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Harnessing Light-Emitting Diode technology for cutting-edge Photovoltaic module characterisation

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Abstract

Significant advancements in Light-Emitting Diode (LED) technologies, including the availability of high-power LEDs at reduced costs, have rendered them a highly desirable and dependable solar simulator. Nonetheless, challenges persist in designing LEDs as solar simulators for assessing the features of specific solar modules across diverse technologies and sizes, particularly with spectral composition and spatial uniformity of adequate irradiation. This work seeks to develop a prototype LED solar simulator capable of generating uniform light with stability of at least 90% (class C) throughout an illumination area of 54 cm × 67 cm for laboratory instructional applications. The employed procedures encompass the selection of high-power LED bulbs, thermal management, electrical design, prototype fabrication, and performance assessment. The International Electrotechnical Commission (IEC) 60904-9:20 standard delineates the performance criteria for solar simulators and serves as a framework for constructing LED solar simulators. The study's results demonstrate that the LED solar simulator prototype has been successfully constructed and is categorized as class C, exhibiting a light non-uniformity and stability level of 10%. The capacity to delineate the current and voltage of a 50 cm × 30 cm small solar module under specified irradiance and temperature circumstances may be attained with a mean absolute error percentage of 0.01 and a root mean square error of 0.21. The hexagonal configuration of the LED array offers advantages for light design, including modularity and ease of expansion to achieve a broader illumination area. This arrangement can serve as an invaluable instrument to enhance solar energy research and maximize the performance of photovoltaic devices under regulated conditions.

Keywords:

High power LEDs, solar simulators, current and voltage characteristics, small photovoltaic modules.

1 Introduction

A device that mimics the spectrum and intensity of natural sunlight using light-emitting diodes is known as an LED solar simulator. Its ability to accurately replicate various environmental conditions has resulted in widespread adoption within Photovoltaic (PV) research [1]. LED solar simulators have the potential to address the limitations of conventional solar simulators, and their research and development have garnered significant attention in recent years. Traditional simulators, such as those utilizing xenon and halogen lamps, have been commonly

used for testing photovoltaic devices. However, these systems present several drawbacks, including issues related to stability, long-term performance, and spectral matching [2]. Consequently, there has been an acceleration in research focused on alternative technologies, such as LED-based solar simulators [3].

LED solar simulators offer several advantages over traditional systems. These benefits include improved stability, reduced power consumption, and greater spectral flexibility [4]. Despite these advantages, significant challenges remain to be addressed in order to fully utilize LED solar simulators [5][6]. The primary obstacles to accurate and reliable testing of PV devices are spectral mismatch and issues concerning uniformity [7]. Light uniformity (homogeneity) and intensity are often problematic in solar simulators. For indoor laboratory testing, light homogeneity must reach at least 90% to achieve class C status, while light intensity can be regulated to range between 200 and 1000 W/m².

Numerous studies have sought to address these issues. For example, Belloni et al. [8] demonstrated enhanced spectral control in their innovative LED-based solar simulator, specifically designed for assessing building-integrated photovoltaic systems. Chojniak et al. [9] proposed a precise spectrum adjustment technique to improve the accuracy of LED and multi-light source simulators. Furthermore, Roest [4] explored the potential of LED solar simulators for measuring perovskite solar cells, emphasizing their applicability in advanced photovoltaic technologies [10][5]. Faba et al. [6] also investigated recent advancements in LED solar simulators for photovoltaic testing, highlighting their potential for use with high-efficiency solar cells. In their discussion on the design and application of LED solar simulators for high-efficiency solar cells, Lozito et al. [11] focused on their performance. Reichmuth et al. [7] provided a comprehensive analysis of the latest advancements in LED solar simulators, offering valuable insights into their advantages and disadvantages. Schachtner et al. [12] examined spectral correction methods for LED solar simulators, emphasizing recent developments in this area. To significantly enhance the accuracy and reliability of LED solar simulators, Rauer et al. [13] focused on improving spectral matching. Bett et al. [14] investigated the application of LED solar simulators for perovskite solar cells, addressing specific testing challenges. Further research is necessary to thoroughly evaluate and optimize these simulators for various photovoltaic systems. For instance, Siefer et al. [15] discussed advancements in LED solar simulator technology and underscored the need for ongoing innovation and improvement.

Despite significant advancements in recent years, further study is still required to fully understand the potential of LED solar simulators for educational purposes, which aid students in comprehending diverse photovoltaic behaviors under specific environmental conditions. Therefore, this study aims to develop a continuous LED solar simulator prototype with adjustable light intensity and a target light uniformity level of ≥ 90% (class C) over a 54 cm × 67 cm test area. It is anticipated that this LED-based solar simulator prototype will facilitate the testing of small solar photovoltaic modules measuring 50 cm by 30 cm under low light conditions.

In addition to further development regarding controlled light simulator studies and with uniform light, this LED-based solar simulator prototype is anticipated to be able to be used for testing the characteristics of small solar PV modules with dimensions of 50 cm × 30 cm under low light intensity irradiation conditions of approximately 400 W/m² on a laboratory scale. Recent developments in LED technology and spectrum adjustment methods are used in designing the modular and portable LED solar simulator prototype. By improving spectrum matching accuracy and uniformity and assessing the created simulator's long-term stability through rigorous testing and validation, this study aims to support the wider adoption and use of LED solar simulators in the PV sector.

2 Methods for Building an LED Solar Simulator

A systematic design and construction procedure was employed to ensure that the LED-based solar simulator could replicate the solar spectrum and provide consistent, stable irradiance for testing Photovoltaic (PV) devices. Fig. 1 illustrates the steps involved in building the LED-based solar simulator.

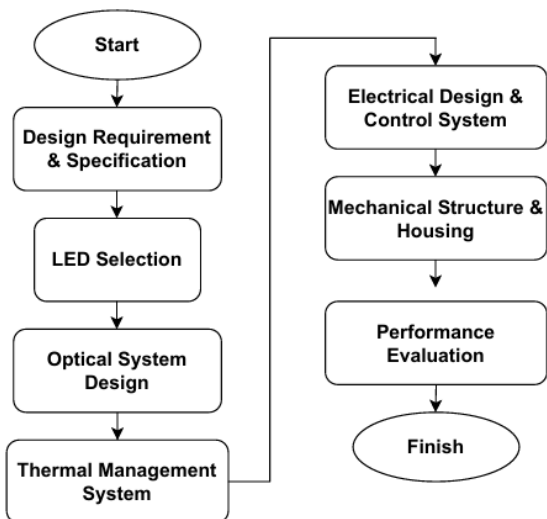


Fig. 1. Flowchart for LED solar simulator construction.

2.1 Design Requirements and Specifications

As shown in Table 1, the initial stage involved defining the design criteria based on the international solar simulator standards IEC 60904-9:2020 [16]. The requirements for solar simulator performance are divided into three classes: A, B, and C, according to this standard. A solar simulator is classified as a class AAA simulator if it meets class A requirements across all three dimensions. The categorization of solar simulators according to IEC 60904-9:2020 [17] is:

1. Class A: Tight tolerances for every criterion, with the highest precision.
2. Class B: Accuracy is moderate.
3. Class C: Wider tolerances, worse precision.

As Table 1 shows, these categories are based on three primary criteria: temporal instability, irradiance non-uniformity, and spectral match.

Table 1. Specification class of solar simulators based on IEC 60904-9:2020 [36]

Class classification	Spectral match	Irradiance non-uniformity	Temporal stability
A	0.75-1.25	≤ 2%	≤ 2%
B	0.6-1.4	≤ 5%	≤ 5%
C	0.4-2.0	≤ 10%	≤ 10%

Designing an LED solar simulator that can continuously emit light with the appropriate spectral match and spatial uniformity, while providing adjustable irradiance levels and uniformity across the target region, is the primary objective of this project. The portable prototype of the LED solar simulator is expected to meet class C specifications, which include a temporal stability of ±10% during the testing period, a spatial uniformity of irradiance with a variation of ≤10%, and a spectral match within the range of 0.4 to 2.0 for key wavelengths (400–1100 nm). Performance-wise, it should replicate the current and voltage characteristics of a 50 cm × 30 cm small solar module when subjected to low light intensity irradiation conditions of approximately 400 W/m².

Selecting the appropriate LED lights and array design that can provide consistent, stable output and precise spectrum matching to the industry standard AM1.5 global is critical to this initial design [18]. To ensure accurate measurement results when testing a photovoltaic solar device, the test area must maintain constant and uniform light intensity over time. The LED lamp used in this

project is a high-power LED [5], which measures 74 mm × 40 mm and features a 120° beam pattern, making it suitable for wide-area illumination as shown in Fig. 2. The lamp consists of a collection of cool white LEDs with a wavelength range of 400 to 800 nm.



Fig. 2. The chosen high-power LED lamp for wide-area illumination.

The chosen LED lights use Chip-On-Board (COB) and High-Power LED (HPL) technologies. Due to their tiny size, they can deliver homogeneous light distribution in a close-tested area and high light intensity at close distances. Their spectral distribution is shown in Fig. 3.

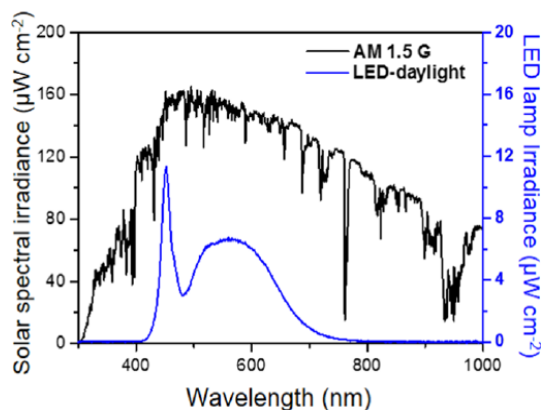


Fig. 3. The comparison of the spectrum of cool white LED used in the proposed solar simulator and the standard spectrum of AM1.5 global.

In total, 32 LED lights are utilised. Every LED has a colour temperature of 6500K, a power of 50 watts, a brightness of 110 Lumens/Watt brightness, and a 220-240 Volts working voltage.

Reflectors composed of thin zinc plates were employed to provide consistent light dispersal. In order to guarantee that every part of the test plane received the same amount of light, these reflectors were utilised to regulate the directionality of the light output.

Optimising the distance between the LED array and the test plane is imperative to minimise hot spots or dark zones and reduce spatial non-uniformity. After some trial and error, an array design that works for the 32 LED lamps has been achieved. For example, the LED lamps have been arranged in various geometric shapes, such as square, rectangular, and hexagonal [19, 20].

From the uniformity study, we found that arranging the LEDs in a hexagonal configuration prevents gaps from forming between them, a common issue with square placements. This arrangement results in a more uniform light distribution across the test area. Fig. 4 illustrates the hexagonal configuration of the LED array.

The simulator incorporated a cooling system to maintain consistent operation, as LED performance is sensitive to temperature fluctuations. This system utilized active cooling with fans to ensure adequate airflow and prevent overheating, as well as heat sinks attached to the LED modules to dissipate excess heat. The thermal management system was designed to minimize irradiance variations caused by temperature changes, thereby ensuring stable light output and extending the lifespan of the LEDs.

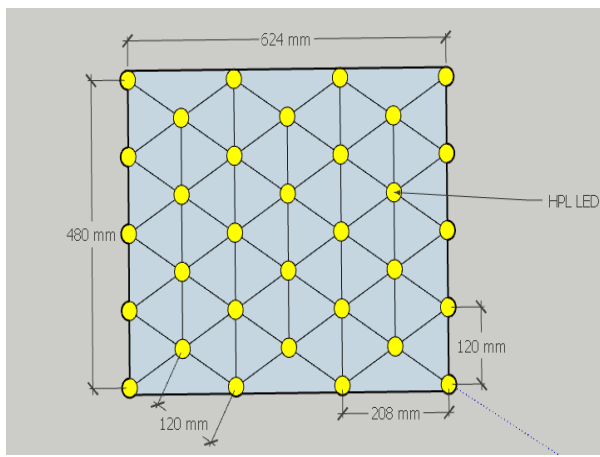


Fig. 4. The illustration of a hexagon shape of the chosen high-power LED.

2.2 Building of an LED Simulator Prototype

At this stage, the prototype of the LED solar simulator has been constructed. It comprises an array of LEDs serving as the light source, a power supply to energize the light source, an AC/DC converter to transform AC power into DC power, several fans, a light control system to regulate irradiance intensity, and a cooling system to ensure the safe operation of the LED lamps. Fig. 5 illustrates the apparatus used in the prototype. The assembly of the prototype was conducted following the acquisition of the necessary equipment.

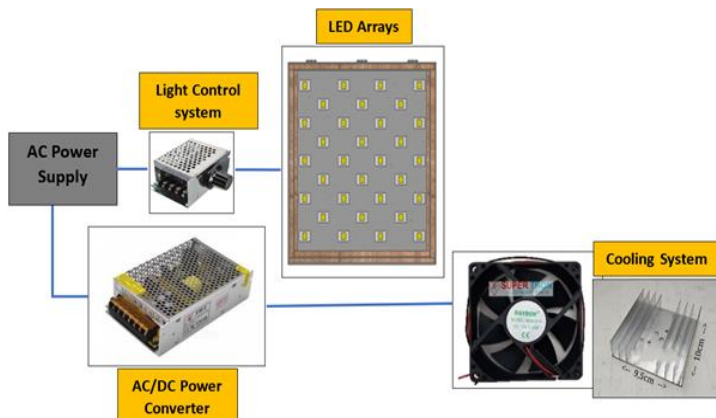


Fig. 5. Components of the proposed LED solar simulator.

The prototype of the LED solar simulator was built as a cubic chamber measuring 85 cm by 70 cm by 20 cm as illustrated in Fig. 6. The chamber is equipped with a fan for cooling and a reflector to minimize light absorption, which could potentially alter the output characteristics of the solar module.

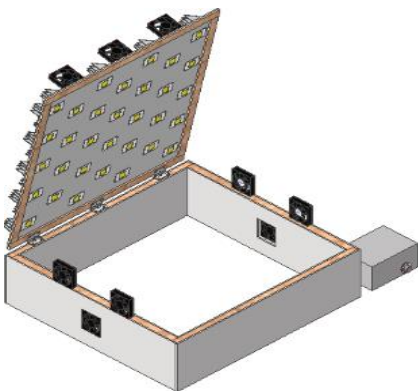


Fig. 6. The proposed prototype of the LED solar simulator.

The LED array is positioned on top of the chamber lid, directing light downward into the test plane, which has a lighting area of 54 cm by 67 cm. All 32 LED lights are connected in parallel as shown in Fig. 7.

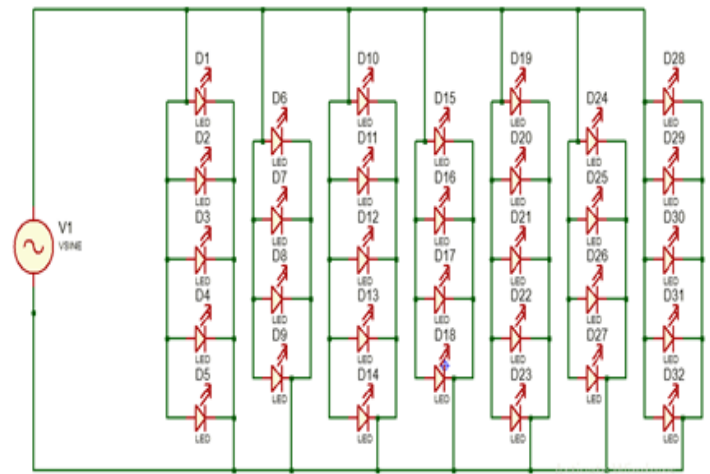


Fig. 7. Parallel connection of LED arrays.

The LED arrays are powered directly from a 220-volt AC supply, with a total power consumption of 1600 watts. Additionally, the device features an AC/DC converter that provides a 12-volt DC supply to operate the fans as part of the active cooling system. By utilizing a dimmer as a light regulator, fluctuations in light intensity within the lighting region were adjusted from 0 to 450 W/m².

2.3 Testing Parameters

The light simulator prototype in this study underwent three different types of testing, including non-uniformity testing, temporal stability testing, and solar module characteristics testing, in compliance with the IEC standard's requirements to meet class C criteria [16].

2.3.1 Non-Uniformity Testing

Radiation levels on a test field object are not homogeneous due to the non-uniformity of light simulator parameters. Eq. 1 determines the non-uniformity of the light intensity the light simulator generates. The LED simulator prototype test field included test points in the shape of a 5 by 5 cm matrix with 154 test points for the light intensity uniformity test.

$$\text{Non uniformity}(\%) = \left(\frac{\text{max. irradiance} - \text{min. irradiance}}{\text{max. irradiance} + \text{min. irradiance}} \right) \cdot 100\% \quad (1)$$

2.3.2 Temporal Stability Testing

The instability of an object at a specific moment in time is known as temporal instability. This test shows how much the LED light's intensity varies over a predetermined period. The LED solar simulator prototype was then run for 60 minutes to test temporal instability (temporal stability). At the same test field position, light intensity measurements were made using a solar meter measuring device at 60-minute intervals. The temporal instability value was then calculated by entering the light intensity measurement findings into Eq. 2.

$$\text{Temporal instability}(\%) = \left(\frac{\text{max. irradiance} - \text{min. irradiance}}{\text{max. irradiance} + \text{min. irradiance}} \right) \cdot 100\% \quad (2)$$

2.3.3 Solar Module Characteristics Testing

One way to understand how a solar module responds to light, enabling the photovoltaic process, is through testing its characteristics [21]. The output of the solar module can be quantified by several metrics, including Maximum Power Point (MPP), maximum current (I_m), maximum voltage (V_m), open-circuit voltage (V_{oc}), and short-circuit current (I_{sc}). The location of the solar module in the test field is selected after identifying an area with a high degree of uniformity during the non-uniformity testing phase.

A multimeter is used to measure the output voltage and current of the solar module. To obtain the voltage and current characteristic curves of the solar module, a variable load is required.

The resistance of the variable load employed in this investigation ranges from 0 to 1000 Ohms. Initially, the load is set to zero Ohms to measure the short-circuit current. Subsequently, the resistance of the load is gradually increased to its maximum value, and the corresponding voltage and current generated by the solar module are recorded to construct the I-V characteristic curve.

2.4 Analysis Method

The main goal of the data analysis of the built-in LED solar simulator is to assess the irradiance uniformity and stability over time [22]. These settings are crucial for determining how well the simulator simulates typical sunshine, especially the AM 1.5G spectrum, and ensuring it satisfies the performance standards for testing solar modules.

The theoretical I-V characteristics derived via simulation using MATLAB SIMULINK software are used to verify the accuracy of the current and voltage (I-V) characteristics acquired from the designed LED solar simulator. Eq. 3 and Eq. 4 [23] demonstrate how the inaccuracy in the data is quantified using the Mean Absolute Percentage Error (MAPE) and the Root Mean Square Error (RMSE).

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left| \frac{A_i - F_i}{A_i} \right| \times 100 \quad (3)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (A_i - F_i)^2} \quad (4)$$

Where A_i is the actual value, F_i is the forecasted value, and n is the number of observations.

The Eq. 3 and Eq. 4 is used to determine the relative difference in spectral irradiance between the high-power LED's spectrum and the reference spectrum AM1.5G [5].

3 Results and Discussion

3.1 Prototype Result of LED Solar Simulator

Fig. 8 illustrates the completed LED solar simulator prototype, measuring 85 cm by 70 cm by 20 cm.

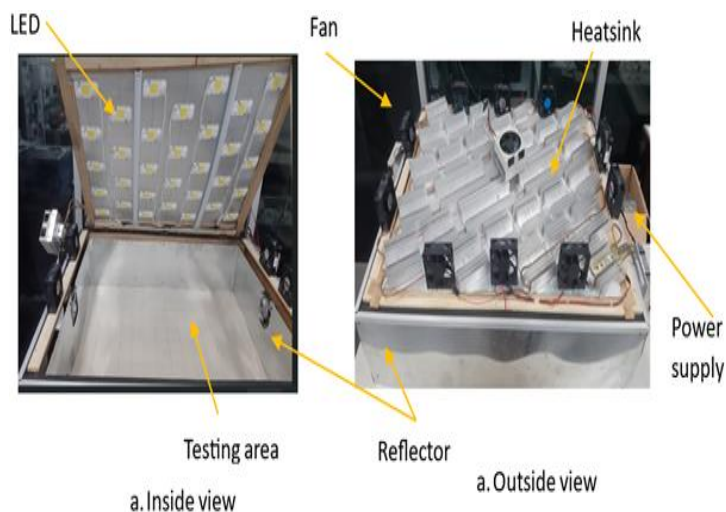


Fig. 8. The resulting prototype of the proposed solar simulator.

The lamp holder on the chamber lid and the testing area are the two primary components of this solar simulator. The lamp holder is equipped with 32 LEDs, which collectively provide a power output of 1600 watts, with each LED delivering 50 watts. Fans and heatsinks are integrated to cool this component, preventing overheating and potential damage to the LEDs. The subsequent

section of the testing chamber is designated for evaluating the voltage and current characteristics of the solar module. A fan cooler and an internal aluminum plate reflector are incorporated in this section.

The test field surface can receive irradiation levels ranging from 0 W/m² to 450 W/m² from the solar simulator. The dimmer can be adjusted to produce variations in the radiation values within the test area. Specific dimmer rotation values are provided for irradiation levels of 450 W/m², 425 W/m², 400 W/m², and 375 W/m².

3.2 Regulating the Thermal Generation

LED arrays produce heat during operation. According to the experiment, the heat generated by LEDs can raise their internal temperature by up to 106.7°C. If the rising temperature of the LED is not managed over an extended period, it may overheat and sustain damage.

To ensure consistent performance over time, control the thermal load from high-intensity bulbs, and prevent damage to the LEDs during operation, a cooling mechanism was incorporated. Two cooling technologies are employed: passive cooling and active cooling. The passive cooling technique utilizes a heatsink installed within the LED housing, which is made from aluminum. In the active cooling system, ten fans rapidly dissipate heat stored in the heatsink into the surrounding air. By combining these two cooling methods, the operating temperature of the LEDs can be maintained at approximately 48°C.

3.3 Results for the Non-Uniformity and the Stability Test

The test area's light homogeneity must be checked to ensure that every component of the tested solar module receives the same amount of light. The test field is divided into tiny squares resembling a five-by-five cm matrix to determine uniformity. A solar meter is then used to measure the light intensity in each matrix area once the test area's irradiance value has been set to a specific value. The next step is to enter the measurement data into Eq. 1 to obtain the uniformity value for the test measurement field after the intensity in each section of the test field has been measured. This measurement was made again with varying levels of light. According to the results of the non-uniformity testing, the LED solar simulator prototype successfully met the class C minimum non-uniformity target with a value of 9.88%. Fig. 9 shows the effects of the distribution of light irradiation on the illuminated area.

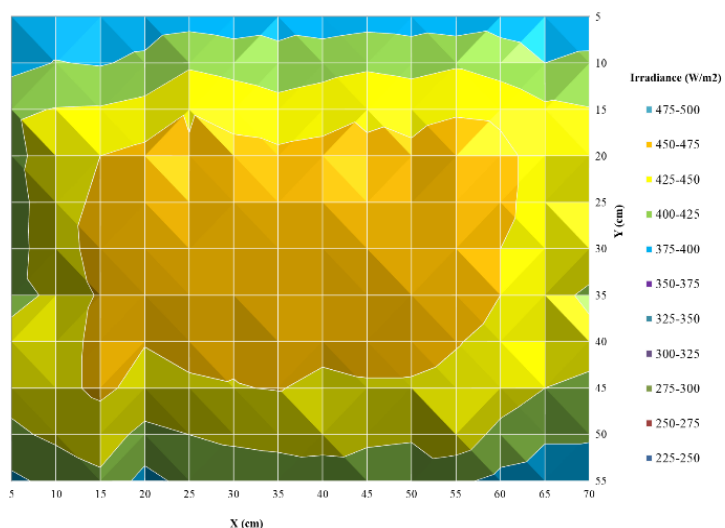
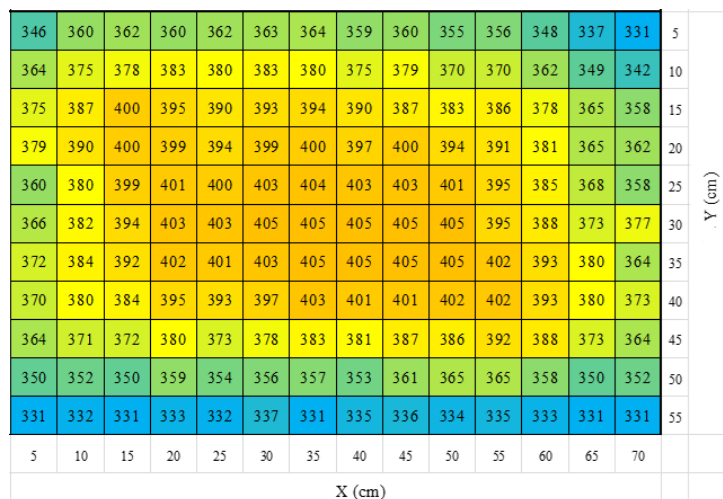


Fig. 9. Distribution of light irradiation on the test area of 70cm x 55cm LED solar simulator.

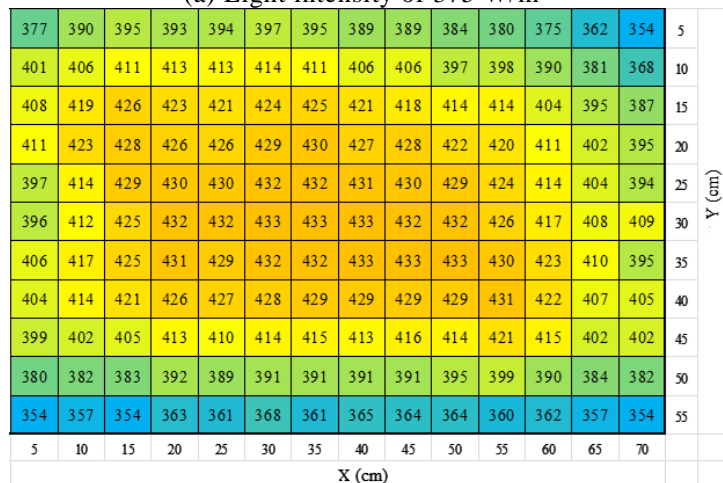
Fig. 10 illustrates the dispersion of various light intensities emitted by the LED array onto the test area.

Fig. 10 illustrates that the light distribution emitted by the evaluated LED arrays exhibits a notably comparable pattern

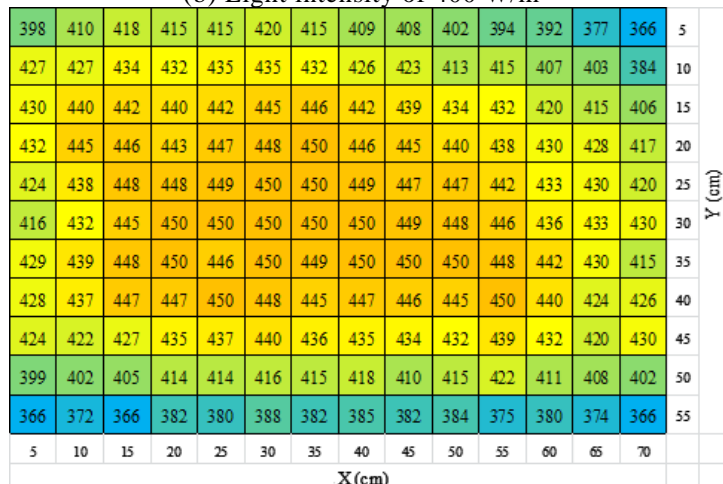
within a test area measuring 70 cm by 55 cm. The findings of the non-uniformity calculation for three irradiance intensities indicate an approximate non-uniformity of 10%. These results confirm that the non-uniformity of illumination in the target area remains consistent at 10% across all irradiance levels. When comparing these non-uniformity results to the irradiance non-uniformity percentage specified by the standard IEC 60904-9:2020, the LED solar simulator prototype is classified as class C.



(a) Light intensity of 375 W/m²



(b) Light intensity of 400 W/m²



(c) Light intensity of 425 W/m²

Fig. 10. Light distribution at different intensities produced by the LED arrays.

To enhance light uniformity and mitigate discrepancies in the light intensity received by the solar module during testing, the illuminated area of the test zone may be reduced. The counterplot in Fig. 11 demonstrates that the uniformly illuminated region measures 55 cm by 35 cm and is centrally positioned. The illumination distribution in this area is notably uniform, as

depicted in Fig. 12. The non-uniformity calculation reveals that the light non-uniformity level within the illumination test region is 3%. Improved homogeneity of the light area can be achieved by decreasing the dimensions of the illumination area. If the illumination area is reduced to 55 cm by 35 cm, the prototype of the LED solar simulator may be classified as class B.

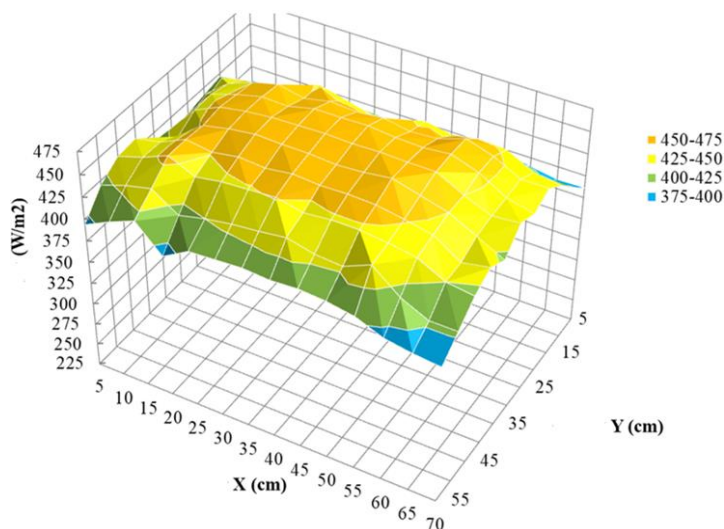


Fig. 11. Light distribution intensity of the proposed solar simulator with a tested area of 70 × 55 cm².

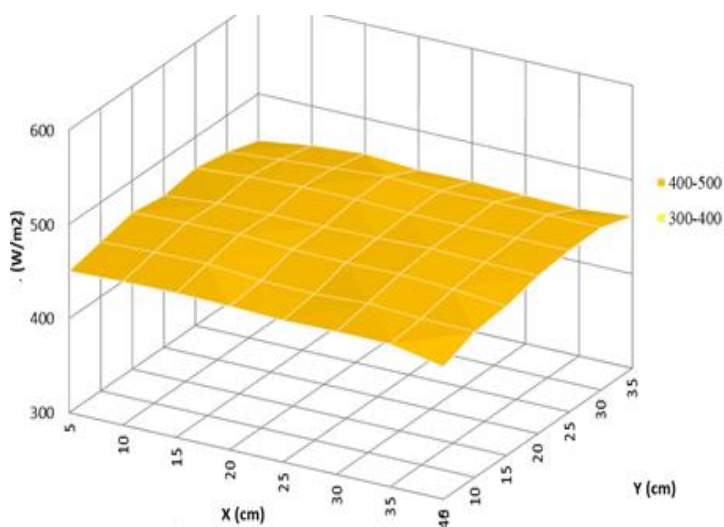


Fig. 12. Light distribution intensity of the proposed solar simulator with a tested area of 50 × 35 cm².

The light stability test was conducted to ascertain the duration necessary for the LED array to generate light at a consistent intensity in the illumination test area. The examination lasted for 60 minutes. The test results are compiled, and subsequent calculations are performed using Eq. 2. The temporal instability test findings for the LED simulator prototype indicate a temporal instability value of 10% for the emitted light. The results obtained are compared with Table 1 regarding the temporal instability of the solar simulator class, indicating that the LED simulator prototype has successfully met the minimal aim of class C.

Fig. 13 presents the outcomes of the temporal stability tests across various irradiance intensities. The light stability test indicates that the irradiance levels incident on the measured region remain stable after 10 minutes of measurement.

The data regarding temporal stability is crucial for maintaining a consistent thermal environment and preventing thermal impacts from distorting the results. Fig. 14 displays the measurement findings of the thermal environment within the lighting chamber.

The assessment of temperature stability in the examined region was conducted at irradiance levels of 375 W/m² and 400 W/m². Fig. 14 illustrates that the room temperature stabilizes after 18

minutes of monitoring. The temperature fluctuations following this period are 0.14°C for an irradiance of 375 W/m^2 , corresponding to a stability level of 0.4%, and 0.10°C for an irradiance of 400 W/m^2 , with a stability level of 0.2%. These results indicate that current and voltage measurements of the tested photovoltaic module can be reliably and accurately conducted 18 minutes after lamp activation to ensure precise outcomes.

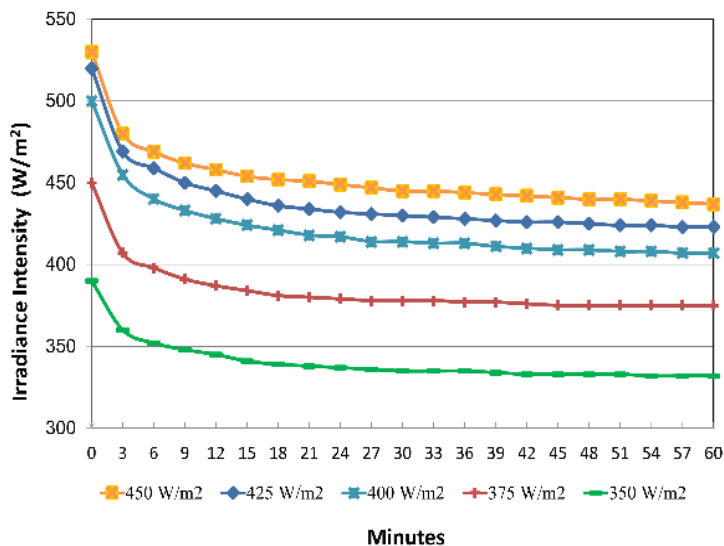


Fig. 13. A temporal stability test of LED arrays.

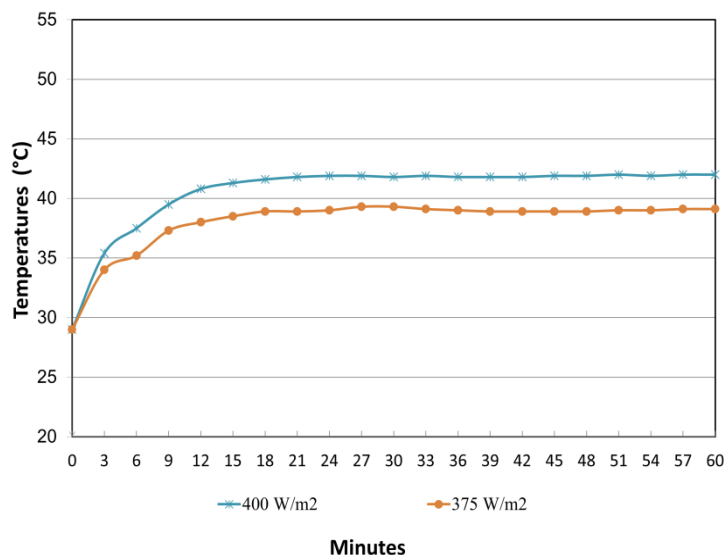


Fig. 14. The stability of temperature conditions during the temporal stability test.

3.4 Results of the Performance Test

The performance test is conducted to verify and assess whether the LED solar simulator prototype accurately generates the current-voltage (I-V) characteristic curve of a solar photovoltaic (PV) module. A monocrystalline photovoltaic module measuring $38\text{ cm} \times 30\text{ cm}$ is utilized as the device under examination. The evaluated photovoltaic module demonstrates a maximum power output of 10 Wp under Standard Test Conditions (STC), characterized by an irradiation level of 1000 W/m^2 , a module temperature of 25°C , and a spectral distribution of 1.5 global. Fig. 15 illustrates the experimental configuration employed to assess the I-V characteristics of miniature solar photovoltaic modules.

The I-V measurement was conducted at an irradiation level of 425 W/m^2 and a module temperature of 35°C . The irradiance incident on the photovoltaic module is directly measured using a solar power meter, while the module temperature is recorded with a temperature sensor affixed to the rear of the examined photovoltaic module. Fig. 16 displays the results of the I-V measurement. Validating measurement results is essential to

confirm their accuracy. Consequently, the theoretical and measured I-V curves are compared.

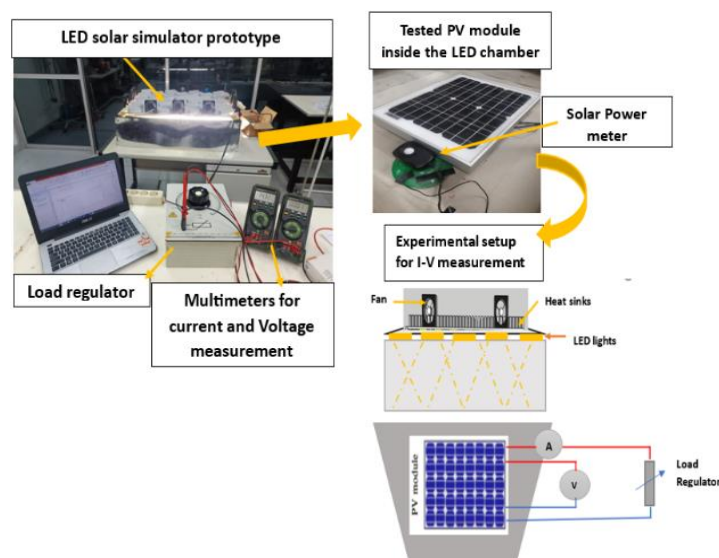


Fig. 15. An experimental setup for a current and voltage measurement of a 10Wp solar PV module and its measurement instruments.

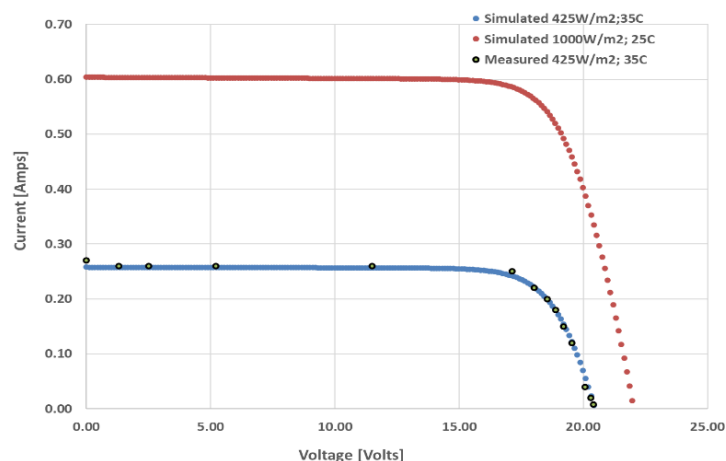


Fig. 16. Performance test of LED solar simulator to produce the current and voltage characteristic curve of a 10 Wp solar PV module at 425 W/m^2 and a chamber temperature of 35°C .

Fig. 16 illustrates that the observed I-V curve results are in strong agreement with the simulated data, thereby validating the measurement outcomes. The evaluated photovoltaic module's measured and predicted Power-Voltage (P-V) curves exhibit strong concordance, as depicted in Fig. 17.

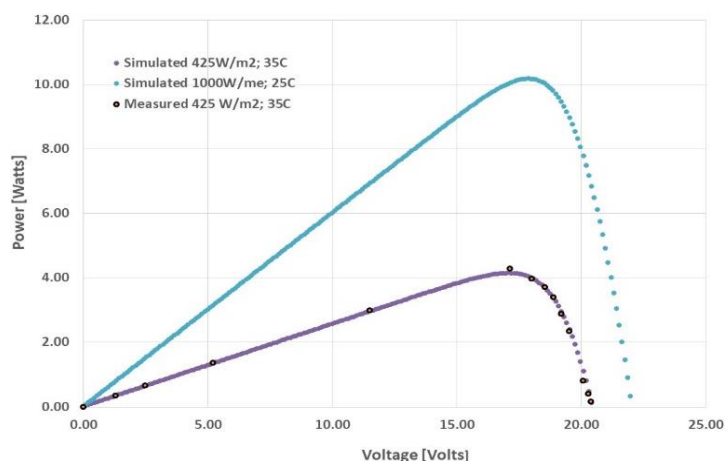


Fig. 17. Performance test of LED solar simulator to produce the current and voltage characteristic curve of a 10 Wp solar PV module at 425 W/m^2 and a chamber temperature of 35°C .

The disparity between the measurement outcomes and the simulation is evaluated by the Mean Absolute Percentage Error (MAPE). In contrast, the extent of error is assessed using the Root Mean Square Error (RMSE). Table 2 presents the MAPE and RMSE for the I-V and P-V readings.

Table 2. MAPE and RMSE values for the I-V and P-V measurements of the tested PV module

Type	MAPE	RMSE
I-V curve	10%	0.01
P-V curve	12%	0.21

The MAPE and RMSE figures indicate that the LED solar simulator prototype performs effectively, enabling accurate acquisition of a mini-PV module's I-V and P-V curves, with measurement errors of 0.01 and 0.21, respectively. The findings indicate that the evaluated photovoltaic module's simulated and actual I-V characteristics, utilising the developed LED solar simulator, are comparable. Despite particular distinctions, the disparities are negligible. The light irradiance produced by the solar simulator is comparable to the norm despite a 12.5% difference in spectral irradiance between the cool white LED and the reference spectral irradiance AM1.5G. The engineered LED simulator can deliver adequate illumination and an appropriate spectrum to the designated area.

Nonetheless, various types of solar cells necessitate distinct optimal spectrums. Solar cells exhibiting high responsivity possess extensive wavelength ranges from 300 nm to 1200 nm, including Cadmium Telluride (CdTe) solar cells, Copper Indium Gallium Diselenide (CIGS) solar cells, and microcrystalline silicon ($\mu\text{c-Si}$). These cells necessitate modifying the simulated light source spectrum to encompass their wavelength intervals [5]. Consequently, utilising solely cool white LEDs is insufficient to encompass the extensive spectral range of those solar cells. Accurate measurement results necessitate the integration of many light sources, such as halogen lamps, to ensure a broad spectrum of wavelength intervals. In addition to enhancing the light spectrum emitted by the LED, various features must be incorporated into the constructed LED solar simulator, including temperature and irradiance controls, to ensure stability during testing. Furthermore, the LED simulator can be upgraded to class A across all categories, specifically addressing non-uniformity of irradiance, temporal instability, and spectral matching.

4 Conclusion

The LED solar simulator prototype has been successfully developed. The constructed LED solar simulator is categorized as class C, exhibiting a light non-uniformity and temporal instability level of 10%. The light irradiance produced by the designed LED solar simulator is analogous to the standard, demonstrating a variation of 12.5%. This variation indicates that the objective of creating a prototype of a continuous LED solar simulator, capable of emulating natural sunlight in a controlled laboratory environment and assessing the current and voltage (I-V) characteristics of a small PV module measuring 50 cm \times 30 cm, is attainable. The inaccuracies in its I-V measurements are quantified using the Mean Absolute Percentage Error (MAPE) and Root Mean Square Error (RMSE), yielding values of 0.01 and 0.21, respectively. These values suggest that the developed LED solar simulator performs effectively and generates an I-V curve that closely aligns with the theoretical I-V characteristic curve.

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