INTERNATIONAL ELECTROTECHNICAL COMMISSION

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IEC 60904: Photovoltaic devices –

Part 1-2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices (Draft A)

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

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Photovoltaic devices –

Part 1-2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices

1 Scope

This part of IEC 60904 describes procedures for the measurement of the current-voltage (I-V) characteristics of bifacial photovoltaic devices in natural or simulated sunlight. It is applicable to single PV cells, sub-assemblies of such cells or entire PV modules.

The requirements for measurement of I-V characteristics of standard (monofacial) PV devices are covered by IEC 60904-1 whereas this standard describes the additional requirements for the measurement of I-V characteristics of bifacial PV devices.

NOTE: This standard may be applicable to PV devices designed for use under concentrated irradiation if they are measured without the optics for concentration and irradiated using direct normal irradiance and a mismatch correction with respect to a direct normal reference spectrum is performed.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. 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 60904-2, *Photovoltaic devices – Part 2: Requirements for reference solar devices*

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

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

IEC 60904-7, *Photovoltaic devices – Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices*

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

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

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

3 Terms and definitions

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

Bifacial PV device
In a bifacial PV device, both surfaces (front and rear sides) are used for power generation.

Bifaciality

Bifaciality refers to the ratios between the main I-V characteristics of the rear side and the front side of a bifacial device, typically at Standard Test Conditions (STC) unless otherwise specified. It is quantified with reference to bifaciality coefficients, namely the short-circuit current bifaciality coefficient φ_{Isc}, the open-circuit voltage bifaciality coefficient φ_{Voc} and the maximum power bifaciality coefficient φ_{Pmax}.

4 General considerations

The final performance of bifacial PV devices in a power plant depends on the spatial distribution of the irradiance incident on the rear surface of the device, which is strongly affected by site-specific conditions such as albedo, reflective surface size, the racking system, the device's elevation and its tilt angle. Due to these dependences and in order to obtain comparable measurement results, I-V characterisation is extended to quantify the bifaciality of the device and the power generation gain it can yield. Bifaciality is an intrinsic property of the device, unlike the site-specific conditions such as albedo. The measurement conditions for bifacial devices should strive to generate extra photocurrents proportional to their bifaciality. In general, this can be achieved with a test spectrum close to the reference spectrum such as provided by natural sunlight under suitable conditions or with a solar simulator whose irradiance level is adjustable. However, measurement conditions will never be perfect and will deviate from the reference conditions. This standard sets limits on the permissible deviations for obtaining valid measurements. Smaller deviations are preferable, but may not be achievable in all cases. In any case, the deviations of the measurement conditions from the reference conditions shall be accounted for in the analysis of measurement uncertainty.

5 Apparatus

In addition to the apparatus requirements described in IEC 60904-1, the following apply for the characterisation of bifacial devices:

5.1 Solar simulator with adjustable irradiance levels for single-side illumination

A solar simulator, as defined in IEC 60904-9, with adjustable irradiance level shall be used for the I-V characterisation of bifacial devices. Simulators must be able to provide irradiance levels above 1000 $W \cdot m^{-2}$ (typically up to 1200 $W \cdot m^{-2}$). The simulator's non-uniformity of irradiance must be below 5% and must remain below this value at irradiance levels used for the characterisation of bifacial devices.

5.2 Solar simulator with adjustable irradiance levels for double-side illumination

A solar simulator, as defined in IEC 60904-9, with the possibility to simultaneously illuminate the bifacial device on both sides shall be used. Such simulators must be able to provide irradiance at different levels on both sides. The non-uniformity of irradiance, the spectral distribution and the temporal instabilities of irradiance must be measured on both sides when the test area is simultaneously illuminated on both sides. The non-uniformity of irradiance must be below 5% on both sides, at the irradiance levels used for the characterisation of bifacial devices.

5.3 Natural sunlight

In addition to the general measurement requirements described in IEC 60904-1, at least 2 additional PV reference devices are required to measure the irradiance level on the rear side and the rear-side irradiance non-uniformity. Their spectral responsivity should be as close as possible to the one of the device to be tested.

5.4 Non-irradiated background and background compensation

For the I-V characterisation of each face of bifacial devices, it must be possible to eliminate completely and temporarily the contribution of the front or the rear sides of the device under test during the measurement by creating a non-irradiated background. The background is considered to be non-irradiated if the irradiance is measured to be below 3 $W \cdot m^{-2}$, on at least 2 points, on the non-exposed side of the device.

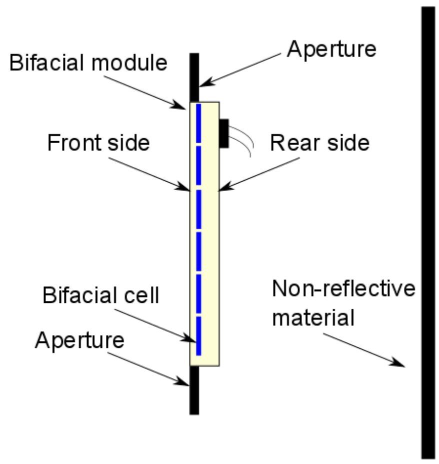

Figure 1: Scheme of a bifacial PV module and the required non-irradiated background and aperture

In order to fulfil this requirement, in the case of PV modules, it is highly recommended to limit the size of the test area to the one of the device under test using apertures as illustrated in Figure 1. Materials with minimized reflection in the wavelength range corresponding to the spectral responsivity of the test specimen, placed at a suitable distance from its non-exposed side, shall be used to reduce the irradiance level (non-reflective material).

In the case of PV bare cells, the use of non-reflective materials to manufacture cell holders may be insufficient to reach irradiance values below 3 $W \cdot m^{-2}$. In that case, background compensation may be performed by extrapolating the short-circuit current as a function of the background irradiance.

NOTE: When the spacing between the cells in a module is significant, it may be difficult to minimize the irradiance on the non-exposed side. In that case, it is allowed to use a mask to prevent the light to go through the spaces between the cells.

6 Additional I-V characterisations for bifacial devices

6.1 General considerations

The procedure for measurement of the I-V characteristics of standard (monofacial) PV devices is described in IEC 60904-1 and its provisions are also valid for the measurement of bifacial PV devices except where explicitly amended by this standard. The procedure for the measurement of the I-V characteristics of a bifacial PV device is based on the same basic principles as in IEC 60904-1, but requires some additional considerations and also provides supplementary characteristics specific to bifacial devices.

The measurement conditions for I-V characteristics of bifacial devices require more attention than for monofacial devices as the measurement results for bifacial devices are more prone to effects due to the measurement conditions deviating from the reference conditions. For instance, the parasitic reflections from the rear side of the device under test can increase significantly the measurement uncertainty.

The parameters calculated as described below shall adhere to the specified limitations, which define the permissible measurement conditions. The calculated parameters shall also be reported with the measurement results as indicated in section 8.

Proper selection of measurement conditions avoids or minimizes the magnitude of the correction that must be applied to the measured characteristics. In any case, a detailed analysis of measurement uncertainties is required.

6.2 Determination of bifaciality coefficients

In order to determine the bifaciality coefficients of the test specimen, the main I-V characteristics of the front and the rear sides must be measured at STC (G=1000 W·m^{-2}). A non-irradiated background, as described in section 5.4, must be used in order to avoid the illumination of the non-exposed side.

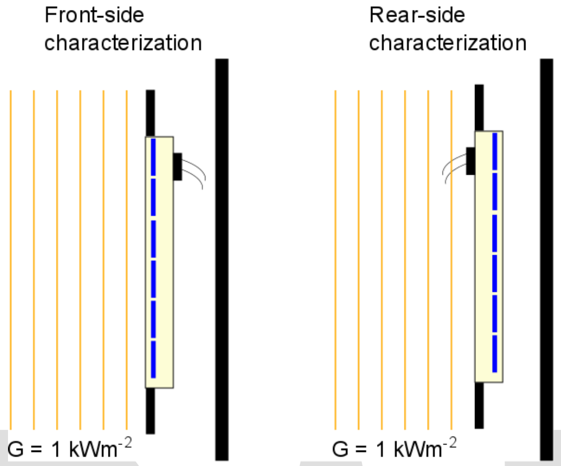

Figure 2: Front- and rear-side characterization for bifaciality

In the case of PV modules, when the rear side of the device is being measured, the recommendations of the manufacturer about the handling of the cables must be applied. If no specific recommendation exists, the cables must be handled as close as possible to the way they are used on a power plant.

Short-circuit current bifaciality coefficient φ_{Isc} is the ratio between the short-circuit current generated exclusively by the rear side of the bifacial device and the one generated by the front side. Both currents are measured at STC (1000 W·m^{-2}, 25 °C, with the IEC 60904-3 reference solar spectral irradiance distribution):

$$\varphi_{Isc} = \frac{Isc_r}{Isc_f} \tag{1}$$

where

φ_{Isc} is the short-circuit current bifaciality coefficient. It is usually expressed in percentages.

Isc_r is the short-circuit current when the device is illuminated only on the rear side, at STC.

Isc_f is the short-circuit current when the device is illuminated only on the front side, at STC.

The spectral mismatch correction shall be applied to the measurement of Isc_f and Isc_r, according to IEC 60904-7, unless it is known that the front and back of the bifacial device have identical spectral responsivity.

Other bifaciality coefficients shall be reported and are calculated as described below:

$$\varphi_{Voc} = \frac{Voc_r}{Voc_f} \tag{2}$$

$$\varphi_{Pmax} = \frac{Pmax_r}{Pmax_f} \tag{3}$$

where

φ_{Voc} is the open-circuit voltage bifaciality coefficient. It is usually expressed in percentages.

φ_{Pmax} is the maximum power bifaciality coefficient. It is usually expressed in percentages.

Voc_r is the open-circuit voltage when the device is illuminated only on the rear side, at STC.

Voc_f is the open-circuit voltage when the device is illuminated only on the front side, at STC.

$Pmax_r$ is the maximum power when the device is illuminated only on the rear side, at STC.

$Pmax_f$ is the maximum power when the device is illuminated only on the front side, at STC.

The spectral mismatch correction shall be applied, according to IEC 60904-7, for the above mentioned calculations, unless it is known that the front and back of the bifacial device have identical spectral responsivity.

6.3 Measurement of the power generation gain yielded by the bifaciality

The gain in power generation yielded by the bifaciality of the device under test must be determined as a function of the irradiance on the rear side. To this end, outdoor or indoor measurement procedures must be applied as described below.

6.3.1 Outdoor power generation gain measurement

In order to perform outdoor measurement of the power generation gain, the non-uniformity of irradiance on the rear side must be below 10%. In order to measure the non-uniformity of irradiance on the rear side, besides the reference device used for the irradiance measurement on the rear side, another reference device must be used to measure the irradiance on the rear side on at least 5 positions, before the I-V characterization is performed. Choose at least 5 positions as shown in Figure 3, with symmetrical distribution, for instance, P1-P3-P5-P7-P9, P2-P4-P5-P6-P8 or P1-P2-P3-P7-P8-P9. Figure 3 schematizes an outdoor measurement setup. Multiple reference devices can also be used for non-uniformity measurement.

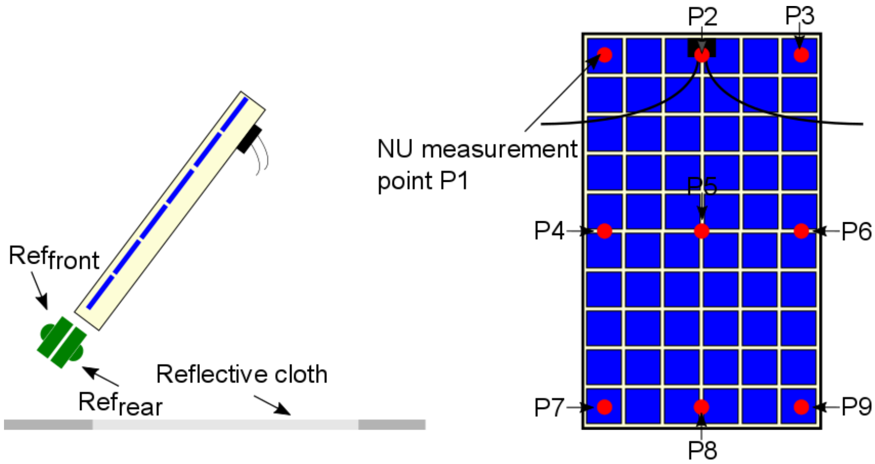

Figure 3: Left: Two reference devices are used to measure the irradiance on the front and the rear sides of the device during outdoor measurements. Right: proposed positions to measure the non-uniformity of irradiance outdoor and the way the cables must be handled

In order to improve the non-uniformity of irradiance on the rear side, it is recommended to elevate the device under test to higher positions. A reflective cloth can also be used to increase the reflection uniformity of the surface behind the device.

Pmax of the device must be measured at 1000 W·m^{-2} on the front side, or corrected to this value, plus different rear side irradiance levels G_{Ri}. At least three different irradiance levels on the rear side are required.

Two specific *Pmax* values, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$, for G_{R1}=100 W·m^{-2} and G_{R2}=200 W·m^{-2} respectively must be reported. If the irradiance levels on the rear side do not correspond to G_{R1} and G_{R2}, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$ must be obtained by linear interpolation of the data series *Pmax* versus G_R.

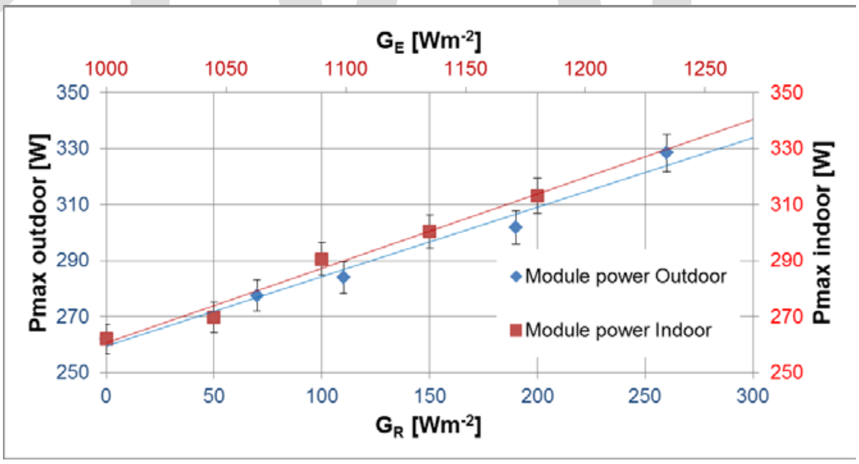

Figure 4: Examples of *Pmax* as a function of irradiance level on the rear side G_R or its 1-side equivalent irradiance G_E

6.3.2 Indoor power generation gain measurement with single-side illumination

In order to perform indoor measurement of the power generation gain, a solar simulator with adjustable irradiance levels for single-side illumination, as described in section 5.1 can be used. To this end, a non-irradiated background is required as described in section 5.4.

Pmax of the device must be measured on the front side at equivalent irradiance levels corresponding to 1000 W·m^{-2} on the front side plus different rear side irradiance levels G_{Ri}. The equivalent irradiance levels are determined as functions of the bifaciality coefficient φ according to the equation below:

$$G_{E_i} = 1000\, W \cdot m^{-2} + \varphi \cdot G_{R_i} \quad (4)$$

$$\varphi = Min(\varphi_{Isc}, \varphi_{Pmax}) \quad (5)$$

φ is the minimum value between the Isc and Pmax bifaciality coefficients φ_{Isc} and φ_{Pmax}.

At least three different equivalent irradiance levels are required ($i = 1, 2, 3, \ldots$).

Example: A device with bifaciality of $\varphi = 80\%$, must be irradiated, on the front side at $G_{E_2} = 1160Wm^{-2}$ to provide the equivalence of $G_{R_2} = 200\, W \cdot m^{-2}$.

Two specific *Pmax* values, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$, for G_{R1}=100 W·m^{-2} and G_{R2}=200 W·m^{-2} respectively, must be reported. If the equivalent irradiance levels do not correspond to G_{R1} and G_{R2}, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$ must be obtained by linear interpolation of the data series *Pmax* versus G_E.

6.3.3 Indoor power generation gain measurement with double-side illumination

Double-side illumination, as described in section 5.2, can alternatively be applied to determine the power generation gain. *Pmax* of the device under test must be measured at 1000 W·m^{-2} on the front side, or corrected to this value, plus different rear side irradiance levels G_{Ri}. At least three different irradiance levels on the rear side are required.

Two specific *Pmax* values, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$, for G_{R1}=100 W·m^{-2} and G_{R2}=200 W·m^{-2} respectively, must be reported. If the irradiance levels on the rear side do not correspond to G_{R1} and G_{R2}, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$ must be obtained by linear interpolation of the data series *Pmax* versus G_R.

NOTE: Reflections between the two light sources may add irradiance non-uniformity. This may generate significant offsets between single-side and double-side measurement methods results. In this case, double-side illumination results must be corrected. Using black masking around the module is recommended to avoid unwanted reflections in double-side measurements.

7 I-V characterisation for bifacial reference devices and for production

Two cases are to be considered for the I-V characteristics measurement of bifacial devices. In the first case, the bifaciality coefficients of the test specimen are not known. This is usually the case for newly developed or modified devices and the measurements are performed by PV laboratories or accredited agents. The second case corresponds usually to PV manufacturing environments, where reference devices, of the same technology as the devices to be tested are available.

The determination of the bifaciality coefficients and the measurement of the power generation gain yielded by the bifaciality of the reference devices are to be performed in PV laboratories whereas these characteristics are used to assess the PV production output. The main differences are described below.

7.1 I-V measurement of reference bifacial devices

In order to assess reference bifacial devices, in addition to the measurements described in IEC 60904-1, the bifaciality coefficients and the power generation gain yielded by the bifaciality must be determined according to the procedures described in this standard.

Determination of the following parameters is required:

- Spectral responsivity (or Quantum Efficiency) of the front side, measured according to IEC 60904-8

- Spectral responsivity (or Quantum Efficiency) of the rear side, measured according to IEC 60904-8
- *Isc*, *Voc* and *Pmax* as functions of irradiance level on the rear side G_R or its 1-side equivalent irradiance G_E

Determination of the following parameters is highly recommended but is not obligatory:

- Transmittances of the Device Under Test, T_{DUT}, and the one of its encapsulant, T_{Enc}, as a function of wavelength (see Figure 5)

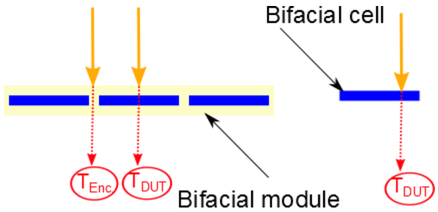

Figure 5 – Transmittances of the device (T_{DUT}) and its encapsulant ($T_{ENC.}$)

The measurement uncertainties must be provided.

7.2 I-V measurement of bifacial devices in production

A reference device, assessed by an accredited agent and of the same technology as the devices to be tested must be used to calibrate the solar simulators used in PV production environments. To this end, the reference key data (Isc, Voc and Pmax) of the front side at STC (G=1000 W·m^{-2}) must be used and I-V assessment must be performed according to IEC 60904-1. $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$ must be reported for each device tested in production. These values must be calculated based on the *Pmax* value determined at STC (i.e. without the contribution of the rear side) and the slope of the *Pmax* versus rear side irradiance function provided for the reference device.

In production environments, non-irradiated backgrounds are not required, as the contribution of the background is compensated by calibration. The irradiation from the background must be stable.

Alternatively, a solar simulator for double-side illumination as described in section 5.2 can be used in production. In that case, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$ are measured on each device and the reference must be used to calibrate the simulator in at least 3 different configurations: with 1000 W·m^{-2} on the front side and 0 W·m^{-2} on the rear side, 1000 W·m^{-2} on the front side and 100 W·m^{-2} on the rear side and finally 1000 W·m^{-2} on the front side and 200 W·m^{-2} on the rear side. These are the measurement configurations to asses *Pmax*, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$.

8 Report

Following completion of the procedure, a certified report of the I-V measurements shall be prepared by the test agency in accordance with the procedures of ISO/IEC 17025. Each certificate or test report shall include the information as required by IEC 60904-1. Additionally the following shall be included:

– Bifaciality coefficients φ_{Isc}, φ_{Voc} and φ_{Pmax}
– *Isc*, *Voc* and *Pmax* as functions of irradiance level on the rear side G_R or its 1-side equivalent irradiance G_E
– Reference key data, namely *Isc*, *Voc*, *Pmax*, Fill factor and Efficiency, for both sides

Optionally the following may be included:

- Transmittances of the device (T_{DUT}) and its encapsulant ($T_{ENC.}$)
- Spectral responsivity of the front and the rear sides
- Back irradiance spatial non-uniformity (for outdoor measurement)