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DARK CURRENT-VOLTAGE MEASUREMENTS ON PHOTOVOLTAIC MODULES AS A DIAGNOSTIC OR MANUFACTURING TOOL

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ABSTRACT

Dark current-voltage (dark I-V) measurements are commonly used to analyze the electrical characteristics of solar cells, providing an effective way to determine fundamental performance parameters without the need for a solar simulator. The dark I-V measurement procedure does not provide information regarding short-circuit current, but is more sensitive than light I-V measurements in determining the other parameters (series resistance, shunt resistance, diode factor, and diode saturation currents) that dictate the electrical performance of a photovoltaic device. The work documented here extends the use of dark I-V measurements to photovoltaic modules, illustrates their use in diagnosing module performance losses, and proposes their use for process monitoring during manufacturing.

INTRODUCTION

Dark I-V measurements have been used to evaluate the electrical performance of photovoltaic cells and diodes for many years. Since the 1960's, both light I-V and dark I-V measurements have been commonly used to analyze the effects on cell performance of series resistance and other parameters [1 - 5]. More recent work describes the distinction between light I-V and dark I-V measurements in the determination of the series resistance of cells [6]. Our work extends the use of dark I-V measurements to modules composed of series/parallel combinations of cells, and uses a non-linear regression procedure to estimate performance parameters for cells in the module.

MEASUREMENT PROCEDURE

The procedure used for dark I-V measurements on solar cells involves covering the cell to eliminate light-generated current, using a power supply to force electrical current through the cell from the positive contact to the negative, and then measuring current and voltage simultaneously as the voltage of the power supply is increased from zero to a predetermined upper limit. The resulting direction for current flow is opposite to that when the cell is exposed to light, but the electrical configuration still results in the cell's p-n junction being in "forward bias", as during typical operation. As a result, dark I-V measurements can be used like light I-V measurements to analyze the electrical characteristics of a cell.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

For modules composed of a combination of cells, the dark I-V measurement procedure is still valid, but it requires a larger power supply and a slightly different interpretation of the measured data. Sandia developed such a system for module dark I-V measurements and is now using it for three purposes: to diagnose changes in module performance following field aging or accelerated environmental testing, to provide performance parameters used in numerical simulation of photovoltaic arrays, and to help evaluate the production consistency of modules. The Sandia system, shown in Fig. 1, is capable of making module dark I-V measurements to a maximum current of 35 amps, a maximum voltage of 60 V, and over a range of temperatures from 10 to 65 °C.

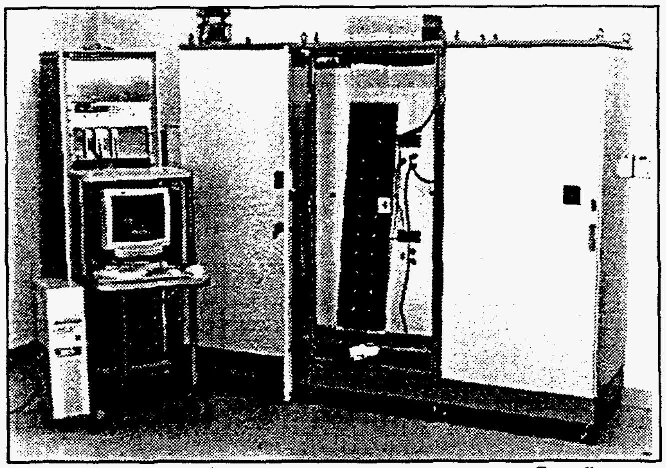

Fig. 1. Module dark I-V measurement system at Sandia.

RESULTS AND APPLICATIONS

Fig. 2 illustrates dark I-V measurements at 25 °C for four different commercially available modules; one crystalline silicon, two multicrystalline silicon, and one triple-junction amorphous silicon (a-Si). The shape and linearity of the measured curve at different current levels can be used to determine electrical parameters for the cells in the module; such as, series resistance, shunt resistance, diode factor, and saturation current. For instance, the degree of curvature to the right at high current levels is an indication of the magnitude of series resistance (R_s). Similarly, large curvature at low current levels indicates low shunt resistance (R_{sh}). An inflection in the curve near mid current levels may indicate the presence of nonideal ($n \neq 1$) carrier recombination losses. For the modules shown in Fig. 2, the typical operating current is approximately 2 to 3 amps, but measurements

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were performed to higher currents for better sensitivity in the determination of R_s.

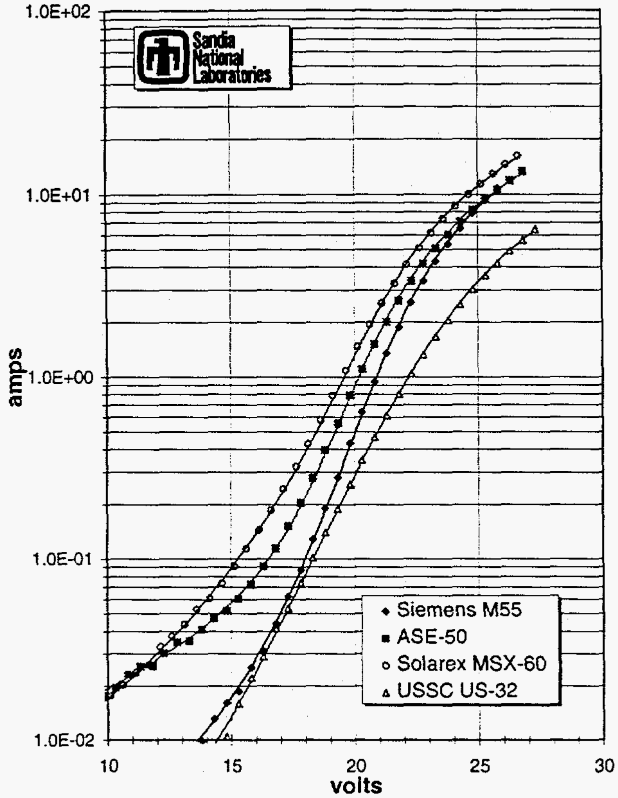

Fig. 2. Dark I-V measurements for four different commercially available modules. Symbols represent measured values and the lines are numerical fits from parameter estimation software.

Fig. 3 further illustrates the effect of series resistance. In this case, dark I-V measurements were made before and after adding 0.15-, 0.31-, and 0.46-ohm resistors in series with a typical 36-cell silicon module. The series resistance of the module itself was about 0.3-ohm.

To effectively use dark I-V measurements, it is beneficial to implement a numerical procedure for rapidly extracting cell parameters from the measured data.

Parameter Estimation Method and Sensitivity

Nonlinear parameter estimation software makes it possible to quickly and repeatedly determine electrical performance parameters from dark I-V measurements. Such software, adapted for dark I-V analysis, is available from MTR Software Incorporated in Toronto, Canada [7]. The electrical model chosen for use in this software is a two-diode equivalent circuit for the solar cell with shunt and series resistance included, Eqn. 1. In the model, one diode is assumed to have a diode factor equal to one (n=1) and the second diode factor (n_2) is one of the five parameters estimated, along with series resistance (R_s), shunt resistance (R_{sh}), and two diode saturation currents (I_{o1} and I_{o2}). The software also provides sensitivity

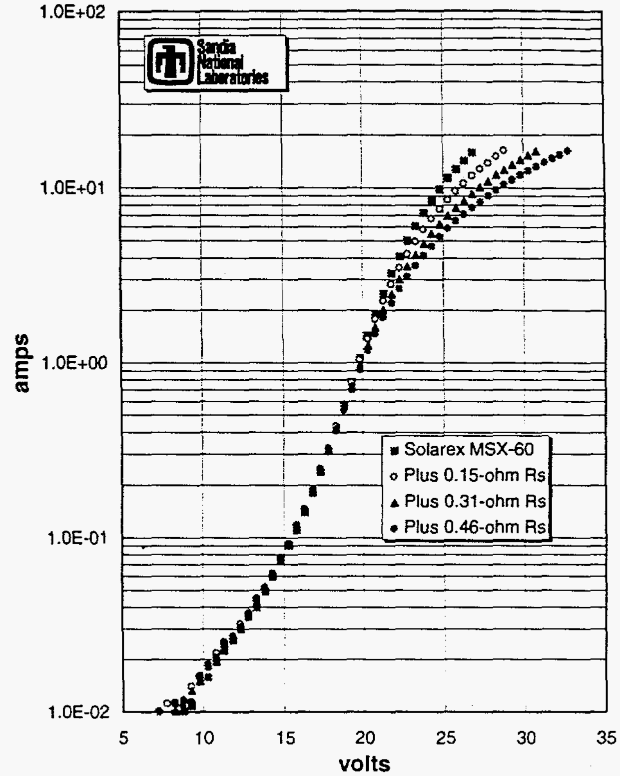

Fig. 3. Dark I-V measurements before and after adding resistors in series with a typical 36-cell mc-Si module.

coefficients as part of the estimation process that indicate when the measured data does not contain sufficient information to accurately estimate all five parameters.

$$I = I_{o1}\left\{e^{\frac{qV_j}{kT}} - 1\right\} - I_{o2}\left\{e^{\frac{qV_j}{n_2 kT}} - 1\right\} - \frac{V_j}{R_{sh}} \qquad (1)$$

$$V_j = V - IR_s$$

Fig. 4 illustrates the relative sensitivity of the dark I-V measurement to each of the five parameters as a function of the current level, for a typical 36-cell crystalline silicon module. Note that at high current levels the sensitivity to R_s is high, and at low current levels the sensitivity to both R_{sh} and to n_2 are high. It is also evident from Fig. 4 that if the current range over which measurements are made is not correctly chosen, then the sensitivity to different parameters will be lost. Using properly measured dark I-V data, this parameter estimation software does a good job of estimating the desired cell parameters. Table 1 gives the cell performance parameters estimated for the module measurements shown in Fig. 2 and Fig. 3.

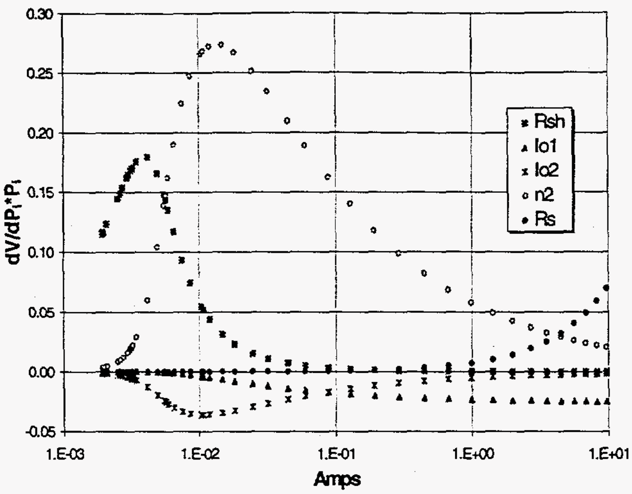

Fig. 4. Relative sensitivity of dark I-V measurements on a Siemens M55 module to five different parameters (P_i), as a function of current level.

Table 1. Cell parameters estimated from module dark I-V curves shown in Fig. 2 And Fig. 3.

Module	R_{sh} (Ω)	I_{o1} (A)	I_{o2} (A)	n_2	R_s (Ω)
M55	98	1.57E-10	6.71E-6	2.19	7.50E-3
MSX60	29	4.15E-10	8.84E-5	2.43	7.48E-3
ASE50	19	3.73E-10	1.42E-4	2.99	9.45E-3
US32	184	0	5.34E-7	1.78	1.29E-2
MSX60	42	3.53E-10	1.20E-4	2.57	7.66E-3
MSX60+.15	28	3.92E-10	8.10E-5	2.42	1.13E-2
MSX60+.31	41	4.76E-10	1.64E-4	2.69	1.54E-2
MSX60+.46	44	5.04E-10	1.99E-4	2.78	1.92E-2

Module Performance Losses

Changes as small as 10% in a module's series resistance are detectable using dark I-V analysis, which is impressive when you realize that the R_s in a typical silicon module would have to double before a 5% drop in power resulted. This sensitivity to changes in R_s has made it possible for us to quantify performance losses related to solder bond fatigue in commercial modules after limited field exposure, prior to detection by other means. Early detection of these losses facilitates the modification of manufacturing processes that then extend the service lifetime of modules. Changes in the other performance parameters (R_{sh}, I_{o1}, I_{o2}, n_2) can also be used to diagnose performance loss mechanisms that occur as a result of field aging, accelerated aging, or manufacturing process variations. The addition of module dark I-V tests to the methods currently used to "qualify" commercial modules would almost certainly improve their sensitivity to changes induced by accelerated aging tests [8].

When coupled with thermal (infrared) imaging equipment, dark I-V procedures can also provide a visual diagnostic tool. By using the dark I-V equipment to supply a continuous current through a module, the R_s distribution in the module produces a temperature distribution that visually shows the evidence of R_s. In new c-Si modules, the temperature distribution is usually highest adjacent to interconnect ribbons. Faulty solder bonds manifest as localized hot spots.

Monitoring the Module Manufacturing Process

Quick and inexpensive diagnostic measurements are of great value at different steps during the module manufacturing process. For instance, if defective or substandard cell strings could be identified after soldering interconnecting ribbons, but prior to module lamination, then manufacturing costs could be reduced and the cause for the defect could be more quickly identified. The dark I-V measurement technique may provide such a diagnostic tool for module manufacturers. Even after module lamination, but prior to framing and installation of junction boxes, dark I-V measurements could be used to identify defective modules, and perhaps even to sort them by performance. It remains to be seen how diagnostic and versatile this method may be for different manufacturers using different photovoltaic technologies.

In order to investigate the feasibility of applying dark I-V analysis to monitor module production, a group of twelve c-Si modules manufactured within a 1-week period were tested using both dark I-V and light I-V methods. Table 2 gives the cell parameters estimated from dark I-V measurements. Since dark I-V measurements were performed at the module level, the parameters in Table 2 represent "average" values for the 36 cells in each module. The relatively large variation in R_{sh} was due to poor low-current resolution of our test equipment, not module variation. The R_{sh} value for the modules tested was relatively large, thus requiring dark I-V measurements to current levels less than 1 mA in order to accurately estimate R_{sh}. The variation in the other cell parameters determined from the module dark I-V measurements was reasonably small and consistent with anticipated values for the cells. It is conceivable that process limits could be defined for each parameter providing a more diagnostic method for monitoring the manufacturing process.

Table 2: Results from dark I-V analysis of twelve 36-cell c-Si modules manufactured within a 1-week period. Parameters given are averages for cells in each module.

#	R_{sh} (Ω)	I_{o1} (A)	I_{o2} (A)	n_2	R_s (Ω)
1	280	2.59E-10	4.83E-5	2.63	7.80E-3
2	410	2.51E-10	2.74E-5	2.50	7.84E-3
3	1020	2.46E-10	7.95E-5	2.90	8.04E-3
4	970	2.68E-10	2.02E-4	3.32	8.02E-3
5	120	1.79E-10	3.18E-6	1.89	7.52E-3
6	75	1.43E-10	8.29E-7	1.64	7.43E-3
7	155	2.42E-10	2.30E-5	2.33	7.62E-3
8	510	2.31E-10	2.92E-5	2.44	7.99E-3
9	455	2.36E-10	9.96E-5	2.90	7.66E-3
10	190	2.58E-10	7.86E-5	2.80	8.05E-3
11	160	2.27E-10	1.22E-5	2.22	7.87E-3
12	170	2.67E-10	1.28E-4	3.03	7.86E-3
Avg=	375	2.34E-10	6.10E-5	2.55	7.81E-3
S=	320	0.37E-10	6.0E-5	0.48	0.21E-3

Predicting Module Performance

Using the cell parameters determined from dark I-V analysis, it is possible to calculate a module's expected light I-V performance by prescribing a value for I_{sc} and inserting the parameters in a two-diode electrical model. A software program (PVSIM) for performing this calculation has been documented elsewhere [9]. Table 3 compares calculated performance using parameters from Table 2 to measured light I-V performance. Three things are evident from the results in Table 3. First, the predicted V_{oc} is in excellent agreement with the measured value. Second, the calculated I_{mp} is larger than the measured value by about 2.5%. Third, the calculated V_{mp} over predicts the measured value by about 3%. The cause for the V_{mp} over prediction was that the R_s value determined from dark I-V measurements differed from the R_s value appropriate for illuminated operation, as will be discussed in the next section. The good news was that, by modifying only the R_s value, good agreement between predicted and measured values was achieved. Adding 3.5-mΩ to the R_s gave V_{mp} within 0.3% and I_{mp} within 2%. Agreement was particularly good when it is recognized that the uncertainty in the measured light I-V parameters was approximately ±1% for voltage and ±2% for current.

Table 3. Light I-V performance predicted from dark I-V parameters, compared to measured light I-V performance.

	Measured				Predicted		
#	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)
1	4.58	21.80	4.14	17.28	21.74	4.24	17.80
2	4.62	21.85	4.15	17.33	21.79	4.31	17.77
3	4.57	21.80	4.17	17.22	21.81	4.28	17.72
4	4.56	21.73	4.15	17.24	21.74	4.27	17.64
5	4.54	21.83	4.18	17.26	21.95	4.22	17.85
6	4.59	21.94	4.17	17.32	21.97	4.24	17.86
7	4.63	21.96	4.17	17.36	21.78	4.27	17.82
8	4.61	21.83	4.16	17.22	21.84	4.28	17.76
9	4.62	21.75	4.16	17.25	21.84	4.31	17.77
10	4.61	21.69	4.16	17.07	21.76	4.27	17.75
11	4.61	21.73	4.19	17.17	21.84	4.29	17.77
12	4.53	21.67	4.14	17.18	21.72	4.20	17.75
Avg=	**4.59**	**21.80**	**4.16**	**17.24**	**21.82**	**4.27**	**17.77**
S=	.033	.091	.014	.079	.079	.034	.059

LIMITATIONS OF THE DARK I-V PROCEDURE

As previously indicated, dark I-V measurements provide no information regarding the short-circuit current (I_{sc}) of a photovoltaic device. However, in a production environment, the average I_{sc} of cells is typically a well known quantity. In which case, dark I-V analysis can still provide a quick method for assessing the consequences of cell handling, cell mismatch, soldering, and lamination on the final module performance. Work by others has shown that for individual cells the R_s parameter determined from dark I-V measurements differs from, and is usually lower than, the value determined from light I-V measurements [6]. Our work has demonstrated the same difference for dark I-V measurements on modules. The cause for the difference in calculated R_s is that the imposed voltage distributions and consequently the current flow patterns are different in dark I-V versus light I-V measurements. Nonetheless, dark I-V measurements provide a valuable method for analyzing module performance parameters.

CONCLUSIONS

The utility of module dark I-V measurements and analysis has been demonstrated by the work documented in this paper. Application of the procedures described makes early detection of the effects of field or accelerated aging possible, provides an alternative means for monitoring manufacturing process variations, and with modification of estimated R_s values does a credible job of predicting module performance when illuminated.

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