NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-464

Capacitance of Solar Cells and Panels Under Various Load Conditions

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Preface

The work described in this report was performed by the Guidance and Control Division of the Jet Propulsion Laboratory.

Abstract

Associated with a solar cell is a diffusion capacitance that is directly proportional to the short circuit current capability of the cell. If one attempts to measure the maximum power capability of a cell or panel by a sweep-loading technique, the current provided by the diffusion capacitance will affect the measurement. In order to reduce the error thus introduced to acceptable levels, the magnitude of the diffusion capacitance must be known. This report presents values one can expect as well as a measurement technique to determine capacitance of cells of various manufacture.

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I. Introduction

One of the characteristics of solar cells and panels that has been largely ignored in previous JPL solar power system designs is the capacitance of the cell or array, primarily because the effect of solar array capacitance is masked by the large capacitors placed across the inputs of the pulse width regulators to absorb their large input ripple currents. One element of a new power system design for solar electric propulsion system — a maximum power point tracker — causes a periodic rapid traversal of the solar panel voltage-current (V-I) characteristic by sweep-loading the panel and measures the instantaneous power capability of the panel during the transient. A proper choice must be made of the magnitude, duration, and sweep rate of the load so that the solar array V-I characteristic may be traversed slowly enough to minimize errors caused by array capacitance discharge currents. In order to make the above choice of parameter values, a fairly accurate knowledge of the effective solar array capacitance is required. This report details the steps taken to obtain the capacitance information and describes the results obtained.

II. Theoretical Basis for Cell Capacitance

The total capacitance of a solar cell is composed of two portions: the transitional capacitance and the diffusion capacitance. The former is relatively independent of cell current and has a value of about 0.1 μF at zero cell current for a 2 cm^2 cell. The diffusion capacitance has a linear relationship with cell current as indicated by the following expression (suggested by Dr. Alex Shumka of JPL):

$$C_D = \beta I \tag{1}$$

where

$$\beta = \left(\frac{q}{kT}\right)^2 \cdot \frac{L^2}{2\mu}, \tag{2}$$

in farads/ampere, where

I = junction current, A

C_D = diffusion capacitance, F

q = electron charge

k = Boltzmann constant

T = temperature, °K

L = diffusion length, cm

μ = mobility, cm^2/V-sec

The junction current may be determined from the following expression:*

$$I_L = I_0 \left\{ \exp \frac{q}{AkT} \left[V + R_s \left(I_{load} + \frac{V}{R_{sh}} \right) \right] - 1 \right\} + \frac{V}{R_{sh}} + I_{load}$$

where

I_{load} = load current, A

I_L = light-generated current, A

I_0 = reverse saturation current, A

q = electron charge

k = Boltzmann constant

T = temperature, °K

I = junction current, A

V = cell terminal voltage, V

R_s = cell series resistance, Ω

R_{sh} = cell shunt resistance, Ω

A = a constant ranging between 1 and 5, depending upon number and type of recombination centers

The junction current is equal to the exponential term in the above equation. The equivalent circuit described by the equation is given in Fig. 1. Because of uncertainties in the value of A and I_L, the junction current may be approximated by making some simplifications in the equivalent circuit. At short circuit conditions $V = 0$, the equation becomes

$$I_L = I_0 \left\{ \exp \left[\frac{q}{AkT} \left(R_s I_{sc} \right) \right] - 1 \right\} + I_{sc} \qquad (3)$$

where the load current becomes the short-circuit current I_{sc}. For measured values of I_0 = 21 μA, R_s = 1.4 Ω, I_{sc} = 46 mA, T = 298°K (room temperature), and an assumed worst-case value of $A = 1$, the calculated value of junction current is 0.24 mA. The error in neglecting this current when simplifying Eq. (3) to $I_L = I_{sc}$ is only about 0.5%.

*Adapted from M. B. Prince and M. Wolf, *Journal British IRE*, Oct. 1958.

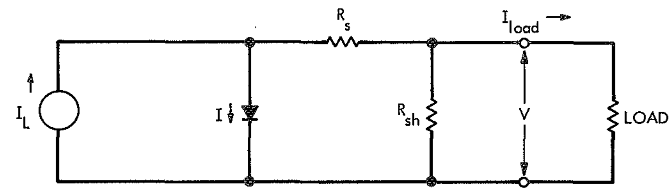

Fig. 1. Simplified equivalent circuit

For an open circuit voltage of 0.6 V and for a measured value of R_{sh} = 18 kΩ, the calculated current in the shunt resistance is only 33 μA, a value that can be neglected. The above two approximations permit the equivalent circuit to be simplified to the circuit shown in Fig. 2. The junction current may then be determined from the following simple expression:

$$I = I_{sc} - I_{load}$$

The calculation of the value of β from Eq. (2) is complicated by the lack of precise values of L and μ, the diffusion length and mobility. Using estimated values of 110 μ for L and 1000 cm²/V-sec for μ for the N/P cell, a value of β of 91.7 μF/A is obtained. In order to confirm this estimate direct measurements of cell and panel capacitances were made; the techniques used and the results of the measurements are discussed in the following section.

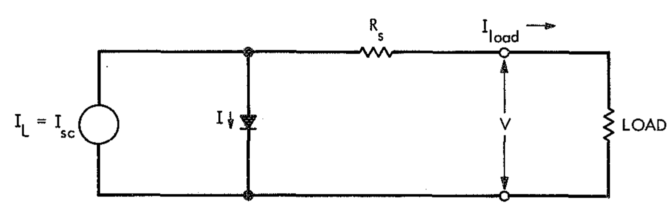

Fig. 2. Solar cell equivalent circuit

III. Capacitance Measurements

Capacitance measurements were first made on a 17.5 ft² *Mariner* Mars 1964 solar panel composed of 84 parallel strings of 84 series P/N 1×2 cm cells. A frequency sweep measurement technique was used; the schematic for this technique is shown in Fig. 3. A large transistor was used to provide both a dc load for the illuminated panel and a small "dither" load about the dc operating point. The variable power supply and adjustment of R_1 controlled the dc operating point and the signal generator provided the ac drive. Approximately 200 mV of ac was applied to the panel. A time-base oscilloscope was used to determine that the sine wave impressed upon the panel remained undistorted. An x-y oscilloscope was used to determine the relative phase between the panel voltage and current as the frequency of the generator was changed; ac voltage and current data were taken with two electronic ac voltmeters, using a 1-Ω shunt for the current measurement. The test sequence involved pointing the normal to the panel directly toward the sun, recording the open circuit voltage, adjusting the panel load to the desired value, and then sweeping the signal generator through the range from 50 Hz to 100 kHz, recording ac voltage and current at intervals in this range. This process was repeated for each dc operating point. Plots of the dc operating points for two runs on different days are shown in Figs. 4 and 5, in which the current variations caused by the "dither" load are indicated by the ΔI brackets. Figure 6 is a plot of the apparent impedance of the solar panel vs frequency for point A of Fig. 5. The −3-dB point occurs at 22 kHz, and the equivalent circuit for the panel at this operating point is a 1.83-Ω resistance shunted by 3.94 μF of capacitance, as shown in Fig. 6. Similar plots were made for each operating point shown in Figs. 4 and 5.

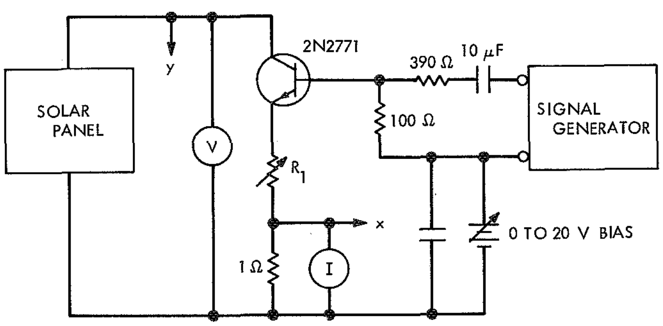

Fig. 3. Load method of measuring panel capacitance

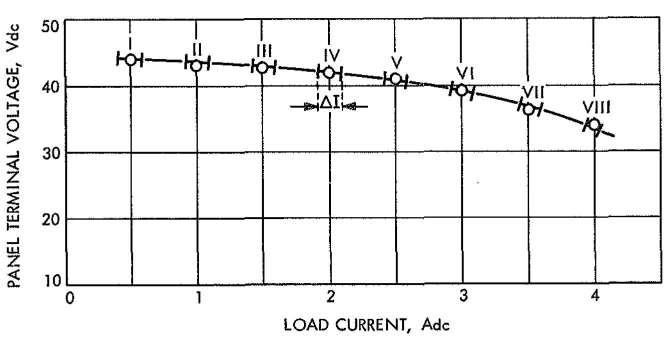

Fig. 4. Steady-state operating points, run 1

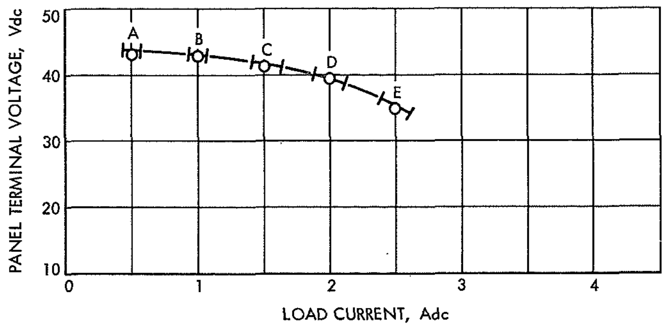

Fig. 5. Steady-state operating points, run 2

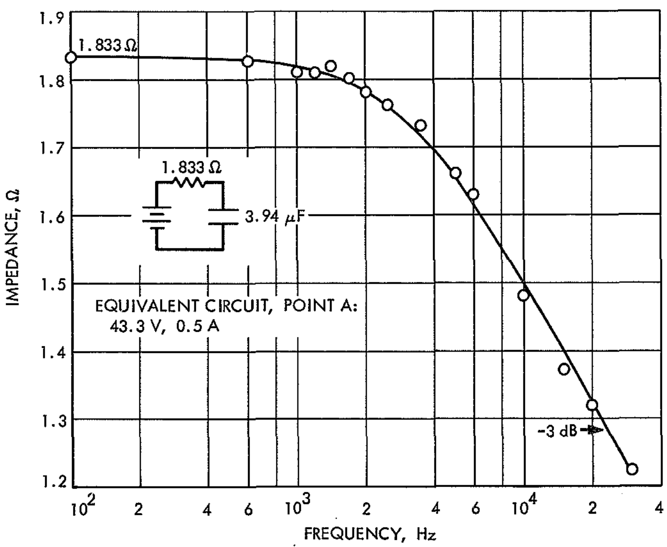

Fig. 6. Apparent impedance of solar array for point *A*

The panel capacitance as determined by the frequency sweep method is plotted vs junction current as the upper curve in Fig. 7. The curve shown is the best visual fit for the data from both test runs. As may be seen from this curve, the effective capacitance is a linear function of the junction current.

In order to compare the results of tests of complete panels with those of single cells, the frequency sweep test method was attempted on a single current-biased unilluminated cell, but the results were so inconsistent that the method was discarded. The use of a commercial bridge was also attempted; this approach only worked properly at zero bias current. A bridge was then constructed that would inject current into an unilluminated cell. This bridge, which worked very well, is described in the following paragraphs.

The circuit of the capacitance bridge is shown in Fig. 8. Both upper arms of the bridge were selected to be

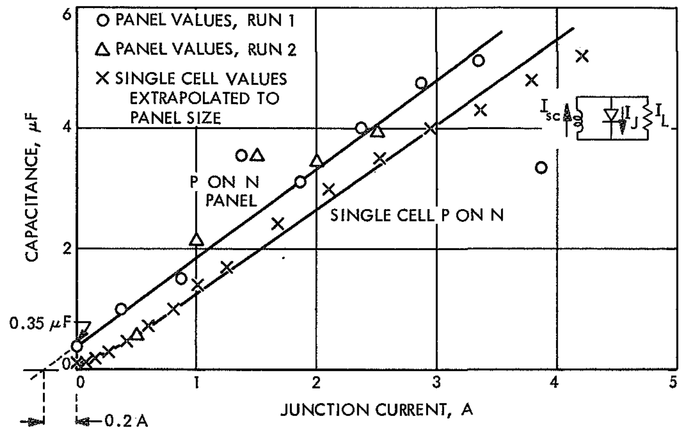

Fig. 7. Capacitance vs junction current for P/N panel and cell

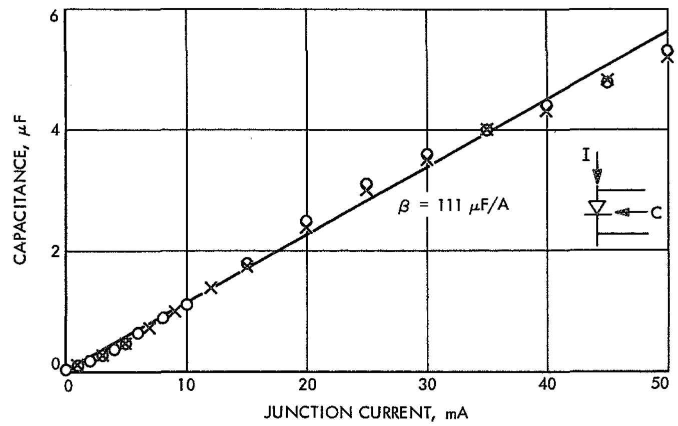

Fig. 9. Capacitance of a single P on N 1 × 2-cm cell with current applied in dark

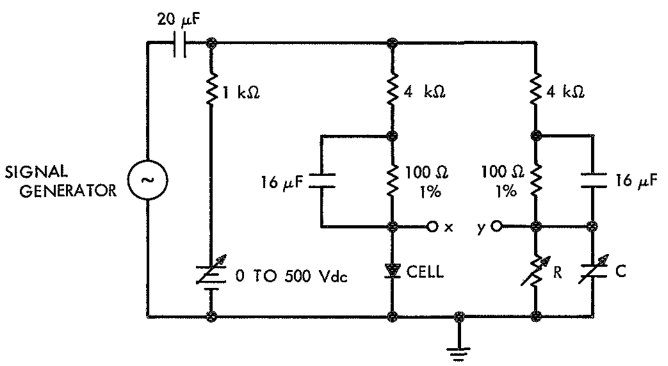

Fig. 8. Bridge used to measure cell capacitance

extremely close in value. The 1% 100-Ω resistors are current shunts; only one is needed, but both were used to keep the circuit symmetrical. A clip-on milliammeter was first used; however, it had to be unclipped before each balancing procedure because it injected an unwanted signal. Also, the milliammeter tended to drift. The bypass capacitors are necessary to ensure that the voltmeter used across the shunt did not alter the balance. It was assumed that the equivalent circuit of the forward-biased unilluminated cell is a shunt resistor and capacitor, hence these (R and C) were inserted as variables in the balancing arm.

Bias current is supplied by the 0- to 500-V power supply; the 1-kΩ resistor provides some series resistance so that it is possible to capacitively couple the signal generator as shown. Two indicators are used; an x-y oscilloscope connected to x, y, and ground, and a time-axis differential input oscilloscope connected to x and y. The x-y lissajou figure helps in finding the approximate bridge arm values since a null detector alone does not give a clue as to which direction to make changes when the balance values are far from null. When a close-to-null value is reached (indicated by a 45-deg line), null is precisely achieved by looking for a minimum signal on the time-axis differential oscilloscope. Sensitivities of 1 MV/cm are needed to avoid overdriving the cell and distorting the sine wave, for then no true balance can be achieved. Values of 1 to 5 mV across the cell did not cause appreciable distortion and balance could be achieved.

Figure 9 shows a plot of measured capacitance vs applied current for a P/N cell. Figure 10 shows similar results for an N/P solar cell. The slopes of these curves, equivalent to the β of Eq. (1), are 111 μF/A and 122 μF/A, respectively. Both of these values are somewhat greater than the 91.7 μF/A figure calculated previously from Eqs. (1) and (2). The value of β is quite sensitive to the diffusion length L, which is determined by carrier lifetime. The lack of precision in knowing the values of L and μ probably accounts for the observed discrepancy between the theory and measurement. The values are close enough to indicate that the experimental values are realistic, and that the experimental procedure is valid. There does not appear to be a great difference in capacitance between N/P and P/N cells.

Since the solar panel is a "square" array—i.e., there are an equal number of series and parallel cells—the capacitance of the array should be equal to that of a single cell, assuming that stray capacitance may be

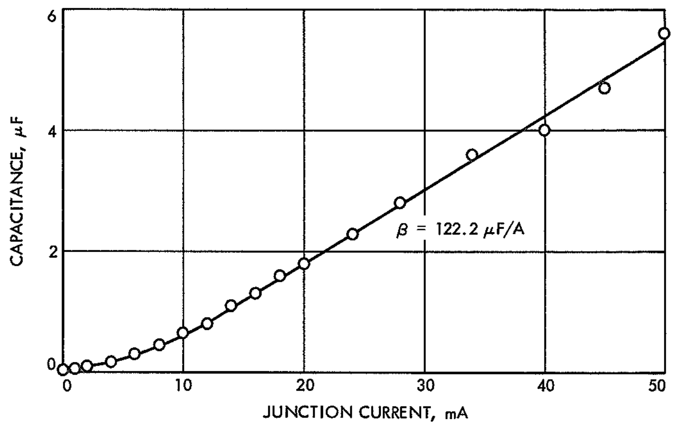

Fig. 10. Capacitance of a single N on P 1 × 2-cm cell with current applied in dark

neglected. By multiplying the current values of Fig. 9 by 84, a direct comparison of cell and panel capacitance can be made. Figure 7 includes the curve of Fig. 9 scaled to match the current capability of the array. As may be seen in Fig. 7, the slopes of the two curves are about the same, indicating about the same capacitance per ampere; however, the zero-current intercept of the panel indicates a considerably higher fixed capacitance.

In order to evaluate this discrepancy, the panel was subjected to a bridge test for capacitance using the same technique as for single cell tests. Using this technique, the panel exhibited a fixed capacitance of 0.0806 μF, compared with a single-cell capacitance of 0.065 μF under the same circumstances. By extending the panel capacitance curve to zero capacitance it appears that a 0.2-A error in reading panel short circuit current could cause the observed capacitance discrepancy. Since 0.2 A represents only about a 5% measurement error, and the solar tests required about one hour to complete, it appears likely that variability in haze and water vapor may account for the capacitance discrepancy.

IV. Conclusions

Capacitance tests on both solar cells and panels have confirmed the theoretical linear relationship between cell capacitance and junction current. The constants as determined from these measurements were 111 μF/A for P/N cells and 122 μF/A for N/P cells. These values compare reasonably well with a calculated value of 91.7 μF/A. Single cell capacitances may be extrapolated to panel capacitances by multiplying by the number of parallel cells and dividing by the number of series cells. Since cell manufacture varies it would be more accurate to make capacitance vs junction current measurements by the bridge method described, using samples of cells that would actually be used in the array.

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15. Supplementary Notes

16. Abstract

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