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"The Calibration of Reference Devices"

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These are preliminary lecture notes, intended only for distribution to participants.

THE CALIBRATION OF REFERENCE DEVICES

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1. INTRODUCTION

It is now widely recognised that, in PV performance rating measurements, one should use a reference cell or module to monitor the irradiance, in order to relate the measurement to a reference solar spectral irradiance distribution, such as that standardised in IEC 904-3. The proper seleotion and calibration of such devices is the key to accurate rating.

The essential requirements for a reference device are :-

1) Its photovoltaic characteristics must be stable.

2) It must be a linear device, i.e. its short-circuit current must vary linearly with irradiance over the range of interest.

3) Its relative spectral response should match as closely as possible that of the module or array to be tested.

4) Its optical properties should be such that the irradiance measured by the reference device is always the same as that incident on the test specimen.

5) Preferably, it should be encapsulated in the same way as the modules to be tested, so that it reaches the same steady-state temperature. This simplifies the transposition of the measured I-V characteristic to STC.

A primary reference device is one whose calibration is based on a radiometer or standard detector conforming to the current World Radiometric Reference (WRR). A secondary reference device is one calibrated against a primary reference device.

The International Electrotechnical Commission has yet to agree on a standard method for calibrating primary reference devices. In this lecture, we shall look at three of the best methods that have been considered and then go on to discuss their relative merits. Finally, the calibration of secondary reference devices, as standardised in IEC 904-2, will be described.

2. GLOBAL SUNLIGHT METHOD

2.1 Apparatus

- A Class 1 pyranometer, calibrated outdoors against a primary absolute cavity radiometer (PACRAD) conforming to WRR, under the conditions set out in para. 2.2 below.

- A platform, horizontal <u>or</u> sunfacing, on which the pyranometer is mounted co-planar with the reference device.

- If a sun-facing platform is used, means to limit ground reflection to no more than 3% of the total irradiance.

- A removeable shade, to keep the reference device at or near ambient temperature.

- Means for measuring the junction temperature of the reference device to an accuracy of ± 1 °C.

- Equipment for measuring the short-circuit current of the reference device to an accuracy of ± 0.5%.

- Data acquisition system.

- For the spectral correction measurements, a suitably calibrated spectroradiometer and means for measuring the relative spectral response of the reference device.

2.2 Environmental conditions

- Clear, sunny weather.

- Total irradiance, as measured with the pyranometer, not less than 800 W/m^2.

- Diffuse/total irradiance ratio not more than 0.25.

- With horizontal platform, solar elevation no less than 54^{o}.

- With sun-facing platform, air mass between AM1 and AM2.

- Radiation sufficiently stable so that the variation in the short-circuit current of the reference device during a measurement is less than ± 0.5%.

2.3 Test procedure

1) Before proceeding to the calibration site, measure the temperature coefficient of short-circuit current of the reference device.

2) At the calibration site, set up the apparatus, with the shade in position over the reference device, and check that the environmental conditions are within the specified limits.

3) When all is ready, remove the shade and immediately make simultaneous measurements of reference device short-circuit current I_{SC} and irradiance G in quick succession, until the ratio

$$\frac{I_{SC} \text{ (corrected to } 25^{o}\text{C)}}{G} \quad A/(W/m^2)$$

varies by less than 1% over 5 successive sets of readings. Record these ratios.

4) Repeat Steps 2 and 3 on at least two other days.

5) Take the mean of the recorded ratios as the uncorrected calibration value CV_U, i.e. the short-circuit current per unit of irradiance having the reference spectral irradiance distribution.

6) Multiply CV_U by the appropriate spectral correction factor k to give the corrected calibration value CV :

$$CV = k.CV_U \qquad A/(W/m^2)$$

2.4 Determination of k

1) Measure the relative spectral response of the reference device.

2) At the same time as, or immediately after each day's calibration, measure the relative spectral irradiance distribution of the incident sunlight, using a suitably calibrated spectroradiometer with an integrating sphere to direct a sample of the total sunlight on to the entrance slit. The spectroradiometer must cover the spectral response range of the reference device.

3) For each day, compute the corrected calibration value CV :-

$$CV = CV_U . \frac{\int k_2G(\lambda).d\lambda \; . \int k_1s(\lambda).G_R(\lambda).d\lambda}{\int G_R(\lambda).d\lambda \; . \int k_1s(\lambda).k_2G(\lambda).d\lambda} \qquad A/(W/m^2)$$

where :

CV_U = the uncorrected calibration value at 25°C. ($A/(W/m^2)$)

$k_1s(\lambda)$ = the measured relative spectral response of the reference device at wavelength λ.

$G_R(\lambda)$ = The reference solar spectral irradiance at wavelength λ.

$k_2G(\lambda)$ = the measured relative spectral irradiance of the sunlight in which the short-circuit current was measured, at wavelength .

The range of all the integrals in the above equation is that of the measured relative spectral irradiance.

4) Calculate :

$$k = \text{mean} \frac{CV}{CV_U}$$

3. SOLAR SIMULATOR METHOD

3.1 Apparatus

- A Class A steady-state solar simulator.
- A very accurately calibrated spectroradiometer.
- A Class 1 pyranometer, calibrated against a primary absolute cavity radiometer (PACRAD) conforming to WRR, under the conditions set out in para. 3.2 below.
- Spectral response measuring equipment.

- Means for maintaining the reference device temperature within 25 ± 1°C.

- Equipment for measuring the short-circuit current of the reference device to an accuracy of ± 0.5%.

- Data acquisition system.

3.2 Environmental conditions

The calibration shall be carried out in a laboratory whose temperature and humidity are maintained within the operational limits required by the test equipment.

3.3 Test procedure

1) Measure the relative spectral response of the reference device at 25 ± 1°C three times or more.

2) Set the irradiance in the test plane of the solar simulator to approximately 1000 W/m², using a previously calibrated reference device.

3) At this setting, measure the relative spectral irradiance distribution in the test plane with the spectroradiometer. At the same time, measure the total irradiance with the pyranometer. From these data determine the absolute spectral irradiance distribution in the test plane as follows :-

$$G(\lambda) = \frac{G}{\int G_M(\lambda).d\lambda} . G_M(\lambda)$$

where :

$G(\lambda)$ = the absolute spectral irradiance of the simulator at wavelength λ .

G = the measured total irradiance of the simulator.

$G_M(\lambda)$ = the measured spectral irradiance of the simulator at wavelength λ .

4) Position the reference device on its mount in the test plane of the simulator, maintain the device temperature within 25 ± 1°C and measure the short-circuit current of the device before and after Step 3.

5) Compute the calibration value CV as follows :-

$$CV = \frac{I_{SC}}{G_R(\lambda).d\lambda} . \frac{\int k_1 s(\lambda).G_R(\lambda).d\lambda}{\int k_1 s(\lambda).G(\lambda).d\lambda} \qquad A/(W/m^2)$$

where :

I_{SC} = the measured short-circuit current of the reference device, averaged over the duration of the measurement of the spectral irradiance distribution.

$k_1 s(\lambda)$ = the measured spectral response of the reference device at wavelength λ .

$G_R(\lambda)$ = the reference solar spectral irradiance at wavelength λ .

$G(\lambda)$ = the absolute spectral irradiance of the simulator at wavelength λ .

6) Repeat Steps 3, 4 and 5 at least three times and take the mean CV as the definitive calibration value.

4. DIFFERENTIAL SPECTRAL RESPONSE METHOD

In this method, the calibration value is computed from the reference solar spectral irradiance distribution and a direct measurement of the absolute spectral response of the reference device, thus :-

$$CV = \frac{\int s(\lambda).G_R(\lambda).d\lambda}{\int G_R(\lambda).d\lambda}$$

First, a relative calibration value CV_{REL} is computed from 5 measurements of the relative spectral response. The absolute spectral response is then measured at three wavelengths, using narrow-band filters and a detector calibrated to WRR. The final calibration is obtained by dividing the mean CV_{REL} by the mean ratio k_1 of the relative spectral response to the absolute spectral response at these three wavelengths.

5. ASSESSMENT OF PRIMARY CALIBRATION METHODS

The calibration of primary reference devices is at present in the hands of a few specialist agencies, each with its own method. To remove this bottleneck, we need a standard method, which does not require special expertise or equipment and which will give reproducible results when carried out by PV laboratories in different parts of the world. Ideally, it should be suitable for both cells and modules.

How well do the above methods meet these criteria ?

The Global Sunlight Method, which is derived from a technique developed by the Royal Aircraft Establishment (now DRA), Farnborough, UK and a proposal by ASTM in USA, is applicable to any type of reference device and has a very good repeatability record, extending over many years. The determination of the spectral correction factor k requires special equipment but experience has shown that k is very consistent and near to unity. Once it has been established for a particular calibration site and type of device, there is no need to repeat the spectral correction procedure. The method then becomes very simple and straightforward, with little likelihood of significant error.

The Solar Simulator Method, developed by JMI in Japan, is basically the same as the Global Method, the only difference being that the calibration is carried out in artificial rather than in natural sunlight. It is therefore independent of the weather. However, no simulator can match the reference solar spectrum as well as natural sunlight and simulators with line spectra are more difficult to measure. Because of this, the calibration is more susceptible to error. The method is applicable to reference modules as well as cells.

The Differential Spectral Response Method, developed by PTB in Germany, is the most scientifically elegant, in that it is independent of the weather and requires no simulator. But the accurate measurement of spectral response in absolute terms calls for very special expertise and equipment and is best left to experts. Small errors can have a significant effect.

From this analysis, it is concluded that the Global Sunlight Method best meets the criteria for an international standard.

6. CALIBRATION OF SECONDARY REFERENCE DEVICES

6.1 Apparatus

- A Class A solar simulator or natural sunlight in conditions conforming to those specified for the Global Sunlight Method.

- A sun-facing platform, on which the reference device to be calibrated is mounted co-planar with a suitable primary reference device.

- Means to limit ground reflection to no more than 3% of the total irradiance.

- A removeable shade, to keep the reference devices at or near ambient temperature. (Not necessary with a pulse simulator).

- Means for measuring the junction temperatures of the devices to an accuracy of ± 1°C.

- Equipment for measuring the short-circuit currents of the devices to an accuracy of ± 0.5%.

6.2 Test procedure (as laid down in IEC 904-2)

1) Before proceeding to the calibration site, measure the temperature coefficient of short-circuit current of the reference device to be calibrated.

2) At the calibration site, set up the apparatus, with the shade in position over both reference devices (unless using a pulse simulator). In natural sunlight, check that the environmental conditions are within the specified limits.

3) Adjust the mount so that the solar beam or centre line of the simulator beam is normal to the devices within ± 5°.

4) Record simultaneous readings of the short-circuit currents and temperatures of both reference devices. Repeat until five successive sets of readings are obtained in which the ratio of the short-circuit currents, corrected to 25°C, does not vary by more than ± 1%.

5) When calibrating in natural sunlight, repeat the calibration a minimum of five times on at least three separate days.

6) From the acceptable data, calculate the mean ratio of the short-circuit currents (secondary/primary) and multiply the calibration value of the primary reference device by this ratio to obtain the calibration value of the secondary reference device.