

Supercapacitor based PV measurement technique – quality assessment with poly-Si PV modules at IEST, Kolkata

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Abstract. Supercapacitors have been used for the first time as load to PV cell/modules for characterizing their behavior. In this paper, a novel and essentially simple design of a $V-I$ plotter is attempted with a bank of super capacitors (SC) as the load to the PV modules of varying capacities. The distinct advantages of the SC's over the erstwhile capacitors have been comparatively experimented. Finally, an elaborate regression analysis (RA) of principal electrical parameters have yielded consistently high values exceeding 0.993 experimental evaluation of quality parameters like fill-factor (FF) and performance ratio (PR) have yielded a range of 70–79% while PR values frequently ranges from 90% to 99%. Suitability of poly-Si PV modules at the level of PV panel configurations have been ascertained through experimental estimate of series and parallel relative power loss (RPL) values. Typical values below 2% obtained for widely varying climatic level is also a quality indicator for the new metrology in question. Such a prototype $I-V$ plotter is expected to be duly considered for commercial testing applications in PV industries.

Keywords: SPS / RES / PV power plants / supercapacitors / PV generators / performance ratio

1 Introduction

The rapid penetration of the solar photovoltaic systems (SPS) into the electrical networks at different voltage levels is now an accepted global phenomenon. Penetration of renewable energy sources (RES) into the average European grid is expected to cross 30% by the end of 2022, 12% of such shares being specifically contributed from photovoltaics [1]. India has already embarked on a policy [2] of delivering at least 20% of grid-power through renewable energy sources (RES) by 2020. Accordingly, massive efforts are currently being undertaken in India for large-scale installations of PV power plants of megawatts capacity. This calls for an appropriate and smart metrological procedure for selecting the PV modules, acting as the building blocks to the high capacity PV arrays [1].

The aforesaid situation is responsible for expanding the role of an online, accurate and inexpensive $V-I$ plotter outside the academic laboratories also. Thus, the next section is essentially devoted to a review of the existing metrological approaches practiced in PV

engineering for establishing the specific merits of the supercapacitor (SC) based method introduced by the authors. Here, supercapacitors have been used in the area of PV metrology for the first time as the load to the PV generators [3–5].

2 Review of existing PV metrology

The conventional analog method of determination of the $V-I$ characteristic of a solar module involves a variable resistance used as the load. A typical $V-I$ characteristics of any PV module is shown in Figure 1, where there are two extremities – the short circuit current point ($I_{sc},0$) and open circuit voltage point ($0, V_{oc}$). The standard electrical parameters of interest in any $V-I$ plot are the following: short circuit current (I_{sc}), open circuit voltage (V_{oc}), peak power current point (I_m), peak power voltage point (V_m), maximum power point (P_m).

By varying the resistive load, the above co-ordinates can be approached but not reached. Further, this manual process consumes sufficient time leading to undesired heating of all the $p-n$ junctions of a PV module.

To minimize the human intervention and to characterize the PV module faster and accurately researchers started to use electronic loads instead of resistive loads.

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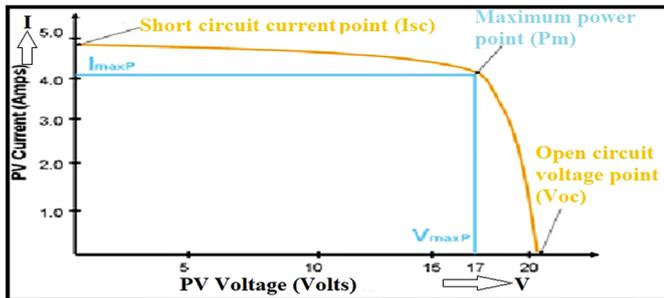


Fig. 1. Photovoltaic module voltage–current characteristics.

Linear MOSFET can be used as an electronic load to test the PV panel. Advantage of the electronic load is the fast variation (scanning) of the equivalent load resistance. Various commercial grade systems for testing PV panels under field conditions are available but they are computer controlled and are very expensive. A MOSFET based electronic load circuit was introduced by Kuai et al. [6]. Recently Sahbel et al. designed a simple electronic circuit for testing the photovoltaic (PV) modules by tracing their I - V characteristics [7]. However, such methods are constrained by a requirement of an expensive test setup primarily suited to the laboratory measurement conditions only. In the next phase of development, researchers developed capacitor charging with the aid of open circuit voltage. Such an effort by Mahmoud [8] has used capacitors as the load to PV Generators. But, such reports contain a detailed transient analysis, which leads to the estimate of I - V plotting time based on open circuit voltage (V_{oc}) and short circuit current (I_{sc}) only. Also, such reports do not contain real traces of I - V characteristics of PV generators. Further, this method calls for a high precision matching DAS, rendering the plotter higher in capital cost, although other researchers like Erkaya et al. and Spertino et al. [9,10] have in the recent past used capacitive load. Very recently Zhikong et al. [11] proposed new capacitor-based design and implementation of an I - V characteristics tester. The setup is quite efficient to characterize PV arrays quickly. But this type of tracer is not able to characterize a single PV cell/module/panel. But neither of these curve tracers provides an assessment of the V - I plotting time and effective means to control the same.

On the above backdrop, authors of this paper have introduced a new technique where Supercapacitors have replaced the capacitors with the plotting time modeled out as a function of four basic electrical parameters (I_{sc} , V_{oc} , I_m , V_m) along with the effective series resistance (ESR) value of the SC bank. This is reported in details in an earlier publication [5].

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- short circuit current (I_{sc}),
- open circuit voltage (V_{oc}),
- maximum current at maximum power point (I_m) and

- maximum voltage at maximum power point (V_m) along with the effective series resistance (ESR) value of the SC bank. This is reported in details in an earlier publication [5].

3 Advantages of super capacitors (SC) over capacitors

In this work, supercapacitors have been used as a measuring element rather than a storage device. In this case, note worthy advantages of SC's are:

- Desirable control of the plotting time when the voltage of SC approaches V_{OC} .
- The thermal management of the Supercapacitor bank is possible without the use of any kind of heatsink, as the heat dissipation is not expected to cross a level of few watts, prevailing for only 10–15s. This is clearly evidenced from Table 1.
- A high Coulombic efficiency exceeding 99%, leading to fast sweep between $V=0$ to $V=V_{oc}$.
- A wide range of capacitances available with low ESR values (within few milliohms) [12].
- A voltage range compatible with the open circuit voltages of standard PV modules and panels.

To establish the superiority of supercapacitor-based loading method a comparative table for SC based and capacitor-based methods with respect to accuracy in estimation of curve tracing time is to be shown in Table 1.

Moreover, an experimental estimation of heat dissipation for 100 Wp PV modules using supercapacitors is shown in Table 2. The heat dissipation values in the last column have been estimated by considering individual ESR value of the supercapacitors to be 0.02Ω and the total ESR value of the Supercapacitor bank is 0.12Ω (optimum combination of six SC's in series). Same experiments were also carried out using capacitances of rating 10,000 μF , 25 V with 1 ohm ESR value and the charging currents utilized to estimate the different heat dissipation amounts as shown in Table 3.

It is clearly seen from the above two tables that capacitor-based characterization calls for a separate heat sink to dissipate the excessive heat generated. Further disadvantage of using the capacitor as the load to the PV generator requires a higher volume, which also makes some capacitor-based plotters inconvenient for transportation.

4 Characterization setup

Figure 2 represents typically a block diagram of the testing scheme used by the authors.

The solar PV modules or panels (combination of PV modules) have been fitted into the steel structure and placed at the roof-top. Voltage and current inputs are via VC (voltage channel) and CC (current channel) respectively. For accurate insolation sensing a 3 Wp c-Si solar PV panel has been placed and considered as the reference module. The module back surface temperature is measured using the resistance temperature detector (RTD) cables

Table 1. Estimate of curve tracing time (for 10Wp, 74Wp and 100Wp poly-Si PV module).

Module wattage	Degree of curve tracing K%	Actual/experimental curve tracing time (T_{ex})	Estimated curve tracing time as per capacitor based method	% Error in capacitor based method (with respect to experimental curve tracing time)	Estimated curve tracing time as per supercapacitor based method	% Error in SC based method (with respect to experimental curve tracing time)
10 Wp Poly-Si	95.11447	3.8	14	268%	3.914	3.00%
	96.73156	4.2	14.8	252%	4.284	2.00%
	97.78194	4.6	15	226%	4.784	4.00%
	98.74078	5.2	15.6	200%	5.408	4.00%
	99.74064	7.5	16.6	121%	7.601	1.35%
	99.99974	9	17	89%	9.17	1.89%
74 Wp Poly-Si	95.11447	3.8	0.5	-87%	3.914	3.00%
	96.73156	4.5	1.2	-73%	4.8	6.67%
	97.78194	5	1.5	-70%	5.2	4.00%
	98.84078	5.8	1.8	-69%	6	3.45%
	99.6864	6.5	2	-69%	6.7	3.08%
	99.99884	7.2	2.4	-67%	7.3	1.39%
100 Wp Poly-Si	95.11447	2.8	1.6	-43%	2.95	5.36%
	96.73156	3.7	2	-46%	3.8	2.70%
	97.78194	5.5	2.4	-56%	5.7	3.64%
	98.72078	6.8	2.6	-62%	7	2.94%
	99.74364	7.4	2.8	-62%	7.7	4.05%
	99.99955	8.1	3	-63%	8.4	3.70%

Table 2. Heat dissipation when 100 Wp PV modules use supercapacitor loading.

Module wattage (Wp)	SC-value (F)	Insolation (W/m^2)	Charging-current (I) (A)	Heat dissipation (W) = (ESR*I*I)
100	0.166	245	1.59	0.3337092
100	0.166	300	1.8	0.42768
100	0.166	350	2.14	0.6045072
100	0.166	450	2.44	0.7858752
100	0.166	580	3.31	1.4462052
100	0.166	850	4.5	2.673

Table 3. Heat dissipation for 100 Wp PV Modules using capacitor loading.

Module-wattage (Wp)	C-value (F)	Insolation (W/m^2)	Charging-current (A)	Heat dissipation (W) = (ESR*I*I)
100	0.001	200	1.535	2.2384
100	0.001	500	4.31	17.6473
100	0.001	650	4.8	21.8880
100	0.001	750	5.616	29.9625

and this value transferred to the cell temperature by using the known standard relation [13]. The solar PV modules are Polycrystalline type in the range of 10 Wp to 320 Wp. The actual measurement setup is shown in Figure 3. The data

acquisition system (DAS) is being made operational on an embedded platform (dsPIC30F4013) making the instrument light-weight and portable. The graphical-LCD (GLCD) display is attached with the measurement setup.

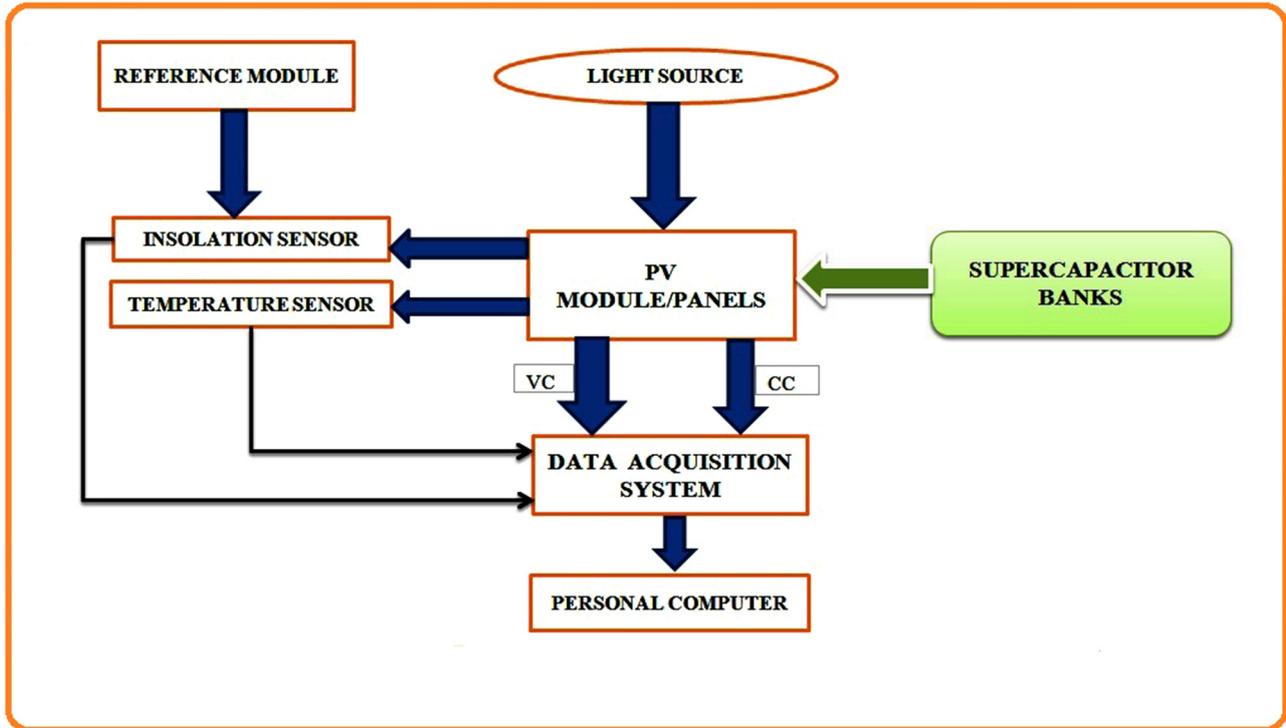


Fig. 2. Functional blocks of the testing setup.

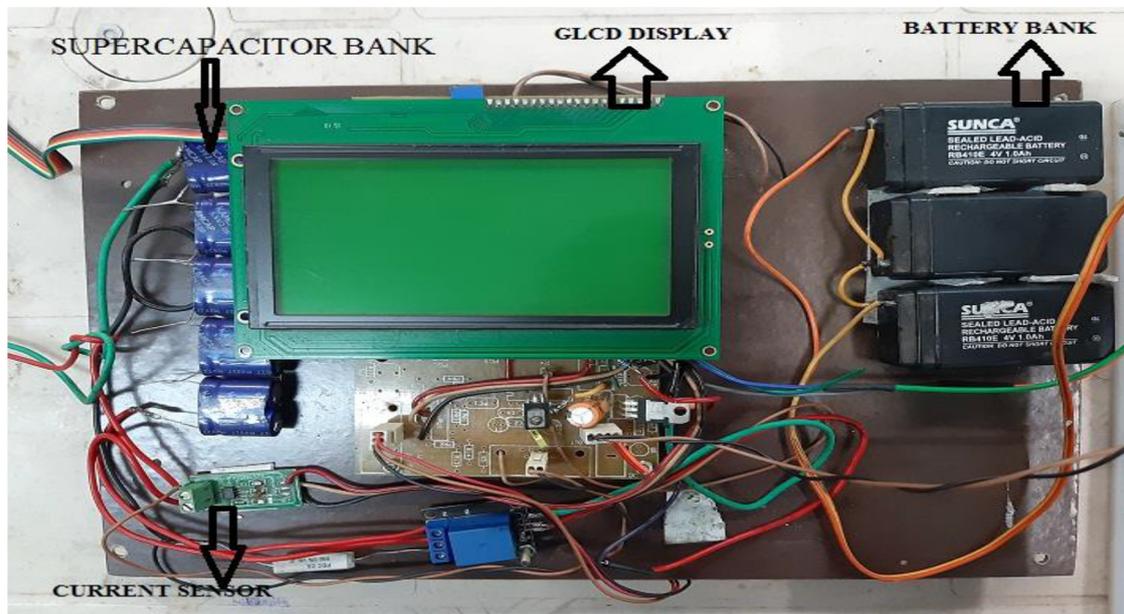


Fig. 3. Components of author $V-I$ measurement setup.

4.1 Configuration of the SC bank

The task of choosing the elements of the SC bank was performed with initial priority on low ESR [14] values. The SC banks were configured in two steps:

- In the 1st phase, the PV Module's capacity is considered between 10 W_p to 100 W_p. Since the V_{oc} of the 10 watts to 100 W_p PV modules lie between 21 V and 25 V levels,

six numbers of series connected 1F, 5.5 V supercapacitors with ESR values (0.022 ohms) were chosen. For the first case, the simple Kamcap supercapacitors have been used, where the equivalent capacitance of the SC Bank = $1/6 = 0.166$ F (seen from Fig. 3).

- In the second stage, the largest capacity building block in Indian PV arrays is considered. Since the V_{oc} of a 300 W_p PV module is 48 V, lowest ESR values (0.022Ω),

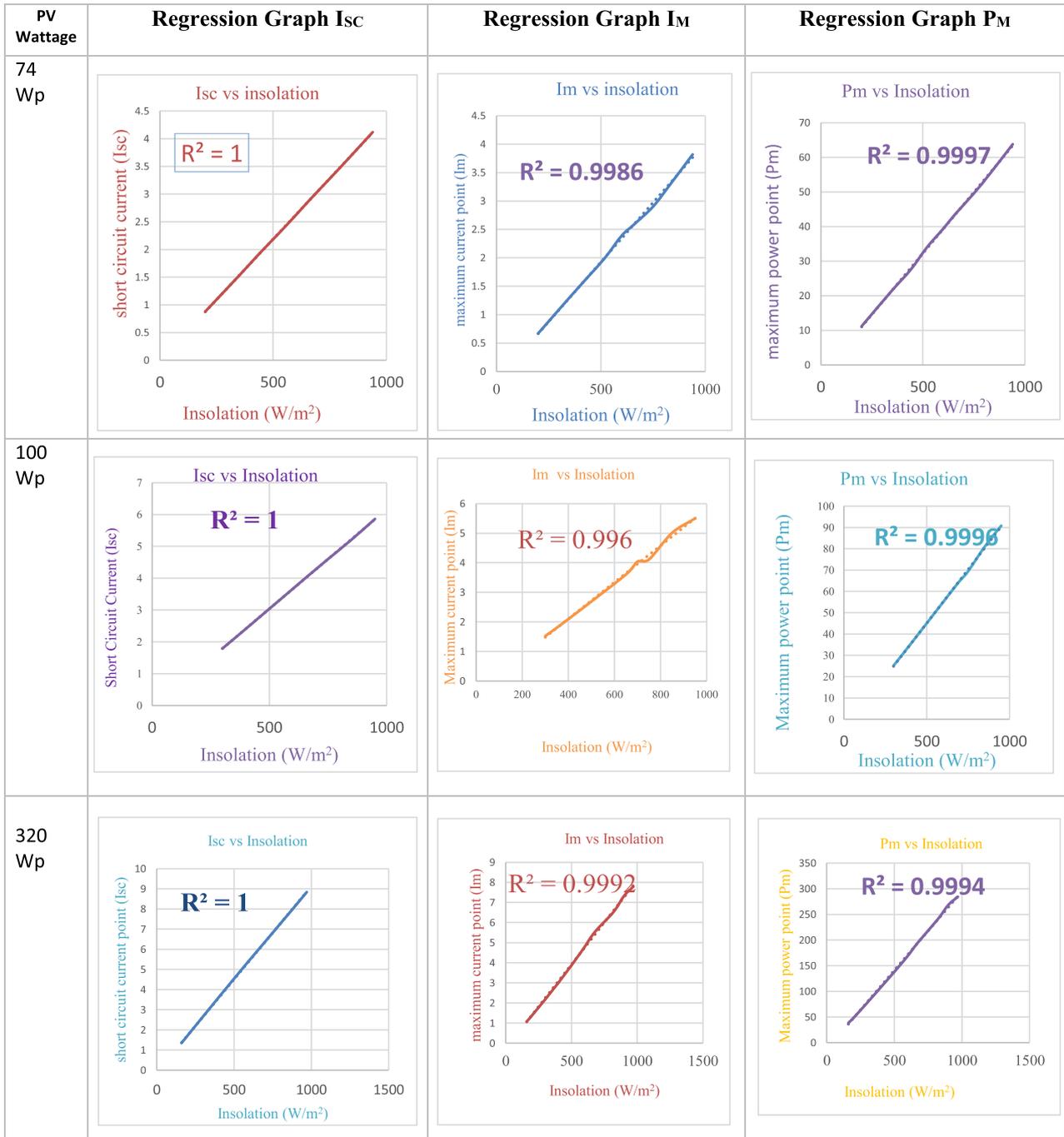


Fig. 4. Linearity check for the solar PV parameters against insolation variation.

supercapacitor bank has been constituted with nine numbers of 7.5F, 5.5V supercapacitors. A series configuration constitutes an equivalent capacitance value 0.83 F (7.5/9).

Kolkata. Analysing the aforesaid set of results, a no. of essential figures of merit transpires with a reasonable degree of consistency. Following figures of merit has been envisaged.

5 Quality of measurement

It may be mentioned at the outset that Poly-Si PV modules technology currently enjoys the largest share of Indian PV market. Accordingly, authors group has planned the entire schedule of measurement with a leading PV industry in

5.1 Regression analysis (RA)

Regression analysis [15] was done for I_{sc} , I_m and P_m of PV modules with changing insolation levels. Figure 4 shows values of regression co-efficient (R^2) consistently above 0.95 was obtained for 74 W, 100 W, 320 W poly-Si modules.

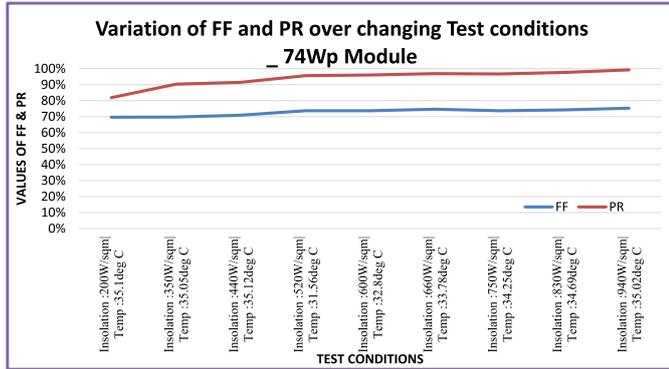


Fig. 5. FF and PR variation with varying insolation for 74 Wp PV modules.

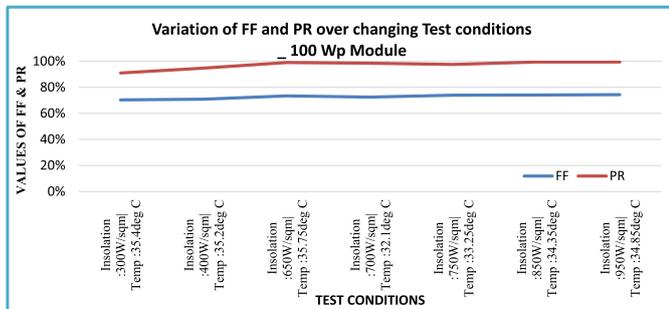


Fig. 6. FF and PR variation with varying insolation for 100 Wp PV modules.

5.2 Fill factor (FF)

It is the ratio of area covered by I_m-V_m rectangle with area covered by $I_{sc}-V_{oc}$ which is given in equation (1) using standard symbols.

$$FF = (V_m \times I_m) / (I_{sc} \times V_{oc}). \quad (1)$$

Fill factor is an intrinsic property of any PV generator and usually from 0.6 to 0.85 for good quality PV generators. The FF variations with varying insolutions and temperature are shown in Figures 5–7. However, in real test conditions FF values lies in the range of 0.7 to 0.8.

5.3 Performance ratio (PR)

The PR is stated as the ratio of the actual and theoretical energy outputs of the PV plant/PV module [16]. Mathematically performance ratio is represented as

$$PR = (mP_{MPP}/P_{STC}) \times (1000 \text{ W/m}^2/G_{POA}), \quad (2)$$

where, mP_{MPP} , measured power in NON-STC condition; P_{STC} , measured power in STC conditions; G_{POA} , insolation actually incident on the plane of array.

However, in real field conditions PR values for a PV plant lies between 0.80 and 0.95. Such values for different wattages of PV modules are shown in Figures 5–7 against varying levels of insolutions.

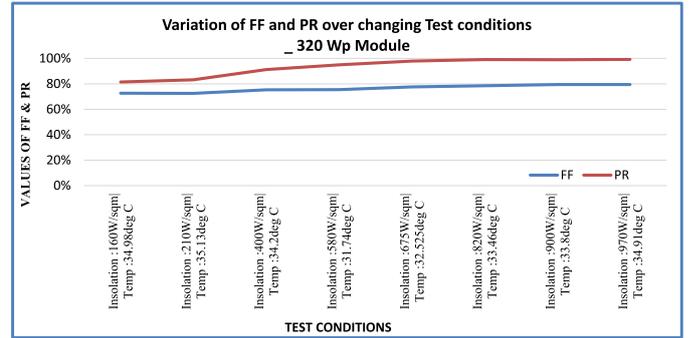


Fig. 7. FF and PR variation with varying insolation for 320 Wp PV modules.

5.4 Smooth and noise free characteristics

It can be observed from the set of $I-V$ characteristics presented in Figure 8 that the curves are all having a smooth trace, where the detection of the maximum power point occurs in a unique fashion for all the curves. Further, no kink/noise level is seen around the maximum power point zone. Uncertainty in determination of maximum power point is thereby eliminated.

5.5 High reproducibility of the measurements

In line with the classical way of understanding the reproducibility of measurements, in case of PV metrology, the same has to be assessed through the infirmity of quality of the PV performance parameter obtained under naturally varying environmental conditions. Figures 5–7 projects the two essential PV quality parameter FF and PR against naturally varying levels of climatic condition over a full day. Such an exercise for a particular PV module capacity has been repeated for a set of chosen PV building blocks – 74 Wp, 100 Wp, and 320 Wp modules. Error-free measurements obtained under various combinations of insolutions and temperatures have been projected in Figure 8 (4×3 matrix), where four selected capacity of PV module has been characterized in three different seasons of the year. Thus result gives adequate confidence in the “Reproducibility of the measurements” can be instilled.

6 Relative power loss (RPL) analysis

Non-identical current-voltage characteristics of PV modules give rise to power loss when modules are connected in series or in the parallel configuration. Such losses are called Mismatch loss. Mismatch losses normally arise due to relative power loss (RPL) or in the form of shading loss. The shading loss is neglected easily by choosing the appropriate PV installation site. RPL loss is the total output power of Series connection or Parallel connection of PV modules will be less than the sum of the total power output of PV modules as if they are acting individually. Table 4 shows the RPL measurement for 50 Wp and 100 Wp Poly-Si PV modules in Eastern Indian Climatic Zones. In fact, the quality of measurement so proposed by the authors’ metrological approach has been

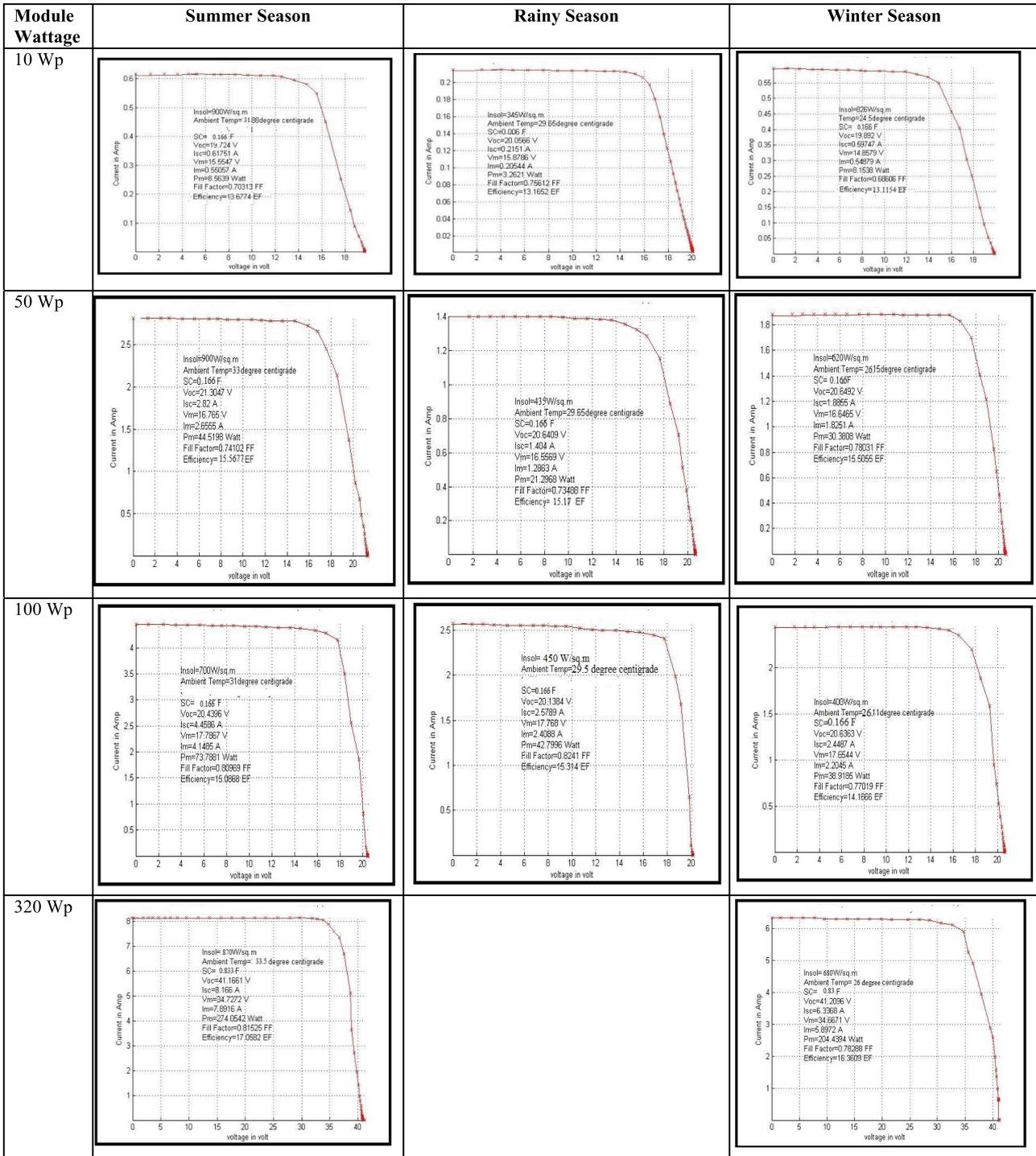


Fig. 8. $V-I$ characteristics of different wattages poly-Si PV modules across three different seasons.

reaffirmed by checking the outdoor performance of small poly-Si PV panels constituted in series and parallel configurations.

7 Conclusion

It is to be noted that the PV Modules experimented upon are all Poly-Si PV modules as such modules

are the predominant ones in the current Indian market. The basic building blocks (PV modules) chosen for the purpose of experimentation with the new metrological procedure are 74 Wp, 100 Wp, and 320 Wp poly-Si PV modules.

(a) It is seen from Figure 4 that, consistently high values of R^2 (above 0.98) are found with respect to regression analysis of I_{sc} , I_m , P_m of the chosen modules.

Table 4. RPL measurement for 50 Wp and 100 Wp poly-Si modules.

50 Wp poly-Si module				100 Wp poly-Si RPL			
Insolation (W/m ²)	Temperature (°C)	RPL-series (%)	RPL-parallal (%)	Insolation (W/m ²)	Temperature (°C)	RPL-series (%)	RPL-parallal (%)
145	31.76	2.31%	1.91%	245	27.67	1.55%	1.40%
245	26.51	1.76%	3.58%	300	27.61	1.56%	1.17%
355	31.45	1.96%	1.17%	350	27.47	1.17%	0.62%
430	26.1	1.56%	0.96%	400	27	1.57%	0.59%
600	26.59	1.59%	0.39%	450	26.68	1.58%	0.57%
680	28.97	1.31%	0.94%	540	25.44	0.94%	0.42%
770	26.56	2.12%	1.19%	600	24	1.42%	0.45%
880	25.8	1.82%	1.15%	680	22.51	1.09%	0.54%

- (b) From Figures 5–7 are clearly seen that
- Estimated FF values for the aforesaid modules are in the range of 70% to 79%.
 - The PR values of the building blocks range typically from 90 to 99% for varying levels of insulations.
- (c) Reproducibility of author's metrology through the new SC-based technique has been confirmed on a particular day (Figs. 5–7) and across three different seasons (Fig. 8).
- (d) Finally, RPL values for 50 pW and 100 pW PV panels are typically less than 2.5% and 1.5% for series and the parallel respectively string of PV modules corresponding to insolation above 300 W/m².

Experimental evidence (a) to (d) is a strong indicator of the inherent quality of the new metrology based on supercapacitors. Field trials with Vikram Solar PV modules are in progress for finalizing an appropriate commercial version of the prototype $I-V$ plotter.

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