MODULE ASSEMBLY BASED PERFORMANCE ANALYSIS OF SOLAR CELLS

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Abstract: Theoretical simulation using MATLAB programming was developed to study the current-voltage (I-V) characteristics of solar cell and its module assembly. Recursive simulation method was developed and used to fit with the laboratory measurement. It was observed that the cells assembled in module exhibited higher series resistance and comparatively poor performance than their individual status. The analysis revealed that the increase in series resistance also damages the junction properties of the solar cells used to assemble the modules. Details are reported in this paper.

Index Terms **- Solar cell, Module assembly, Series resistance, Ideality factor, Fill Factor.**

I. INTRODUCTION

Solar cell is a semiconductor device and it works as low voltage and high current power generator [1]. Therefore, solar cells with identical I-V performance are connected in series and parallel to constitute a module with desired output power [2, 3]. Assembly of cells into module utilizes additional connecting materials between solar cells, which are supposed to be the source for add-on resistance [1,4]. This add-on resistance endorses as series resistance (R_s) and leads to very significant amount of power loss in module assembly, which in turn causes reduction in fill factor as described by the relation $\Delta FF \approx -R_sI_{sc}/V_{oc}$ [5]. Numerous reports were discussed about the effect of series resistance on the performance characteristics such as fill factor (*FF*), output power (P_{out}), output voltage (V_L) and conversion efficiency (η) of solar cells and their modules [4-9]. Del Cueto [5] demonstrated the light intensity dependent increase in series resistance and its impact on the reduction in fill factor from 3.5 to 4% . Van Dyk et al. [4] reported a loss in the maximum power output upto 50% due to the rise in R_s. Mohamed et al. [6] reported a reduction in I_{sc} due to an increase in R_s. In addition, a reduction in open circuit voltage (V_{oc}) and an increase in the value of diode ideality factor (n) of a solar cell with respect to the increase in R_s were reported by many researchers [4, 7-11]. However, so far, there were no clear explanations that correlated the entire degradation mechanisms accompanied with R_s. In this regard, we deem that it is important to understand the degradation mechanism behind the R_s induced reduction in solar cell performance characteristics in order to ascertain the quality and compatibility of the solar cell modules as direct source for external loads. In general, the loss in *FF* is the loss in fundamental operational behavior of a solar cell. So, it is worth to analyze the diode ideality factor of the cells, which can directly evidence the quality of the solar cell semiconductor junction [12].

In this paper, we analyzed the solar cell as well as its module performance in terms of their output I-V characteristics by using theoretical simulation and laboratory measurement. The values of maximum output voltage (V_m), maximum output current (I_m), maximum output power (P_{max}), fill factor (*FF*), reverse saturation current (I_o) and diode ideality factor (n) were obtained using simulation in comparison with laboratory measurement. It was found that the series resistance (R_s) and diode ideality factor (n) of the module assembly increased than the value of their independent cell. The details of the results were analyzed and presented.

II. EXPERIMENT

Current – Voltage (I-V) characteristics of a single solar cell and its module with 36 solar cells in series provided by Maharishi Solar Technology Pvt. Ltd, AP, India were measured under AM1.5 (100 mW/cm^2) illumination condition at room temperature (RT) . The measurement revealed that the individual cell with an area of 156.25 cm^2 resulted in the open circuit voltage (V_{oc}) of 0.610 V and short circuit current (I_{sc}) of 6.898 A. Similarly, the module assembled using 36 cells in series resulted in the V_{oc} of 21.812 V and I_{sc} of 2.530 A. The P_{max} of the single cell was found as 3.192 W with *FF* of 75.91%. Similarly, the P_{max} of the module was found as 38.7 W with *FF* of 70.13%. The reduction in *FF* and P_{max} values of the module were analyzed further using theoretical simulation aided by MATLAB programming as described in the theoretical section.

III. THEORY AND SIMULATION

In the present study, we analyzed “Silicon” (Si) based solar cell fabricated using diffusion process. In general, it is believed that the cell works with proper “PN” junction without any possibility for the presence of an additional junction. Thus, we considered single diode model for theoretical simulation as described elsewhere [13]. As we are interested to understand the degradation mechanism behind the overall performance of the cell, we considered both the current generation and transport for our present analysis. According to the current transport equation of the single junction “Si” solar cell under dark condition, the flow of diode current (I_d) can be described as [6],

$$I_d = I_o\left[e^{q\left[\left(V_l + I_l R_s\right)/nKT\right]} - 1\right] \tag{1}$$

Where q - Electronic charge (Coulombs), K - Boltzman's constant (J/K), T - Junction temperature (K), V_L - Output voltage of solar cell (V), R_s - Series resistance of the given solar cell (Ω) and I_L - Output current of the solar cell (A).
Similarly, the open circuit voltage (V_{oc}) can be defined using the following relation [9]

$$V_{oc} = \frac{nKT}{q}\ln\left(\frac{I_{sc}}{I_o}\right) \tag{2}$$

at which, it is assumed that the cell experiences infinity value of shunt resistance (R_{sh}). While, under short circuit condition, the photo-generated current (I_{ph}) flows out of the cell as a short-circuit current (I_{sc}) in the direction opposite to the diode current, I_d. Thus, Eq. (1) gets modified into the following form under illumination condition,

$$I_L = I_{sc} - I_d \tag{3}$$

$$I_L = I_{sc} - I_o\left[e^{q\left[\left(V_l + I_l R_s\right)/nKT\right]} - 1\right] \tag{4}$$

Eq. (4) was solved numerically using MATLAB programming and compared with measurement for both the cell and module assembly. Since Eq. (4) is a transcendental equation [11], as such it can't be solved for dynamic mode. So, Newton's method as described below was used to solve the Eq. (4) for dynamic mode,

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \tag{5}$$

Where $f'(x)$ is the derivative of the function $f(x) = 0$, x_n is present value, and x_{n+1} is next value. Applying Eq. (5) as a tool, Eq. (4) was constituted theoretically using MATLAB programming to obtain recursive outputs. Input parameters such as the V_{oc}, I_{sc}, R_s, I_o, n and T were selected from measured I-V characteristics and computed. Under iterative computation, the recursive equation gives the value of I_L with respect to the output voltage V_L. Simulation was repeated by changing the "R_s" and "n" until perfect match between theoretical simulation and measured plot is reached. This procedure was followed for both the individual cell and its module for analysis. Diode ideality factor (n), R_s and I_o values were considered for the present analysis.

IV. RESULTS AND DISCUSSIONS

Establishment of MATLAB programming for the Eq. (4) using Eq. (5) as sampling tool was found very sensitive to the profile of the simulated current – voltage (I-V) curve. Thus, it provided sensitive fine tuning of both diode ideality factor (n) and series resistance (R_s) for the purpose to obtain perfect fit with experimental plot. Fig. 1 shows the plot of simulated as well as measured I-V of the single solar cell before assembled in to module.

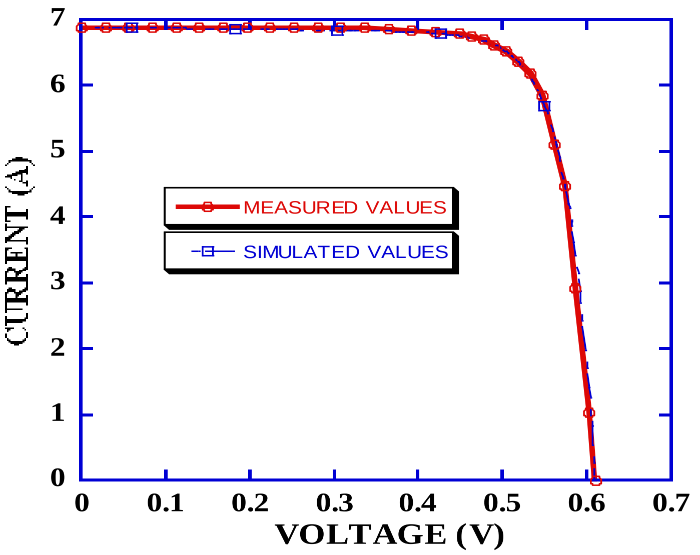

Fig. 1. Current – Voltage characteristics of solar cell

It can be observed from the figure that both the measured and simulated curves are exactly matched. We found that "*n*" and "R_s" played vital role in attaining perfect match based on the following sensitive relation [14],

$$R_s = -\left.\frac{dV_l}{dI_l}\right|_{V_{oc}} - \frac{nKT/q}{I_o \times e^{\frac{qV_{oc}}{nKT}}} \qquad (6)$$

where $\left.\frac{dV_l}{dI_l}\right|_{V_{oc}}$ is the slope of the I-V curve at constant V_{oc}.

Above said relation states that both the "*n*" and "R_s" are directly proportional to each other.

Table 1 shows the parameters of the cell obtained from both the simulated and measured I-V characteristics. It can be observed that the simulation resulted in better *FF* (78.37 %) and P_{max} (3.298 W) than the values obtained by measurement, while fitting for similar "R_s" and "*n*" values.

Table 1

Simulated and measured parameter values for solar cell

Sl. No.	Parameters	Simulated values for solar cell	Measured values for solar cell
1	Open circuit voltage (V_{oc}) V	0.610	0.610
2	Short circuit current (I_{sc}) A	6.898	6.898
3	Diode Ideality Factor (*n*)	1.3	1.3
4	Reverse saturation current (I_o) A	8.05 e-8	8.05 e-8
5	Maximum Voltage (V_m) V	0.515	0.512
6	Maximum Current (I_m) A	6.4047	6.230
7	Maximum Power (P_{max}) W	3.2984	3.192
8	Fill Factor (*FF*) %	78.37	75.91

Since the simulation was able to result in fair fitting to experimental curve, similar approach was used to analyze the module performance. Fig. 2 shows both the measured and simulated I-V curves of the module of 36 cells connected in series. It can be observed that there is only optimum fitting between both the curves with slight mismatch in the maximum power point. This mismatch occurs due to the presence of non-symmetrical profile of the measured curve rather than the contribution from R_s and n.

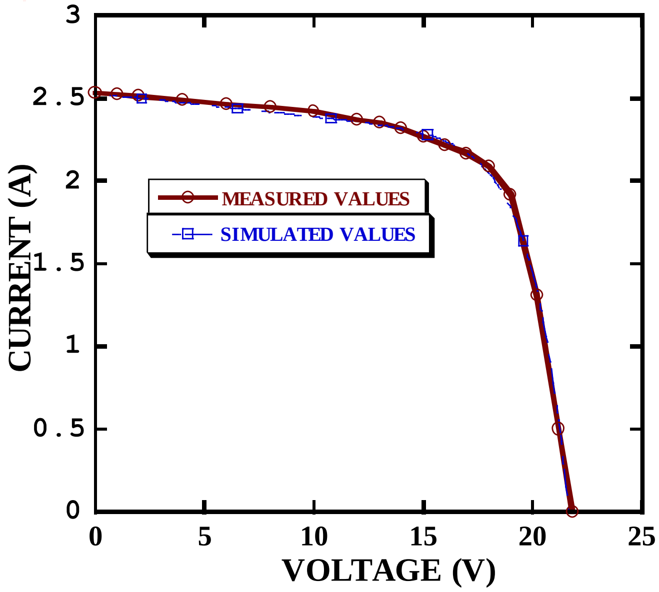

Fig. 2. Current – Voltage characteristics of solar module

This problem in the profile of the measured curve can be contributed from measurement conditions, which correspondingly relates to the non-linear addition of R_s from connecting materials. Since the theoretical simulation resulted in very symmetrical profile, nearly perfect fitting was further used to extract the series resistance "R_s" and "n" and presented in Table 2.

Table 2

Simulated and measured parameter values for solar module

Sl. No.	Parameters	Simulated values for solar module	Measured values for solar module
1	Open circuit voltage (V_{oc}) V	21.812	21.812
2	Short circuit current (I_{sc}) A	2.530	2.530
3	Diode Ideality Factor (n)	1.7	1.7
4	Reverse saturation current (I_o) A	2.38 e-6	2.38 e-6
5	Maximum Voltage (V_m) V	17.06	18
6	Maximum Current (I_m) A	2.09	2.15
7	Maximum Power (P_{max}) W	35.65	38.7
8	Fill Factor (*FF*) %	65.41	70.13

Table 2 shows that the simulation was resulting in lower power performance than the measured values. This difference in power performance was due to the decrease in both V_m (17.06 V instead 18 V) and I_m (2.09 A instead 2.15 A), which also leads to the observation of decreased *FF* of 65.41 % instead of 70.13 % (measured). However, we acquired the "R_s", "I_o" and "n" values from the fitting for further analysis.

Comparing Table 1 and Table 2, it can be observed that the diode ideality factor (n), reverse saturation current (I_o) and series resistance values of the module was found increased than the values of individual cell. Primarily R_s was found increased from 80 μΩ (cell) to 1 mΩ (module) upon module assembly accompanied by an increase in "n" from 1.3 to 1.7 and I_0 from 8.05e^{-8} A to 2.38e^{-6} A.

In continuation of the fore-mentioned observation, simulation was further used to analyze the impact of series resistance on the change in ideality factor of the module. Fig. 3 shows the plot between series resistance and theoretically obtained ideality factor. It can be observed from the plot that the increase in series resistance became effective in changing the n value only after 1.2, which is lower than the value of 1.7 obtained for the module. In the case of Si solar cell, defective junction always results in high value of n [12].

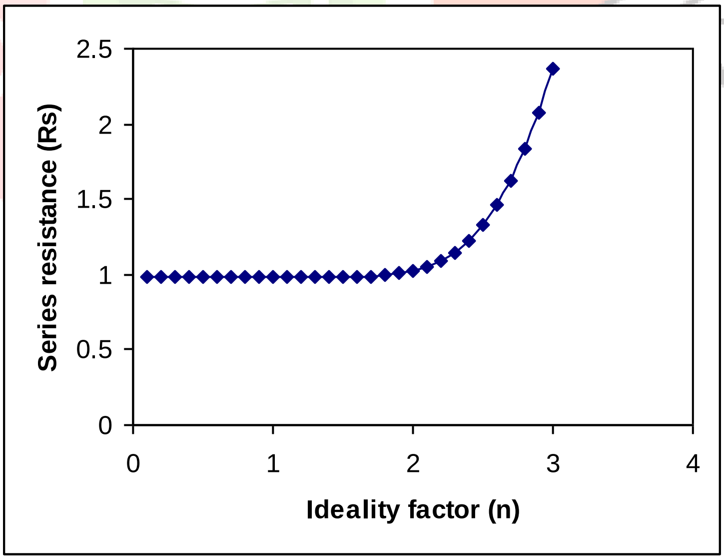

Fig. 3. Diode ideality factor (n) versus Series resistance (R_s)

Moreover, simulation was also extended to analyze the effect of change in ideality factor on the *FF* of the individual cell as well as the module. Fig.4 shows the ideality factor (n) versus *FF* plot of both the cell and module. It can be observed from the plot that the increase in "n" decreases the *FF* of both the single cell and module almost linearly.

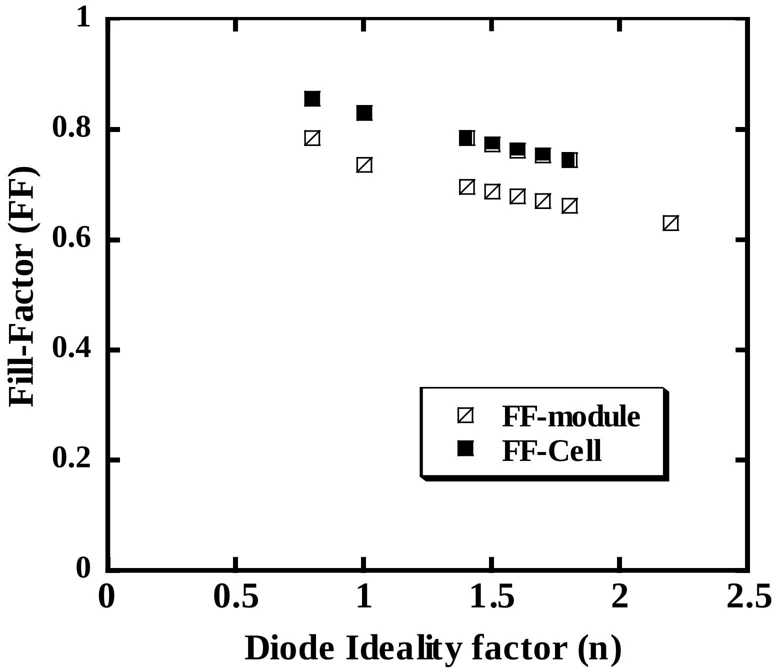

Fig. 4. Diode ideality factor (*n*) versus Fill Factor (*FF*)

Considering the observations of an accompanied increase in "*n*" and "I_0" values with an increase in R_s and the plots presented in Fig. 3 & Fig. 4, we can propose that the cells used to assemble module undergoes a serious degradation in to its junction performance. Usually, the ideality factor of a better efficiency PN junction Si solar cell exhibits the value of ~ 1 and any further increase in the value above 1 indicates the deterioration of the junction performance [12]. This deterioration occurs when there is an introduction of defects into the junction, which spontaneously increase the reverse saturation current [8,15]. In the case of module, the cells were connected using an additional electrode materials, which obviously only contribute an increase in series resistance, than any other physical damage. The change in ideality factor with respect to the transport mechanism of the semiconductor junction was discussed by many researchers [11,12,15]. Value of "1" represents the diffusion dominated transport mechanism[16]. Whereas, if the value is less than 1, then the transport is governed by high level injection called thermionic emission [13]. On the other hand, if the transport mechanism dominates by recombination current in space charge region then the value of "*n*" lies between 1 – 2 [17] and Trap assisted tunneling current / Poole-Frenkel effects lead to the ideality factor larger than two[15]. In general, the increase in diode ideality factor from 1 to higher value represents the junction transport from ideal junction to defective junction [12]. Since we observe an increase in the value "*n*" from 1.3 to 1.7 as a consequence of increase in "R_s" (Fig. 3) with an accompanied increase in I_0 of a solar cell in module, we conclude that the assembly of module induced increase in series resistance damages the junction performance of individual solar cells used and this damage in junction performance may arise from a possible damage in the space charge region (SCR) of the solar cell due to an increase in electron-hole recombination and related effects .

V. CONCLUSION

Theoretical simulation was developed using MATLAB programming to simulate the I-V characteristics of solar cell and its module assembly. Comparison between the values of R_s, *n* and I_0 of the cell and module indicated an accompanied increase in their values for module assembly. Detailed analysis revealed that the increase in R_s upon module assembly effectively damages the solar cell's internal junction performance probably through by damaging space charge region of the solar cell. This damage in junction performance also found decreasing the over all performance down to about 16.5%.

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