THE INTERACTIVE COMPUTER PROGRAM TO FIT I-V CURVES OF SOLAR CELLS

Tadeusz Zdanowicz

Institute of Electron Technology, Solar Lab
Technical University of Wrocław
ul. Janiszewskiego 11/17, 50-372 Wrocław, Poland

ABSTRACT: Computer program has been developed to fit illuminated I-V curves of solar cells. The main effort has been put to achieve reliable fit rather than the optimum speed. A concept of a new weight factor modifying an object function has been introduced. I-V curves of the cells fabricated and measured in different laboratories were analysed. Results are compared with other concepts of the object functions. It is shown that the best fit is achieved with the exponential weight which gives the best linearization of the I-V curves in respect to the parameters being calculated.

1. INTRODUCTION

I-V curve of any illuminated solar cell is commonly described by either of three theoretical diode models defined as follows:

SEM (Single Exponential Model):

\[ I = I_a - I_e \exp \left( \frac{V + I R_s}{A V_t} \right) - \frac{V + I R_s}{R_s} \]

DEM (Double Exponential Model):

\[ I = I_a - I_e \exp \left( \frac{V + I R_s}{V_t} \right) - \frac{\exp \left( \frac{V + I R_s}{2 V_t} \right) - 1}{V + I R_s} \]

VDEM (Variable Double Exponential Model):

\[ I = I_a - I_e \exp \left( \frac{V + I R_s}{V_t} \right) - \frac{\exp \left( \frac{V + I R_s}{A V_t} \right) - 1}{V + I R_s} \]

where the parameters to be found are \( I_p \) - generated photocurrent, \( R_s \) and \( R_{sh} \) - series and shunt resistance, respectively, \( I_{a1}, I_{a2} \) - saturation currents and \( A \) is diode ideality factor; \( V_t = k T / e \) where \( k, e \) and \( T \) have their usual meaning.

SEM and DEM models (nomenclature taken after Charles et al. [1]) require finding five independent parameters whereas in the case of VDEM there are six of them.

Double exponential model is most closely related to the physical phenomena in solar cells under low injection conditions. Usually \( A \) is chosen as equal 2.0 and in such case first diode represents diffusion current which is influenced by the neutral regions, either emitter or base, whereas second diode is usually attributed to generation-recombination phenomena within the space charge region of a solar cell. Sometimes \( A \) is taken as a variable parameter (VDEM model) giving often values higher than 2.0 which has no physical meaning and is used merely for better numerical fit of the I-V curve.

Assuming the appropriateness of the theoretical model and sufficient quality of measurement, the basic problem when fitting a given experimental characteristic to an analytical model is to define a proper object function for the difference between two characteristics, theoretical and experimental. Then the minimum of this function must be found thus defining the best fit parameters.

Most accurate fitting methods are based on the iterative techniques which require extensive computer calculations. For this reason, until recently, many authors have been looking for fast analytical methods to extract solar cell parameters from the measured data [1,2]. Now, when the relatively fast personal computers are widely available time consuming is not a critical factor and the iterative exact fitting techniques are very attractive for on-hand laboratory use.

The aim of this work was to define an optimum object function to fit illuminated curves of solar cells by introducing an appropriate weight function.

2. DEFINING OBJECT MINIMIZATION FUNCTIONS

The least mean square (LMS) fit given as

\[ LMS = \frac{1}{N} \sum_{i=1}^{N} \left[ \frac{I_{meas} - I_{calc}}{I_{meas}} \right]^2 \]
is known to be an excellent technique when the measured curve has a linear character in respect to the parameters that are to be fitted. Unfortunately this is not the case for I-V curves of solar cells and hence some authors tried to use either more sophisticated fit techniques [3,4,5] or to apply different object functions [1,6]. In order to obtain right relative weight Polman et al. [7] also proposed sampling the current of the cell at equidistant voltage values. The most frequently modification of the LMS is an object function defined as follows

\[
SD = \frac{1}{N} \sum_{i=1}^{N} [(y_i - \hat{y}_i)^2]^{1/2}[(\hat{y}_i)^2]
\]

and it is usually referred as Standard Deviation (SD). The use of both these criteria, however, tends to a very good fit to the part of the curve near the open circuit region at the expense of the quality of fit in the short circuit region. Chan et al [6] proposed an original object function, hereafter referred as “Area”, where minimisation is taken over the area which can be found between experimental and theoretical curves, i.e.

\[
\Delta A = \sum_{i=1}^{N} \left[ A_{exp}(i) - A_{th}(i) \right] A_{exp}(i)
\]

and when we define the total area under the measured curve as

\[
Area = \sum_{i=1}^{N} A_{exp}(i)
\]

then a parameter \( \varepsilon \) describes the quality of the fit

\[
\varepsilon = \frac{\Delta A}{Area} \times 100\%
\]

Parameter \( \varepsilon \) as defined in Eqn. (8) has been used in this work to estimate the final quality of fit for different object functions.

2.1. SIMPLE ALGORITHM TO DEFINE WEIGHT FACTOR FOR OBJECT FUNCTIONS:

Let us define factor as an array of number values that are used to modify LMS value given by (4). It is calculated in such way that its values are always in the range \(0..1\) regardless what is the range and number of the data taken into calculations. It is always recalculated whenever the set of experimental data is changed. This allows to avoid confusion with overflow problems during calculations and to compare quality of fit for different object functions. The whole procedure may be described briefly as follows (the assumption is made that the experimental points are labelled consecutively starting from the negative voltage values):

Step 1°: Transformation of measured data values i.e. all voltage values of the measured curve are transformed proportionally to the values within \( <Max..1> \) according to the following formula:

\[
(V_{ex}) = \frac{\text{Max} - 1}{(V_{max})} \cdot (V_{exp}) + B
\]

where

\[
A = \frac{\text{Max} - 1}{(V_{max})}, \quad B = \frac{\text{Max} \cdot A - (V_{exp})}{(V_{max})}
\]

where Max is an arbitrary positive number, chosen as 10 in a program, and \( (V_{exp}) \) and \( (V_{max}) \) are the lowest and highest values of measured voltage, respectively.

2° Calculation of a weight factor array:

\[
SD: \quad \text{(factor)}_j = 1
\]

\[
SD(\text{modif.}): \quad \text{(factor)}_j = (V_{exp})_j / \text{Max}
\]

\[
\text{Logarithmic:} \quad \text{(factor)}_j = \ln((V_{exp})_j) / \ln(\text{Max})
\]

\[
\text{Exponential:} \quad \text{(factor)}_j = 1 - 1.72/(\exp((V_{exp})_j) - 1)
\]

where \( j \) is an index of the I-V data point.

The object function is calculated as follows:

\[
SD(\text{modif}) = \frac{1}{N} \sum_{j=1}^{N} \left[ (\text{(factor)}_j \times [(\text{area}_{exp})_j - (\text{area}_{th})_j]) \right]^2
\]

Object function modified by factor equal to unity, Eqn.(10), is in fact equivalent to SD given by (4).

Once the object function is defined SIMPLEX DOWNHILL method [8] is used to minimise it.

3. RESULTS

Results of fitting are presented for the cells measured in either of three different laboratories, i.e. Solar Lab, TU Wrocław (Poland), IMEC, Leuven (Belgium) or Solar Experimental Station, Kozy (Poland).

The meanings of denotations on the plots are as follows:

\(-1\) - LMS, Eqn.(4);

\(1/\text{I_meas}\) - Eqn.(5);

Area Dev. - Eqn.(6);

Exponential - Eqns.(13) and (14);

Logarithmic - Eqns.(12) and (14);

\(1/\text{I_meas}.\text{normalised}\) - Eqns.(11) and (14);

The relative error of fit defined as

\[
df/I_{\text{meas}} = (I_{\text{meas}} - I_{\text{theor}})/I_{\text{meas}}
\]
is shown under each I-V curve as it is seen on the screen of the computer in the course of calculations.

![Graph showing I-V curve fit parameters](image)

**Fig. 1** Typical fit (DGM) and a relative fit error dI/I_{meas} for medium quality silicon cell with use of different object functions; cell was manufactured in Solar Experimental Station in Kozy (Poland) and measured in Solar Lab, TU Wroclaw.

![Graph showing I-V curve fit parameters](image)

**Fig. 2** Small fragment of the I-V curve from Fig. 1 showing subtle differences in the quality of fit for different object functions.

![Graph showing I-V curve fit parameters](image)

**Fig. 3** Plot of increment of ΔI as defined by (6) and calculated for I-V curves from Fig. 1 showing almost linear dependence for the exponential-type object function.

![Graph showing I-V curve fit parameters](image)

**Fig. 4** Fit (DGM) of high quality multi-crystalline silicon cell using exponential object function; note the extended range of voltage and current measured and preferential density of data points taken in the range of “flat” part of the I-V curve; cell was fabricated and measured in IMEC.
REFERENCES


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