Validation of Spectral Response Polychromatic Method Measurement of Full Size Photovoltaic Modules using Outdoor Measured Data

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Abstract

This paper presents the validation of a polychromatic method of spectral response measurement applied to full size mono-crystalline silicon photovoltaic modules using outdoor measured data. The difference between short-circuit current modelled from the measured spectral response and outdoor spectral irradiance and the directly-measured current is below 5% which confirms the validity of the spectral response curve obtained using the polychromatic measurement method.

Introduction

Energy yield prediction of photovoltaic (PV) devices is important in order to design a PV system that can deliver maximum energy at specific location. For this, information about the characteristics of the device and meteorological data from the site are necessary. Depending on the material, generation of power in response to the incident spectral irradiance varies from one PV device to another. Therefore, it is important to know the spectral response characteristic of the device to evaluate energy yield estimation and even for making accurate spectral mismatch corrections for power rating at Standard Test Conditions.

To date, there are very few reports available on the indoor spectral response measurement of a full size PV module using filter based monochromatic methods in a flasher system, because it is very challenging to achieve accuracy due to the high uncertainties in measurement, especially those due to low signal strength contributed by the employment of narrowband filters. The polychromatic measurement used here is a unique filter based method that can be applied to measure spectral response characteristics of large PV devices. Instead of narrowband filters, the method employs different broadband filters to create variation of spectral distribution incident on the device under test (DUT) while concurrently measuring the generated current. As a result, a relatively larger signal read out can be detected, and uncertainty can be improved. The determination of spectral response by this method is done by numerical modelling based on the measurements of spectral irradiance and current.

The feasibility of this method has been demonstrated previously, where the modelled spectral response of small-area PV devices of different technologies showed a good agreement in comparison to the spectral response curves determined via a standard monochromatic method, within ±5% difference [1]. In this work, the polychromatic measurement method is applied to a full size PV module. Due to the high uncertainties in measurement of the spectral response characteristic monochromatically at such large areas, the validation of the polychromatic method is performed indirectly by comparison of short-circuit currents measured outdoors under a range of different natural spectra to those modelled with the spectral response characteristic determined indoors with the polychromatic method.

Polychromatic spectral response measurement

The modelling of a spectral response curve of PV device by polychromatic method is carried out in two steps: optical/electrical measurement and numerical fitting. These are described in the following. The PV module measured in this work is of mono-crystalline silicon, with dimensions 1.6m×0.8m.

Spectra and current measurement

Measurement of current-voltage (I-V) characteristics of full size PV modules using a flash type solar simulator is common in the PV industry and in research laboratories. In such a system, the uniformity of the projected light across the measurement plane is high, to meet simulator classification. For the Pasan 3b simulator as used at CREST, the non-uniformity is less than 2% over a measurement area of 2m×2m. The system is equipped with a filter cassette to house up to 20 filters and a filter shifting system adjacent to the main light source. This projects a uniform light across the measurement plane at 8m distance.

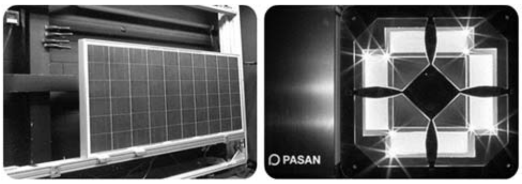

Fig. 1 Image of light bulbs (right) and measurement rig (left) of the solar simulator used.

A set of broadband filters have been selected for maximum variation in spectra, based on their transmission profiles. As can be seen in Fig. 2, the wavelengths of the cut-off type filters are evenly distributed across the wavelength range. These are supplemented with a smaller number of visible band colour filters. Most of the filters are made of cost-friendly thermoplastic material. This gives an economical advantage over the monochromatic filter based measurement method which requires a set of costly narrowband/interference filters to ensure a good quality measurements.

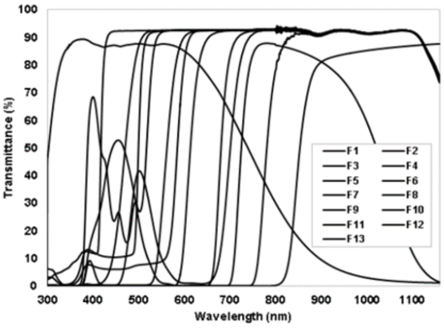

Fig. 2 Transmission profile of the broadband filters.

An AvaSpec-UL (Avantes) spectrometer is positioned in the measurement plane, with the optical input aligned with the DUT to measure incident spectral irradiance. Time delay issues (rise of flash pulse intensity and detector triggering) have been raised in a few reports as one of the major uncertainty contributions in spectral measurement of short-pulse light sources [2]. The unit used here however is triggered optically on the rising pulse edge, with a delay to acquire the spectrum during the same period as the I-V curve sweep. Fig. 3 illustrates the measured spectral irradiance of the Pasan spectral irradiance distribution transmitted through the broadband filters.

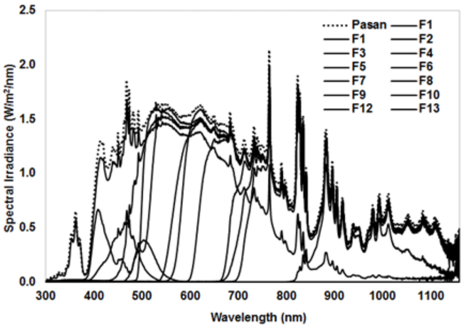

Fig. 3 Spectral irradiance distributions used for spectral response determination, measured by Avantes spectrometer.

The measured incident spectral irradiance of each filter and corresponding short-circuit current generated by the DUT are organised as shown in Table 1 below.

λ nm	F1 $Wm^{-2}nm^{-1}$	F2 $Wm^{-2}nm^{-1}$	…	F13 $Wm^{-2}nm^{-1}$
257	0	0	…	0
304	0.0029	0.0034	…	0.0012
…	…	…	…	…
1176	0.0168	0.0434	…	0.0819
I_{sc} (A)	5.5234	4.3188	…	1.0564

Table 1 Example of tabulated data of measured irradiance spectra and currents (each column is a different spectrum, each row a different wavelength).

Fitting algorithm

The determination of spectral response in this work utilises a Levenberg-Marquardt (LM) fitting tool to optimise the parameters of a Gaussian summation model of the device spectral response. The Gaussian model and measured irradiance spectra are used together to model a set of short-circuit currents (one for each different spectrum). The error between the measured short-circuit currents and the modelled ones is evaluated as a sum of the squared differences and the LM tool is used to minimise this. The calculation of short-circuit current can be made using equation (Eq. 1) below:

$$I_{sc} = A \cdot \int_{\lambda_{min}}^{\lambda_{max}} SR_{\lambda} \times E_{\lambda} \cdot d_{\lambda} \qquad \text{(Eq. 1)}$$

Where A is the area of the PV device (or cell in the case of a series-connected string), SR_λ is the spectral response characteristic, and E_λ is the incident spectral irradiance. To model current values, SR_λ in Eq. 1 is replaced with a Gaussian sum model (the 'SR model' from here onwards) as per (Eq. 2). E_λ is filled with measured spectral irradiance data.

$$SR_{mod} = \sum_{i=1}^{N} a_i \cdot exp\left[\frac{-(\lambda - b_i)^2}{2{c_i}^2}\right] \qquad \text{(Eq. 2)}$$

The LM fitting tool iteratively minimises the error between measured and modelled currents (Fig. 4).

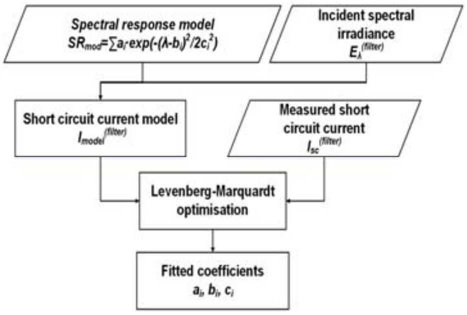

Fig. 4 Simplified flow chart illustrating the process of the fitting algorithm.

This fitting algorithm is applied to spectra and current measurement data taken to model the spectral response curve. An additional algorithm to find a reasonable set of starting values is also applied before executing the main LM fitting tool, to ensure that the tool works reliably. Fig. 5 shows the result of modelled currents and its comparison with respective measured currents generated by the DUT for the different optical filters. The figure shows that the difference between the two falls in a relatively small band, ±2%.

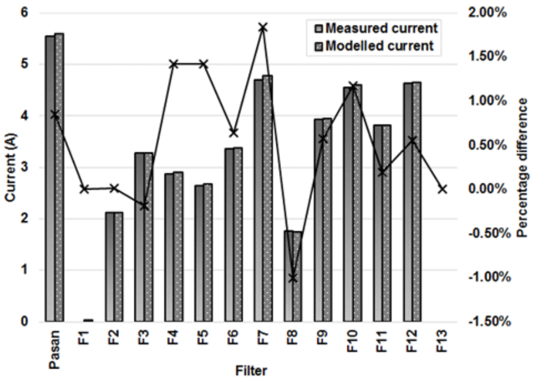

Fig. 5 Comparison of measured and modelled currents of the DUT under each filtered spectrum.

The final result of the modelled spectral response when plotted using the fitted parameters output by the LM fitting tool is illustrated in Fig. 6.

The modelled spectral response curve indicates that the DUT is most responsive in the near infrared, which is sensible since it is made from mono-crystalline silicon material. It also has a relatively similar shape to the monochromatically measured spectral response curve of the device of same technology (different size) which qualitatively confirms its validity.

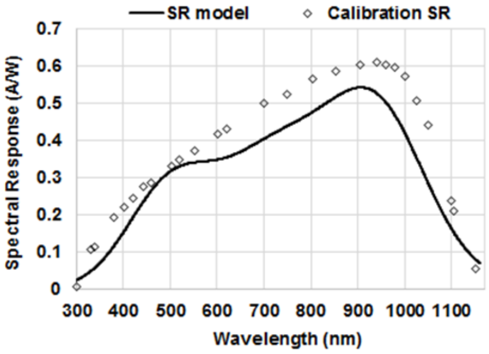

Fig. 6 Spectral response model curve plotted using final determined fitted parameters.

Validation of modelled spectral response

It is difficult to spectrally characterise a full size PV module due to requiring extremely high power light sources to enable monochromatic separation. Even then, with single-pulse type sources (as are the majority of solar simulators at this scale) one cannot employ standard techniques for extracting information from low signal-to-noise measurements (eg: phase locked loops) [3].

On account of this, the validation of the polychromatically-determined spectral response is performed by means of short-circuit current comparison (modelled from the spectral response and actual measurements) of a module of the same manufacturer, model number and production batch monitored outdoors with spectral irradiance measurements.

<u>Outdoor data measurement</u>

Fig. 7 Outdoor PV performance and meteorological data monitoring system.

The outdoor PV module performance monitoring site at CREST is equipped with pyranometers and spectrometers to record the meteorological conditions experienced by the modules. All the modules and detectors used for this work are fixed on a rack with 35° inclination, facing south.

Fig. 8 illustrates the inclined irradiance shift throughout one cloudy day

(27/02/2016), recorded by the pyranometer. The maximum irradiance of the day is recorded at around mid-day, when the solar zenith angle is small, despite the relatively intense cloud cover condition (high irradiance fluctuation).

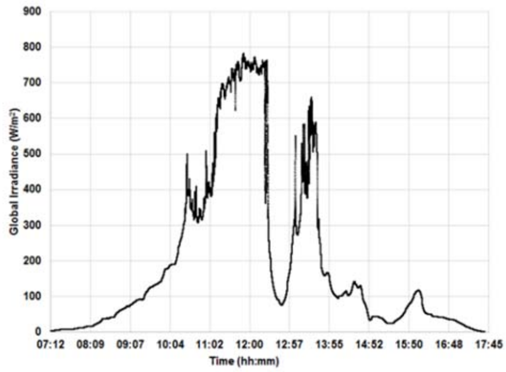

Fig. 8 Inclined irradiance shift over different meteorological conditions for a day.

For this validation work, 3 set of spectral distributions at 3 different conditions of the day (as presented in Table 2) are selected by looking at Fig. 8, to be used for short-circuit current modelling.

Time	Condition
11:02	Low irradiance, mild cloud cover
12:00	High irradiance, mild cloud cover
13:55	Low irradiance, heavy cloud cover

Table 2 3 selected points of the day and description of its meteorological condition.

Outdoor spectral irradiance is recorded by an EKO MS700 spectrometer every minute within a 350nm-1050nm wavelength range. Fig. 9 shows the inclined spectral irradiance of the selected conditions, as measured by EKO.

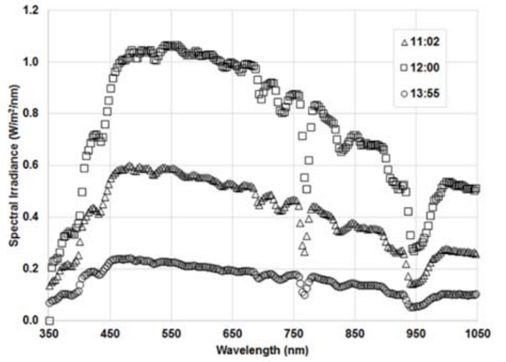

Fig. 9 Variation of spectral irradiance distribution measured by EKO MS700 at different conditions.

Current calculation and comparison

Eq. 1 is again used to calculate the current at the 3 selected conditions. In this case, spectral data recorded by the EKO is substituted for E_λ, and the polychromatic spectral response for SR_λ. Short-circuit current measurements of the PV module under these conditions are extracted from the monitoring data and compared with the respective modelled currents. The result for this is shown in Fig. 10.

The overall difference between modelled and measured currents is below 5%. The highest difference is observed at the time of the lowest current generation, which is reasonable since low signal contributes to higher uncertainty in the spectral measurements.

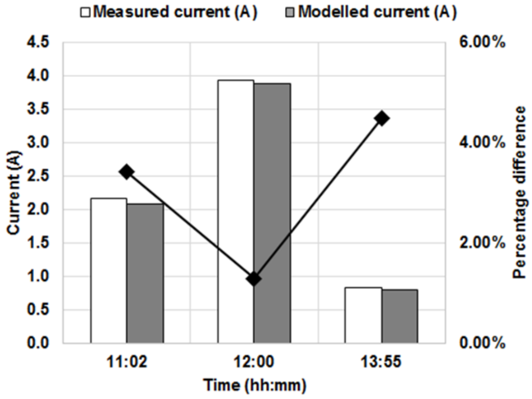

Fig. 10 Comparison of short-circuit currents measured outdoors and modelled using the polychromatic spectral response and measured spectral irradiance under different conditions.

Conclusions

The spectral response curve of a 1.6m×0.8m full size mono-crystalline silicon PV module has been determined using the polychromatic measurement method. The spectral response curve has been validated by comparison to actual currents recorded under 3 different outdoor conditions. The comparison between the two exhibits differences below 5%. The following step for this work is to perform a thorough uncertainty analysis on the method.

Acknowledgements

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References

[1] H. Alhusna, A. Smith, M. Krawczynski, T. Betts and R. Gottschalg, “Spectral Response Measurements of Photovoltaic Devices using a Pulsed Source Solar Simulator,” in PVSAT-11, Leeds, 2015.

[2] F. Schubert, K. Klameth, S. Darou and D. Spinner, “Meausurement uncertainties of a compact array spectrometer,” Energy Procedia, vol. 77 (2015), pp. 179-186, 2015.

[3] “Measurement of spectral responsivity of a photovoltaic device (Part 8),” IEC 60904-8, 2014.