THE EFFECT OF THE DIODE IDEALITY FACTOR ON THE EXPERIMENTAL DETERMINATION OF SERIES RESISTANCE OF SOLAR CELLS

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Summary

Two experimental methods of determining the lumped series resistance of silicon solar cells are investigated. Both methods are based on the solution of the basic solar cell equation in conjunction with actual data taken from a single current–voltage (I–V) output curve. The assumption of a constant diode ideality factor along the entire I–V output characteristic is common in the derivation of both methods. It is shown that this assumption is inaccurate at normal intensities and can lead to erroneous results. It is evident that both methods are useful over only a limited range of solar cell operation and are accurate only for cells operating under very high illumination conditions where it is appropriate to assume that the diode ideality factor is constant at unity along the entire I–V curve.

1. Introduction

The series resistance has a significant effect on the performance of a solar cell. An accurate knowledge of the value of the series resistance is important particularly in computer modeling of solar arrays. Many techniques are available for estimating the series resistance of solar cells. Some imply measurements of two current–voltage (I–V) characteristics [1 - 3], others use data extracted from a single I–V curve [4 - 7]. The basis for most of these methods is the single-exponential lumped-constant parameters model. The equivalent circuit diagram of such a model is shown in Fig. 1, and the theoretical solar cell equation based on this model is given by

$$I = I_L - I_o \left[\exp\left\{ \frac{q}{nkT} (V + IR_s) \right\} - 1 \right] \qquad (1)$$

where I_L is the photocurrent, I_o is the diode saturation current, n is the diode ideality factor, R_s is the lumped effective series resistance, q is the

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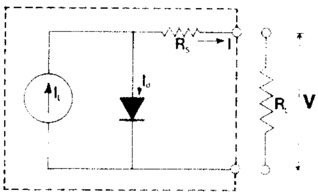

Fig. 1. Single exponential lumped-parameter model of a solar cell.

electronic charge, k is Boltzmann's constant and T is the temperature. At normal intensities and temperatures, $I_L \approx I_{sc}$ (the short-circuit current) and $I_o \ll I_L$. Therefore eqn. (1) can be written as

$$I = I_{sc} - I_o \exp\{B(V + IR_s)\} \tag{2}$$

where $B = q/nkT$.

This paper presents the results of a study of two experimental methods used for the determination of the lumped series resistance. Both methods involve the solution of the basic solar cell equation (eqn. (2)) in conjunction with actual data taken from a single $I-V$ output curve. The assumption of a constant diode ideality factor along the entire $I-V$ curve is used in the derivation of both methods. It is shown, from the physics underlying the device behavior, that this assumption is not accurate at all illumination levels and may led to erroneous results in the calculated value of R_s. It is also shown that methods using measurements extracted from two $I-V$ curves are more reliable in that they yield a virtually constant R_s value at different illumination levels. This is because the determination of R_s is independent of other solar cell parameters such as n and I_o, provided these are constant at the two operating points at which the measurements were made. Methods using a single $I-V$ output curve, however, yield R_s values which are functions of n.

2. Theory

The diode ideality factor n depends on the particular operative current transport mechanism through the diode junction. The diode current is the sum of a variety of diode currents: a diffusion component in the quasi-neutral regions of the junction, a generation–recombination component in the bulk space-charge layer and a surface component. Some of these components attain a dominating influence in different portions of the $I-V$ characteristic [8]. The diffusion component, for example, dominates at large forward biases and is characterized by a diode ideality factor of unity. However, the recombination and surface components dominate at small bias levels where the diode ideality factor is greater than unity [9].

While for a regular diode the diode current is simply the dark forward current, for a solar cell the diode current depends on the light intensity level and the terminal current. This is apparent from an examination of the solar cell model in Fig. 1. For a constant terminal current I, the diode current I_d

increases as the light intensity level increases, and hence I_L increases. At a sufficiently high intensity, the diode current can reach high enough values for diffusion to dominate and n becomes unity. However, for a constant light intensity level I_L, the diode current I_d decreases as the terminal current I increases. Under such conditions, n varies along the $I-V$ output curve. Near the open-circuit point, the current passing through the diode junction is high (high injection level) and occurs mainly by diffusion causing n to be unity. Along the knee of the $I-V$ curve, however, the terminal current is near its maximum value causing the diode current to be small (low injection level) and n is greater than unity. Figure 2 illustrates how the diode ideality factor of a solar cell varies with light intensity and terminal current. It should be noted, however, that at very high illumination levels the $I-V$ output curve approaches a straight line [6]. Under these conditions, the diffusion current becomes dominant along almost the entire characteristic, and therefore, it is appropriate to assume that n is constant at unity.

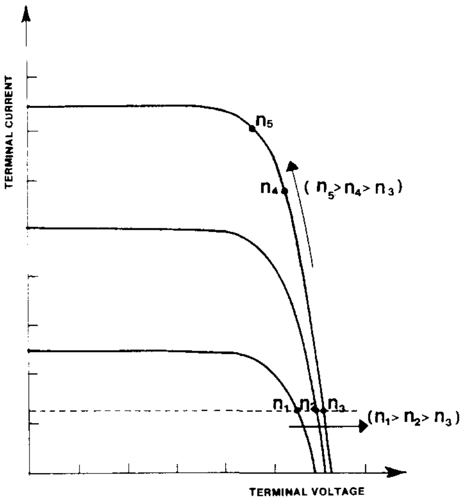

Fig. 2. Variation of diode ideality factor n with terminal current and light intensity level.

Some of the methods which use data extracted from a single $I-V$ output curve in determining the series resistance of solar cells are derived on the assumption that n is constant along the entire $I-V$ curve. As discussed above, this assumption is inaccurate especially at normal intensities. Two such methods, namely the maximum power point method [4], and the $I-V$ area method [7] are investigated in this paper. A comparison with the illuminated curve method [1] and the dark curve method [2], both of which use measurements of two $I-V$ curves, is also presented.

3. Experimental details

The test specimen selected for this study is a commercial n on p gridded solar cell of area 4.8 cm × 4.8 cm. Five ENH projector bulbs provided illumination. Intensity calibration was carried out with a secondary cell tested in natural sunlight. Measurements were made at light intensity levels of approximately 1, 2 and 3 suns. The I–V output characteristics were obtained by continuously varying the external load across the solar cell while the cell was being illuminated. The dark I–V characteristic was obtained by forward biasing the cell with a regulated d.c. power supply. All measurements were performed at a constant cell temperature of 22 °C. The cell temperature was monitored with a thermistor placed in good thermal contact with the surface of the cell. The temperature was controlled by water cooling the cell mounting using a water pump with a controlling valve. The I–V characteristics used in this study are shown in Figs. 3 and 4.

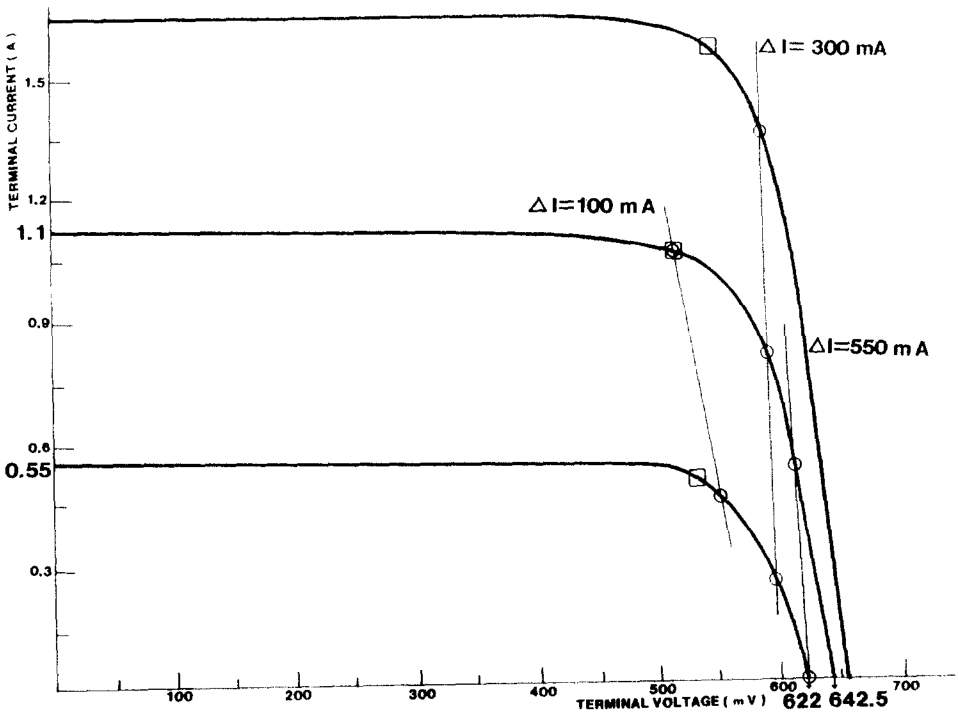

Fig. 3. Experimental I–V characteristics at three different levels of illumination, showing sample calculations of the series resistance by the illuminated curve method [1]: □, maximum power point.

4. Results

First, the illuminated and the dark curve methods are used in determining R_s of the tested solar cell using data extracted from Figs. 3 and 4. Both methods rely on the comparison between two operating points having the same diode current. The results are given in Tables 1 and 2.

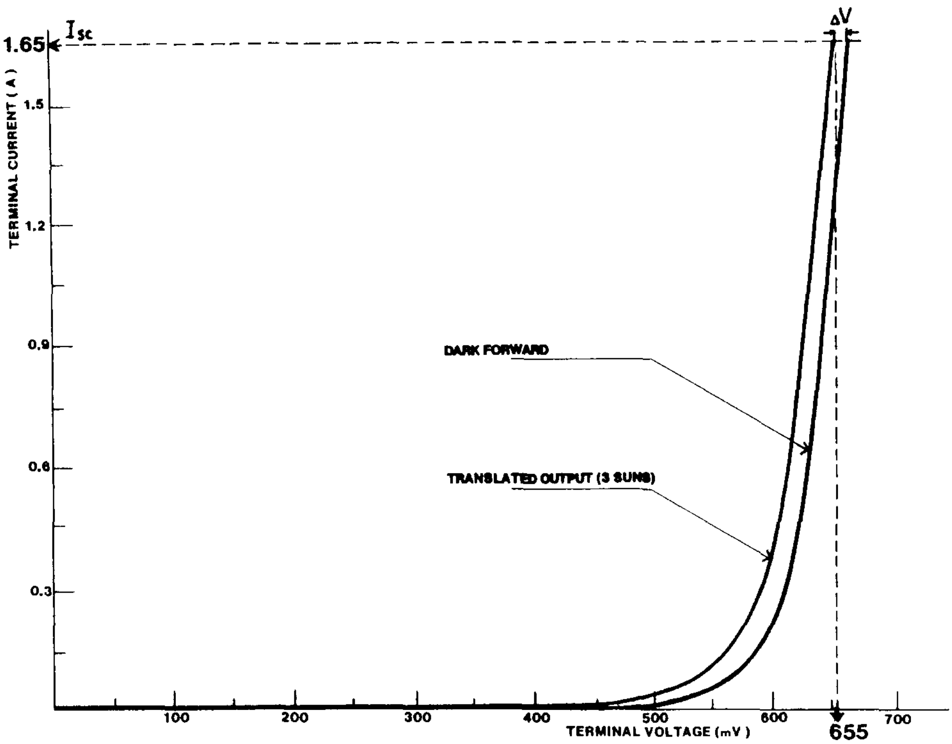

Fig. 4. Experimental dark forward and translated output characteristics used in the determination of the series resistance by the dark curve method [2].

TABLE 1

Series resistance by the illuminated curve method

Curves used	*Light-generated current difference* ΔI_L (mA)	*Correlation current difference* ΔI (mA)	*Voltage difference* ΔV (mV)	$Rs = \Delta V/\Delta I_L$ (mΩ)
1 and 2 suns	550	100	4	7.3
		300	3	5.5
		550	3	5.5
1 and 3 suns	1100	100	6	5.5
		300	5	4.5
		550	6	5.5

Next, the maximum power point and the I–V area methods are applied. Both methods were derived on the assumption that n is constant along the entire I–V output curve. The derived equations for the maximum power point method [4] are summarized as follows:

$$B = \frac{I_m/(I_L - I_m) + \ln\{(I_L - I_m)/I_L\}}{2V_m - V_{oc}} \tag{3}$$

TABLE 2

Series resistance by the dark curve method

I_{sc} (mA)	*Diode current* (mA)	*Voltage difference* ΔV (mV)	$R_s = \Delta V/I_{sc}$ (mΩ)
1650	1650	9	5.5
	1500	9	5.5
	1200	9	5.5
	900	9	5.5
	600	8	4.9
	300	9	5.5
	150	11	6.5

$$R_s = \frac{V_m}{I_m} - \frac{1}{B(I_L - I_m)} \tag{4}$$

Where $I_L \approx I_{sc}$, V_m is the voltage at maximum power point, I_m is the current at maximum power point, and V_{oc} is the open-circuit voltage.

The equation used in determining R_s by the I–V area method is given by [7]

$$R_s = 2\left(\frac{V_{oc}}{I_{sc}} - \frac{A}{I_{sc}^2} - \frac{nkT}{qI_{sc}}\right) \tag{5}$$

where A is the area under the I–V output characteristic. The results of applying both methods using data extracted from Fig. 3 are given in Table 3.

TABLE 3

Series resistance by the maximum power point and the I–V area methods

Intensity (suns)	I_{sc} (mA)	V_{oc} (mV)	I_m (mA)	V_m (mV)	R_s (mΩ)	
					Maximum power point method	*I–V area method*[a]
1	550	622	500	532	−99	10.5
2	1100	642.5	1000	560	−68	−46
3	1650	655	1575	546	210	−31.6

[a] Area under I–V curves is calculated using the trapezoidal rule and R_s is calculated using $n = 1$.

5. Discussion

It is seen from the results of Tables 1 and 2 that the series resistance values determined by the illuminated curve method correlate very well with that of the dark curve method (approximately 5.5 mΩ). However, the inaccuracy of the maximum power point and the $I-V$ area methods even for an intensity level as high as 3 suns is shown in Table 3. Not only are some of the R_s values negative, but also the magnitudes are far from close to the exact value.

The dependence of the R_s value on the diode ideality factor n is shown in eqns. (4) and (5). Such a property is common to all methods which use data extracted from a single $I-V$ output curve in determining the lumped series resistance of solar cells. Both equations were derived on the assumption of a constant diode ideality factor along the entire $I-V$ output curve. Under normal intensities such an assumption is inaccurate and usually leads to erroneous R_s values as found in Table 3. Under these conditions n varies along the $I-V$ output curve, being greater than unity in the knee area around the maximum power point and approaching unity near the open-circuit voltage point.

As the illumination level increases, however, the $I-V$ output characteristic starts to deviate from its conventional shape and the terminal current reaches its maximum value (I_L) at a negative terminal voltage instead of at short circuit [1]. At very high illumination the $I-V$ output curve eventually approaches a straight line [6] and it is appropriate to assume that n is constant and unity along the entire $I-V$ characteristic. Under these conditions eqns. (4) and (6) would yield accurate R_s values. An earlier analysis by Phang *et al.* [10] concluded that the area method is highly inaccurate at air mass (AM) 1 illumination and that it works well only for a cell with low R_s and when measured at high illumination.

The determination of R_s by methods using two $I-V$ characteristics (either two $I-V$ output curves at different illumination levels [1], or one output and one dark forward curve [2], or one p–n junction curve and one dark forward curve [3]) has several advantages over methods using a single $I-V$ output curve. First, the determination of R_s is independent of n. This is because R_s is found from a comparison between two operating points having the same diode current and hence the same n, and hence R_s at any particular operating point of the characteristic can be determined accurately without any limiting approximations. Furthermore, the equations used in calculating R_s are very simple and do not include as many parameters as those found in methods using a single $I-V$ output curve. Fewer parameters mean less uncertainty error in reading those parameters from the graph and hence less error in the calculated value of R_s.

6. Conclusion

The determination of the series resistance of solar cells using two $I-V$ characteristics is more reliable than using a single $I-V$ curve and yields accurate R_s values at any operating point on the characteristic. Methods using data extracted from a single $I-V$ output curve yield R_s values that are functions of the diode ideality factor. Because the derivation of such single-curve methods is based on the assumption that the diode ideality factor is constant along the entire *I–V* curve, an assumption which can be true only at very high illumination levels, R_s values found using a single *I–V* output curve at normal intensity levels will be greatly erroneous.

References

1 M. Wolf and H. Rauschenbach, Series resistance effects on solar cell measurements, *Adv. Energy Convers.*, *3* (1963) 455 - 479.
2 M. S. Imamura and J. I. Portscheller, An evaluation of the methods of determining solar cell series resistance, *Proc. 8th IEEE Conf. Photovoltaic Specialists, Seattle, WA, August 1970*, IEEE, New York, 1970, pp. 102 - 109.
3 K. Rajkanan and J. Schewchun, A better approach to the evaluation of the series resistance of solar cells, *Solid-State Electron.*, *22* (1979) 193 - 197.
4 W. T. Picciano, Determination of the solar cell equation parameters, including series resistance, from empirical data, *Energy Convers.*, *9* (1968) 1 - 6.
5 S. K. Agarwal, R. Muralidharan, A. Agarwala, V. K. Tewary and S. C. Jain, A new method for the measurement of series resistance of solar cells, *J. Phys. D*, *14* (1981) 1643 - 1646.
6 J. Chaffin and G. C. Osborn, Measurement of concentrator solar cell series resistance by flash testing, *Appl. Phys. Lett.*, *37* (7) (1980).
7 L. Araujo and E. Sanchez, A new method for experimental determination of the series resistance of a solar cell, *IEEE Trans. Electron Devices*, *10* (1982) 1511 - 1513.
8 M. A. Wolf and M. Wolf, Characteristics and performance of silicon solar cells between low and high level injection, *Proc. 15th IEEE Conf. Photovoltaic Specialists, Orlando, FL, May 12 - 15, 1981*, IEEE, New York, 1981, p. 387.
9 A. Neugroschel, F. A. Lindholm and C. T. Sah, A method for determining the emitter and base lifetimes in p–n junction diodes, *IEEE Trans. Electron Devices*, *ED-24*, (1977) 662 - 671.
10 J. C. H. Phang, D. S. H. Chan and Y. K. Wong, Comments on the experimental determination of series resistance in solar cells, *IEEE Trans. Electron Devices*, *5* (1984) 717.