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NORME INTERNATIONALE

Photovoltaic devices – Procedures for temperature and irradiance corrections to measured I-V characteristics

Dispositifs photovoltaïques – Procédures pour les corrections en fonction de la température et de l'éclairement à appliquer aux caractéristiques I-V mesurées

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CONTENTS

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PHOTOVOLTAIC DEVICES – PROCEDURES FOR TEMPERATURE AND IRRADIANCE CORRECTIONS TO MEASURED I-V CHARACTERISTICS

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International Standard IEC 60891 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

This second edition cancels and replaces the first edition issued in 1987 and its Amendment 1 (1992) and constitutes a technical revision.

The main technical changes with regard the previous edition are as follows:

– extends edition 1 translation procedure to irradiance change during I-V measurement;
– adds 2 new translation procedures;
– revises procedure for determination of temperature coefficients to include PV modules;
– defines new procedure for determination of internal series resistance;
– defines new procedure for determination of curve correction factor.

The text of this standard is based on the following documents:

FDIS	Report on voting
82/581/FDIS	82/588/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

PHOTOVOLTAIC DEVICES – PROCEDURES FOR TEMPERATURE AND IRRADIANCE CORRECTIONS TO MEASURED I-V CHARACTERISTICS

1 Scope

This standard defines procedures to be followed for temperature and irradiance corrections to the measured I-V (current-voltage) characteristics of photovoltaic devices. It also defines the procedures used to determine factors relevant for these corrections. Requirements for I-V measurement of photovoltaic devices are laid down in IEC 60904-1.

NOTE 1 The photovoltaic devices include a single solar cell with or without a protective cover, a sub-assembly of solar cells, or a module. A different set of relevant parameters for I-V correction applies for each type of device. Although the determination of temperature coefficients for a module (or sub-assembly of cells) may be calculated from single cell measurements, it should be noted that the internal series resistance and curve correction factor should be separately measured for a module or subassembly of cells.

NOTE 2 The term "test specimen" is used to denote any of these devices.

NOTE 3 Care should be taken regarding the use of I-V correction parameters. The parameters are valid for the PV device for which they have been measured. Variations may occur within a production lot or the type class.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60904-1, *Photovoltaic devices – Part 1: Measurements of photovoltaic current-voltage characteristics*

IEC 60904-2, *Photovoltaic devices – Part 2: Requirements for reference solar devices*

IEC 60904-7, *Photovoltaic devices – Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices*

IEC 60904-9, *Photovoltaic devices – Part 9: Solar simulator performance requirements*

IEC 60904-10, *Photovoltaic devices – Part 10: Methods of linearity measurement*

3 Correction procedures

3.1 General

Three procedures for correcting measured current-voltage characteristics to other conditions of temperature and irradiance (such as STC) can be applied. The first is identical to the procedure given in Edition 1 of this standard, but the equation has been rewritten for easier understanding. The second procedure is an alternative algebraic correction method which yields better results for large irradiance corrections (>20 %). Both procedures require that correction parameters of the PV device are known. If not known they need to be determined prior to performing the correction. The third procedure is an interpolation method which does not require correction parameters as input: It can be applied when a minimum of three current-voltage curves have been measured for the test device. These three current-voltage curves span the temperature and irradiance range for which the correction method is applicable.

All methods are applicable to linear devices as defined in IEC 60904-10.

NOTE 1 An estimate on the translation accuracy is required (see Clause 7).

NOTE 2 All PV devices should be linear within a limited range of irradiances and device temperature. Details are described in IEC 61853-1.

Common to all procedures is that I-V characteristics of the PV device are to be measured in accordance with IEC 60904-1.

Usually irradiance G shall be calculated from the measured short circuit current (I_{RC}) of the PV reference device as defined in IEC 60904-2, and its calibration value at STC ($I_{RC,STC}$). A correction should be applied to account for the temperature of the reference device T_{RC} using the specified relative temperature coefficient of the reference device (1/°C) which is given at 25 °C and 1 000 W/m^2.

$$G = \frac{1\,000\ \text{Wm}^{-2} \cdot I_{RC}}{I_{RC,STC}} \cdot [1 - \alpha_{RC} \cdot (T_{RC} - 25\ °\text{C})]$$

The PV reference device shall either be spectrally matched to the test specimen, or a spectral mismatch correction shall be performed in conformance with IEC 60904-7. The reference device shall be linear in short-circuit current, as defined in IEC 60904-10 over the irradiance range of interest.

3.2 Correction procedure 1

The measured current-voltage characteristic shall be corrected to standard test conditions or other selected temperature and irradiance values by applying the following equations:

$$I_2 = I_1 + I_{SC} \cdot \left(\frac{G_2}{G_1} - 1\right) + \alpha \cdot (T_2 - T_1) \quad (1)$$

$$V_2 = V_1 - R_S \cdot (I_2 - I_1) - \kappa \cdot I_2 \cdot (T_2 - T_1) + \beta \cdot (T_2 - T_1) \quad (2)$$

where:

- I_1, V_1 are coordinates of points on the measured characteristics;
- I_2, V_2 are coordinates of the corresponding points on the corrected characteristic;
- G_1 is the irradiance measured with the reference device;
- G_2 is the irradiance at the standard or other desired irradiance;
- T_1 is the measured temperature of the test specimen;
- T_2 is the standard or other desired temperature;
- I_{SC} is the measured short-circuit current of the test specimen at G_1 and T_1;
- α and β are the current and voltage temperature coefficients of the test specimen in the standard or target irradiance for correction and within the temperature range of interest;
- R_S is the internal series resistance of the test specimen;
- κ is a curve correction factor.

NOTE 1 As the data point V_{oc1} will be shifted off the current axis when translating from lower to higher irradiance, the translated V_{oc2} has to be determined by linear extrapolation from at least 3 data points near and below V_{oc1} or the original IV curve has to be measured sufficiently far beyond V_{oc1}.

NOTE 2 The units of all correction parameters should be consistent.

NOTE 3 If the test specimen is a module the cell I-V correction parameters can be derived from the interconnection circuit. These cell parameters may be used to calculate the module I-V correction parameters for other module types using the same cells.

NOTE 4 For crystalline silicon PV devices α is normally positive and β negative.

Procedures for determination of the I-V correction parameters of the test specimen are described in sections 4 to 6.

Equation (1) is only applicable for I-V curves measured at irradiances which are constant during the acquisition of the entire I-V curve. For pulsed solar simulators with decaying irradiance or any other kind of irradiance fluctuations during I-V measurement Equation (1) is not applicable as such. In this case, each measured I-V curve has to be corrected to an equivalent I-V curve at constant irradiance which requires an additional scaling factor in front of I_{SC}. For practical reasons this scaling factor is related to the irradiance corresponding to measured I_{SC}. For non-constant irradiance Equation (1) will become the following translation equation.

$$I_2 = I_1 + \frac{G_1'}{G_{SC}} \cdot I_{SC} \cdot \left(\frac{G_2}{G_1'} - 1 \right) + \alpha \cdot (T_2 - T_1) \qquad (3)$$

where G_{SC} is the irradiance value at the time of I_{SC} measurement and G_1' is the irradiance measured at time of data acquisition of individual I-V data points.

3.3 Correction procedure 2

This procedure is based on the simplified one-diode model of PV devices. The semi-empirical translation equations contain 5 I-V correction parameters which can be determined by measurement of I-V curves at different temperature and irradiance conditions. Besides the temperature coefficients for short circuit current (α) and open circuit voltage (β) an additional temperature coefficient (κ') is commonly used which accounts for changes of the internal series resistance (and fill factor) with temperature.

The correction procedure is defined by the following equations for current and voltage:

$$I_2 = I_1 \cdot \left(1 + \alpha_{rel} \cdot (T_2 - T_1)\right) \cdot \frac{G_2}{G_1} \qquad (4)$$

$$V_2 = V_1 + V_{OC1} \cdot \left(\beta_{rel} \cdot (T_2 - T_1) + a \cdot \ln\left(\frac{G_2}{G_1} \right) \right) - R_S' \cdot (I_2 - I_1) - \kappa' \cdot I_2 \cdot (T_2 - T_1) \qquad (5)$$

where:

I_1, V_1 are coordinates of points on the measured I-V characteristic;

I_2, V_2 are coordinates of the corresponding points on the corrected I-V curve;

G_1 is the irradiance as measured with the reference device;

G_2 is the target irradiance for the corrected I-V characteristic;

T_1 is the measured temperature of the test specimen;

T_2 is the target temperature of the test specimen;

V_{OC1} the open circuit voltage at test conditions;

α_{rel} and β_{rel} are the relative current and voltage temperature coefficients of the test specimen measured at 1 000 W/m^2. They are related to short circuit current and open circuit voltage at STC;

a is the irradiance correction factor for open circuit voltage which is linked with the diode thermal voltage D of the pn junction and the number of cells n_S serially connected in the module;

R'_S is the internal series resistance of the test specimen;

κ' is interpreted as temperature coefficient of the internal series resistance R'_S.

NOTE 1 A typical value for the irradiance correction factor a is 0,06.

NOTE 2 Care should be taken that the numerical values for R'_S for procedure 2 may be different to R'_S of correction procedure 1.

3.4 Correction procedure 3

3.4.1 General

This procedure is based on the linear interpolation or extrapolation of two measured I-V characteristics. It uses a minimum of two I-V characteristics, and requires no correction parameters or fitting parameters. The measured current-voltage characteristics shall be corrected to standard test conditions or other selected temperature and irradiance values by applying the following equations:

$$V_3 = V_1 + a \cdot (V_2 - V_1) \tag{6}$$

$$I_3 = I_1 + a \cdot (I_2 - I_1) \tag{7}$$

The pair of (I_1, V_1) and (I_2, V_2) should be chosen so that $I_2 - I_1 = I_{SC2} - I_{SC1}$:

where:

I_1, V_1 are coordinates of points on the measured characteristics at an irradiance G_1 and temperature T_1.

I_2, V_2 are coordinates of points on the measured characteristics at an irradiance G_2 and temperature T_2.

I_3, V_3 are coordinates of the corresponding points on the corrected characteristics at an irradiance G_3 and temperature T_3.

I_{SC1}, I_{SC2} are the measured short-circuit current of the test specimen.

a is a constant for the interpolation, which has the relation with the irradiance and temperature as follows.

$$G_3 = G_1 + a \cdot (G_2 - G_1) \tag{8}$$

$$T_3 = T_1 + a \cdot (T_2 - T_1)\,. \tag{9}$$

This method should be applicable to most PV technologies. Equations (6) to (9) can be used for the irradiance correction, temperature correction, and simultaneous correction of irradiance and temperature.

3.4.2 Correction for the irradiance and temperature from two measured I-V characteristics

The procedure to correct the I-V characteristics to the irradiance and temperature (G_3, T_3) from two I-V characteristics measured at the irradiances and temperatures of (G_1, T_1) and (G_2, T_2) is as follows (Figures 1(a) and 1(b)).

a) Measure the two I-V characteristics at the irradiances and temperatures of G_1, T_1 and G_2, T_2, respectively (solid lines in Figure 1(a)). Find the values of I_{SC1} and I_{SC2}.

b) Calculate a by Equation (8) or (9). For example, when the two measured I-V curves were made at:

   G_1 = 1 000 W/m^2 and T_1 = 50 °C

   G_2 = 500 W/m^2 and T_2 = 40 °C.

   And the irradiance of interest is G_3 = 800 W/m^2:

   Then using Equation (8) a = 0,4.

   And using Equation (9) T_3 = 46 °C.

c) Choose a point (V_1, I_1) on the I-V characteristic 1. Find a point (V_2, I_2) on the I-V characteristic 2, so that the relation $I_2 - I_1 = I_{SC2} - I_{SC1}$ is satisfied (Figure 1(b)).

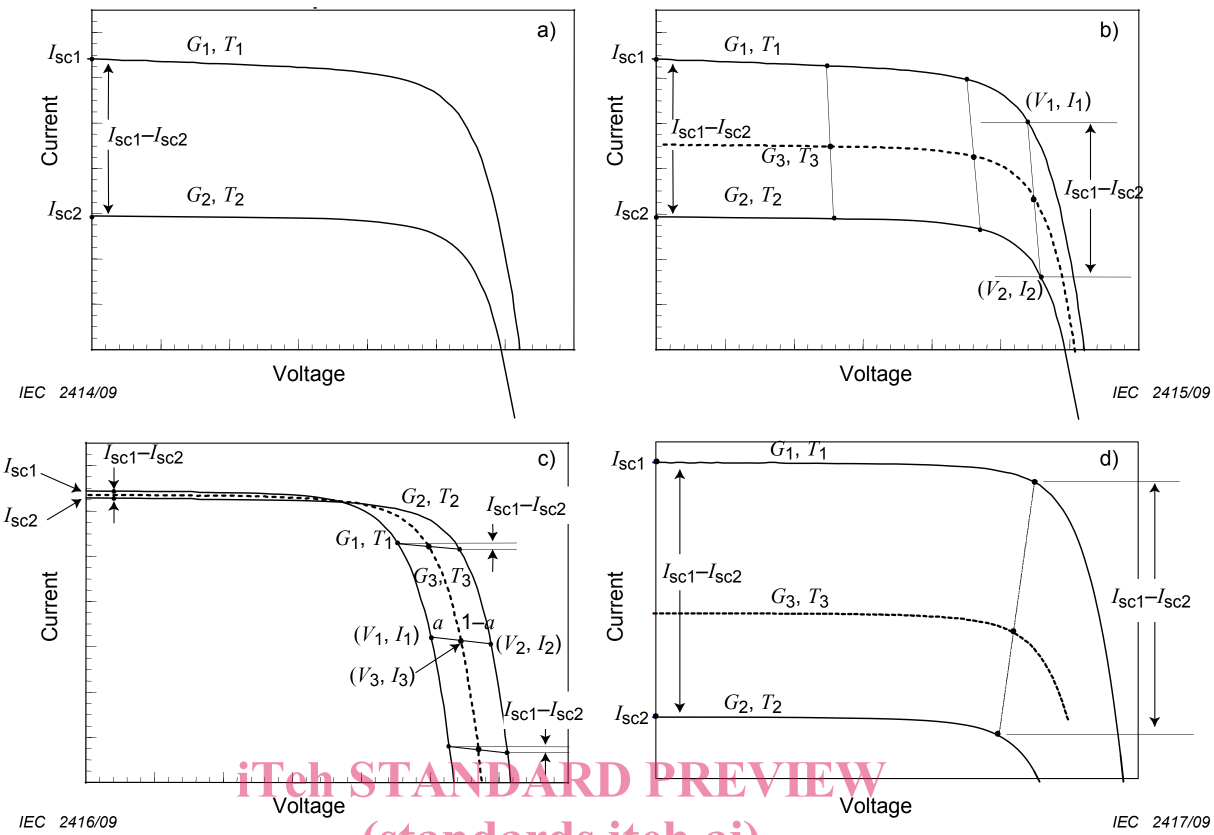
d) Calculate V_3 and I_3 by Equations (6) and (7).

e) Select multiple sets of data points (V_1, I_1) on the I-V characteristics 1, and calculate (V_3, I_3) for each by the procedures (c) and (d).

f) The I-V characteristics 3 at the irradiance G_3 and temperature T_3 are given by the set of data points (V_3, I_3) (broken line in Figure 1(b)).

Figures 1(a) and 1(b) show an example of an irradiance correction. Figures 1(c) shows an example of a temperature correction. Figure 1(d) shows a simultaneous correction of irradiance and temperature. When 0 < a < 1, the procedure is interpolation. Otherwise, the procedure is extrapolation.

It should be noted that when G_1, G_2, T_1 and T_2 are fixed, G_3 and T_3 cannot be chosen independently, because they have the relationships given in Equations (8) and (9) (Figure 2). For example, when G_1 = 1 000 W/m^2, T_1 = 20 °C, G_2 = 0 W/m^2, T_2 = 60 °C (dark I-V curve at 60°C), and you wish to have the new curve at G_3 = 750 W/m^2, a is calculated to be 0,25 by Equation (8). Therefore, T_3 should be 30 °C from Equation (9).



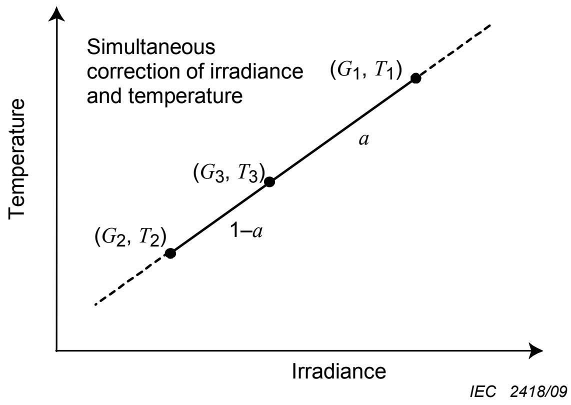
Subfigures (a) and (b) show irradiance corrections, (c) shows a temperature correction and (d) shows simultaneous correction of irradiance and temperature.

Figure 1 – Example of the correction of the I-V characteristics by Equations (6) and (7)

NOTES 1 Interpolation usually gives better results than extrapolation.

NOTE 2 When $I_{SC1} \neq I_{SC2}$ and the corrected I-V characteristics around the open-circuit voltage is required, the measured characteristics should extend beyond V_{oc}.

NOTE 3 When there are no measured data points which exactly satisfy $I_2 = I_1 + (I_{SC2} - I_{SC1})$, the V_2 and I_2 may be calculated from interpolation of the data points in the I-V curve 2.



The solid line and broken line show the range of G_3 and T_3 which are calculable by the interpolation and extrapolation, respectively.

Figure 2 – Schematic diagram of the relation of G_3 and T_3 which can be chosen in the simultaneous correction for irradiance and temperature, for a fixed set of T_1, G_1, T_2, and G_2 by Equations (8) and (9)

3.4.3 Correction to various irradiances and temperatures from three I-V characteristics

The correction of the I-V characteristics to various ranges of irradiance and temperature is possible by combining the procedures described in 3.4.2. For example, when three characteristics measured at irradiances and temperatures of (G_a, T_a), (G_b, T_b) and (G_c, T_c) are available as shown in Figure 3(a), the I-V characteristics at any irradiances and temperatures (G_n, T_n) can be calculated as follows.

a) The characteristics at (G_m, T_m) are calculated from those at (G_a, T_a) and (G_b, T_b).

b) The characteristics at (G_n, T_n) are calculated from those at (G_m, T_m) and (G_c, T_c).

For example, when (G_a, T_a), (G_b, T_b), (G_c, T_c) and (G_n, T_n) are (950 W/m^2, 15 °C), (850 W/m^2, 25 °C), (1 100 W/m^2, 30 °C) and (1 000 W/m^2, 25 °C) respectively, then (G_m, T_m) are (900 W/m^2, 20 °C).