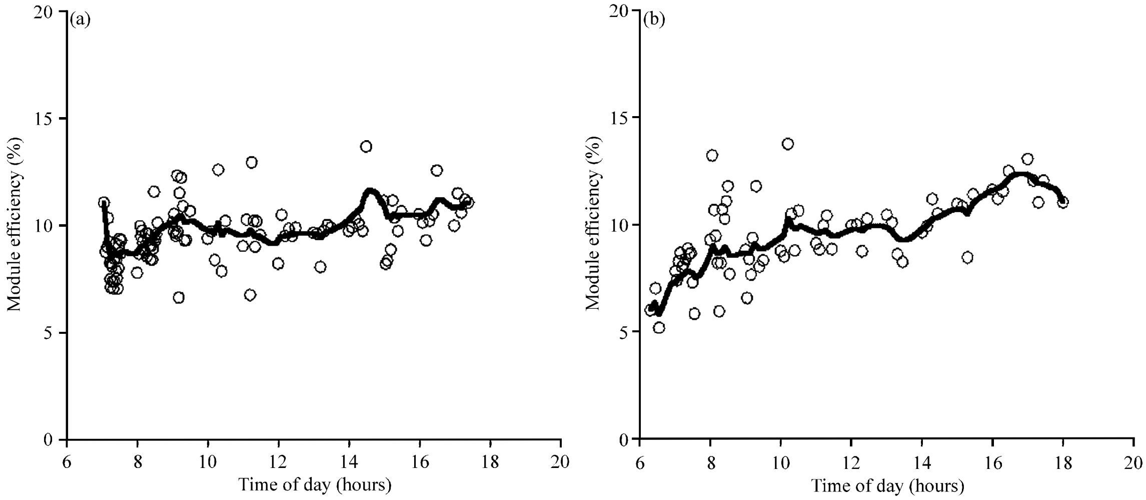

Fig. 4(a-b): (a) Efficiency vs. the time duration of the day 15DS11 and (b) Efficiency vs. the time duration of the day 02DD11

behavior is different from the report (Khan *et al*., 2010). In lieu of this, it is also reported that at the lower illumination flux, a solar cell results in higher efficiency due to the presence of higher shunt resistance (Sanchez *et al*., 2011). Further, the daily performance of efficiency of the module was determined for the high and low illumination days of 15DS11 and 02DD11. Overall module efficiency of the day (η_{day}) was obtained from the ratio between the daily module output powers to the illumination input as stated earlier in Eq. 3. The values are found as 9.84 and 9.81% for the days of 15DS11 and 02DD11, respectively. Therefore, we can state that the solar module deployed under outdoor exposure to the sun results in an identical integrated daily efficiency (η_{day}) irrespective of the illumination intensity.

Beside the efficiency factor, the measurements revealed that the blow of air mass disturbs the leniency of the module output profile. Moreover, the overall increase or decrease in solar irradiance up-shift or down-shift the SPV output profile. Hence, the dynamic variation in the solar illumination and its associated up or down shift of the bell-shaped output profile of the SPV module inflict complication on the output design and forces to work below the peak power specified either from STC or peak of day illumination. The output power of the solar module is found highly variable with time as well as with the blow of air mass. Hence, the power rating also varies with the time and blow of air mass. Therefore, it may be stated from the measurements and analysis that the specified operational hours of SPV system highly depends on the output rating that is fixed. Lesser fixed power rating leads to the longer the duration of operation.

In concise, a solar photovoltaic module with 5 W output capacity was deployed for outdoor measurements simultaneously with an installed optical pyranometer. The measurements and the analysis of the measured data revealed that the site of this measurement has heavy blow of air mass that in turn found greatly affecting the linearity of the output profile. However, the heavy blow of air mass found increasing the percentage of performance than the expected linear performance variation. The daily module efficiency was calculated as 9.8% irrespective of the solar illumination level.

CONCLUSION

Outdoor performance characteristics of the multi-crystalline silicon solar module was studied at the site of Pondicherry University, Puducherry, India (Latitude: 12.0107° and Longitude: 79.856°) near the sea coast. The site is found with heavy float of air mass that in-turn found hampering the leniency of the output profile, increasing the percentage of current yield at heavy float condition and so on. The time dependent efficiency of the SPV module was found increasing with the time duration but the daily efficiency found remaining identical at all illumination levels.

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