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

FOREWORD

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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.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document 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- withdrawn,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 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 ±40% of the target irradiance. The second procedure is an alternative algebraic correction method which yields better results for large irradiance corrections (exceeding ±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 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 W/m^2.

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

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 G1 and T1;
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. β = –2,3 mV/°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.

$$I_2 = I_1 + \frac{G_1'}{G_{SC1}} \times I_{SC1} \times \left(\frac{G_2}{G_1'} - 1\right) + \alpha \times (T_2 - T_1) \tag{4}$$

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:

$$I_2 = \frac{G_2}{G_1} I_1 \frac{\left(1 + a_{rel} \times (T_2 - 25°C)\right)}{\left(1 + a_{rel} \times (T_1 - 25°C)\right)} \tag{5}$$

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

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

$$R_{S1}' = R_S' + \kappa' \times (T_1 - 25°C) \tag{8}$$

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/m². 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. α_{rel} = 0,045 % K^{-1} = 0,00045 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:

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

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 ± 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 ± 0,01 and B_2 in the range of 0,004 ± 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.