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# Characterization of Simulator and Relative Spectral Responsivity Measurements of Photovoltaic Modules with Band Pass Filter Technique

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## Abstract

One of the most important parameter used for the evaluation of the energy rating of PV modules is, their spectral responsivities which are the measure of electrical performance parameters per incident solar radiation. In this work, spectral responsivity measurements of a mono-crystalline, a poly-crystalline, a CIGS thin film and a bifacial module were measured using xenon-based flash type solar simulator system and a set of band pass filters. For the comprehensive characterization of parameters that may influence the spectral responsivity measurements, initially the simulator system was characterized both optically and thermally according to the IEC60904-9 and IEC60891 standard requirements. The optical characterizations in terms of spectral match, spatial non-uniformity and temporal instability indicate that the measured results (~3.0%, ~0.30% and ~0.20%) according to the IEC 60904-9 standard's classification requirements correspond to A+A+A+ classes. Moreover, thermal characterizations in terms of the temperature uniformity show that over the 2 × 2 m area temperature uniformity of simulator system's light distribution (1˚C) is almost two times better than the IEC 60891 standard requirements (±2˚C). Next, PV modules were electrically stabilized according to the IEC 61215-2 standard requirement's (stability test) to reduce the fluctuations in their electrical performance parameters. Then, using the band pass filters, temperature controlled xenon-based solar simulator system and a reference PV module of the spectral responsivity of PV modules were measured from 400 nm to 1100 nm with 50 nm steps with relative uncertainty of $10^{-3}$ level.

## Keywords

Photovoltaic Modules, Responsivity, Solar Simulator, Band Pass Filters

## 1. Introduction

In general, electrical performance parameters (short-circuit current, $I_{sc}$; open-circuit voltage, $V_{oc}$; maximum power, $P_{max}$) of PV modules are determined at Standard Test Conditions (STC) so as to ensure their standardization. In IEC TS 61836 standard, the STC is defined as 1000 $Wm^{-2}$ irradiance, 25˚C device temperature and AM1.5 spectral irradiance distribution [1]. However, PV modules in real applications can be exposed to wide range of environmental conditions. Therefore, for the evaluation of the efficiencies of PV modules in real applications the measurements should be done according to these parameters. Contributions of these parameters of the real conditions to the efficiencies of PV modules have been studied by several authors [2]. It has been stated that the temperature-irradiance matrix, the operating temperature, the spectral responsivity and the angle of incidence are the main parameters affecting the energy rating of PV modules [3] [4].

Due to the geographic locations and seasons the solar spectra can be different from AM1.5 spectra, angle of incidence of solar radiation, wind speed; environmental temperature can be different from STC. Besides these factors, the sensitive wavelength regions of PV modules may not coincide with these spectra due to the variation of spectra on different geographic locations and seasons, and response of PV modules to the incident solar spectra due to these possible environmental conditions being different. Therefore, for the energy rating the measurements of PV modules have to be performed taking these realistic conditions into account. There have been many works on characterizations of PV modules at realistic conditions so as to evaluate energy rating according to the IEC 61853 standard [5]. Here in this work, our aim is to perform the spectral responsivity component of energy rating measurements correctly in the laboratory and to investigate the effects of the optical and thermal properties of the solar simulator on it.

The responsivity of PV modules is the measure of amount of current produced at any given spectral irradiance. The responsivity can be obtained by irradiating PV devices by means of a narrow-bandwidth light source at a series of different wavelengths covering its response range, and measuring the short circuit current and irradiance at each of these wavelengths [6]. There are different methods for the measurements of spectral responsivities of PV devices [7] [8] [9] [10]. One of these methods as studied in this work is the measurement method using pulse type solar simulator together with band pass filters provided that both solar simulator and band pass filters have to meet some requirements. The requirements in terms of simulator system briefly are; a solar simulator system to be used for irradiating the PV modules and measuring their electrical performance parameters must be calibrated with a reference PV device whose short-circuit current versus irradiance has to be determined in accordance with IEC 60904-2 standard requirements [11]. Besides these, the solar simulator system also has to fulfill the IEC 60904-9 standard's requirements of spectral match, spatial non-uniformity of irradiance and temporal instability [12].

On the other hand the requirements in terms of band pass filters are; the band pass filters used for selectable spectral irradiance should contain a sufficient number of narrow-band filters to cover whole response range of the PV device in wavelength steps not exceeding 50 nm [13]. Moreover, the band pass filters must not affect the spatial non-uniformity of irradiance distribution. This is crucially important when the reference and test devices have different dimensions. Therefore, due to these mentioned requirements the steps to be followed for the measurements of the spectral responsivities of PV modules using simulator system and band pass filters can be listed as; optical and thermal characterizations of the simulator system and band pass filters in accordance with the IEC60904-9 and IEC60891 standard requirements [12] [14], electrical stabilizations of the PV modules under test according to the IEC 61215-2 standard requirements [15] and the spectral responsivity measurements of PV modules under the test.

## 2. Methodology

### 2.1. Optical and Thermal Characterization of Solar Simulator

The PV modules are in general used at outdoor to convert solar radiation into electrical energy. Therefore, the light sources that are used to determine the electrical performance parameters of the PV modules in the indoor must have similar behavior as solar energy. In other words, the irradiance's spectral distribution, spatial homogeneity and instability of light sources have to be as close as to those of the solar radiation on the earth. For this purpose the devices that could simulate these behaviors have been developed and used. These devices are called solar simulators. In order to standardize the solar simulators the standardization bodies have defined a number of conditions for the simulators irradiance spectral distribution, spatial homogeneity and instability. Depending on the ability to meet these conditions, simulators are classified as class A, B and C simulators [12]. The accuracy of the electrical performance parameters of PV modules can clearly vary depending on the class of simulator used. Besides this, since the PV modules made from semiconductor devices, they are also sensitive to temperature. For these reasons, in order to accurately determine the electrical performance parameters of the PV modules the initial step is to make both the optical and thermal characterizations of the simulator in terms of spectral distribution, spatial non uniformity, instability of irradiance of simulator's light source at the PV module holder site and temperature non uniformity on the PV module.

### 2.2. Determination of Spectral Distribution of Solar Simulator

The measurement of spectral distribution of solar simulator (**Figure 1**) is needed to be done so as to check how closely the spectral irradiance of simulator matches with that of solar energy. In this work, the measurement system used for this purpose consists of solar simulator, a spectroradiometer, incidence

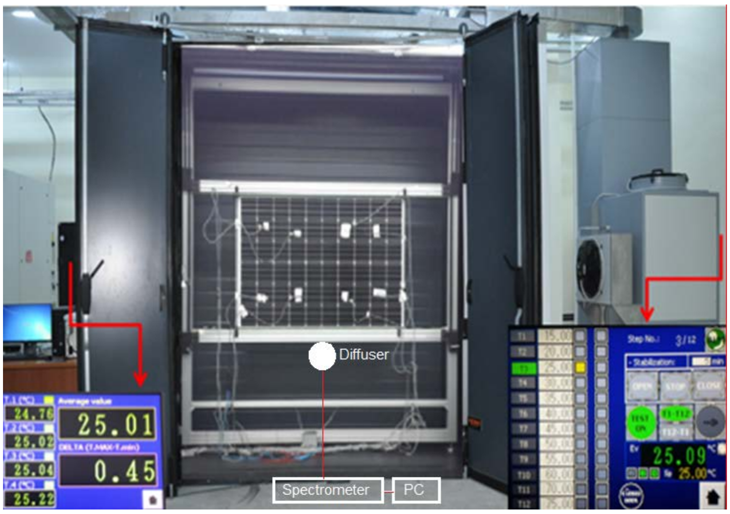


**Figure 1.** Thermal chamber integrated solar simulator system.

optics and software. The solar simulator is a xenon light source based, pulse type simulator with 10 ms pulse widths; the spectroradiometer is an array type spectrometer has 300 nm - 1100 nm wavelength range, 5 nm band width and 1 - 1000 ms exposure time; the incidence optics has perfect reflecting diffuser and optical fiber; and the software can evaluate spectral irradiance and the spectral match. Before the measurements, the solar simulator system was calibrated using the reference PV cell (2 × 2 cm) which is traceable to PTB DSR measurement system and calibrations of the other components (irradiance, wavelength and diffuse reflectance) of this system were performed as traceable to TÜBİTAK UME Optics Laboratory. Then the spectral match measurement system was established as shown in **Figure 1**. The measurements were performed for both 200 $Wm^{-2}$ and 1000 $Wm^{-2}$ irradiance levels. At each irradiance level, the radiation from solar simulator incident on the perfect diffuser where a portion of the reflecting rays fall on the optical fiber, which was placed slightly opposite to the diffuser surface, transmits these rays to the spectroradiometer. The spectroradiometer dispersed this light beams into wavelengths within 300 nm - 1100 nm wavelength interval with 5 nm band width. Then with the software, spectral irradiance and from which the spectral matches were evaluated respectively as vary from 0.95 to 1.08 for 200 $Wm^{-2}$ and 0.99 to 1.06 for 1000 $Wm^{-2}$ irradiance level (**Figure 2** and **Figure 3**). Comparing these spectral match intervals with the IEC 60904-9 standard requirements [12], this simulator's spectral matches corresponds to A+ simulator spectral match interval (0.875 to 1.125) (**Figure 4** and **Figure 5**).

### 2.3. Determination of Spatial Non-Uniformity of Solar Simulator

PV modules consist of series combinations of PV cells which almost have equivalent efficiencies. Therefore, the electrical performance of the PV cell determines the total performances of PV modules. In order to get almost equal contributions from all cells, it is necessary to irradiate all the cells equally. To accomplish

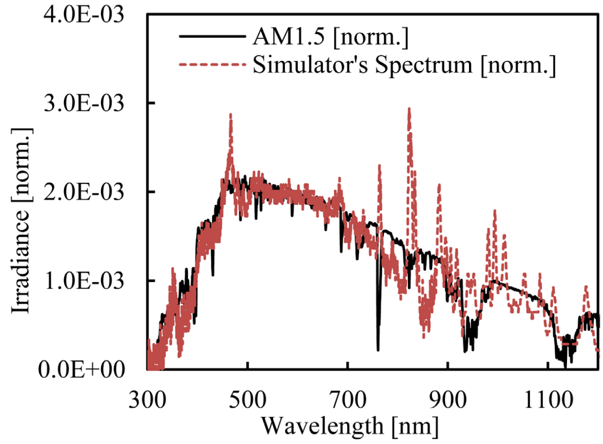


**Figure 2.** Spectral distribution of simulator versus AM1.5 at 1000 $Wm^{-2}$.

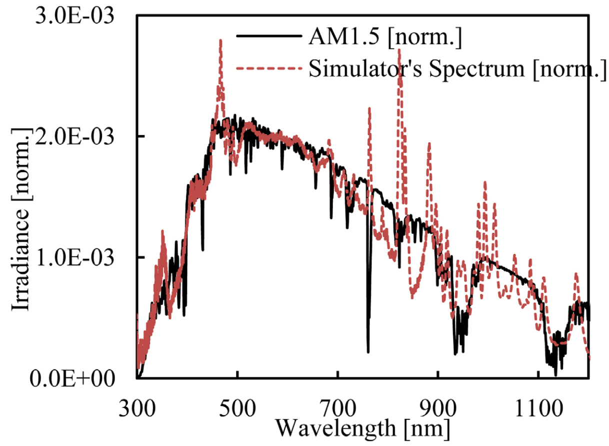


**Figure 3.** Spectral distribution of simulator versus AM1.5 at 200 $Wm^{-2}$.

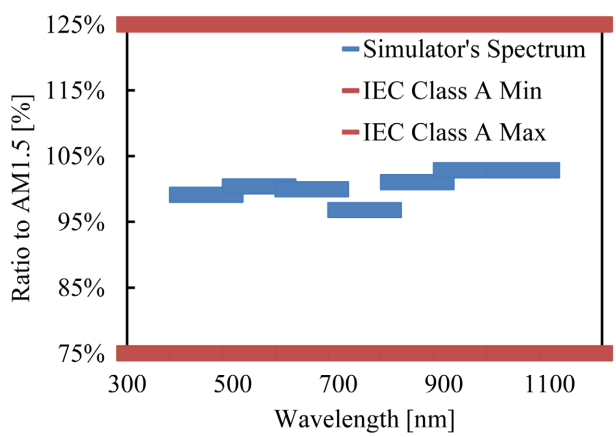


**Figure 4.** Evaluation of the simulator's spectrum versus AM1.5 at 1000 $Wm^{-2}$.

this, the solar simulators should have acceptable spatial distribution of the irradiation on whole active area of PV modules. The solar simulator used in this work

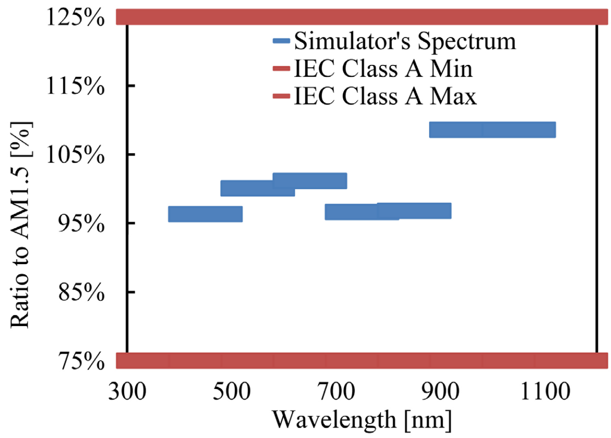


**Figure 5.** Evaluation of the simulator's spectrum versus AM1.5 at 200 $Wm^{-2}$.

is xenon light source based, pulse type simulator. In order to measure the spatial distribution of light sources of this simulator at the module holder site, an irradiated area of 2 × 2 m was divided into 64 identical parts as described in IEC 60904-9 standard [12]. Moreover, for this measurement specially designed 16 × 16 cm PV cell also was used. The output connectors and cables of this cell were designed in the same way as the PV modules and can be connected to the simulator's electronic system. Then the measurements were carried out by moving the PV cell to all 64 identical parts, irradiating with the simulator and recording the performance parameters. From the recorded values, using (1) [12] and the method described in IEC 60904-9 standard the spatial non uniformities of solar simulator was evaluated (Figure 6 and Figure 7). The non-uniformities were obtained at 200 $Wm^{-2}$ and 1000 $Wm^{-2}$ irradiance levels over 2 × 2 m area are 0.59% and 0.34% respectively. These non-uniformities are lower than the value of A+ simulators according to the IEC standard requirements.

$$\text{Nonuniformity} = 100 * \left[ (\text{Max Irr.} - \text{Min Irr.}) / (\text{Max Irr.} + \text{Min Irr.}) \right] \tag{1}$$

where Max Irr., and Min Irr., are respectively maximum and minimum irradiance values were measured with 16 × 16 cm PV cell.

### 2.4. Determination of Temporal Instability of Solar Simulator

The temporal instability of xenon based flash type solar simulator was measured according to IEC 60904-9 standard requirements [12]. As it was described in the standard, there are two types of instabilities; short term instability (STI) and long term instability (LTI). The STI relates to the data sampling time of a data set (irradiance, current, voltage) during an I-V measurement and it was determined from the worst case data sets on the I-V curve. On the other hand LTI related to the time period for taking the entire I-V curve. Both STI and LTI were evaluated using the maximum and minimum irradiance values and the relation given in (2) [12]. The measured values shown in Figure 8 and Figure 9 for STI (<0.25%) and LTI (<1.0%) indicate that the temporal instabilities of xenon based

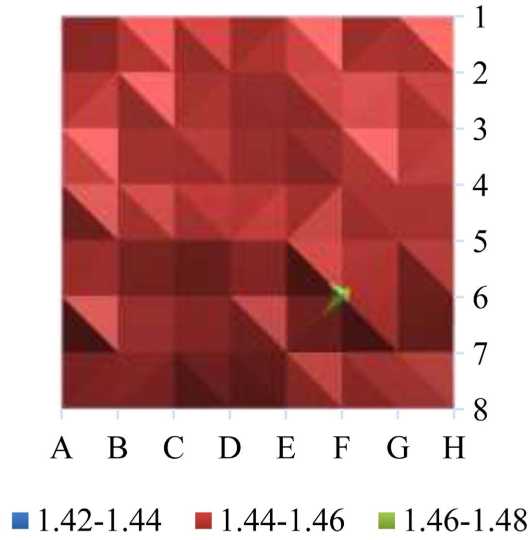


**Figure 6.** Non uniformity measurement of solar simulator as a function of irradiance at 1000 $Wm^{-2}$.

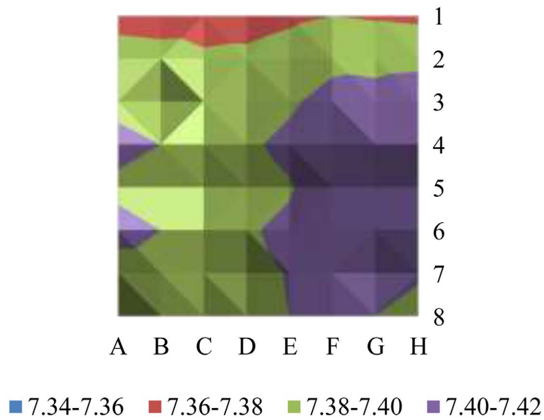


**Figure 7.** Non uniformity measurement of solar simulator as a function of irradiance at 200 $Wm^{-2}$.

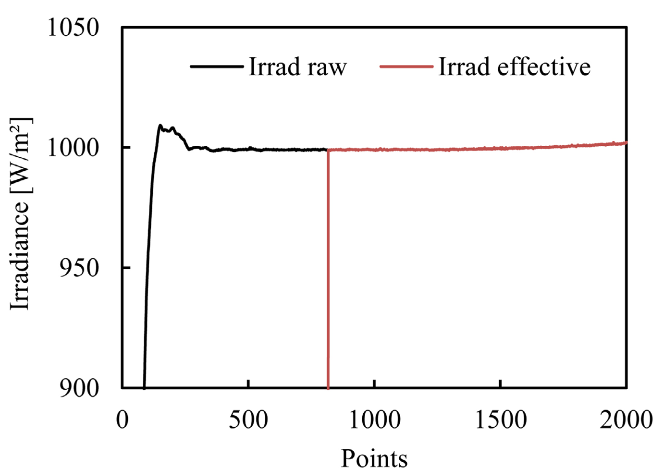


**Figure 8.** Temporal instabilities of solar simulator regulated by optical sensor.

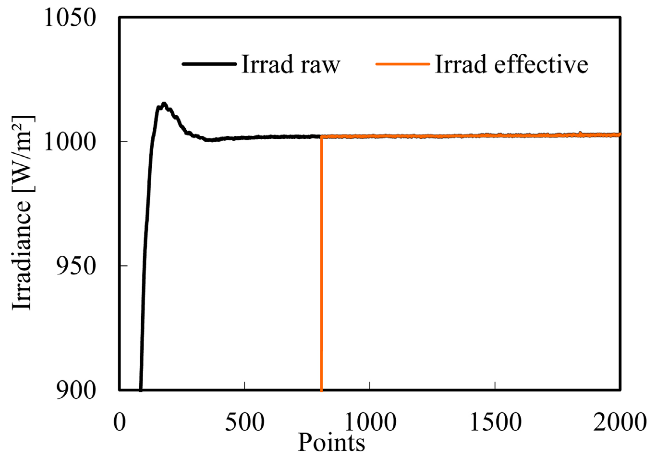


**Figure 9.** Temporal instabilities of solar simulator regulated by control cell.

flash type solar simulator used in this work are better than the IEC60914-9 standard requirements for class A simulator.

$$\text{Temporal Instability} = 100 * \left[ \left( \text{Max Irr.} - \text{Min Irr.} \right) / \left( \text{Max Irr.} + \text{Min Irr.} \right) \right] \quad (2)$$

where Max Irr., and Min Irr., are respectively maximum and minimum irradiance values were measured with 16 × 16 cm PV cell.

## 2.5. Determination of Temperature Non-Uniformity of Solar Simulator

In general PV modules constitute series combinations of PV cells. So, in order to get nearly same contribution from each cell to the module's performances, besides the homogeneous irradiation of all the cells the homogeneous distribution of the temperature is also critical parameter. Since the solar simulator used in this work for the irradiation of PV modules is a pulse type simulator with short pulse duration (10 ms) it has a quite low heating effect. However, the variations in the laboratory conditions may cause the temperature to exceed the limits (25˚C ± 2˚C) specified in STC. To keep modules at these limits during the measurements thermal chamber integrated to simulator was used. The thermal chamber both can heat/cool the modules from 15˚C to 75˚C and also at each temperature level can create a homogeneous temperature distribution over the entire surfaces modules. To record the temperature distribution of PV modules, totally eight (8) temperature sensors were mounted to their back sides, directly behind the cells. Each temperature sensor has ±1˚C accuracy and ±0.5˚C repeatability. Then, using (3) the temperature set to 25˚C and the temperature from each sensor was recorded to check the temperature nun-uniformity.

$$\text{Temperature Nonuniformity} = \left( T_{\max} - T_{\min} \right) / \left( T_{\max} + T_{\min} \right) \quad (3)$$

where $T_{\max}$ and $T_{\min}$ are respectively maximum and minimum temperature values.

As shown in **Table 1** the temperature non uniformity of less than ±1˚C, over

**Table 1.** Temperature distribution over the whole back surface of PV module.

| T1 (˚C) | T2 (˚C) | T3 (˚C) | T4 (˚C) | T5 (˚C) | T6 (˚C) | T7 (˚C) | T8 (˚C) | $\frac{T_{max} - T_{min}}{T_{max} + T_{min}}$ |
|---|---|---|---|---|---|---|---|---|
| 25.04 | 25.01 | 24.95 | 25.01 | 24.98 | 25.02 | 24.98 | 25.02 | 0.02 |

the module area was obtained, which is almost two times better that the IEC 60891 standard requirements (±2˚C) [14].

## 2.6. Transmittance Measurements of Band Pass Filters

In order to separate the polychromatic light into wavelengths or simply select the light in the desired band range, the band-pass filters were used. In this work, each having a bandwidth of 50 nm totally 15 band-pass filters were used. The important parameters to be considered when using these filters are the temperature-dependent transmittance of the filters, the homogeneity of light on the PV module and linearity of the PV module at low light level. These band-pass filters have 30 × 30 cm dimensions and for measurements they were placed to the sample holder constructed for these filters at just in front of the light source of the simulator system. The fan in the sample holder prevents the heat generated by the operation of the chamber of the light source. Also, since the laboratory temperature was set to 25˚C no temperature dependent changes were observed in the measurements. The measurements related to the linearity of the simulator system between 80 $Wm^{-2}$ and 1000 $Wm^{-2}$ irradiance levels according to the requirements of IEC 60904-10 standard [16] and also the homogeneity measurements at each irradiance level according to the requirements of IEC60904-9 standard [12] indicate that at the transmittance levels of these bands pass filters both the homogeneity and linearity still meet related standard requirements.

The total transmittance values of the band pass filters in the specified band intervals were measured in the simulator system. In the measurements, firstly when band pass filters were not attached to the filter holder of the simulator, the solar simulator system was adjusted to give 1000 $Wm^{-2}$ irradiance via measuring the short circuit current value produced by the PV device in the sample holder of the simulator. Then, the band pass filters respectively were placed in the filter holder of the simulator and the short circuit current produced by the PV device were measured again. Taking the ratio of the measurement results obtained with and without filters the transmittance values of filters were obtained as given in **Table 2**.

## 2.7. Stabilizations of PV Modules

Since the PV modules made from semiconductor materials they may be electrically unstable due to possibility of defects in their internal structures after production. The spectral responsivities of PV modules are the measure of electrical parameters (current, voltage) created per incident radiation. Therefore, in order to accurately determine the spectral responsivities of PV modules it is necessary

**Table 2.** Transmittance values of band pass filters.

| $\lambda$ (nm) | $T$ (%) | $\lambda$ (nm) | $T$ (%) |
|---|---|---|---|
| 400 | 3.2 | 800 | 7.4 |
| 450 | 5.8 | 850 | 6.0 |
| 500 | 7.6 | 900 | 6.9 |
| 550 | 8.9 | 950 | 4.9 |
| 600 | 8.9 | 1000 | 5.6 |
| 650 | 9.6 | 1050 | 2.1 |
| 700 | 9.2 | 1100 | 1.1 |
| 750 | 8.6 | | |

to electrically stabilize them before the measurements. Stabilization of PV modules was done in the stabilization system shown in the **Figure 10**. This system according to the requirements of IEC 60904-9 standard corresponds to CBC class simulator which already meets the IEC 61215-2 standard requirements [3]. For the stabilization the PV modules separately replaced inside the system and the irradiance level using the reference cell was adjusted to 1000 $Wm^{-2}$. For the PV modules having different technologies the mismatch correction was applied to get the right irradiance. Then, in this system PV modules successively exposed to the defined irradiation (10 $kW\cdot hm^{-2}$) and their maximum powers were measured until the stable output power level reached according to the (4).

$$\left(P_{\max} - P_{\min}\right)/P_{av} < x \quad (4)$$

where $P_{\max}$ and $P_{\min}$ are respectively maximum and minimum power values and $x$ is the values of PV modules defined in related technology specific parts of IEC 61215 [13] [17] [18] [19] [20].

## 2.8. Spectral Responsivity Measurements of PV Modules

The spectral responsivities of PV modules are the measure of electrical parameters (current, voltage) created per incident solar radiation. It is known that solar radiation reach on the earth surface mainly constitute UV, VIS and NIR radiations. The radiation levels in these regions are approximately 5% UV, 45% VIS and 50% NIR and these regions form the standard AM1.5 spectrum. Factors affecting the efficient conversion of incident solar radiation into electrical parameters are the sensitive wavelength range and sensitivity coefficients of the PV modules, and the AM1.5 spectrum distribution of incident solar radiation and the irradiation level in this distribution. However, all the types of PV modules do not have same sensitive wavelength region and their electrical performance parameters besides the spectrum and irradiance level depends also on angle of incidence of the solar radiation, wind-speed and ambient temperature. Also, the AM1.5 spectrum distribution and total radiation level in the spectrum vary according to geographic location and seasons. Therefore, for the energy rating in


**Figure 10.** PV module electrical stabilization system.

addition to the knowledge of spectral responsivities of PV modules, the knowledge of the effects of the possible environmental factors on responsivity due geographic location and seasons are also needed.

Since our the aim in this work is to perform spectral responsivity measurements correctly in the laboratory and to investigate the effects of the optical and thermal properties of the solar simulator used in the measurements on spectral responsivity, the effects of mentioned environmental factors on responsivity will not be included.

After all the characterizations described above, the spectral responsivity measurements of a monocrystalline, a polycrystalline, a CIGS thin film and a bifacial PV modules were performed taking into account the requirements of IEC 60904-8 standard [15] using the measurement system shown in **Figure 1**. For the measurements, as it was totally 15 bands pass filters were used in order to separate the polychromatic light into bands within the wavelength interval from 400 nm to 1100 nm with 50 nm steps. The critical point using the bandpass filters is the linearity of PV modules at the irradiance levels within the 50 nm bandwidth intervals. As it seen from the **Table 2** the transmittance of filters are low, so the irradiance levels on the PV at the peak wavelengths of bandpass filters range from 10 $m \cdot Wm^{-2}$ to 100 $m \cdot Wm^{-2}$. Therefore, before the responsivity measurements the linearity of PV modules within 10 $m \cdot Wm^{-2}$ to 100 $m \cdot Wm^{-2}$ irradiance range needs to be measured. This irradiance levels were adjusted using a 100 W neutral density filter and a set of mesh grids. The measured $I_{sc}$ - $V_{oc}$ and the evaluated $I_{sc}$ - $G$ (Irradiance) curves of monocrystalline PV modules are shown in **Figure 11** and **Figure 12**.

After the linearity measurements the band-pass filters were placed respectively to the sample holder constructed for them just in front of the light source of the simulator system. Then the spectral responsivities were obtained by measuring the short circuit current at each band pass filter interval for both reference and test PV modules respectively. The reference PV module is the polycrystalline PV

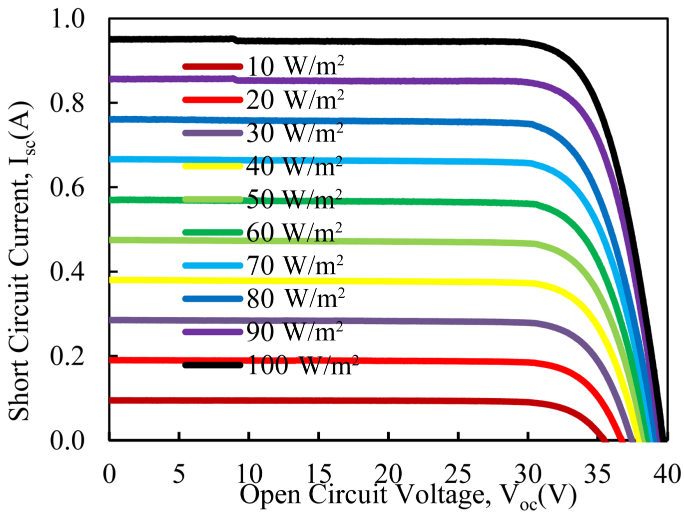


**Figure 11.** $I_{sc}$ - $V_{oc}$ curves of a monocrystalline PV module.

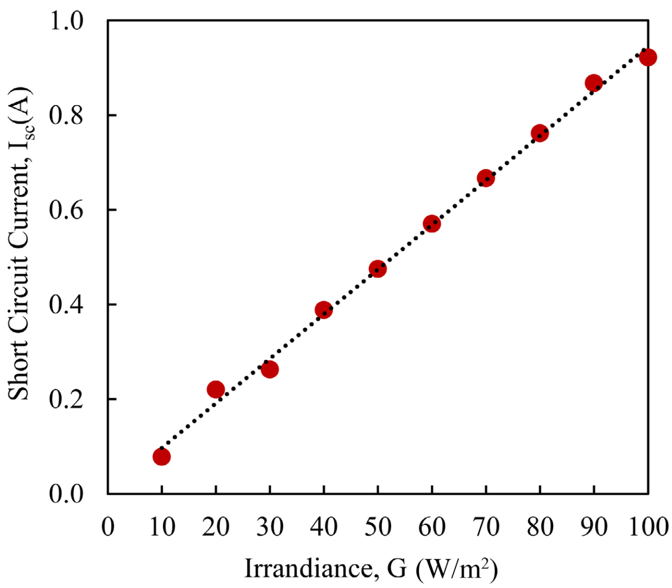


**Figure 12.** $I_{sc}$ - $G$ curves of a monocrystalline PV module.

module which was calibrated as traceable to the Fraunhofer ISE. The measurement results for the spectral responsivity of PV modules are shown in the **Figures 13-18**.

## 3. Results and Discussion

The measurements of the spectral responsivities of PV modules are required for two reasons. First, in order to accurately determine the electrical performance parameters of PV modules. Second, for the energy rating of PV modules in the fields. In the first case, solar simulators are calibrated either with WPVS or reference PV modules. In calibration, the simulator is adjusted to provide 1000 $Wm^{-2}$ irradiance level in the spectral wavelength range of the reference PV module. After the calibration, for the measurements of PV modules having the

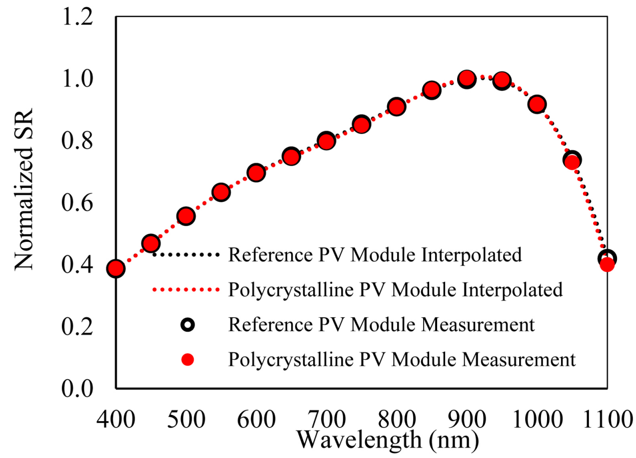


**Figure 13.** Spectral responsivity of polycrystalline PV module.

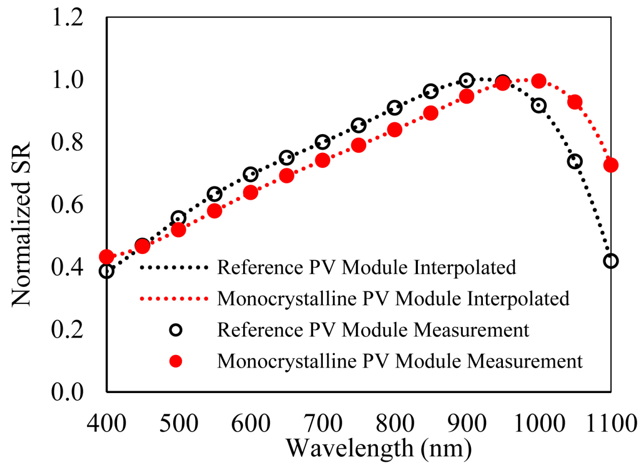


**Figure 14.** Spectral responsivity of monocrystalline PV module.

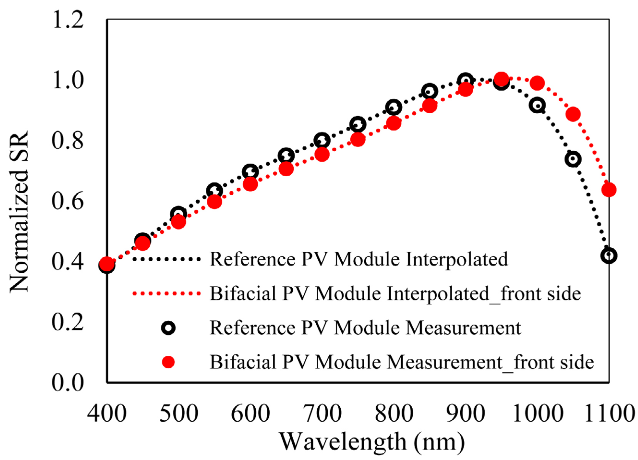


**Figure 15.** Spectral responsivity of bifacial PV module.

technologies different than the reference PV module a mismatch correction factor is required. This is achieved via using spectral responsivities of both reference and test PV modules. This measurement method ensures the measurements

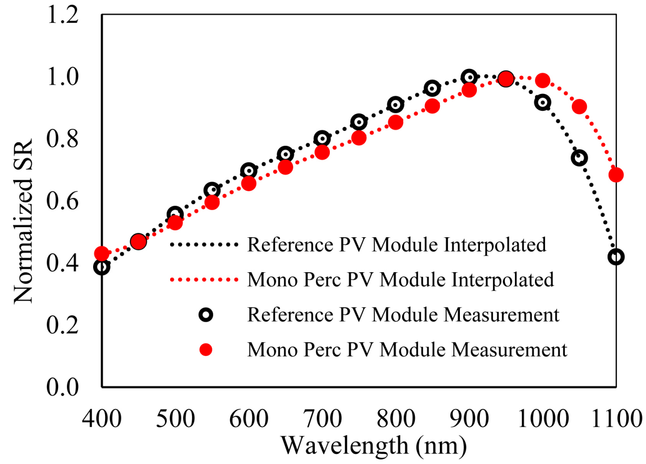


**Figure 16.** Spectral responsivity of MonoPerc PV module.

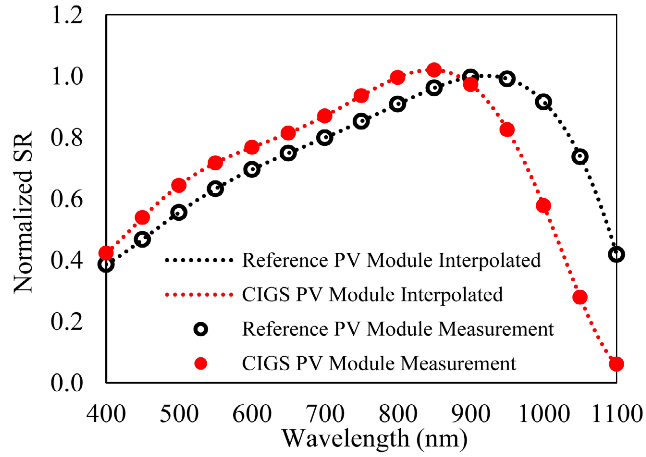


**Figure 17.** Spectral responsivity of CIGS_1 PV module.

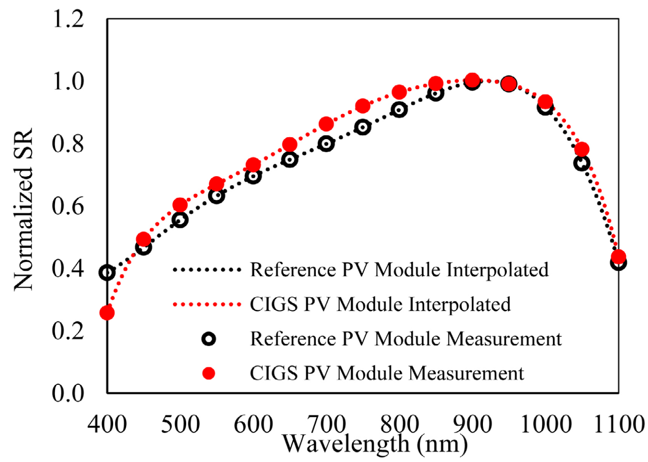


**Figure 18.** Spectral responsivity of CIGS_2 PV module.

of the test PV modules to be carried out more accurately and therefore reduce the measurement uncertainty. Reducing the uncertainty provide a major contribution to reducing financial losses of PV modules.

In the second case, PV modules are measured in laboratory at standard test conditions (STC) which is defined as 1000 W/m$^2$ irradiance, 25˚C device temperature and AM1.5 spectral irradiance distribution.

However, the performances of the PV devices in real applications can be completely different from the performances at STC due to the effects they can be subjected to. Depending on the seasons and geographical locations, PV devices can be exposed to various conditions like wind-speed, ambient temperature; spectrum, irradiance level and angle of incidence of the solar radiation. These conditions have impacts the performance parameters and hence the energy efficiency of PV devices. In order to calculate energy yield correctly, all these parameters need to be determined accurately. The spectral responsivities of PV modules are one of the most important parameter contributing to the energy yield.

Therefore, evaluating the responsiveness of the PV modules measured in this context, since simulator is calibrated with a polycrystalline PV module, the spectral responsivities modules having the same technology matched well with the reference (**Figure 13**). On the other hand, the spectral responsivities modules having different technologies didn't match with the reference (**Figures 13-18**). For the accurate evaluation of electrical performance parameters of these PV modules the mismatch correction factor is needed.

## 4. Conclusions

One of the most important parameter used for the evaluation of the energy rating of PV modules is, their spectral responsivities which are the measure of electrical performance parameters per incident solar radiation. In real applications due to the geographic locations, seasons, etc. the spectra of incident solar radiation can be different from the spectra defined at STC. Therefore, the knowledge of spectral responsivities of PV modules enables the users to evaluate the real application performance of PV modules in accurately. To use in such an application in this work the spectral responsivities of a mono-crystalline, a polycrystalline, a CIGS thin film and a bifacial module were measured with band pass filter technique. The possible factors which have effects on the measurements are; non linearity of PV modules at the irradiance levels within the band pass of filters, electrical non stabilities of PV modules, temperature non uniformities, etc.

The necessary characterizations related to these factors were done and their contribution to the uncertainty was determined with a relative uncertainty of $10^{-3}$ level. This work was realized using band pass filter technique and the measurements were performed at 15 wavelengths. Increasing the number of measurement points will increase the measurement accuracy and decrease the uncertainty, and accordingly, financial losses arising from the measurement uncertainty of the PV panels will decrease.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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