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

Manit Seapan[1], Yoshihiro Hishikawa[2], Masahiro Yoshita[2], Keiichi Okajima[1]

1 Department of Risk Engineering, University of Tsukuba

2 Renewable Energy Research Center, AIST

Research purpose

- Degradations and failures occur in PV modules during their outdoor operation, such as cell cracks and an increase in series resistance (R_s).
- Previous detection techniques, such as *I*–*V* curve measurement, had a problem because they needed to interrupt the system operation.
- This study utilizes the temperature corrected of current-voltage at maximum power (I_{mp}–V_{mp}) curve instead of the *I*–*V* curve using the new formulas recently proposed [1].
- Cracked cell and increase in R_s were investigated by simulations for detecting degradation using I_{mp}–V_{mp} curve.

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

The measured V_{mp} and I_{mp} are corrected to 25 °C using Eqs. (1) and (2) [1], as shown in Fig. 1.

$$V_{mp2} = \left[V_{mp1} + \frac{T_2 - T_1}{T_1}\left(V_{mp1} - \frac{nE_g}{q}\cdot N_c\right)\right] \times [1 + \alpha(T_2 - T_1)], \quad (1)$$

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

Here, T_1 and T_2 is the measured and target module temperature 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, 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 value of 0.05%/K . I_{mp1} and I_{mp2} are the I_{mp} at T_1 and T_2, respectively. nE_g/q is estimated to have a value of approximately 1.232 V.

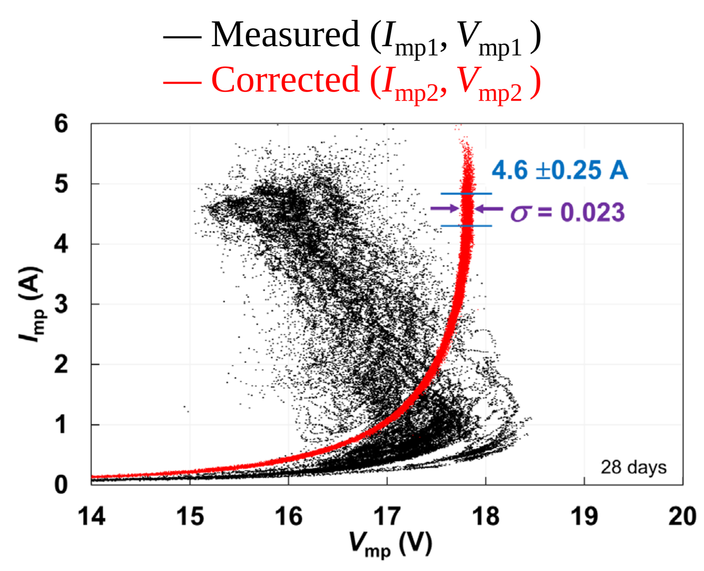

Fig. 1 Measured I_{mp} and V_{mp} are shown by the black symbols. The red symbols show the curve corrected to 25 °C using Eqs. (1) and (2).

Cell crack and effect of R_s

Cell crack

Numerical simulation has been performed to investigate the possible detection of cell cracks using the I_{mp}–V_{mp} curve.

A cracked cell is represented by a cell with a reduced active area, as shown in Fig. 2.

The output current of a silicon PV cell for simulation is expressed by the Bishops model [2] as follows:

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

Here, I_{ph} is the photocurrent, I_0 is the diode reverse saturation current, V is the output voltage, 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.

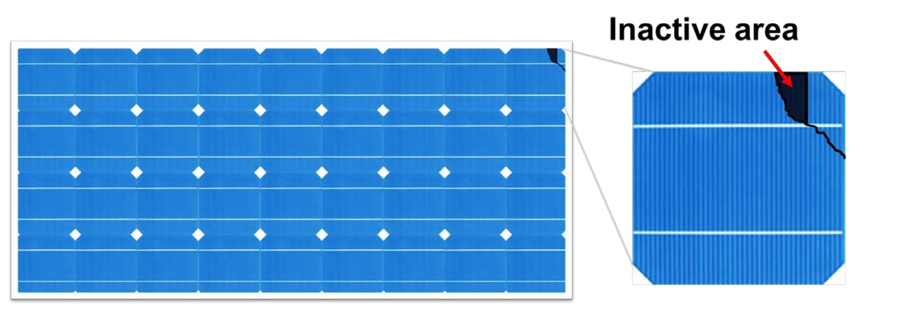

Fig. 2. Model of a module with a cell with crack. A black line shows a crack on a cell, and a dark area shows an inactive area.

Effect of R_s

Another numerical simulation has been 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 interconnection failure or solder bond failure as an example of increased R_s-based degradation.

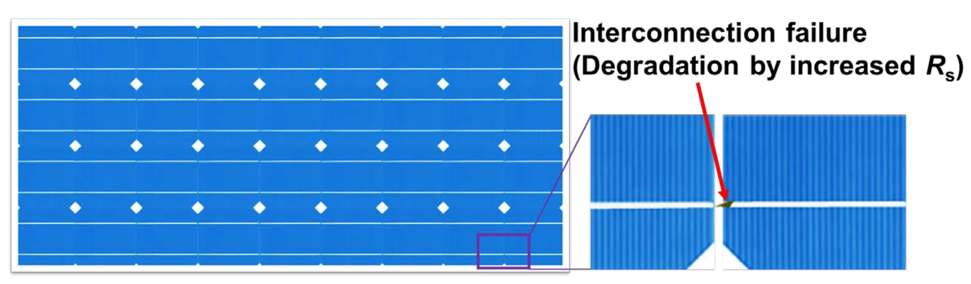

Fig. 3. Model of a module with a cell with an increased R_s; an interconnection failure is an example of degradation by increased R_s.

Results and discussions

Simulation of cell crack effect

The 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 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} curves with a cracked cell shift toward a higher voltage as the ratio of cracked cell increases (A cracked area from 7% to 14% of the cell area). An illustration of the variation of I_{mp} and V_{mp} by a cracked cell is shown in Fig. 5, where one of the 36 series-connected cells was assumed to have a crack.

Simulation of R_s effect

The simulation results with and without a cell with an increased R_s are demonstrated by the blue lines and a red line in Fig. 6, 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 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} curves. An illustration of the variation of I_{mp} and V_{mp} by an increase in R_s is shown in Fig. 7, where one of the 36 series-connected cells was assumed to have an increased R_s.

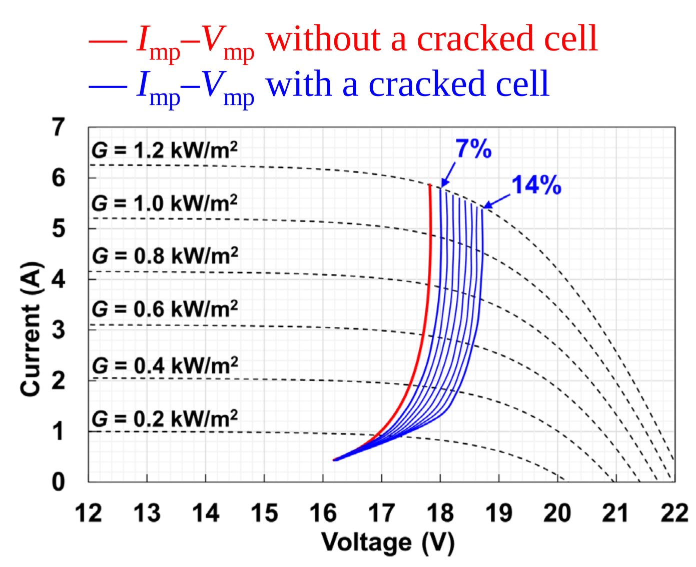

Fig. 4. I_{mp}–V_{mp} curves of a PV module with and without a cracked cell are represented by blue lines and a red line, respectively.

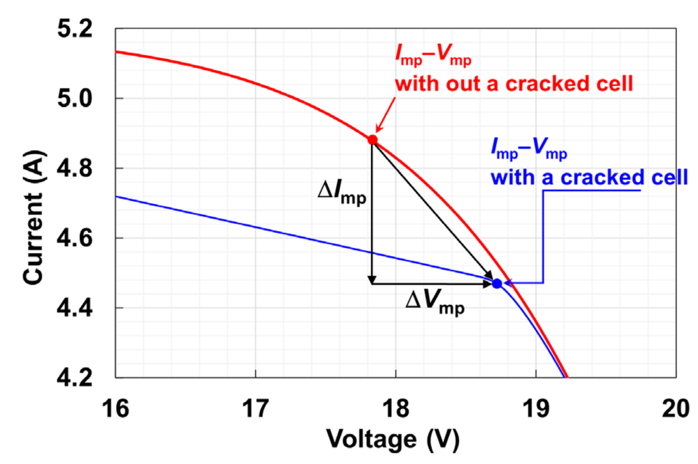

Fig. 5. An illustration of the variation of the I_{mp} and V_{mp} by the effect of cracked cell.

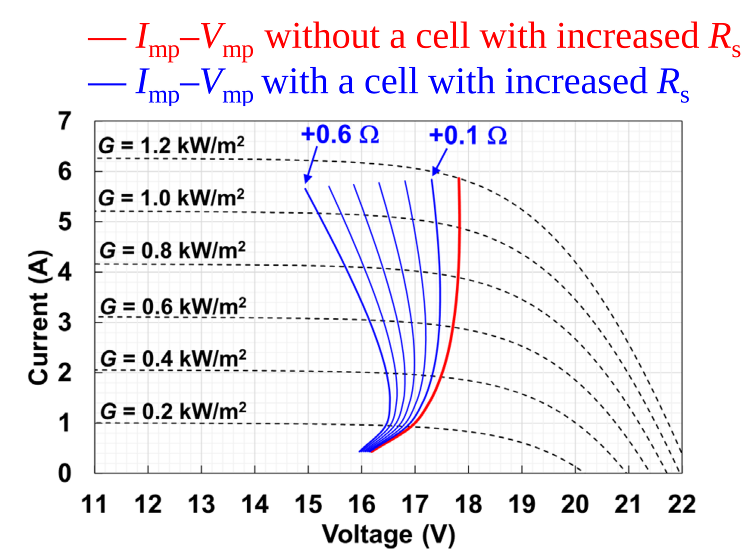

Fig. 6. I_{mp}–V_{mp} curves of a PV module with and without an increase in R_s are represented by blue lines and a red line, respectively.

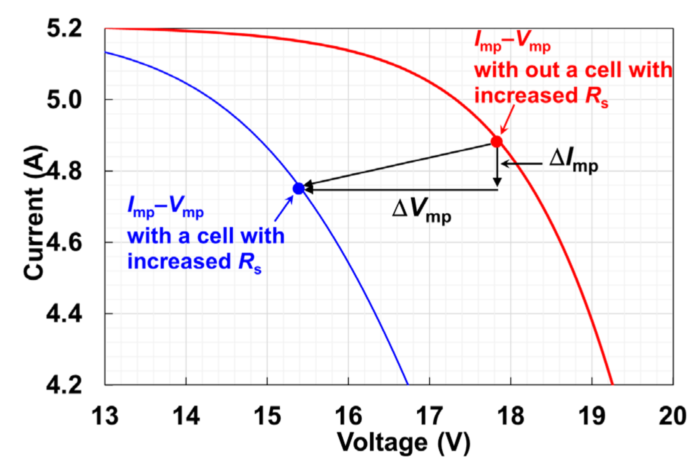

Fig. 7. An illustration of the variation of the I_{mp} and V_{mp} by the effect of in crease in R_s.

Conclusion

- This method uses the new formulas corrected time-series data of V_{mp} and I_{mp} for temperature.
- Only the V_{mp}, I_{mp}, and module temperature are necessary without other module-specific parameters, such as the TC.
- We firstly utilize the I_{mp}–V_{mp} curve to identify a cracked cell and increase in R_s in the PV module.
- The results are applicable to a single PV module and multiple PV modules connected in series.
- The proposed method can be flexibly applicable for various types of PV modules and systems as it uses only the V_{mp}, I_{mp}, and module temperature.

Acknowledgment

This work was supported in part by NEDO under METI

References

[1] M. Seapan, Y. Hishikawa, M. Yoshita, K. Okajima. Temperature and irradiance dependences of the current and voltage at maximum power of crystalline silicon PV devices. Sol. Energy, vol. 204, 459-465, (2020).

[2] J.W. Bishop. Computer simulation of the effects of electrical mismatches in photovoltaic cell interconnection circuits. Sol. Cells, vol. 25, 73-89, (1988).