B. Electrochem 4(3) March 1988, pp 281-285

ELECTROCHEMICAL MATERIALS SCIENCE

COMPUTER-AIDED CHARACTERIZATION OF SOLAR CELL FROM A SINGLE ILLUMINATED CURRENT (I)-VOLTAGE (V) CURVE

M JAYACHANDRAN, SP MANOHARAN and MARY JULIANA CHOCKALINGAM
Central Electrochemical Research Institute, Karaikudi-623 006, INDIA

[Received 1987 October 28; Accepted: 1988 January]

A computer aided characterization technique has been proposed to calculate the five parameters of a solar cell represented by one diode model. The nonlinear I-V relation is linearized by Taylor series expansion. The cell parameters I_{ph}, I_s, A, R_s and R_{sh} are obtained by solving five analytical expressions simultaneously. The influence of fixing the values to these parameters on the I-V characteristics has been studied.

Key words: Solar cell, characterization, computer aided

INTRODUCTION

In the area of data analysis of solar cells a number of authors have investigated the current (I)-voltage (V) characteristics using various iterative methods and different assumptions. The I-V relation of a solar cell is described by an implicity function and is nonlinear in its parameters. The determination of these parameters is important for the following reasons: (1) the I-V equation is used to optimize the design aspects of solar cells and (2) the parameter values are important for evaluation of the solar cell in research, development and production.

The calculation of the cell parameters could be accomplished either by using a few points selected from the experimental I-V characteristics or by considering all the points. A single I-V characateristic has been used for determining four parameters [1] neglecting the shunt resistance. A modified Gauss-Newton method [2] was used for the optimization procedure to determine the solar cell parameters. Nineteen points of the I-V curve were used for fitting in which five parameter equation was transformed into three parameter equation [3]. A numerical solution [4] has been proposed which employs only three selected points from the I-V characteristics.

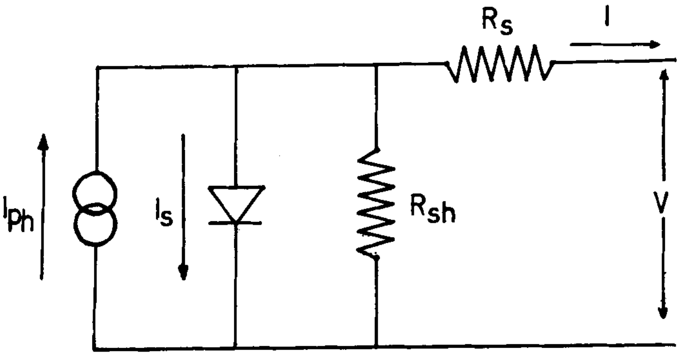

Fig. 1: Equivalent circuit of the one diode model of an illuminated solar cell

Here, we consider a five-parameter I-V equation and present a simple approach in which the nonlinear equation is linearized by Taylor series expansion. Partial derivatives of the analytical expression are used to construct the 5 x 5 matrix to solve the five parameters simultaneously and iterations are performed to obtain the best fit.

The five parameter model of the solar cell equation

In most cases the I-V characteristics of an illuminated solar cell can be described by the lumped parameter equivalent circuit as in Fig.1. The photocurrent I_{ph} is delivered by the solar cell under illumination which flows in the diode impedance I_s, the shunt resistance R_{sh}, the series resistance R_s. For a given intensity of incident light, the voltage (V) produced and the current (I) delivered are given by the equation

$$I = I_s \left[\exp \frac{B}{A}(V - IR_s) - 1\right] + \frac{V - IR_s}{R_{sh}} - I_{ph} \quad \dots (1)$$

where $B = \frac{q}{KT}$

which is implicit, nonlinear and analytically non-solvable. 'A' is the diode quality factor.

The typical I-V behaviour of a solar cell is shown in Fig.2. The open circuit voltage V_{oc} is obtained from the intercept of the curve with voltage axis and the short circuit current I_{sc} is from the intercept with current axis. The series resistance R_s and the shunt resistance R_{sh} are given by the slope of the curve at $V = V_{oc}$ ($I = 0$) and $I = I_{sc}$ ($V = 0$) respectively. V_{mp} and I_{mp} are the experimental values of the voltage and current at the maximum power point.

EXPERIMENTAL SET UP

A silicon solar cell of area 0.12 cm^2 was used for the I-V measurement. The measurements were carried out with a high precision rotating potentiometer. Light from a 24 V (250W) ORIEL quartz tungsten- halogen lamp was passed through a water filter and used to illuminate the cell with Air mass 1.5 condition (75mW/cm_2). Over the whole range of the I-V curve 20 points were used to give corresponding values of load current and load voltage. These values can be analysed using any micro computer by the proposed method.

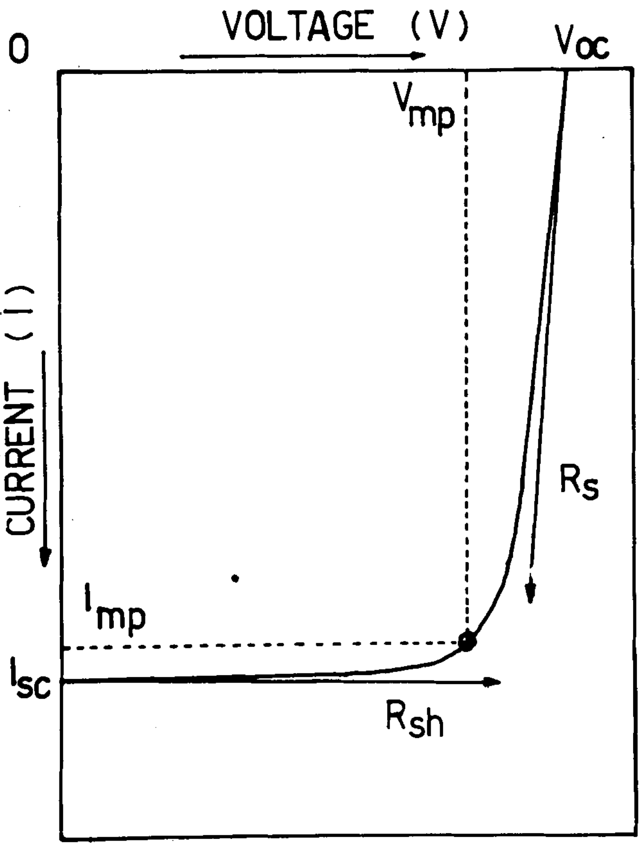

Fig.2: A typical I-V curve showing the various parameters of the solar cell

Nonlinear least squares fit procedure

In general, a set of N measurements (I_i, V_i), where i = 1,2 .... N, can be simulated with a function of the independent variable V and a set of parameters $a_1, a_2 \ldots a_n$). The form of this function I (V, $a_1, a_2 \ldots a_n$) depends on the physical model used to explain the observed experimental data. The best fit of this function is found through minimizing the sum of the weighted squares of the differences between the experimental and the simulated data sets which can be expressed as

$$\phi = \sum_{i=1}^{N} W_i \, [I_i \exp - I\,(V_i, a_1, \ldots a_M)]^2 \quad (2)$$

When the function I (V_i, $a_1 \ldots a_M$) is linear in the parameters a_M, this can be done by setting the partial derivatives of ϕ equal to zero (i.e.) $\frac{\partial \phi}{\partial a_m} = 0$. The resulting M simultaneous equations can then be solved and the parameters can be uniquely evaluated.

For the nonlinear functions, the best fit is obtained through any one of the two approaches: (1) the function may be expanded as a "Taylor Series" and correction to the several parameters are carried out at each iteration on the assumption of local linearity and (2) various modified forms of steepest descend [5] method may be used whose usage is restricted by the nonconvergence of some parameters under required conditions.

Following Marquardt's model [6] based on Taylor series expansion, the nonlinear function I (V, $a_1 \ldots a_M$) is linearized by expanding into a Taylor series around a set of starting values $a_M°$ and neglecting the higher order terms expressed as

$$I\,(V, a_1, \ldots a_M) = I\,(V, a_1^{\circ}, \ldots a_M^{\circ}) + \sum_{m=1}^{M} \frac{\partial I(V, a_1, \ldots a_M)}{\partial a_M} \times \partial a_m \quad \ldots\ldots (3)$$

Substituting equation (3) in equation (2) and setting $\frac{\partial \phi}{\partial a_m} = 0$, we obtain a set of M simultaneous equations in δa. In matrix form

$$\alpha_{mk} \quad \delta a = \beta_K \quad \ldots (4)$$

where

$$\alpha_{mk} = \sum_{i=1}^{N} W_i \frac{\partial I(V_i, a_1, \ldots a_M)}{\partial a_m} \cdot \frac{\partial I}{\partial a_k} (V_i, a_1, \ldots a_M \quad \ldots\ldots (5)$$

which is a 5 x 5 matrix to be used to represent the five parameters of the I- V relation as $a_1 = I_{ph}$, $a_2 = I_s$, $a_3 = R_s$, $a_4 = G_{sh}$ and $a_5 = A$

and

$$\beta_k = \sum_{i=1}^{N} W_i \, [I_{i\exp} - I(V_i, a_1, \ldots a_M)] \cdot \frac{\partial I}{\partial a_k} (V_i, a_1, \ldots a_M) \quad \ldots (6)$$

which is a 1 x 5 matrix and all the derivatives are taken in the point $a_1°, a_2° \ldots a_M°$

The parameters δa_m can be found, by multiplying both sides of equation (4) with the inverse matrix of $\alpha, \eta = \alpha^{-1}$. Then δa_m are found from

$$\delta_{am} = \sum_{K=1}^{m} \eta_{mk} \, \beta_k \quad \ldots (7)$$

As the higher order terms in the Taylor expansion have been ignored, this is only an approximate solution. Hence, these δa_m values are used to construct a new, and better set of starting values for $a_M°$ by setting

$$a_m^1 = a_m^0 + \delta a_m, \; m = 1, 2, \ldots M \quad \ldots (8)$$

The partial derivatives of the fitting function in equations (5) and (6) are numerically obtained by changing one parameter at a time by a small amount Δa_m in both positive and negative directions as given by

$$\frac{\delta I(V,a_1,a_2 \ldots a_M)}{\delta a_m} = \frac{I(V,a_m + \Delta a_m) - I(V,a_m - \Delta a_m)}{2\Delta a_m} \quad \ldots (9)$$

The disadvantage of this numerical partial differentiation method is that the fitting function has to be evaluated 2M times in order to obtain a set of M partial derivatives. Besides, if the derivatives become very small relative to I (V, a_m) the rounding off errors in the computation become more pronounced.

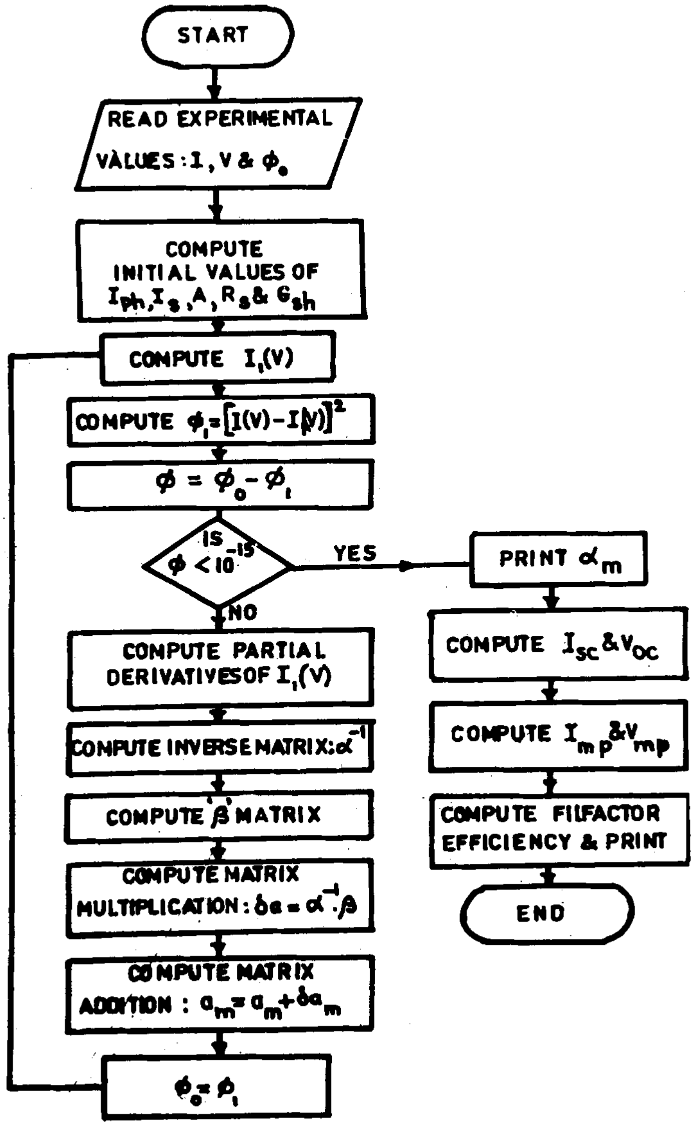

Fig.3: Flow chart of the program

To overcome the disadvantages of this numerical step, the partial derivatives of the I-V relation (1) are derived analytically and used to construct the α and β matrices. It is explicit that usage of these analytical derivatives in the curve fitting procedure gives precise solutions and saves expensive computation time.

Description of the computer program

The program for non linear curve fitting has been developed in BASIC language. Any mini/micro computer can be used. The flow chart of the routine is presented in Fig.3. The programming has been done in such a way that the starting values of the parameters $a_m°$ are calculated by the computer itself as described below:

Assuming $R_s << \frac{1}{G_{sh}}$ and from equation (1) it can be derived that

$$\ldots \quad \left[\frac{\delta I}{\delta V}\right]_{I = I_{sc}} = -G_{sh} \quad \ldots (10)$$

which is nothing but the slope of the I-V curve at V = 0 and the value is the starting point for G_{sh}. The intercept of the line, joining the points around V = 0, with the current axis gives the initial value for I_{ph}.

The slope of the I-V curve at I = 0 has been taken as the starting value for R_s. V_{oc} is estimated from the experimental value of V at I = 0. Since the parameter A is appearing in exponential function, a slight variation in 'A' will result in a large variation in the shape of the simulated curve. Hence the starting values are calculated at a certain fixed value of A (between 1 and 2). Then I_s was computed from the equation

$$I_s = \frac{I_{ph}}{\exp(\frac{b}{A}V_{oc})} \quad \ldots (11)$$

These initial values of the parameters I_{Ph}, I_s, A, R_s and G_{sh} are used to initiate the program and the current values corresponding to the voltage values selected from all over the I-V curve are computed. This is stored as $I_1(V)$ and the partial derivatives of I_1 with respect to the five parameters are executed to solve α and β matrices. Inverse of α matrix is computed and the error value δ a is estimated. New values of a_m are determined using δa_m and the new ϕ value is computed. The difference in consecutive ϕ values are estimated to obtain the best fit. If the difference is less than 10^{-20}, the values of the five parameters, corresponding to the best fit, are printed out together with the simulated current values. These values are substituted in equation (1) to simulate the I-V values which are compared with the experimental values for error computation. Then V_{oc} and I_{sc} are computed by setting I = 0 and V = 0 in simulated equation.

The maximum power (P_{mp}) point is estimated by searching for the maximum in the V vs IV product from both the measured and simulated values and compared. The I_{mp} and V_{mp} corresponding to this maximum power point are printed out.

Finally, the fill factor (FF), defined as

$$FF = \frac{P_{mp}}{V_{oc} I_{sc}} \quad \ldots (12)$$

and the efficiency

$$\eta = \frac{100 \times P_{mp}}{\text{Area} \times \text{Input power}} \quad \text{... (13)}$$

are computed and printed.

RESULTS AND DISCUSSION

Since five parameters are involved, investigation of the uniqueness and errors in the values found are fixed by the minimum value of ϕ and the corresponding 'A' value. Fig.4 shows the variation of ϕ with different 'A' values which predicts a minimum point at A = 1.28. Fig.5 a,b,c,d show the percentage error

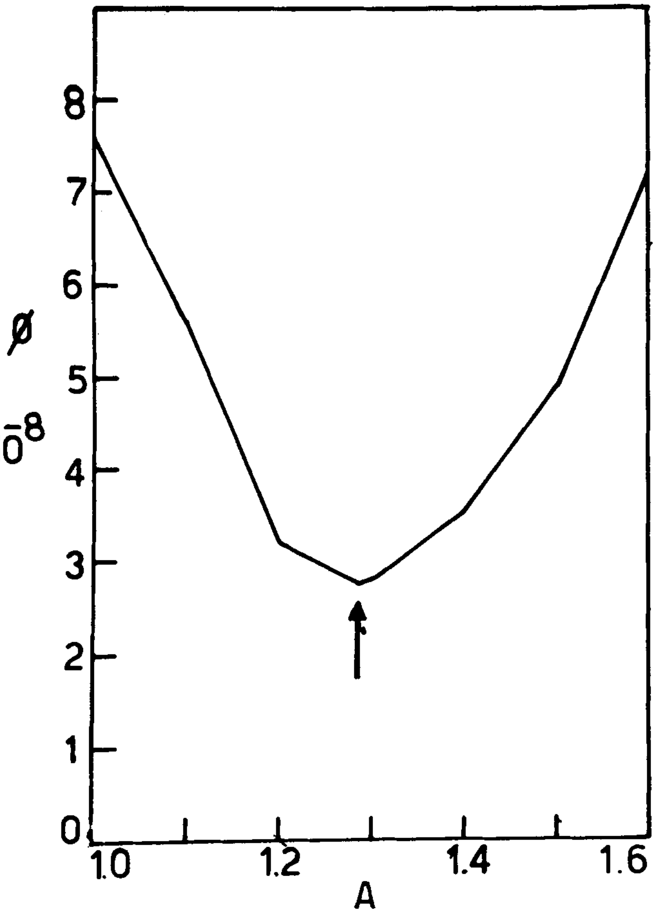

Fig.4: Variation of the minimum error function 'ϕ' with different diode quality factors 'A'

in the computed current values for A = 1.0, 1.28, 1.5 and 2.0 respectively. The best fit is obtained for A = 1.28 which is evident from the uniform distribution of the percentage error points about the zero axis and the relatively minimum percentage error as shown in Fig.5.b. For other values of A, percentage error is large and distribution of error points are rather nonuniform.

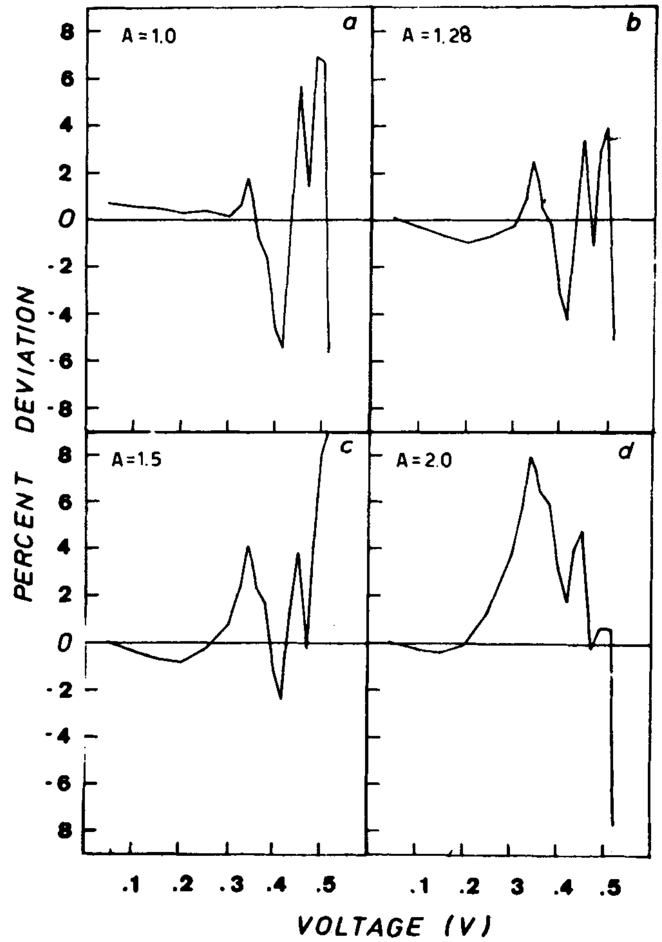

Fig.5: Percentage deviation of the calculated current values from the experimental values for various 'A' values: (a) A = 1 (b) A = 1.28 (c) A = 1.5 and (d) A = 2.0

Once all the parameter values I_{ph}, I_S, R_s, R_{sh} and A are computed, they are substituted into the equation (1) and the current values for a given voltage are computed. The computed parameter values are given in Table I and compared with the experimental values. Fig.6.a is the experimental curve and 6.b is the curve obtained from the best computer fit with A = 1.28. Both curves coincide very well revealing the reliability of this computer characterization technique.

The importance of fixing the parameter values R_s, R_{sh} and A in characterizing a solar cell are studied. Keeping A = 1.28 and making R_s = G_{sh} = 0, the I-V curve 6.c is obtained. It shows

TABLE I

	Experimental	Computer fit
I_{ph} (mA)	---	3.18
I_s (A)	---	5.46 x 10^{-10}
A	---	1.28
R_s (Ω)	---	3.5
R_{sh} (Ω)	---	9.64 x 10^4
V_{oc}(V)	0.520	0.523
I_{sc}(mA)	3.170	3.174
η (%)	11.1	10.9
I_{mp}(mA)	2.88	2.74
V_{mp}(V)	0.348	0.36

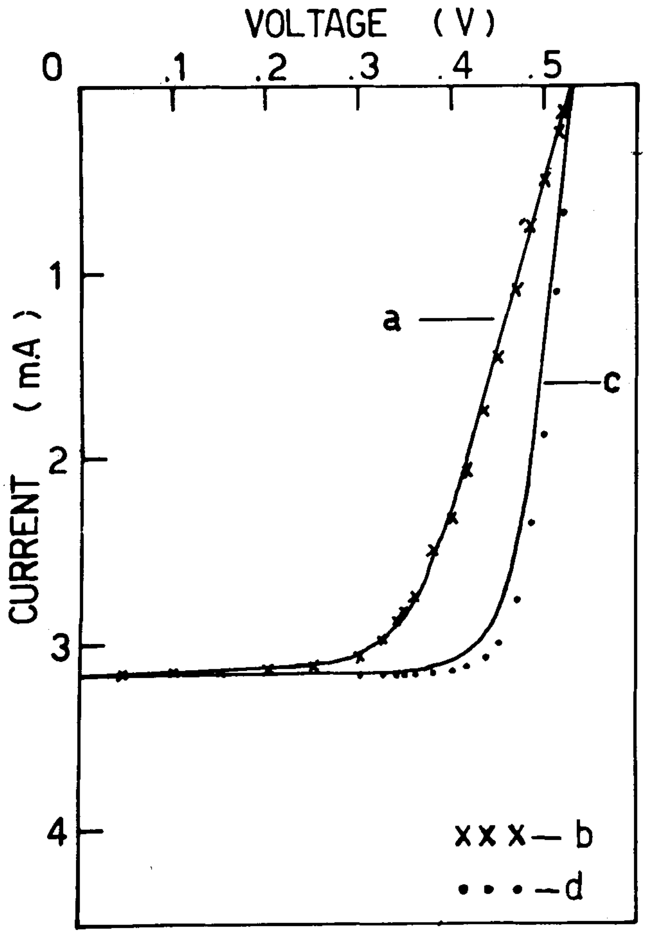

Fig.6: Different I-V characteristics: (a) experimental curve (b) calculated best fit I-V curve (c) curve with A = 1.28 and R_s = G_{sh} = 0 (d) curve with A = 1 and R_s = G_{sh} = 0

a large deviation at the maximum power point and at high voltage region of the curve compared to curves 6.a and 6.b. When the conditions for an ideal solar cell is imposed with A = 1, R_s = G_{sh} = 0, the resulting curve 6.d deviates more at the maximum power point than for all other curves. It emphasises that one should not neglect any of these parameters under some assumption in characterising the solar cells.

CONCLUSION

This computed aid characterisation makes use of the experimental data taken at 20 points from all over the I-V curve. The salient feature of this program is that the minimum error function ϕ is connected with the diode quality factor A. Since 'A' takes into account the relative influence of the depletion region recombination and the diffusion components of the current, unique fixation of 'A' by the minimum value of ϕ gives the best fit to the experimental values.

The porgram is written in BASIC language. This has the advantage that it can be implanted in a micro-computer which performs both an automatic acquisition of the I-V data using suitable electronic interface [7] and an on line characterization to study the performance of a solar cell under field conditions.

REFERENCES

1 W T Picciano, *Energy Conversion,* **9** (1969) 1

2 F J Bryant and R W Glew, *Energy Conversion,* **14** (1975) 129

3 A Braunstein, J Bany and J Appelbaum, *Energy Conversion,* **17** (1977) 1

4 J P Charles, M Abdelkrim, Y H Muoy and P Mialhe, *Solar Cells,* 4 (1981) 169

5 D R Hartree, *Numerical Analysis,* Oxford University Press - London (1958)

6 D W Marquardt, *J Soc Indust Appl Math,* **11** (1963) 431

7 L Castaner, A Alabau, M Sanchez-Monell, J Cabestany and A J Ventosa, *IEEE Trans Instrumentation and Measurement.* **27** (1978) 152