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Temperature-Irradiance Matrix and Determination of Temperature Coefficients of a Monocrystalline PV Module

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Abstract

Photovoltaic (PV) modules performance testing and energy rating as described in IEC 61853-1 standard depend on electrical performance parameters (short-circuit current, open-circuit voltage, maximum-power) of PV modules as a function of temperature and irradiance. In this work, in order to precisely determine the effects of temperature on the electrical parameters of a monocrystalline PV module, the temperature controlled, xenon light based solar simulator system with irradiance attenuating masks was used. This solar simulator, according to the IEC 60904-9 standard in terms of spectral match, spatial non-uniformity and temporal instability has A+A+A+ classes which are two times better than the standard requirements for a solar simulator to be used in PV module measurements. Moreover, the thermal chamber used in this work is a closed type chamber with fast opening door for not allowing the distortion of temperature uniformity over the surface of PV modules under test. Within about 2 m × 2 m area within 15˚C to 75˚C temperature interval, the temperature uniformity obtained for this system is less than 1.0˚C which is almost two times better than the IEC 60891 standard requirements (±2.0˚C). The temperature and irradiance dependent measurements of the electrical performance parameters of a mono-crystalline PV module at various irradiance levels and the evaluation of its temperature coefficients [α (% ˚C^{-1}), β (% ˚C^{-1}) and δ (% ˚C^{-1})] were done by implementing the interpolation method described in IEC 60891 standard.

Keywords

Photovoltaic, Temperature Coefficient, Linearity, Energy Rating

1. Introduction

In general, the 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 Condition (STC) so as to ensure their standardization. In IEC 61836 standard, the STC is defined as 1000 Wm^{-2} irradiance, 25˚C device temperature and AM 1.5 spectral irradiance distribution [1]. However, the performance of the PV modules in real applications can be completely different from their performances at STC due to the possible environmental conditions they can be subjected to [2] [3] [4] [5] [6]. Depending on the seasons and geographical locations, PV devices can be exposed to various parameters like wind-speed, ambient temperature; spectrum, irradiance level and angle of incidence of the solar radiation. There have been many works on investigating the effects of these parameters on performances of PV modules and it has been stated that among the mentioned parameters the temperature is the most effective parameter on the performances of PV modules [7] [8]. Moreover, photovoltaic (PV) modules performance testing and energy rating as described in IEC 61853-1 standard depend on electrical performance parameters of PV modules as a function of temperature [9]. Therefore, in order to evaluate the effects of temperature on the electrical performance parameters of PV modules, the electrical performance parameters obtained at STC should be extrapolated to any temperature via translation equations developed for this purpose as given in (1) [10] [11]. As it is seen from, the extrapolations given in (1), the electrical performance parameters from STC to any temperature require the knowledge of α, β and δ temperature coefficients for short-circuit current, open-circuit voltage and maximum power respectively.

$$\begin{aligned} I_{sc,c} &= I_{sc}\left[1+\alpha\left(T_2-T_1\right)\right] \\ V_{oc,c} &= V_{oc}\left[1+\beta\left(T_2-T_1\right)\right] \\ P_{\max,c} &= P_{\max}\left[1+\delta\left(T_2-T_1\right)\right] \end{aligned} \tag{1}$$

These α, β and δ temperature coefficients are generally defined as the percentage change of the electrical parameters with change in temperature as α (% ˚C^{-1}), β (% ˚C^{-1}) and δ (% ˚C^{-1}). Accurate determination of these temperature coefficients will ensure the right extrapolation of performance parameters obtained from STC to any temperature and therefore lead correct evaluation of energy yield. This is important for the evaluation of energy yield especially in large-scale applications like solar power plants.

These α, β and δ temperature coefficients of PV modules can be determined using solar simulators or natural sunlight by measuring short-circuit current, open-circuit voltage and maximum power parameters under the constant irradiance level and a range of temperatures. The irradiance can be provided by the solar simulators, which are the devices that provide illumination approximating natural sunlight. There are two types of solar simulators can be used as an irradiance source; steady state and flash simulator. Steady state solar simulators as they do continuous irradiation they also provide the required heat for heating the module to measure the temperature dependent performance of the electrical parameters. On the other hand, flash type solar simulators since they have pulse type irradiations with a short pulse durations they have a quite low heating effect. Therefore, a different mechanism is needed to vary the temperature of the PV module to be measured. In this type of solar simulators in general a thermal chamber integrated to solar simulator is needed to be used.

In this work, as a solar simulator xenon light based solar simulator system and to vary the temperature of the PV module the thermal chamber integrated to solar simulator was used. This thermal chamber is a closed type chamber with fast opening door which do not allow the distortion of temperature uniformity over the surface of PV modules under test. For the temperature coefficient measurements, contrary to the most of the works published in the literature for which temperature coefficient measurements have been made at 1000 Wm^{-2} irradiance level, temperature coefficient measurements were realized at 200 Wm^{-2} - 1000 Wm^{-2} irradiance and 15˚C to 75˚C temperature interval. The main motivation for us to make measurements at these intervals is that, according to the standards the temperature coefficient measurements are done at 1000 Wm^{-2} irradiance level, however in the field, depending on the seasons and the changes during a day, PV modules can be exposed to various irradiance and temperatures levels. For the energy rating, according to the IEC 61853-1 standard, considering the possible conditions that the PV modules may encounter in the field, it is necessary to create a temperature irradiance matrix and to carry out measurements under these conditions. The temperature irradiance matrix and related measurements are the most important input for the energy rating. Therefore, in order to accurately make these measurements this work is organized as follows.

At first step, comprehensive optical, electrical and thermal characterization of the measurement system has been done. Then, traceability of all devices used in the measurement system has been ensured. Finally, the temperature dependent electrical performance parameters of PV modules at various irradiance levels were measured and the, β and δ temperature coefficients of PV module were evaluated using interpolation method described in IEC 60891 standard [12] [13].

2. Materials and Methods

2.1. Optical Characterization of Measurement System

Temperature dependent electrical performance parameters of a mono-crystalline PV module was measured using the xenon light source based flash type solar simulator integrated to thermal chamber as shown Figure 1. In order to accurately determine the electrical performance parameters of the PV modules, the initial step is to make optical 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. Then calibrate the simulator with a suitable reference cell.

The measurement of spectral distribution of solar simulator is needed to be

Figure 1. Thermal chamber integrated solar simulator system.

done so as to check how closely the spectral irradiance of simulator matches with that of solar energy. The solar simulator used in this work is xenon light source based, pulse type simulator with 10 ms pulse width. The spectral match of the solar simulator was measured using a set of apparatus consisting of a spectroradiometer, incidence optics and software. 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. The spectral match 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 as seen from the **Figure 2** and **Figure 3**. Comparing these spectral match intervals with the IEC 60904-9 standard requirements [14], this simulator's spectral matches corresponds to A+ simulator spectral match interval (0.875 to 1.125).

The spatial non-uniformity of solar simulator is needed to see whether all the cells of module under test can be irradiated equally or not. 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 [14]. A specially designed 16 × 16 cm PV cell was used for the measurements of irradiance at each part. The measurements were carried

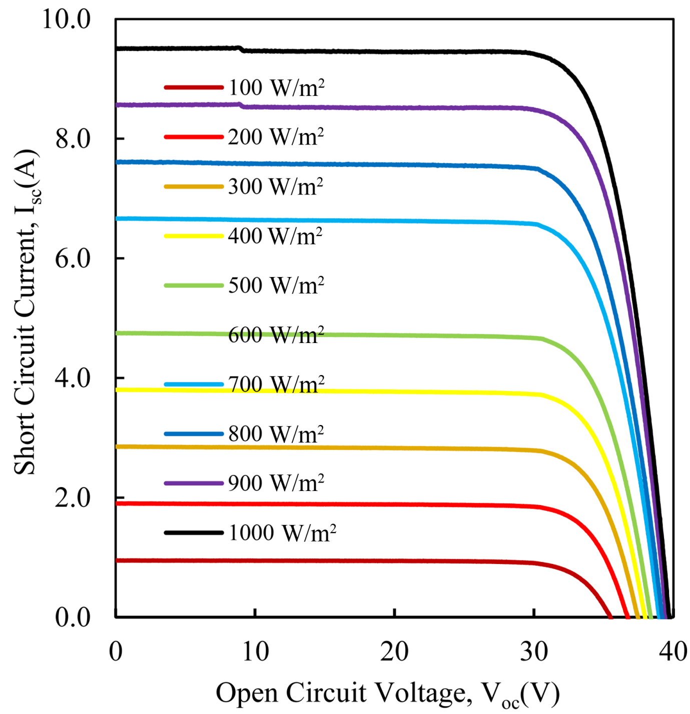

Figure 2. I_{sc}- V_{oc} curves of monocrystalline PV module.

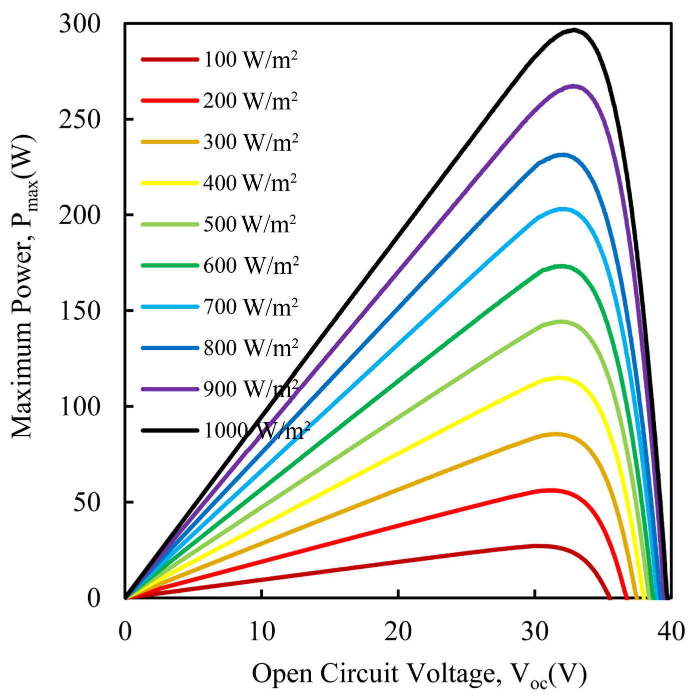

Figure 3. P_{max}- V_{oc} curves of monocrystalline PV module.

out by placing the PV cell to all 64 identical parts respectively, irradiating with the simulator and recording the performance parameters. From the recorded values, using (2) [14] and the method described in IEC 60904-9 standard the spatial non uniformities of solar simulator was evaluated. 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.

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

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

The temporal instability of solar simulator is needed to see the instability level of light source of during the measurements period. According to IEC 60904-9 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 (3). The measured values for STI (<0.25%) and LTI (<1.0%) indicate that the temporal instabilities of xenon based flash type solar simulator used in this work are better than the standard requirements for class A simulator.

$$\text{Temporal Instability} = 100 * \left[(\text{Max Irr.} - \text{Min Irr.}) / (\text{Max Irr.} + \text{Min Irr.}) \right] \quad (3)$$

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

2.2. Characterization of Temperature Non Uniformity of Measurement System

The thermal chamber used in this work is a closed type chamber with fast opening door for not allowing the distortion of temperature uniformity over the surface of PV module under test. This chamber was constructed just in front of solar simulator at the PV module holder site according to the IEC 60891 standard requirements. It mainly consists of a power supply, blowers, an air circulation unit, air flow diffusers, temperature feedback sensors, temperature uniformity control and monitoring units. As it seen from the **Figure 1**, the module holder, which has thermally nonconductive mounting blocks, is located just at the center of this chamber. The air sent via blowers passes through air circulation channel and the diffuser, spreads homogeneously to the PV module holder area. To control and provide feedback to the blower two temperature sensors were placed in the space outside the area of the PV module holder and four temperature sensors were attached back side of PV module. These four temperature sensors while used to provide feedback to the blower to control the air flow to inside the chamber, their outputs as shown right side of **Figure 1**, were also displayed from the temperature control unit of thermal chamber so as to observe the temperature uniformity.

In addition to these temperature sensors, four temperature sensors from the simulator systems electronic load were also attached to the back side of PV module. Output of these temperature sensors were measured via simulator software.

The temperature uniformity over the surface of PV module was measured through the outputs of eight temperature sensors connected to their back side just on the cells (four temperature sensors from simulator systems, four temperature sensors from thermal chamber system). All the temperature sensors used in this system have ±1˚C accuracy and ±0.5˚C repeatability.

The temperature uniformity capability of this system over about 2 m × 2 m area within 15˚C to 75˚C temperature interval was investigated as described in the IEC 60891 standard. A 62 cell PV module was mounted to the module holder and eight temperature sensors were attached to its backside. Then, all the doors of chamber were closed and the temperature was set to 15˚C. After the desired temperature stability was achieved temperature values from each sensor were recorded. This process was repeated for all the temperatures from 15˚C to 75˚C with 5˚C intervals. Then, after the completion of measurements the temperature uniformities were calculated using (4) and the results are shown in Table 1. For the all temperature levels the obtained temperature uniformities are less than 1˚C which is almost two times better that the IEC 60891 standard requirements.

$$\text{Temperature Nonuniformity} = \left(T_{\max} - T_{\min}\right) / \left(T_{\max} + T_{\min}\right) \quad (4)$$

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

Table 1. Temperature non uniformities on PV modules.

T1 ˚C	T2 ˚C	T3 ˚C	T4 ˚C	T5 ˚C	T6 ˚C	T7 ˚C	T8 ˚C	$\frac{T_{\max} - T_{\min}}{T_{\max} + T_{\min}}$*
14.6	15.1	14.6	14.6	14.5	15.0	14.5	14.5	0.02
20.3	20.4	20.7	20.2	20.3	20.3	20.7	20.2	0.01
25.4	25.6	25.9	25.3	25.8	25.6	25.8	25.5	0.01
29.5	29.8	29.9	29.5	29.6	30.0	30.0	29.5	0.01
34.2	34.5	34.5	34.3	34.3	34.6	34.6	34.3	0.01
39.8	40.1	40.4	39.8	40.0	40.2	40.0	40.0	0.01
44.6	44.8	45.3	44.8	44.9	45.0	45.2	44.6	0.01
49.6	49.8	50.6	49.9	49.5	50.0	50.6	49.9	0.01
54.7	54.9	55.8	55.0	54.7	55.0	56.0	55.2	0.01
59.2	59.5	60.1	59.5	59.4	59.6	60.1	59.2	0.01
64.3	64.5	65.4	64.6	64.2	64.6	65.3	64.5	0.01
69.8	70.1	70.9	70.1	69.6	70.0	70.8	70.1	0.01
75.6	75.6	77.0	75.8	75.4	75.6	76.8	75.8	0.01

*Temperature nonuniformity.

2.3. Measurements and Evaluations of Temperature Coefficients

The temperature dependent measurements of the electrical performance parameters (short-circuit current, open-circuit voltage, and maximum-power) of a monocrystalline silicon was performed by implementing the interpolation method described in IEC 60891 standard. According to the IEC 60891 standard the measured temperature coefficients can be valid over ±30% of the measured irradiance value if the PV module under the test is linear; otherwise it can be valid at the irradiance level at which the measurements are done. Therefore, due to these conditions in this work before the temperature dependent measurements, the linearity of PV module under the test was done over 100 Wm^{-2} - 1000 Wm^{-2} irradiance range. The irradiance levels at 900 Wm^{-2} and 1000 Wm^{-2} were adjusted using the solar simulator's control cell, from 100 Wm^{-2} to 800 Wm^{-2} were adjusted using totally eight attenuation masks which are filters produced by Pasan and they can be placed in front of the simulator's light source for the attenuation of irradiance level. The linearity of electrical performance parameters of PV module under the test with respect to irradiance levels was evaluated using the least-squares fit method as described in IEC 60904-10 standard [15] and other works [16] [17]. The measurement results and evaluated linear behavior of PV module under tests are shown in the **Figures 2-5**.

As it seen from the **Figure 4** and **Figure 5**, since the PV module under the tests is linear then the temperature coefficients measurements according to the IEC 60891 standard can be valid over ±30% of the measured irradiance value. Therefore, in order to cover the largest possible irradiance range the temperature dependent measurements were determined to be done at 200 Wm^{-2}, 400 Wm^{-2}, 600 Wm^{-2} and 1000 Wm^{-2} irradiance levels. In that way the measured temperature coefficients can be valid over the irradiance range from 140 Wm^{-2} to 1300

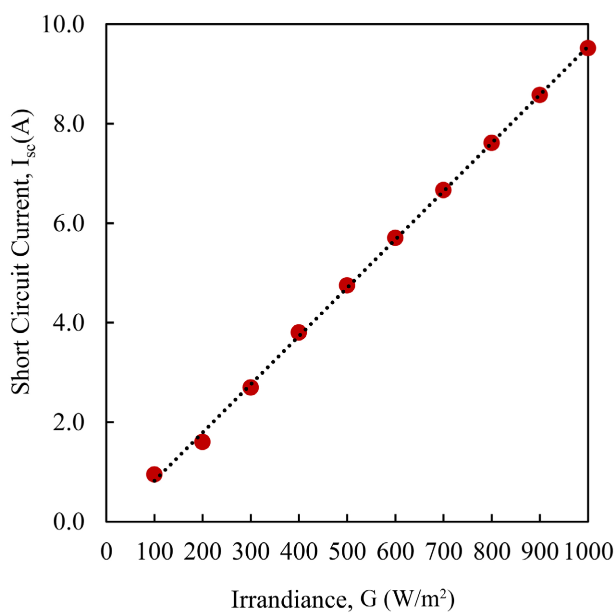

Figure 4. I_{sc}-G curve of monocrystalline PV module.

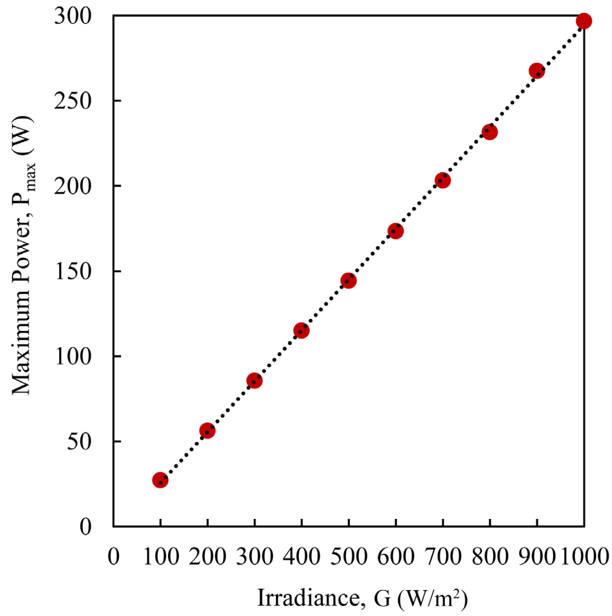

Figure 5. P_{max}-G curve of monocrystalline PV module.

Wm^{-2}.

After determining the irradiance levels (200 Wm^{-2}, 400 Wm^{-2}, 600 Wm^{-2} and 1000 Wm^{-2}) the measurements of the temperature dependent electrical performance parameters of PV module under the tests were performed. In this work, the temperature interval was taken as from 15˚C to 75˚C to both meet the IEC 60891 standard requirements (at least 30˚C temperature range) and also to get the information about temperature dependent variation of electrical parameters in a large scale. For the measurements, PV module under the tests was mounted to the Solar Simulator's module holder respectively and totally eight PT-100 temperature sensors were attached to its back side in Figure 1. Then the temperature inside the thermal chamber was set to be changed from 15˚C to 75˚C with 5˚C intervals. At each temperature level after the desired thermal stability was reached, the PV module front surface was irradiated by flash type simulator and the electrical parameters as a function of temperature were measured. These measurements were performed for 200 Wm^{-2}, 400 Wm^{-2}, 600 Wm^{-2} and 1000 Wm^{-2} irradiance levels as given in Figure 6 and Figure 7. From the short-circuit current versus open circuit voltage (I_{sc}-V_{oc}) and the maximum power versus open circuit voltage (P_{max}-V_{oc}) graphs the temperature dependent values of short circuit current, open circuit voltages and the maximum power values for the PV module under the test were obtained as given in Figure 8, Figure 9 and Figure 10. Applying the a least-square linear fits to the temperature dependent graphs of short circuit current versus temperature, the open-circuit voltage versus temperature, the maximum power versus temperature and evaluating their slopes [$\Delta I_{sc}/\Delta T$, $\Delta V_{oc}/\Delta T$, $\Delta P_{max}/\Delta T$) the α (% ˚C^{-1}), β (% ˚C^{-1}) and δ (% ˚C^{-1}) relative temperature coefficients for the short circuit current, the open circuit voltage and the maximum power were obtained using (4). The evaluated temperature

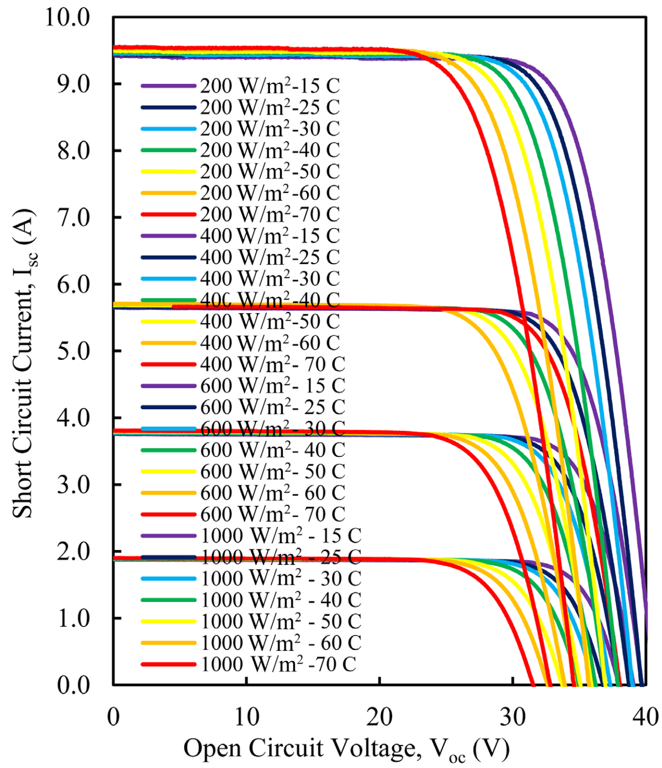

Figure 6. I_{sc}- V_{oc} measurements of monocrystalline PV module at various irradiance levels.

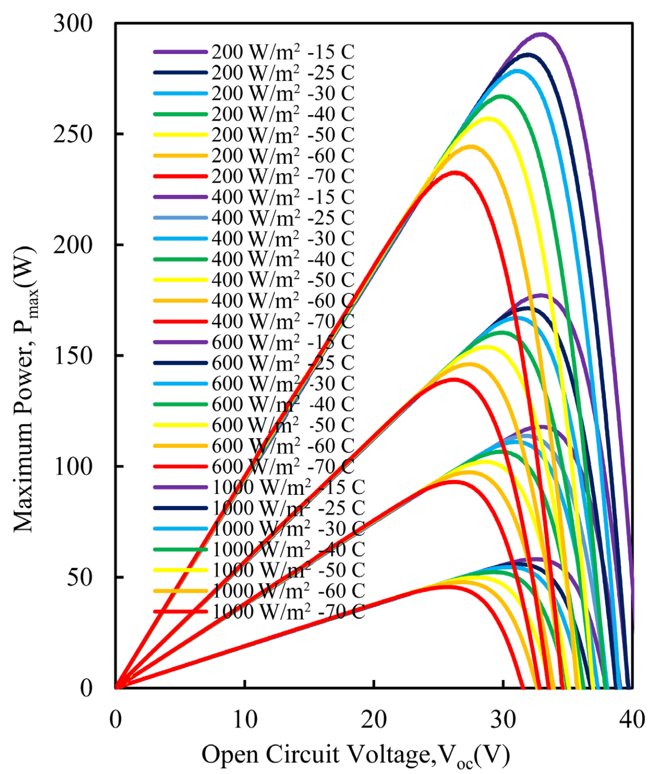

Figure 7. P_{max}- V_{oc} measurements of monocrystalline PV module at various irradiance levels.

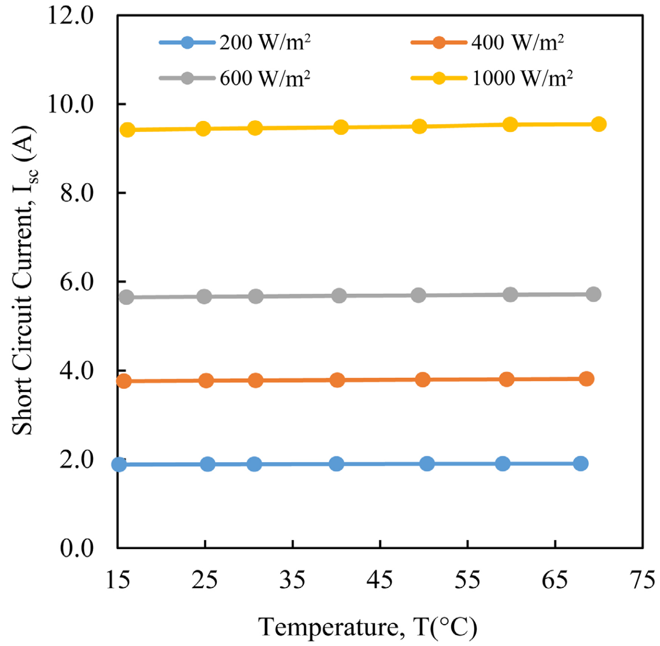

Figure 8. I_{sc}-T graph of monocrystalline PV module at various irradiance levels.

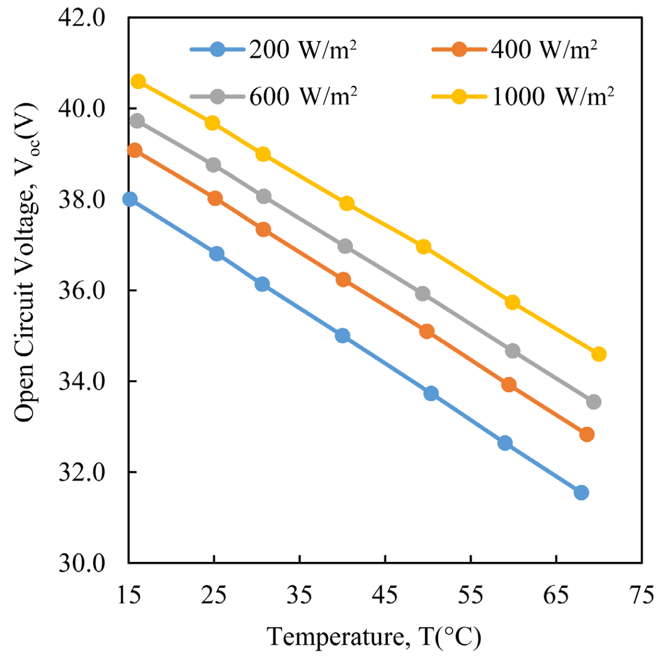

Figure 9. V_{oc}-T graph of monocrystalline PV module at various irradiance levels.

coefficients of the PV module at various irradiance levels were shown in **Table 2**.

$$\begin{aligned} \alpha &= 100*\left(\Delta I_{sc}/I_{sc}\right)/\Delta T \\ \beta &= 100*\left(\Delta V_{oc}/V_{oc}\right)/\Delta T \qquad \left(\%\cdot{}^{\circ}\mathrm{C}^{-1}\right) \\ \delta &= 100*\left(\Delta P_{\max}/P_{\max}\right)/\Delta T \end{aligned} \tag{4}$$

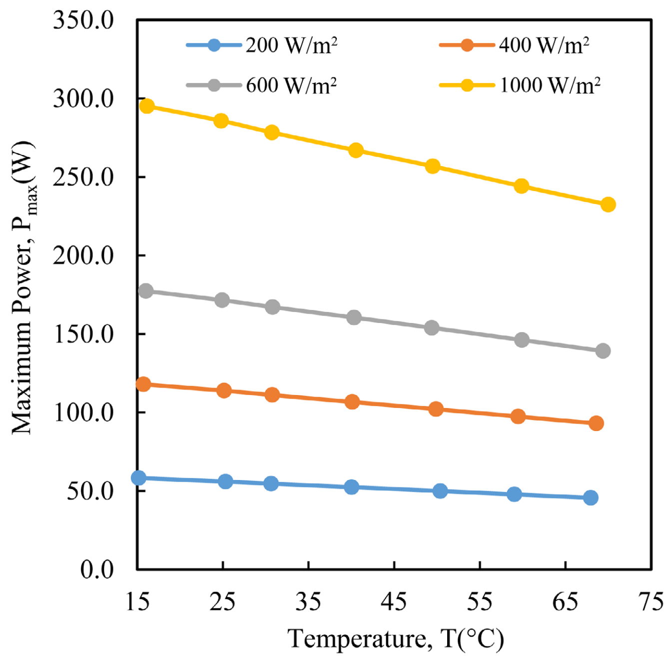

Figure 10. P_{max}-T graph of monocrystalline PV module at various irradiance levels.

Table 2. Temperature coefficients of a monocrystalline PV module at different irradiance level.

G (W·m^{-2})	α (%/˚C)	β (%/˚C)	δ (%/˚C)
200	0.064	−0.37	−0.39
400	0.066	−0.31	−0.42
600	0.064	−0.30	−0.42
1000	0.067	−0.29	−0.41

3. Conclusions

In general, electrical performance parameters of PV devices are determined at Standard Test Condition (STC) (1000 Wm^{-2}, 25˚C, AM1.5). 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. All these conditions have effect on the temperature of a PV module. This, impacts the performance parameters and hence the energy efficiency of PV devices. In order to calculate energy yield correctly, the performance parameters obtained at STC have to be extrapolated to any temperature. This can be done via knowledge of the well-defined temperature coefficients which can be valid over a large temperature and irradiance ranges. In this work by creating a simple irradiance-temperature matrix the measurements of temperature coefficients were performed at 200 Wm^{-2}, 400

Wm^{-2}, 600 Wm^{-2} and 1000 Wm^{-2} irradiance levels and 15˚C to 75˚C temperature range. The α (% ˚C^{-1}), β (% ˚C^{-1}) and δ (% ˚C^{-1}) temperature coefficients obtained in this work were evaluated with 0.002 % ˚C^{-1}, 0.02 % ˚C^{-1} and 0.02 % ˚C^{-1} respectively. The temperature non uniformity, and the uncertainties of the electrical parameters of the simulator are the important parameters that have significant contribution on these uncertainties.

The market volume of renewable energy sources has been increasing rapidly in recent years. It is known that the uncertainty of the performance parameters of solar energy-based systems (photovoltaics) leads to very high financial uncertainties. Studies have predicted that the market share of photovoltaic-based solar energy systems will increase significantly in the future. This high market volume necessitates measurement needs with high accuracy standards traceable to SI units. For this reason, studies to reduce the uncertainties of the measurements made within the scope of this study will make an important contribution for reducing the mentioned losses.

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Conflicts of Interest

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

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