BS EN 60891:2010

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

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National foreword

This British Standard is the UK implementation of EN 60891:2010. It is identical to IEC 60891:2009. It supersedes BS EN 60891:1995 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee GEL/82, Photovoltaic Energy Systems.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

ISBN 978 0 580 65689 7

ICS 27.160; 31.260

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 July 2010.

Amendments issued since publication

Amd. No.	Date	Text affected

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 60891

March 2010

ICS 27.160

Supersedes EN 60891:1994

English version

Photovoltaic devices - Procedures for temperature and irradiance corrections to measured I-V characteristics (IEC 60891:2009)

Dispositifs photovoltaïques - Procédures pour les corrections en fonction de la température et de l'éclairement à appliquer aux caractéristiques I-V mesurées (CEI 60891:2009)

Verfahren zur Umrechung von gemessenen Strom-Spannungs-Kennlinien von photovoltaischen Bauelementen auf andere Temperaturen und Bestrahlungsstärken (IEC 60891:2009)

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Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CENELEC member.

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CENELEC
European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

Central Secretariat: Avenue Marnix 17, B - 1000 Brussels

Ref. No. EN 60891:2010 E

Foreword

The text of document 82/581/FDIS, future edition 2 of IEC 60891, prepared by IEC TC 82, Solar photovoltaic energy systems, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 60891 on 2010-03-01.

This European Standard supersedes EN 60891:1994.

The main technical changes with regard to the EN 60891:1994 are as follows:

– extends existing 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.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN and CENELEC shall not be held responsible for identifying any or all such patent rights.

The following dates were fixed:

– latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2010-12-01
– latest date by which the national standards conflicting with the EN have to be withdrawn	(dow)	2013-03-01

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 60891:2009 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following note has to be added for the standard indicated:

IEC 60904-5 NOTE Harmonized as EN 60904-5.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60904-1	-	Photovoltaic devices - Part 1: Measurement of photovoltaic current-voltage characteristics	EN 60904-1	-
IEC 60904-2	-	Photovoltaic devices - Part 2: Requirements for reference solar devices	EN 60904-2	-
IEC 60904-7	-	Photovoltaic devices - Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices	EN 60904-7	-
IEC 60904-9	-	Photovoltaic devices - Part 9: Solar simulator performance requirements	EN 60904-9	-
IEC 60904-10	-	Photovoltaic devices - Part 10: Methods of linearity measurement	EN 60904-10	-

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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.

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

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:

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

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

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:

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

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

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)).

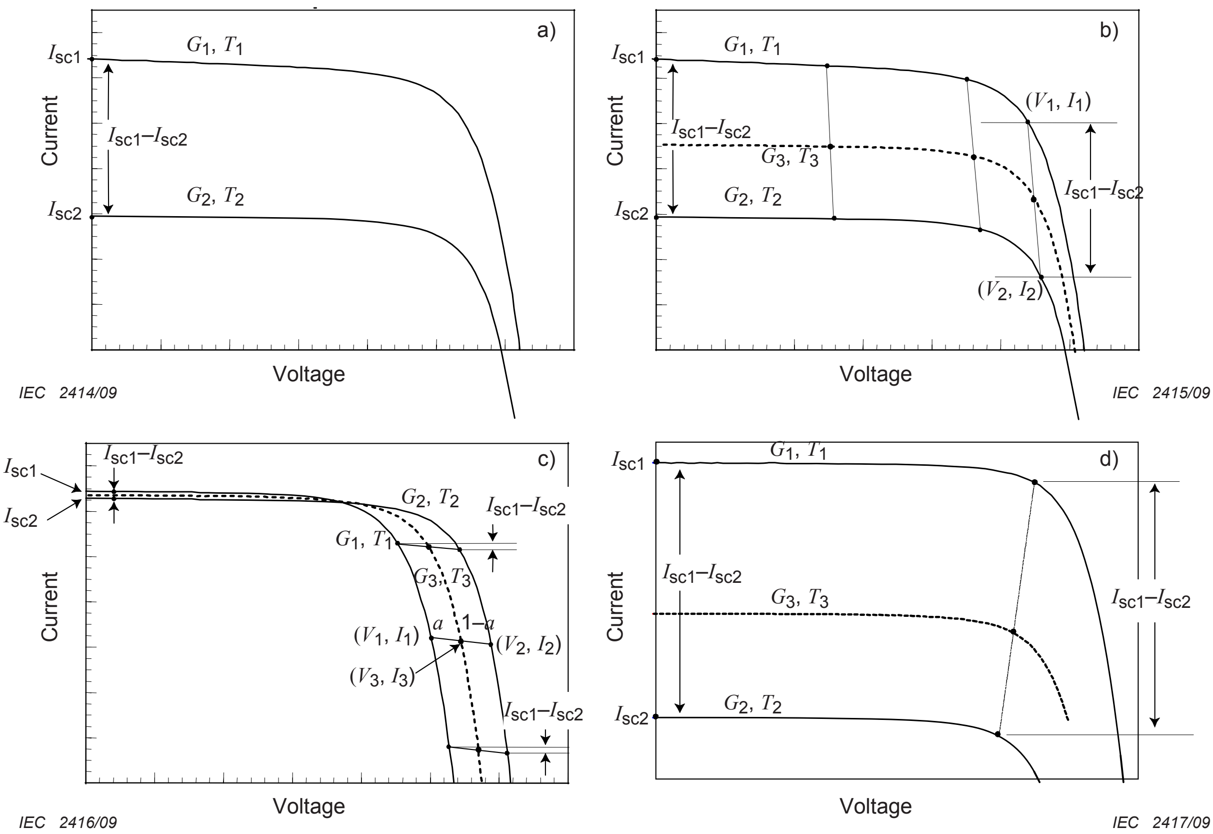
d) Calculate V_3 and I_3 by Equations (6) and (7).

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).



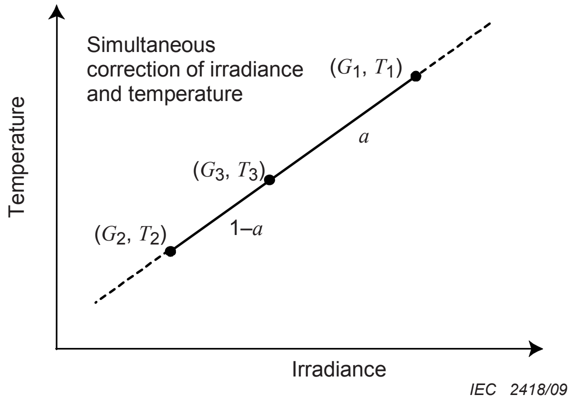
Subfigures (a) and (b) show irradiance corrections, (c) shows a temperature correction and (d) shows simultaneous correction of irradiance and temperature.

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)

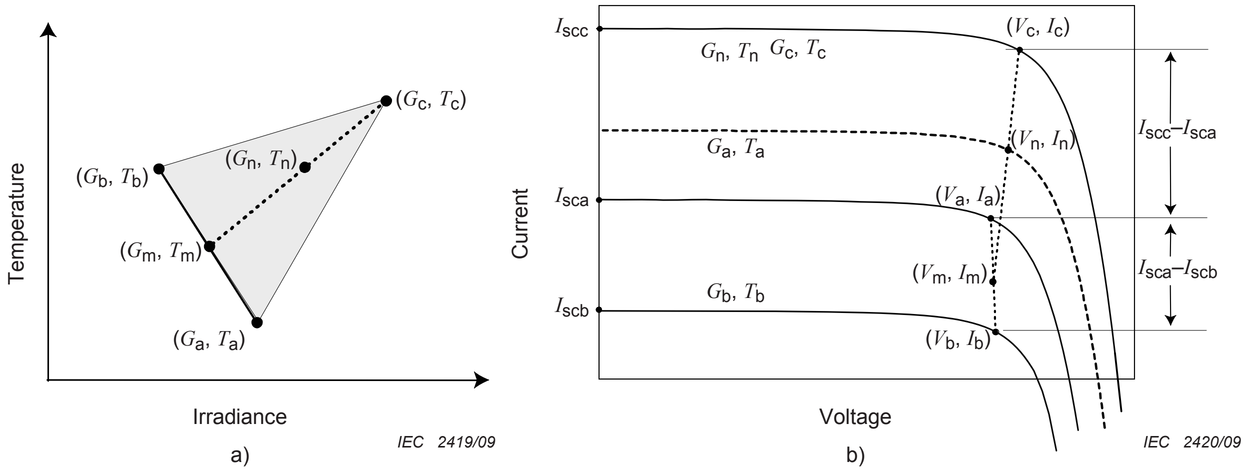
3.4.3 Correction to various irradiances and temperatures from three I-V characteristics

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).



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

3.4.4 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 irradiances and temperatures (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.

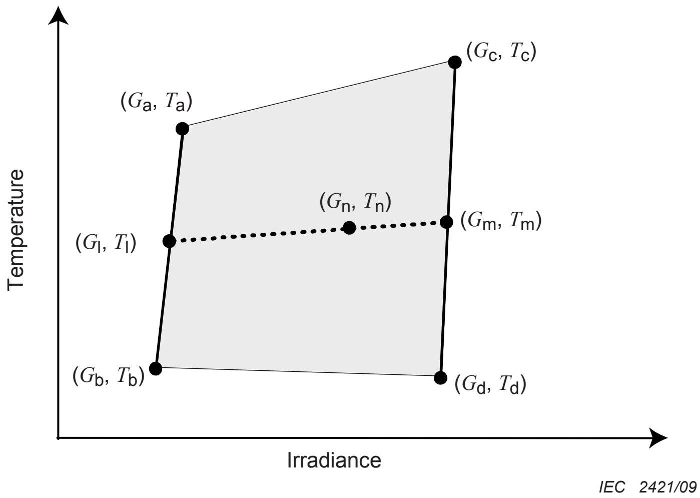
a) The characteristics at (G_l, T_l) are calculated from those at (G_a, T_a) and (G_b, T_b).

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

c) The characteristics at (G_n, T_n) are calculated from those at (G_l, T_l) and (G_m, T_m).

For example, when (G_a, T_a), (G_b, T_b), (G_c, T_c), (G_d, T_d) and (G_n, T_n) are (500 W/m^2, 55 °C), (400 W/m^2, 31 °C), (1 000 W/m^2, 60 °C), (950 W/m^2, 32 °C) and (800 W/m^2, 45 °C) respectively, then (G_l, T_l) and (G_m, T_m) are (450 W/m^2, 43 °C) and (975 W/m^2, 46 °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 interpolation. The characteristics in the range other than the shaded area can be calculated by using extrapolation. However, care should be taken that extensive extrapolation not result in bad correction results and a 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 Determination of temperature coefficients

4.1 General

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

These parameters may be determined from measurements in natural sunlight or simulated sunlight. The coefficients so determined are valid at the irradiance at which the measurements were made. For linear PV devices, they are valid over an irradiance range of ±30 % of this level.

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

See IEC 60904-10 for evaluation of module temperature coefficients at different irradiance levels.

4.2 Apparatus

The measuring apparatus shall comply with the following:

a) The apparatus and instrumentation shall comply with the requirements of IEC 60904-1.
b) If a solar simulator is used as radiant source it shall comply with class BBB or better in accordance with IEC 60904-9.
c) The apparatus includes equipment necessary to change the temperature of the test specimen over the range of interest.

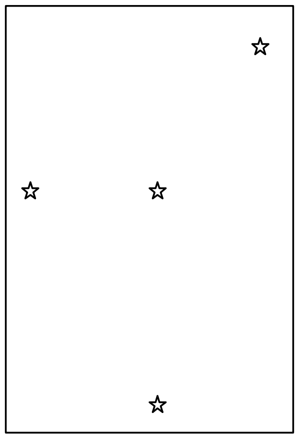
NOTE The following equipment has been used successfully:

– blowers, allowing cooling and heating of the specimen 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 sunlight is used.

d) If the test device is a module, the temperature of the module shall be measured at approximately the four positions shown in Figure 5 (assuring that each position is directly behind a cell) and their values averaged.



IEC 2422/09

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

4.3 Procedure in natural sunlight

Measurement in natural sunlight shall only be made when:

– the total irradiance is at least as high as the upper limit of the range of interest;

– the irradiance variation caused by short-term oscillations (clouds, haze, or smoke) is less than ±2 % of the total irradiance as measured by the reference device;

– the wind speed is less than 2 $m \cdot s^{-1}$.

NOTE 1 Measurements in natural sunlight shall be made as expeditiously as possible within a few hours on the same day to minimize the effect of changes in the spectral conditions. If not, spectral corrections may be required.

a) If the test specimen and reference device (IEC 60904-2) are equipped with temperature controls, set the controls at the desired level.

b) If temperature controls are not used, shade the specimen and the reference device from the sun and wind until its temperatures are uniform within ±2 °C of the ambient air temperature. Alternately, allow the test specimen to equilibrate to its stabilized temperature, or cool the test specimen to a point below the required test temperature and then let the module warm up naturally. The reference device should also stabilize within ± 2 °C of its equilibrium temperature before proceeding.

NOTE 2 For large-area modules an alternate approach is to use the equivalent cell temperature (ECT) in accordance with IEC 60904-5, if the temperature requirement is not met.

c) Record the I-V characteristic and temperature of the specimen concurrently with recording the short-circuit current and temperature of the reference device at the desired temperatures. If necessary, make the measurements immediately after removing the shade. Take the values of I_{SC}, V_{oc} and P_{max}.

d) Adjust the device temperature by means of a temperature control or alternately exposing and shading the test module as required to achieve and maintain the desired temperature. Alternately, the test device may be allowed to warm-up naturally with the data recording procedure of item b) performed periodically during the warm-up.

e) Ensure that the test device and reference device temperature are stabilized and remain constant within ±2 °C and that the irradiance as measured by the reference device remains constant within ±1 % during the recording period for each data set.

f) If necessary, translate data to the irradiance level for which temperature coefficients shall be reported using one of the procedures in this standard. The translation can only be performed within the range of irradiance where the module is linear as defined in IEC 60904-10.

g) Repeat steps d) through f). Module temperatures shall be such that the range of interest is at least 30 °C and that it is spanned in at least four approximately equal increments.

4.4 Procedure with a solar simulator

The procedure using a solar simulator is as follows:

a) Heat or cool the module to the temperature of interest until its temperature is uniform within ±2 °C. Once the module temperature has stabilized, set the irradiance to the desired level, using the reference device (IEC 60904-2).

b) Record the current-voltage characteristic and temperature of the specimen and take the values of I_{SC}, V_{oc} and P_{max}.

c) Change the module temperature in steps of approximately 5 °C over a range of interest of at least 30 °C and repeat steps a) and b).

4.5 Calculation of temperature coefficients

4.5.1 Plot the values of I_{SC}, V_{OC} and P_{max} as functions of the device temperature and construct a least-squares-fit curve through each set of data.

4.5.2 From the slopes of the least squares fit. draw straight lines for current, voltage and P_{max}. Calculate α, the temperature coefficient of short circuit current, β, the temperature coefficient of open circuit voltage, and δ, the temperature coefficient of P_{max}, for the module.

NOTE 1 See IEC 60904-10 to determine if the test modules can be considered to be linear devices.

NOTE 2 Temperature coefficients are only valid at the irradiance level and spectrum at which they were measured.

NOTE 3 Relative temperature coefficients expressed as percentages can be determined by dividing the calculated value of α, β, and δ by the values of current, voltage and peak power at 25 °C.

NOTE 4 Because the fill factor of the module is a function of temperature, it is not sufficient to use the product of α and β as the temperature coefficient of peak power.

5 Determination of internal series resistance R_S and R'_S

5.1 General

The experimental method for determination of R_S or R'_S is different for correction procedures 1 and 2 although they both start from the same data set of I-V curves. These parameters may be determined in natural sunlight or simulated sunlight by the following procedure.

Trace current-voltage characteristics of the test specimen at constant temperature and at three or more different irradiances (G_1 … G_N) covering the range of interest within which the curve translation shall be performed. The exact values of irradiances need not be known. For linear devices they can be calculated according to $G_N = I_{SC,N}/I_{SC1} \times G_1$. During the I-V measurements the device temperature shall be stable within ±2 °C. Plot the I-V curves in a diagram (Figure 6a).

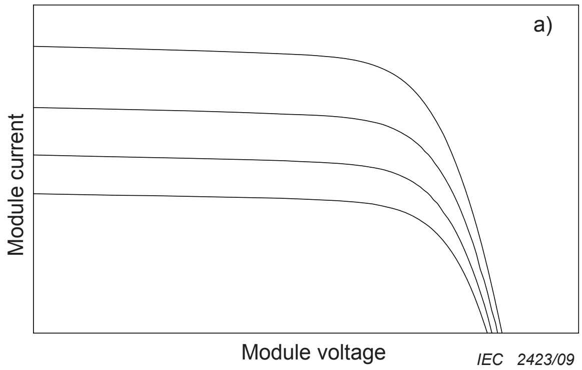
NOTE For the purpose of changing irradiance, large area meshes with uniform transmittance can be used. Regarding spectral irradiance, these can be considered as neutral mesh filters.

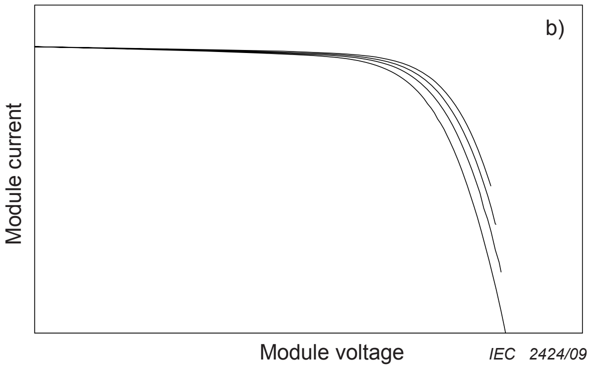
5.2 Correction procedure 1

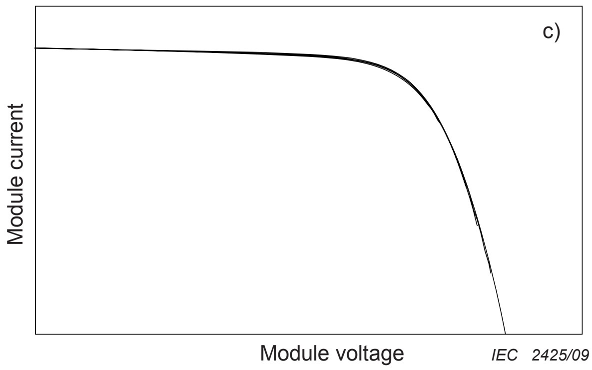
5.2.1 Assuming that I_{SC1} is the short-circuit current of the I-V characteristic recorded at highest Irradiance G_1, translate sequentially all other (N–1) curves recorded at lower irradiance (G_2 .. G_N) to the G_1, using R_S = 0 Ω.

5.2.2 Plot the corrected I-V curves in a diagram (Figure 6b).

5.2.3 Change R_S in steps of 10 mΩ in the positive or negative direction. The proper value of "R_S" has been determined, if the deviation of maximum output power values of the transposed I-V characteristics coincide within ± 0,5 % or better (see Figure 6c).







a) Measured I-V characteristics at different irradiances and constant temperature

b) Corrected I-V characteristics at R_S = 0 Ω

c) Corrected I-V characteristics at R_S = optimal

Figure 6 – Determination of internal series resistance

5.3 Correction procedure 2

5.3.1 Assuming that I_{SC1} is the short-circuit current of the I-V characteristic recorded at highest Irradiance G_1, translate sequentially all other (N–1) curves recorded at lower irradiance (G_2 .. G_N) to the G_1, using R'_S = 0 Ω, a = 0 as starting values using Equations (4) and (5).

5.3.2 Plot the corrected I-V curves in a diagram (see Figure 7b).

NOTE At given start values R'_S = 0 Ω, a = 0 only the translated short circuit currents will coincide.

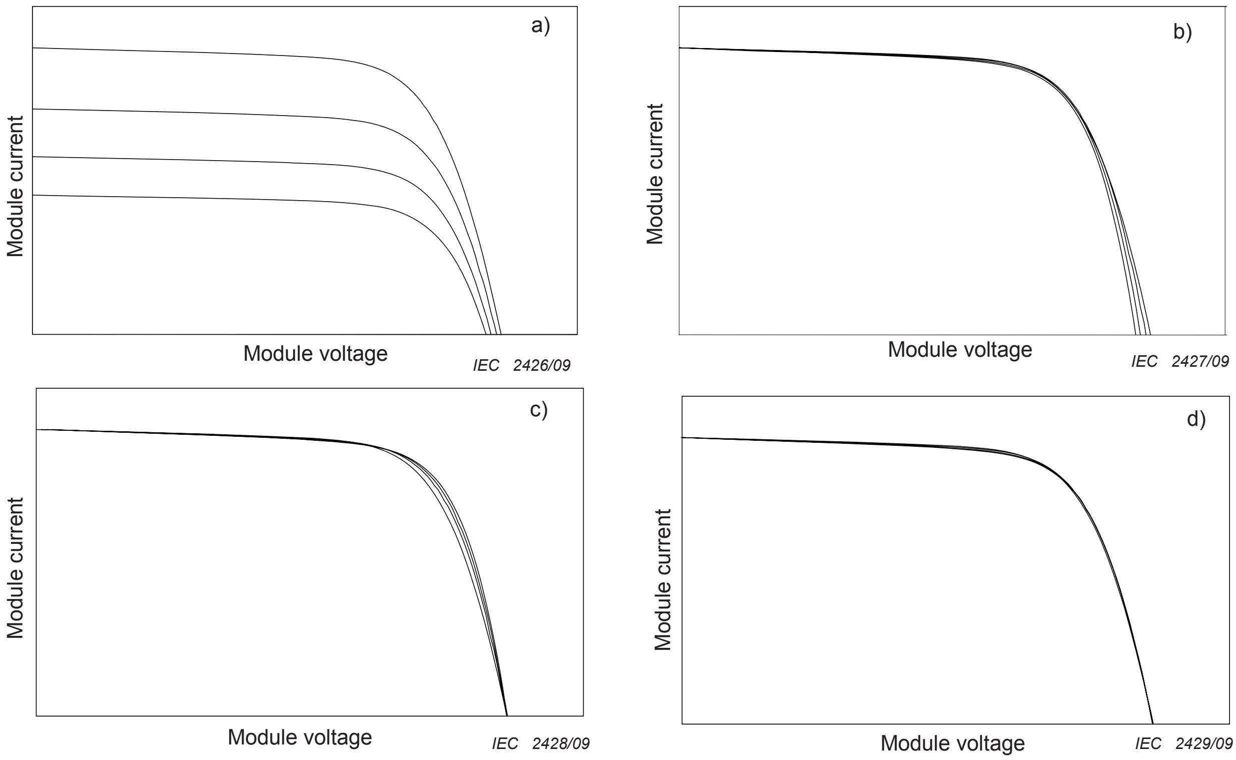
5.3.3 Increase the parameter "a" of Equation (5) in steps of 0,001 and keep R'_S = 0 Ω. The proper value of "a" has been determined, when the open circuit voltages of the transposed I-V characteristics coincide within ±0,5 % or better (see Figure 7c).

NOTE 1 If it is not possible to find a suitable parameter resulting in conformance of translated V_{OC} values, the correction procedure is not suitable for this PV device technology.

NOTE 2 The V_{OC} irradiance correction factor is typically < 0,1 for linear PV devices

5.3.4 Fix "a" to the value determined in step 5.3.3. Use $n_S/n_P \times$ 10 mΩ as an estimate for the internal series resistance R'_S where n_S is the number of serially connected cells and n_P is the number of parallel connected blocks in the test device.

5.3.5 Change R'_S in steps of 10 mΩ in the positive or negative direction. The proper value of "R'_S" has been determined, if the deviation of maximum output power values of the transposed I-V characteristics coincide within ±0,5 % or better (see Figure 7d).



a) Measured I-V characteristics at different irradiances and constant temperature

b) Corrected I-V characteristics at a =0 and R'_S=0 Ω

c) Corrected I-V characteristics at a =optimal and R'_S=0 Ω

d) Corrected I-V characteristics at a =optimal and R'_S=optimal

Figure 7 – Determination of V_{OC} irradiance correction factor and internal series resistance

6 Determination of the curve correction factor κ and κ'

6.1 General

The experimental method for determination of curve correction factors κ and κ' is identical for both correction procedures 1 and 2. They may be determined in natural sunlight or simulated sunlight by the following procedure. The temperature coefficients α and β must be known as they are used as inputs for determination of κ and κ'.

6.2 Procedure

6.2.1 Trace current-voltage characteristics of the test specimen at a constant irradiance and at different temperatures ($T_1...T_N$) covering the range of interest within which curve translation shall be performed. During the I-V measurements irradiance shall not differ by more than ±1 %. The irradiance value shall lie within the range which has been used for determination of the irradiance correction parameters in Clause 5 (see Figure 8a).

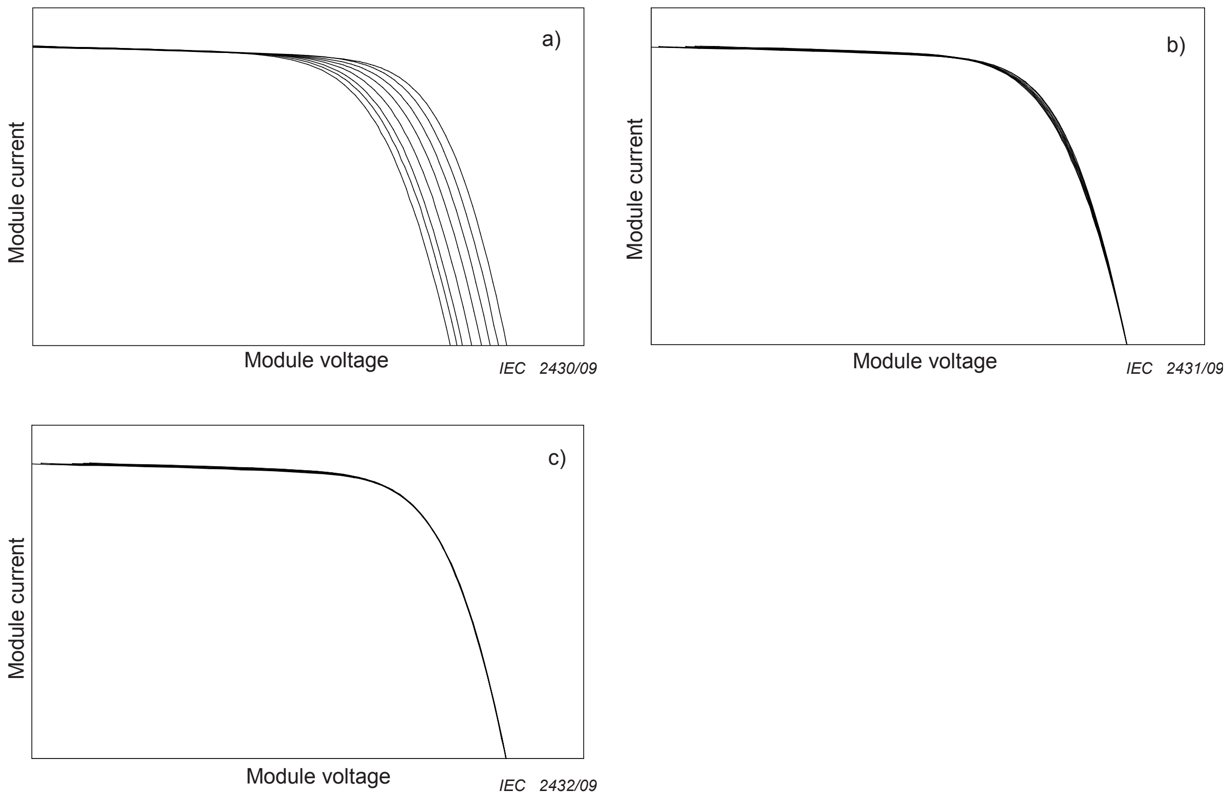
NOTE 1 See 4.1 for information on equipment and measurement techniques for temperature control

NOTE 2 When measuring the I-V characteristics of a module, precautions must be taken to ensure uniformity of the device temperature within ±2 °C of the intended level.

6.2.2 Assuming that T_1 is the lowest device temperature, translate sequentially all other (N–1) curves recorded at higher temperatures (T_2... T_N) to T_1 using κ = 0 Ω/K in Equation (2) or κ'= 0 Ω/K in Equation (5).

6.2.3 Plot the corrected I-V curves in a diagram (see Figure 8b).

6.2.4 Starting from 0 mΩ/K change κ or κ' in steps of 1 mΩ/K in the positive or negative direction. The proper value of κ or κ' has been determined, if the deviation of maximum output power values of the transposed I-V characteristics coincide within ±0,5 % or better (see Figure 8c).



a) Measured I-V characteristics at different device temperatures.

b) Temperature corrected I-V characteristics with κ = 0 Ω/K or κ' = 0 Ω/K.

c) Corrected I-V characteristics with κ = optimal or κ' = optimal.

Figure 8 – Determination of curve correction factor

7 Reporting

The following information shall be given if temperature and irradiance corrections are applied to measured I-V characteristics:

a) description of the test device;

b) measurement conditions of irradiance and device temperature. If the linear interpolation method is applied all sets of (G_i,T_i) shall be reported;

c) identification of the correction procedure used;

d) values and origin of I-V correction parameters;

e) irradiance level to which temperature coefficients are referred;

f) a statement of the estimated translation accuracy.

If I-V correction parameters are measured the following information shall be given:

- identification of measurement method used;
- ranges for irradiance and device temperature that were used as basis for determination of I-V correction parameters;
- measurement protocol and derived results supported by tables, graphs and photographs as appropriate;
- spectral irradiance distribution of the light source;
- a statement of estimated measurement uncertainty for I-V correction parameters;
- statement whether the PV device can be regarded as linear in accordance with IEC 60904-10 and over what range of irradiances and temperatures it is linear;
- electrical condition of the test specimen regarding history of temperature and light treatment prior to the measurements, if applicable;
- any deviations from, additions to, or exclusions from the measurement procedures for determination of I-V correction parameters.

Bibliography

IEC 60904-5, *Photovoltaic devices – Part 5: Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method*

IEC 61853-1, *Photovoltaic (PV) module performance testing and energy rating – Part 1: Irradiance and temperature performance measurements and power rating*[1)]

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