MODELING THE PERFORMANCE OF SEVERAL PHOTOVOLTAIC MODULES

Jun Tsutsui, Yusuke Sato, Kosuke Kurokawa
Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei, Tokyo 184-8588, Japan

ABSTRACT

The model equations to estimate the photovoltaic module performance for outdoor were proposed by many institutions. This work proposes the new model, which is the high predictive accuracy on low irradiance, combines the model proposed by National Renewable Energy Laboratory (NREL) and the model proposed by Joint Research Centre (JRC); meanwhile, we estimate the photovoltaic module performance using the linear interpolation method, which is being deliberated at the conference that International Electro technical Commission (IEC) sponsor. This paper describes the new model, and a result of comparing both models which adopted several photovoltaic modules; a crystalline silicon module (c-Si), a polycrystalline silicon module (poly-Si), and a copper-indium-diselenide module (CIS).

INTRODUCTION

The outdoor maximum power (P\text{max}) of solar module differs from the indoor P\text{max} which is evaluated on Standard test condition (STC). For example, the junction temperature of solar cell reaches almost 50 °C at 1kW/m\textsuperscript{2}, moreover, are influenced by the ambient temperature. And the solar spectrum changes during a day because of the aerosol and water vapor, therefore it is rare to fit the air mass 1.5 (AM1.5) means the standard spectrum. Consequently, to estimate the module performance, our proposal models need to take the module temperature, the solar irradiance and the solar spectrum into account.

This work proposes the new model which combines the model proposed by NREL and JRC.[1][2] Using the model of NREL, open-circuit voltage (V\text{oc}) and short-circuit current (I\text{sc}) of module are estimated, plus using the model of JRC, fill factor (FF) is estimated. Crossing the calculated value (V\text{oc}, I\text{sc}, and FF), arbitrary maximum power is obtained. On the other hand, as another model, we estimate the performance using the linear interpolation method which is deliberated as the energy rating. [3][4]

MODEL OF V\text{oc} and I\text{sc}

According to NREL, V\text{oc} and I\text{sc} are shown by equation (1), (2). V\text{oc}, I\text{sc} on STC are expressed by subscript zero.

\[
V_{\text{oc}} = V_{\text{oc}(0)} \left[ 1 + \beta(T - T_0) \right] \left[ 1 + \delta \ln \left( \frac{E}{E_0} \right) \right]
\]

Where:
- E=irradiance [kW/m\textsuperscript{2}]; E\textsubscript{0} = 1kW/m\textsuperscript{2}
- T=PV module temperature [°C]; T\textsubscript{0} = 25 °C
- \beta=V_{\text{oc}} correction factor for PV module temperature
- \delta=V_{\text{oc}} correction for irradiance

\[
I_{\text{sc}} = \frac{E}{E_0} I_{\text{sc}(0)} \left[ 1 + \alpha(T - T_0) \right]
\]

\[
\alpha = \text{Isc correction factor for PV module temperature}
\]

MODEL OF FF

According to JRC, FF is shown by equation (3). The feature of this model is to obtain coefficient a, b, c, d, and e by the regression. Therefore, FF on STC is not needed to decide arbitrary FF. In addition, the regression coefficients are able to decide from I-V curve data a day.

\[
FF = a + \frac{bE + c}{\ln E} + T(d + eE)
\]

Where:
- E=irradiance [W/m\textsuperscript{2}];
- T=PV module temperature [K]
- a,b,c,d,e=regression coefficient

The result of our verifying predictive accuracy, we found the equation (3) model was not good to predict in low irradiance area. The reason is that third section of equation (3) expresses the temperature coefficient of FF is linear to the irradiance. But, according to the outdoor result, the temperature coefficient becomes smaller while the irradiance decreases. Fig.1 shows the irradiance dependency of the temperature coefficient of FF. Therefore, we proposed to add the new regression coefficient “f”, which works so that the temperature coefficient becomes smaller. Equation (4) is our proposed equation.

\[
FF = a + \frac{bE + c}{\ln E} + T(d + eE + \frac{f}{E})
\]

Fig.2 shows the comparison of modeled value by Equation (3) and (4), and measured value of outdoor result. Depending on a new regression coefficient, modeled value by equation (4) is coincided with the measured value in low irradiance area, which is from 0.1kW/m\textsuperscript{2} to 0.3kW/m\textsuperscript{2}.
MODEL OF $P_{\text{max}}$

$P_{\text{max}}$ is calculated by equation (5), using $V_{\text{oc}}$ and $I_{\text{sc}}$ by equation (1), (2), and FF by equation (4).

$$P_{\text{max}} = V_{\text{oc}} \cdot I_{\text{sc}} \cdot \text{FF}$$ (5)

THE LINEAR INTERPOLATION METHOD

The linear interpolation method is estimated by using the I-V curve under four different environments; High irradiance & Low temperature (HILT), High Irradiance & High temperature (HIHT), Low irradiance & Low temperature (LILT), Low irradiance & High temperature (LIHT). The characteristic of this method doesn’t need to calculate the series resistance ($R_s$) and the curve correction factor ($K$), which is included by conventional equation in IEC 60891. Following is the equation of the linear interpolation method. Equation (6) indicates the temperature interpolation; meanwhile equation (7) indicates the irradiance interpolation. (See Fig.3, Fig.4)

$$V_{T3}(I) = V_{T1}(I) + \frac{T_3 - T_1}{T_2 - T_1} \left( V_{T2}(I) - V_{T1}(I) \right)$$ (6)

$$I_{E3}(V) = I_{E1}(V) + \frac{E_3 - E_1}{E_2 - E_1} \left( I_{E2}(V) - I_{E1}(V) \right)$$ (7)

Where:

$V_T(I) =$V-I curve points on arbitrary temperature

$I_E(V) =$I-V curve points on arbitrary irradiance

$T_1$=High temperature, $E_1$=High irradiance

$T_2$=Low temperature, $E_2$= Low irradiance

$T_3$, $E_3$=temperature and irradiance on wanted I-V curve

The input parameter necessary for the estimate is four I-V curves and arbitrary temperature and irradiance measured by the pyranometer. But the irradiance contains a slight error, for example there is a spectrum mismatch of
the solar module and the pyranometer. And when the solar altitude is low, incident angle loss occurs to the module. Hence we estimated by using the $I_{sc}$ instead of the irradiance this time, that is to say, equation (7) was replaced by equation (8).

$$I_{E3}(V) = I_{E1}(V) + \frac{I_{sc3} - I_{sc1}}{I_{sc2} - I_{sc1}} \cdot (I_{E2}(V) - I_{E1}(V))$$ (8)

DEFINITION OF THE ERROR

Before the estimated accuracy is indicated, we introduce the expression that shows the error as follows.

$$\text{Error}\% = \frac{\text{Calculated value} - \text{Measured value}}{\text{Each Parameter on STC}}$$ (9)

Equation (9) shows the error which is the absolute error divided by $P_{\text{max}}$ on STC. In this paper, we defined this as the error.

RESULT

Confirmation of calculation accuracy of $V_{oc}$, $I_{sc}$ =

According to the equation (1), (2), the temperature coefficients $\alpha$, $\beta$, and $\delta$ expressed $V_{oc}$ correction for irradiance as a function is necessary to calculate the arbitrary $V_{oc}$, $I_{sc}$. In this study, these coefficients were calculated by outdoor result. $\beta$ and $\delta$ were able to calculate by high decision coefficient ($R^2$), which was more than 0.98. (See Table 1) On the other hand, $\alpha$ was not accurate because of slight inclination. Therefore we valued $\alpha$ at 0.05%/°C on a temporary basis.

Table 1 Results of $\beta$, $\delta$

<table>
<thead>
<tr>
<th>Mod.</th>
<th>$\beta$</th>
<th>$R^2$</th>
<th>$\delta$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si</td>
<td>-0.29</td>
<td>0.98</td>
<td>5.27</td>
<td>1.00</td>
</tr>
<tr>
<td>poly-Si</td>
<td>-0.31</td>
<td>0.99</td>
<td>4.96</td>
<td>0.98</td>
</tr>
<tr>
<td>CIGS</td>
<td>-0.29</td>
<td>0.99</td>
<td>6.30</td>
<td>0.99</td>
</tr>
<tr>
<td>UNIT</td>
<td>%/°C</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
</tbody>
</table>

Next, using the result of $\beta$, $\delta$, we calculated $V_{oc}$, $I_{sc}$ from equation (1), (2). Table 2 shows the calculation accuracy of them. According to table 2, the calculation accuracy of $V_{oc}$ is high, that is the calculated value corresponded with the measured value. On the other hand, the calculation accuracy of $I_{sc}$ is not better than $V_{oc}$, as the standard deviation is over 1.0%. In this case, we didn’t consider the influence of the solar spectrum; so that it might enlarge the error of calculated $I_{sc}$ and measured $I_{sc}$ which is influenced by the outdoor solar spectrum.

<table>
<thead>
<tr>
<th>Mod.</th>
<th>$\Delta V_{oc}$</th>
<th>$\Delta I_{sc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si</td>
<td>0.06%</td>
<td>0.46%</td>
</tr>
<tr>
<td>poly-Si</td>
<td>0.23%</td>
<td>1.64%</td>
</tr>
<tr>
<td>CIGS</td>
<td>-0.17%</td>
<td>0.86%</td>
</tr>
</tbody>
</table>

Table 2 Confirmation of calculation accuracy

<table>
<thead>
<tr>
<th>Mod.</th>
<th>$V_{oc}$</th>
<th>$I_{sc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si</td>
<td>AVE.</td>
<td>SD.</td>
</tr>
<tr>
<td>poly-Si</td>
<td>-0.02%</td>
<td>0.35%</td>
</tr>
<tr>
<td>CIGS</td>
<td>0.11%</td>
<td>0.27%</td>
</tr>
</tbody>
</table>

Table 3 View of the regression coefficients

<table>
<thead>
<tr>
<th>Mod.</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>$d$</th>
<th>$e$</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si</td>
<td>1.73E-01</td>
<td>6.84E-01</td>
<td>8.72E-01</td>
<td>-3.98E-04</td>
<td>-7.20E-07</td>
<td>-2.06E-02</td>
</tr>
<tr>
<td>poly-Si</td>
<td>1.62E-03</td>
<td>5.89E-03</td>
<td>8.51E-01</td>
<td>-4.53E-04</td>
<td>-2.51E-06</td>
<td>-1.74E-02</td>
</tr>
<tr>
<td>CIGS</td>
<td>8.72E-01</td>
<td>8.54E-01</td>
<td>8.54E-01</td>
<td>-5.44E-04</td>
<td>-1.15E-06</td>
<td>-2.60E-02</td>
</tr>
</tbody>
</table>

Table 4 Confirmation of calculation accuracy

<table>
<thead>
<tr>
<th>Mod.</th>
<th>$\text{FF}$</th>
<th>$P_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si</td>
<td>0.06%</td>
<td>0.15%</td>
</tr>
<tr>
<td>poly-Si</td>
<td>0.23%</td>
<td>-0.99%</td>
</tr>
<tr>
<td>CIGS</td>
<td>-0.17%</td>
<td>0.37%</td>
</tr>
</tbody>
</table>

Using the regression coefficient, estimated FF of each module is calculated. Table 4 shows the confirmation of calculation accuracy of FF and $P_{\text{max}}$. The average error of the estimated FF is possible to calculate within 1% as well as the $V_{oc}$. Fig.5, 6 compares the measured and estimated FF or $P_{\text{max}}$ on c-Si module.
Comparing to table 4, table 5 indicates the average and standard deviation of the error was slight at all modules. Therefore, the estimated $P_{\text{max}}$ doesn’t depend on the kind of module. We establish the linear interpolation method is the superior estimated equation. However, in this estimate, we ignore the spectral mismatch parameter and the dependence of the solar angle of incidence, because the module’s $I_{\text{sc}}$ is used. Hence, as the next task, the linear interpolation method is improved to include their influences.

**CONCLUSION**

We have compared two kinds of model equations for the $P_{\text{max}}$ of a c-Si, poly-Si, and CIGS module respectively. One model is to combine the conventional equations to calculate $V_{\text{oc}}$, $I_{\text{sc}}$, and the new equation of FF improved around the low irradiance, so that the standard deviation of the error has become within about 1.5%. The other model is the linear interpolation method, which accuracy is within about 0.5%. Hence, the linear interpolation method is the accurate model that it is possible to adapt to the various modules.

**REFERENCE**


