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**Photovoltaic concentrators (CPV) – Performance testing –
Part 3: Performance measurements and power rating**

**Concentrateurs photovoltaïques (CPV) – Essai de performances –
Partie 3: Mesurages de performances et rapport de puissance**



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

FDIS	Report on voting
82/1204/FDIS	82/1233/RVD

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

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

A list of all parts in the IEC 62670 series, published under the general title *Photovoltaic concentrators (CPV) – Performance testing*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

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PHOTOVOLTAIC CONCENTRATORS (CPV) – PERFORMANCE TESTING –

Part 3: Performance measurements and power rating

1 Scope

This part of IEC 62670 defines measurement procedures and instrumentation for determining concentrator photovoltaic performance at concentrator standard operating conditions (CSOC) and concentrator standard test conditions (CSTC), defined in IEC 62670-1, including power ratings.

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

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

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

IEC 60904-4:2009, *Photovoltaic devices – Part 4: Reference solar devices – Procedures for establishing calibration traceability*

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

IEC 62670-1, *Photovoltaic concentrators (CPV) – Performance testing – Part 1: Standard conditions*

IEC 62817:2014, *Photovoltaic systems – Design qualification of solar trackers*

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

ISO 2859-1, *Sampling procedures for inspection by attributes – Part 1: Sampling schemes indexed by acceptance quality limit (AQL) for lot-by-lot inspection*

ISO 9060:1990, *Solar energy – Specification and classification of instruments for measuring hemispherical solar and direct solar radiation*

3 Concepts

The following concepts are used through this document.

- a) CSOC – concentrator standard operating conditions per IEC 62670-1 (direct normal irradiance (DNI) 900 W/m², 20 °C ambient temperature, 2 m/s wind speed, AM1.5D spectrum per IEC 60904-3).
- b) CSTC – concentrator standard test conditions per IEC 62670-1 (DNI 1 000 W/m², 25 °C cell temperature, AM1.5D spectrum per IEC 60904-3).

- c) SMR – spectral matching ratio, $SMR(i,j) = \frac{I_i/I_j}{I_{i,ref}/I_{j,ref}}$ where I_i and I_j are the short-circuit

current or short-circuit current densities under prevailing spectral conditions per the i and j distinct subcells in the multi-junction solar cell. $I_{i,ref}$ and $I_{j,ref}$ are the associated short-circuit currents/current densities under the AM 1.5 direct spectrum as defined by IEC 60904-3. The subcell is assigned a number in the ordering of their band gap energy (E_g) starting with 1 for the highest E_g and up to n for the lowest E_g . In this manner a multi-junction solar cell with n distinct sub cells has $(n^2-n)/2$ unique SMR values. For example, for $n = 3$ (three-junction device) there is SMR(1,2), SMR(1,3) and SMR(2,3). For a lattice matched triple junction cell: GaInP is junction 1, GaInAs is junction 2, and Ge is junction 3.

SMR as applied to outdoor I-V curves does NOT imply that the outputs from subcells will match the DUT but to a more generic set of subcells used by the test laboratory to characterize deviations in the prevailing outdoor spectrum from the reference AM1.5D spectrum. A specific DUT match is not required as precipitable water vapor, aerosols, and airmass are the dominant variables which drive changes in the outdoor spectrum. It has been shown that filtering based on measurements in three sub-bands of the spectrum is sufficient to minimize CPV DUT performance variation. Component reference cells (8.1.4) can be used to determine SMR values or the SMR can be calculated under the prevailing spectrum. In this case I_1 , I_2 and I_3 are generally defined as the direct normal spectral irradiance in sub-bands from 370 nm to 650 nm, 650 nm to 870 nm and 870 nm to 1 650 nm respectively. This is equivalent to assuming a set of component reference cells which have external quantum efficiencies (EQE) of 100 % in the defined bands.

SMR as applied to indoor I-V curves DOES refer to outputs from the subcells that match the DUT. The indoor measurements specifically refer to matching subcells as the spectrum under simulated sunlight is known to deviate from the characteristic shape of the outdoor spectrum. Therefore three sub-bands are not always sufficient to minimize variation in CPV DUT performance. SMR can be determined from device specific component reference cells or can be calculated from the measured spectrum and the spectral responses of device specific component reference cells.

- d) Separate SMR crossing – event in outdoor data measurements where the given SMR value is within the defined boundaries around unity and the event is separated by at least an hour from other events where the SMR value is within the defined boundaries around unity.
- e) MPP – global maximum power point of an I-V curve.
- f) V_{mp} – the voltage at MPP.
- g) I_{mp} – the current at MPP.
- h) DNI– direct normal irradiance.
- i) GNI– global normal irradiance.
- j) η – efficiency of the DUT at MPP for an individual I-V curve.
- k) DUT – device under test.
- l) Aperture – aperture area of the DUT, measured from inside edge to inside edge of the DUT frame. If no clear transition from lens to frame is present an opaque tape can be used to mask off the edge of lens area and define the edge of the aperture area. This shall be completed prior to the collection of I-V curves. If this method is not applicable to the DUT, alternate methods can be considered. The test report shall document the procedure used for determining aperture area.
- m) Opening half-angle – half-angle of a device with a collimating tube defined as the $\arctan(R/L)$ per Figure 1.
- n) Field of view or opening full-angle– two times the opening half angle.

- o) Slope angle – angle of a device with a collimating tube defined as the $\arctan[(R-r)/L]$ per Figure 1.
- p) Limit angle – angle of a device with a collimating tube defined as the $\arctan[(R+r)/L]$ per Figure 1.
- q) Primary and secondary axis pointing error – measured angle between the pointing vector of the tracker and the pointing vector of the sun (see Figure 2) [adapted from IEC 62817:2014, 7.2]. Typically the pointing vector of the tracker is defined by the sensor that is used for measuring pointing error. The sensor has a plane which is responsive to the direct beam from the sun. Therefore the normal vector to this measurement plane is representative of the pointing vector of the tracker or the pointing vector of the DUT. Although pointing error as defined is a single angular deviation, the sensor measures this error in two separate angles in relation to reference plane

$$\text{pointing error} = \sqrt{\text{primary axis pointing error}^2 + \text{secondary axis pointing error}^2}$$

In this document, primary and secondary axis pointing error are defined by the above equation. As it is also assumed that the plane of the DUT is aligned with the pointing error sensor, the primary and secondary axes are also representative for the DUT.

- r) Acceptance angle – minimum full angle through which the DUT can be rotated (with respect to the sun) while continuing to produce 90 % of its DNI normalized maximum power. Although a two dimensional plot is necessary to fully determine acceptance angle, herein acceptance angle refers to the minimum full angle as resulting from angular measurement sweeps limited to the primary and secondary axes of the DUT (see 9.8.5). For example the DUT described in Figure 3. Figure 3 shows acceptance angle measurement results of $0,75^\circ$ for the primary axis and $0,7^\circ$ for the secondary axis. Therefore the acceptance angle for this DUT is reported as $0,7^\circ$. Caution should be noted that Figure 3 shows measurement results that are symmetric around the zero point (normal angle of incidence) but a DUT can have asymmetric results.
- s) Half acceptance angle – half acceptance angle is defined as the acceptance angle defined above divided by two. This definition is introduced as it is more relevant to filtering restrictions placed on pointing error later in this document. Although asymmetry around the zero angle of incidence is not consistent with this definition of half angle, the definition is retained for simplicity.
- t) 98 % acceptance angle and 98 % half acceptance angle – the definitions acceptance angle and half acceptance angle given above apply with the exception that when preceded by 98 % the terms now refer to full and half angles through which DUT orientation can be rotated while continuing to produce 98 % of its DNI normalized maximum power (not the original 90 %). For example the DUT in Figure 3 shows a 98 % acceptance angle of $0,32^\circ$ and a 98 % half angle measurement of $0,16^\circ$.

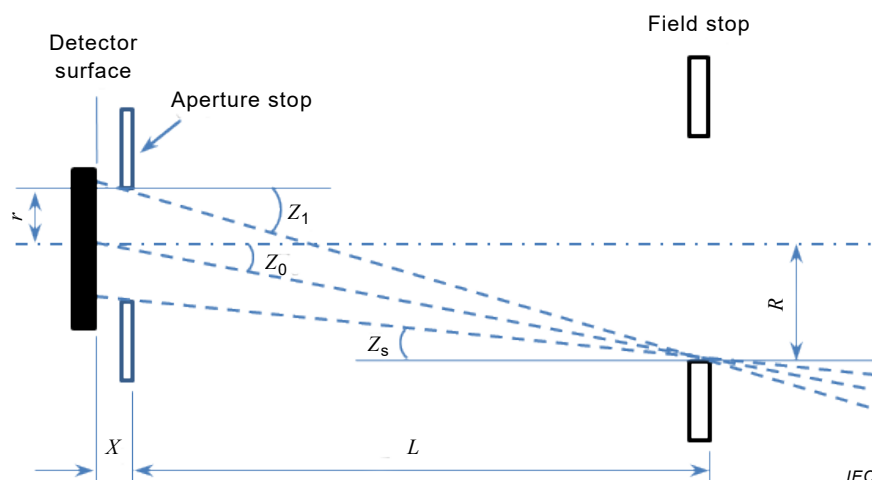


Figure 1 – Collimating tube geometry

In Figure 1 the field stop represents the limiting entry point for light into the collimating tube and has a radius of R . The aperture stop represents further limitation of the light which can reach the detector and has a radius of r . L is the distance between the front of the field stop and aperture stop. It is assumed that the distance, X , between the aperture stop and the detector is small and negligible.

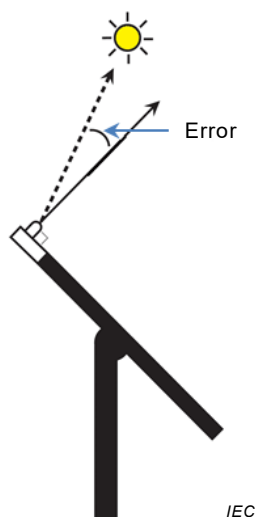


Figure 2 – Solar tracker pointing error

IEC 62817 defines pointing error of a solar tracker as the measured angle between the pointing vector of the tracker and the vector of the sun's rays. As shown here the pointing vector of the tracker is the vector which is normal to the plane of sensor that measures pointing error.

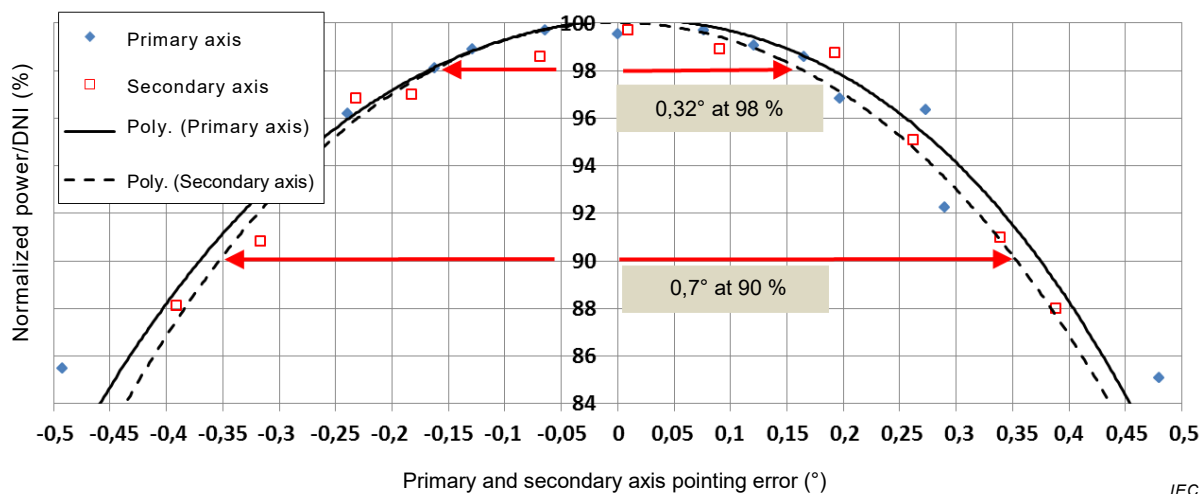


Figure 3 – Example of acceptance angle data for a CPV DUT

In Figure 3 the secondary axis acceptance angle is slightly less than the primary axis acceptance angle and therefore the secondary axis is used in reporting. The DUT has an acceptance angle of $0,7^\circ$ (half acceptance angle of $0,35^\circ$) and a 98 % acceptance angle of $0,32^\circ$ (98 % half acceptance angle of $0,16^\circ$).

4 Sampling

For performance qualification testing three specimens shall be selected at random from a production batch or batches in accordance with the procedure given in ISO 2859-1. For measurements of prototype devices which are not from production, sampling shall not apply. This shall be noted in the test report.

When the results will be used for ascribing a name-plate rating, the modules or assemblies, hereafter referred to as device under test (DUT), shall have been manufactured from specified materials and components in accordance with the relevant drawings and process sheets and shall have been subjected to the manufacture's normal inspection, quality control and production acceptance procedures. The DUT shall be complete in every detail and shall be accompanied by the manufacturer's handling and final assembly instructions regarding the recommended installation of any diodes, frames, brackets, etc.

5 DUT marking and information

5.1 Indelible marking

Each DUT shall carry the following clear and indelible markings:

- name, monogram or symbol of the manufacturer;
- type or model number;
- serial number;
- polarity of terminals or leads (colour coding is permissible);
- the date and place of manufacture shall be marked on the DUT or be traceable from the serial number.

5.2 Preliminary information indicated by manufacturer

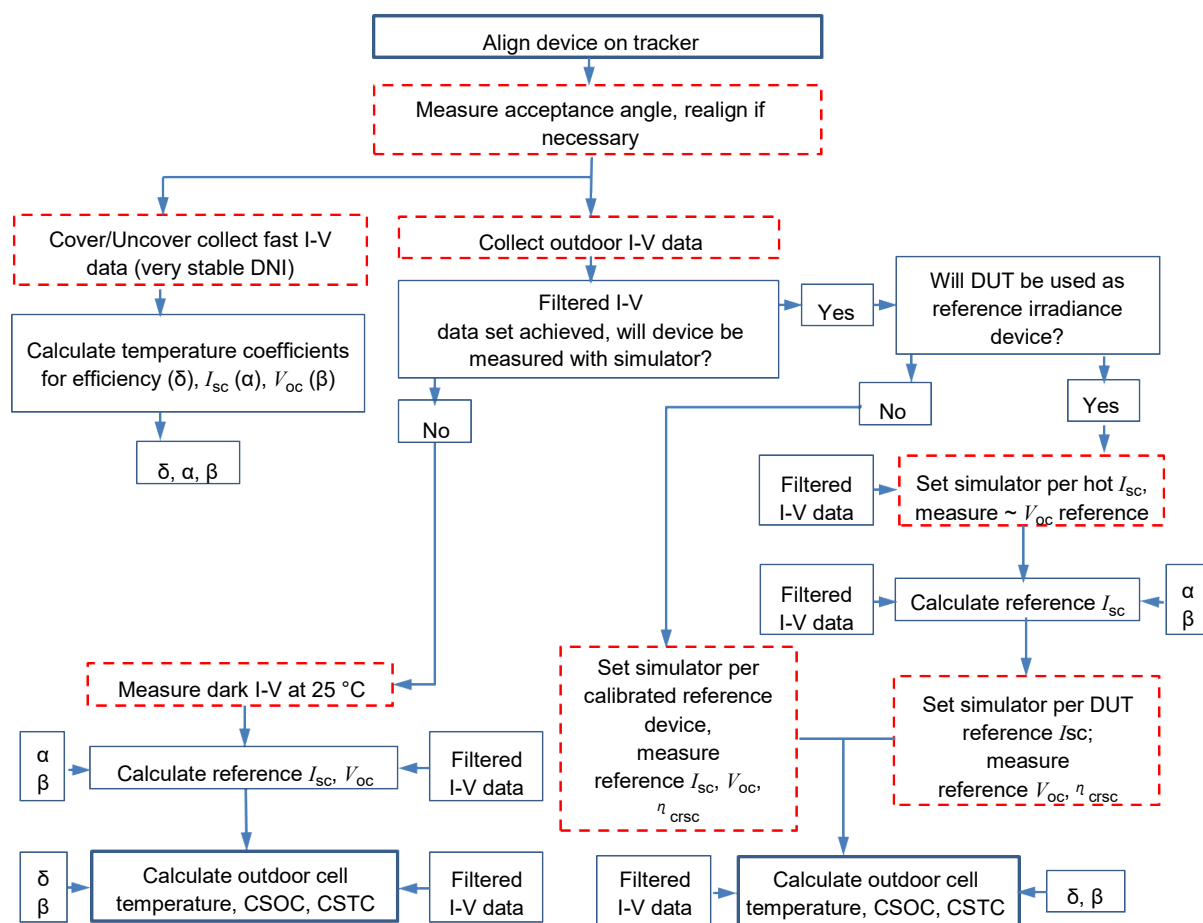
Indicative values shall be provided by the manufacturer to the test laboratory for the purpose of measurement setup:

- expected maximum power point (MPP), V_{OC} , and I_{SC} at CSOC;
- acceptance angle;
- installation instructions.

6 Testing

The DUT shall be subjected to the procedure for irradiance and temperature performance measurements defined in Clause 9. In carrying out the tests, where applicable the tester shall observe the manufacturer's handling, mounting and connection instructions.

Testing of the DUT shall follow the test sequence as defined in Figure 4.



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NOTE The dashed boxes indicate actual measurements while solid boxes indicate calculations or decisions in the flow chart.

Figure 4 – Flow chart of performance testing for the DUT

7 Report

Following completion of the procedure, a certified report of the performance tests, with measured power characteristics shall be prepared by the test agency in accordance with the procedures of ISO IEC 17025. Each certificate or test report shall include at least the following information.

- a title;
- name and address of the test laboratory and location (including latitude, longitude and altitude if outdoor measurements were included) where the calibration or tests were carried out;
- unique identification of the certification or report and of each page;
- name and address of client, where appropriate;
- description and identification of the item calibrated or tested;
- characterization and condition of the calibration or test item;
- date of receipt of test item, date(s) of calibration, and dates and time of outdoor testing, where appropriate;
- identification of calibration or test method used;
- reference to sampling procedure, where relevant;

- j) any deviations from, additions to or exclusions from the calibration or test method, and any other information relevant to a specific calibration or test, such as environmental conditions;
- k) measurements, examinations and derived results, include the following as a minimum: a histogram of all CSOC data points and the mean CSOC power, the mean power at CSTC (include a histogram of all translated data points if outdoor data is used to determine CSTC), DUT temperature coefficients, and the reference V_{oc} and I_{sc} used for cell temperature calculations;
- l) a statement of the estimated uncertainty of test results;
- m) a statement as to whether the measured CSOC powers agree with the manufacturer's indicated values within the test laboratory's measurement uncertainty (if appropriate);
- n) a signature and title, or equivalent identification of the person(s) accepting responsibility for the content of the certificate or report, and the date of issue;
- o) where relevant, a statement to the effect that the results relate only to the items calibrated or tested;
- p) a statement that the certificate or report shall not be reproduced except in full, without the written approval of the laboratory;
- q) identification of the tracker used, the tracker pointing error sensor including sensor calibration data and date, and the documented tracker accuracy characterization per IEC 62817:2014, Clause 7;
- r) identification of the wind sensor used, the location of the wind sensor and the calibration of the wind sensor;
- s) identification of the normal incidence pyrheliometer (NIP) used and the calibration of the pyrheliometer;
- t) identification of the current and voltage sensors used and their calibration;
- u) identification of the alignment method used for the DUT;
- v) identification of distance between NIP and DUT;
- w) identification of the component reference cells or spectroradiometer used and the calibration;
- x) identification of the cleaning dates for the DUT, the NIP, and the component reference cells if applicable;
- y) statement of determination of aperture area.

A copy of this report shall be kept by the manufacturer for reference purposes.

8 Standard apparatus requirements

8.1 Irradiance measurement equipment

8.1.1 Normal incidence pyrheliometer (NIP)

The DNI measurements shall be made using a first class normal incidence pyrheliometer in accordance with ISO 9060:1990. The reference device shall be linear in measurement as defined in IEC 60904-10 over the irradiance range of interest.

8.1.2 Global normal irradiance pyranometer

GNI measurements shall be made using a PV reference device packaged and calibrated in conformance with IEC 60904-2 or a pyranometer.

8.1.3 Spectral measurement device

For outdoor measurements, the spectral measurement device shall be capable of determining the direct normal spectral irradiance at least in the 3 distinct ranges of wavelengths necessary

for determining SMR values as defined by item c) of Clause 3. For simulator measurements, the spectral measurement device shall be capable of determining direct normal spectral irradiance in the separate ranges of wavelengths which correspond to subcells in the DUT. The device shall include collimating tubes such that the opening full-angle is 5° and the slope angle is 1° . The device shall be calibrated as a primary or secondary reference device and show traceability per 3.3, 3.4 and 3.5 of IEC 60904-4:2009 respectively. Calibration shall be completed at least once per year. The spectral measurement device could be a spectroradiometer, component reference cells as defined by 8.1.4, or another suitable instrument. The uncertainty of the SMR values that are generated shall be documented. For indoor measurements, the designated test area of the solar simulator's beam shall include also the aperture area of this spectral measurement device.

8.1.4 Component reference cells

8.1.4.1 General

Component reference cells are a set of devices that together can serve as the spectral measurement device for this document. A minimum of 3 separate cells/junctions are required for outdoor spectral irradiance measurements.

8.1.4.2 Standard component reference cells

Standard component reference cells are a set of component reference cells that are an acceptable outdoor spectral measurement device regardless of the DUT. The standard set of component reference cells shall be equivalent to the individual junctions from a latticed matched triple junction cell with bandgaps of 1,9 eV, 1,4 eV, and 0,7 eV. It is expected that component cells from a conventional triple junction latticed matched GaInP/GaInAs/Ge cell will meet these requirements.

NOTE This standard set of component reference cells is not intended to be a specific match to the subcells in the DUT or to the current generated from each of the DUT subcells. While not specific to the DUT, the standard component reference cells enable filtering of outdoor data which limit spectral variation and minimize uncertainty in performance reported at CSOC and CSTC (derived from outdoor I-V data).

8.1.4.3 DUT matched component reference cells

Component reference cells that are specifically matched to the DUT can provide improved information about the current matching of the subcells in the DUT and are applicable as a spectral measurement device both indoors and outdoors. With sufficient test data, specifically matched component reference cells can lead to SMR filtering criteria that reduce uncertainty of ratings at CSOC and CSTC. The test laboratory is permitted to use DUT matched component reference cells if the following are true:

- a) the component cells meet all requirements of 8.1.3;
- b) the component cells are of the same design, materials and manufacturer as the subcells in the DUT.

8.1.5 Indoor reference irradiance sensor

The indoor reference irradiance sensor is a sensor used for calibrating the irradiance output from the solar simulator for the DUT. The indoor reference irradiance sensor serves as a secondary reference instrument per calibration against a primary reference instrument (NIP). The indoor reference irradiance sensor shall be linear and stable as defined in IEC 60904-10 over the irradiance range of interest. (Calibration is described in 9.4). The solar simulator is adjusted such that the indoor reference irradiance sensor produces its calibrated $I_{sc,cal}$ when illuminated. The indoor reference irradiance device shall have a construction that is nearly identical to the DUT. To be nearly identical it shall meet the following criteria:

- a) the individual optical train between external collimated light and the cell (primary and secondary if applicable) shall be of the same design, materials, focal length, and size, and manufacturer;

- b) the cell or cells used shall be of the same design, materials, size, and from the same manufacturer,

In other words the indoor reference irradiance sensor shall be a representative match to the DUT but it can have fewer optical/cell pairs resulting in a fraction of the full device aperture area. The smallest device shall have at least one optical/cell pair, hereafter called a “mono-module”.

The above criteria are to ensure the sensor has nearly identical responsivity, measured per I_{sc} , to irradiance, to angular alignment, and to spectrum as the DUT. If for any reason the reference irradiance sensor has suspected deviation in response compared to the DUT, an alternate reference irradiance sensor should be chosen. If there are strong misalignments between the performances of the cells within the DUT, the angular response of a mono-module may differ from that of the DUT. In this case the DUT should also serve as the reference irradiance sensor. This point shall be examined for every technology and may change as a manufacturer changes factory controls for alignment.

NOTE 1 If only one specimen is available for a given technology, then the test specimen itself can be used as the indoor reference irradiance sensor.

NOTE 2 For sensors which contain series connected cells, non-uniform illumination can cause an overestimation of the ISC and thus an underestimation of the irradiance.

8.1.6 Auxiliary irradiance sensor

An auxiliary irradiance sensor is a PV device for which the I_{sc} response has been calibrated against the I_{sc} response of the indoor reference irradiance sensor over the range of interest. This sensor can be used for monitoring instantaneous changes in irradiance during the simulator flash. If this sensor does not include concentrating optics, the sensor shall include a collimating tube which has an opening full-angle of 5° and a slope angle of 1°. The auxiliary irradiance sensor shall be linear and stable as defined in IEC 60904-10 over the irradiance range of interest.

8.2 Solar simulator

8.2.1 General requirements

Methods for classifying collimated light solar simulators as necessary for determining if a particular simulator is appropriate for use with a particular CPV DUT may be specified in IEC 60904-9-11. The simulator used should be documented in the test report along with its classification per IEC 60904-9-12.

8.2.2 Continuous light simulator

A continuous light solar simulator has a light source which is in the on or in the steady-state illuminated state for sufficient time such that the device under test can be exposed and measured under this steady-state light. It has been shown that CPV cells within a module and under continuous high concentration light for more than 10 ms can heat multiple degrees Celsius and therefore this type of simulator is often not appropriate for use with CPV devices. As heating rate can depend on DUT design it is possible that even a few milliseconds of continuous light could have significant influence. Note that if the simulator light source is on continuously but that the simulator has an aperture window which prevents continuous illumination of the DUT, such heating problems can be avoided.

1 Under consideration.

2 Under consideration.

8.2.3 Single-flash pulse simulator

A single-flash pulse simulator is a simulator which uses a measurement system that can measure the entire I-V curve for the DUT in a single flash pulse of the simulator light source. The measurement duration shall be short enough that no more than 2 °C heating occurs to the cell(s) in the DUT. Verification is completed by performing an I-V curve sweep in both directions. The hysteresis between the two I-V curves shall be used to determine that no more than 2 °C heating has occurred. Heating shall be measured as the hysteresis voltage divided by β (see 9.1.4 for determination of β).

8.2.4 Multi-flash pulse simulator

A multi-flash pulse simulator is defined as a simulator using a measurement system that only records one or a limited range of current-voltage points for every flash pulse of the light source. The entire I-V curve for the DUT is completed through multiple flashes and multiple measurements.

8.3 Solar tracker or DUT mounting system

8.3.1 General

A solar tracker is required for pointing the DUT and other alignment sensitive equipment toward the incident sunlight and shall be consistent with definitions per IEC 62817. Indoors, the DUT mounting system is the equipment used to mount the DUT and align it with the incident light from the solar simulator. Both the tracker and the DUT mounting system shall be able to maintain alignment of the DUT to the incident light as specified in the corresponding test procedure. In the case of a CPV DUT designed for single-axis tracking, a 2-axis tracker should be used in order to avoid the rating becoming dependent on the time of year.

8.3.2 Pointing error sensor

The pointing error sensor measures the angular deviation between the normal vector of the sensor and the vector of the sun's direct beam (see Figure 2). The pointing error can be broken down into components of primary and secondary axis pointing error. The device shall be consistent with IEC 62817:2014, Clause 7.

8.4 Temperature measurement and control

8.4.1 DUT temperature sensor

Equipment for monitoring the temperature of the DUT shall have an accuracy of ± 1 °C and repeatability of $\pm 0,5$ °C. At least two sensors shall be used. The sensors shall be mounted on the back of the DUT as close to the center of a cell assembly as possible, using one cell chosen from the central part of the DUT and the second near the edge of the DUT. If placement of DUT temperature sensors requires modification of the DUT, then the modification shall be done by the manufacturer.

8.4.2 Ambient temperature sensor

The ambient temperature sensor shall have an accuracy of ± 1 °C, and a repeatability of $\pm 0,5$ °C. The temperature sensor shall be installed within a multi-plate radiation shield with passive ventilation and within 10 m of the DUT.

8.4.3 Lens or optics temperature sensor

The optics temperature sensor shall have an accuracy of ± 1 °C, and a repeatability of $\pm 0,5$ °C. The response time should be on the order of 1 s or less. The temperature sensor shall be selected to provide minimal interference to incoming light to the optics, i.e. as small as possible including wiring to the sensor. The actual transducer shall be attached to the surface of the optics using a method that ensures thermal conductivity. The side of the transducer which faces the sun shall be covered with a thin reflective foil or white film.

designed to reject/reflect incoming solar irradiance. The purpose of the foil or film is to minimize heating of the sensor due to sunlight exposure and improve the accuracy of measuring the optical surface temperature. The sensor location and wires shall remain fixed during measurements so that any impact on incoming irradiance to the DUT is constant throughout the test.

8.4.4 Temperature control system

The general requirements for temperature control are as follows:

- While measuring the DUT indoors per a solar simulator, the DUT temperature sensors shall be maintained at $(25 \pm 2) ^\circ\text{C}$. For indoor measurements temperature control can be generally achieved per laboratory room temperature controls. It is noted that appropriate solar simulators as described in 8.2 shall be used per indoor testing which do not heat the cells within the DUT more than $2 ^\circ\text{C}$ during the flash measurement. Continuous illumination of the DUT typically does not meet this requirement.
- DUTs, which have liquid or other temperature control systems per manufacturer designs, shall be tested with the cooling system active where this is appropriate.

8.5 Current-voltage measurement

The general requirements for I-V measurements are as follows:

- a) The I-V measurements may be done using a data acquisition package that can scan the I-V curve, or may use separate current and voltage sensors with a variable load. The manufacturer may require that an electrical load is used to maintain the DUT near or at MPP between I-V sweeps outdoors. It is known that operating at V_{oc} between I-V sweeps can elevate the lens temperature above what it would normally be at the given ambient conditions and therefore this operation mode can bias reported results. Voltages and currents shall be measured using instrumentation with an accuracy of 0,2 % of the open-circuit voltage and short-circuit current using independent leads from the terminals of the DUT and keeping them as short as possible. The measurement ranges of the data acquisition should be carefully chosen. The 4-wire connection should start at the terminals or connectors of the DUT.
- b) The short-circuit current shall be measured at zero voltage, using a variable bias (preferably electronic) to offset the voltage drop across the external series resistance. Alternatively, short circuit current may be extrapolated from the current-voltage characteristic. The curve is extrapolated to zero voltage provided that voltage drop is not higher than 3 % of the device open-circuit voltage and that there is a linear relationship between current and voltage.
- c) The direction of the I-V sweep shall be noted in the test report.
- d) The duration of a single I-V sweep shall be noted in the test report.

8.6 Anemometer

An instrument to measure wind speed (with a minimum threshold of 0,25 m/s and an accuracy of at least $\pm 0,15$ m/s at the minimum threshold) shall be installed within 3 m in the vertical orientation in relation to the mean height of the tracker module test plane when the tracker is in the vertical position. In the horizontal orientation the wind equipment shall be installed within 10 m of the DUT. The wind sensor shall not be installed in a location such that wind obstructions create a separate and different wind regime compared to the tracker to which the DUT is mounted.

8.7 Electrical load

An electrical load is a general device which can be used to maintain the DUT near or at MPP between I-V sweeps.

9 Test procedures

9.1 Measurement of DUT temperature coefficients

9.1.1 Purpose

CPV DUT thermal performance has two primary contributions: (1) cell electrical output depends on cell temperature (2) the optical focusing characteristics depend on the temperature of the optics (where cell electrical output depends on focusing characteristics). Subclause 9.1 herein is specific to measuring the DUT temperature coefficients that pertain to item (1) and not item (2). This is achieved by validating that the optical temperature is stable (as described in the data requirements) during the following testing. Item (2), performance associated with optical temperature, is addressed in 9.10 and 9.11.

9.1.2 Apparatus

General apparatus requirements are defined in Clause 8;

- a) normal incidence pyrheliometer;
- b) solar tracker;
- c) I-V measurement instrument (at least at a 1 min interval but 15 s or less is desired);
- d) anemometer;
- e) ambient temperature sensor;
- f) two DUT temperature sensors;
- g) spectral measurement device;
- h) pointing error sensor;
- i) one lens/optics temperature sensor.

9.1.3 Data collection procedure and data requirements

The following list provides recommendations and requirements for collecting various data as needed throughout this document.

- a) Mount the pointing error sensor, pyrheliometer, spectral measurement device, and other alignment sensitive equipment per 9.9.
- b) Mount the DUT per manufacturer's instructions or per 9.8. Document the alignment method that was used.
- c) Ensure that the irradiance measurement equipment viewing windows and DUT are clean and free from soil. Verify this throughout the duration of the test as necessary.
- d) Mount the DUT temperature sensors and anemometer per standard requirements in Clause 8.
- e) Mount the lens/optics temperature sensor defined per 8.4.3. The transducer location should be along the high side of the device's optical array. It is ideal to attach the transducer directly on the optics and at least 7 cm to 10 cm from the edge of the optical array in order to minimize edge effects. An I-V curve shall be recorded both before and after mounting the lens temperature sensor under equivalent irradiances. The I-V curves shall be compared to validate that maximum power decreases no more than 2 % due to the sensor interference. Note that this test data is not used to measure absolute DUT power output and therefore a 2 % loss that is consistent for all measurements can be tolerated. If interference is too high, the sensor can be moved to the edge of the active optical area and I-V curve validation shall be repeated. If the optics are of a design/material which have performance properties that are proven to be stable over a 10 °C change in temperature as applicable to the given test conditions, measurement of the optics temperature can be considered optional.
- f) It is recommended to record the following parameters at least every 15 s while the maximum interval shall be 1 min:

- time stamp;
 - I-V sweep;
 - DNI (within 1 s both before and after I-V sweep);
 - SMR values from standard component reference cells or as applicable from a suitable spectral measurement device;
 - wind speed;
 - pointing error as related to the DUT;
 - ambient temperature;
 - DUT temperature (2);
 - lens temperature.
- g) Cover the DUT with a cloth or other cover to allow for cooling of the DUT. It is expected that diffuse light will penetrate a cloth and V_{oc} will not be zero during the cooling but this does not interfere with achieving accurate results. Test results have indicated that if the cloth or cover rests on the optical surface of the DUT that the optics can cool more than 2 °C after the cloth or cover is removed (resulting in false temperature coefficients). This issue has been resolved by elevating the cloth more than 7 cm from the optical surface while the DUT cools. The elevation allows air at near ambient temperature to pass between the cover and the optics, avoiding heating of the optics. Monitor the DUT temperature sensors to ensure the DUT has cooled sufficiently from precovered conditions (investigations of various high concentration CPV modules have shown that at least 15 °C of cooling can be achieved). After the DUT temperature has cooled and is stable to within 2 °C over a 5 min period, the DUT is quickly uncovered (<2 s) while I-V curves and the additional parameters are measured as the DUT heats. It is assumed that in the first few seconds after removing the cloth the cell temperature and DUT temperature sensors are not moving in parallel (the cell heats rapidly in ms while the DUT temperature sensors lag behind). After the first 3 s to 5 s the cell and the DUT temperature increase at an approximate one-to-one rate. This one-to-one rate makes it possible to use the measured changes in DUT temperature as a proxy for changes in cell temperature.
- h) The following shall be true to use the data collected after an uncover event for determining temperature coefficients: note that the data collection period for determining a temperature coefficient can be shorter than the time period from when the uncover occurs to the last I-V curve. The data collection period is considered to begin at the first valid I-V curve after the uncover event until the last valid I-V curve while the DUT heats. For example the last valid curve might occur because a cloud passes in front of the sun, the wind speed increases, or the rate of increase in DUT temperature is significantly less than the previous series of I-V curves.
- Data points can be deleted at the beginning and end of a data collection period but no data points shall be removed from within the remaining time interval.
 - For the remaining time interval the DUT temperature shall show at least a 10 °C change while 15 °C is recommended (this typically requires 5 min to 10 min of stable DNI per requirements below).
 - The remaining time interval shall span at least 5 min and contain at least 10 data points.
 - DNI immediately before and after each I-V sweep for all data points shall be within 0,5 %.
 - Maximum and minimum DNI throughout the data collection period shall be within 2 %;
 - DNI shall be between 700 W/m² and 1 100 W/m².
 - SMR(1,2), SMR(1,3) and SMR(2,3) shall be within 5 % of unity.
 - Instantaneous wind speed should be under 5 m/s (Note that wind blocks can be put in place to mitigate changes in wind speed from causing significant deviations in the heating rate of the DUT as well as to provide for a larger increase in DUT temperature during the test). Test results have shown improved fit results for the temperature coefficients when using wind blocks to decrease direct wind to the back side of the

DUT. Note that instantaneous wind speed is applicable here while average wind speed is used in other tests in this document. The DUT in this test is not at a steady-state condition and therefore the average wind speed is not applicable.

- The ambient temperature shall change no more than 1 °C during the data collection period. (The DUT manufacturer may request that this test is performed at an ambient temperature where it is known the lens/cell alignment is relatively stable.)
 - The lens temperature shall change no more than 2 °C throughout the data collection period.
 - Pointing error shall be within the limits as demonstrated by misalignment sensitivity data, see 9.8, which indicate that normalized MPP/DNI drops by no more than 1 %. Maintaining pointing error to be less than $\pm 0,1^\circ$ is generally recommended for this test.
 - The one-to-one increase for the average of DUT temperature sensors and the cell temperature shall be validated (see i) below).
 - The difference between the two DUT temperature sensors shall be constant to $\pm 1^\circ\text{C}$ during the data collection period. Note it is typically expected that the DUT temperature measurement near the center of the DUT will be higher than the measurement near the edge of the DUT.
- i) One-to-one increase for the average of the DUT temperature sensors and the cell temperature shall be validated per the following: (As stated above, data points can be deleted at the beginning and end of a data collection period and therefore this validation is only applicable to the remaining time interval). The validation is completed by plotting DUT V_{oc} against DUT temperature and fitting the data with a least squares regression. The following shall be true: (see Figure 5 and Figure 6 for an example of this procedure).
- The Root Square Error (RSE) as a percent of the least squares predicted value shall be less than or equal to 0,25 % for each data point. The RSE as a percent is defined as

$$RSE = \frac{100\sqrt{(V_{oc} - V_{oc,fit})^2}}{V_{oc,fit}}$$

- The coefficient of determination, R squared, shall be greater than or equal to 0,98.

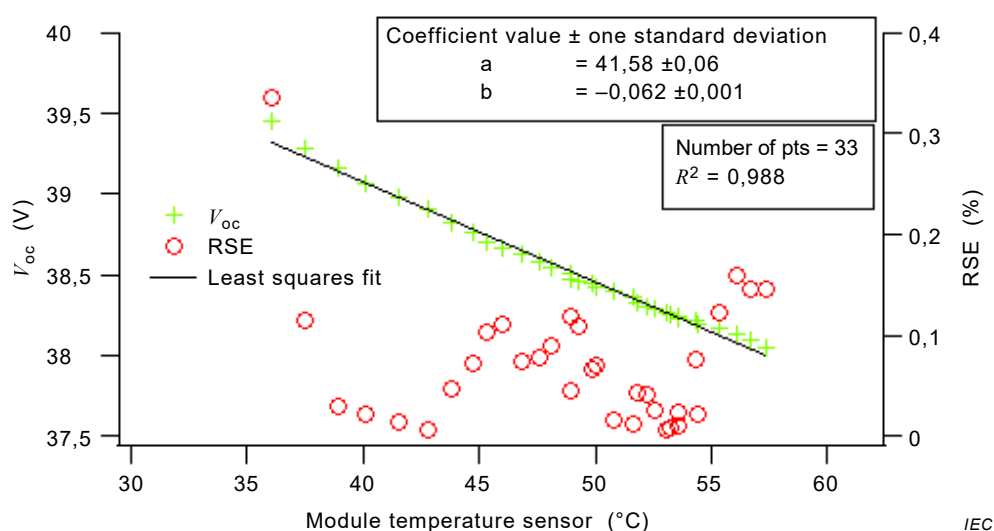


Figure 5 – V_{oc} data after an uncover event

Figure 5 shows V_{oc} data from I-V curves after an uncover event which are plotted against temperature data from the back of the DUT. The solid line is the least squares fit and the open circles are the RSE as a percent of the predicted value. The percent RSE and the coefficient of determination, R squared, are used to determine if relative changes in the DUT temperature sensor sufficiently represent changes in cell temperature. The percent RSE shall be less than or equal to 0,25 % for every data point and R squared shall be greater than or equal to 0,98.

equal to 0,98. In the graph, RSE is above 0,25 % for the first data point near 36 °C while R squared is greater than 0,98.

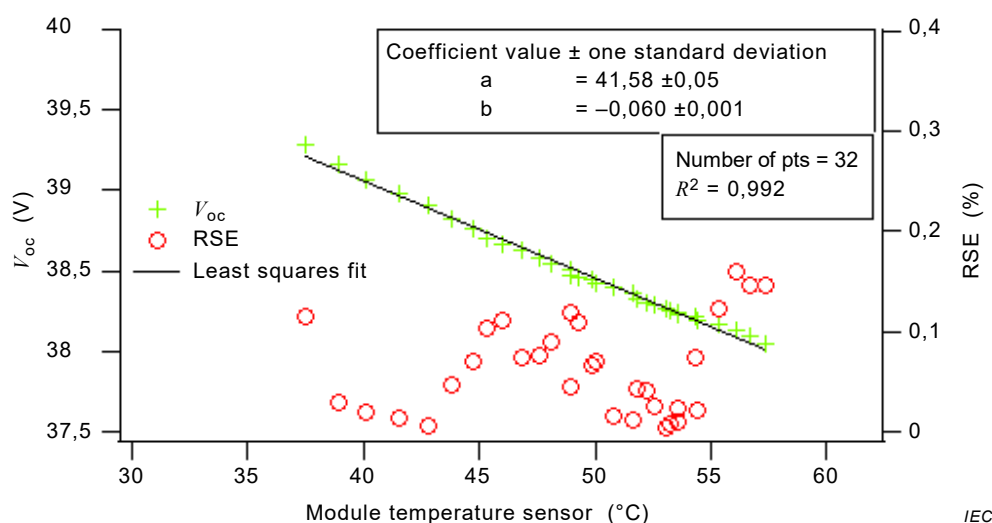


Figure 6 – Figure 5 repeated after removing one data point

Figure 6 is identical to Figure 5 other than the one data point from Figure 5 that exceeded the RSE requirement was removed and then the least squares fit was recalculated. The remaining data set meets the requirement of this subclause.

9.1.4 Temperature coefficient determination

The procedure described in 9.1.3 shall be repeated as many times as necessary to have acceptable data from at least 5 different uncover events which are from at least 2 different days. The maximum tolerable deviation between the average temperature coefficients for DUT efficiency on the two separate days shall be within 30 % or the test shall be repeated. For each unique uncover event create plots of the average of the 2 DUT temperature sensors against V_{oc} , I_{sc}/DNI , η , and FF. Calculate the least squares fit for each plot. The slope of the least squares fit is an individual instance of a particular coefficient for the given DUT. The “ b ” coefficient in Figure 6 is an example of an individual instance of the V_{oc} coefficient for the given device. The reported temperature coefficients shall be the average coefficient determined from at least 5 or more acceptable uncover events. Throughout this document, δ is the coefficient of efficiency (absolute %/K), β is the coefficient of V_{oc} (V/K), and α the coefficient for I_{sc} (A/K), (Note that the plot described above is for I_{sc}/DNI therefore to determine α the average slope for I_{sc}/DNI shall be multiplied by the reference irradiance which is 900 W/m² as applicable to Equation (5). Note that DUT efficiency is calculated per Equation (9).

Note that it is recommended that data from an uncover event be excluded if the associated least squares fit for FF meets either of the following criteria:

- $R^2 > 0,7$ and the slope is greater than 0 %/K,
- $R^2 > 0,7$ and the slope is less than $-0,1$ %/K,

This recommendation is based on the assumption that the FF coefficient for multiple junction cells is typically near $-0,05$ %/K. If the measured FF coefficient is over a 100 % different relative to this typical value (as in the above recommended exclusions) it is thought that this is likely due to lens temperature effects which the above test was not intended to include. Test results have shown for various CPV DUTs that if the lens temperature variation is held to less than 2 °C the FF recommend range is achieved.

9.2 DUT reference V_{oc} at (900 W/m² and 25 °C cell temperature)

9.2.1 General

The DUT reference V_{oc} is primarily used as an input to the calculation of cell temperature when the CPV device is on-sun outdoors. The cell temperature calculation is sensitive to uncertainty in the reference V_{oc} and therefore high accuracy is desired in the determination of the reference V_{oc} . Two methods are provided for determining the reference V_{oc} , dark I-V and simulator based measurements. When calculating cell temperature, it is ideal to use a reference V_{oc} at the mean irradiance for the outdoor I-V data set for the DUT and 25 °C: 900 W/m² has been prescribed here as this is the middle value in the permissible range of irradiances (700 W/m² to 1 100 W/m²). (An alternate reference irradiance or temperature can be used assuming all necessary terms are modified accordingly in the cell temperature calculation and changes are documented in the test report.)

9.2.2 Reference V_{oc} dark I-V procedure

The following provides procedures and equations for determining the reference V_{oc} from dark I-V curves measured for the DUT.

The reference V_{oc} shall be determined by measuring successive dark I-V curves on the DUT, one curve beginning at zero current and ending at least 1,7 times the expected I_{sc} under 1 000 W/m², the other curve beginning at 1,7 times the expected I_{sc} under 1 000 W/m² and ending at zero current (the outdoor I-V data set and assumed linearity between I_{sc} and irradiance can be used to determine the expected I_{sc} under 1 000 W/m²). The manufacturer may need to provide a DUT that has had blocking diodes removed in order to make dark I-V measurements possible. Caution shall be taken by limiting maximum currents achieved (per manufacturer instructions) during the dark I-V measurement so as not to damage the DUT. The dark I-V measurements shall be conducted in a controlled environment that ensures the DUT is at (25 ± 2) °C. (As stated prior, an alternate reference temperature can be used assuming all necessary terms are modified accordingly in the cell temperature calculation and changes are documented in the test report.) Temperature shall be verified by at least one DUT temperature sensor. The device for conducting the dark I-V should either have sufficient speed or be a pulsed measurement system in order to ensure that the cell(s) does not heat sufficiently due to the injected current. The hysteresis between the two dark I-V curves shall be used to determine that no more than 2 °C heating has occurred. Heating shall be measured as the hysteresis voltage divided by β (see 9.1.4 for determination of β).

The individual voltage points of the dark I-V curve are translated to corresponding light conditions per Equation (1) where V represents voltage, I current, and R_s resistance. The subscripts light and dark represent light and dark conditions respectively and R_s represents the series resistance of the DUT. Note that Equation (1) is not considered a valid method to translate the entire dark I-V curve to lighted conditions, rather it is only considered valid for determining the reference V_{oc} in lighted conditions.

$$V_{light} = V_{dark} - I_{light} \times R_s \quad (1)$$

Equation (1) becomes Equation (2) when it is evaluated to solve for the reference V_{oc} (V_{ocr}).

$$V_{ocr} = V_{dark}(I_{scr}) - I_{scr} \times R_s \quad (2)$$

$V_{dark}(I_{scr})$ is the voltage point on the dark I-V curve where $I_{dark} = I_{scr}$. I_{scr} is measured per 9.4. The series resistance shall be extracted from the high current region of the dark I-V curve. The high current region is recommended to be limited to dark I-V pairs where the voltage is greater than $(V_{oc} + V_{mp})/2$. V_{oc} and V_{mp} can be estimated from outdoor I-V data. The series resistance shall be considered equal to the intercept of the linear fit of the dark I-V data

plotted as $\frac{dV}{dI}$ against $\frac{1}{I}$. If the plot of $\frac{dV}{dI}$ against $\frac{1}{I}$ shows significant nonlinear behavior at the lower current/voltage pairs, the nonlinear portion should be excluded from the fit (one may exclude I-V pairs for voltages up to but not greater than V_{oc}). If the intercept of the fit is negative, the series resistance shall be considered zero for the purpose of evaluating Equation (2).

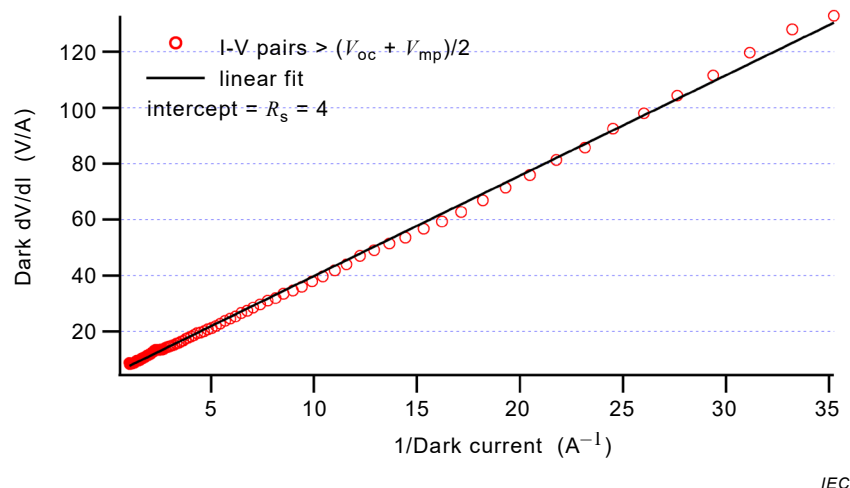


Figure 7 – The derivative of dark I-V data plotted to determine R_s

Figure 7 shows the derivative of the dark I-V data in the high current region as it is used to extract the series resistance for the DUT. The open circles in Figure 7 are the calculated derivatives between successive dark I-V pairs for I-V pairs $> \sim (V_{oc} + V_{mp})/2$. The series resistance is determined from the intercept of the solid line, which is the linear fit for the open circles. Caution shall be taken to avoid including nonlinear behavior at lower currents per the dark I-V data set.

9.2.3 Reference V_{oc} using a solar simulator

The following provide requirements for determining V_{ocr} per a solar simulator.

- If a separate indoor reference irradiance sensor is used: The temperature control system is used to maintain the DUT at $(25 \pm 2)^\circ\text{C}$. The solar simulator is adjusted so the indoor reference irradiance sensor achieves $I_{sc,cal}$ while an I-V curve is measured for the DUT. V_{ocr} is determined as the V_{oc} from the measured I-V curve.
- If the DUT serves as the indoor reference irradiance sensor: The temperature control system is used to maintain the DUT at $(25 \pm 2)^\circ\text{C}$. The solar simulator is adjusted so that $I_{sc,hot900}$ (see Equation (4)) is achieved per the illuminated I-V curve measured for the DUT. The $\sim V_{ocr}$ is determined as the V_{oc} from the measured I-V curve. The average cell temperature associated with $I_{sc,hot900}$ (see Equation (4) and 9.4.3) is calculated per 9.3, where $I_{sc,hot900}$ and $\sim V_{ocr}$ are used as reference values. Equation (5) is then used to correct $I_{sc,hot900}$ to 25°C (i.e. determine $I_{scr} = I_{sc,cal}$ for the DUT). The simulator is now set to achieve $I_{scr} = I_{sc,cal}$ for the DUT and V_{ocr} is determined per the illuminated I-V curve. (See Figure 8 for a graphical representation of this procedure.)

9.3 Calculating the average DUT cell temperature

9.3.1 Purpose

There is no accepted method available for directly measuring the temperature of cells operating under concentrated light. DUT performance is correlated with cell temperature and therefore it is valuable to calculate on-sun cell temperature for every outdoor power measurement. The procedure described hereafter is consistent with IEC 60904-5.

to DUTs with multijunction cells. The described calculation is applicable when correcting outdoor performance measurements to CSTC and CSOC conditions.

9.3.2 Procedure

Equation (3) is used to calculate the equilibrium mean solar cell junction temperature within a CPV DUT for a given I-V curve measured outdoors.

NOTE Equation (3) is evaluated in Kelvin, not Celsius.

$$T_c = \frac{V_{oc} - V_{ocr} + \beta \times T_r}{N_s \left(\frac{nk}{q} \right) \ln \left(\frac{I_{sc}}{I_{scr}} \right) + \beta} \quad (3)$$

where

V_{oc} is the measured DUT open-circuit voltage, (V);

N_s is the number of cells in series within the DUT;

V_{ocr} is the DUT open-circuit voltage at 298,15 K and 900 W/m² (see 9.2).

Note the V_{ocr} can be at an alternate temperature and irradiance but that I_{scr} and T_r shall be modified to these alternate conditions.

n is the diode ideality factor for cell (dimensionless, 3 assumed for triple junction cells, 4 with four junction cells);

k is the Boltzmann's constant, 1,380 66 x 10⁻²³, (J/K);

T_c is the calculated average temperature of cells inside DUT, (K);

q is the elementary charge, 1,602 18 x 10⁻¹⁹, (C);

I_{sc} is the measured DUT short-circuit current, (A);

I_{scr} is the DUT short-circuit current at 298,15 K and 900 W/m² (see 9.4);

β is V_{oc} temperature coefficient, (V/K) (see 9.1);

T_r is the reference temperature for cell measurements, (298,15 K).

9.4 Reference irradiance sensor calibration and reference I_{sc} determination

9.4.1 Purpose

The indoor reference irradiance sensor and the DUT shall be measured outdoors to determine I_{sc} at reference conditions (the actual DUT can serve as the indoor reference sensor or this can be an alternate sensor, see 8.1.5). The indoor reference irradiance sensor is used to set the output of the solar simulator for determining performance at CSTC while the reference I_{sc} for the DUT is also used for calculating on-sun cell temperature. The following method describes determination of a calibration of I_{sc} under natural sunlight against a pyrheliometer (traceable to world radiometric reference, see 8.1.1) under a limited range of spectral conditions per measurements of the spectrum with spectral measurement device (calibrated as primary or secondary reference cells, see 8.1.3). The reference irradiance sensor is calibrated per I-V data collected according to 9.6.

9.4.2 Data requirements

Data requirements are identical to 9.7.1.

9.4.3 Determination of the calibrated and reference I_{sc} , ($I_{sc, cal}$ and I_{scr})

Note that $I_{sc, cal}$ and I_{scr} are both determined through the following procedure where $I_{sc, cal}$ is a calibrated short-circuit current for use as an indoor reference irradiance sensor and I_{scr} is a reference short-circuit current for a specific DUT and is used for outdoor cell temperature

calculation for that specific DUT. I_{scr} is specifically referenced to 900 W/m^2 but $I_{sc,cal}$ can be determined for other irradiances in the range of 700 W/m^2 to $1\,100 \text{ W/m}^2$ per linear scaling, for example $1\,000 \text{ W/m}^2$ per CSTC.

For all measured I-V curves fulfilling the data requirements per 9.7.1 calculate the hot I_{sc} at 900 W/m^2 per Equation (4), where N is the total number of filtered I-V curves. This is termed hot I_{sc} because outdoor I-V measurements are typically at higher cell temperatures than the 25°C reference temperature.

$$I_{sc,hot900} = 900 \left(\sum_i \frac{I_{sc,i}}{DNI_i} \right) / N \quad (4)$$

The reference or calibrated I_{sc} is then calculated using the temperature correction per Equation (5), where the average cell temperature of the filtered I-V curves is given by Equation (6), (see 9.3 for cell temperature calculation and 9.1 for temperature coefficient determination).

$$I_{scr} = I_{sc,hot900} - \alpha(T_{c,avg} - T_r) \quad (5)$$

$$T_{c,avg} = \left(\sum_i T_{c,i} \right) / N \quad (6)$$

Note that the calculation of $T_{c,i}$ per Equation (3) requires I_{scr} , i.e. Equation (5), while Equation (5) requires the result of the cell temperature calculation. The interdependence of these two equations is overcome by using a single iterative approach as described below. The cell temperature, Equation (3), requires both a reference V_{oc} and I_{sc} . The first step is to use the filtered outdoor I-V data set to determine $I_{sc,hot900}$. $I_{sc,hot900}$ is then used to determine an approximate reference voltage ($\sim V_{ocr}$). The $\sim V_{ocr}$ is either calculated by substituting $I_{scr} = I_{sc,hot900}$ in Equation (2) or by measuring the DUT I-V curve under the solar simulator set to $I_{sc,calibration} = I_{sc,hot900}$. In either case the $\sim V_{ocr}$ is expected to be a reasonable approximation for calculating cell temperature. Equation (3) is evaluated using $V_{ocr} = \sim V_{ocr}$ and $I_{scr} = I_{sc,hot900}$. Equation (6) can then be determined with the approximate calculations for cell temperature and Equation (5) can be solved for I_{scr} . I_{scr} is now used with dark I-V data or a solar simulator to determine the V_{ocr} . Further iterations can be calculated but as the I_{sc} coefficient for a triple junction cell is typically on the order of $0,07 \text{ \%}/\text{K}$, a second iteration is likely to have less than $0,5^\circ\text{C}$ impact on the calculation of $T_{c,avg}$, significantly less than the uncertainty in the cell temperature calculation.