

INTERNATIONAL STANDARD

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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INTERNATIONAL
ELECTROTECHNICAL
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COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 27.160

ISBN 978-2-8322-1036-0

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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 third edition cancels and replaces the second edition published in 2009. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- adds guidance on which correction procedure shall be used depending on application;
- introduces translation procedure 4 applicable to c-Si technologies with unknown temperature coefficients;
- introduces various clarifications in existing procedures to improve measurement accuracy and reduce measurement uncertainty;
- adds an informative annex for supplementary methods that can be used for series resistance determination.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
82/1936/FDIS	82/1957/RVD

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

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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

1 Scope

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

The PV 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 curve correction applies for each type of device. The determination of temperature coefficients for a module (or sub-assembly of cells) may be calculated from single cell measurements, but this is not the case for the internal series resistance and curve correction factor, which should be separately measured for a module or subassembly of cells. Refer to Annex A for alternative procedures for series resistance determination.

The use of I - V correction parameters is valid for the PV device for which they have been measured. Variations may occur within a production lot or the type of class.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 TS 60904-1-2, *Photovoltaic devices – Part 1-2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices*

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 60904-8, *Photovoltaic devices – Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device*

IEC 60904-9, *Photovoltaic devices – Part 9: Classification of solar simulator characteristics*

IEC 60904-10:2020, *Photovoltaic devices – Part 10: Methods of linear dependence and linearity measurements*

IEC 61215-2, *Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 2: Test procedures*

IEC TS 61836, *Solar photovoltaic energy systems – Terms, definitions, and symbols*

3 Terms and definitions, symbols and abbreviated terms

For the purposes of this document, the terms and definitions given in IEC TS 61836, together with the following, apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1

B_1

irradiance correction factor for open-circuit voltage which is linked with the diode thermal voltage, V_t of the p-n junction and n_S

Note 1 to entry: It is used in correction procedure 2.

3.2

B_2

irradiance correction factor for open-circuit voltage which accounts for non-linearity of V_{OC} with irradiance scaling

Note 1 to entry: It is used in correction procedure 2.

3.3

DUT

device under test

3.4

R_S

internal series resistance of the DUT employed by correction procedures 1 and 4

3.5

R'_S

internal series resistance of the DUT employed by correction procedure 2

Note 1 to entry: Although determined by a different method than R_S , both quantities share the same physical meaning and therefore their values for the same DUT are similar.

3.6

n_S

number of cells serially connected in the DUT

3.7

a

interpolation constant employed in correction procedure 3, that has a relation with the irradiance and temperature

3.8

ε

product of ideality factor of the DUT with the bandgap of the photovoltaic material divided by electron's elementary charge

Note 1 to entry: It is used in correction procedure 4.

4 Correction procedures

4.1 General

This document provides four procedures for correcting measured current-voltage characteristics to other conditions of temperature and irradiance, such as Standard Test Conditions (STC), that can be applied. The first procedure describes a system of linear equations for current and voltage, which is best applicable for irradiance corrections within $\pm 40\%$ of the target irradiance. The second procedure is an alternative algebraic correction method which yields better results for large irradiance corrections (exceeding $\pm 40\%$). 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 two current-voltage curves have been measured for the DUT. This correction method is applicable in the temperature and irradiance range spanned by the two current voltage curves. The fourth procedure is based on the single-diode model and provides a methodology for determining a correction parameter R_S from a single $I-V$ curve, when the parameter is unknown. The method is best applicable to irradiance corrections when the measured and target irradiance are both in the range 300 W/m^2 to $1\,200 \text{ W/m}^2$ and the series resistance R_S is unknown. It is suitable for translations when the characteristics under STC have to be estimated from a single experimental $I-V$ curve.

Table 1 and Table 2 provide an overview of the four different correction procedures, and describe qualitatively the advantages, disadvantages and required correction parameters for each procedure. The purpose of these tables is to provide guidance to the user of this document on which correction procedure to use for different applications.

For simultaneous corrections of irradiance and temperature, the benefits and limitations listed in Table 1 and Table 2 apply concurrently.

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

All PV devices should be linear at least within the range of irradiances and device temperature over which corrections are made. Details on how to assess the deviation from the ideal linear dependence are described in IEC 60904-10.

An estimate of the translation accuracy is required (see Clause 8).

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

$$G = \frac{1000 \text{ Wm}^{-2} \times I_{RC}}{I_{RC,STC} \times [1 + \alpha_{RC,rel} \times (T_{RC} - 25^\circ\text{C})]} \quad (1)$$

Ideally, the reference device shall be linear in short-circuit current over the entire irradiance range of interest, as defined in IEC 60904-10. In practice, even for linear devices it is recommended to apply a correction for linearity of the reference device according to IEC 60904-10. If the device is not linear according to IEC 60904-10 over the entire irradiance range of interest, then corrections shall be applied to avoid errors in the corrections of its I - V characteristics. The PV reference device shall either be spectrally matched to the DUT, or a spectral mismatch (SMM) correction shall be performed in conformance with IEC 60904-7. Since the spectral responsivity of the device can vary with temperature, the apparent change in temperature coefficient with spectra should be taken into account in the correction. An interpolation method of temperature against SMM correction can minimize the error sources.

Table 1 – Overview of correction procedures for irradiance corrections (i.e. $T_1 = T_2$)

Procedure 1 Correction parameter requirement: R_S	
Advantages	Disadvantages
Suitable where R_S is determined (typically within ± 40 % of the irradiance at which R_S was determined)	Assumes superposition of current at all voltages
Works reasonably well over a broader range of irradiance (typically within ± 80 % of the irradiance at which R_S was determined) for devices that are linear with respect to irradiance according to IEC 60904-10. This is typically the case for c-Si.	Cannot produce complete I-V curves for higher irradiance corrections (part of I-V curve between $P_{\max}$ and V_{OC} is missing), when the I-V curve is not measured sufficiently far into the negative current regime. In this case extrapolation for V_{OC} is necessary
Procedure 2 Correction parameter requirement: B_1 , B_2 , R'_S , κ' and β_{rel}	
Advantages	Disadvantages
Suitable in the irradiance range where R'_S is determined (typically within ± 40 % of the irradiance at which R'_S was determined)	Requires more parameters to be known than procedures 1 and 4
Works reasonably well over a broader range of irradiance (typically within ± 80 % of the irradiance at which R'_S was determined) for devices that are linear with respect to irradiance according to IEC 60904-10. This is typically the case for c-Si.	Not recommended for I-V translation over irradiance exceeding ± 40 % of the target irradiance, when the DUT has significant leakage current (low shunt resistance)
Can produce complete I-V curves for higher irradiance corrections	
Provides information for relative comparison of the DUT modelling parameters used in single-diode model (ideality factor and R'_S)	
Procedure 3 Correction parameter requirement: None	
Advantages	Disadvantages
Best accuracy for I-V corrections when interpolating	Requires knowledge of I-V curves at higher and lower levels of irradiance compared to target irradiance
Fitting parameters not required	Not possible to perform comparison between different technologies, because fitting parameters cannot be extracted
Least technology specific method	Interpolation gives better results than extrapolation. Extrapolation should be practiced with caution

Procedure 4 Correction parameter requirement: None	
Advantages	Disadvantages
Suitable when the correction parameter R_S is unknown	Approximate R_S is determined from a single $I-V$ curve
Does not require multiple $I-V$ curves measured at different levels of irradiance for R_S determination	Not suitable for technologies which do not follow the single-diode model

Table 2 – Overview of correction procedures for temperature corrections (i.e. $G_1 = G_2$)

Procedure 1 Correction parameter requirement: R_S , κ , α and β	
Advantages	Disadvantages
Suitable as long as the measured irradiance is within ± 30 % of the irradiance at which temperature coefficients were determined	Not recommended when the measured irradiance differs by more than ± 30 % from the irradiance at which the temperature coefficients were determined
Procedure 2 Correction parameter requirement: B_1 , B_2 , R'_S , κ' , α_{rel} and β_{rel}	
Advantages	Disadvantages
Suitable as long as the measured irradiance is within ± 30 % of the irradiance at which temperature coefficients were determined	Requires more parameters to be known than procedures 1 and 4
Applicable over the entire range of irradiance for which the device is proven to be linear with respect to irradiance according to IEC 60904-10. This is typically the case for c-Si.	Not recommended for devices that are not linear with respect to irradiance when the measured irradiance differs by more than ± 30 % from the irradiance at which the temperature coefficients were determined
Procedure 3 Correction parameter requirement: None	
Advantages	Disadvantages
Best accuracy for $I-V$ corrections when interpolating	Requires knowledge of $I-V$ curves at higher and lower temperatures
Fitting parameters not required	Fitting parameters cannot be extracted
Least technology specific method	Interpolation gives better results than extrapolation. Extrapolation should be practiced with caution
Procedure 4 Correction parameter requirement: ε , α_{rel} and n_S	
Advantages	Disadvantages
The same value of the device dependent constant, ε can be used for all c-Si PV devices	Not suitable for technologies which do not follow the single-diode model
ε is independent of temperature and irradiance	

4.2 Correction procedure 1

The first procedure relies on the principle of superposition of the currents at all voltages, which assumes that the diode current does not depend on photocurrent [1]¹. This is typically not the case when the target irradiance is significantly different from the measured irradiance.

The current-voltage characteristic measured at condition 1 shall be corrected to STC or other selected temperature and irradiance values (condition 2) by applying the following formulae:

$$I_2 = I_1 + I_{SC1} \times \left(\frac{G_2}{G_1} - 1 \right) + \alpha \times (T_2 - T_1) \quad (2)$$

$$V_2 = V_1 - R_S \times (I_2 - I_1) - \kappa \times I_2 \times (T_2 - T_1) + \beta \times (T_2 - T_1) \quad (3)$$

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, corrected for temperature and linearity of the reference device and the SMM;
- G_2 is the target irradiance for the DUT;
- T_1 is the measured temperature of the DUT;
- T_2 is the target temperature of the DUT;
- I_{SC1} is the measured short-circuit current of the DUT at G_1 and T_1 ;
- α and β are the short-circuit current and open-circuit voltage temperature coefficients, respectively, of the DUT at the target irradiance for correction and within the temperature range of interest (e.g. $\beta = -2,3 \text{ mV/}^\circ\text{C}$);
- R_S is the internal series resistance of the DUT;
- κ is a curve correction factor.

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

As the data point V_{OC1} will be shifted off the original axis when translating from lower to higher irradiance, the translated V_{OC2} has to be determined by linear extrapolation near and above V_{OC2} (i.e. for negative currents), or by linear extrapolation near V_{OC2} if there are no voltage points above V_{OC2} . To minimize errors caused by extrapolation, it is recommended that I - V curves shall be measured as far into forward bias beyond V_{OC} as possible.

V_{OC2} may be also extrapolated by polynomial fit of the I - V curve. In particular, this is recommended if measured V_{OC1} is translated to an I - V data point with current offset. For the polynomial curve fit all I - V data points in the voltage range larger than V_{Pmax} shall be considered. The resulting curve shall be plausible in the whole voltage range V_{Pmax} to V_{OC} . Alternative methods to linear extrapolation (such as diode fitting) are also allowed.

¹ Numbers in square brackets refer to the Bibliography.

The extrapolation method used has to be stated in the report together with a statement of its estimated uncertainty on the translated V_{OC2} .

Procedures for determination of the I - V correction parameters of the DUT are described in Clauses 5 to 7.

Formula (2) 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, formula (2) 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_{SC1} . For practical reasons, this scaling factor is related to the irradiance corresponding to measured I_{SC1} . For non-constant irradiance, formula (2) will become the following translation formula.

$$I_2 = I_1 + \frac{G'_1}{G_{SC1}} \times I_{SC1} \times \left(\frac{G_2}{G'_1} - 1 \right) + \alpha \times (T_2 - T_1) \quad (4)$$

where G_{SC1} is the irradiance value at the time of I_{SC1} measurement and G'_1 is the irradiance measured at time of data acquisition of individual I - V data points.

Correction procedure 1 assumes that the normalized spectra corresponding to G_1 and G_2 are identical. If they are not, an additional uncertainty component is required to account for the variation of α with spectrum by calculating the effect based on the measured spectral responsivity of the DUT as a function of temperature or of irradiance and on the measured spectral irradiance. Spectral mismatch corrections shall be implemented in accordance with IEC 60904-7.

4.3 Correction procedure 2

This procedure is based on the simplified one-diode model of PV devices [2]. The semi-empirical translation formulae contain six I - V curve correction parameters which can be determined by measurement of I - V curves at different temperature and irradiance conditions (see Clauses 5 to 7). Besides the relative temperature coefficients for short-circuit current (α_{rel}) and open-circuit voltage (β_{rel}) an additional temperature coefficient (κ') is commonly used which accounts for changes of the internal series resistance (and fill factor) with temperature. Furthermore, correction procedure 2 introduces a quadratic irradiance factor $f(G)$ with coefficients B_1 and B_2 , which accounts for the non-linear scaling of diode's ideality factor with irradiance. The correction procedure is defined by the following formulae for current and voltage:

$$I_2 = \frac{G_2}{G_1} I_1 \frac{(1 + \alpha_{rel} \times (T_2 - 25^\circ C))}{(1 + \alpha_{rel} \times (T_1 - 25^\circ C))} \quad (5)$$

$$V_2 = V_1 - R'_{S1} \times (I_2 - I_1) - \kappa' \times I_2 \times (T_2 - T_1) + V_{OC,STC} \times \left\{ \beta_{rel} \times [f(G_2) \times (T_2 - 25^\circ C) - f(G_1) \times (T_1 - 25^\circ C)] + \frac{1}{f(G_2)} - \frac{1}{f(G_1)} \right\} \quad (6)$$

$$f(G) = \frac{V_{OC,STC}}{V_{OC}(G)} = B_2 \times \ln^2 \left(\frac{1\,000\,Wm^{-2}}{G} \right) + B_1 \times \ln \left(\frac{1\,000\,Wm^{-2}}{G} \right) + 1 \quad (7)$$

$$R'_{S1} = R'_S + \kappa' \times (T_1 - 25^\circ C) \quad (8)$$

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, corrected for temperature and linearity of the reference device and the SMM;
G_2	is the target irradiance for the corrected I - V characteristic;
T_1	is the measured temperature of the DUT;
T_2	is the target temperature of the DUT;
V_{OC1}	is the open-circuit voltage at test conditions G_1 and T_1 ;
$V_{OC,STC}$	is the open-circuit voltage at standard test conditions;
α_{rel} and β_{rel}	are the relative short-circuit current and open-circuit voltage temperature coefficients, respectively, of the DUT measured at 1 000 W/m ² . They express the relative change of short-circuit current and open-circuit voltage with respect to their values at STC; both coefficients are expressed in percent per unit temperature and should be scaled by a fraction of 100 when used in the formulae (e.g. $\alpha_{rel} = 0,045 \text{ \% K}^{-1} = 0,00045 \text{ K}^{-1}$);
B_1	is the irradiance correction factor for open-circuit voltage which is linked with the diode thermal voltage D of the p-n junction and the number of cells n_S serially connected in the DUT;
B_2	is the irradiance correction factor for open-circuit voltage which accounts for non-linearity of V_{OC} with irradiance scaling;
R'_S	is the internal series resistance of the DUT determined at 25 °C;
R'_{S1}	is the internal series resistance of the DUT at measured temperature T_1 ;
κ'	is interpreted as temperature coefficient of the internal series resistance R'_S .

Care should be taken that the numerical values for κ' and R'_S for procedure 2 can be different from κ and R_S of correction procedure 1, as correction procedure 2 requires the series resistance to be explicitly determined at 25 °C.

When unknown, $V_{OC,STC}$ can be derived from the actual measurement using the following expression:

$$V_{OC,STC} = \frac{V_{OC1} \times f(G_1)}{1 + \beta_{rel} \times (T_1 - 25^\circ\text{C}) \times f^2(G_1)} \quad (9)$$

NOTE 1 For c-Si modules when V_{OC} scales with the irradiance term $\ln(1\,000/G)$ linearly, a typical range for the irradiance correction factor B_1 is $0,05 \pm 0,01$ while B_2 is 0. When V_{OC} scales non-linearly with the irradiance term $\ln(1\,000/G)$, B_1 typically varies in the range of $0,04 \pm 0,01$ and B_2 in the range of $0,004 \pm 0,001$.

NOTE 2 A typical range for the temperature coefficient α_{rel} of c-Si modules is from 0,03 %/°C to 0,06 %/°C with respect to the I_{SC} at STC. A typical range for the temperature coefficient β_{rel} of c-Si modules is from -0,35 %/°C to -0,2 %/°C with respect to the V_{OC} at STC.

4.4 Correction procedure 3

4.4.1 General

This procedure may be applied only to devices proven to be linear according to IEC 60904-10. It is based on the linear interpolation or extrapolation of two measured I - V characteristics [3]. The method 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 STC or other target temperature and irradiance values by applying the following formulae:

$$V_3 = V_1 + a \times (V_2 - V_1) \quad (10)$$

$$I_3 = I_1 + a \times (I_2 - I_1) \quad (11)$$

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 DUT at irradiances G_1 and G_2 .

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

$$G_3 = G_1 + a \times (G_2 - G_1) \quad (12)$$

$$T_3 = T_1 + a \times (T_2 - T_1) \quad (13)$$

This method should be applicable to most PV technologies. Formulae (10) to (13) can be used for the irradiance correction, temperature correction, and simultaneous correction of irradiance and temperature. This procedure assumes that the normalized spectra corresponding to G_1 , G_2 and G_3 are identical. If they are not, then there will be an additional source of uncertainty in G_3 . Measuring G_1 and G_2 with SMM corrections based upon the spectral responsivity measured at T_1 and T_2 according to IEC 60904-8 will minimize these errors. If the spectral responsivity is nonlinear in relation to irradiance then it should be measured at bias light intensities equal to G_1 and G_2 .

4.4.2 Correction for the irradiance and temperature from two measured I - V curves

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 (Figure 1a) and 1b):

- 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 1a)). Find the values of I_{SC1} and I_{SC2} .

- b) Calculate α by formula (12) or (13) choosing a target irradiance or temperature. For example, when the two measured I - V curves were made at:

$$G_1 = 1\,000 \text{ W/m}^2 \text{ and } T_1 = 50 \text{ }^\circ\text{C}$$

$$G_2 = 500 \text{ W/m}^2 \text{ and } T_2 = 40 \text{ }^\circ\text{C}.$$

and the target irradiance is $G_3 = 800 \text{ W/m}^2$:

then, using formula (12) $\alpha = 0,4$

and using formula (13) $T_3 = 46 \text{ }^\circ\text{C}$.

- c) Choose a point (V_1, I_1) on the I - V curve 1. Find a point (V_2, I_2) on the I - V curve 2, so that the relation $I_2 - I_1 = I_{SC2} - I_{SC1}$ is satisfied (Figure 1b)).
- d) Calculate V_3 and I_3 by formulae (10) and (11).
- e) Select multiple sets of data points (V_1, I_1) on the I - V curve 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 is given by the set of data points (V_3, I_3) (broken line in Figure 1 b)).

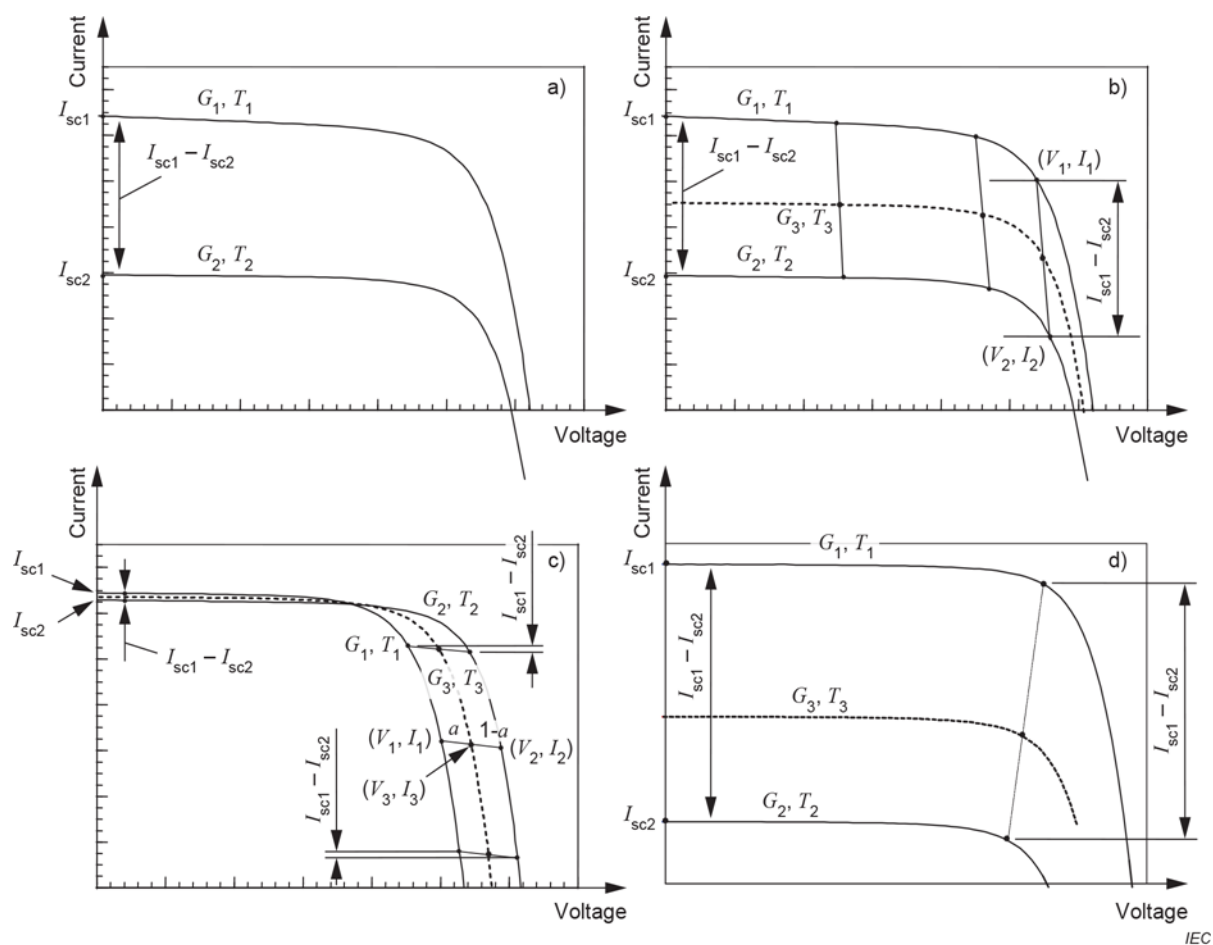
Figure 1a) and Figure 1b) show an example of an irradiance correction ($T_1 = T_2$). Figure 1c) shows an example of a temperature correction ($G_1 = G_2$). Figure 1d) shows a simultaneous correction of irradiance and temperature. When $0 \leq \alpha \leq 1$, the procedure is interpolation. Otherwise, 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 may not be chosen independently, because they have the relationships given in formulae (12) and (13) (Figure 2). For example, when $G_1 = 1\,000 \text{ W/m}^2$, $T_1 = 20 \text{ }^\circ\text{C}$, $G_2 = 0 \text{ W/m}^2$, $T_2 = 60 \text{ }^\circ\text{C}$ (dark I - V curve at $60 \text{ }^\circ\text{C}$), and you wish to have the new curve at $G_3 = 750 \text{ W/m}^2$, α is calculated to be 0,25 by formula (12). Therefore, T_3 is $30 \text{ }^\circ\text{C}$ from formula (13).

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} .

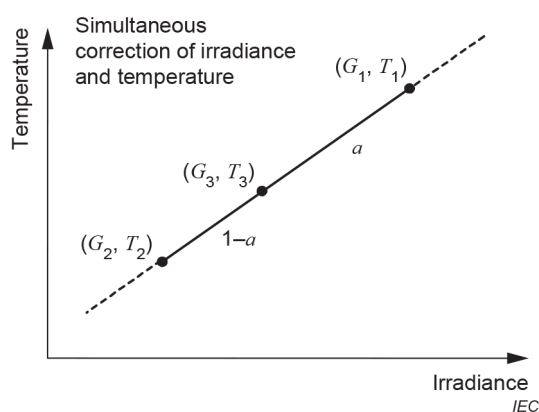
When there are no measured data points which exactly satisfy $I_2 = I_1 + (I_{SC2} - I_{SC1})$, the V_2 and I_2 may be calculated from interpolation of the data points in the I - V curve 2.

This method is applicable to both interpolation ($0 \leq \alpha \leq 1$) and extrapolation ($\alpha < 0$ or $\alpha > 1$). Interpolation gives better results than extrapolation. Extrapolation should be practiced with caution; the user should avoid extrapolating in I - V curve regions beyond the known range and especially in I - V curve regions where steps or kinks may interfere.



Subfigures a) and b) show irradiance corrections ($T_1 = T_2$), c) shows a temperature correction ($G_1 = G_2$) and d) shows simultaneous correction of irradiance and temperature.

Figure 1 – Example of the correction of the I - V characteristics by formulae (10) and (11)



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

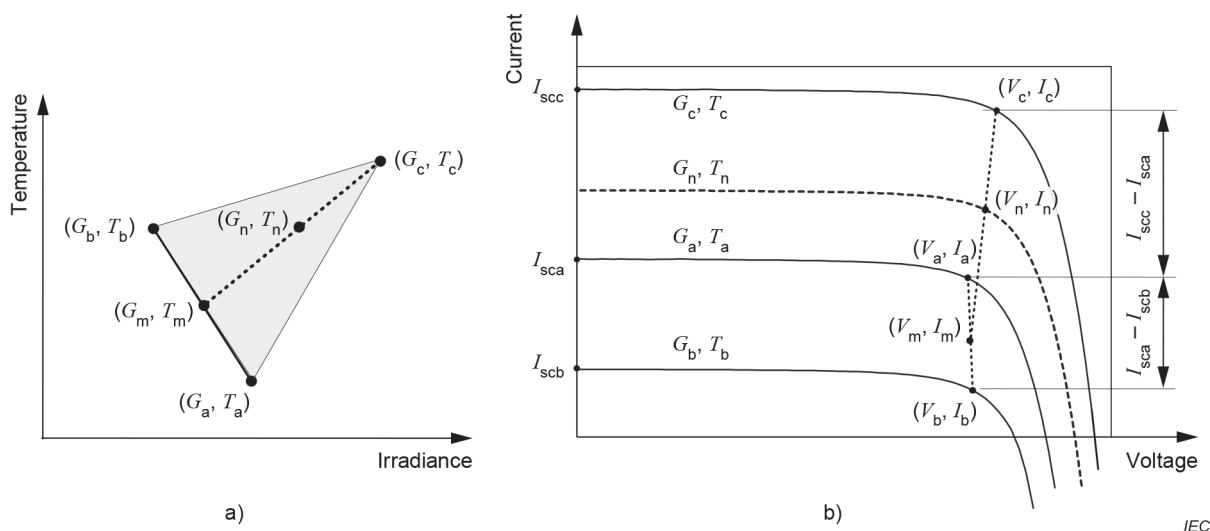
Figure 2 – Schematic diagram of the relation of G_3 and T_3 which can be chosen in the simultaneous correction for irradiance and temperature, for a fixed set of T_1 , G_1 , T_2 , and G_2 by formulae (12) and (13)

4.4.3 Correction to various irradiances and temperatures from three I - V curves

The correction of the I - V characteristics to various ranges of irradiance and temperature is possible by combining the procedures described in 4.4.2. For example, when three I - V 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 irradiance and temperature (G_n, T_n) can be calculated as follows, assuming a linear PV device.

- The characteristics at (G_m, T_m) are calculated from those at (G_a, T_a) and (G_b, T_b) .
- The characteristics at (G_n, T_n) are calculated from those at (G_m, T_m) and (G_c, T_c) .

EXAMPLE: When (G_a, T_a) , (G_b, T_b) , (G_c, T_c) and (G_n, T_n) are $(950 \text{ W/m}^2, 15^\circ\text{C})$, $(850 \text{ W/m}^2, 25^\circ\text{C})$, $(1\,100 \text{ W/m}^2, 30^\circ\text{C})$ and $(1\,000 \text{ W/m}^2, 25^\circ\text{C})$ respectively, then (G_m, T_m) are $(900 \text{ W/m}^2, 20^\circ\text{C})$.



The shaded area in subfigure a) shows the range which can be calculated by interpolation only. Subfigure b) shows an example of the I - V characteristics which correspond to subfigure a).

Figure 3 – Schematic diagram of the processes for correcting the I - V characteristics to various ranges of irradiance and temperature based on three measured characteristics

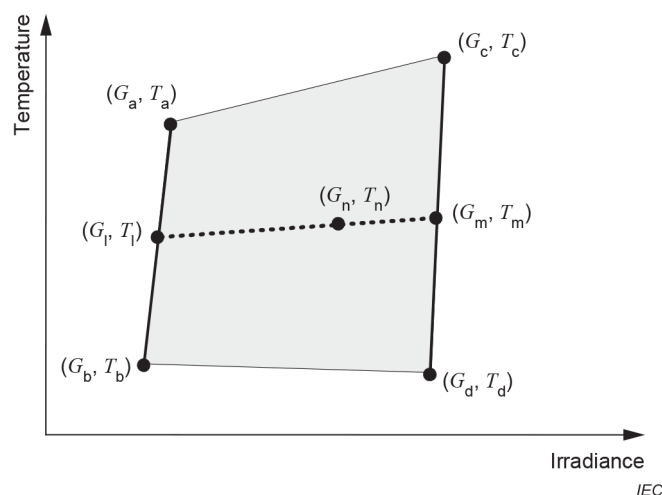
4.4.4 Correction to various irradiances and temperatures from four measured I - V curves

When four I - V characteristics measured at irradiances and temperatures of (G_a, T_a) , (G_b, T_b) , (G_c, T_c) and (G_d, T_d) are available as shown in Figure 4, the I - V characteristics at any irradiance and temperature (G_n, T_n) can be calculated as follows. This process is useful for correction of the characteristics in a wide range of irradiance and temperature. Although the pair of (G_l, T_l) and (G_m, T_m) to calculate the characteristics at (G_n, T_n) is not unique, good correction results are usually available when $(G_a - G_l)/(G_a - G_b) = (G_c - G_m)/(G_c - G_d)$ is satisfied.

- The characteristics at (G_l, T_l) are calculated from those at (G_a, T_a) and (G_b, T_b) .
- The characteristics at (G_m, T_m) are calculated from those at (G_c, T_c) and (G_d, T_d) .
- The characteristics at (G_n, T_n) are calculated from those at (G_l, T_l) and (G_m, T_m) .

EXAMPLE 2: When (G_a, T_a) , (G_b, T_b) , (G_c, T_c) , (G_d, T_d) and (G_n, T_n) are $(500 \text{ W/m}^2, 55^\circ\text{C})$, $(400 \text{ W/m}^2, 31^\circ\text{C})$, $(1\,000 \text{ W/m}^2, 60^\circ\text{C})$, $(950 \text{ W/m}^2, 32^\circ\text{C})$ and $(800 \text{ W/m}^2, 45^\circ\text{C})$ respectively, then (G_l, T_l) and (G_m, T_m) are $(450 \text{ W/m}^2, 43^\circ\text{C})$ and $(975 \text{ W/m}^2, 46^\circ\text{C})$ respectively.

The I - V characteristics in the range of irradiance and temperature shown by the shaded area of Figure 4 can be calculated by linear interpolation. The characteristics in the range other than the shaded area may be calculated by using linear extrapolation. However, care should be taken that extrapolation not result in poor correction accuracy.



The shaded area shows the range which can be calculated by interpolation only.

Figure 4 – Schematic diagram of the processes for correcting the I - V characteristics to various ranges of irradiance and temperature based on four measured characteristics

4.5 Correction procedure 4

When the correction performance parameters are unknown, correction procedure 4 provides a method for I - V curve corrections [4]. The procedure is fundamentally based on the single-diode model and requires only the bandgap of the material and the number of cells connected in series to be known. The method has been validated under a broad range of temperatures for c-Si technologies. It is best applicable to irradiance corrections when the measured and target irradiance are both in the range 300 W/m² to 1 200 W/m². This procedure may not be applicable to devices which do not follow the single-diode model, such as degraded devices and partially shaded devices.

The R_S which is used for the irradiance correction in formula (15), can be determined from a single I - V curve as described in 6.5. The value of ε , which is used for the temperature correction in formula (17), is basically independent of temperature and irradiance. A typical value of 1,232 V is applicable to c-Si PV devices.

The measured current-voltage curve shall be translated to the target temperature and irradiance values by applying the following formulae:

$$I'_1 = I_1 + I_{SC1} \times \left(\frac{G_2}{G_1} - 1 \right) \quad (14)$$

$$V'_1 = V_1 - R_S \times (I'_1 - I_1) \quad (15)$$

$$I_2 = I'_1 + \alpha_{rel} \times I_{SC,STC} \times (T_2 - T_1) \quad (16)$$

$$V_2 = V'_1 + (T_2 - T_1) \times \frac{1}{T_1} \times (V'_1 - n_S \times \varepsilon) \quad (17)$$

where:

- I_1, V_1 are coordinates of points on the measured characteristics;
- I'_1, V'_1 are coordinates of points on the characteristics corrected for irradiance;
- I_2, V_2 are coordinates of the corresponding points on the characteristic corrected for irradiance and temperature;
- G_1 is the irradiance measured with the reference device, corrected for temperature and linearity of the reference device and the SMM;
- G_2 is the target irradiance for the DUT;
- T_1 is the measured temperature of the DUT;
- T_2 is the target temperature;
- I_{SC1} is the measured short-circuit current of the DUT at G_1 and T_1 ;
- $I_{SC,STC}$ is the short-circuit current of the DUT at STC ;
- α_{rel} is the relative current temperature coefficient of the DUT measured at 1 000 W/m². It expresses the relative change of short-circuit current with respect to its value at STC; the coefficient is expressed in percent per unit temperature and should be scaled by a fraction of 100 when used in the formulae (e.g. $\alpha_{rel} = 0,045 \text{ \% K}^{-1} = 0,00045 \text{ K}^{-1}$). For commercial c Si a typical value of 0,045 % K⁻¹ may be used when the specific value is not available;
- R_S is the internal series resistance of the DUT;
- n_S is the number of cells connected in series;
- ε is a device dependent constant expressed in units of volt. The constant represents the product of ideality factor of the DUT with the bandgap of the photovoltaic material and divided by electron's elementary charge; for c-Si it is typically 1,232 V. For devices other than c-Si, the value should be optimized to yield best translation results.

When unknown $I_{SC,STC}$ can be derived from the actual measurement using the following expression:

$$I_{SC,STC} = \frac{1000 \text{ W m}^{-2}}{G_1} \times \frac{I_{SC}}{(1 + \alpha_{rel} \times (T_1 - 25^\circ \text{C}))} \quad (18)$$

NOTE A typical range for the temperature coefficient α_{rel} of c-Si modules is from 0,03 %/K to 0,06 %/K with respect to the I_{SC} at STC.

5 Determination of temperature coefficients

5.1 General

For PV devices, temperature coefficients (TCs) are commonly used for the following electrical parameters: short-circuit current (TC = α), open-circuit voltage (TC = β) and maximum power (TC = δ).

These parameters may be determined from measurements in natural or simulated sunlight. A distinction has to be made between temperature coefficients (in respective unit/K or unit/°C) and the relative temperature coefficient expressed in percentage per unit temperature (%/K or %/°C).

- Temperature coefficients (α , β and δ) expressed in units of current, voltage or power per unit temperature (A/K, V/K and W/K or A/°C, V/°C and W/°C respectively) are only valid at the irradiance level and spectrum at which they were measured. For linear PV devices with respect to irradiance (typically the case for c-Si), α , δ coefficients scale approximately linearly with irradiance, while β remains approximately constant. This approximation may be used over an irradiance range of ± 30 % of this level.
- Relative temperature coefficients (α_{rel} , β_{rel} and δ_{rel}) expressed in percentage per unit temperature (%/K or %/°C) can be determined by dividing the calculated value of temperature coefficients α , β , and δ by the values of short-circuit current, open-circuit voltage and maximum power respectively determined from the least squares fit at 25 °C corresponding to an irradiance of 1 000 W/m². The relative coefficients so determined are valid at the irradiance and spectrum at which the measurements were made. For linear PV devices with respect to irradiance (typically the case for c-Si), relative temperature coefficients α_{rel} and β_{rel} are valid over the entire range of irradiance for which the device is linear according to IEC 60904-10.

The temperature coefficients of a thin-film PV device may depend upon the total irradiance, the spectral irradiance and the thermal history of the PV device. When temperature coefficients are referred to, the history concerning the conditions and the results of irradiation along with thermal history shall be indicated.

Formula (1) can be utilized to determine the irradiance from the measured short-circuit current of the reference cell, in order to measure the temperature coefficients of the DUT at irradiance levels other than 1 000 W/m². Formula (1) only holds for linear reference cells which are linear in I_{SC} with irradiance, otherwise a correction according to IEC 60904-10 should be made. A linearity check according to IEC 60904-10 on the DUT should be performed if interpolation of temperature coefficients between irradiances is needed.

Some technologies, such as silicon heterojunction (SHJ)[5], or thin-film may exhibit a non-linear temperature coefficient with temperature. For these devices, it is recommended to measure the temperature dependence over a broad temperature range (e.g. 15 °C to 75 °C) and specify the temperature range for which the determined temperature coefficient is applicable.

5.2 Apparatus

The measuring apparatus shall comply with the following:

- a) The apparatus and instrumentation shall comply with the requirements of IEC 60904-1 and its relevant subparts.

- b) If a solar simulator is used as radiant source it shall comply with class BBB or better in accordance with IEC 60904-9. The solar simulator shall produce continuous spectral irradiance (i.e. uninterrupted in wavelength) near the bandgap of the DUT in order to avoid measurement artefacts due to a possible shift of the spectral responsivity edge with temperature and therefore a change in the spectral mismatch of the DUT during the measurement sequence. IEC 60904-10 provides guidance on how to deal with the possible changes in spectral mismatch due to temperature for measurements with solar simulators and under natural sunlight.
- c) The apparatus includes equipment necessary to change and/or control the temperature of the DUT over the range of interest. Each equipment used to change temperature can produce a different temperature non-uniformity on the DUT and therefore a specific uncertainty calculation is necessary to account for this.

NOTE The following equipment has been used successfully:

- blowers, allowing cooling and heating of the DUT by airflow;
- mounting blocks with variable temperature in close contact with a single cell or an entire module;
- chambers with a transparent window, where internal temperature can be controlled;
- a removable shade when natural or steady-state simulated sunlight is used.

If the DUT is a module, the temperature of the module should be measured at least at four positions. Each sensor shall be placed in such a way that is located directly behind a cell. The position of the four sensors shall be optimised, so the average temperature of all sensors coincides with the average effective junction temperature of the module at thermal equilibrium. Deviations between the average sensor temperature and the average effective junction temperature of the module shall be accounted for in the measurement uncertainty analysis. There is no general optimum position for the temperature sensors, but this rather depends on the measurement set-up. An example configuration is shown in Figure 5, which corresponds to a set-up where the temperature non-uniformity is vertically distributed without significant effects around the edges.

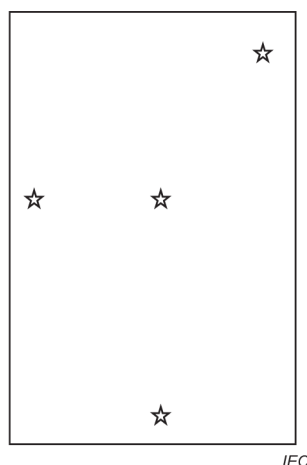


Figure 5 – Example positions for measuring the temperature of the test module behind the cells

- d) For bifacial modules, temperature coefficient measurements can be performed utilising either single-side, or double-side illumination method. When the single-side illumination method is employed determine the temperature coefficients utilizing the same procedure as in mono-facial modules but insuring no backside irradiation. The backside shall be covered such that the contribution from the non-exposed side of the module is limited to or below the levels specified for “non-irradiated background” in IEC TS 60904-1-2. When the double-side illumination method is employed, care shall be taken to minimise shading from the temperature sensors. When contact sensors are used, sensors should be placed preferably along the solar cell busbars and fixed with transparent thermal tape.