Reliability Evaluation of Failure Diagnosis for \(I-V\) Curve Obtained by Advanced Technique

Youichi HIRATA†, Takumi AOKI, Keigo NAKASHIMA, and Satoru MIYAZAWA

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We propose an advanced technique to obtain \(I-V\) curves in the first quadrant and the forth quadrant more accurately than by a conventional technique. In this study, we focus on the examination of the irradiance dependence to evaluate \(I-V\) curves of modules with different deterioration states. The \(I-V\) curves were swept in the first and the fourth quadrant obtained for different irradiances. Then, four constants of an equivalent circuit of the solar cells, i.e., series resistance \((R_s)\), shunt resistance \((R_{sh})\), diode factor \((n)\), and saturation current \((A)\) were analyzed. \(R_s\) values were obtained for different irradiances and were stable for modules of the same model. \(R_s\) can be used to detect the failures and disconnections of modules in a string. Similarly, \(R_{sh}\), \(n\), and \(A\) can also serve as diagnostic indices. To examine the feasibility of using the four constants as diagnostic indices, the values of the four constants were examined for different irradiances.

Key Words
PV power system, Failure diagnosis, \(I-V\) characteristic, Reliability evaluation, Fourth quadrant data

1. Introduction
1.1 Background

The number of photovoltaic (PV) systems being produced and installed has been increasing exponentially worldwide. However, the number of cases of failure has also been increasing. PV arrays are important components in a PV system. Even failure in one module or cluster in a PV module leads to a decrease in output from not only the affected modules or clusters but also other modules and clusters. This state of decreased output continues until the next inspection of the system, which decreases the available system capacity and the level of cumulative power generation.

We propose a diagnostic system with an advanced technique to measure \(I-V\) curves in the first quadrant and the fourth quadrant, as shown in Fig. 1. A highly precise and reliable diagnosis is expected.
1.2 Reliability of diagnostic technique

The $I^{-V}$ curves obtained by the advanced technique should be evaluated to verify the reliability of the diagnostic technique. In this study, we used the electronic load control method with a high measurement accuracy to obtain $I^{-V}$ curves in the first and the fourth quadrant. The $I^{-V}$ curves of modules were obtained under various environmental conditions and analyzed to examine the irradiance dependence. Here, the level of deterioration differs for each module. Four constants $i$ of an equivalent circuit of solar cells, i.e., series resistance ($R_s$), shunt resistance ($R_{sh}$), diode factor ($n$), and saturation current ($I_0$), were calculated and analyzed.

2. Measurement Equipment and Technique

2.1 Modules to be measured

In this study, 10 single-crystalline silicon PV modules of the same model were used. These modules were classified into three classes (classes A, B, and C) considering the maximum power ($P_{max}$), the shape of $I^{-V}$ curves, electroluminescence (EL) images, and so forth.

Five modules belong to class A: their output is in the range of 98-101 W under outdoor reference condition (ORC): irradiance 1.08 kW/m², module temperature 62°C, and their $I^{-V}$ curves have a large fill factor ($FF$). Two modules belong to class B: their output is in the range of 90-93 W under ORC. Three modules belong to class C: their output is in the range of 76-81 W under ORC. Table 1 shows the $P_{max}$ and $FF$ of the 10 modules under ORC. Their $I^{-V}$ curves were obtained for evaluation.

Fig. 2 shows the typical EL images of the (a) class A (SN L0201) and (b) class C (SN L0104) modules selected from the 10 modules. The class C module contains cracks in several solar cells and disconnections in bus bars. These two modules are included in ten modules as in Table 1.

Table 2 shows the output characteristics of the above two modules; SN L0201 is a standard module with an output of 100.5 W and SN L0104 is a failure module with an output of 81.4 W, which is smaller than that of SN L0201.

2.2 Measurement equipment

To obtain $I^{-V}$ curves, the $I^{-V}$ meter 4601 (ADC Corporation) was used. This meter adopts the electronic load control method and contains a booster for applying voltage to PV modules. In this study, 10 deteriorated modules with different deterioration states were examined. The voltage was increased from 0 to 40 V at increments of 0.5 V every 10 ms. This step time was determined to ensure the accuracy of the $I^{-V}$ curve for the time required for one sweep of an $I^{-V}$ curve. In addition, the calculation accuracy in the fitting of the four constants, explained later, is also
considered. Eighty data values are obtained in 0.8 s. The time required for the measurement of 10 modules is 20 s or less including the time required for scanning (switching) the modules. The change in the short-circuit current Isc of the 10 modules within 20 s was designed to be suppressed on sunny days. Therefore, the data obtained at times of less change in irradiance were selected. The I-V curves of the 10 modules were obtained at irradiiances of 0, 0.3, 0.7, and 1.1 kW/m².

Fig. 3 Installed situation of deteriorated modules

The 10 modules were installed on the roof of a building at the SUWA Campus of Tokyo University of Science. A pyranometer and PV modules were positioned to face south with an angle of inclination of 30°. The temperature of the modules was measured using thermocouples attached to the back of the modules. Fig. 3 shows a photograph of the deteriorated modules with different deterioration states with characteristics summarized in Tables 1 and 2 installed on the roof.

2.3 Four constants used as diagnostic indices

The electric characteristics of a standard module are represented by the equation of an equivalent circuit of a solar cell expressed by

\[ I_{c} = I_{ph} - A \left( \exp \frac{q}{nkT} (V_{L} + I_{L}R_{s}) - 1 \right) \frac{V_{L} + I_{L}R_{s}}{R_{sh}} \]  

(1)

Where \( R_{s} \) is the series resistance [Ω], \( R_{sh} \) is the shunt resistance [A], \( n \) is the diode factor, \( A \) is the saturation current [A], \( k \) is the Boltzmann constant, and \( T \) is the scale temperature [K].

In this study, we define fitting as determining the four constants (i.e., \( R_{s}, R_{sh}, n, \) and \( A \)) that optimally express the obtained I-V curves as follows.

1) Draw the I-V curves for the data calculated by the Newton-Raphson method. The measured short-circuit current \( (I_{sc}) \) was used as the photocurrent \( (I_{ph}) \) to obtain I-V curves. The measured scale temperature \( T \) was also used as the cell temperature. Calculate the current of the I-V curve \( (I_{LC}) \) for a given voltage \( (V_{L}) \) by substituting appropriate values for the four constants.

2) Calculate the deviation between the calculated and measured currents \( (I_{LC}) \). Add the squares of deviations of the I-V curves. Then, obtain the sum of the squares of deviations of the calculated and measured currents \( (\epsilon) \) using

\[ \epsilon = \sum_{s} (I_{LC} - I_{LM})^{2} \]  

(2)

Where \( I_{LC} \) [A] is the calculated current of the I-V curve for a given voltage \( (V_{L}) \), \( I_{LM} \) is the measured current, and \( S \) is the number of evaluated points.

3) Repeat steps 1) and 2) to determine the four constants until the sum of the squares of deviations becomes minimum.

The four constants of the 10 modules under various environmental conditions were determined and analyzed.

3. I-V Curve Simulation Using Equivalent Circuit

3.1 Simulation of electric circuit and setting condition

The changes in I-V curves with changing \( R_{s} \) and \( R_{sh} \) are simulated using simulation software for electric circuits, “B2 spice”. The irradiance was varied to 0, 0.3, 0.7, and 1 kW/m², and the cell temperature was fixed at 300 K.

3.2 Deterioration parameters, \( R_{s} \) and \( R_{sh} \)

The four constants are related to the deterioration of PV modules. \( R_{s} \) and \( R_{sh} \) changed near their mean values of the standard modules of the same model. Fig. 4 shows the I-V curves obtained by simulation with changing \( R_{s} \) for four different irradiances. Fig. 5 shows the I-V curves obtained by simulation with changing \( R_{sh} \) at an irradiance of 0 kW/m² (dark state). Similar I-V curves were obtained even when the irradiance was changed.

3.3 Change in I-V curves with changing \( R_{s} \) and \( R_{sh} \)

The simulation data show that the I-V curves become gentle at around the maximum power point (the \( P_{max} \) point) and FF decreases with increasing \( R_{s} \) at the high irradiance of 11 kW/m², as shown in Fig. 4(a). The change in I-V curves in the first quadrant increases with increasing irradiance and FF decreases with increasing \( R_{s} \). This trend is considered to be affected by the magnitude of the current in the first quadrant.

The change in I-V curves with changing \( R_{sh} \) is smaller than that with changing \( R_{s} \). With increasing irradiance, the change in the \( P_{max} \) point or in FF decreases relatively.
4. Measured I-V Curves Obtained under Various Conditions

4.1 Measured I-V curves of 10 modules

Figs. 6(a)-6(e) show I-V curves for the 10 modules obtained at irradiances of 0, 0.1, 0.3, 0.7, and 1.1 kW/m², which were identical to those in the simulation of I-V curves using an equivalent circuit of solar cells. As shown in Figs. 6(a)-6(e), Isc values for the 10 modules are almost the same as those in the simulation. For the data with the same Isc, the measured data were selected to easily compare the shape of I-V curves with those of other I-V curves.

All irradiances were measured similarly with I-V curves measurement interval for 1 min. The temperature of the modules was measured in the field and is shown at the lower part of each figure.

4.2 Comparison of I-V curve obtained under different Rs and Rsh values

At irradiances of 0, 0.1 and 0.3 kW/m², only the slope of Rs changes in the I-V curves of the 10 modules. This finding indicates that the slope in Rs is measurable at the irradiance of 0 kW/m². If the slope in Rs is traced for a long time, developing failures can be detected from the change in Rs. At irradiances of 0.7 and 1.1 kW/m², the I-V curves become gentle at around the Pmax point and thus FF decreases with increasing Rs. This phenomenon is similar to that observed in the I-V curves obtained by simulation using an equivalent circuit of solar cells, as shown in Fig. 4. In the 10 deteriorated modules with different deterioration states, this effect is stronger than the effect of the change in Rsh.

At irradiances of 0, 0.1 and 0.3 kW/m², the slope of Rsh in the I-V curves for the 10 modules are almost flat. At irradiances of 0.7 and 11 kW/m², the slope of Rsh in the deteriorated modules with different deterioration states slightly changes at the left side of the Pmax point compared with that of stable standard modules. This difference is
considered to be due to the difference in state between cells and bus bars caused by failure and large current flow. Considering the simulation data shown in Fig. 5, the effect of $R_{sh}$ on $I-V$ curves is considered to be caused by the difference in state between the cells in the modules. In the 10 deteriorated modules with different deterioration states, this effect is smaller than the effect of the change in $R_s$.

5. Constants under Different Irradiance

Fig. 7 shows (a) $R_s$, (b) $R_{sh}$, (c) $n$, and (d) $A$ for the 10 modules (labelled with the module number) classified into three classes (classes A, B, and C). It is considered that the four constants can be used to detect the failures and disconnections of modules in a string, and can serve as diagnostic indices. By examining the changes in the four constants under different irradiances, the feasibility of using...
these four constants as diagnostic indices was examined. The number of cells that constitute one module is 54 (6 × 9), as shown in Fig. 2. All cells of module are connected in series. The values of the four constants in Fig. 7 are those obtained using eq. (1) assuming that variables in eq. (1) are determined for one module.

As shown in Fig. 7(a), $R_s$ changes negligibly with changing irradiance. The $R_s$ values of class A and class B modules become almost constant and stable with changing irradiance. However, the $R_s$ values of class C modules become higher than those of class A and class B modules, and unstable with changing irradiance.

$R_s$ values can be reproduced reasonably well by fitting using the four constants of an equivalent circuit of solar cells. As shown in Fig. 7(b), $R_{sh}$ values become unstable with changing irradiance. $R_{sh}$ values are unrelated to the class of modules and cannot be reproduced reasonably well by fitting using the four constants.

As shown in Fig. 7(c), the $n$ values of class A modules become stable with changing irradiance. In contrast, the $n$ values of class B and class C modules increase with increasing irradiance. $n$ values can be reproduced reasonably well by fitting using the four constants. As shown in Fig. 7(d), the $A$ values of, in particular, class C modules increase exponentially with increasing irradiance. This tendency is similar to that of $n$. This phenomenon is considered to depend on the increase in $I_{sc}$, the state of cells, and the cell temperature.

In summary, the $R_s$ values of class A and class B modules become almost stable with changing irradiance. The $n$ values of class A modules become stable with changing irradiance. $R_s$ and $n$ values can be reproduced reasonably well by fitting using the four constants. $n$ and $A$ values show similar tendencies with changing irradiance for each class. The four constants are expected to be used as diagnostic indices after more data are accumulated by diagnosing more modules.

6. Conclusion

In this study, we evaluated the technique of a diagnostic system with an advanced technique to obtain $I$-$V$ curves in the first and the fourth quadrant under different irradiances. 10 deteriorated modules with different deterioration states in the same model were used for evaluation. The four constants (i.e., $R_s$, $R_{sh}$, $n$, and $A$) of an equivalent circuit of a solar cell can be used as diagnostic indices and were analyzed to evaluate the irradiance dependence using these constants. We obtained the following conclusions.

1) As indicated by the $I$-$V$ curves obtained by simulation,
the \( I-V \) curves became gentle at around the \( P_{\text{max}} \) point with increasing \( R_s \). The \( I-V \) curves of the 10 modules used in this study showed a similar tendency to those obtained by simulation. The \( I-V \) curves were observed to be more affected by \( R_s \) than by \( R_{\text{sh}} \).

2) At irradiances of 0, 0.1, and 0.3 kW/m\(^2\), only the change in \( R_s \) was observed in the \( I-V \) curves of the 10 modules. For the diagnosis of the disconnections of modules in a string, our proposed technique can be used to predict them under irradiance less than 0.3 kW/m\(^2\) from the slope of \( R_s \).

3) Four constants of an equivalent circuit of solar cells were obtained by fitting them to the obtained \( I-V \) curves. \( R_s \) and \( n \) values were reproduced reasonably well by fitting using the four constants. However, \( R_{\text{sh}} \) values were observed to be unstable and could not be reproduced reasonably well by the fitting. \( n \) and \( A \) values showed similar tendencies that the value increase with increasing irradiance. These four constants are expected to be used as diagnostic indices.

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