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Screening of Solar Cells

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SCREENING OF SOLAR CELLS

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SUMMARY

Because solar cells in a production batch are not identical, screening is performed to obtain similar cells for aggregation into arrays. A common technique for screening is based on a single operating point of the I-V characteristic of the cell, usually the maximum power point. As a result, inferior cell matching may occur at the actual operating points. Screening solar cells based on the entire I-V characteristic will inherently result in more similar cells in the array. An array consisting of more similar cells is likely to have better overall characteristics and more predictable performance. This paper deals with solar cell screening methods and cell ranking. The concept of a mean cell is defined as a cell "best" representing all the cells in the production batch. The screening and ranking of all cells are performed with respect to the mean cell. The comparative results of different screening methods are illustrated on a batch of 50 silicon cells of the Space Station Freedom.

1. INTRODUCTION

One of the disadvantages of solar cells for electric power generation is that the device is a low power source. To obtain the desired power level, many solar cells must be connected in series and parallel combinations. As differences in production between single cells are inevitable, screening is usually performed to obtain cells with "similar" characteristics. A representative or a "mean" cell may then be defined that represents all the solar cells in a production batch. The purpose is to select cells having characteristics which deviate least from the mean cell. Such an

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array composed of closely similar cells should possess better characteristics, more predictable performance and better known tolerances.

A common technique for cell screening is based on a single operating point, e.g. the maximum power point. However, the cells in the array may not match at other operating points. In addition, the single point measurement may also contain errors thus affecting the screening results. Therefore, the screening of cells based on the entire I-V characteristics is desirable since it insures the selection of more similar cells for the array. This requires the measurement and storage of many data points for each produced cell. A method for screening solar cells was introduced in Ref. 1. The purpose of the present article is to further introduce an additional screening method, and to compare the quality of the screening between this method and the method based on single operating point. The screening is demonstrated on a batch of 50 8- by 8-cm silicon solar cells such as those used in the preliminary design of the Space Station Freedom.

2. SCREENING METHODS

2.1 Method Based on Curve Fitting

In Ref. 1 we introduced a screening method for solar cells. This method is based on modeling the solar cell using an equivalent electrical circuit represented by either a single or double exponential I-V characteristic with five or seven parameters. Curve fitting methods were used to determine the solar cell equation parameters from the experimental data. It was expected that "similar" cells would produce similar parameter sets and that the screening could be based on comparing the parameter values. This could not be accomplished because unique parameter values could not be obtained as discussed in Ref. 1. The results of the curve fitting procedure for the cell parameters are listed in Table 1. A model with double exponents and seven parameters was used for the cell, and its I-V equation is given by:

$$I = I_{ph} - I_{01}\left\{\exp\left[\frac{q(V + IR_s)}{n_1 kT}\right] - 1\right\} - I_{02}\left\{\exp\left[\frac{q(V + IR_s)}{n_2 kT}\right] - 1\right\} - \frac{V + IR_s}{R_{sh}} \qquad (1)$$

where I_{ph} is the photogenerated current, I_{01} and I_{02} are reverse saturation currents, n_1 and n_2 are ideality factors, R_s is the series resistance and R_{sh} is the shunt resistance. The 50 solar cells are denoted by SS01 through SS50. The measured I-V characteristics of all 50 cells at 25 °C are shown in Fig. 1. It should be noted that these cells were already pre-screened (for a desired current range) at 0.495 V. The dispersion of the measured data is noticeable, but one may argue that they are obviously "similar" cells. It should also be noted that the parameter values for each cell gives a very good fit to the measured data, as discussed in Ref. 1. Nevertheless, Table 1 shows that the corresponding parameters are different for these "similar" cells, and screening cells by comparing parameter values is not warranted. The concept of a "mean cell" was thus introduced to represent the entire production batch of cells and to describe the performance of the entire I-V characteristic. The procedure for determining the mean cell is as follows:

(1) Perform a curve fit for each cell to find the cell parameters.

(2) Compute the currents for each cell using its parameters at the same voltage. Repeat at other voltages covering the entire I-V curve at equal intervals.

(3) Compute the average for all currents (at each particular voltage) thereby generating new data points for the I-V characteristic of a hypothetical "mean cell."

(4) Perform a fit for the mean cell to obtain the parameter values.

The screening of the solar cells was based on the difference in the area ΔA under the I-V characteristic of each cell as compared to the mean cell. When normalized, the $\Delta A/A$ (Ref. 2), represents the overall deviation, from a performance viewpoint, of each cell from the average (mean) performance of the production batch. Once a comparison of each cell to the mean cell is made, it is possible to rank the cells in terms of their similarity to the mean cell, as shown in Table 2 under the column "Reference 1" for the 50 cells used in the study. To select K cells for an array, one simply uses the top K cells in the list. Column "Reference 1" shows that the most similar cell to the mean cell is number 33. In computing the area under the I-V curve for all cells including the mean cell, the model Eq. (1) was used with the corresponding parameter values.

2.2 Methods Based on Measured I-V Points

The method described in Ref. 1 and summarized in section 2.1 represents a viable technique for screening of solar cells. However, it must be noted that the method resorts to a curve fitting procedure. The concept of a mean cell and the expression $\Delta A/A$ may be computed from the measured data points without using the cell model Eq. (1), cell parameters and curve fitting procedures. A mean cell data point (I-V curve) may be generated by computing the average of the currents for all cells at particular voltages. Since the I-V measured points are not usually sampled at identical voltages for all the cells, one cannot directly use the I-V measured data of the cells to produce the mean cell. It is necessary therefore to transform the I-V measured data to new data having common voltage points. This may be simply accomplished by interpolating between successive measured points of the cells. The mean cell may then be generated and the $\Delta A/A$ computed for all the cells along with their ranking. It should be noted that the I-V data of the mean cell include measurement errors of the same category as the cells in the batch. On the other hand, it should also be noted that the characteristics of all the cells, including the mean cell, are smooth curves for the screening method based on curve fitting. The results of screening and ranking of the 50 cells based on the common voltage points are listed in Table 2 under the column "Common voltage." The same screening procedure may be performed with common current points. The results in this case are somewhat different because of the interpolation process. The results of screening and ranking of the 50 cells based on common current points are listed in Table 2 under the column "Common currents."

The values of either common current or common voltage points may be used for connecting cells in series or in parallel, respectively, to obtain the I-V characteristic of an array.

2.3 Method Based on a Single Point

The method for screening cells based on a single measured point assumes a given voltage for which the corresponding currents of the cells fall in an acceptable range. Using the concept of a mean cell, one may define such a cell by averaging the currents of all the cells in the production batch for the given voltage. Denoting the average current by I_m (mean) the screening and ranking may be performed based on the criterion of $|I_j - I_m|/I_m$, where I_j is the current of cell j. The results of ranking the original pre-screened 50 cells based on 0.495 V are listed in Table 2 under the column "0.495 Volt".

3.0 CELL RANKING

Table 2 shows that the ranking of the cells is different for the different screening methods. The degree of difference in the ranking may be calculated by comparing the difference in the position of the same cell in the column in the table for two compared methods and taking the root mean square, i.e.,

$$\left\{ \frac{1}{N} \sum |a(y) - b(y)|^2 \right\}^{1/2}$$

where y = 1,2,. . ., N is the cell number, and a(y) and b(y) are the position of cell y in the column for methods a and b, respectively. A smaller number corresponds to a more similar ranking of the two compared methods. The results are summarized in Table 3. The closest ranking (1.60) is obtained for the screening method based on the measured I-V points (common voltage) and the curve fitting method column "Reference 1." The number 1.60 indicates that the degree of difference in the ranking for the two methods is 1.60. The largest difference in ranking (14.64) is for the single point method and the curve fitting method. The screening method based on measured I-V points, for common voltage and common current, is the same; the difference as shown in Table 3 comes from measurement errors and the interpolation process. The main conclusion of the cell ranking comparison is that the method based on the measured I-V points results in similar ranking as the curve fitting method. Consequently, no fitting method is required and hence a less complicated screening method may be used.

4. EFFECTIVENESS OF SCREENING

The purpose of cell screening is to select cells with similar characteristics from a production batch for their aggregation into arrays. The effectiveness of the screening may be measured by the difference in the power output of an array made of a given number of screened cells and the power output of the mean cell of the batch times the same number of cells. The comparison may be made for a single point, a desired range or for the entire I-V characteristic. The effectiveness of the cell screening is demonstrated numerically on 9 of the above mentioned 50 cells. In the example we compare the power output of the 9 most similar cells connected in series, as screened by the current method, and the power output of 9 randomly selected cells, as screened by the single point method. We also compare the difference in power output between the array made of the 9 most similar cells, based on the current screening method, and the power output of the mean cell multiplied by 9. This comparison, for the entire current range of the I-V characteristic, indicates the predictable performance tolerance of the solar cells. Figure 2 describes the variation in the percent power error $(P_a - 9P_j)/P_a$ of the above 9 screened cells, as screened by the current method and by the single point method, where P_a is the array power and P_j is the power of a single cell. The figure shows that the power error of the cells screened by the current method, based on the entire I-V characteristic, is smaller than for the single point screening method. In the vicinity of the maximum power point (marked by P_{max}), the power error is somewhat smaller for the single point screening method. This result is expected since pre-screening was performed at 0.495 V. The results in Fig. 2 also show that the 9 selected cells for the array are indeed very similar since the difference in array output power and the power of the mean cell multiplied by 9 is very small for a large range of the I-V characteristic.

5. CONCLUSIONS

Solar cells are produced in batches and cell screening is usually performed before arraying. A common technique for screening is based on a single operating point. At other operating points the deviation in performance may be considerably larger. Two additional screening methods were discussed in this article which use information from the entire I-V characteristic. One method is based on curve fitting and another is based on measured I-V points. A mean cell is conveniently defined representing all the cells in the production batch from an overall performance viewpoint. The screening and ranking of the cells is performed with respect to the mean cell, obtaining subsets of cells with similar characteristics. These two methods were compared to the single point method used in practice. The screening of all methods were demonstrated on 50 pre-screened cells. The proposed methods result in more similar cells for arraying purposes and a more predictable array performance. The disadvantage of the procedures based on the entire I-V characteristic is that they require the measuring and storing of many points. This additional conceptual complexity should be weighed against the potential gain of superior performance from the solar arrays.

REFERENCES

1. J. Appelbaum, A. Chait, and D.A. Thompson, "Parameter Estimation and Screening of Solar Cells," Progress in Photovoltaics, vol. 1, 93–106 (1993).

2. J.C.H. Phang and D.S.H. Chan, "A Review of Curve Fitting Error Criteria for Solar Cell I-V Characteristics," Solar Cells, vol. 18, No. 1, 1–12 (1986).

TABLE 1.—SOLAR CELL PARAMETERS OBTAINED FROM CURVE FITTING

I_{ph}	R_s	R_{sh}	I_{o1}	I_{o2}	n_1	n_2	Cell Number
2.61157e+00	7.54240e-03	2.94187e+00	8.54175e-11	1.11735e-05	1.00653e+00	1.99645e+00	ss01
2.59961e+00	5.99155e-03	2.67465e+00	3.57257e-11	9.76180e-06	9.91570e-01	1.96442e+00	ss02
2.58153e+00	5.25852e-03	6.05362e+00	7.19331e-11	1.46943e-05	1.01352e+00	1.98820e+00	ss03
2.61234e+00	3.51455e-05	3.53620e+00	1.52646e-11	4.35708e-05	1.04571e+00	2.16848e+00	ss04
2.62220e+00	4.30860e-03	7.09841e+00	8.07427e-11	2.00052e-05	1.02438e+00	2.01106e+00	ss05
2.64113e+00	4.31451e-03	2.01823e+00	3.68972e-11	1.07986e-05	1.00751e+00	2.00441e+00	ss06
2.62044e+00	4.29865e-03	2.51243e+00	4.62006e-11	1.32633e-05	1.01146e+00	2.00393e+00	ss07
2.62657e+00	2.44792e-03	2.64711e+00	3.40499e-11	2.09424e-05	1.02546e+00	2.06086e+00	ss08
2.56744e+00	7.87564e-03	4.68615e+00	6.57282e-11	1.55357e-05	1.00144e+00	2.03810e+00	ss09
2.61420e+00	9.66599e-03	4.13767e+00	4.88744e-11	1.37353e-05	9.95619e-01	2.03183e+00	ss10
2.61260e+00	5.18982e-03	5.41601e+00	6.55981e-11	1.86465e-05	1.01543e+00	2.01441e+00	ss11
2.61299e+00	7.38549e-03	4.52605e+00	1.02469e-10	1.29908e-05	1.00427e+00	1.99838e+00	ss12
2.63673e+00	4.32982e-04	5.34011e+00	1.47637e-11	4.69633e-05	1.04607e+00	2.15081e+00	ss13
2.57073e+00	5.81684e-03	4.93108e+00	4.84873e-11	1.46390e-05	1.01724e+00	2.00331e+00	ss14
2.62680e+00	3.19797e-04	4.55083e+00	5.92837e-12	5.59225e-05	1.02945e+00	2.19305e+00	ss15
2.62405e+00	7.93514e-04	3.64450e+00	2.76261e-11	4.04318e-05	1.04684e+00	2.17220e+00	ss16
2.61181e+00	6.05638e-03	6.88232e+00	7.95575e-11	1.37371e-05	1.00013e+00	2.00766e+00	ss17
2.61433e+00	6.22829e-03	4.60840e+00	3.24856e-11	1.60775e-05	9.95394e-01	2.01070e+00	ss18
2.58946e+00	9.46442e-03	6.37078e+00	8.60302e-11	1.10454e-05	1.00306e+00	1.99829e+00	ss19
2.61569e+00	9.22948e-03	4.34710e+00	6.52127e-11	1.20096e-05	1.00187e+00	2.01010e+00	ss20
2.62583e+00	2.35995e-03	1.83795e+00	2.39091e-11	1.11582e-05	9.94974e-01	2.01921e+00	ss21
2.62527e+00	9.81188e-03	4.22056e+00	6.81871e-13	4.45457e-04	8.46342e-01	3.04865e+00	ss22
2.60877e+00	4.93914e-03	1.88789e+00	3.54945e-11	1.12030e-05	9.98058e-01	2.04756e+00	ss23
2.62008e+00	7.26908e-03	2.55680e+00	5.93115e-11	1.12756e-05	9.98057e-01	2.02024e+00	ss24
2.61844e+00	8.94333e-03	2.90682e+00	7.37097e-11	1.04229e-05	1.00609e+00	1.99755e+00	ss25
2.60940e+00	5.92112e-03	3.76136e+00	7.57730e-11	1.80507e-05	1.01143e+00	2.03825e+00	ss26
2.57991e+00	7.64475e-03	6.96502e+00	2.88323e-11	1.88639e-05	1.02559e+00	2.03429e+00	ss27
2.58733e+00	7.57904e-05	3.85681e+00	2.10945e-13	3.88446e-05	1.04261e+00	2.16494e+00	ss28
2.59673e+00	9.64365e-03	7.49358e+00	4.21654e-11	1.52041e-05	1.01275e+00	2.01393e+00	ss29
2.59948e+00	1.00798e-02	3.37649e+00	3.98945e-11	1.08463e-05	1.00676e+00	2.00997e+00	ss30
2.61125e+00	8.92983e-03	3.05040e+00	4.00425e-11	3.38081e-05	9.64539e-01	2.28332e+00	ss31
2.62517e+00	6.87255e-03	2.73826e+00	6.50408e-11	1.14791e-05	1.00196e+00	2.00713e+00	ss32
2.60698e+00	4.02196e-03	3.98035e+00	5.68658e-11	2.87697e-05	1.03524e+00	2.12570e+00	ss33
2.61259e+00	2.55329e-03	3.19396e+00	3.74518e-11	3.19782e-05	9.97754e-01	2.16520e+00	ss34
2.63418e+00	7.47046e-03	1.99595e+00	4.37944e-11	1.11173e-05	9.98161e-01	2.06364e+00	ss35
2.62321e+00	8.31723e-03	3.85747e+00	7.55469e-11	1.20284e-05	1.01018e+00	1.99285e+00	ss36
2.61449e+00	5.66134e-03	3.25703e+00	4.89840e-11	1.44266e-05	9.99581e-01	2.01609e+00	ss37
2.62801e+00	3.22301e-03	1.01881e+01	1.27436e-11	3.39379e-05	1.06688e+00	2.09758e+00	ss38
2.62237e+00	6.19599e-04	2.39908e+00	1.98158e-11	2.30953e-05	1.00250e+00	2.11552e+00	ss39
2.61163e+00	4.67277e-03	3.21633e+00	4.88935e-11	1.36266e-05	1.01672e+00	1.99850e+00	ss40
2.63278e+00	2.74811e-04	5.32073e+00	1.96227e-14	5.18767e-05	1.05948e+00	2.20474e+00	ss41
2.62979e+00	7.29151e-03	4.62664e+00	1.04543e-11	1.61837e-05	9.81298e-01	2.00234e+00	ss42
2.57553e+00	6.37155e-03	2.52110e+00	5.04545e-11	9.16689e-06	1.00690e+00	1.99910e+00	ss43
2.60878e+00	7.49815e-04	3.18127e+00	2.14818e-11	2.76553e-05	1.03305e+00	2.09003e+00	ss44
2.62334e+00	4.57293e-03	2.58448e+00	6.27943e-11	9.87233e-06	1.00429e+00	1.99784e+00	ss45
2.62229e+00	4.70237e-03	2.17369e+00	3.82108e-11	9.04782e-06	1.00105e+00	2.00096e+00	ss46
2.61894e+00	6.54638e-03	5.09190e+00	7.02592e-11	2.03178e-05	1.00540e+00	2.11912e+00	ss47
2.60905e+00	3.25506e-03	3.69796e+00	3.93874e-11	1.37208e-05	1.01496e+00	2.00488e+00	ss48
2.63050e+00	6.66549e-03	3.86526e+00	4.20478e-11	1.46467e-05	9.99195e-01	2.01556e+00	ss49
2.62308e+00	1.36545e-02	5.02332e+00	5.42532e-11	1.10797e-05	1.00583e+00	2.00160e+00	ss50
2.61367e+00	6.13232e-03	3.49099e+00	4.08717e-11	1.76558e-05	9.98980e-01	2.05583e+00	Mean
1.69328e-02	3.22705e-03	1.79423e+00	2.52041e-11	6.22907e-05	3.18599e-02	1.58871e-01	S. Deviation

TABLE 2.—THE RANKING OF SOLAR CELLS BASED ON

DIFFERENT SCREENING METHODS

Number	Reference 1	Common voltage	Common current	0.495 Volt
1	33	33	40	33
2	40	40	33	32
3	4	4	4	18
4	34	37	34	31
5	37	32	44	35
6	10	34	24	6
7	32	10	10	39
8	44	44	37	37
9	24	24	32	29
10	25	8	8	13
11	7	25	7	10
12	8	27	31	24
13	20	7	25	50
14	27	31	27	5
15	14	20	16	16
16	49	16	14	42
17	31	29	20	34
18	29	14	18	3
19	18	18	2	40
20	2	49	48	38
21	16	48	29	30
22	36	36	30	36
23	45	26	26	12
24	48	2	1	25
25	42	42	36	11
26	50	50	50	14
27	26	45	19	28
28	1	1	3	27
29	19	30	28	7
30	30	19	45	1
31	47	3	47	8
32	28	28	9	2
33	3	47	12	20
34	22	22	42	49
35	15	15	17	23
36	9	12	11	22
37	6	9	22	46
38	41	6	49	21
39	39	11	6	41
40	38	41	39	26
41	11	17	35	43
42	12	39	46	9
43	35	35	15	19
44	17	13	41	15
45	13	38	43	4
46	46	46	21	44
47	43	5	23	45
48	21	43	5	48
49	5	21	38	17
50	23	23	13	47

TABLE 3.—DIFFERENCE IN RANKING OF THE SCREENING METHODS

	Reference 1	Common voltage	Common current	0.495 Volt
Reference 1	-------	1.60	3.72	14.64
Common voltage	1.60	-------	3.16	14.12
Common current	3.72	3.06	-------	14.20
0.495 V	14.64	14.12	14.20	-------

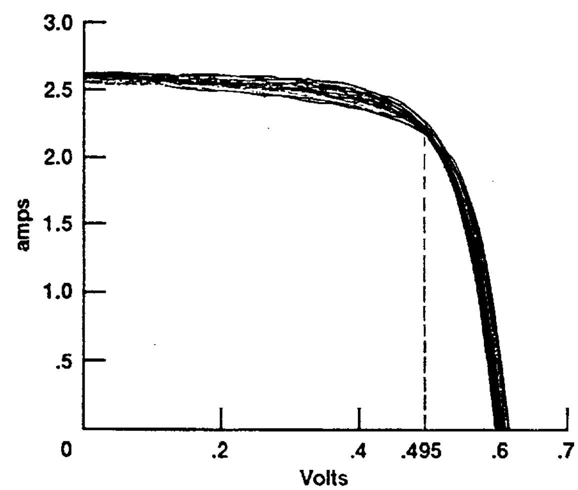

Figure 1.—Measured I-V characteristics of 50 solar cells.

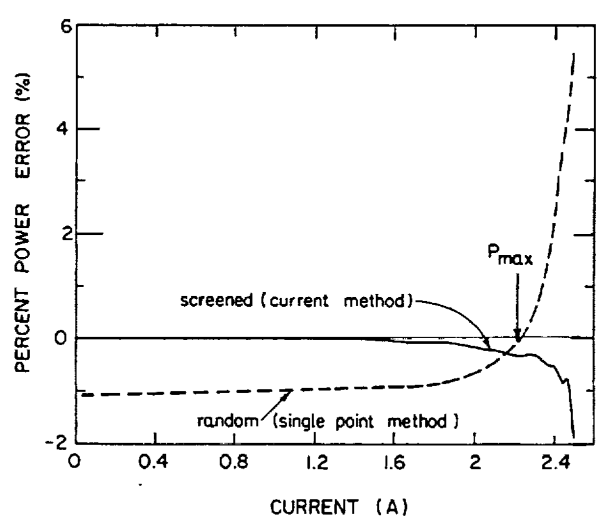

Figure 2.—Percent power error of an array made of 9 cells screened by the current method and 9 randomly selected cells screened by the single point method.

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13. ABSTRACT ***(Maximum 200 words)***

Because solar cells in a production batch are not identical, screening is performed to obtain similar cells for aggregation into arrays. A common technique for screening is based on a single operating point of the I-V characteristic of the cell, usually the maximum power point. As a result, inferior cell matching may occur at the actual operating points. Screening solar cells based on the entire I-V characteristic will inherently result in more similar cells in the array. An array consisting of more similar cells is likely to have better overall characteristics and more predictable performance. This paper deals with solar cell screening methods and cell ranking. The concept of a mean cell is defined as a cell "best" representing all the cells in the production batch. The screening and ranking of all cells are performed with respect to the mean cell. The comparative results of different screening methods are illustrated on a batch of 50 silicon cells of the Space Station Freedom.

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