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SIMULATION OF THE I - V CHARACTERISTICS FOR SOLAR CELLS

R. S. MOMTAZ
Department of Physics and Mathematics , Fac. of Engineering , Suez Canal University. Port said -Egypt

ABSTRACT

A new model for the characteristic calculations using the two-exponential model has been implemented by using experimental data. The determination of the cell equation parameters when all tested points are taken into consideration is accomplished by applying the least-squares method. Commercial solar cells were measured and their parameters were calculated for the diode factors $m_1=1$ and $m_2=2$. Series resistance values obtained experimentally from measurments of the dynamic resistance are used. After a set of itteration ,the parameters corresponding tothe minimum value of deviation are chosen as those charecterising the solar cell.

INTRODUCTION.

The equivalent circuit of a solar cell permits describing the physical behaviour of this cell and its characteristics. The measured characteristic of a solar cell can be approximated through different mathematical functions. The physical relations derivated by Shockly [1] for an ideal p-n junction are the fundamentals of a very often used equivalent circuit for photovoltaic solar cells, fig.1. The diode dark current I_D can be calculated by the following relation:

$$I_D = I_o \left[\exp(V/V_T) - 1\right] \quad (1)$$

where I_o is the saturation current

$$I_o = q\, v_e\, (n_p + p_n)\, A \quad (2)$$

and

q = electron charge
v_e = charge carrier velocity
n_p = charge carrier concentration (electrons in p conductor)
p_n = charge carrier concentration (holes in n conductor)
A = Area of the p-n junction
V = Applied voltage
V_T = the so called temperature tension $V_T = k\, T/q$
k = Boltzmann's constant
T = Absolute temperature.

Generally, semiconductor resistances can not be neglected. Hence, resistances of the cell can be represented as series resistance and leakage currents as parallel resistances. Although these resistances in a real solar cell appear destributed, they will be represented in the equivalent circuit as concentrated

Illuminating the p-n junction, an external load current I_L will flow :

$$I_L = I_{ph} - I_D \quad (3)$$

where I_{ph} is the generated photo-current.

Substituting eq.(1) in (3) and considering the voltage drop due to the series resistance R_S and the leakage current in the shunt resistance R_{sh} we obtain the following relation between the load current I_L and the load voltage V, i.e. the I-V characteristic of the solar cell:

$$I_L = I_{ph} - I_o[\exp(V+I_L R_S)/(m_1 V_T) - 1] - (V+I_L R_S)/R_{sh} \quad (4)$$

In this equation appears the diode factor m_1, which represents the non-linear performance of the p-n junction. This factor lies in the range of 1-2 [2]. However, there are measured values of it up to 4 [3]. Only very accurately produced solar cells of Germanium give, according to the Shockley model a performance of m_1=1 [4].

The determination of the parameters of a solar cell described by a single exponential equation has previously been attempted by analytic [5,6] and numerical methods [7], [8] and [9]. The single-exponential approach can be used for many design calculations of solar electrical systems. However, as the phenomena are considered globally in the single-exponential model, its parameters can lose their meanings because the parameters are related to physical phenomena. Therefore a simple and computationally efficient double-exponential model should be of interest.

Studies of Wolf and Rauschenbach [10] showed that the characteristic of a solar cell can conveniently be represented by an additional diode, fig.2. The dark current-voltage (I-V) characteristic can be then described by the equation considering the voltage drops due to the series resistance R_S :

$$I = -I_{o1}\{\exp[e(V-IR_s)/m_1kT] - 1\} - I_{o2}\{\exp[e(V-IR_s)/m_2kT]-1\} - (V-IR_s)/R_{sh} \quad (5)$$

where the parameters I_{o1},I_{o2},m_1,m_2,R_s and R_{sh} have their usual meanings described above. Thus, by illumination the eq.(4) can be modified into:

$$I_L = I_{ph}-I_{o1}\{\exp[e(V+I_LR_s)/m_1kT] -1\} - I_{o2}\{\exp[e(V+I_LR_s)/m_2kT] -1\} - (V+I_LR_s)/R_{sh} \quad (6)$$

A simple method for determining the parameters in eq. (6) from experimental data is important to predict the behaviour of the solar cell under illumination and under various working conditions e.g. various operating temperatures. The temperature dependances of the saturation currents I_{o1} and I_{o2} are given in [11] and [12] as follows:

$$I_{o1} \cong T^3\exp(-E_g/kT) \quad \text{and} \quad (7)$$

$$I_{o2} \cong T^{5/2}\exp(-E_g/2kT) \quad (8)$$

The band gap energy E_g of the semiconductor is again temperature dependent. In case of Silicon, values between -2.3×10^{-4} to -2.8×10^{-4} eV/^{o}K are registered for a middle band gap of E_g=1.15 eV at 273 ^{o}K. The currents I_{o1} and I_{o2} can be separated by measurements at different temperatures.

2. Experimental evaluation of the series resistance.

The determination of the series resistance R_s can be obtained through two characteristics by different illumination intesities [10]. The series resistance will be defined near the maximum power point. This procedure has been used here with the simplification that one of the two characteristics was measured in dark while the other by the desired illumination level. The diode dark characteristic gives according to eq.(5) for I_L=-I^* and V=V^*:

$$I^* = I_{o1}\{ \exp[e(V^*-I^* R_s)/m_1kT] - 1\} + I_{o2} \{ \exp[e(V^*-I^* R_s)/m_2kT] -1\} + (V^*-I^* R_s)/R_{sh} \quad (9)$$

The characteristic of the illuminated solar cell will be evaluated by the open circuit, i.e. I_L=0 and V=V_{oc}:

$$0 = I_{ph} - I_{o1}\{ \exp[eV_{oc}/m_1kT] - 1\}- I_{o2} \{ \exp[eV_{oc}/m_2kT] -1\} - V_{oc}/R_{sh} \quad (10)$$

Assuming a current $I^* = I_{ph}$, the comparison of eq (9) and (10) results in

$$[V_{oc}-(V^*-R_s I_{ph})] / R_{sh} = I_{o1}\exp(V_{oc}/m_1V_T) [\exp[(V^*-R_s I_{ph}-V_{oc})/m_1V_T] -1] + I_{o2}\exp(V_{oc}/m_2V_T) [\exp[(V^*-R_s I_{ph}-V_{oc})/m_2V_T] -1] \quad (11)$$

and this gives as solution

$$V_{oc} - (V^*- R_s I_{ph}) = 0 \quad (12)$$

which results in :

$$R_s = (V^* - V_{oc})/ I_{ph} \quad (13)$$

provided that for a certain photo-current I_{ph} the corresponding o.c. voltage V_{oc} and for a diode dark voltage V^* the corresponding current $I^* = I_{ph}$ are known. Fig.3 shows the evaluation of the series resistance for a 5x5 cm^2 polychrystalline Silicon solar cell. Fig.4 shows the dark characteristic of the solar cell. The diode factors, m_1 and m_2 can be evaluated using this representation so that the slopes of this curve at high and low currents are index for the factors m_1 and m_2 as shown in the figure..

3. Parameter determination from dark current-voltage measurements

As the current-voltage characteristic of a solar cell, eq.(5), is non-linear in its parameters, methods such as the modified Gauss-Newton technique should be used for its solution, [13] and [14]. The approach presented here for the determination of the cell parameters from experimental data is based on a least-squares standard deviation technique for linear functions, since we consider m_1,m_2 and R_s as constant parameters. With this assumption, eq.(5) is linear in its remaining parameters I_{o1},I_{o2} and R_{sh}, thus these parameters and the standard deviation can be calculated [15]. Thus

$$\sigma = \text{r.m.s.}(\Delta I / I_{meas})$$

$$= \left[(1/N) \sum_{i=1}^{i=N} \{ [I_{calc}(V_i) - I_{meas}(V_i)] / I_{meas}(V_i) \}^2 \right]^{1/2} \qquad (14)$$

After a matrix of σ values has been evaluated, the parameters corresponding to the minimum value of the standard deviation are chosen as those of the best fit.

For most practical cases the calculations can be simplified considerably assuming the m_1 exponential term generally according to

Shockley's diffusion theory equals to 1. Additionally, to a first approximation we can assume that $m_2=2$, corresponding to the Shockley-read-hall recombination currents in the junction space charge region. Finally, the vector $\sigma(R_s j)$ is calculated for a set of R_s values around a quickly estimated values according to eq.(13).

4. Method

Two kinds of commercial flat-plate solar cells of different manufacturers are used in this test. One is circular monochrystalline Si of 5 cm diameter and the other is polychystalline Si 5x5 cm^2 are used in the measurements in order to calculate the belonging parameters for each type. Calculated parameters for the best fit of the standard deviation for $m_1=1$ and $m_2=2$ are presented in Table1. Series resistance values obtained experimentally from measurements of the dynamic resistance are also included. It should be noted that there is a good agreement between the two sets of series resistance values.

The agreement is rather good when the temperature dependence is considered. For the solar cell type 1 a ratio $I_{o1}(50^oC) / I_{o1}(25^oC) =$ 6.6 is obtained, while a ratio of 7.0 is obtained if we consider a temperature dependence of the form $J_{o1} \cong T^3 \exp(-E_g/kT)$, as predicted by Shockley's diffusion theory.

For the I_{o2} component, however, the agreement is not so good. The ratio $I_{o2}(50^oC)/I_{o2}(25^oC)$ for the same cell is 2.4 if calculated from the values in Table1 and is 3.1 calculated from a dependence of the type $I_{o2} \cong T^{5/2} \exp(E_g/2kT)$ corresponding to a space charge recombination model. Furthermore, the fits between the measured I-V and the calculated I-V from the best fit parameters show some discrepancy in the low current region, as can be seen in Fig.2, precisely in the range where the I_{o2} term becomes dominant. All this can be interpreted as a failure of the mathematical model with $m_2 = 2$. In fact we realized that the fit improves for m_2 values greater than 2.

An examples for the approximated characteristic according to this technique is presented in fig.5. It shows the measured and calculated characteristics of a commercial PV generator consisting of 36 10x10 cm^2 monochrystalline Si solar cells in series under 100 $mWcm^{-2}$ illumination at AM1 The agreement between measured and calculated characteristics is very good. Generally in most of the cases a good approximation can be achieved using the ideal diode factors. It was possible for all examined cases to obtain a good approximation using the two-exponential representation.

5. Limits of the two-exponential representation.

The appearance of non-linear diode factors $m_1 = 1$ and $m_2 = 2$ verifys the fact that the two-exponential representation in fig.2 is actually only a useful approximation. In high currents cases, e.g. solar cells for concentration applications, it results a potential distribution in the semiconductor, [10],[16] and [17]. In ref. [16]iit results a potential distribution iit results a potential distribution in the semiconductor, [10],[16] and [17]. In ref. [16] some inner resistance componenets ofit results a potential distribution in the semiconductor, [10],[16] and [17]. In ref. [16] some inner resistance componenets ofit results a potential distribution in the semiconductor, [10],[16] and [17]. In ref. [16] some inner resistance componenets ofit results a potential distribution in the semiconductor, [10],[16] and [17]. In ref. [16] some inner resistance componeniit reing the distributed series resistance representation.

The mentioned aspects arise approximation problems so that even by the two-exponential representation non-ideal diode factors could appear. The physical procedures can be in such cases not perfectly described. Thus, the validity of the above described equivalent circuit should be case by case carefully examined.

5. Conclusions

The determination of the parameters of the two-exponential model of a solar cell from experimental data is possible using the least-squares standard deviation technique described in this paper.This procedure is closely related to the physical phenomena and suitable for simulation purposes.

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REFERENCES

1. W. Shockley, Electrons and Holes in Semiconductors, D.Van Nostrand Co.,Princeton (1950)
2. W. Bloss, Elektronische Energiewandler, Wissens.Verlag, Stuttgart (1968)
3. J. Hoval, Semiconductors and Semimetals, Solar Cells, Vol.11, Academic Press, New York (1975)

4. J. Loferski, An Introduction to the Physics of Solar Cells, Solar Cells, Outlook for Improved Efficiency, Ad Hoc Panel on Solar Cell Efficiency, Nat Res. Council, Nat. Acd. of Sciences, Washington (1972).
5. W.T. Picciano, Energy Convers., 9(1968)
6. R.T. Otterbein, D.L.Evans et.al., Proc. 13th PV Spec. Conf., Washington DC, June 5-8,1978, IEEE, p.1074
7. F.J.Bryant and R.W.Glew, Energy Convers., 14(1975) 129
8. A.Braunstein, J.Bany and J.Appelbaum, Energy Convers.17(1971)
9. M.A.Hamdy, Performance Analysis of Photovoltaic Systems Using Numerical Iterative Procedures, Advances in Energy Development and Environment, Cairo, Egypt, Oct. 1994, p.299-312
10. M. Wolf and H. Rauschenbach, Series Resistance Effects on Solar Cells Measurements, Adv. Energy Conv., Vol.3 (1963), p.455 Measurements, Adv. Energy Conv., Vol.3 (1963), p.455
11. R. Stirn, Measurements, Adv. Ene Measurements, Adv. Energy Conv., Vol.3 (1963), p.455
12. R. Stirn, Junction Characteristics of Sili Measurements, Adv. Energy Conv., Vol.3 (1963), p.455
13. R. Stirn, Junction Char Measurements, Adv. Energy Conv., Vol.3 (1 Measurements, Adv. Energy Conv., Vol.3 (1963), p.455
14. R. Stirn, Junction Characteristics of Silicon Solar Ce Measuremen Measurements, Adv. Energy Con Measurements, Adv. Energy Conv., Vol.3 (1963), p.455
15. R. Stirn, Measurements, Adv. Ene Analysis of the Series Resistance of a Solar Cell, Solid State Electr.,Vol. 10 (1967)
16. C. Fang, and J.Hauser, A Two-Dimensional Analysis of Sheet

Resistance and Contact Resistance Effects in Solar Cells, Proc. of the 13th PV Sp. Conf. (1978)

17. J. Mahan, and G.Smirnow, A New Perspective on Distributed Series Resistance Effects in Photovoltaic Devices, Proc. of the 14th PV Sp. Conf.(1980)

Table (1) : Results for the best fits of standard deviation with m_1=1and m_2 =2.

Cell Type	Area (cm^2)	T (^oC)	R_s (mΩ)	R_s (mΩ) calc.	I_{o1} (Acm^{-2}) meas.	I_{o2} (Acm^{-2}) $x10^{-12}$	R_{sh} (Ω) $x10^{-6}$	σ
mono	19.6	25	22	21	1.75	0.34	1442	0.101
	19.6	50	22	21	11.6	0.82	1402	0.125
poly	25	25	72	70	2.09	1.5	986	0.082
	25	50	72	70	10.81	2.1	965	0.103

FIGURE CAPTIONS

Fig.1. Common equivalent circuit for solar cells.

Fig.2. Two-exponential representation for solar cells.

Fig.3 Series resistance of a 5x5 cm^2 polychrystalline Si solar cell vs. photocurrent.

Fig.4 Diode I-V characteristic for a 5x5 cm^2 polychrystalline Si solar cell.

Fig.5 PV generator; measured and calculated characteristic.

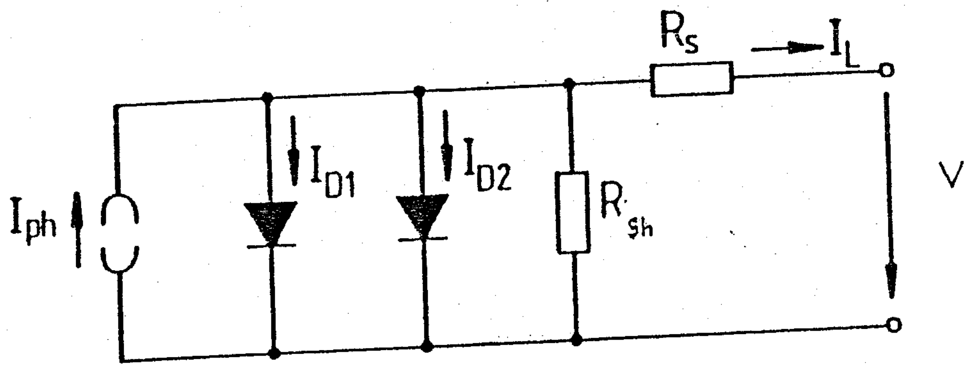
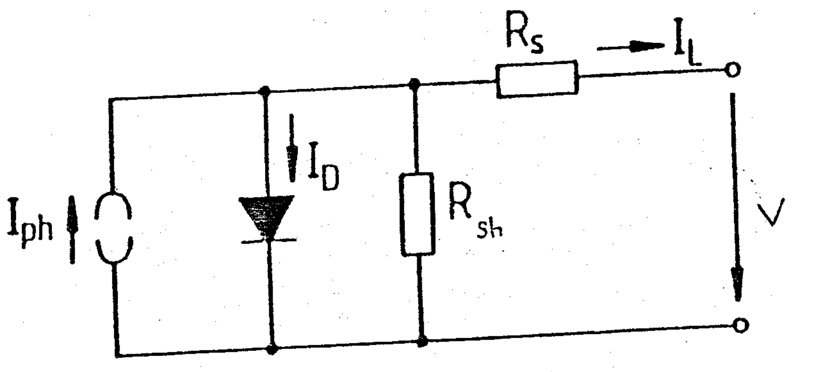
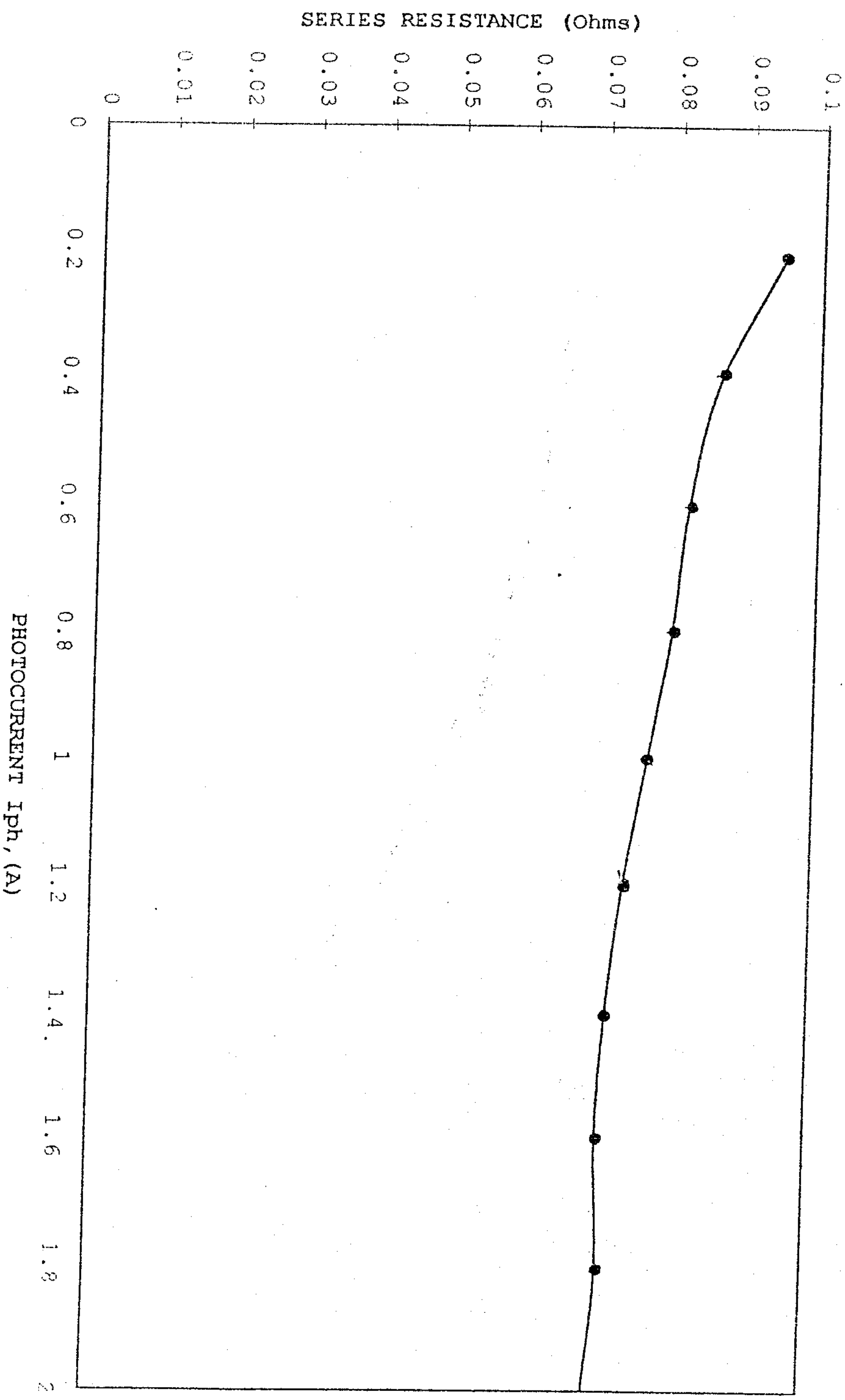


Fig-(1)




SERIES RESISTANCE (Ohms)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
PHOTOCURRENT Iph,(A)

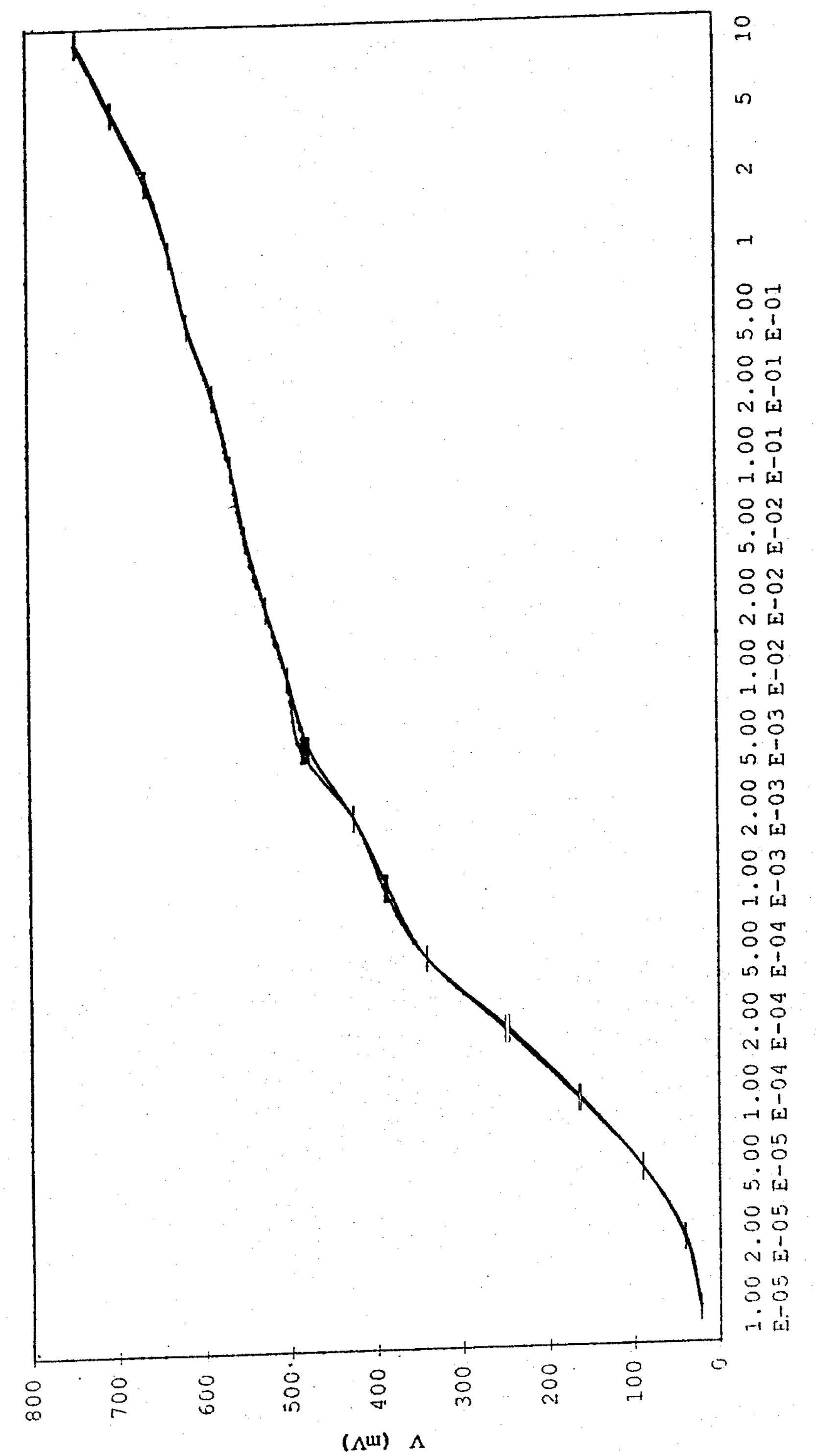

V (mV)
0
100
200
300
400
500
600
700
800
I (A)
1.00 E-05
2.00 E-05
5.00 E-05
1.00 E-04
2.00 E-04
5.00 E-04
1.00 E-03
2.00 E-03
5.00 E-03
1.00 E-02
2.00 E-02
5.00 E-02
1.00 E-01
2.00 E-01
5.00 E-01
1
2
5
10

Fig. (4)

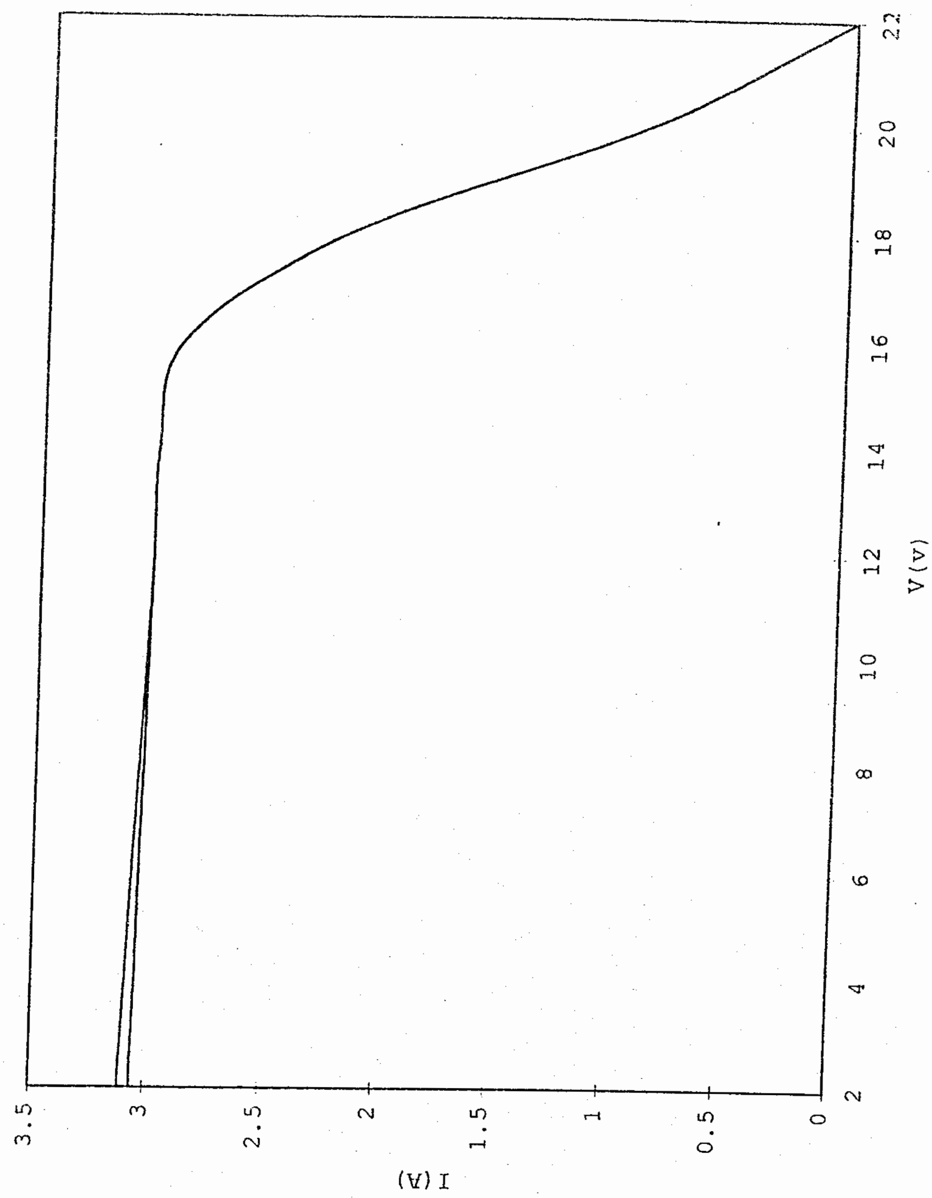


Fig.- (5)

محاكاة لمنحنيات الجهد – التيار المميز للخلايا الشمسية.

يتناول البحث وضع أ نموذج جديد لحساب المنحنيات المميزة للتيار – الجهد فى الخلايا الشمسية بإستخدام أ نموذج ثنائى الأس حيث تم تعيين معاملات معادلة الخلية بوضع $m_1 = 1$, $m_2 = 2$ وأخذ فى الإعتبار جميع نقاط الإختبار العملية حيث طبق عليها طريقة أقل المربعات للإنحراف القياسى.

وتتلخص الطريقة فى قياس خلايا شمسية تجارية لتعيين قيم المقاومة على التوالى وذلك عن طريق المقاومة الديناميكية لها ثم نجرى مجموعة من التقاربات لإختيار البارامترات المقابلة للقيم الصغرى للإنحراف كمميزات للخلية الشمسية. وكان نوعا الخلية المستخدم هى خلايا سيليكونية إحداهما إحادى البللورى بقطر ٥ سم والآخر مربع عديد التبلر طول ضلع الخلية ٥ سم وأظهرت القياسات تطابقا فى قيم المقاومة على التوالى.

وبهذه الطريقة فإنه يمكننا تعين معاملات النموذج ثنائى الأس للخلية الشمسية بالطريقة المذكورة حيث تكون هى أقرب ما يكون للظاهرة الطبيعية.