Parameters Extraction Methods of Compound Semiconductor Photovoltaic Modules

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Abstract. The parameters extraction method of the single diode model is usually used to analyse silicon-based solar cells to predict their behaviour from IV curves. However, the film solar cells based on compound semiconductor, for example the CdTe and CIGS, which have been widely used in the market, have few relevant studies still now. This paper presents two parameters extraction methods and applies to two photovoltaic modules, then we use a function in MATLAB to refine the results. Finally, the error of the two methods has been compared to find the best fitting result. Final fitting results show that these methods have their own advantages and disadvantages and both have great fitting accuracy on the two modules, and they can be used in various irradiance conditions.

1. Introduction
The IV characteristics of photovoltaic (PV) modules are an important factor during the process of production and use. In recent years, many related fitting studies have been done [1,2,3]. It is a typical regression analysis problem and the main research method is curve fitting. Research objects are usually the silicon-based solar cells, and the average errors are usually between $10^{-3}$ and $10^{-4}$. But it is seldom used in CdTe and CIGS solar cells.

In this paper, the single diode model (SDM) is applied to the CdTe and CIGS PV modules. As shown in figure 1. It contains five parameters [4,5], photovoltaic current ($I_{ph}$), diode reverse saturation current ($I_0$), diode ideal factor ($n$), series resistor ($R_s$) and parallel conductance ($G_{sh}$). We reduce the number of parameters from 5 to 2 ($n$ and $R_s$) with the conditions of open circuit, short circuit and the maximum power, in order to simplify calculation [6]. Then, Newton-Raphson method (NR) and particle swarm optimization (PSO) are used to find out the optimal solution of $n$ and $R_s$ under the condition of the least squares fitting. Finally, five parameters of SDM can be extracted out by back substitution.

Tests on PV module of CdTe and CIGS had been done under various environmental conditions. The fitting results show that NR has faster calculation speed, the PSO has smaller error. They both show better fitting results after refinement, and finally results are not inferior to other methods It indicates they are both appropriate parameters extraction methods for compound semiconductor modules.
2. Parameter extraction methods

2.1. Parameters reduction
The mathematical expression of PV module can be gotten by doing circuit analysis in figure 1 with Kirchhoff’s current law. As shown in equation (1), and thermal voltage $V_t = kT/q$.

$$I = I_{ph} - I_0 \left[ \exp \left( \frac{V + IR_s}{nV_t} \right) - 1 \right] - G_{sh} (V + I \cdot R_s)$$ (1)

It is too complicated to deal with the five parameters directly. We find a method to reduce parameters [7]. According to the open circuit ($I=0$, $V=V_{oc}$), short circuit ($I=I_{sc}$, $V=0$) and maximum power ($I=I_{mp}$, $V=V_{mp}$) conditions, $I_{ph}$, $I_0$ and $R_{sh}$ can be expressed with $n$ and $R_s$. As shown in equations (2)-(4).

$$I_0 = \frac{V_{oc}(I_{sc} - I_{mp}) - V_{mp}l_{sc}}{A_1 \exp_{sc} + A_2 \exp_{mp} + A_3 \exp_{oc}}$$ (2)

$$G_{sh} = \frac{\exp_{oc}(I_{mp} - I_{sc}) + \exp_{mp}l_{sc} - \exp_{sc}I_{mp}}{A_1 \exp_{sc} + A_2 \exp_{mp} + A_3 \exp_{oc}}$$ (3)

$$I_{ph} = \frac{l_{sc}V_{oc}(\exp_{mp} - 1) + l_{sc}V_{mp}(1 - \exp_{oc}) + l_{mp}V_{oc}(1 - \exp_{sc})}{A_1 \exp_{sc} + A_2 \exp_{mp} + A_3 \exp_{oc}}$$ (4)

Among them, abbreviations are as following equations (5)-(10).

$$\exp_{oc} = \exp \left( \frac{V_{oc}}{nV_t} \right)$$ (5)

$$\exp_{mp} = \exp \left[ \left( \frac{V_{mp} - R_sI_{mp}}{nV_t} \right) \right]$$ (6)

$$\exp_{sc} = \exp \left( \frac{R_sI_{sc}}{nV_t} \right)$$ (7)

$$A_1 = V_{mp} + R_sI_{mp} - V_{oc}$$ (8)

$$A_2 = V_{oc} + R_sI_{sc}$$ (9)

$$A_3 = R_sI_{sc} - R_sI_{mp} - V_{mp}$$ (10)

2.2. NR method
Firstly, a function $SE$ has been constructed to evaluate the effect of curve fitting. As shown in equation (11).

$$SE = \sum_{i=1}^{N} \left[ I_i - I_{ph} + I_o \exp \left( \frac{V_i + I_iR_s}{nV_t} - 1 \right) + G_{sh} (V_i + I_iR_s) \right]^2$$ (11)

The best fitting means that $SE$ needs to be the minimum. For a binary function, studying two points whose partial derivatives are zero can find the minimum. Thus, I choose the NR method to solve this problem [8]. The related expressions and iterative equations are shown in equations (12)-(14).
\[ f_{R_s} = \frac{\partial SE}{\partial R_s} = -2 \sum_{i=1}^{N} \left[ \frac{I_i}{nV_t} \exp\left( \frac{V_i + I_iR_s}{nV_t} \right) + G_{sh}(V_i + I_iR_s) \right] \left[ I_i - I_{ph} + I_0 \exp\left( \frac{V_i + I_iR_s}{nV_t} - 1 \right) + G_{sh}(V_i + I_iR_s) \right] \quad (12) \]

\[ f_n = \frac{\partial SE}{\partial n} = 2 \sum_{i=1}^{N} \left[ \frac{I_0}{n^2V_t} \right] \left[ I_i - I_{ph} + I_0 \exp\left( \frac{V_i + I_iR_s}{nV_t} - 1 \right) + G_{sh}(V_i + I_iR_s) \right] \quad (13) \]

\[
\begin{bmatrix}
R_{s}^{t+1} \\
R_{n}^{t+1} \\
\end{bmatrix}
= \begin{bmatrix}
\frac{\partial f_{R_s}}{\partial R_s} & \frac{\partial f_{R_s}}{\partial n} \\
\frac{\partial f_n}{\partial R_s} & \frac{\partial f_n}{\partial n} \\
\end{bmatrix}^{-1} \begin{bmatrix}
f_{R_s}(R_{s}^{t}, n^{t}) \\
f_n(R_{s}^{t}, n^{t}) \\
\end{bmatrix}
\]

(14)

The experiment proves that SE decreases rapidly with the number of iterations, and iteration will be ceased when SE changes very little. However, this method needs accurate initial values. Otherwise, it will fall into local optimization and get a bad fitting.

### 2.3. PSO method

Considering the problem of local optimization, as a common global optimization algorithm, PSO can be used to solve it [9]. We can assume the problem as a point with coordinates \( n \) and \( R_s \), looking for the deepest pit on the plane with \( n \) and \( R_s \), in which the deepest pit means the smallest SE.

This method can let different number of points search the deep pit along with different directions, in different velocities. Recording the depth every time to get the deepest pit which means the global optimal solution with compare. The logic chart is shown in figure 2.

![Figure 2. The logic chart of PSO method.](image)

This method can choose the initial values in a certain range. It depends on the number of cells in series, the \( V_{oc} \) and the \( I_{sc} \) of the module. Usually, the inertia weight in the iterative equation and the number of particles have an influence on solution speed and fitting results.

### 3. Parameters extraction and fitting results

We choose two kinds of PV modules’ data, which is from National Renewable Energy Laboratory, Golden, CO, USA [10], to test the two methods. They are two practical film solar cells, and one is based on CdTe, the other one is based on CIGS. In order to get the more accurate results, a refinement step has been added after that. The optimization function "lsqnonlin" in MATLAB is good for the least square problem, and the previous results can be substituted in it as initial values to get refined results.

Finally, the analyses of the results have been done, including the root mean squared error (RMSE), the mean absolute error (MAE) and the calculation steps in different irradiance conditions. Due to the large amount of data, we list the five parameters extracted under 1000W/m² and average analysis results to form a table, which is shown in table 1.
Table 1. Five parameters under 1000W/m², average error analysis and iteration steps of all methods.

| module | CdTe | CIGS |
|--------|------|------|
| method | NR   | PSO  | NR_rf | PSO_rf | NR | PSO  | NR_rf | PSO_rf |
| parameters | 1000w/m² | 1000w/m² |
| n      | 239.305 | 239.794 | 239.788 | 239.794 | 105.853 | 106.301 | 106.301 | 106.301 |
| Rs     | 7.199  | 7.173  | 7.174  | 7.173  | 0.975  | 0.968  | 0.968  | 0.968  |
| Iph    | 1.181  | 1.181  | 1.181  | 1.181  | 2.491  | 2.491  | 2.491  | 2.491  |
| I0     | 4.035E-06 | 4.140E-06 | 4.139E-06 | 4.140E-06 | 1.004E-06 | 1.068E-06 | 1.068E-06 | 1.068E-06 |
| Gsh    | 5.294E-04 | 5.279E-04 | 5.280E-04 | 5.279E-04 | 2.413E-03 | 2.379E-03 | 2.379E-03 | 2.379E-03 |
| error  | average |
| RMSE   | 1.254E-03 | 1.243E-03 | 1.243E-03 | 1.243E-03 | 5.470E-03 | 5.398E-03 | 5.398E-03 | 5.398E-03 |
| MAE    | 1.050E-03 | 1.043E-03 | 1.043E-03 | 1.043E-03 | 4.815E-03 | 4.750E-03 | 4.750E-03 | 4.750E-03 |
| steps  | 8 | 78 | 1 | 0 | 14 | 84 | 2 | 0 |

Under different irradiance conditions (400, 600, 800, 1000 and 1200 W/m²), the best fitting results are shown in figure 3.

4. Conclusion

The fitting results and error analysis show that: (1) Five parameters of compound semiconductor PV module can be extracted out accurately by the three methods; (2) No negative values appear, which means that results are in accords with their physical meanings, SDM is also suitable for CdTe and CIGS solar cells; (3) NR has faster solution, but the accuracy of PSO is better than NR; (4) CIGS module has worse fitting result than CdTe module, maybe other algorithm can solve this problem.

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