IEC 60904-10

Edition 2.0 2009-12

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Photovoltaic devices –
Part 10: Methods of linearity measurement

Dispositifs photovoltaïques –
Partie 10: Méthodes de mesure de la linéarité

IEC 60904-10:2009

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 27.160

ISBN 978-2-88910-325-6

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FOREWORD

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International Standard IEC 60904-10 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

This second edition cancels and replaces the first edition published in 1998 and constitutes a technical revision.

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

a) Added clause for two-lamp method for I_{sc} linearity.
b) Changed standard deviation as a metric for linearity to percent deviation from linearity. This was done because a non-linear device can have a low standard deviation and percent deviation is the quantitative number that matters for the parameter of interest.
c) Removed clause on spectral responsivity nonlinearity because it is not used by any PV testing / calibration group. For testing real PV devices it is difficult to make this error significant in the spectral mismatch correction factor while still passing I_{sc} linearity. Measuring the responsivity over the entire response range means that the device will probably fail the temperature linearity near the band edge.

d) Added a clause to allow short circuit linearity with temperature or total irradiance to be determined from absolute spectral responsivity measurements. This data is routinely reported in PTB primary reference cell calibration certificates.

e) Added report clause in compliance with ISO/IEC 17025 requirements.

f) Often the temperature coefficient of short circuit current is very small so measurement errors can result in percent deviations outside the accepted range. Therefore, the following text was added to 7.3c): "If the temperature coefficient of short circuit current is less than 0,1 %/K, then the device can be considered linear with respect to this parameter."

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

FDIS	Report on Voting
82/582/FDIS	82/589/RVD

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

A list of all parts of IEC 60904 series, under the general title *Photovoltaic devices*, can be found on the IEC website.

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

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

PHOTOVOLTAIC DEVICES –

Part 10: Methods of linearity measurement

1 Scope and object

This part of IEC 60904 describes procedures used to determine the degree of linearity of any photovoltaic device parameter with respect to a test parameter. It is primarily intended for use by calibration laboratories, module manufacturers and system designers.

Photovoltaic (PV) module and system performance evaluations, and performance translations from one set of temperature and irradiance conditions to another frequently rely on the use of linear equations (see IEC 60891 and IEC 61829). This standard lays down the linearity requirements and test methods to ensure that these linear equations will give satisfactory results. Indirectly, these requirements dictate the range of the temperature and irradiance variables over which the equations can be used.

The methods of measurement described in this standard apply to all PV devices and are intended to be carried out on a sample or on a comparable device of identical technology. They should be performed prior to all measurement and correction procedures that require a linear device. The methodology used in this standard is similar to that specified in IEC 60891 in which a linear (straight-line) function is fitted to a set of data points using a least-squares fit calculation routine. The variation of the data from this function is also calculated, and the definition of linearity is expressed as an allowable variation percentage.

A device is considered linear when it meets the requirements of 7.3.

General procedures for determining the degree of linearity for these and any other performance parameter are described in Clauses 5 and 6.

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 60891, *Photovoltaic devices – Procedures for temperature and irradiance corrections to measured I-V characteristics*

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

IEC 60904-3, *Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*

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

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

IEC 61215, *Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval*

IEC 61646, *Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval*

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

3 Apparatus

a) Equipment necessary to measure an I-V curve (see IEC 60904-1).

b) Any equipment necessary to change the irradiance over the range of interest without affecting the relative spectral irradiance distribution and the spatial uniformity, such as mesh filters or neutral density filters.

NOTE The equipment and procedure used to change the irradiance are to be verified with a radiometer. The change in relative spectral irradiance distribution should not result in more than 0,5 % change in the short-circuit current of the device (see IEC 60904-7 and IEC 60904-8). Mesh filters are believed to be the best method for large surfaces.

c) Any equipment necessary to change the temperature of the test specimen over the range of interest.

d) A means for controlling the temperature of the test specimen and reference device, or a removable shade.

e) Equipment for measuring the spectral response of the test specimen (or a representative sample equivalent to the test specimen) in accordance with IEC 60904-8 to a repeatability of ± 2 % of the reading.

NOTE IEC 60904-7 provides methods for the computation of spectral mismatch error introduced in the testing of photovoltaic devices, and IEC 60904-8 provides guidance for spectral measurement.

4 Sample selection

This procedure shall be applied to a full-sized test specimen if possible. If this is not possible, a small sample equivalent in construction and materials should be used.

5 Procedure for current and voltage linearity test

There are three acceptable procedures for performing the linearity test of short-circuit current with respect to temperature and irradiance. There are two acceptable procedures for performing the linearity test of open-circuit voltage with respect to temperature and irradiance.

5.1 Procedure in natural sunlight

5.1.1 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 $m \cdot s^{-1}$.

5.1.2 Mount the reference device co-planar with the test specimen so that both are normal to the direct solar beam within ± 1°. Connect to the necessary instrumentation.

NOTE The measurements described in the following subclauses should 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.

5.1.3 If the test specimen and reference device are equipped with temperature controls, set the controls at the desired level. If temperature controls are not used, shade the test specimen from the sun and allow it to stabilize within ± 1 °C of the ambient air temperature. The reference device should also stabilize within ± 1 °C of its equilibrium temperature before proceeding.

5.1.4 Remove the shade (if used) and immediately take simultaneous readings of the test parameter X_i , the test specimen device parameter Y_i and the temperature and short-circuit current of the reference device.

5.1.5 The irradiance G_o shall be calculated from the measured short circuit current (I_{sc}) of the PV reference device, and its calibration value at Standard Test Conditions, STC (I_{rc}). A correction should be applied to account for the temperature of the reference device T_m using the current-temperature coefficient of the reference device α_{rc}.

$$G_o = \frac{1\,000 \times I_{sc}}{I_{rc}} \times \left[1 - \alpha_{rc}\ (T_m - 25)\right]$$

5.1.6 If the test parameter being varied is the irradiance, reduce the irradiance on the test specimen to a known fraction k_i without affecting the spatial uniformity or the spectral irradiance distribution. There are various methods by which to accomplish this:

a) Using calibrated, uniform density mesh filters. If this method is selected, the reference device should remain uncovered by the filter during the operation to enable the incident irradiance to be measured. In this case, k_i is the filter calibration parameter (fraction of light transmitted).

b) Using uncalibrated, uniform density mesh filters. If this method is selected, the reference device should also be covered by the filter during the test. In this case, k_i is the ratio of the reference device short-circuit current (I_{sc}) to its calibration value (I_{rc}).

NOTE 1 The maximum filter mesh opening dimension should be less than 1 % of the minimum linear dimension of the reference device and the test specimen, or a variable error may occur due to positioning.

c) By controlling the angle of incidence. If this method is selected, the reference device should have the same reflective properties as the test specimen, and should be mounted co-planar with the test specimen within ± 1°. In this case, k_i is the ratio of the reference device short-circuit current (I_{sc}) to its calibration value (I_{rc}).

NOTE 2 For cells with thick metallization, the rotation axis should be parallel to the direction of the metalized lines in order to minimize or eliminate shadowing.

5.1.7 Calculate the irradiance level on the test specimen G_i as follows:

$$G_i = k_i \times G_o$$

where G_o is determined by the method described in 5.1.5.

5.1.8 If the test parameter being varied is the temperature, adjust the temperature by means of a controller or alternately exposing and shading the test specimen as required to achieve and maintain the desired temperature. Alternately, the test specimen may be allowed to warm-up naturally with the data recording procedure of 5.1.4 performed periodically during the warm-up.

5.1.9 Ensure that the test specimen and reference device temperatures are stabilized and remain constant within ± 1 °C and that the irradiance as measured by the reference device remains constant within ± 2 % during the data recording periods.

5.1.10 Repeat steps 5.1.4 through 5.1.9. The value of the test parameter selected shall be such that the range of interest is spanned in at least four approximately equal increments. A minimum of three measurements shall be made at each of the test conditions.

5.2 Procedure with a solar simulator

NOTE Emission lamps such as xenon should be evaluated before use. As the band gap of the test device varies due to temperature changes, it can pass through various emission lines in the lamp spectrum and give rise to shifts in performance. Based on the linearity of spectral response and the lamp spectrum the magnitude of this effect can be calculated by performing a mismatch correction as a function of temperature.

5.2.1 Mount the test specimen and the reference device co-planar in the test plane of the simulator so that both are normal to the center line of the beam within ± 2°. Connect to the necessary instrumentation.

5.2.2 If the test specimen and reference device are equipped with temperature controls, set the controls at the desired level. If temperature controls are not used, allow the test specimen and reference device to stabilize within ± 1 °C of the room air temperature.

5.2.3 Set the irradiance at the test plane to the upper limit of the range of interest using the reference device measured current (I_{sc}), and its calibration value at STC (I_{rc}).

5.2.4 Conduct the test and take simultaneous readings of the test parameter X_i, the test specimen device parameter Y_i and the temperature and short-circuit current of the reference device.

5.2.5 The irradiance G_o shall be calculated from the measured short circuit current (I_{sc}) of the PV reference device, and its calibration value at STC (I_{rc}). A correction should be applied to account for the temperature of the reference device T_m, using the current-temperature coefficient of the reference device α_{rc}.

$$G_o = \frac{1\,000 \times I_{sc}}{I_{rc}} \times [1 - \alpha_{rc}\,(T_m - 25)]$$

5.2.6 If the test parameter being varied is the irradiance, reduce the irradiance on the test specimen to a known fraction k_i without affecting the spatial uniformity or the spectral irradiance distribution. The various methods by which to accomplish this are:

a) by increasing the distance between the test plane and the lamp. With the reference device maintained in the same plane as the test specimen, k_i is the ratio of the reference device short-circuit current (I_{sc}) to its calibration value (I_{rc});

b) by the use of an optical lens. In this case, k_i is the ratio of the reference device short-circuit current (I_{sc}) to its calibration value (I_{rc}). Care should be exercised to ensure that the lens does not significantly change the relative spectral irradiance in the wavelength range in which the test and reference specimens are responsive;

c) by controlling the angle of incidence. If this method is selected, the distance between the lamp source and the specimen shall be large to limit the irradiance change across the tilted surface to 0,5 % or less. Also, if this method is selected, the radiant beam shall be collimated, the reference device should have the same reflective properties as the test specimen, and should be mounted co-planar with the test specimen. In this case, k_i is the ratio of the reference device short-circuit current (I_{sc}) to its calibration value (I_{rc});

d) calibrated, uniform density mesh filters. If this method is selected, the reference device should remain uncovered by the filter during the operation to enable the incident irradiance to be measured. In this case, k_i is the filter calibration parameter (fraction of light transmitted);

e) uncalibrated, uniform density mesh filters. If this method is selected, the reference device should also be covered by the filter during the test. In this case, k_i is the ratio of the reference device short-circuit current (I_{sc}) to its calibration value (I_{rc}).

NOTE The maximum filter mesh opening dimension should be less than 1 % of the minimum linear dimension of the reference device and the test specimen, or a variable error may occur due to positioning.

5.2.7 Calculate the irradiance level on the test specimen G_i as follows:

$$G_i = k_i \times G_o$$

where G_o is determined by the method described in 5.2.5.

5.2.8 If the test parameter being varied is the temperature, adjust the temperature by appropriate means (see 10.4 of IEC 61215 and IEC 61646).

5.2.9 Ensure that the test specimen and reference device temperatures are stabilized and remain constant within ± 1 °C during the test.

5.2.10 Repeat steps 5.2.4 through 5.2.9. The value of the test parameter selected shall be such that the range of interest is spanned in at least four approximately equal increments. A minimum of three measurements shall be made at each of the test conditions.

5.3 Procedure for short-circuit linearity from absolute spectral responsivity

Following IEC 60904-8 measure the absolute spectral responsivity as a function of bias light or temperature in at least four approximately equal increments over the temperature or irradiance range of interest. Compute the short-circuit current density by integrating the measured responsivity with the reference spectrum given in IEC 60904-3.

6 Procedure for short-circuit current linearity from two-lamp method

6.1 Background

If a PV device is linear then the short circuit current (photo-current) from a cell illuminated by two light sources shall equal the sum of the short circuit currents (photo-currents) from the individual light sources or;

$$I_A + I_B = I_{AB}$$

where:

I_{AB} is the short-circuit current with both lamps illuminating the cell,

I_A or I_B is the short-circuit current with one lamp on the cell and the light from the other lamp blocked.

NOTE The advantage of this method is that no filter or lamp properties have to be measured.

6.2 Apparatus - Light sources A and B

For specimens that are single junction cells the spatial nonuniformity of the light or spectral irradiance is not important. For specimens that are modules, two IEC 60904-9 class BBA or better light sources are required. The temporal instability of the light shall be less than 0,5 % during the measurement period of I_{AB} ,I_A and I_B.

6.3 General procedure

6.3.1 Connect the test specimen to the apparatus to measure I_{sc}.

6.3.2 Set the test specimen temperature to the value of interest, and maintain within ± 5 °C.

6.3.3 Adjust the light sources to give the desired irradiance and allow the light sources to stabilize. The best results will be obtained when the two light sources produce approximately the same short circuit current.

NOTE The irradiance may be changed using filters or by changing the light intensities.

6.3.4 Measure I^*_{AB} ,I^*_A, I^*_B *and* I_{room} (the short circuit current with both beams blocked) with a given combination of filters or intensities for light source A and light source B . Calculate:

$$I_{AB} = I^*_{AB} - I_{room}$$
$$I_A = I^*_A - I_{room}$$
$$I_B = I^*_B - I_{room}$$

6.3.5 Repeat steps 6.3.3 and 6.3.4 with values of irradiance leading to short circuit currents I_A and I_B equivalent to the I_{AB} *of* the previous step.

6.3.6 Continue the process (steps 6.3.3 to 6.3.5) until the range of irradiances of interest has been spanned.

NOTE In order to get more data points in the range of interest, any combination of values of irradiance leading to short circuit currents I_A and I_B measured in steps 6.3.4 to 6.3.6 can then be utilized.

7 Linearity calculation

Verify that any variable parameters other than the one being evaluated were held constant during the testing. Small changes in temperature or irradiance may be corrected analytically to the desired condition using IEC 60891. This can be an iterative process which should be updated when linearity is established and when more refined correction coefficients are determined.

7.1 Slope linearity determination

For performance characteristic slopes such as the open-circuit voltage versus temperature, or short-circuit current versus irradiance, calculate linearity using the following method:

7.1.1 Calculate the mean values of the test parameters, and the characteristics of the best-fit straight line using the least-squares fit method as follows:

Step 1: Compute the mean value of the X and Y data points as follows:

$$X = \frac{\sum_{i=1}^{n} X_i}{n}$$

$$Y = \frac{\sum_{i=1}^{n} Y_i}{n}$$

where n is the number of measurements.

Step 2: Compute the slope, m, of the best fit line as follows:

$$m = \frac{\sum_{i=1}^{n} (X_i - X) \cdot (Y_i - Y)}{\sum_{i=1}^{n} (X_i - X)^2}$$

Step 3: The best-fit straight line, also known as the regression line, can now be written as follows: