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Detection of cell cracks and increased series resistance of crystalline silicon photovoltaic modules by using voltage and current at maximum power point

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ABSTRACT

Various types of degradations and failures occur in photovoltaic (PV) modules during their outdoor operation, such as cell cracks and an increase in series resistance. Sensitive detection of them is essential to improve the efficiency and reliability of the PV modules and systems. Previous detection techniques such as the *I*–*V* curve measurement had a problem because they needed to interrupt the maximum power point tracking (MPPT) operation of the PV system. This study proposes a new method to detect those degradations and failures without interrupting the MPPT operation by using the time-series data of the voltage and current at the maximum power point (V_{mp} and I_{mp}, respectively). The V_{mp} and I_{mp} are corrected for temperature using recently developed temperature correction formulas, and are analyzed as the I_{mp}–V_{mp} curves. It is shown that the existence of a cracked cell in a PV module can be sensitively detected from the I_{mp}–V_{mp} curve, since the decrease in the photocurrent of a cracked cell tends to shift a part of the I_{mp}–V_{mp} curve of the module toward high voltage. The experimental and simulation results indicate that a small cell crack less than 10% of a cell area can be detected. In addition, the simulation results also reveal that the increase in series resistance can be detected by the distortion of the I_{mp}–V_{mp} curve toward a lower voltage in the high I_{mp}, or high irradiance, region. These simulation results indicate that the present method is very powerful for detecting the degradation and failure of PV modules and systems.

Keywords: cell-crack, series resistance, voltage at maximum power point, current at maximum power point, temperature correction, crystalline silicon photovoltaics

1. INTRODUCTION

Photovoltaic (PV) modules and systems operate under various environmental conditions such as temperature, irradiance, and surrounding environment. Some defects, such as cell cracks and an increase in series resistance (R_s), which are caused by mechanical stresses and solder bond failure, affect the reliability of the PV modules and systems. These deteriorations would reduce energy production and impose severe risks on the PV modules and systems over time [1, 2].

Previous studies have proposed several techniques, such as the electroluminescence (EL) [1, 2, 3] and current-voltage (*I*–*V*) curve measurement [4], to investigate cell cracks. Although the *I*–*V* curves and power-voltage (*P*–*V*) curves are useful for assessing the failure of the PV modules and systems, there is a significant disadvantage as well; the measurements need to stop the maximum power point tracking (MPPT) operation of the system, and require additional test equipment, i.e., the *I*–*V* tester [5]. In order to solve the problem, the present study measures the voltage (V_{mp}) and current (I_{mp}) at the maximum power point, which are practically the only electrical parameters that can be measured without interrupting the MPPT operation. The present study also firstly utilizes the temperature-corrected I_{mp}–V_{mp} curves instead of the *I*–*V* curve. Conventionally, the analysis of the V_{mp} was not straightforward because it significantly fluctuates [6] owing to the variation in module temperature (T_m) and irradiance. Therefore, this study has utilized new formulas that can accurately translate the V_{mp} and I_{mp} for temperature and irradiance, which were recently proposed by the authors [7].

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In this study, the effect of degradation, such as the cell crack and increase in R_s, was investigated by a numerical simulation to investigate the basic method for detecting degradation by using the I_{mp}–V_{mp} curve.

2. METHODS

2.1 Temperature correction of V_{mp} and I_{mp}

Figure 1 shows an example of the correction of V_{mp} and I_{mp} for temperature. Because the experimental timeline data of V_{mp} are strongly affected by the variation of the T_m, the measured raw data of the I_{mp}–V_{mp} curve has a rather complex shape, as shown by the black symbols in Fig. 1. Therefore, further precise analysis is difficult based on the raw I_{mp}–V_{mp} curve. The measured V_{mp} and I_{mp} are corrected to 25 °C using Eqs. (1) and (2) [7], which are indicated by red symbols in Fig. 1. Evidently, the variation of V_{mp} due to the fluctuation of the measured module temperature (T_1) is significantly reduced by the temperature correction, and the relation between I_{mp} and V_{mp} (e.g., the I_{mp}–V_{mp} curve) is well defined. The standard deviation, σ, of the voltage after correction V_{mp2} in the I_{mp} ranges of 4.6 ± 0.25 A was relative 0.023 V. The variation of V_{mp} at the same range of I_{mp} is approximately ±1%.

$$V_{\mathrm{mp2}} = \left[V_{\mathrm{mp1}} + \frac{T_2 - T_1}{T_1}\left(V_{\mathrm{mp1}} - \frac{nE_{\mathrm{g}}}{q} \cdot N_{\mathrm{c}}\right)\right] \times [1 + \alpha(T_2 - T_1)], \quad (1)$$

$$I_{\mathrm{mp2}} = I_{\mathrm{mp1}}. \quad (2)$$

Here, T_1 and T_2 are the measured and target T_m in Kelvin (K), respectively. V_{mp1} and V_{mp2} are the V_{mp} at T_1 and T_2, respectively. E_g is the bandgap energy of silicon. n is the diode ideality factor of the p–n junction, q is the electron charge, N_c is the number of series-connected cells, and α is the temperature coefficient (TC) of the short-circuit current (I_{sc}). α is estimated to have a typical value of 0.05%/K [8, 9]. I_{mp1} and I_{mp2} are the I_{mp} at T_1 and T_2, respectively. nE_g/q, which is known to reproduce the TC of the output voltage for various kinds of crystalline silicon PV modules, is estimated to have a value of approximately 1.232 V. An advantage of these formulas over the previously proposed ones [7, 9, 10] is that they are applicable to various crystalline silicon PV modules without advanced information of I–V curve parameters or diode parameters.

2.2 Cell crack

Numerical simulation was performed in this study to investigate the possible detection of cell cracks using the I_{mp}–V_{mp} curve. A cracked cell was represented by a cell with a reduced active area. The output current of a

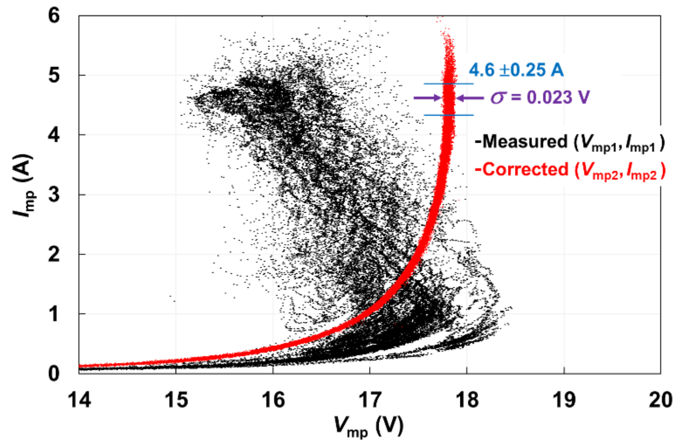

Fig. 1 Measured V_{mp} and I_{mp} are shown by the black symbols. The red symbols show the curve corrected to 25 °C using Eqs. (1) and (2). Details of the experiments are described in reference [11].

silicon PV cell for simulation in this study was expressed by the Bishops model as follows [12]:

$$I = I_{\mathrm{ph}} - I_0\left[\exp^{\left(\frac{q(V+IR_{\mathrm{s}})}{N_{\mathrm{c}}nkT}\right)} - 1\right] - \frac{V+IR_{\mathrm{s}}}{R_{\mathrm{sh}}}\left[1 + a\left(1 - \frac{V+IR_{\mathrm{s}}}{V_{\mathrm{br}}}\right)^{-m}\right]. \quad (3)$$

Here, I_{ph} is the photocurrent, I_0 is the diode reverse saturation current, V is the output voltage, R_s is the series resistance, k is Boltzmann's constant, T is the device temperature in K, R_{sh} is the shunt resistance, a is the fraction of ohmic current involved in avalanche breakdown, m is the avalanche breakdown exponent, and V_{br} is the junction breakdown voltage. V_{br} is known to be in the range between - 12 V and - 30 V for a mono-crystalline silicon cell [13]. For the cracked cell, I_{ph} and I_0 are assumed to be proportional to the active area of the cell. Therefore, R_s and R_{sh} are assumed to be inversely proportional to the cell area. The I_{mp} and V_{mp} of a module with one cracked cell are determined from the I–V curve of the module, where the output voltage of the module is calculated by the sum of the voltage of the component cells. For the simulation, the total number of series-connected cells in the module is assumed to be 36, with two bypass diodes. A model of a cracked cell for simulation is shown in Fig. 2, where the dark area is considered as the inactive area.

2.3 Effect of R_s

Another numerical simulation was performed for assessing the degradation with increasing R_s. The I_{mp} and V_{mp} of a module, with one of the 36 series-connected cells with increased R_s, were determined from the I–V curve of a module. A model of a module with an increased R_s is shown in Fig. 3, which exhibits the

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interconnection failure or solder bond failure as an example of increased R_s-based degradation.

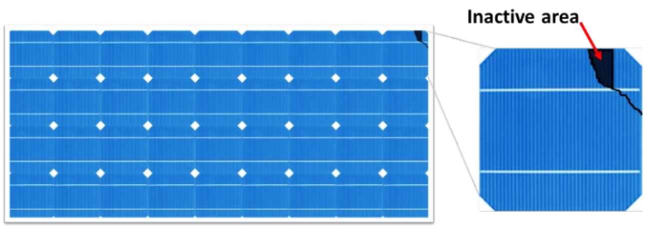

Fig. 2. Model of a module with a cell with crack. A black line shows a crack on a cell, and a dark area shows an inactive area.

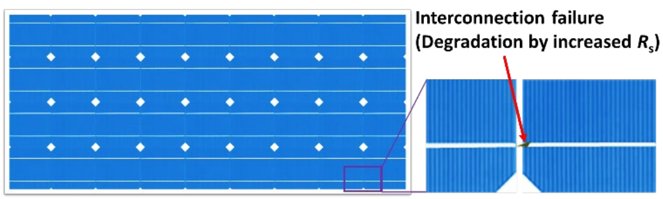

Fig. 3. Model of a module with a cell with an increased R_s; an interconnection failure is an example of degradation by increased R_s.

3. RESULTS AND DISCUSSIONS

3.1 *Simulation of cell crack effect*

The numerical simulations of the I_{mp}–V_{mp} curves of a crystalline silicon PV module with and without a cracked cell using Eq. (3) were carried out, as shown in Fig. 4 by the blue lines and a red line, respectively. For the cell without a crack, the cell parameters of I_{ph} = 5.262 A at irradiance (G) = 1.0 kW/m^2, I_0 = 5.3 × 10^{-9} A, R_s = 6.4 mΩ/cell, R_{sh} = 7 Ω/cell, n = 1.147, T = 25 °C, a = 0.1, V_{br} = -30 V, and m = 4 were chosen to fit the experimental data of Fig. 1. The results show that the I_{mp}–V_{mp} curve with a cracked cell shifts toward a higher voltage as the ratio of cracked cell increases. A crack of 7% and 14% of the cell area resulted in a shift in V_{mp} of approximately 0.18 V and 0.90 V, respectively. Considering the result shown in Fig. 1, the experimental scatter in V_{mp} can be suppressed to 0.14 V by the temperature correction. The plots in Fig. 4 suggest that a cell crack in the range of 7 - 14% can be detected by the I_{mp}–V_{mp} curve.

3.2 *Simulation of R_s effect*

The results of the simulation with and without a cell with an increased R_s are demonstrated by the blue lines and a red line in Fig. 5, respectively. The parameters of normal cells (i.e., without an increased R_s) were assumed to be identical to those in Fig. 4. The results show that the I_{mp}–V_{mp} curve with an increased R_s shifts toward lower voltages as R_s increases. The shift in V_{mp} is larger for a higher I_{mp} or a higher irradiance. The figure indicates that the shift in V_{mp} at I_{mp} of about 5.66 A amounts to 0.50 - 2.88 V when R_s is increased to 0.1 - 0.6 Ω on one cell. Therefore, the present results suggest that an increase in R_s in the range of 0.1 - 0.6 Ω on one cell can be detected by the I_{mp}–V_{mp} curve.

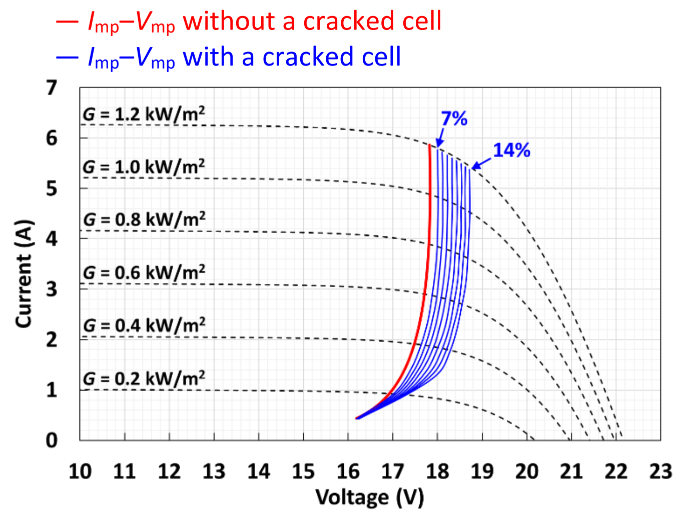

Fig. 4. I_{mp}–V_{mp} curves of a PV module with and without a cracked cell are represented by blue lines and a red line, respectively. One of the 36 series-connected cells was assumed to have a crack ranging from 7% to 14% of the cell area. The I–V curves of the module under an irradiance range of 0.2 - 1.2 kW/m^2 are also shown by black dashed lines.

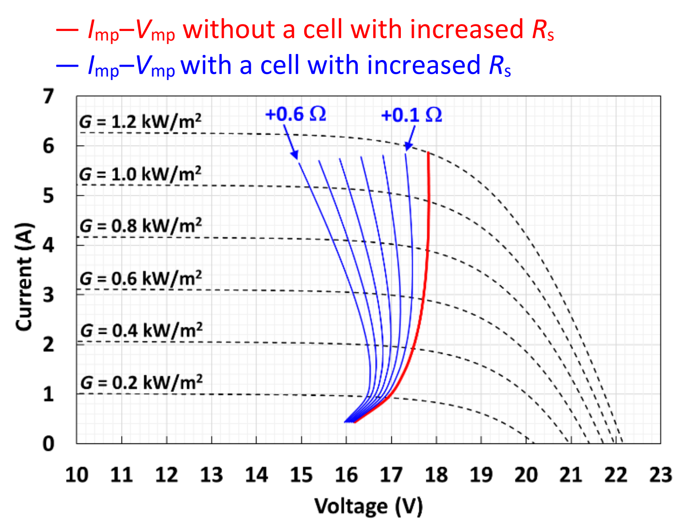

Fig. 5. I_{mp}–V_{mp} curves of a PV module with and without an increase in series resistance are represented by blue lines and a red line, respectively. One of the 36 series-connected cells was assumed to have an increased R_s. The I–V curves of the module under an irradiance range of 0.2 - 1.2 kW/m^2 are also shown by black dashed lines.

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4. CONCLUSIONS

This study has firstly investigated methods to detect the degradation of a PV module from the temperature-corrected I_{mp}–V_{mp} curve, which is applied for degradation detection, using experimental data. It is an advantage over the I–V curve measurement which needs to interrupting the MPPT operation. In this study, the time-series data of experimental I_{mp} and V_{mp} are corrected for temperature using recently developed formulas to reduce the scatter in V_{mp} due to the large variation in the module temperature and to clarify the I_{mp}–V_{mp} curve. The simulation results indicate that the I_{mp}–V_{mp} curve shifts toward high V_{mp} when the existence of a cracked cell in the module is occurred. Therefore, the existence of a cracked cell can be detected by the shift of the I_{mp}–V_{mp} curve toward a higher voltage. In addition, the results show that the I_{mp}–V_{mp} curve shifts toward lower voltages as R_s increases. The shift in V_{mp} increases for a higher I_{mp} or a higher irradiance. Therefore, an increase in R_s can also be detected from the I_{mp}–V_{mp} curve. Further, this study found that a cell crack in the range of approximately 7 - 14% and an increase in R_s in the range of approximately 0.1 - 0.6 Ω in one cell can be detected using the I_{mp}–V_{mp} curve. The results are applicable not only to a single PV module but also to a PV system where multiple modules are connected in series. The detection sensitivity should vary depending on the type of PV module and the measurement conditions of I_{mp} and V_{mp}.

The proposed method can be flexibly used for various types of PV modules and systems as it uses only the V_{mp}, I_{mp}, and T_m, which can be measured by inexpensive equipment and without interrupting the MPPT operation. Furthermore, the temperature correction formulas in Eqs. (1) and (2) can be applied to various kinds of crystalline silicon PV modules without advanced knowledge of module-specific parameters, such as the temperature coefficient. Therefore, this method is useful for identifying the cell crack and cell degradation which increases R_s, by using the time-series data of I_{mp} and V_{mp} from the PV system monitoring. Experimental confirmation of the obtained results and applicability of the proposed method for other degradation modes, such as potential-induced degradation (PID) and bypass diode failure, are subjects of future potential studies in this field.

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