Research Center for Photovoltaics

Temperature and Irradiance Dependences of the Current and Voltage at Maximum Power of Crystalline Silicon PV Modules

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Purpose

This study analytically and experimentally investigated expressions for the temperature and irradiance dependences of current at maximum power I_{mp} and voltage at maximum power V_{mp} of crystalline silicon solar cells. Based on these results, a new formula for temperature correction of V_{mp} was discussed. The simple formula for estimating maximum power point (MPP) P_{max} was presented, which was derived from the corrected I_{mp} and V_{mp}. The correction formulas were investigated without information on current-voltage (*IV*) curve parameters or diode parameters.

Formulas of I_{mp} and V_{mp}

The output current I of the PV module can be approximately expressed as follow,

$$I = I_{sc} - I_0 \exp\left(\frac{q(V+IR_s)}{N_c nkT}\right) - \frac{V+IR_s}{R_{sh}}. \qquad (1)$$

The derivative of V in (1) with respect to I at MPP and the following is satisfied,

$$-\left.\frac{dV}{dI}\right|_{mp} = \frac{V_{mp}}{I_{mp}}. \qquad (2)$$

The I_{mp} can be expressed as follow

$$I_{mp} = V_{mp} \cdot \frac{\frac{1}{R_{sh}} + \frac{qI_0}{N_c nkT}\exp\left(\frac{q(V_{mp}+I_{mp}R_s)}{N_c nkT}\right)}{1+\frac{R_s}{R_{sh}} + \frac{qI_0 R_s}{N_c nkT}\exp\left(\frac{q(V_{mp}+I_{mp}R_s)}{N_c nkT}\right)}. \qquad (3)$$

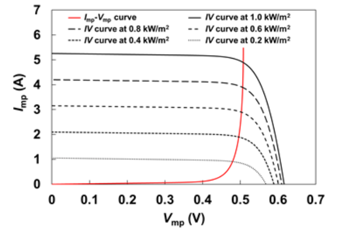

Fig. 1. The I_{mp} vs. V_{mp} curve calculated from Eq. (3) and *IV* curves at 5 irradiance levels.

Simulation of the temperature and irradiance dependences of I_{mp}

From Eq. (1), we obtain

$$I_{mp} = I_{sc} + I_{sc}(T-T_0) - A\cdot\exp\left(\frac{q(V_{mp}+I_{mp}R_s)}{N_c nkT} - \frac{E_g}{kT}\right) - \frac{V_{mp}+I_{mp}R_s}{R_{sh}}. \quad (4)$$

Here, α is the temperature coefficient of I_{sc} which is assumed to be 0.05%/K, T_0 = 25 °C (298.15 K), N_c is the number of series-connected cells in the module, and I_0 is assumed to be expressed as $I_0 = A\cdot\exp\left(\frac{-E_g}{kT}\right)$. Here, A is constant parameter and E_g is the bandgap energy. The E_g was assumed to be 1.12 eV [1]. The results show that the temperature coefficient of I_{mp} is within ±0.015 or 0.02%/K and the nonlinearity of I_{mp}/G is within ±0.013.

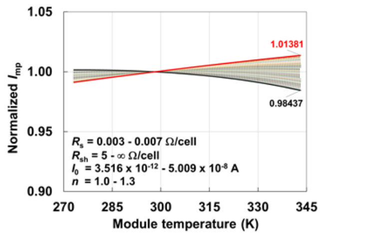

Fig. 2. Normalized I_{mp} vs. module temperatures at 1 kW/m².

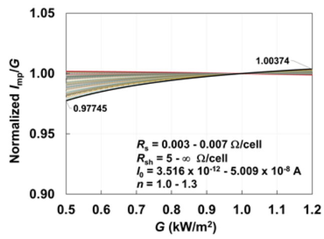

Fig. 3. Normalized I_{mp}/G vs. G at 25 ºC.

Translation equation

As discussed in the previous sections, the I_{mp} is nearly constant for a wide range of temperature variation. Therefore, the translation formula for voltage from [2] can be used as follow,

$$V'_{mp2} = V_{mp1} + \frac{T_2-T_1}{T_1}\left(V_{mp1} - \frac{nE_g}{q}\cdot N_c\right). \qquad (5)$$

Considering the slight temperature dependence of I_{sc} Eq. (5) can be corrected as follows,

$$V_{mp2} - V'_{mp2} = \frac{N_c nkT_2}{q}\ln\left(\frac{I_{sc2}-I_{mp1}}{I_{sc1}-I_{mp1}}\right) \qquad (6)$$

$$-\left.\frac{\partial V}{\partial I}\right|_{mp} = \frac{V'_{mp2}}{I_{mp1}} = \frac{\Delta V}{\Delta I} \qquad (7)$$

$$\Delta V = V'_{mp2}\frac{\Delta I}{I_{mp1}} \qquad (8)$$

if R_s is small, $\Delta I \cong I_{sc}\cdot\alpha(T_2-T_1)$. (9)

If we approximate $\frac{I_{mp}}{I_{sc}} \approx 1$,

$$\Delta V \cong V'_{mp2}\times\alpha(T_2-T_1). \qquad (10)$$

The equation for temperature correction of V_{mp}, which does not include I_{sc}, can be expressed as follow,

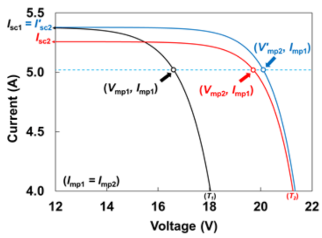

Fig. 4. The V_{mp1} is measured V_{mp} and V'_{mp2} is corrected V_{mp} by Eq. (5).

$$V_{mp2} = V'_{mp2} + V'_{mp2}\times\alpha(T_2-T_1). \quad (11)$$

The P_{max} at the target temperature can be estimated if the G is known by a separate measurement,

$$P_{max2} \cong V_{mp2}\times\frac{1000}{G_1}I_{mp1}. \qquad (12)$$

Equations (5) and (11) were used for the outdoor experimental V_{mp} of a commercial crystalline silicon PV module. Here, the nE_g/q = 1.2 V was chosen from the best-fit to experimental data. The N_c of the module is 36.

Experimental results

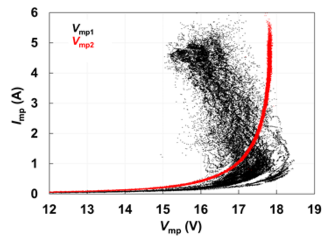

Fig. 5. Experimental I_{mp} vs. V_{mp1} and V_{mp2} plots for 28 days.

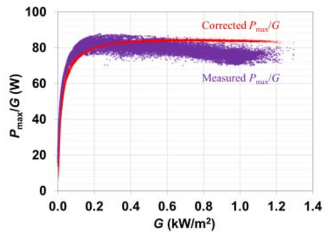

Fig. 6. Corrected P_{max}/G vs. G plot (28 days). Corrected P_{max} was calculated by corrected $P_{max} = V_{mp2} \times I_{mp1}$.

Conclusion

- From the experiments and simulations by using single diode model, the I_{mp} is shown to be nearly constant for temperature range about 0-70 ºC. The simulation showed that the I_{mp} is nearly proportional to G in the irradiance range between 0.5 and 1.2 kW/m².
- The I_{mp}-V_{mp} curves corrected to 25 ºC by the formula showed good reproducibility for many days.
- The P_{max} also showed good reproducibility with the standard deviation within 3.3% for the irradiance range between 0.2 and 1.2 kW/m².
- These results are useful for characterizing the performance of crystalline silicon PV cells and modules by using the I_{mp} and V_{mp} values.

Acknowledgment

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References

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