A novel parameter extraction method for the one-diode solar cell model

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Received 27 October 2009; received in revised form 11 March 2010; accepted 12 March 2010

Available online 10 April 2010

Communicated by: Associate Editor Arturo Morales-Acevedo

Abstract

With the increase in the capacity of photovoltaic generation systems, studies are being actively conducted to improve system efficiency. To develop precise solar cell simulators or design a high-performance photovoltaic generation system, it is important to accurately understand the physical properties of solar cells. However, solar cell models have a non-linear form with numerous parameters. To obtain accurate parameter values, assumptions that differ from real operating conditions must be made to avoid computational complexity. In this paper, a new method for extracting parameter values is proposed. The proposed method deduces the characteristic curve of an ideal solar cell without resistance using the $I-V$ characteristic curve measured and reported by solar cell manufacturers and calculates the difference between the deduced and actual measured curves. In addition, the precision of the proposed method is demonstrated by calculating the correlation between the $I-V$ characteristic curve based on modeling parameters and the $I-V$ curve actually measured employing the least-squares method.

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Keywords: Solar cell model; Parameter extraction; Reverse saturation current; Ideality factor; $I-V$ curve

1. Introduction

Among existing methods to extract solar cell parameters, a relatively simple method is to estimate series and shunt resistances of solar cells using the slope of the current–voltage ($I-V$) curve at the point of open circuit voltage and short circuit current, respectively. Another method is to estimate series resistance from the ratio of the changes in voltage and current of $I-V$ curves measured at two different levels of irradiance (Bashahu and Hayaramana, 1995). There are other methods such as finding parameters through complicated numerical analysis using Lambert’s W function, calculating the resistance by expressing the difference between the diode characteristic curve for the dark state and the curve for the bright state as an equation, and estimating parameters from the relationship between the slope and intercept of the $I-V$ curve represented by an equation that includes conductance (Jain and Kapoor, 2004, 2005a,b; Aberle et al., 1993; Ouennoughi and Chegaar, 1999). However, these methods require extremely complicated processes for accurate extraction of many parameters from a non-linear solar cell equation. Therefore, in many cases, the ideality factor is assumed to be 1 (i.e., parallel resistance is neglected). So that there can be hardly found a method which can properly extracts all parameters to date. In addition, in most studies, the $I-V$ curve obtained from extracted parameters was not compared with a measured $I-V$ curve, making it difficult to demonstrate the accuracy of the methods used.

In this paper, the ideality factor was found using characteristics of the diode obtained from the $I-V$ curve of a solar cell, and the reverse saturation current was calculated from a solar cell equation that neglected resistance. The values were substituted into the solar cell equation to give ideal $I-V$ curve data with no resistance. Values of series and shunt resistances were determined by calculating the
difference between the ideal curve and measured curve. The correlation between the \( I-V \) curve drawn using final parameter values and the measured \( I-V \) curve was demonstrated by the least-squares method.

2. Theory

2.1. Solar cell model

The model of the solar cells for which the superposition principle is applicable can be represented by the equivalent circuit in Fig. 1 and expressed as Eq. (1) which includes light-generating current source \( (I_{ph}) \), series resistance \( (R_s) \) and shunt resistance \( (R_{sh}) \) of diode with the diode equation shown by Eq. (2).

\[
I = I_{ph} - I_{sat} \left( \frac{\exp(q(V + IR_s))}{N_s nkT} - 1 \right) - \frac{V + IR_s}{R_{sh}} \tag{1}
\]

\[
I_D = I_{sat} \left( \frac{q V_D}{nkT} - 1 \right) \tag{2}
\]

\( I_{sat} \) is the reverse saturation current, \( n \) the quality factor, \( k \) the Boltzmann’s constant, \( T \) the absolute temperature, \( q \) the electron charge, \( N_s \) is the number of cells in series.

Measurement data provided by the manufacturer include the \( I-V \) curve, open circuit voltage \( (V_{oc}) \), short circuit current \( (I_{sc}) \), and voltage \( (V_{mpp}) \), current \( (I_{mpp}) \), and power \( (P_{max}) \) at the maximum power point (MPP), measured at 25 °C under a standard AM 1.5 solar spectrum and irradiation of 100 mW/cm². To establish the singular diode solar cell model in Eq. (2), four parameters of the solar cell equation—\( R_s, R_{sh}, n, \) and \( I_{sat} \)—must be extracted using data provided by the manufacturer.

2.2. Effects of parameters on the shape of the \( I-V \) curve

Figs. 2–5 show the effect of the four parameters of the solar cell on the solar cell output. Parameters were substituted into Eq. (2) to draw an \( I-V \) curve. While leaving other parameters constant, a parameter was increased or decreased to observe changes in the shape of the \( I-V \) curve. The curve was drawn using LabVIEW software. Changes in the shape of the \( I-V \) curve due to changes in parameter values were displayed in real time by the continuous execution of LabVIEW, allowing easy verification of visual effects of specific parameters on the shape of \( I-V \) curve. First, as seen in Fig. 2, the shape of the \( I-V \) curve in the voltage source region is depressed horizontally with a gradual increase in the value of \( R_s \) from zero. When \( R_{sh} \) decreases from infinity, the shape of the \( I-V \) curve in the current source region is depressed leftward as shown in Fig. 3. The distinct change in the shape of the \( I-V \) curve due to changes in the ideality factor and reverse saturation current is that the open circuit voltage of the solar cell changes as shown in Figs. 4 and 5, respectively.

Therefore, if parameters are extracted while assuming the ideality factor to be 1, there is significant error in the \( I-V \) curve drawn using the parameters.

2.3. Proposed method of parameter extraction

The parameter extraction method proposed in this paper uses characteristics of the diode \( I-V \) curve to extract the ideality factor from the measured \( I-V \) curve of the solar cell. The initial value of the reverse saturation current can be found using the extracted ideality factor and conditions of the open circuit for the solar cell. Ideal \( I-V \) curve data, which exclude series and shunt resistances, are then obtained by substituting the ideality factor and reverse saturation current into the solar cell equation. As found in Section 2.2, the measured \( I-V \) curve has a smaller fill factor than the ideal \( I-V \) curve because of the reduction in output due to resistances. Therefore, \( R_s \) and \( R_{sh} \) are found by calculating the difference between the ideal \( I-V \) curve and measured \( I-V \) curve. In addition, when calculating the reverse saturation current, the optimum parameter value was found through repeated calculation of the reverse saturation current and \( R_{sh} \) to correct the error resulting from the assumption that the shunt resistance is infinite. The accuracy of the extracted parameter values was tested using the least-squares method by examining the correlation between the \( I-V \) curves measured for various solar cell modules and the \( I-V \) curves drawn using extracted parameters.

2.3.1. Determination of the ideality factor

The ideality factor \( n \) is determined by the material and temperature of the diode and represents the degree of deviation from ideal diode characteristics. This coefficient generally has a value between 1 and 2, with the ideal case being \( n = 1 \). The ideality factor of a diode can be estimated from the slope of the curve drawn by taking a natural logarithm of the current of the diode \( I-V \) curve. Since the slope is the quality factor, \( (n/kT) \) of the diode is extracted. As shown in Eq. (2) was neglected for easier calculation (Bhattacharya, 1994). Thus, by simplifying Eq. (2) as Eq. (3) and taking the natural logarithm of both sides, Eq. (4) is obtained.

\[
I_D = I_{sat} \left( \frac{q V_D}{nkT} \right) \tag{3}
\]

\[
\ln(I_D) = \left( \frac{q}{nkT} \right) V_D + \ln(I_{sat}) \tag{4}
\]
Fig. 2. Effect of $R_s$ variation on the $I-V$ curve.

Fig. 3. Effect of $R_{sh}$ variation on the $I-V$ curve.

Fig. 4. Effect of $n$ variations on the $I-V$ curve.
The ideality factor can be expressed as Eq. (5) using the inverse relationship between the slope of the curve obtained from Eq. (4) and the ideality factor.

\[ n = \frac{q}{kT} \frac{\Delta \ln(I_D)}{\Delta V_D} \]  

(5)

If the \( I-V \) characteristic curve of a normal diode is converted to a curve written as Eq. (4), it has an S-shape as shown in Fig. 6. If the diode is assumed to be ideal, the value of \( n \) in Eq. (5) is 1 and the slope is the tangent line drawn in region 2 of Fig. 6 (Bhattacharya, 1994; Sze, 2002; Dimitrijev, 2000). In an actual semiconductor, \( n \) is less than 2 in regions 1 and 3 and has a value between 1 and 2 in region 2. The maximum slope of the tangent line in region 2 is taken as the ideality factor. The reason that the slope of the curve in region 1 is less than that in region 2 is the recombination of electrons and electron holes that were separated by low bias voltage in the forward direction. The reason for the lower slope in region 3 is the loss due to parasitic resistance in the P–N junction (Dimitrijev, 2000; Singh, 2001). The ideality factor can be extracted by applying the above diode characteristics for solar cells. The ideality factor is determined by converting the measured \( I-V \) curve data into a diode characteristic curve, drawing the curve of Eq. (4), and substituting the maximum slope of the curve in region 2 into Eq. (5).

2.3.2. Determination of the reverse saturation current

Reverse saturation current is the asymptotic limit of the reverse dark current for an infinite reverse bias. Its origin is the diffusion of carriers through the space-charge zone even against an unlimited electric field. It is a unique value decided by manufacturing conditions of the diode and is not influenced by the reverse bias voltage. Reverse saturation current increases by about a factor of two with a temperature increase of 10 °C (Boylestad and Nashelsky, 2002). Reverse saturation current is found by the solar cell equation as Eq. (6) and substituting the ideality factor found earlier, ideal resistance under open circuit condition, and measured \( I-V \) data. Accordingly, the value of the reverse saturation current differs according to the \( I-V \) curve data. Since diode current is greatest under the open circuit condition of the solar cell, the influence of reverse saturation current is also greatest under this condition. Therefore, the accuracy of the reverse saturation current calculated using data at this point is highest (Villalva et al., 2009). In addition, since the output current is zero and there is no voltage drop due to series resistance in an open circuit voltage condition, \( R_{sh} \) is the only unknown element for finding the reverse saturation current after substi-
tuting values of the ideality factor, open circuit voltage, and short circuit current into Eq. (6). However, in the numerator of Eq. (6), the current \(I_{sh}\) flowing through the shunt resistor \(R_{sh}\) has an extremely small value and does not significantly affect the reverse saturation current. Therefore, \(R_{sh}\) can be assumed as infinite. For extraction of accurate parameters in this paper, the value of reverse saturation current found from Eq. (6) was used as the initial value. It was allowed to converge to the actual value by substituting \(R_{sh}\) values again into Eq. (6) and recalculating the reverse saturation current.

\[
I_{sat} = \frac{I_{ph}}{C_0} \left( I + \frac{V + R_s}{R_{sh}} \right) \exp \left( \frac{V + R_s}{N_{sat} k T} \right) \frac{1}{C_1} \tag{6}
\]

2.3.3. Determination of the resistance

Using the ideality factor and initial value of the reverse saturation current, the data of the \(I-V\) curve with ideal \(R_s\) and \(R_{sh}\) can be obtained. As shown in Fig. 2, the series resistance \(R_s\) reduces the output voltage in the voltage source region of the \(I-V\) curve by the difference between the voltage from the ideal \(I-V\) curve \(V_{ideal}\) and the voltage from the measured \(I-V\) curve \(V\). This can be expressed as:

\[
V_{ideal} = V = R_s I \tag{7}
\]

\[
R_s = \frac{V_{ideal} - V}{I} \tag{8}
\]

Fig. 7. \(I-V\) curves at various irradiance levels.

Fig. 8. \(\ln(I) - V\) curve of the 200 W module.
As shown in Fig. 3, the shunt resistance $R_{sh}$ reduces the output current of the current source of the $I$–$V$ curve by the difference between the current from the ideal $I$–$V$ curve ($I_{ideal}$) and the current from the measured $I$–$V$ curve. This can be expressed as Eqs. (9) and (10).

$$I_{ideal} - I = \frac{V + IR_s}{R_{sh}}$$  \hspace{1cm} (9)

$$R_{sh} = \frac{V + I(V_{ideal} - V)}{I_{ideal} - I} = \frac{V_{ideal}}{I_{ideal} - I}$$  \hspace{1cm} (10)

3. Experiments

3.1. Extraction of parameters

The $I$–$V$ curve of a 200 W module having 54 cells connected in series was measured under standard irradiation at standard temperature (25 °C). The curve on the datasheet was converted to digital data, as shown in Fig. 7. Parameters were extracted from the $I$–$V$ curve for standard irradiation according to the method described earlier. First, to extract the ideality factor, the $I$–$V$ curve was converted to the curve of Eq. (4) as shown in Fig. 8. The ideality factor $n$ was
calculated as 1.1780 in region 2 using Eq. (5), and the initial
value of the reverse saturation current was 1.4665 \times 10^{-9} \text{ A}
as calculated by substituting n into Eq. (6) under the open
circuit condition. Fig. 9 shows the I–V curve with ideal $R_s$
and $R_{sh}$ obtained from the extracted ideality factor and
reverse saturation current and measured I–V curve of the
solar cell module on the datasheet. As explained above, com-
pared with the ideal curve, the measured curve has small
depressions in voltage and current in the voltage source
and current source regions respectively due to $R_s$ and $R_{sh}$.
The fill factor is 0.847 for the ideal curve and 0.758 for the
measured curve. Output power is reduced by about 10%
by $R_s$ and $R_{sh}$

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measured curve. Output power is reduced by about 10%
by $R_s$ and $R_{sh}$

Rs and $R_{sh}$ were calculated with data of the
I–V curve at each point using Eqs. (8) and (10), and the cal-
culated values at each point are shown in the graph of
Fig. 10. The figure shows that $R_s$ and $R_{sh}$ are not constant.
Therefore, a decision must be made as to which point on
the I–V characteristic curve gives the values of $R_s$ and $R_{sh}$
most similar to values for the measured curve. For this pur-
pose correlation between the I–V curves drawn using the
extracted $Rs$ and $R_{sh}$ parameters at each point and the one
on the data sheet was analyzed. A program was written using
LabVIEW software to automatically calculate the correlation
between two curves employing the least-squares method. The
program was used to determine series and shunt resistances
that return optimum results. As a result, the I–V curve using the
$Rs$ value (0.2015 Ω) at 92% (30.27 V) of the open circuit
voltage and the $R_{sh}$ value (138.19 Ω) at 28% (9.12 V) of the
open circuit voltage showed highest correlation (99.96%) with
the measured curve. For generalization of this method, the
I–V curves measured for various types of commercial mod-
ules (20, 40, 130, 170, 190, and 210 W) and a 2.2 W unit cell
were obtained. The ideality factor, reverse saturation current,
series resistance, and shunt resistance were extracted using the
proposed method, and the parameters that gave the highest
correlation between the ideal I–V curve and measured I–V
curve are summarized in Table 1. The I–V curve drawn using the
$Rs$ value at 92% of the open circuit voltage and the $R_{sh}$ value at 28% of the open circuit voltage had an almost perfect
match with the measured I–V curve with over 99.7% accuracy.

3.2. Repeated calculation of the reverse saturation curve and
shunt resistance

Using the parameter extraction method proposed ear-
lier, parameters with over 99.7% accuracy were extracted

<table>
<thead>
<tr>
<th>Capacity (W)</th>
<th>n</th>
<th>$I_{sat}$ (A)</th>
<th>$R_{sh}$ (Ω)</th>
<th>$R_s$ (Ω)</th>
<th>$R^2$ (COD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>210</td>
<td>1.0064</td>
<td>7.3382e−12</td>
<td>6355.56</td>
<td>1.0705</td>
<td>0.9997</td>
</tr>
<tr>
<td>200</td>
<td>1.1780</td>
<td>1.4665e−08</td>
<td>138.19</td>
<td>2015</td>
<td>0.9996</td>
</tr>
<tr>
<td>190</td>
<td>1.0722</td>
<td>3.0496e−11</td>
<td>1500.00</td>
<td>1.9371</td>
<td>0.9992</td>
</tr>
<tr>
<td>130</td>
<td>1.1685</td>
<td>1.2573e−08</td>
<td>56.47</td>
<td>0.1526</td>
<td>0.9981</td>
</tr>
<tr>
<td>40</td>
<td>1.4526</td>
<td>2.1135e−07</td>
<td>799.73</td>
<td>0.5573</td>
<td>0.9977</td>
</tr>
<tr>
<td>20</td>
<td>1.2463</td>
<td>5.9204e−09</td>
<td>2214.29</td>
<td>1.3121</td>
<td>0.9971</td>
</tr>
<tr>
<td>2.2</td>
<td>1.0912</td>
<td>1.0692e−11</td>
<td>2630.77</td>
<td>0.5953</td>
<td>0.9982</td>
</tr>
</tbody>
</table>
Therefore, to correct the errors and extract parameters more accurately, an additional process of error removal is required with repeated calculation of the reverse saturation current and $R_{sh}$. The process is illustrated by the flow chart in Fig. 11. The entire process was automated as shown in Fig. 12 using LabVIEW. All parameters were automatically extracted by inputting the measured $I-V$ curve data. First, using the proposed method, the ideality factor was found and the initial value of the reverse saturation current was calculated. Using these values, $R_{sh}$ and $R_s$ were found at 28% and 92% of the open circuit voltage, respectively. They were taken as initial values of the series and shunt resistances. The change in a parameter due to a

<table>
<thead>
<tr>
<th>Irradiance (W/m$^2$)</th>
<th>$n$</th>
<th>$I_{sat}$ (A)</th>
<th>$R_{sh}$ (Ω)</th>
<th>$R_s$ (Ω)</th>
<th>$R^2$ (COD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>1.1780</td>
<td>1.4665e-08</td>
<td>138.19</td>
<td>0.2015</td>
<td>0.9996</td>
</tr>
<tr>
<td>600</td>
<td>1.1093</td>
<td>3.6186e-09</td>
<td>276.36</td>
<td>0.3714</td>
<td>0.9995</td>
</tr>
<tr>
<td>200</td>
<td>1.0525</td>
<td>1.0842e-09</td>
<td>1727.64</td>
<td>1.2222</td>
<td>0.9993</td>
</tr>
</tbody>
</table>

Therefore, to correct the errors and extract parameters more accurately, an additional process of error removal is required with repeated calculation of the reverse saturation current and $R_{sh}$. The process is illustrated by the flow chart in Fig. 11. The entire process was automated as shown in Fig. 12 using LabVIEW. All parameters were automatically extracted by inputting the measured $I-V$ curve data. First, using the proposed method, the ideality factor was found and the initial value of the reverse saturation current was calculated. Using these values, $R_{sh}$ and $R_s$ were found at 28% and 92% of the open circuit voltage, respectively. They were taken as initial values of the series and shunt resistances. The change in a parameter due to a
small increase or decrease in $R_s$ was then substituted into the solar cell equation to recalculate the ideal $I-V$ curve and determine the correlation with the measured $I-V$ curve. Here, if the value of the coefficient of determination (COD) increased, $R_s$ was changed in the direction of the initial change. If the COD decreased, $R_s$ was changed in the opposite direction. In this way, the COD was used to converge $R_s$ to an optimum value. Likewise, the COD was used to converge $R_{sh}$ to an optimum value. With a change in $R_{sh}$, the reverse saturation current was recalculated using Eq. (6). The correlation between the $I-V$ curve based on the recalculated parameters and the measured curve was also calculated again to determine the direction of change in $R_{sh}$. If the value of COD converges to a value above 0.999, parameter extraction is terminated. If not, the procedure is repeated from the step finding out the $R_s$ value in order to extract all parameters with extremely high accuracy.

### 3.3. Parameter extraction at different levels of irradiance

It was shown in the above section that the accuracy of the parameters extracted using the proposed method with the $I-V$ curve measured under standard irradiation is high. In this section, the accuracy of the parameters extracted by the proposed method using $I-V$ curves measured at differ-

![Fig. 14. $I-V$ curve used in the experiment.](image1)

![Fig. 15. $I-V$ curves drawn using existing methods and the proposed method.](image2)
ent levels of irradiance is analyzed. In the experiments, measured $I-V$ curves of a 200 W module at different levels of irradiance, as shown in Fig. 7, are used to extract the parameters and the results are presented in Table 2. The values of the COD are above 0.999 in all cases and Fig. 13 shows good agreement between the measured curves and the curves drawn with the extracted parameters. Thus, it is concluded that the proposed method is valid for

![Graphs](image)

Fig. 16. Magnified regions of $I-V$ curves drawn using existing methods and the proposed method: (a) current source region, (b) maximum power point region, (c) voltage source region.
all measured $I-V$ curves regardless of the level of irradiance.

3.4. Comparison with other methods

To verify the usefulness of the proposed extraction method, results obtained using the proposed method were compared with the results of extraction using four different methods for the same solar cell module. The $I-V$ curve used in this experiment is shown in Fig. 14. Method 1 estimates the Levenberg parameters from the non-linear solar cell equation using the Gauss–Newton method (Easwarakhanthan et al., 1986). Method 2 calculates the conductance of the $I-V$ curve and draws the curve of the conductance divided by the difference between light-generating current ($I_{ph}$) and output current ($I$), and estimates the parameters from the relationship between the slope and intercept of the drawn curve (Ouennoughi and Chegaar, 1999). Method 3 finds parameters through numerical analysis based on the least-squares method and Newton’s method by modifying the equation of conductance of method 2 (Chegaar et al., 2004). Lastly, method 4 modifies the solar cell equation, takes the natural logarithm of both sides, substitutes a random point on the $I-V$ curve, and removes the term that includes the reverse saturation current (Chegaar et al., 2008). From the modified equation, parameters are extracted through linear regression analysis. Table 3 lists the parameters extracted using the method proposed in this paper and methods presented in other studies. Fig. 15 shows the $I-V$ curves drawn using parameters extracted with each method and the measured $I-V$ curve. For accurate comparison, Fig. 16 shows curves magnified for the current source region, voltage source region, and MPP region. In the current source and MPP regions, the $I-V$ curve obtained using the proposed method was the most similar to the measured $I-V$ curve. Method 3 provided the closest result for the voltage source region. However, while method 3 had high accuracy in the voltage source region, its accuracy in other regions was extremely poor. Fig. 17 shows the absolute error between the $I-V$ curve drawn using each method and the measured curve. In conclusion, the $I-V$ curve drawn using the proposed method offers excellent results for all regions.

4. Conclusions

In this paper, a simple and powerful method of extracting parameters of a solar cell model was proposed. The proposed method is useful for the accurate and easy extraction of solar cell parameters from the $I-V$ curve provided by the manufacturer or a measured $I-V$ curve. Experiments were conducted with modules having different capacities and a unit cell made by different manufacturers. It was found that in obtaining the series and shunt resistances from the difference between the ideal curve and measured curve after extraction of the ideality factor and reverse saturation current, optimum values were obtained at specific points of the curves. The proposed method directly calculates the ideality factor and reverse saturation current from the $I-V$ curve. Parameters were extracted with high accuracy by letting resistance values converge to the actual value through repeated calculations. The proposed parameter extraction method is expected to be useful in the development of an accurate solar cell simulator, performance evaluation, degradation diagnosis, and the development of new MPP tracking algorithms.

Acknowledgments

This work (research) is financially supported by the Ministry of Knowledge Economy (MKE) and Korea Institute for Advancement in Technology (KIAT) through the Workforce Development Program in Strategic Technology.
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