UNDERSTANDING THE EFFECT OF SERIES RESISTANCE FOR SOLAR PV MODULE

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***Abstract*—Solar Photo voltaic industry is tipped to be one of the front runners in the renewable industry. Typically, PV Module manufacturers provide a linear or step warranty of 80% of original power over 20 Years. This power loss is during the field exposure is primarily attributed to the development of performance affecting defects in the PV modules. Quality inspection of PV-modules includes measurement of peak-power Pmax and internal series resistance Rs. Peak Power is defined as maximum power under standard test conditions (STC). As the peak-power can decrease due to degradation effects, a continuous quality inspection has to be realized on-site under natural ambient conditions.**

Keywords: Series resistance-1, fill factor-2, Maximum power-3, Series Resistance-4, Shunt Resistance-5

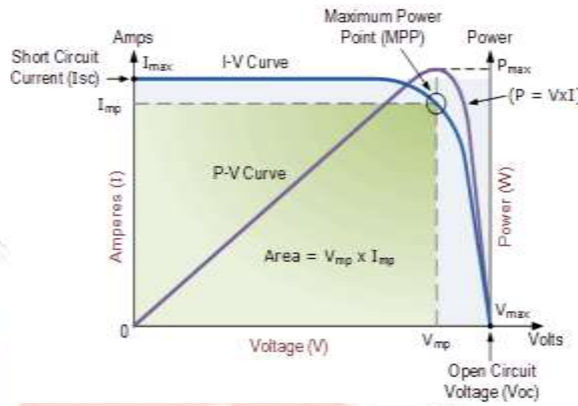
I. INTRODUCTION

Quality inspection of PV-Modules under natural ambient conditions is a necessary service for users of photovoltaic equipment, considering a guarantee period of up to 20 years or even more. The operating behavior of a solar cell is described by its current-voltage-characteristic (I-V characteristic), by measurement of present I-V characteristics under natural ambient conditions [2]. In addition to the present operating behavior, information's about possible degradation processes should be obtained. Measurement of stationary characteristic features such as peak power and internal series resistance are necessary. Change in parameters of I-V characteristic curve with change in series resistance is described. How the maximum power and fill factor will change with change in internal resistance is determined.

II. SOLAR CELL CHARECTERISTIC CURVE

A solar cell is a semiconductor device in the form of p-n junction diode which directly converts sunlight into electricity. Light shining on the solar cell produces both a current and a voltage to generate electric power. The generation of current in a solar cell, known as the "light-generated current", which involves two resistive effects known as series resistance Rs and shunt resistance Rsh. Resistance is the opposition that a substance offers to the flow of electric current.

There are various solar panel output parameters that can be measured and obtained during flash test, helping to judge on the performance quality of a solar panel.



- **V_{OC} = open-circuit voltage: –** This is the maximum voltage that the array provides when the terminals are not connected to any load (an open circuit condition). This value is much higher than Vmp which relates to the operation of the PV array which is fixed by the load. This value depends upon the number of PV panels connected together in series.

- **I_{SC} = short-circuit current –** The maximum current provided by the PV array when the output connectors are shorted together (a short circuit condition). This value is much higher than Imp which relates to the normal operating circuit current.

- **Pmax = maximum power point –** This relates to the point where the power supplied by the array that is connected to the load (batteries, inverters) is at its maximum value, where MPP = Imp x Vmp. The maximum power point of a photovoltaic array is measured in Watts (W) or peak Watts (Wp).

- **FF = fill factor –** The fill factor is the relationship between the maximum power that the array can actually provide under normal operating conditions and the product of the open-circuit voltage times the short-circuit current, (Voc x Isc) This fill factor value gives an idea of the quality of the array and the closer the fill factor is to 1 (unity), the more power the array can provide. Typical values are between 0.7 and 0.8.

- **%eff = percent efficiency –** The efficiency of a photovoltaic array is the ratio between the maximum electrical power that the array can produce compared to the amount of solar irradiance hitting the array.

- **SERIES RESISTANCE (RS)** = as series resistance increases, the voltage drop between the junction voltage and the terminal voltage becomes greater for the same current. The result is that the current-controlled portion of the I-V curve begins to sag toward the origin, producing a significant decrease in the terminal voltage and a slight reduction in I_{SC}, the short-circuit current. Very high values of R_S will also produce a significant reduction in I_{SC}; in these regimes, series resistance dominates and the behavior of the solar cell resembles that of a resistor.

$$R_S = \frac{dV}{I} \; --[1]$$

  The above equation is valid up to where the short circuit current is not affected by series resistance.

- **SHUNT RESISTANCE (Rsh) =** Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current. Such a diversion reduces the amount of current flowing through the solar cell junction and reduces the voltage from the solar cell. The effect of a shunt resistance is particularly severe at low light levels, since there will be less light-generated current. The loss of this current to the shunt therefore has a larger impact. In addition, at lower voltages where the effective resistance of the solar cell is high, the impact of a resistance in parallel is large.

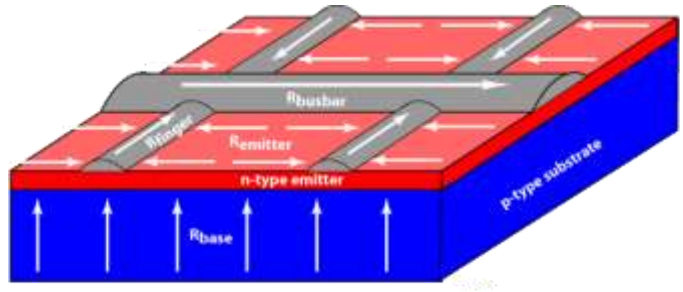
$$R_{SH} = \frac{V}{dI} \; ---[2]$$

  This equation is valid up to where the open circuit voltage is not affected by shunt resistance.

III. SERIES RESISTANCE

The final condition necessary to design a high efficiency solar cell is to minimise parasitic resistive losses. Both shunt and series resistance losses decrease the fill factor and efficiency of a solar cell. A detrimentally low shunt resistance is a processing defect rather than a design parameter. However, the series resistance, controlled by the top contact design and emitter resistance, needs to be carefully designed for each type and size of solar cell structure in order to optimise solar cell efficiency.

The series resistance of a solar cell consists of several components as shown in the diagram below. Of these components, the emitter and top grid (consisting of the finger and bus bar resistance) dominate the overall series resistance and are therefore most heavily optimised in solar cell design.



Resistive components and current flows in a solar cell

The metallic top contacts are necessary to collect the current generated by a solar cell. "Bus bars" are connected directly to the external leads, while "fingers" are finer areas of metallization which collect current for delivery to the bus bars. The key design trade-off in top contact design is the balance between the increased resistive losses associated with a widely spaced grid and the increased reflection caused by a high fraction of metal coverage of the top surface.

Series resistance in a solar cell has three causes: firstly, the movement of current through the emitter and base of the solar cell; secondly, the contact resistance between the metal contact and the silicon; and finally the resistance of the top and rear metal contacts. The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the short-circuit current.

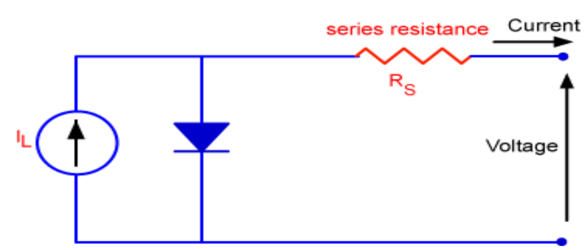


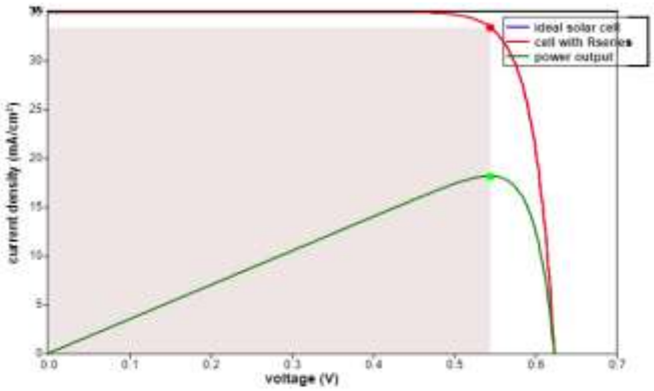
Fig. Schematic of a solar cell with series resistance.

The output current with respect to series resistance is

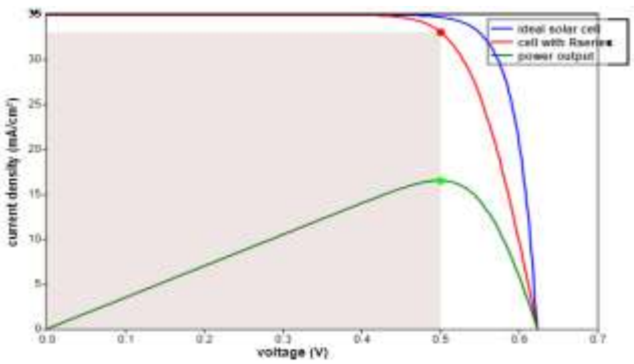
$$I = I_L - I_O \exp\left[\frac{q(V+IRs)}{nkT}\right] \; --- [3]$$

A. EFFECT OF SERIES RESISTANCE(Rs) ON MAXIMUM POWER(Pmax)

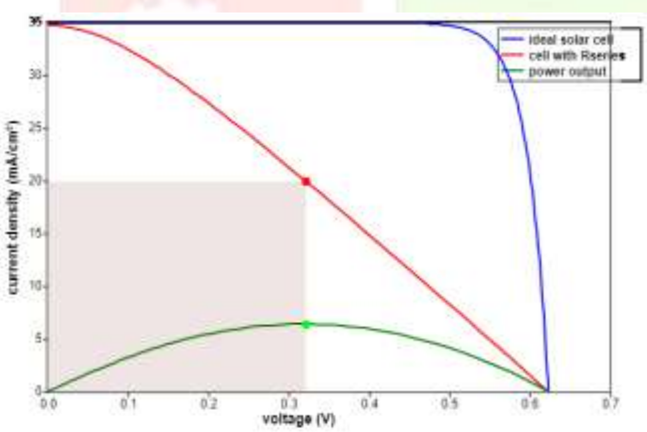
For the measurement of internal series resistance two iv curves of different irradiance but of the same spectrum and at the same temperature are necessary according to IEC 60891. The series resistance will effect on I-V Curve of solar module. As the maximum power Pmax is the product of maximum voltage and current, the Pmax will also change with change in I-V Curve.



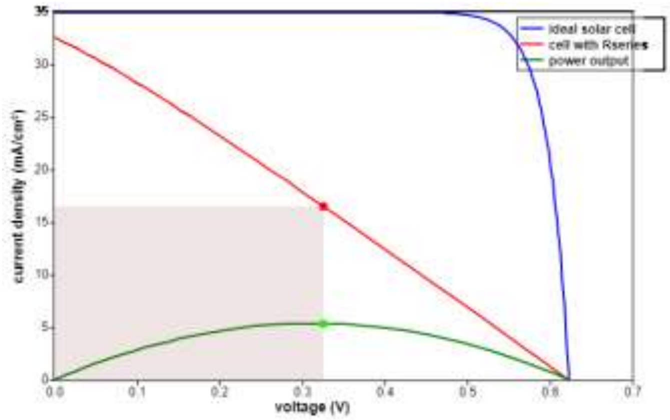
Condition 1: At series resistance Rs = 0/cm² the cell generates maximum power and it is the product of Vmax and Imax.



Condition 2: At Rs =1.5Ω/cm² the cell voltage & current density is decreased than to its max value.



Condition 3: At Rs = 14 Ω/ cm² the cell voltage is made constant at 0.32V and current density is continuously decreasing.



Condition 4: At Rs = 17 Ω/ cm² the cell voltage is 0.32V (constant) and current density is decreased and the short circuit current is also affected.

As per above conditions at low resistance values the voltage is more effected than current and after a certain value of resistance the voltage is almost constant and the current is varied. At large values of series resistance the Short circuit current is also affected. The fig1 to 4 are for basic understanding how the current, voltage and power of a solar cell will change with change in series resistance.

B. EFFECT OF Rs ON FILL FACTOR

The short circuit current is not affected by series resistance until it is a large value. Series resistance does not affect the solar cell at open-circuit voltage since the overall current flow through the solar cell, and therefore through the series resistance is zero. However, near the open-circuit voltage, the IV curve is strongly affected by the series resistance. A straight-forward method of estimating the series resistance from a solar cell is to find the slope of the IV curve at the open-circuit voltage point.

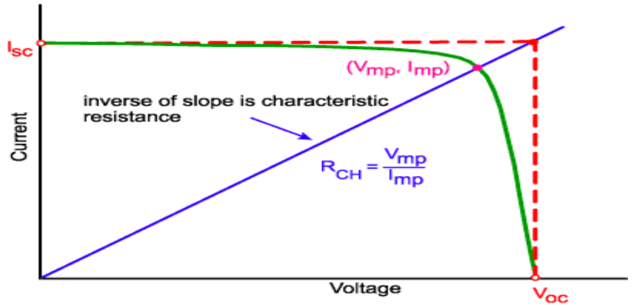
An equation for the FF as a function of series resistance can be determined by noting that for moderate values of series resistance, the maximum power may be approximated as the power in the absence of series resistance minus the power lost in the series resistance [3]. The equation for the maximum power from a solar cell then becomes:

$$P_{MP}' \approx V_{MP}I_{MP} - I_{MP}^{\,2}R_S = V_{MP}\, I_{MP} \left[1 - \frac{I_{MP}}{V_{MP}} R_S\right] =$$

$$P_{MP}\left[1 - \frac{I_{SC}}{V_{OC}} R_S\right] \text{ ---- [4]}$$

$$P_{MP}' = P_{MP} \left[1 - \frac{R_S}{R_{CH}}\right] \text{---- [5]}$$

Where R_{CH} is known as characteristic resistance, and it is the output resistance of the solar cell at its maximum power point [3].



$$R_{CH} = \frac{V_{MP}}{I_{MP}} \approx \frac{V_{OC}}{I_{SC}} \text{ ---- [6]}$$

$$r_s = \frac{R_S}{R_{CH}} \text{ ---- [7]}$$

$$P_{MP}{}' = P_{MP}\,(1 - r_s) \text{ ---- [8]}$$

Assuming that the open-circuit voltage and short-circuit current are not affected by the series resistance allows the impact of series resistance on FF to be determined;

$$V_{OC}{}' I_{SC}{}' \; FF' = V_{OC} I_{SC} FF (1 - r_s) \text{ --- [9]}$$

$$FF' = FF(1 - r_s) \text{ --- [10]}$$

In the above equation the fill factor which is not affected by series resistance is denoted by FF_0 and FF' is called FF_S [5]. The equation then becomes;

$$FF_S = FF(1 - r_s) \text{ ---- [11]}$$

IV. EXPERIMENTAL RESULTS

Selected standard solar PV modules of 325Wp of 72 full cells and connected additional variable resistance in series to observe the effect of series resistance on Pmax and Fill Factor.

Mod	Voc	Isc	Pmax	Vmax	Imax	FF	Rs	Rsh
REF	45.5	8.9	328.3	39.0	8.4	81.1	0.5	53.2

Standard 72 cell 325Wp Modules Electrical results.

By adding resistances in series to find out the electrical parameters and variations in IV curve using dark IV measurement is given below table.

Mod	Voc	Isc	Pmax	Vmax	Imax	FF	Rs	Rsh
REF1	45.6	8.7	258.1	34.5	7.5	64.9	1.4	76.8
REF2	45.7	8.6	185.2	30.2	6.1	47.1	2.2	78.1
REF3	44.7	8.2	153.1	28.9	5.3	41.7	3.0	9.7
REF4	45.1	6.6	124.3	29.2	4.3	41.6	3.8	11.7
REF5	45.2	5.5	103.5	29.2	3.5	41.6	4.6	14.1
REF6	45.5	4.7	89.1	29.4	3.0	41.6	5.3	16.8
REF7	45.6	4.1	77.9	29.5	2.6	41.6	6.1	19.2
REF8	45.7	3.6	69.2	29.6	2.3	41.6	6.9	21.8
REF9	45.8	3.3	62.2	29.7	2.1	41.6	7.7	24.2
REF10	45.8	3.0	56.6	29.6	1.9	41.7	8.2	27.0
REF11	45.5	1.7	32.4	29.6	1.1	41.2	15.4	43.1
REF12	41.5	0.4	7.0	26.8	0.3	41.8	39.2	166.2
REF13	40.4	0.3	5.7	26.1	0.2	42.5	44.0	179.3
REF-14	39.3	0.3	4.6	25.4	0.2	41.8	46.4	237.0

By using formula [1], it is easy to find out the Rs from Voc, Isc, Vmax & Imax from the electrical parameters. If it is <0.8 Ohm it is acceptable that the module will perform in the field without any issue subject to the Environmental conditions.

The Formulas mentioned above will give exact results with Sun simulator data when R_{CH} (Voc/Isc & Vmax/Imax) condition matched the equation [6].

Mod	R_{CH} - 1	R_{CH}-2	RS	RS - 1
REF	5.1	4.6	0.5	0.8
REF-1	5.2	4.6	1.4	1.5
REF-2	5.3	4.9	2.2	2.5
REF-3	5.4	5.5	3.0	3.0
REF-4	6.8	6.9	3.8	3.7
REF-5	8.2	8.2	4.6	4.5
REF-6	9.7	9.7	5.3	5.3
REF-7	11.1	11.2	6.1	6.1
REF-8	12.6	12.7	6.9	6.9
REF-9	14.0	14.2	7.7	7.7
REF-10	15.5	15.5	8.2	8.5
REF-11	26.4	27.1	15.4	14.5
REF-12	102.1	102.1	39.2	55.8
REF-13	122.5	120.6	44.0	65.9
REF-14	140.0	140.0	46.4	76.6

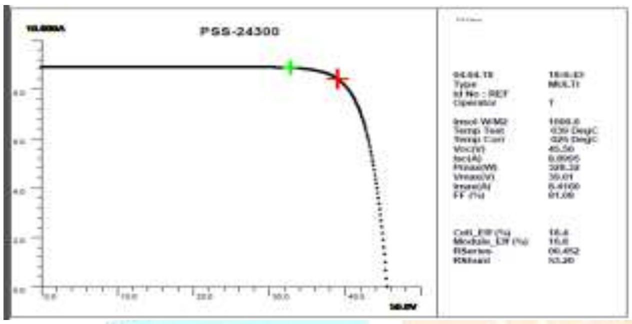
Where R_{CH} – 1 = Voc /Isc and R_{CH} – 2 = Vmax/Imax, Rs is the series resistance measured by dark IV and Rs – 1 is the series resistance measured using formula [1].

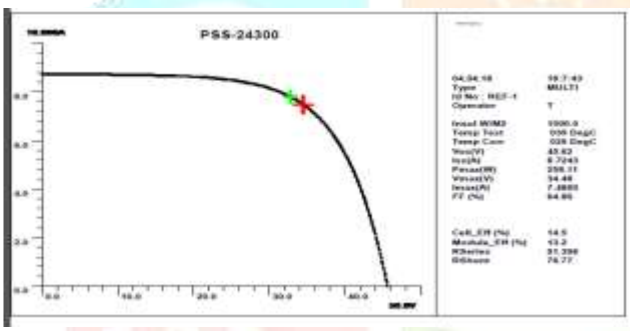
From the above table REF 3 to REF 13 the RCH is meeting the conditions and by using formula 1 it is matching to the calculation as per theoretical and experimental results of Rs.

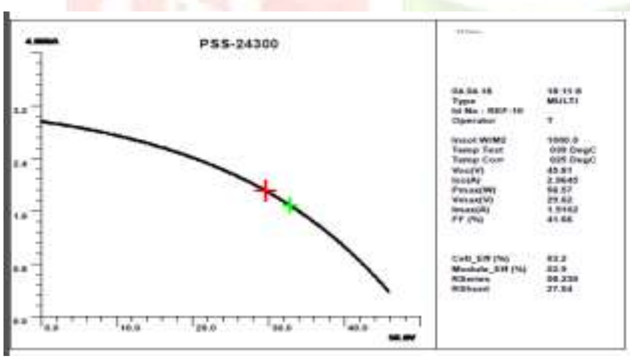
After internal analysis, the formulas to find out the Rs are defined in many ways and these can be used and applied only if the following conditions are meeting.

1. If the R_{CH} is meeting condition 1
2. Voc is not changing from the initial value more than 2V.

The IV curves are shown below for the above table to understand the Curve shape.







V. Conclusion

The description of the operating behavior of solar module by the effective internal resistance allows explicit calculation of the parameters of the effective solar module characteristic from the measured parameters I_{sc}, V_{oc}, I_{max}, V_{max} Related to power of the solar generator[1].

To find out the Rs (Series Resistance) of PV cell/Module having many formulas but, IV curves measured from Sun simulators are not matching to this formula.

These formulas can be applied and matching to theoretical and IV curves from sun simulators only if the following conditions are meeting.

a. RCH is matching to condition

b. Voc cannot be changed from its initial value < 2V

Due to aging of the module corrosion formed between cell busbar and interconnect ribbon leads to increase in series resistance, this may observed in Damp heat 1000hrs (85ºC & 85% RH as per IEC 61215)

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