LED Based Solar Simulator

Abhay Mohan M.V, *Student Member, IEEE,* Jishnu Pavithran, *Student Member, IEEE,* K Lijo Osten, Jinumon A and Prof. C. P. Mrinalini

Government Engineering College, Sreekrishnapuram under the University of Calicut, Kerala, India.

Abstract—Solar energy is one of the most underutilized among the renewable energy sources available to us. Thus, the testing of the solar panels and photovoltaic cells used to harvest solar energy are extremely important. A solar simulator provides a controllable indoor test facility for testing solar cells and photovoltaic modules under laboratory conditions by producing illumination approximating natural sunlight. This project focusses on matching the output spectrum of the simulator to the reference spectral distribution of sunlight in the visible spectral range at AM1.5G as defined in ASTM G173-03 standard. The aim is to achieve Class A Spectral Concurrence (matching) as defined in the ASTM E927-05 standard in the 400 nm - 700 nm region. The high power LEDs used for this purpose have wavelengths 470 nm, 505 nm, 530 nm, 655 nm and white LEDs.

Index Terms—Solar Simulator, Photovoltaic Testing, ASTM Standards

I. Introduction

IN this period of energy crisis, researches in the field of renewable energy resources are gaining considerable momentum. Solar energy is one of the most underutilized among them, mostly because of the low efficiency of solar cells. Thus, the testing of the solar panels and photovoltaic cells are extremely important. A solar simulator is an equipment that provides illumination approximating natural sunlight. Solar simulator is widely used to provide a controllable indoor test facility under laboratory conditions for the testing of solar cells. Several types of lamps have been used as the light sources within solar simulators. They are Xenon arc lamps, Metal Halide arc lamps and Quartz Tungsten Halogen (QTH) lamps. The limitations and disadvantages of solar simulators today such as cost, power consumption etc. are mainly due to the light sources used and a very attractive solution is to use LEDs. They have a narrow output wavelength and are available in colors over the entire spectrum. These features not only help in accurately representing the standard spectrum but also for adjusting the spectral output as needed to match any realistic spectral output required.

The LED based Solar Simulator presented here is capable of determining the IV characteristic of a solar cell. The Irradiance of the output spectrum can be varied by the user to simulate the variations in light intensity according to the time of the day. The user is able to calibrate the instrument to bring it to the A.M (air mass) 1.5 G reference spectrum. The test plane temperature can also be controlled with a temperature control arrangement.

E-mail: abhaymv@ieee.org; jishnupavithran@gmail.com; lijoostenk@gmail.com; 777jinu@gmail.com.

II. Literature Review

Most of the commercial solar simulators available today use Xenon arc lamp as light source. Generally, only the light intensity and module temperature can be varied in these simulators. LEDs offer an additional degree of freedom and allows the control of the spectrum. Moreover, the cost of the simulators can be significantly lessened by using LED as a light source. Hence, LEDs were found to be more preferable if used as a light source in a solar simulator [5]. A prototype of such a solar simulator [6] was built by the Centre for Renewable Energy Systems Technology (CREST). The equipment developed by CREST was used to calibrate the V-I characteristics of a solar cell. The LED placement for uniformity of light is a challenge in this area, as LEDs are point sources and a solar simulator requires uniformity. Some of the earliest works in this area appears in [4] and [9], covering the subject of LED placement and uniformity. This project focusses on the realization of an LED based solar simulator complying with the ASTM standards.

III. Standards Applied

International standards exist to benchmark solar simulation lighting. The standards used in this project are:

- ASTM G173-03 Standard Tables for Reference Solar Spectral Irradiances
- ASTM E927-05 Standard Specification for Solar Simulation for Terrestrial Photovoltaic Testing.

The reference spectral distribution of sunlight at Air Mass 1.5 Global is defined in ASTM G173-03 [10] and IEC 60904-3. The values of the Spectral Irradiance as specified in the ASTM G173-03 Standard Tables for Reference Solar Spectral Irradiances is plotted in Fig. I. For classification of solar simulation systems, this standard is restricted to the wavelengths from 400 nm to 1100 nm. The total irradiance of the AM1.5G spectrum is obtained by integrating it and is found to be 759 W/m^2.

The light source of the solar simulator must replicate this standard spectrum to ensure effective testing of the solar cell. Conventional simulators use optical filters to shape the spectrum. However, LED solar simulators make use of the narrowband spectral output of LEDs to match the light source spectrum to the standard spectrum. In order to provide irradiance levels required by the AM1.5G, high power LEDs are used. Unfortunately, high power LEDs in the infrared region cost nearly double that of those in the visible region. Also, some of the required wavelengths for IR LEDs are not

commercially available. Hence, a halogen lamp was used to produce light spanning the infrared region.
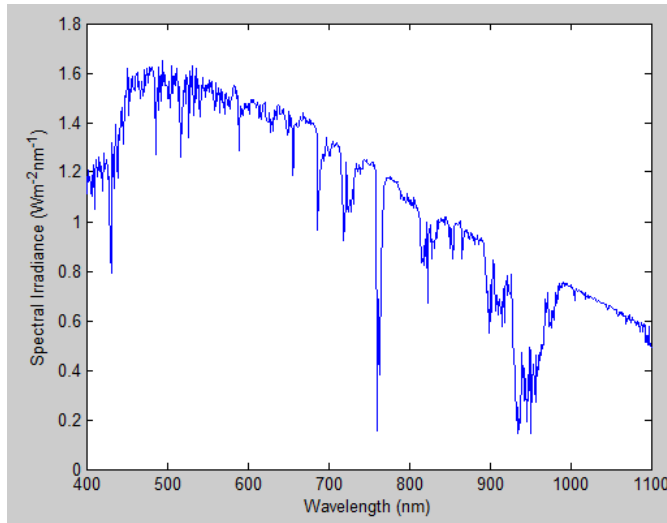

Fig. 1: AM1.5G standard solar spectrum

The overall spectrum of the light source plotted along with the AM1.5G spectrum is shown in Fig. II.
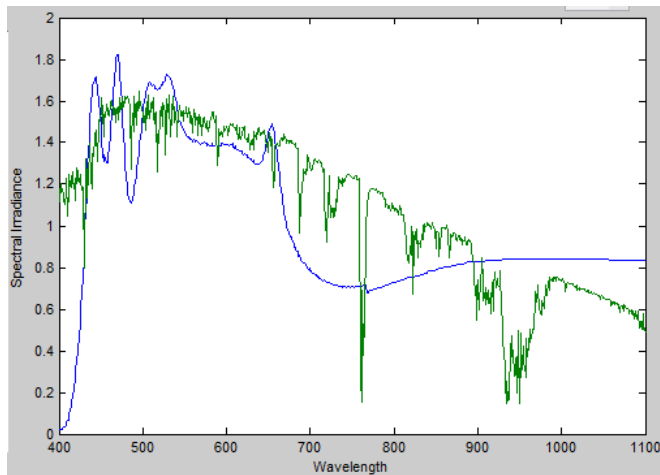

Fig. 2: Spectral Irradiance of the light source

The level of matching of the spectrum of the light source with the standard spectrum (AM1.5G) is an important parameter in quantifying the quality of the solar simulator. This parameter is called Spectral Match. It is one of the three parameters used to classify commercial solar simulators. To measure spectral matching, the 400 nm - 1100 nm region is divided into six wavelength bands. Each of these bands contain a particular percentage of the total integrated irradiance. This is specified in the ASTM E927-05 standard [11]. The distribution of irradiance as specified in the standard is shown in Table I. Spectral Match is calculated as the ratio of the actual percentage of irradiance falling on the interval of concern and the required percentage of irradiance.

$$SM = \frac{Actual\,Percentage\,of\,Irradiance}{Required\,Percentage\,of\,Irradiance} \qquad (1)$$

The spectral match of the solar simulator system is the worst case match among all the intervals. Based on the value of spectral match obtained from the equation above, the solar simulator may be classified to class A, B or C in spectral match.

TABLE I: Distribution of Irradiance Performance Requirements

Wavelength (nm)	Percentage of Total Irradiance (AM1.5G)
400-500	18.4%
500-600	19.9%
600-700	18.4%
700-800	14.9%
800-900	12.5%
900-1100	15.9%

An important conclusion that can be drawn from this table is that the spectral match criterion is independent of the shape of the spectrum in the wavelength interval. It merely deals with the power needed in each interval. For broadband sources shaped by filters, this issue is of no concern, but for LED, a narrowband source, the spectrum of the light source can vary significantly within a 100 nm interval. So special care has to be taken to match the spectrum to levels corresponding to AM1.5G within each wavelength band.

In addition to Spectral Match, there are two more parameters that are used to classify solar simulation systems; Spatial Non-Uniformity of Irradiance(S_{NE}), and Temporal Instability of Irradiance(T_{IE}). Three classes are defined for each of these categories; Class A, Class B and Class C. The ASTM E927-05 standards give the performance requirements for the classification. These are quoted in Table II.

TABLE II: Classifications of Simulator Performance

Characteristics	Class A	Class B	Class C
SM	0.75-1.25	0.6-1.4	0.4-2.0
S_{NE}	$\leq 2\%$	$\leq 5\%$	$\leq 10\%$
T_{IE}	$\leq 2\%$	$\leq 5\%$	$\leq 10\%$

This paper shows how the spectral matching criterion is met in an LED solar simulator.

IV. LED SOLAR SIMULATOR SYSTEM

A. System Overview

The block diagram of the LED based Solar Simulator System is shown below. A specific color is set by the user

on the laptop GUI. The laptop sends a control word to the microcontroller. The control word is used to generate a PWM waveform that controls the intensity of the LEDs that correspond to the color controlled by the control word. The LED driver responds to the PWM and adjusts the intensity of the specific color. This is how the spectral matching procedure is carried out. The IV tracing unit measures the current and voltage values for various loads of the solar simulator. The Halogen lamp is driven by separate drive circuitry and placed at an appropriate distance from the solar cell. Because a halogen lamp is used, spectral matching in the IR region is poor. A photodetector and sensing circuit is used to measure the Spatial Non-uniformity of the test plane. The current from a solar cell can be monitored to measure the temporal instability. The data is sampled by an ADC and sent to the laptop for analysis. A power supply unit supplies adequate power to all the required blocks.
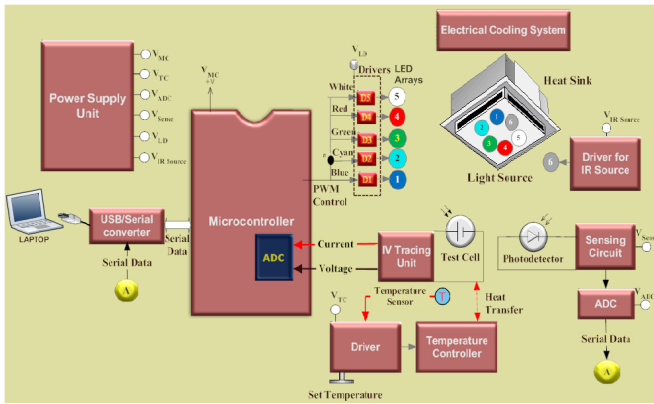

Fig. 3: Block Diagram

For the above arrangement to function as a solar simulator, the irradiance levels of the individual LEDs must be matched to meet the values specified in ASTM G173-03 standard. Irradiance of a High Power LED can be varied by controlling the current driven through them. The current regulator can be of Linear or Switched power supply. Here a switched power supply is used. A buck converter LED driver IC that accepts as input a DC voltage level and PWM for dimming purposes adjusts the voltage drop across the LED strings to control the current through it. Spectral Matching is done by creating a specific voltage drop across the LED string according to the current voltage characteristics of the LED. The required current for a specific light intensity is found from the current-luminous flux characteristics of the LED.

B. Spectral Matching

In terms of irradiance values, Equation (1) can be rewritten as:

$$SM = \frac{Actual\ Irradiance\ in\ the\ interval}{Required\ Irradiance\ in\ the\ interval} \quad (2)$$

The best case spectral match that can be obtained with the combination of LEDs was obtained by simulation and

is shown in Fig. 2. The spectrum shown in the figure is a result of a certain combination of intensity multipliers for each LED string. These intensity multipliers are simply the relative luminous flux values. The current to be flowed through each LED string is obtained from the relative luminous flux vs current graph given in the datasheet. The spectral matching procedure adopted for LED strings are to control the current through them to get a desired lumen output. The required lumen for a specific Spectral Irradiance is found with the help of MATLAB simulation. The program for the simulation uses the following equations.

$$Lux\ value = Lumen\ Value \times Conversion\ Factor \quad (3)$$

$$Conversion\ Factor = \frac{1}{4\pi D^2 \times (1 - cos(\alpha/2))} \quad (4)$$

Where D is the distance of the test plane from the light source and α is the viewing angle of the LED (125° for color LEDs and 120° for white LEDs). This illuminance value is converted to irradiance with the help of the following conversion factor (CF).

$$CF = \frac{\Sigma S_n(\lambda)}{683 \times \Sigma(S_n(\lambda) \times P_L(\lambda))} \quad (5)$$

Where $S_n(\lambda)$ is the spectral distribution of the LED normalized to 1 and $P_L(\lambda)$ is the normalized photopic luminosity function at that wavelength.

Using these formulae, the following table gives the required current values and the actual current values to which the led strings were adjusted to. The required irradiance vales for each LED string was obtained by simulation. Test plane in the product was placed at a distance of 20 cm from the light source.

[See Table III on Page 6.]

The values of actual irradiance to which the LEDs were adjusted to were substituted in the program to yield the following spectrum. The obtained spectral match is also shown.
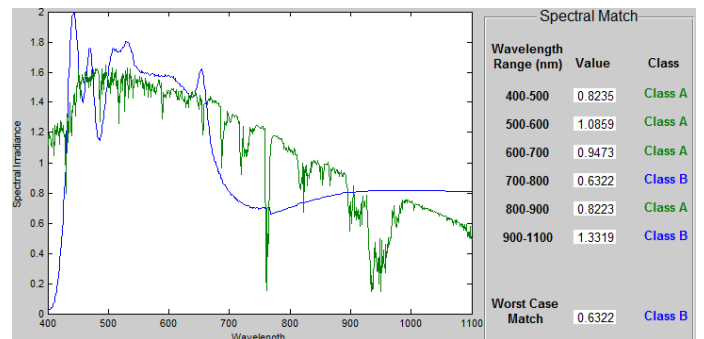

Fig. 4: Obtained Spectral Irradiance and Spectral Match

V. Results

The Spectral Match of each range of wavelengths is found by the MATLAB simulation program by substituting the actual irradiance values corresponding to the current flowing through the strings. From the calculations done by the program, it is clear that Class A spectral match was obtained in the visible region of the spectrum. The system's overall spectral match is class B due to the wavelength bands in the IR region with poor matching. The reason for this is the use of a halogen lamp, which is a broadband source.

Acknowledgement

We express our sincere gratitude to Dr. Martin Bliss, Research Associate at Centre for Renewable Energy Systems Technology (CREST), Loughborough University for giving us access to his research on the subject and providing answers to our questions through correspondence. His expertise in photovoltaic testing and his willingness to share his knowledge was a great boon to us.

VI. Conclusion

The Solar Simulator with LED as light source is found to meet Class A specification in the visible region. Furthermore, it is found that the spectrum almost exactly matches that of the standard spectrum for the visible spectral range. When LED is used as light source, very precise spectral matching can be done. Moreover, the cost of the equipment developed is much less than an equivalent simulator with Xenon arc lamp or other light sources. With the LED Solar Simulator, the output spectrum can also be controlled. This is not possible with the present day simulators.

References

[1] Ali M. Bazzi, *Member, IEEE*, Zach Klein, Micah Sweeney, Kevin P. Kroeger, Pradeep S. Shenoy, *Student Member, IEEE*, and Philip T. Krein, *Fellow, IEEE*, "Solid-State Solar Simulator," in IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 48, NO. 4, JULY/AUGUST 2012.
[2] Steve Winder, "Power Supplies for LED Driving"
[3] Tom Markvart and Luis Castañer, "Practical Handbook of Photovoltaics: Fundamentals and Applications"
[4] Shogo Kohraku, Kosuke Kurokawa, Tokyo University of Agriculture and Technology, "NEW METHODS FOR SOLAR CELLS MEASUREMENT BY LED SOLAR SIMULATOR"
[5] M.Bliss, T.R. Betts, R. Gottschalg *Centre for Renewable Energy Systems Technology (CREST)*, Department of Electronic and Electrical Engineering, Loughborough University, "ADVANTAGES IN USING LEDS AS THE MAIN LIGHT SOURCE IN SOLAR SIMULATORS FOR MEASURING PV DEVICE CHARACTERISTICS" in Proc. of SPIE Vol. 7048 704807-1.
[6] Martin Bliss, Stefan Wendlandt, Thomas R. Betts, Ralph Gottschalg, *Centre for Renewable Energy Systems Technology (CREST)*, Department of Electronic and Electrical Engineering, Loughborough University, "TOWARDS A HIGH POWER, ALL LED SOLAR SIMULATOR CLOSELY MATCHING REALISTIC SOLAR SPECTRA" in 24th European Photovoltaic Solar Energy Conference, 21-25 September 2009, Hamburg, Germany.
[7] M. Bliss, T.R. Betts, R. Gottschalg *Centre for Renewable Energy Systems Technology*, Department of Electronic and Electrical Engineering, Loughborough University "AN LED-BASED PHOTOVOLTAIC MEASUREMENT SYSTEM WITH VARIABLE SPECTRUM AND FLASH SPEED," in Technical Digest of the International PVSEC-17, Fukuoka, Japan, 2007.
[8] Held, Gilbert, "Introduction to light emitting diode technology and applications."
[9] Shogo Kohraku and Kosuke Kurokawa, Tokyo University of Agriculture and technology(TUAT), "A fundamental experiment for discrete-wavelength LED Solar Simulator."
[10] ASTM G173-03 Standard tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37 Tilted Surface.
[11] ASTM E927-05 Standard Specification for Solar Simulation for Terrestrial Photovoltaic Testing.
[12] Sergio Franco, "Design with operational amplifiers and analog integrated circuits"
[13] *www.wikipedia.org*
[14] *www.allaboutcircuits.com*

Prof. C. P. Mrinalini received the B.Tech degree in Electronics and Communication Engineering from College of Engineering, Trivandrum (affiliated to University of Kerala, India) in 1985, and M.Tech degree in Electronics Design and Technology from CEDT, IISc, Bangalore, India in 1996. She has twenty seven years of teaching experience in various Government Engineering Colleges in Kerala. She held the post of IT expert at University of Calicut from 2006 to 2009. As part of Industry Institute Interaction, She has served as project evaluation committee member at C-MET (Centre for Materials for Electronics Technology), a research center at Thrissur, Kerala. She is presently working as Professor in the Department of Electronics and Communication Engineering at Government Engineering College, Sreekrishnapuram, India.

Abhay Mohan M V is a Third Year Electronics and Communication Engineering student of Government Engineering College, Sreekrishnapuram. He has completed and presented the project work, 'LED based Solar Simulator', at the Centre for Materials for Electronics Technology (CMET). The Project has won a consolation prize at a state level contest for student projects.

Jishnu Pavithran is a Third Year Electronics and Communication Engineering student of Government Engineering College, Sreekrishnapuram. He has completed and presented the project work, 'LED based Solar Simulator', at the Centre for Materials for Electronics Technology (CMET). The Project has won a consolation prize at a state level contest for student projects.

K Lijo Osten is a Third Year Electronics and Communication Engineering student of Government Engineering College, Sreekrishnapuram. He has completed and presented the project work, 'LED based Solar Simulator', at the Centre for Materials for Electronics Technology (CMET). The Project has won a consolation prize at a state level contest for student projects.

Jinumon A is a Third Year Electronics and Communication Engineering student of Government Engineering College, Sreekrishnapuram. He has completed and presented the project work, 'LED based Solar Simulator', at the Centre for Materials for Electronics Technology (CMET). The Project has won a consolation prize at a state level contest for student projects.

Color	Relative luminous flux	Required Current (A)	Required Voltage (V)	Required Irradiance (W/m^2)	Measured Current	Measured Voltage (V)	Actual Irradiance (W/m^2)
White	0.9	0.62	23	131.86	0.63	23.016	134.07
White	0.95	0.661	23.08	143.37	0.67	23.09	145.38
Cyan	0.25	0.09	16.8	16.02	0.096	16.83	17.12
Green	0.25	0.09	16.8	11.67	0.09	16.8	11.67
Blue	0.2	0.117	11.436	21.78	0.126	11.472	23.53
Red	0.15	0.098	7.38	9.33	0.104	7.4	9.928

TABLE III: Required and Actual Irradiance