Facility to measure solar cell ac parameters using an impedance spectroscopy technique

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An experimental setup has been developed to measure the solar cell ac parameters using an impedance spectroscopy technique. It consists of an electrochemical interface to set the dc bias voltage and to apply the signal voltage across the solar cell and a frequency response analyzer to generate the excitation signal with varying frequency and analyze the result. The setup is calibrated with a standard *RC* network and measured an error of ±4% (maximum). Solar cell capacitance, parallel resistance and series resistance are calculated from the measured data. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1386632]

I. INTRODUCTION

Photovoltaics as a source of electrical energy have tremendous potential both in space and ground applications. The demand for higher power and higher efficiency has necessitated the use of high-speed switching charge controllers for solar array power conditioners. To design an efficient and reliable switching charge controller, both the static (dc) and the dynamic (ac) characteristics of a solar cell need to be understood. The static and dynamic equivalent circuits of a solar cell are shown in Fig. 1. The dynamic equivalent circuit of a solar cell is derived from a static equivalent circuit by substituting the diode with its junction capacitances [transition capacitance (C_t) and diffusion capacitance (C_d)] and its dynamic resistance.[1]

The ac parameters of a solar cell can be measured either by a frequency domain technique or a time domain (transition) technique. In the frequency domain technique, a small signal is applied around the operating point and the ac parameters are measured. These are steady state values. In the time domain technique, the cell voltage varies from short circuit to open circuit or vice versa. Hence, the measured values of solar cell ac parameters are integral values from short circuit to open circuit or vice versa depending on the test conditions. Time domain or single frequency techniques have certain limitations and disadvantages for making measurements on solar cells.[1] Mueller *et al.*[2] measured the ac parameters of a GaAs/Ge solar cell in terms of complex impedance. However the study was limited to approximating an estimate only of cell capacitance. Hence, an experimental setup has been developed to measure the ac parameters of solar cells using an impedance spectroscopy technique.

II. PRINCIPLE

Impedance spectroscopy is particularly characterized by the measurement and analysis of some or all impedance related functions and plotting of these functions in a complex plane. Such a plot can be used to interpret the small signal model of a device. In impedance spectroscopy, the complex impedance ($R+jX$) of a device is measured directly in the frequency domain over a large range (two to four decades) of frequencies. A purely sinusoidal voltage with different frequencies is applied to the device under test and the phase shift and amplitude are measured, i.e., the real and imaginary parts of the resulting current at that frequency. The ratio between the applied voltage and resultant current is calculated and this is the impedance (both real and imaginary) of the device under test. A plot of the real and imaginary parts of impedance ($R+jX$) on a complex plane for varying frequency gives the impedance spectrum of the device. From this, the equivalent circuit parameters are calculated. The impedance spectrum of a circuit with resistor (R_p) and capacitor (C_p) in parallel is a semicircle in the fourth quadrant about the real axis touching the origin, with a radius of $R_p/2$. If the semicircle is away from the origin, it indicates the presence of series resistance in the network. The shape of the impedance spectrum depends on the circuit parameters and changes if the parameter depends on frequency and also on the circuit configuration.

III. DESCRIPTION OF THE TEST SETUP

The experimental setup shown in Fig. 2 consists of an electrochemical interface (ECI), frequency response analyzer (FRA), personal computer and the solar cell whose ac parameters are to be measured.

The electrochemical interface (Solartron, model No. 1286) is a potentiostat used to set the dc bias voltage and to apply a signal voltage to the cell under test. The current flow is between "CE" and "WE" but the set voltage is maintained between "RE1" and "RE2" as shown in Fig. 2. The set dc bias and the ac voltage are also measured between RE1 and RE2. Hence, the magnitude and phase errors due to resistance and inductance of the connecting leads are eliminated. The input impedance between RE1 and RE2 is very

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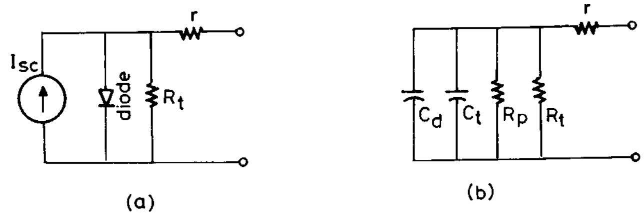

FIG. 1. (a) dc equivalent circuit of a solar cell; (b) ac equivalent of a solar cell.

high (>10 GΩ). Thus, the current that flows through the reference electrodes is negligible. The voltage (dc and ac) between RE1 and RE2 is measured with a five and a half digit digital voltmeter to an accuracy of ±0.05% and the current in the cell is measured by a zero impedance ammeter. The latter measures current by measuring the voltage drop across a feedback resistance, whose value can be set between 0.1 Ω and 10 kΩ depending on the current in the cell. However, analog voltages proportional to the voltage between RE1 and RE2 and the current in the cell are outputted by the instrument for processing by an external instrument. The ac excitation signal from an external source (the FRA) is superimposed on the dc voltage between CE and WE through a summing amplifier. The ac voltage however is measured between RE1 and RE2.

The frequency response analyzer (Solartron, model No. 1250) generates an excitation signal from 0.1 mV to 15 V [root mean square (rms)] in the frequency range of 10 μHz to 65 kHz, which is applied to the cell under test through the ECI. The signal generated has less than 1% distortion and the instrument sweeps the frequency between preset limits in equal logarithmic or linear steps. The signal analyzers (channels 1 and 2) measure both in-phase and quadrature components of the voltages applied to channels 1 and 2 simultaneously. The signals are divided into 104 equally spaced intervals over one full wave. Instantaneous measurements of the signals are made at each of the 104 points by a digital volmeter and each of these measurements is time tagged and stored in a random access memory for further computation. From the data stored in the memory, the FRA calculates the in-phase and quadrature components of the voltages by numerical integration.

$$V_{(\text{in phase})}=\frac{2}{T}\int_0^T V(t)\sin\omega t\,dt, \qquad (1)$$

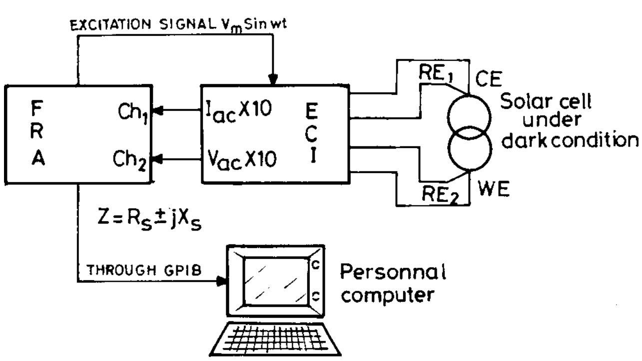

FIG. 2. Experimental setup to measure ac parameters of a solar cell.

$$V_{(\text{quadrature})}=\frac{2}{T}\int_0^T V(t)\cos\omega t\,dt, \qquad (2)$$

where T is the period of the applied signal.

The FRA calculates the complex ratio of voltages between channels 1 and 2 in polar or rectangular form. The present setup gives the impedance of the solar cell, since channel 1 measures the voltage and channel 2 measures the current.

The following precautions have been taken to reduce the noise in the setup.

(i) In this setup the measurement of ac parameters of a solar cell is carried out at different cell voltages with an external bias under the dark condition. Since the solar cell is a nonlinear device, the applied signal amplitude should be less than the thermal voltage (V_T). To ensure that the response of the system is linear piecewise to good approximation, the amplitude of the excitation signal of 10 mV (rms) is selected. The shield cables are used in the setup to reduce noise from the environment. Further, the signal to noise ratio is improved by keeping the signal amplitude 10 times higher than the excitation signal during generation and transmission between the FRA and ECI and vice versa.

(ii) Four-wire measurement is employed to eliminate errors due to lead resistance and inductance.

(iii) Since the cell voltage and current contain ac and dc components, bias compensation is applied to filter the dc component, which reduces the error.

(iv) The excitation signal is applied and the measurements are carried out after the system attains steady state.

(v) The measurements made for five cycles are averaged. The FRA considers this value only when the running average of last three measurements is within 1%.

(vi) The response of the solar cell may contain harmonics of the excitation voltage in its current due to its non-

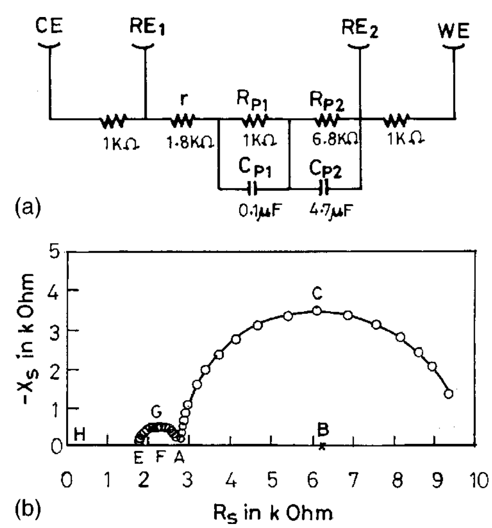

FIG. 3. (a) Electrical network; (b) impedance spectrum of the electrical network.

TABLE I. Calculated values of R_{p2}, X_{p2}, and C_{p2} for different frequencies.

Frequency, f (Hz)	R_{p2} (kΩ)	X_{p2} (kΩ)	C_{p2} (μF)
5.08	6.80	6.80	4.61
3.98	6.76	8.42	4.74
6.31	6.79	5.33	4.73

linearity. These harmonics are removed during the measurement by integrating the response over a complete cycle.

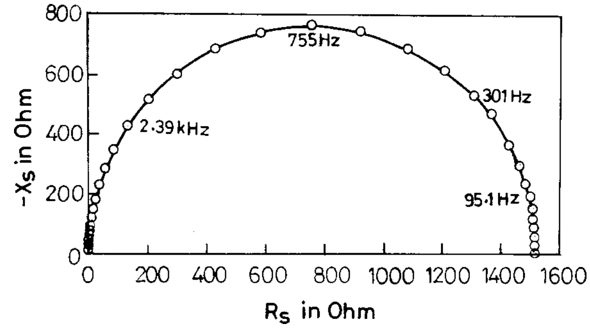

FIG. 4. Impedance spectrum of a BSR silicon solar cell at 0.2 V.

IV. CALIBRATION OF THE EXPERIMENTAL SETUP

The experiment setup shown in Fig. 2 is calibrated using an electrical network with passive components as shown in Fig. 3(a). The ac signal of 10 mV (rms) with varying frequencies (1 Hz–10 kHz) is applied along with a dc bias voltage of 1 V. The real and imaginary impedance parts of the network are measured in the form of series equivalent impedance (R_s and X_s) at frequencies ranging from 1 Hz to 10 kHz with 10 steps per decade.[1] Figure 3(b) shows an impedance spectrum of the network drawn using the series equivalent impedance. For convenience, the positive Y axis is considered as the negative imaginary impedance. The impedance spectrum consists of two semicircles with an offset from the origin. This indicates the existing of series resistance (r). The two semicircles are in the fourth quadrant, indicating the existence of two parallel *RC* networks connected in series. The two semicircles are clearly separate. This indicates that the time constants of the two *RC* networks are quite apart. For the larger semicircle the first set of *RC* circuit parameters is calculated. At point '*C*' the magnitude of the imaginary (Z) is equal to the magnitude of the real (Z), i.e., $|X_{s2}|=R_{s2}$, where the line *CB* represents X_{s2} and $AB(HB-HA)$ represents R_{s2}. From the impedance spectrum the value of R_{s2} is 3.35 kΩ and X_{s2} is 3.40 kΩ. At this X_{s2} the corresponding value of signal frequency f_2 is 5.08 Hz.[1] The R_{s2} and X_{s2} are series equivalent circuit parameters of the network. Using the equation for converting series equivalent values into parallel circuit parameters[3] their values are $R_{p2}=6.80\,\mathrm{k}\Omega$ and $X_{p2}=6.80\,\mathrm{k}\Omega$. From this parallel reactance X_{p2}, the parallel capacitance C_{p2} is 4.16 μF at frequency of 5.08 Hz.

In a similar way for different frequencies the values of series equivalent impedance are taken from the measured data and the corresponding values of R_{p2}, X_{p2} and C_{p2} are calculated. These values are shown in Table I. For better accuracy, the above calculations are done around the maximum value of reactance X_{p2}. The average values of R_{p2} and C_{p2} are 6.78 Ω and 4.69 μF, respectively.

The second set of *RC* circuit parameters is calculated similar to the smaller semicircle. The line "*EF*" gives the real (Z) equal to $R_{s1}=0.51\,\mathrm{k}\Omega$ and line *GF* gives the magnitude of imaginary (Z) equal to $X_{s1}=0.52\,\mathrm{k}\Omega$ at signal frequency of $f_1=1584.90$ Hz.[1] From the series equivalent circuit parameters, the parallel circuit elements are calculated as $R_{p1}=1.04\,\mathrm{k}\Omega$, $X_{p1}=1.03\,\mathrm{k}\Omega$ and $C_{p1}=0.097\,\mu$F. The offset from the origin (line *HE*) gives the value of the series resistance ($r=1.8\,\mathrm{k}\Omega$) from the impedance spectrum. The measured values are compared with the actual network values in Table II.

TABLE II. Comparison between the measured and the actual values of circuit parameters.

Circuit parameters/ elements	Actual value	Measured value	Error (%)
Series resistance, r	1.8 kΩ	1.8 kΩ	0
Parallel resistance, R_{p1}	1 kΩ	1.04 kΩ	−4
Parallel resistance, R_{p2}	6.8 kΩ	6.78 kΩ	0.29
Parallel capacitance, C_{p1}	0.1 μF	0.097 μF	3
Parallel capacitance, C_{p2}	4.7 μF	4.69 μF	0.21

V. MEASUREMENTS ON SOLAR CELLS

The measurements were carried out on BSR and BSFR silicon solar cells, with resistivity of 2 and 10 Ω cm, respectively, and GaAs/Ge solar cells at cell temperature of 22 ±1 °C under the dark condition.[1] The beginning of life (BOL) efficiency of the silicon BSR solar cell is 12.75%, that of the silicon BSFR solar cell is 14.3% and that of the GaAs/Ge solar cell is 18.5%. The size of each solar cell is

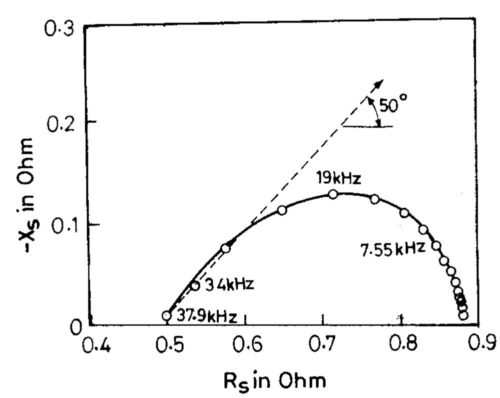

FIG. 5. Impedance spectrum of a BSR silicon solar cell at 0.5 V.

TABLE III. BSR silicon solar cell ac parameters.

Cell voltage (V)	Cell current (A)	Cell capacitance, C_p (μF)	Cell dynamic resistance, R_p (Ω)	Series resistance, r (Ω)
0.2	43 μ	0.13	1542	⋯
0.3	175 μ	0.15	399	⋯
0.4	1.29 m	0.33	27	⋯
0.45	5.01 m	1.71	3.4	1.65
0.5	30.7 m	28.14	0.3	0.56

TABLE IV. BSFR silicon solar cell ac parameters.

Cell voltage (V)	Cell current (A)	Cell capacitance, C_p (μF)	Cell dynamic resistance, R_p (Ω)	Series resistance, r (Ω)
0.2	34 μ	0.13	2018	⋯
0.3	146 μ	0.16	438	⋯
0.4	0.78 m	0.47	49.4	⋯
0.45	2.4 m	2.54	12.3	⋯
0.5	9.4 m	16.6	2.9	0.29
0.55	40.6 m	98	0.6	0.08
0.6	⋯	450	0.1	0.05

20 mm×40 mm. The amplitude of the excitation (ac) signal is kept at 10 mV (rms) and its frequency is varied from 1 Hz to 60 kHz, with 10 points per decades (distributed equally on a log scale). In this article, only details of measurements on the BSR silicon solar cell are presented. Typical data collected on the silicon BSR solar cell for cell voltages of 0.2 and 0.5 V are shown in Figs. 4 and 5, respectively. The impedance spectrum at cell voltage of 0.2 V is nearly a semicircle, indicating the predominance of a single time constant. The semicircle is touching the origin; this indicates that the series resistance is very small compared with the impedance of the solar cell. The cell capacitance (C_p) and the cell dynamic resistance (R_p) are calculated around points where the imaginary component (X_s) is maximum and the average values are determined. As mentioned earlier this helps in calculating the values of C_p and R_p with better accuracy. But at 0.5 V the impedance spectrum shown in Fig. 5 is not a perfect semicircle at frequencies below 19 kHz, the impedance spectrum is very close to the semicircle and at frequencies greater than 19 kHz tends to deviate from the semicircle. This deviation can be attributed to variation of C_p and R_p with frequency at a cell bias voltage of 0.5 V.[1] That the impedance spectrum is shifted along the positive real axis away from the origin indicates the existence of series resistance. At cell voltage of 0.5 V, the series resistance (0.56 Ω) is comparable with its impedance value (0.7 Ω).

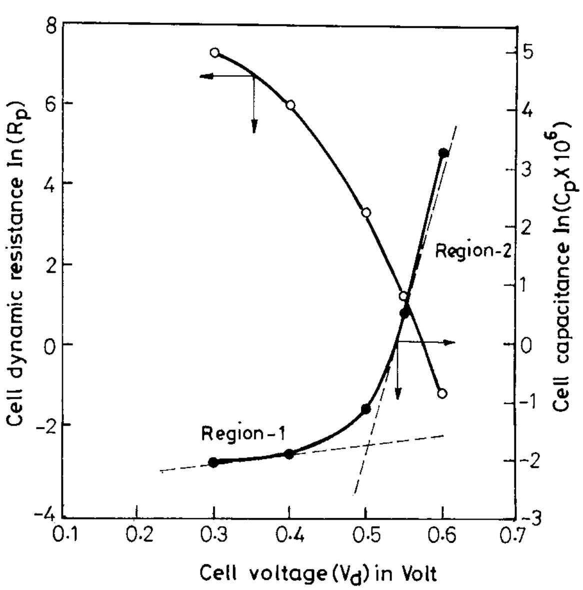

FIG. 6. Variation of C_p and R_p with the cell voltage of a BSR silicon solar cell.

Similarly, the average values of C_p, R_p and r at different cell voltages (V_d) are calculated from measured data. They are shown in Table III. The solar cell capacitance (C_p) increases from 0.13 to 28.14 μF and the dynamic resistance (R_p) decreases from 1542 to 0.3 Ω when the cell voltage is varied from 0.2 to 0.5 V. The series resistance (r) is comparable to the impedance at cell voltages 0.45 and 0.5 V. C_p and R_p are functions of frequency at 0.5 V. The variation in cell capacitance C_p and R_p from the 0.2 (near short circuit) to the 0.5 V (open circuit) condition is quite large. Hence a graph between $\ln(C_p)$ and $\ln(R_p)$ versus cell voltage is plotted and shown in Fig. 6. The capacitance plot has two regions (1 and 2). It has been found mathematically[3] the capacitance in region 1 follows

$$C_t = \frac{B}{(V_0 - V_d)^{1/2}}, \tag{3}$$

where C_t is the transition capacitance, B is a constant, V_0 is the junction voltage, and V_d is the cell voltage.

Hence the capacitance in region 1 is attributed to the transition capacitance. It has been found mathematically that the diffusion capacitance depends exponentially on the cell voltage.[3] Region 2 has a very large slope and is linear on a log scale. Hence it is attributed to the diffusion capacitance. In order to monitor the reliability of the experimental setup another solar cell (from the same source) is subjected to similar measurements. Its parameter values are found within the measurement error. Tables IV and V show the ac param-

TABLE V. GaAs/Ge solar cell ac parameters.

Cell voltage (V)	Cell current (A)	Cell capacitance, C_p (μF)	Cell dynamic resistance, R_p (Ω)	Series resistance, r (Ω)
0.3	2.0 μ	1.13	43 800	⋯
0.4	6.5 μ	1.18	14 570	⋯
0.5	17.3 μ	1.26	5116	⋯
0.5	60 μ	1.34	1310	⋯
0.7	0.24 m	1.44	282	⋯
0.8	1.2 m	1.57	52	⋯
0.87	4.06 m	1.71	12.5	⋯
0.9	7.09 m	1.86	6.4	0.4
0.95	23.43 m	2.45	1.2	0.3

eters of the BSFR silicon and GaAs/Ge solar cell, respectively.

The impedance spectroscopy technique is quite accurate for measuring a wide range of impedance of a nonlinear device (solar cell), because the impedance is taken when $1/\omega C_p \simeq R_p$. The solar cell ac parameters C_p (C_t and C_d), R_p, r and also the effect of frequency on C_p and R_p at different cell voltages can be estimated only with this technique. These parameters enable the design of a charge controller for photovoltaic applications.

ACKNOWLEDGMENTS

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