TRANSLATION EQUATIONS FOR TEMPERATURE AND IRRADIANCE OF THE I-V CURVES OF VARIOUS PV CELLS AND MODULES BY LINEAR INTERPOLATION

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A new translation procedure based on the linear interpolation/extrapolation is proposed, in order to translate the I-V curves to target conditions of irradiance and temperature. The accuracy of the method is investigated, based on the indoor and outdoor I-V curves of various kinds of PV cells and modules. The calculated I-V curves over a wide range of irradiance and temperature well agree with experimental results for various kinds of PV cells and modules. These results indicate that the translation of the I-V curve based on the method is effective for estimating the performance of the PV devices under various climatic conditions.

Keywords: I-V curves, translation, temperature, irradiance

INTRODUCTION

It is useful to understand the effect of the irradiance and temperature on the photovoltaic (PV) cell and module performance, in order to estimate their I-V curves under various climate conditions for power rating and energy rating. Although translation equations based on "shifted approximation" are employed on irradiance dependence in some current standards [1], those equations can deviate from experiments when the variation in the irradiance and/or temperature is large. Also some equations are applicable for limited kinds of PV devices. Recently, the linear interpolation method for the I-V curves was proposed based on experimental (indoor and outdoor) data on various kinds of PV cells and modules [2-5]. This method can accurately estimate the performance of various kinds of PV cells and modules for a wide range of irradiance (G) and (T). This method requires that G or T of the reference I-V curves is the same. However, it is not always possible to obtain such reference I-V curves, especially under outdoor conditions. In this study a new practical formation for the linear interpolation/extrapolation is proposed. The accuracy of the method based on the experimental I-V curves of various kinds of PV cells and modules is investigated.

LINEAR INTERPOLATION METHOD

The present study demonstrates the new practical formulae [6, 7], which are extension of the equations and do not require adjustment of the reference I-V curves. The procedure of the linear interpolation/extrapolation of the present study is as follows. The measured current-voltage characteristics are corrected to target G and T values by equations (1) and (2).

$$V_3 = V_1 + a \cdot (V_2 - V_1) \tag{1}$$

$$I_3 = I_1 + a \cdot (I_2 - I_1) \tag{2}$$

Here, I_1 and V_1 are the current and voltage of the reference I-V curve measured at an irradiance G_1 and temperature T_1. I_2 and V_2 are the current and voltage of the reference I-V curve measured at G_2 and T_2. I_3 and V_3 are current and voltage of the I-V curve at G_3 and T_3. which is the target of the translation. The pair of (I_1,V_1) and (I_2, V_2) should be chosen so that $I_2 = I_1 + (I_{sc2} - I_{sc1})$. Here, I_{sc1} and I_{sc2} are the short circuit current of the reference I-V curves. a is a constant for the interpolation, which has the relation with the irradiance and temperature as shown in Eqs. (3) and (4) (Figs. 1-3). When $0< a <1$, the procedure is interpolation, When $a <0$ or $a >1$, the procedure is extrapolation.

$$G_3 = G_1 + a \cdot (G_2 - G_1)\ . \tag{3}$$

$$T_3 = T_1 + a \cdot (T_2 - T_1)\ . \tag{4}$$

Equation (5) is also applicable, when the I_{sc} of the device is linear with G. Here, I_{sc3} is the short circuit current of the target I-V curve.

$$I_{sc3} = I_{sc1} + a \cdot (I_{sc2} - I_{sc1})\ , \tag{5}$$

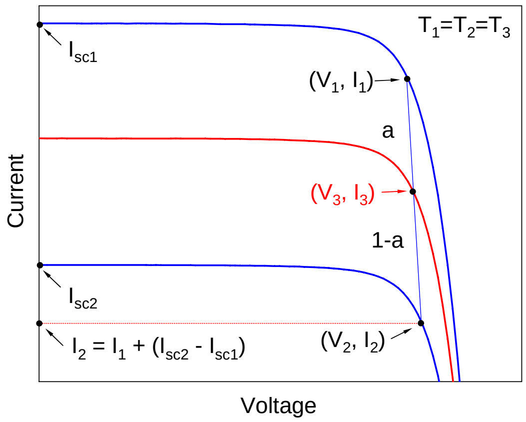

Fig.1 Schematic procedure for the calculations based on Eqs. (1)-(2); translation for G at constant T.

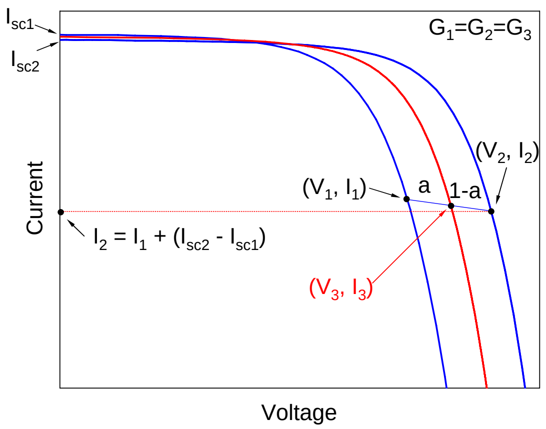

Fig.2 Schematic procedure for the calculations based on Eqs. (1)-(2); translation for T at constant G.

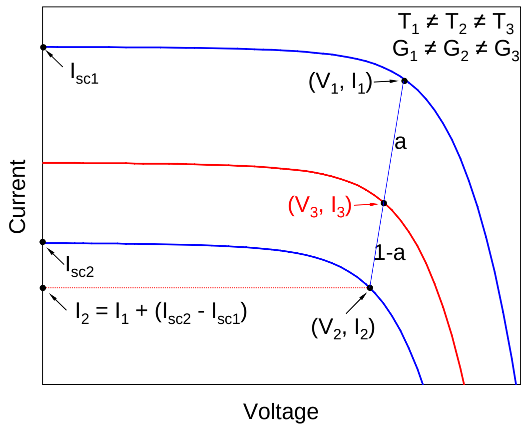

Fig. 3 Schematic procedure for the calculations based on Eqs. (1)-(2); simultaneous translation for G and T.

The primary advantage of the Eqs. (1), (2) is that there is no restriction for the I_{sc}(or G) and the T of the reference I-V curves. Therefore, any I-V curves can be used as the reference I-V curves without adjustment. Translation of the I-V curves for G at constant T (Fig. 1) and translation for T at constant G (Fig. 2) are possible by the same formulae. Furthermore, simultaneous translation for both G and T is possible within the relation of Eqs. (3) and (4).

By utilizing present procedure, I-V cures at wide range of G and T can be calculated from only three or four reference I-V curves measured at indoor or outdoor.

Fig. 4 shows the example of the linear interpolation/extrapolation of four reference I-V curves into the target I-V curve. 1-4 are reference I-V curves. 7 is the target I-V curve. First, I-V curves 5 under target temperature are calculated from I-V curves 1 and 2. Similarly, I-V curves 6 under target temperature are calculated from I-V curves 3 and 4. Then I-V curve 7 under target temperature and irradiance is calculated from I-V curves 5 and 6. It is noted that other order of the calculation is also possible. At least three reference I-V curves can calculate the I-V curves at wide range of G and T.

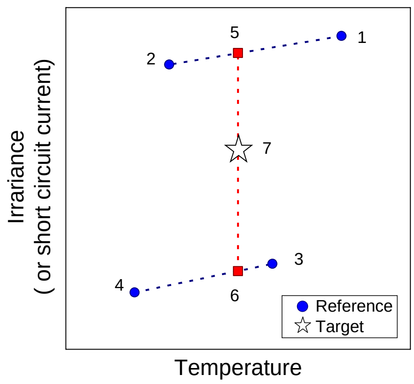

Fig.4 Example of the linear interpolation/extrapolation of four reference I-V curves into the target I-V curve. 1-4 are reference I-V curves. 7 is the target I-V curve.

TRANSLATION OF THE I-V CURVES

Indoor results

The I-V curves at various G and T were calculated by the present procedure using equations (3) and (4) from the experimental reference I-V curves. Typical single-crystalline Si, polycrystalline Si, amorphous Si and a-Si/thin-film crystalline Si tandem cells were used as samples. Their sizes ranged 2-10 cm^2. They were attached on metal plates, whose temperature was stabilized at 20°C, 30°C, 40°C, and 50°C by a flow of temperature controlled water. The temperature was controlled within a nominal accuracy of ±0.2 °C. A solar simulator was used as the light source of 100 mW/cm^2. Irradiance was controlled by metallic thin film neutral density filters. For each solar cell, four reference I-V curves with irradiance of 0 and 100 mW/cm^2 and temperatures of 20°C and 50°C.

The calculated I-V curves well agree with the experiment for all the samples measured in the present study. For example, Fig. 5 shows the results for a polycrystalline Si cell. Measured and calculated I-V curve parameters I_{sc}, V_{oc}, maximum power (P_{max}) and fill factor FF excellently agreed, as shown in Figs. 6 and 7. Root mean square error (RMSE) between measured and calculated P_{max} for all the samples was <0.5%.

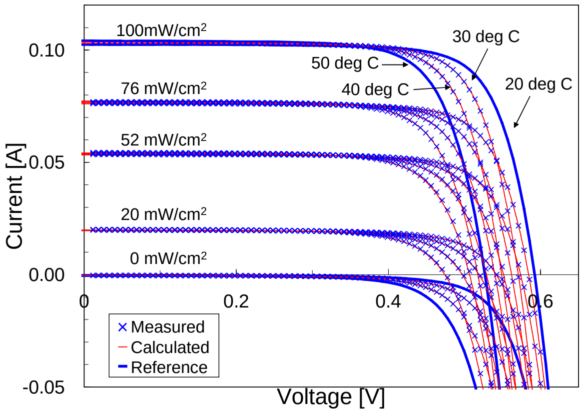

Fig. 5 Measured (circles) and calculated (lines) I-V curves of a polycrystalline Si solar cell. I-V curves measured at G = 0 and 100 mW/cm^2 and T = 20°C and 50°C were used for the reference I-V curves. Calculated results show very good agreement with the experiment.

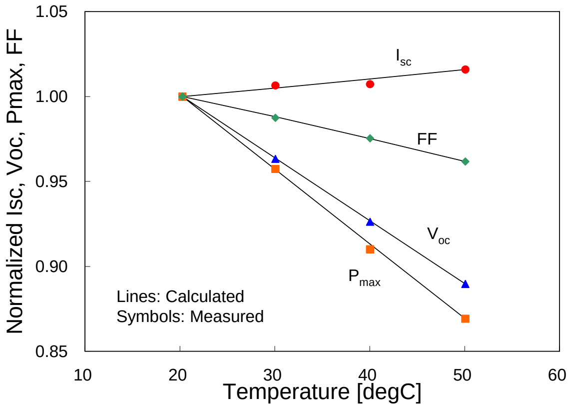

Fig. 6 Measured (circles) and calculated (lines) I_{sc}, V_{oc}, P_{max} and FF for the polycrystalline Si cell shown in Fig. 5 as functions of the temperature T. The irradiance G is 100 [mW/cm^2]. The parameters are normalized to the value at T=20°C. The measured and calculated results agree within the RMSE of 0.1%.

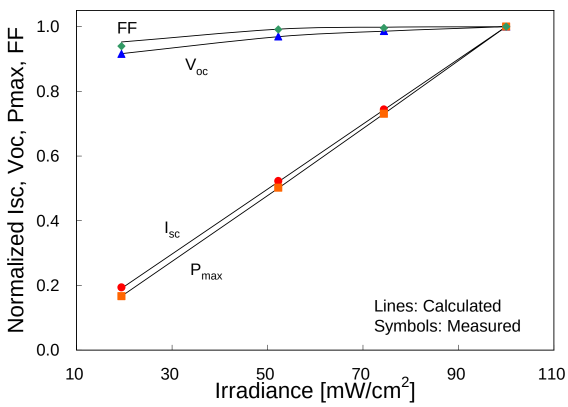

Fig. 7 Measured (circles) and calculated (lines) I_{sc}, V_{oc}, P_{max} and FF for the polycrystalline Si cell shown in Fig. 5 as functions of the irradiance G. The temperature T is 20 °C. The parameters are normalized to the value at G=100 [mW/cm^2]. The measured and calculated results agree within the RMSE of 0.5%.

The present method does not restrict the G and T of the reference I-V curves , and can simultaneously translate the I-V curves for G and T. Fig. 8 shows the example that the I-V curves at (100 mW/cm^2, 25°C) and (20 mW/cm^2, 50°C) is successfully translated into the I-V curve at (52 mW/cm^2, 40°C). The error of measured and calculated Pmax was -0.1%. By utilizing present procedure (Eqs. (1) – (5)), the I-V curves at wide range of G and T can be calculated from only three or four reference I-V curves measured indoor or outdoor.

Another feature of the present formulae is that the series resistance R_s of the PV devices need not be considered, because the effect of R_s in the translation for G is automatically cancelled by the procedure of Eqs. (1)-(5).

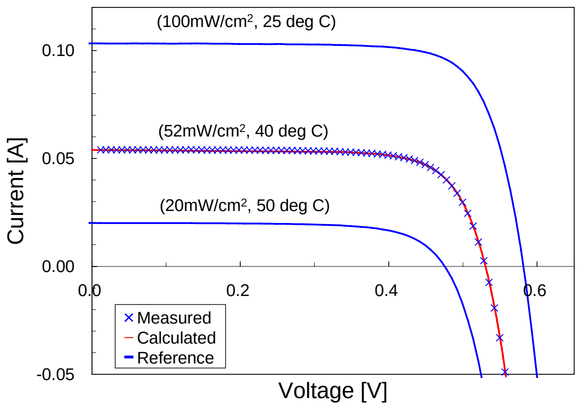

Fig. 8 Measured (symbol) and calculated (line) I-V curves of polycrystalline solar cell. The I-V curves at (100 mW/cm^2, 25°C) and (20 mW/cm^2, 50°C) were successfully translated into the I-V curve at (52 mW/cm^2, 40°C). Blue lines are two reference I-V curves measured at different irradiance and temperature.

Outdoor results

Translation of the I-V curves was also investigated by using the experimental I-V curves of the outdoor PV modules which are located in Tsukuba, Japan. Data were taken for about 3 months. The total number of the I-V curves used was about 15,000. The four I-V curves with the (I_{sc} and T) of (5.36A, 65.3°C), (5.01A, 49.0°C), (1.02A, 37.9°C) and (0.81A, 23.4°C), were used as the reference (Fig. 8). The I-V curves calculated by the reference I-V curves showed very good agreement with the experimental data (Fig. 9). For example, the standard deviation between the measured and calculated P_{max} was about 0.75% (Fig. 10), which demonstrates the accuracy and usefulness of the present procedure of the linear interpolation. Similar results for other PV technologies are also reported based on the outdoor data taken at different location in Japan [6].

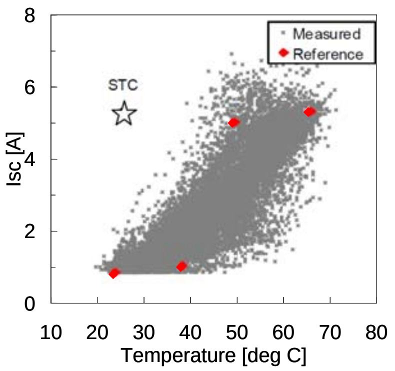

Fig. 9 Temperature and I_{sc} for the outdoor I-V curves investigated in the present study. Each "x" symbol corresponds to one I-V curve. Four reference I-V curves are shown by squares. It is noted that the I_{sc} and T of the reference I-V curves can be chosen without restriction.

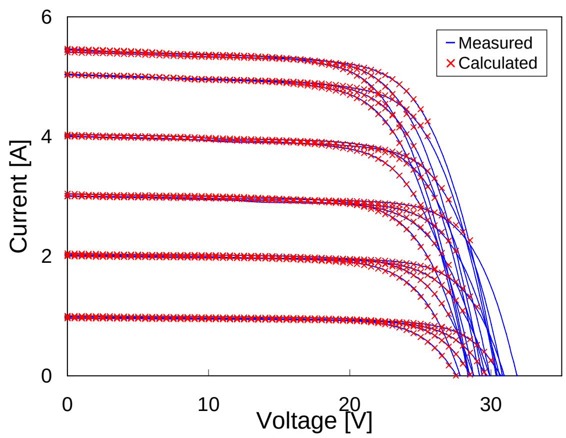

Fig. 10 Examples of measured (lines) and calculated (circles) I-V curves of a polycrystalline Si PV module. Calculated results show very good agreement with the experiment.

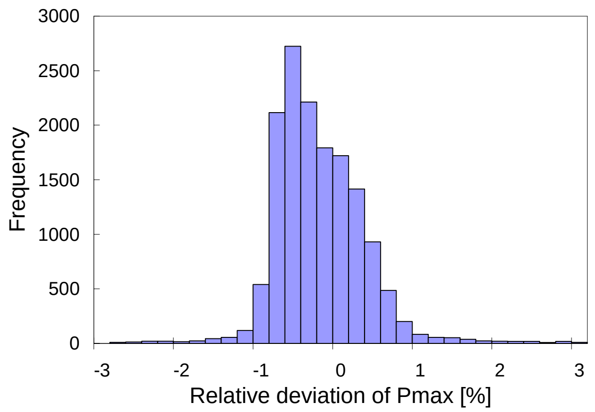

Fig. 11 Deviation of the measured and calculated P_{max} of the outdoor poly-Si modules shown in Fig. 8. Equations (3)-(5) were used for the calculation, based on the experimental four I-V curves, which are also shown in Fig 8.

CONCLUSION

A new practical formulation for the linear interpolation/extrapolation has been investigated, in order to translate the I-V curves of the PV devices for the irradiance G and temperature T. The accuracy of the translation has been investigated based on the experimental indoor and outdoor I-V curves of various kinds of PV cells and modules. By utilizing this method, four or three I-V curves measured at any G and T can be used as the reference I-V curves. This makes practical translation procedure much easier. The results over a wide range of G and T well agree with measured maximum power for various kinds of PV cells and modules. For indoor experiments, root mean square error (RMSE) between the measured and calculated P_{max} for four kinds of PV cells was <0.5%. For outdoor experiments, standard deviation of the measured and calculated maximum power of PV modules was within 1% for wide range of G and T. The present method is expected to be very useful for the energy rating and power rating of the PV devices.

ACKNOWLEDGEMENT

This work was supported in part by NEDO under the Ministry of Economy, Trade and Industry.

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