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

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ABSTRACT

A new practical formulation for the linear interpolation/extrapolation is proposed in order to translate the I-V curves to target conditions of irradiance (G) and PV device temperature (T). The accuracy of the method is investigated based on the experimental 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 calculated I-V curves over a wide range of G and T well agree with measured results for various kinds of PV cells and modules. The difference between the calculated and measured P_{max} was 0.5% or less for indoor experiments, and 1.0% or less for outdoor experiments. These results indicate that the translation of the I-V curve based on the method is effective for estimating the performance of various PV devices under various climatic conditions.

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, 2], those equations can deviate from experiments when the variation in the irradiance and/or temperature is large. Also some equations are applicable only for limited kinds of PV devices. Translation of the I-V curves for G was discussed by Hishikawa et al. originally for a-Si solar cells [3] and incorporated in JIS standards. Recently, the linear interpolation method of the I-V curves by a linear interpolation for both G and T was proposed based on experimental (indoor and outdoor) data on various kinds of PV cells and modules by Marion et al.[4]. The method can accurately estimate the performance of various kinds of PV cells and modules for a wide range of irradiance (G) and temperature (T) [4, 5]. It requires that G (I_{sc}) 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/EXTRAPOLATION METHOD

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 (I_1,V_1) and (I_2,V_2) shold 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 refrence I-V curves. a is an arbitary constant (See Fig. 1). When 0< a <1, the procedure is interpolation, When a <0 or 1> a , the procedure is extrapolation.

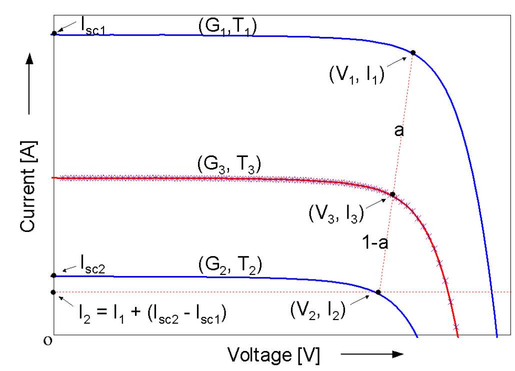

Fig.1 Schematic procedure for the calculations based on Eqs. (1)-(4). I-V curves measured at the irradiance and temperature of (G_1, T_1) and (G_2, T_2), shown by blue lines, are translated into the I-V curve at (G_3, T_3), shown by the red line. Measured I-V curve at (G_3, T_3) is also shown by crosses, which is in good agreement with the calculation.

The G_3 and T_3 cannot be chosen independently, and are determined from T_1, G_1, T_2, G_2 and a from equations (3) and (4).

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

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

Equation (5) is also valid, as the present procedure assumes linear devices.

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

Here, I_{sc3} is the short circuit current of the target I-V curves.

INDOOR RESULTS

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 I-V curves at various irradiances and temperatures were calculated by using equations (1) and (2) from the reference I-V curves. The calculated I-V curves well agree with the experiment for all the samples measured in the present study. For example, Fig. 2 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. 3 and 4. Root mean square error (RMSE) between measured and calculated P_{max} for all the samples was <0.5%.

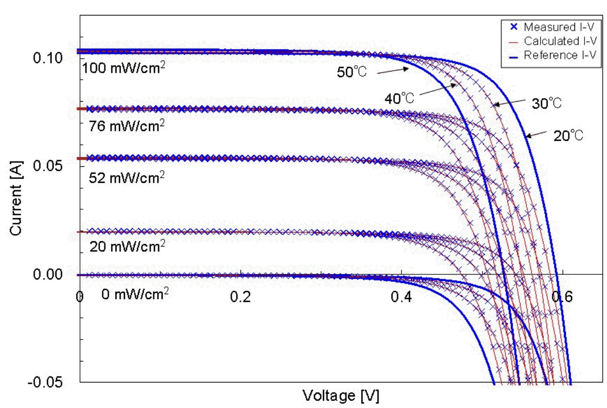

Fig.2 Measured (circles) and calculated (lines) I-V curves of a polycrystalline Si solar cell. I-V curves measured at G=0 and 100 mW/cm^2 and T = 20°C and 50°C were used for the reference I-V curves.

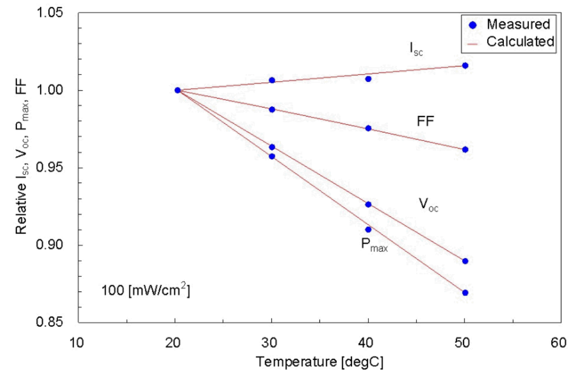

Fig.3 Measured (circles) and calculated (lines) I_{sc}, V_{oc}, P_{max}, FF for the polycrystalline Si cell shown in Fig. 1 as functions of the temperature T. The irradiance G is 100 [mW/cm^2]. The parameters are normalized to the value at T=20°C. The measured and calculated results agree within the RMSE of 0.1%.

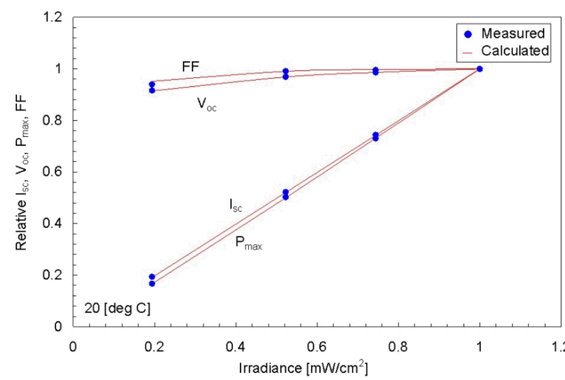

Fig.4 Measured (circles) and calculated (lines) I_{sc}, V_{oc}, P_{max}, FF for the polycrystalline Si cell shown in Fig. 1 as functions of the irradiance G. The temperature T is 20 °C. The parameters are normalized to the value at G=100 [mW/cm^2]. The measured and calculated results agree within the RMSE of 0.5%.

The present method does not restrict the G and T of the reference I-V's, and can simultaneously translate the I-V curves for G and T. Fig. 5 shows the example that the I-V curves at (100 mW/cm^2, 25°C) and (20 mW/cm^2, 50°C) are successfully translated into the I-V curve at (52 mW/cm^2, 40°C). The error of measured and calculated P_{max} was -0.1%. By utilizing present procedure (Eqs. (1) – (4)), 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.

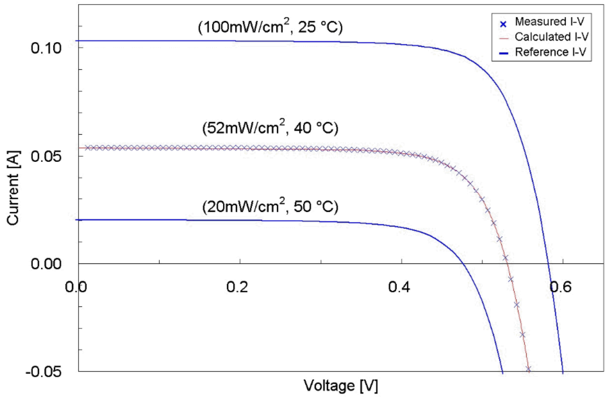

Fig.5 Measured (symbol) and calculated (line) I-V curves of polycrystalline solar cell. The I-V curves at (100 mW/cm^2, 25°C) and (20 mW/cm^2, 50°C) is successfully translated into the I-V curve at (52 mW/cm^2, 40°C). Blue lines are two reference I-V curves measured at different irradiance and temperature. I-V curve measured at (52 mW/cm^2, 40°C) is also shown by crosses, which is in good agreement with the calculation.

Fig. 6 shows the example of the linear interpolation/extrapolation based on four reference I-V curves into the target I-V curve by the following procedure (1)-(3). Points denoted as 1-4 represents the reference I-V curves. The point denoted as 7 is the target I-V curve.

(1) I-V curve 5 is calculated by I-V curves 1 and 2.
(2) I-V curve 6 is calculated by I-V curves 3 and 4.
(3) I-V curve 7 is calculated by 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 as will be demonstrated in Fig. 10.

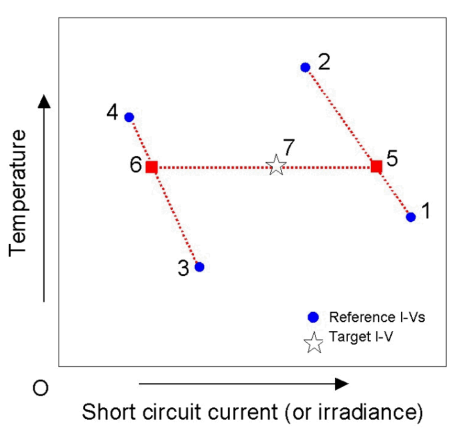

Fig.6 Example of the linear interpolation/extrapolation of four reference I-V curves into the target I-V curve. 1-4 are reference I-V curves. 7 is the target I-V curve.

OUTDOOR RESULTS

Single crystalline and polycrystalline silicon modules, CIS and hetero-junction module were investigated at outdoor conditions. Data measured for about a year were used for the present study. The total number of I-V curves was about 86000 for each module. The module temperature was measured by thermocouples attached to the backside of each module simultaneously with the I-V curve.

In this experience, I_{sc} was used instead of G (equation (5)), because irradiance measured by pyranometer is not proportional to I_{sc} due to spectral effects. Fig.8 shows typical example of experimental and calculated results for c-Si modules. This figure demonstrates that the calculated I-V curves agree with the experimental curves very well, also for modules. These resulting I-V curves in this figure do not include data near V_{oc} because measurement data points of reference I-V curves were measured from I_{sc} to I=0. If data near V_{oc} is desired, reference I-V curves shall be measured down to near -I_{sc}.

Comparisons of calculated and measured I-V curves were made using RMSE between measured and calculated P_{max}. Fig.9 shows RMSE of P_{max} for c-Si module, plotted versus the short circuit current I_{sc} and module temperature T. Each point includes data from 30-600 I-V curves. RMSE for wide range of G (0.1-1.0mW/cm^2) and T (5 -70°C) is less than 1.5%. This result indicates that the present method can calculate the I-V curves of the PV modules for the whole range of G and T of the outdoor conditions of the present study, based on only four reference I-V curves. It should be noted that the number of the reference I-V curves may be further reduced in some cases. Fig.10 also shows plot of RMSE of P_{max} for c-Si module. The number of the reference I-V curves is three, as shown by the open circles in the figure. RMSE at most of the conditions is less than 1.5%.

Table 1 shows average and standard deviation of the difference between measured and calculated P_{max} of each module. This result indicates that the linear interpolation method is applicable for various kinds of PV modules under various climatic conditions.

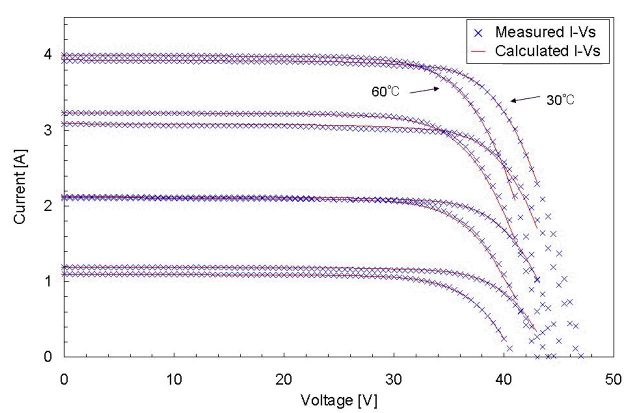

Fig 8. Measured (symbols) and calculated (lines) I-V curves of single crystalline PV module.

Although both the interpolation and extrapolation are possible by the present procedure, interpolation usually results in better agreement with the experiments than extrapolation. Therefore, choice of the reference I-V's is important for calculating the I-V's in a wide-range of G and T, as shown in Figs. 9 and 10.

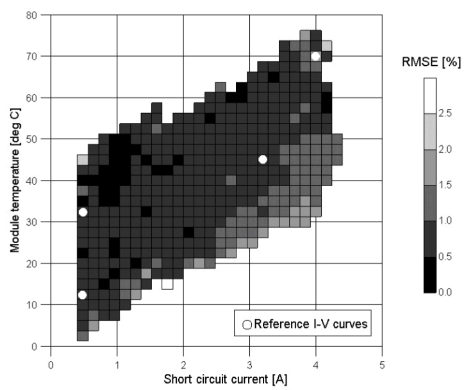

Fig 9 RMSE between measured and calculated P_{max} for a single crystalline silicon module, plotted versus the short circuit current I_{sc} and module temperature T. Circles represent the conditions of reference I-V curves.

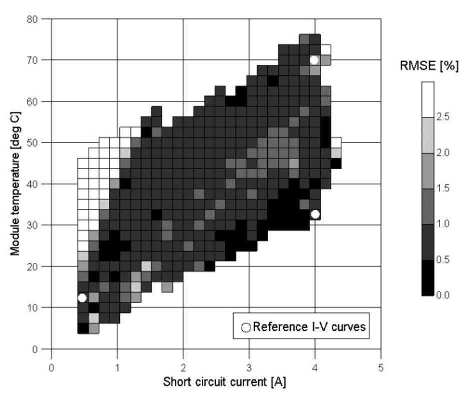

Fig.10 RMSE between measured and calculated P_{max} for a single crystalline silicon module, plotted versus the short circuit current I_{sc} and module temperature T. Circles represent the conditions of reference I-V curves.

Table 1 Average and standard deviation of the difference between measured and calculated maximum power of each module.

Module	Ave [%]	SD [%]
c-Si	0.1	0.8
c-Si (3 references)	0.4	2.1
pc-Si	0.2	0.8
Hetero-junction	0.1	1.0
CIS	0.4	0.8

CONCLUSIONS

A new practical formulation for the linear interpolation/extrapolation is proposed, in order to translate the I-V curves for the irradiance G and temperature T. The accuracy of the translation is 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 four kinds 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.

ACKNOWLEDGEMENTS

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