SOLAR CELL SHUNT RESISTANCE - A PARAMETRIC STUDY

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ABSTRACT

Analytical equations are derived for solar cell's parameters using measurements under reverse bias conditions as well as the open circuit voltage and the short circuit current of the cell under practical illumination. A typical commercial cell is used in the present analysis. The sensitivities of solar cell's parameters are studied. The effects of solar cell's *shunt resistance* on the cell's output characteristics and operation reliability under shadowing conditions are analyzed in detail. Moderate values of the solar cell's shunt resistance are determined to protect a photovoltaic string against "hot spot" problems during the string lifetime. An approach to vary the value of the equivalent cell's shunt resistance during measurements is presented. An accurate non-destructive technique for detecting small defective area in the installed photovoltaic string is proposed. Methods for controlling the solar cell's equivalent shunt resistance during fabrication are discussed.

Keywords: Solar cell, Photovoltaic, Shunt resistance, Photovoltaic hot spot

1. INTRODUCTION

Several papers discussed how to estimate the solar cell's parameters, namely: the photon generated current I_L, the series resistance R_S, the shunt resistance R_{SH}, the leakage current I_o, and the diode non ideality factor n [1-5]. Most of these techniques rely on measurement points on the cell's I-V curve under illumination in the forward bias condition. The solar cell parameters are determined through the solution of a non linear equation which will not help in the complete understanding of their effects. On the other hand, deriving analytical expressions for the cell's parameters, which will help in understanding the parameter effects, is not straightforward. In the present paper, practical approximations have been introduced to derive analytical equations for the solar cell's parameters, in the sense that, they will suit typical commercial solar cell parameters.

We define a good commercial solar cell as the cell which has the following parameter ranges, under AM1 and 25 °C :

- Short circuit current density, J_{SC}, (25-30) $mA.cm^{-2}$.
- Open circuit voltage, V_{OC}, (570-630) mV.
- Normalized series resistance, R_{SN}, (< 10) $\Omega.cm^2$.
- Leakage current density, J_O, $(10^{-8}\text{-}10^{-7})$ $mA.cm^{-2}$.

With respect to "hot spot" analysis, we concentrate on the solar cell's shunt resistance effects since it is responsible for the amount of dissipated power in the defected cell of an illuminated PV string. In literature, hot spot analysis and prevention techniques recommended that the number of series cells per bypass diode in the PV string should not exceed 9 cells connected in series to limt the dissipated power in a defected cell [6-7]. In the present paper, a typical PV string, of 36 solar cells connected in series is considered in the analysis. The reduction of the amount of dissipated power in a defected string rely on either reducing the cell's shunt resistance to a moderate value without sacrificing the output peak power or increasing the amount of critical safe load resistance.

In the case of PV string fabricated from solar cells with high shunt resistances, the probability of hot spot problems occurrence during string life time is increased specially for a large number of series cells string. To increase the string life time, a regular check for defected cell(s) has to be performed. This requires a non destructive detection technique to short circuit the permanently damaged solar cells. However, this will cause a mismatching in the PV array if more than one string are connected in parallel and therefore, only can be used for single string applications.

In the case of unreparable string, the defected string has to be labeled with minimum load value, which will limit the amount of the power dissipated in the defected cell down to a safe level.

The present analysis consists of the following sections:

- Determine the suitable solar cell equivalent model for a good commercial cell.
- Derive analytical equation for each cell parameter.
- Study the sensitivity of cell peak power due to parameters variation.
- Explain the hot spot concept and problems.
- Concentrate on the shunt resistance and critical load resistance as control tools to reduce the amount of power dissipation in a defected cell.
- Modify a previous non destructive technique so that the defected area in the PV string as well as the amount of defection are detected accurately.
- Discuss the possibility of controlling the value of effective shunt resistance during measurements as well as fabrication.

2. SOLAR CELL EQUIVALENT CIRCUIT

The solar cell can be represented by either a first or second order lumped constants equivalent circuit models [8]. In the second order model, there are two diodes having different leakage currents. Theoretical analysis has been done on such a model and it is found that the second diode is effective only for cells with high leakage current and diode non ideality factor of less than 1.5. For commercial solar cells, the second diode has no effect on the power output calculations and a single diode equivalent circuit is considered to be a good representative.

Figure (1) shows the chosen equivalent circuit model for a pn junction solar cell.

The IV characteristic equation can be derived as follows :

$$I = I_1 - I_2 = I_L - I_D - I_2 \qquad (1)$$

$$I = I_L - I_o\left[e^{D\left\{IR_S + V\left(1+\frac{R_S}{R_{SH}}\right)\right\}} - 1\right] - \frac{V}{R_{SH}}$$

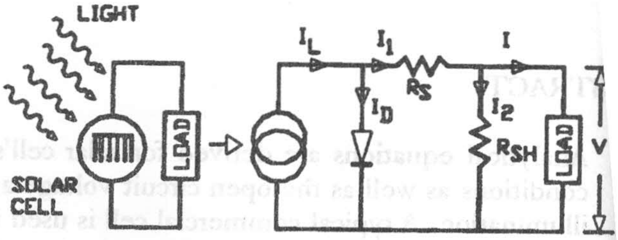

Figure 1. The solar cell's equivalent circuit.

For a good commercial cell, the value of R_S/R_{SH} i much less than unity and can be neglected so that eqn.(2) becomes,

$$I = I_L - I_o\left[e^{D(V+IR_s)} - 1\right] - \frac{V}{R_{SH}} \qquad (3)$$

where D = q/(nKT) ≈ 38 at T = 300 °K and n = 1. Figure (2) shows the percentage error due to using Eqn. (3) instead of Eqn. (2) for a good commercial solar cell.

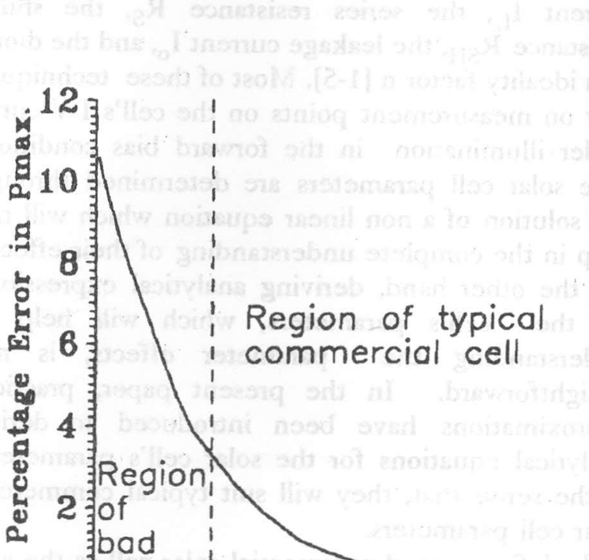

Figure 2. Percentage error of using (3) instead of (2).

It is clear from Figure (2) that for commercial cells where $R_{SH}/R_S \geq 100$, the percentage error between Eqn. (2) and Eqn. (3) is less than 4%. Therefore in the following analysis Eqn. (3) will be used.

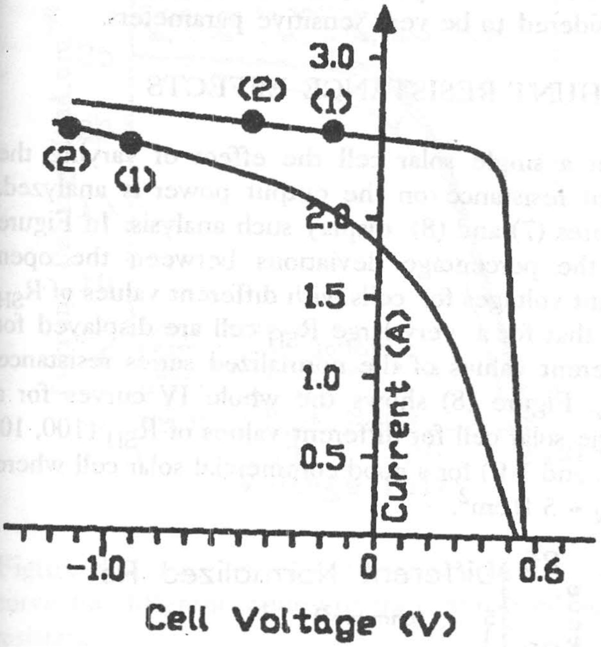

Figure 3. I-V curves of good and bad solar cells extended to the reverse characteristic regions.

Eqn. (3) contains four unknowns, namely : I_L, I_O, R_S, and R_{SH}. I_L and R_{SH} can be determined from two measurements on the IV curve of an illuminated cell under reverse bias condition. For a good commercial cell the behavior of the cell under reverse bias condition is shown in Figure (3).

The linear portion of the IV characteristic curve is achieved under reverse bias voltage condition at V_R less than one volt for a good cell. In Figure (3) an IV curve of a bad cell is displayed as well to show that the linear portion of the characteristic occurs at higher reverse bias voltage.

At points 1 or 2 on Figure (3) where $|V_R| > IR_S$, Eqn. (3) becomes,

$$I_R = I_L + \frac{|V_R|}{R_{SH}} \tag{4}$$

Substitution of V_{R1}, I_{R1}, V_{R2}, and I_{R2} of points 1 and 2, respectively into Eqn. (4) and solving the resulted two linear equations will determine I_L and R_{SH}. Figure (4) shows the experimental setup used for the measurements. The measurements consist of determining the short circuit current, I_{SC}, open circuit voltage, V_{OC}, and two points on the linear part of the IV curve of the solar cell under reverse bias, V_{R1}, I_{R1}, V_{R2}, and I_{R2}.

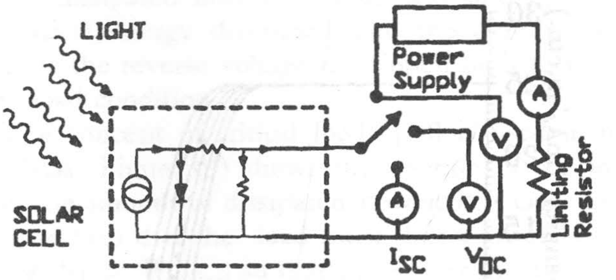

Figure 4. Experimental setup used for measurements.

From Eqn. (3) the leakage current can be derived as follows :

$$I_O = \frac{I_L - \dfrac{V_{OC}}{R_{SH}}}{e^{D V_{OC}} - 1} \tag{5}$$

and the series resistance equation can be derived from the short circuit condition as follows :

$$R_s = \frac{1}{D I_{SC}} \ln\left(\frac{I_L - I_{SC} + I_O}{I_O}\right) \tag{6}$$

In the present analysis, the diode non ideality factor, n is taken as 1. However, the value of n can be determined from the measurement of two open circuit voltages V_{OC1} and V_{OC2} at two different temperatures T_1 and T_2, respectively. From these measurements, n is derived as,

$$n = \frac{\dfrac{q}{K}}{V_{OC1} T_1 - V_{OC2} T_2} \ln\left(\frac{R_{SH} I_L - V_{OC1}}{R_{SH} I_L - V_{OC2}}\right) \tag{7}$$

Since I_L slightly depends on the solar cell temperature, T, the two temperatures T_1 and T_2 have to be as close as possible to each other so that I_L can be considered constant with respect to T without error.

The value of the diode quality factor in D may be fine tuned towards an accurate value by plotting the experimental IV curve of the cell under test and different theoretical IV curves for different values of n ranging from n = 1 to 2 as shown in Figure (5). On this figure, the adjustment of the n value is possible.

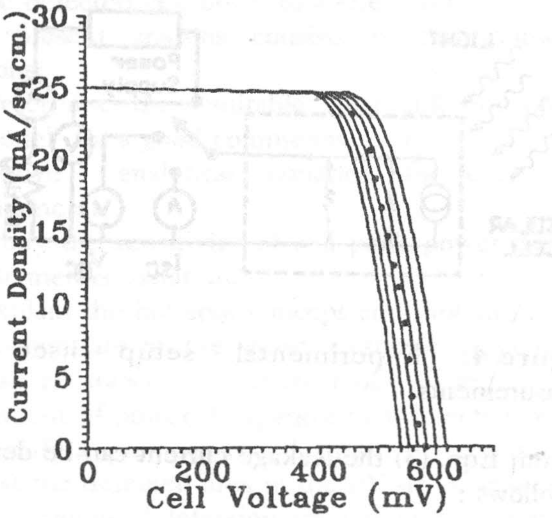

Figure 5. Theoretical IV curves for different values of n from 1 to 2 along with the experimental curve (circles) to correct the value of the estimated n.

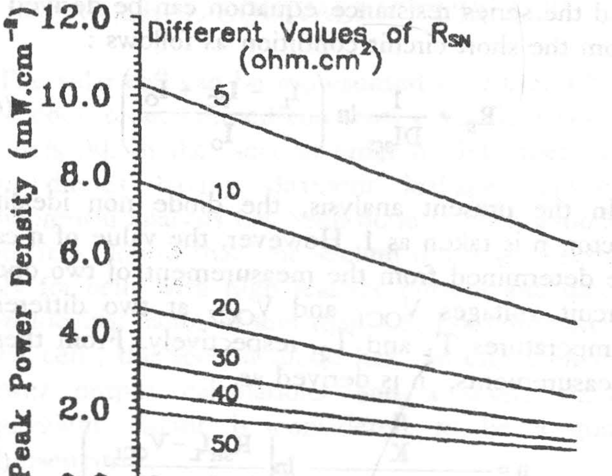

Figure 6. The effect of saturation current density J_o on the peak power density for different values of the normalized series resistance, R_{SN}.

To study the effect of varying saturation current I_O on the solar cell's peak power at different values of normalized series resistance, R_{SN}, Figure (6) is generated. It is clear from Figure (6) that both I_o and R_S have a large effect on controlling the amount of cell's peak power. Therefore, they are considered to be very sensitive parameters.

3. SHUNT RESISTANCE EFFECTS

For a single solar cell the effect of varying th shunt resistance on the output power is analyzed Figures (7) and (8) display such analysis. In Figur (7) the percentage deviations between the ope circuit voltages for cells with different values of R_{SH} and that for a very large R_{SH} cell are displayed fo different values of the normalized series resistanc R_{SN}. Figure (8) shows the whole IV curves for single solar cell for different values of R_{SH} (100, 1 5, 3, and 1 Ω) for a good commercial solar cell wher R_{SN} = 5 Ω.cm^2.

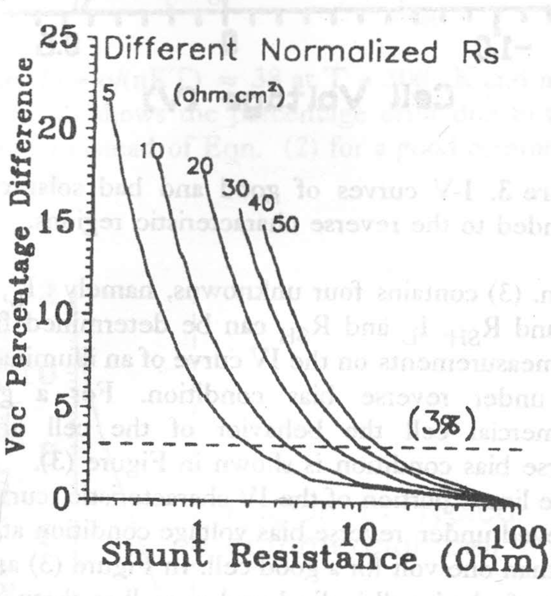

Figure 7. The effect of the shunt resistance on th solar cell open circuit voltage for different R_{SN}.

It is clear from Figures (7) and (8) that the shun resistance can be reduced down to low values (3 5 Ω) without sacrificing the power output by a appreciable amount (< 3%). This is valid only fo cells with normalized series resistance of less than 1 Ω.cm^2. From Figure (7) it is clear also that even fo a bad cell of large R_{SN} values, the shunt resistance still can be reduced to 10 - 20 Ω without reducing the cell power output by a large value.

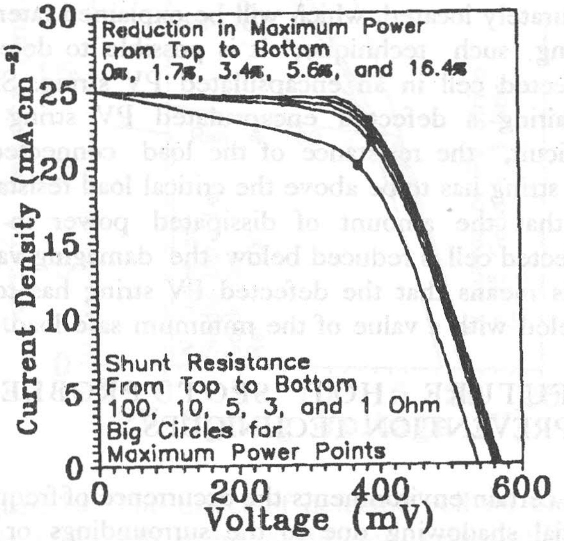

Figure 8. The effect of shunt resistance on the IV curve for different values of the normalized series resistance.

4. HOT SPOT CONCEPT

The photovoltaic array consists of a number of modules connected in series and / or parallel. In terrestrial applications, all the cells of a PV module are connected in series, resulted in a PV string. In a single PV string applications, the number of cells usually is 36 cells which will give output voltage of 14 to 16 voltage under normal operating conditions (AM1 and 25 °C) for silicon solar cells. In PV array applications, each PV string is shunted by a bypass diode to limit the amount of reverse voltage (developed under certain load conditions) to a value below the damaging voltage level. The cells of the PV string itself cannot be protected in the same way unless each cell is shunted by a bypass diode. Therefore, it is required to have a technique for protecting the individual cells against future development of large reverse bias during its lifetime. Hot spot heating is caused when one of the cell's operating current level is much less than the other cells operating current. Such a situation may occurred in case of partial shadowing or cell cracking. The defected cell (shadowed or cracked) temperature, T_D is determined by the energy flow balance equation, using Stefan-Boltzmann's law gives

$$\varepsilon K T_D^4 = P_S + P_E \tag{8}$$

where ε is the system emissivity, K is Boltzmann's constant, P_S is the part of the solar energy (80% to 90%) dissipated into the cell as heat, and P_E is the electrical energy dissipated into the defected cell due to the reverse voltage developed on it to satisfy the load condition.

The concept of critical load [10] is used in our analysis. Figure (9) shows the relation of the load and the amount of dissipated power. It is clear from Figure (10) that the load must has a lower bound value $R_L > R_{critical}$ so that the power dissipated in the reduced photon current generated defected solar cell is neglected if $R_L > R_{critical}$.

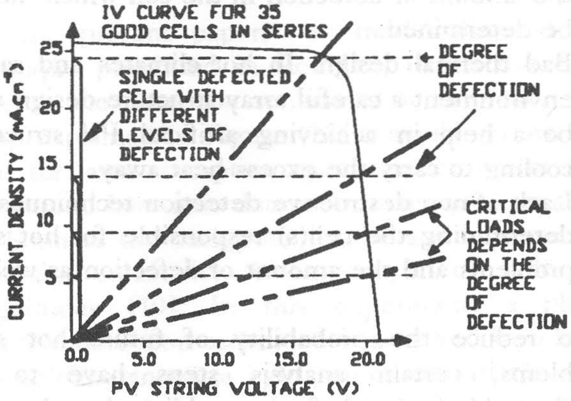

Figure 9. The critical load concept.

As the defected cell's temperature is increased due to power dissipation the probability of hot spot creation is increased. The magnitude of the hot spot depends on the solar cell micro structure and PV string thermal design. Potentially damaging heating of reverse biased solar cells can occur if heat dissipation in the cell is of sufficient duration and of sufficient magnitude relative to the quantity of heat conducted and radiated away from the solar cell [11-13].

The existence of a weak thermal spot in the micro structure of the cell makes the thermal power density to be dissipated very high. This may lead to permanent damage of the cell. Permanent damaging of the cell in a PV string will result in an open circuit condition and therefore losing the whole power of this string. A situation where replacing the string with another is the only solution. This will make the promotion of PV application in the developing countries very difficult. For a single string applications, alternative PV string design where a physical access to the damaged cell terminals is possible for string repair as recommended was IN [14]. In this case, even after a couple of cell failures, the PV string is still in operating condition because of the string oversizing (extra two cells).

In conclusion, future hot spot heating problems are foreseen if the following conditions occurred :

- The load is less than the critical load, a parameter which is not predictable because it depends on the amount of defection in the cell which has to be determined.
- Bad thermal design. In hot climates and sandy environment a careful array structure design may be a help in achieving artificial PV structure cooling to carry the excess heat away.
- Lack of non destructive detection techniques for determining the cell(s) responsible for hot spot problems and the amount of defection as well.

To reduce the probability of future hot spot problems, certain analysis steps have to be conducted before and after assembling the solar cells into the PV string and during the string lifetime if its power is degraded below certain amount. Before PV string assembly, the solar cells have to be matched with respect to their current output at a certain value of voltage (usually 0.44 V for silicon cells). Connecting the cells in series to form a cell matrix followed by encapsulation for weathering protection may result in the introduction of mismatching due to bad connection or cell cracking specially if the assembly is manual. In this case, a mismatching test on the cell matrix is highly recommended. During PV string lifetime a mismatching test is required if the PV string power output is degraded. In this case, additional light spot scanning technique can be used to detect the defected cell(s) in the encapsulated string where there is no way to physically access individual cells terminals. Such techniques discussed in [10, 15, and 16]. In the present p we suggest a modification to the technique of so that bad connections and cell cracking can accurately located, which will be explained later Using such technique, it is possible to dete defected cell in an encapsulated PV string. Si repairing a defected encapsulated PV string difficult, the resistance of the load connecte the string has to be above the critical load resista so that the amount of dissipated power in defected cell is reduced below the damaging va This means that the defected PV string has t labeled with a value of the minimum safe load.

5. FUTURE HOT SPOT PROBLE PREVENTION TECHNIQUES.

In certain environments the occurrence of freq partial shadowing due to the surroundings or accumulation of dirt (humid and sandy climate birds drops may lead to PV string perma damage. This is certain if the defected cell h very high shunt resistance.

To study the role of shunt resistance on the spot, Figure (10) is generated to show the reduc of the power output of the PV string which cont a defected cell for different values of the cell sh resistance. It is clear from Figure (10) that amount of power to be dissipated into the defe cell is increased for cells with high shunt resista This will put a limitation on the value of the load because the critical load will be reduced. If critical load is moved towards the open circuit p this gives an indication of a definite hot problem creation. The value of the critical (which depends on the amount of defection of defected cell(s)) can be decreased by decreasing shunt resistance.

During cell manufacturing, it is difficult to con the shunt resistance value by additi manufacturing step. The only way to protect the against hot spot problems, so far, is to integrat bypass diode on each cell.

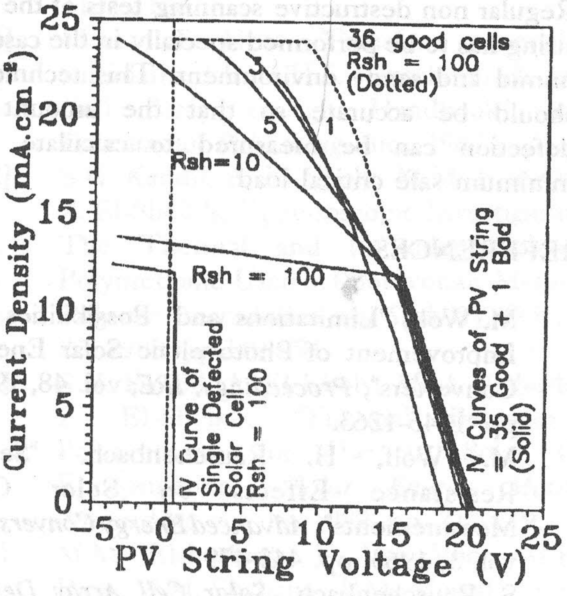

Figure 10. The effect of defected cell on the IV curve of 36 cells string for different values of R_{SH}.

In an effort to study the effect of solar cell shunt resistance experimentally, the simple solar cell configuration shown in Figure (11) is used. Using this configuration, several IV curves of solar cells with variable artificial shunt resistance values are generated. It is found that the peak power of cell under AM1 illumination does vary too much at very low resistance. This approach may be used, somehow, during cell manufacturing to reduce the value of the effective cell shunt resistance.

6. NON DESTRUCTIVE DETECTION TECHNIQUE

In previous work [17-18], we showed that an extra simple light source or salt solution can be used to detect a defected cell in an encapsulated PV string. The extra light source will compensate for the active area reduction of the defective cell, therefore the PV string short circuit current will be increased if light shines on the defected cell. The water in the salt solution will be evaporated first from the area of the defected cell due to its higher temperature than the surroundings, thus visual inspection is used to detect the defected cell. Both techniques rely on short circuiting the PV string to increase the sensitivity of detection. However, this may cause a permanent damage in the defected cell specially for a 36 cells string and long time measurements.

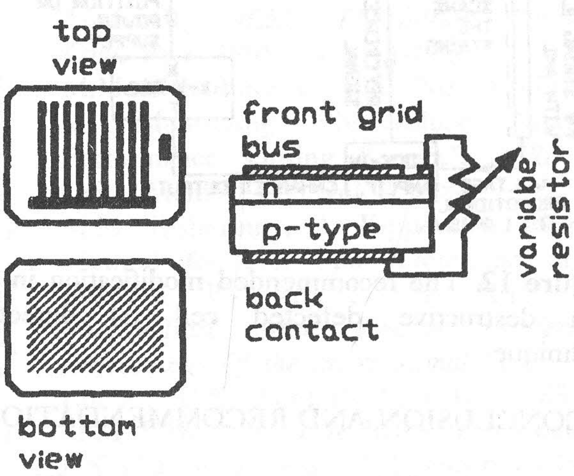

Figure 11. A configuration used to vary R_{SH}.

In the present paper, a modification of the technique presented in Ref. [10] is introduced to increase the detection sensitivity at any load. The setup explained in Figure (12) is similar to the one used for laser absorption spectrometer where first and second harmonic detection techniques are used to eliminate the background noise and increase the detection sensitivity by a couple of order of magnitudes [19]. In this experiment a phase sensitive detection technique is achieved by a lock-in amplifier, an extra light source of variable spot size and intensity, a mechanical chopper to produce a square wave modulation at 180 Hz (utility power supply frequency is 50 Hz), and an X-Y recorder to record the output of the scanned PV string areas. The PV string is illuminated under AM1 insolation level. The X-axis signal is either proportional to the extra light source intensity for measuring the degree of defection or the position of the light spot on the cell or the string to detect the defective area. Once a defected cell is located, the second harmonic detection technique is applied to measure the amount of defection.

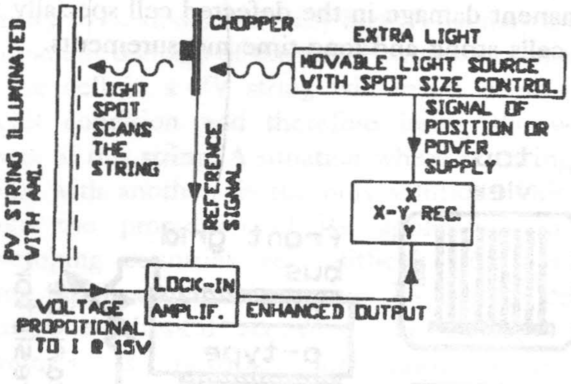

Figure 12. The recommended modification in the non destructive defected cell (s) detection technique.

7. CONCLUSION AND RECOMMENDATIONS

Based on I_{SC}, V_{OC}, and two points on the IV curve of the solar cell under full illumination and reverse condition, analytical equations for the most important cell parameters are derived. The sensitivity of these parameters are studied.

Hot spot future problems elimination technique is proposed. This technique rely on three steps:-

- Firstly, lowering the shunt resistance of the cell, this may be an additional integrated step during cell manufacturing. The shunt resistance of the cell can be physically reduced by connecting a resistor across a separate bus bar and the back contact. The amount of shunt resistance variation depends on the value of the shunted physical resistor and the spacing between the additional bus bar and the original cell grid which is used for current collection. As the distance between the bus bar and the grid is reduced, the physical shunt resistance has a greater effect. One may reach a short circuit condition (of the cell) in this way.
- Secondly, the sorted cells have to be tested against mismatch before and after encapsulation. If there is a permanent defection in the PV string, a minimum safe critical load value has to be marked on the defected PV string. Such technique is mainly used to promote the PV application in developing countries where replacing the defected string with a new one is out of the question.
- Regular non destructive scanning tests of the PV string has to be performed specially in the case o humid and sandy environment. This technique should be accurate so that the amount o defection can be measured to calculate the minimum safe critical load.

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