Research Journal of Applied Sciences, Engineering and Technology 15(6): 227-235, 2018
DOI:10.19026/rjaset.15.5862
ISSN: 2040-7459; e-ISSN: 2040-7467
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Submitted: January 18, 2018 Accepted: February 21, 2018 Published: June 15, 2018

Research Article

Spectral Irradiance Estimation of Light Emitting Diode Solar Simulator Based on Genetic Algorithm

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Abstract: This study aims to achieve a close spectral match to the AM1.5 solar spectrum from 400 nm to 1100 nm. LEDs are selected to achieve this target due to its wide utilization in markets; a vast range of LED wavelengths is available from UV through visible to IR. The spectral mismatch can increase the measurement uncertainty significantly. Solar simulator lighting subsystem design based on LED as a light source only is presented. Selecting the required LEDs combination to match the AM 1.5 using traditional methods is very difficult. This complex optimization problem has been solved by Genetic Algorithm (GA) to obtain the optimal combination of different LEDs in the range of 400 to 1100 nm. Moreover, spectral match and spectral ratio have been calculated. The results proved that, as the number of LED data entry varying, the solar simulator classification changes.

Keywords: Genetic algorithm, LED, solar simulator, spectral match, spectral ratio

INTRODUCTION

Solar simulator is a device that delivers illumination approximately matching natural sunlight. Solar simulator is commonly used to provide an accurate indoor test under laboratory conditions for solar cells. There are different types of lamps used as a light source for solar simulator (Abhay Mohan *et al*., 2014a). Solar simulators are more controllable than outdoor measurements and take shorter time for photovoltaic modules characterization. Progresses in photovoltaic technologies, multi-junction, high efficiency and high capacity devices lead to increase the complexity of indoor measurements. Typically I-V characteristics are measured by 1000 W/cm^2 and AM 1.5 of commercial solar simulators used Xenon lamp (Bliss *et al*., 2009). Xenon lamp has several weaknesses such as high cost, large space and high power consumption. Nowadays there are several reports on solar simulators employing LED lamps as a light source due to their high stability, low cost and low power consumption than xenon lamp (Jang and Shin, 2010; Plyta, 2015; Novickovas *et al*., 2014). Nowadays manufacturers are searching for improving light sources and filters for enhancing solar simulators performance. The main two types of solar simulators used today are steady-state and flash simulators which have specific advantages and drawbacks in accurate measurements of solar devices. The disadvantages of steady-state solar simulators are high maintenance cost and thermal control issues (Bliss *et al*., 2009). Flash simulators overcome these disadvantages but capacitance affects measurement (Monokroussos *et al*., 2006). Using single light source in solar simulator types spectral matching is affected. LED based solar simulator can overcome these disadvantages through higher LED lifetime (up to 100,000 h in some cases) and thus reduced maintenance costs. Also LED has almost zero emission in far infrared part of solar spectrum and thus easier thermal control. LEDs can be accurately controlled the output intensity in less than one millisecond. Using LEDs in solar simulator construction poses a number of difficulties mainly because of narrower output spectral width which leads to use multiple LEDs with different emission wavelengths. According to the International Electrotechnical Commission (IEC) standards, a class AAA solar simulator need to match the AM1.5 solar spectrum between 400 nm and 1100 nm in 6 bins (Plyta *et al*., 2013). The first 5 bins are 100 nm wide and the last bin is 200 nm wide. The spectral match in each interval needs to be between 0.75 and 1.25 to meet class A i.e., the spectral mismatch can be up to 25%. Also, non-uniformity and temporal stability need to be less than or equal to 2% to reach class A.

Solar simulator based on hybrid light source of LED and halogen lamps to overcome wavelength in the

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range of visible to infrared was designed (Grandi *et al*., 2014). Kolberg *et al*. (2011) was conveyed on LED based solar simulator for PV industry. The temporal stability of light intensity achieved was ±0.3%. (Namin *et al*., 2013) presented low to moderate cost of LED based solar simulators for solar cells characterization. The five simulators were categorized as class B according to irradiance uniformity and temporal instability. The solar simulator can test I-V curves of area 12.5×12.5 cm^2 of the solar cell. (Stuckelberger *et al*., 2014) presented LEDs based solar simulator of class AAA. The simulator consists of 19 LEDs with 11 different colors of (400-750 nm) with an illuminated area of 18 cm×18 cm. (Leary *et al*., 2016) studied the performance of two different types of solar simulators by comparing between xenon lamp based (class AAA) and LED-based solar (class AAA) simulators. (Watjanatepin, 2016) was presented Chip-On-Board LEDs solar simulator. Eighteen 50Watt COB LEDs were applied as a light source. The non-uniformity of irradiance is approximately of class C on tested area of 224 cm^2. The developed simulator realized 1-sun intensity and complete control of the light sources whereas variable intensities and spectral distribution was achieved (Monokroussos *et al*., 2006). Implementation of a newly developed LED solar simulator including optical source design, electrical system design and software based GUI was achieved (Linden *et al*., 2014).

This study focuses on design a lighting subsystem of solar simulator based on LED as a light source only. Genetic Algorithm (GA) as an optimization technique is used to choose the best combinations from different types of LED available in the market. Spectral match classification and spectral ratio are used as constraints to achieve a class AA.

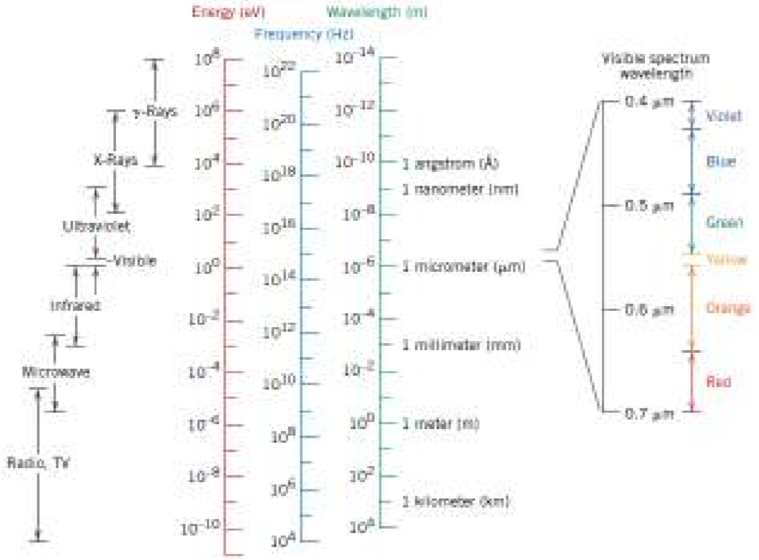
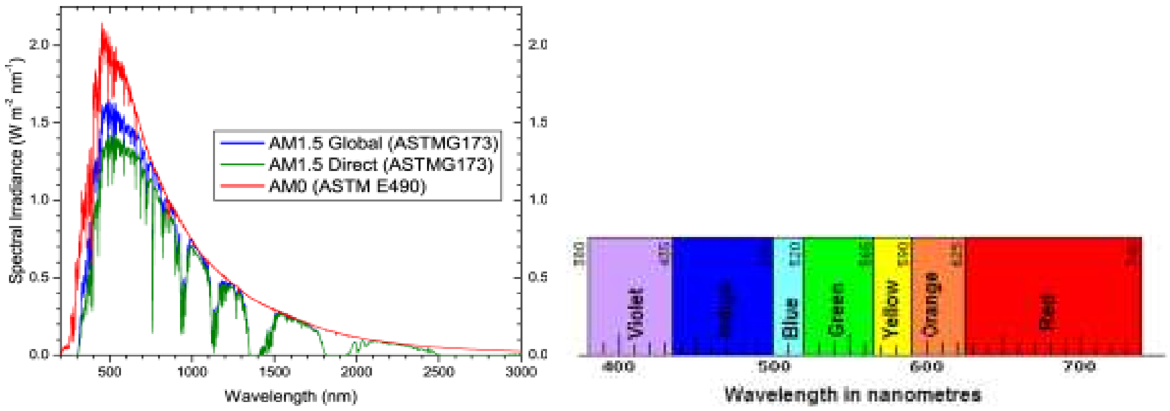


Fig. 1: The electromagnetic radiation spectrum (Callister and Rethwisch, 2013)



(a)

(b)

Fig. 2: (a): Solar Spectrum and; (b): Visible Light Band (NREL, 2004)

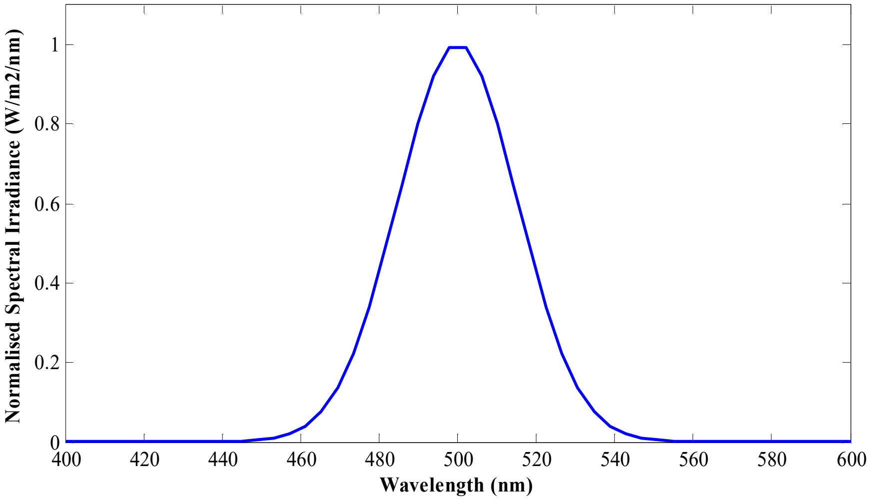


Fig. 3: Spectrum of a LED with a CWL at 500 nm

Solar spectrum: The electromagnetic radiation spectrum is shown on a logarithmic scale in Fig. 1. Visible light lies within a very narrow region of the spectrum, with wavelengths ranging from 0.4 mm to 0.7 mm.

All electromagnetic radiations differ from each other by their wavelength. Violet, green and red have a wavelength of approximately 0.4 mm, 0.5 mm and 0.65 mm, respectively. Figure 2 presents solar spectrum and visible light band.

MATERIALS AND METHODS

Due to outdoor environmental predictability, PV module characterization in indoor systems is necessary. LED-based solar simulator prototype has been proposed to combine the advantages of the most commonly used simulators (steady state and pulsed) and to eliminate their disadvantages. To achieve 1-Sun intensity at a closely matched and continuous spectrum, it requires an optimization method to choose the optimal LED spectrum from various types of LEDs in the market. Genetic algorithm is selected to carry out this problem. The following sections discuss modeling of LED sources, solar simulator classification, optimization problem parameters and finally results and discussion. This study was carried out in Electronics Research Institute in Egypt during the previous year.

Mathematical modeling: This section gives a brief description of LED modeling, solar simulator parameters and solar simulator classification which will be taken into account during the optimization process.

LED Modeling: The energy band gap of the semiconductor defines the central wavelength at which they emit. LED can be classified as colored and white LEDs. Colored LEDs have a specific central wavelength and a narrow emission band whereas white LEDs have a broader emission band.

The spectral output of colored LEDs based on their datasheet values is approximated using the Gaussian function as follows (Plyta, 2015):

$$f(x) = Ae^{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2} \tag{1}$$

where, A is function height, σ is standard deviation of the function and μ is mean value. LEDs' datasheets provided by the manufacturers include radiant flux, *CWL* and *FWHM*. *CWL* is the wavelength at which LED has its maximum power. *FWHM* is the function width at which the function is equal to half of its maximum value. LED spectrum with *CWL* equal to 500 nm and *FWHM* of 50 nm is cleared in Fig. 3.

The Gaussian function specific to the LEDs is described as (Plyta, 2015):

$$f(x) = Pe^{-\frac{1}{2}(\frac{\lambda-CWL}{\sigma})^2} \tag{2}$$

where, P is radiant flux curve peak of LED and the mean value is equal to central wavelength, *CWL*.

The standard deviation depends on *FWHM* as follows (Plyta, 2015):

$$\sigma = \frac{FWHM}{2\sqrt{2\,ln2}} \tag{3}$$

Solar simulator parameters: Spectral Match (*SM*) is an important parameter for solar simulator performance. It measures the matching of a simulated spectrum to the standard spectrum (AM1.5G). If the two spectrums are perfectly matched, the spectral match will take the value 1. If not, it will take values either greater than or lesser than 1depending on the difference

Table 1: Distribution of solar irradiance performance requirements

Wavelength (nm)	Proportion of total irradiance (%)
400-500	18.4
500-600	19.9
600-700	18.4
700-800	14.9
800-900	12.5
900-1100	15.9

Table 2: Solar simulator standard class specification

Class	Spectral ratio	Spectral match
A	0-0.25	0.75-1.25
B	0.25-0.4	0.6-1.4
C	0.4-1	0.4-2

between the two spectrums. The wavelength range for a solar simulator is approximately around 400 nm to 1100 nm according to the American Society for Testing and Materials (ASTM) standards. This can vary slightly based on the standard adopted. For the purpose of checking spectral match, the wavelength range of interest is divided into six wavelength bands. There are five 100 nm bands from 400 nm to 900 nm and one 200 nm band from 900 nm to 1100 nm. Each of these bands contains a particular percentage of the total integrated irradiance. This is specified in the international standard ASTM E927-05 (ASTM 2012). Irradiance distribution as specified in the standard is shown in Table 1.

Solar simulators classification: According to the IEC 60904-3(IEC 60904-3, 2016), the quality of a solar simulation system divided into three main classification groups: Spatial or irradiance non-uniformity, temporal instability and spectral match. Table 2 illustrates specifications of solar simulator standard classes. A solar simulator meets class A specification in all three dimensions is referred to as class A solar simulator or sometimes a class AAA.

Genetic algorithm: Genetic Algorithm (GA) paves the road to optimization problems which increasing availability of high performance computers at relatively low costs. GA is easy to understand, heuristic or meta-heuristic method, modular, efficient with multi objective functions, non-differential, non-continuous problems and used for the noisy environment (Whitley, 1994).

The solution obtained by GA is not necessarily the optimal but it is well suited to problem needs and can be acquired more rapidly than the other methods. GA is also a stochastic method which means that it generates a population probabilistically to determine the solution (Gibbs *et al*., 2011; Lobo and Lima, 2007; Maaranen *et al*., 2007).

To design GA problem, GA is required to follow several steps. GA required a problem to solve, encoding technique (gene, chromosome), initialization procedure (creation), evaluation function (environment), selection of parents (reproduction), genetic operators (mutation, recombination and crossover) and parameter settings (practice and art) (Singh, 2011).

Problem formulation: The main objective is to minimize the difference between theoretical AM1.5 solar spectrum and estimated spectrum of LEDs in order to achieve a minimum spectral mismatch by using as fewer LEDs as possible. The standards take into account 400 nm-1100 nm wavelength range and specify a class A spectral match, if it is within 0.75-1.25 range, i.e., up to 25% mismatch for 5 different 100 nm bins and a 200 nm bin. The objective function is described as below:

Minimize:

$$f(x) = \begin{cases} RLS & CL' <= 0.25\,, SM <= 1 \\ SM * RLS & CL' <= 0.25\,,\ SM > 1 \\ (CL'+1) * RLS & CL' > 0.25\,,\ SM <= 1 \\ SM * \left((CL'+1) * RLS + 1\right) & CL' > 0.25\,,\ SM > 1 \end{cases} \tag{4}$$

The relative value of least-squares (*RLS*) calculation is given by (Plyta, 2015):

$$RLS = \frac{(Solar\ Spectrum - LED\ Spectrum)^2}{Solar\ Spectrum} \tag{5}$$

$$CL' = |1 - S| \tag{6}$$

$$CL = max(CL') \tag{7}$$

where, CL' corresponds to the classification of the spectrum. Spectral ratio is defined as the ratio between the spectral response of LEDs and that of AM1.5 across the specified bin. *RLS* is used for fitting and minimizing the difference between the actual value of the solar spectrum and the value estimated by the synthesis of the LEDs' wavelengths. For the wavelength range (λ_1, λ_2), the spectral ratio is given by (Abhay Mohan *et al*., 2014b):

$$S = \frac{\int_{\lambda_1}^{\lambda_2} g(\lambda)}{\int_{\lambda_1}^{\lambda_2} f(\lambda)} \tag{8}$$

SM is calculated as the ratio of the actual percentage of irradiance falling during the specified interval and the required percentage of irradiance as follows (Abhay Mohan *et al*., 2014b):

$$SM = \frac{Actual\ Percentage\ of\ Irradiance}{Required\ Percentage\ of\ Irradiance} \tag{9}$$

$$Actual\ Percentage\ of\ Irradiane = \frac{\int_{\lambda_1}^{\lambda_2} g(\lambda)}{\int_{400}^{1100} f(\lambda)} \tag{10}$$

where $g(\lambda)$ is LED spectrum function, $f(\lambda)$ is solar spectrum function and λ_1, λ_2 are starting and end point of a wavelength band respectively. The GA flowchart for the optimization process is shown in Fig. 4.

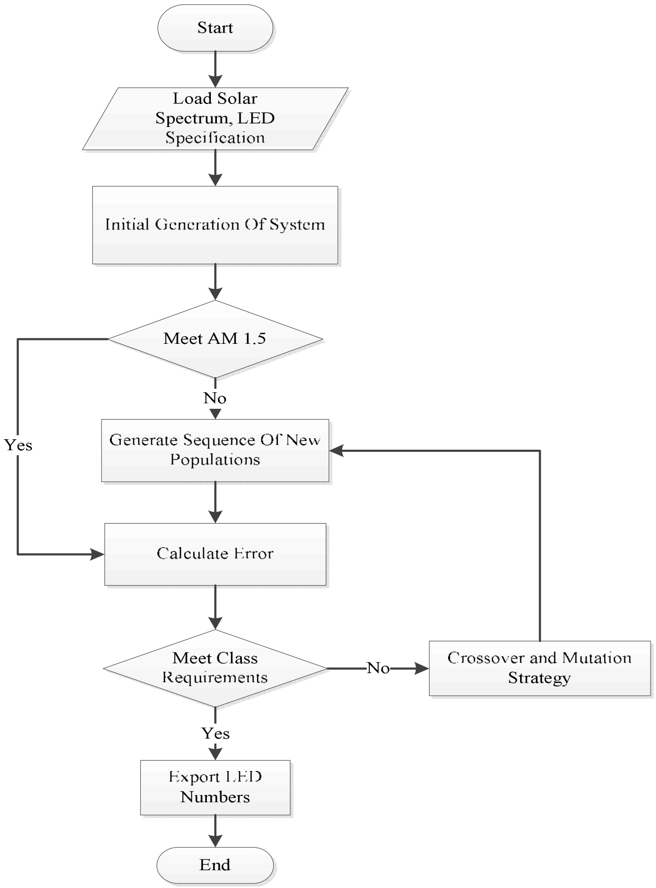


Fig. 4: Optimization process flowchart using GA

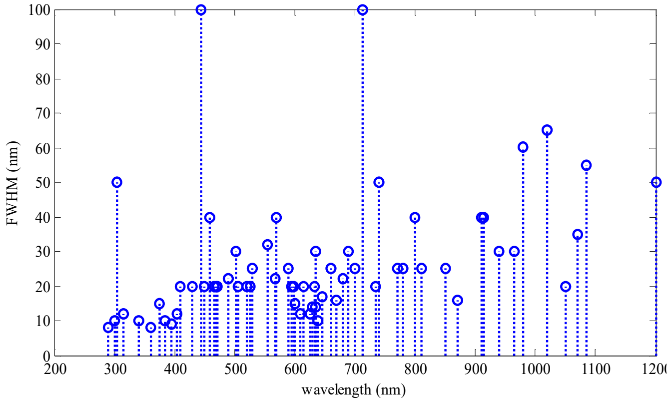


Fig. 5: The *FWHM* distribution of different LEDs across the 300 nm-1100 nm

RESULTS

Figure 5 shows the *FWHM* distribution of proposed LEDs. It can detect that there is a wide range of LEDs with different characteristics depending mainly on the material of their dies. They all come in a variety of outputs power. Some of them are really powerful due to the usage of multiple dies that construct the chip. There is a wide range of LEDs in the range of 400 nm-700 nm and the distribution of LEDs in the final band (900 nm-1100 nm) is low which will affect GA results.

The accuracy of LED-based solar simulator determined by the combination of different wavelengths used in matching the solar spectrum.

A selection of LEDs available on the market was chosen to simulate the solar spectrum. An optimization method was followed to specify which and how many of those LEDs lead to a class A spectral match. The

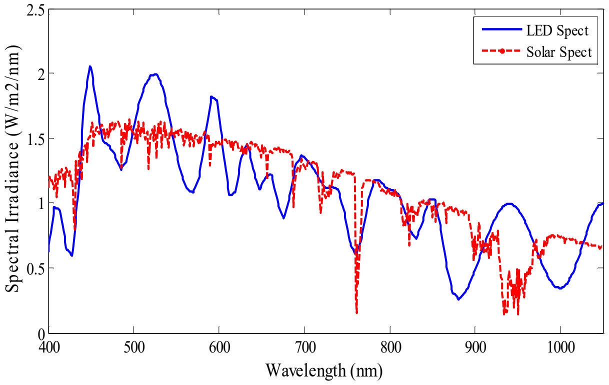


Fig. 6: LED spectrum and AM 1.5 using 18 LED in Case 1

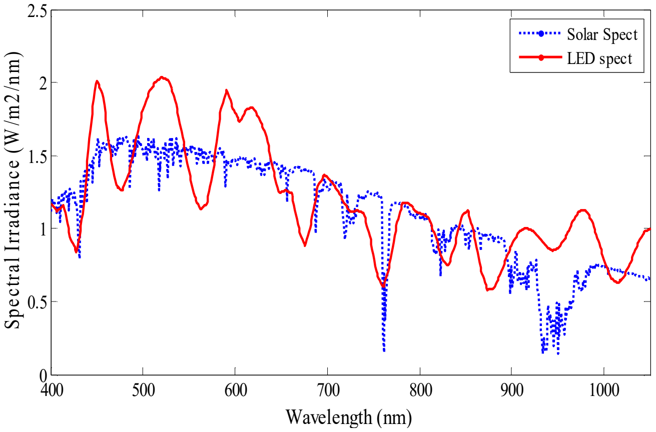


Fig. 7: LED spectrum and AM 1.5 using 18 LED in Case 2

Table 3: Distribution of irradiance performance for case 1

Wavelength (nm)	Proportion of total irradiance (%)	Spectral match
400-500	19.8	1.07
500-600	27.8	1.39
600-700	11.5	0.625
700-800	13.9	0.93
800-900	10.2	0.816
900-1100	16.7	1.05

Table 4: Distribution of irradiance performance for case 2

Wavelength (nm)	Proportion of total irradiance (%)	Spectral match
400-500	19.4	1.05
500-600	24.7	1.24
600-700	13.5	0.73
700-800	12.3	0.83
800-900	9.09	0.72
900-1100	20.7	1.3

main objective is to minimize the difference between the theoretical AM1.5 solar spectrum and the spectrum constructed by the LEDs by using as fewer LEDs as possible. The standards specify a class A spectral match if it is within 0.75-1.25 range for 5 different 100 nm bins and a 200 nm bin. The simulation results organized into three cases according to the number of LED combination entered to GA program.

In the first case; the available number of LED wavelengths was 33, the second case was 36 and the final case was 63 LEDs. Figure 6 shows LED spectrum and solar spectrum for case 1. GA reached minimum value of least square error by using 18 LED from 33 LED wavelengths. Table 3 gives the distribution of irradiance performance and spectral match. By comparing the obtained results to the reference values, it cleared that solar spectrum is approximately matched LED spectrum in first band 400-500 nm and proportion of total irradiance is 19.18%. In second wavelength band (500-600 nm), there are some peaks in LED spectrum so the ratio of LED spectrum to total LED spectrum is 26.5%. In the other wavelength bands, solar spectrum is approximately matching LED spectrum. The solar simulator classified as class B. the spectral ratio obtained is 0.0549.

Case 2, the entered number of LEDs wavelengths is 36 types and reached the minimum value of least square error by using 18 LED. Figure 7 shows LED spectrum and solar spectrum for Case 2. Table 4 gives the distribution of irradiance performance and spectral match.

The main difference between Case 1 and Case 2 is in six band 900-1100 nm. The proportion of total

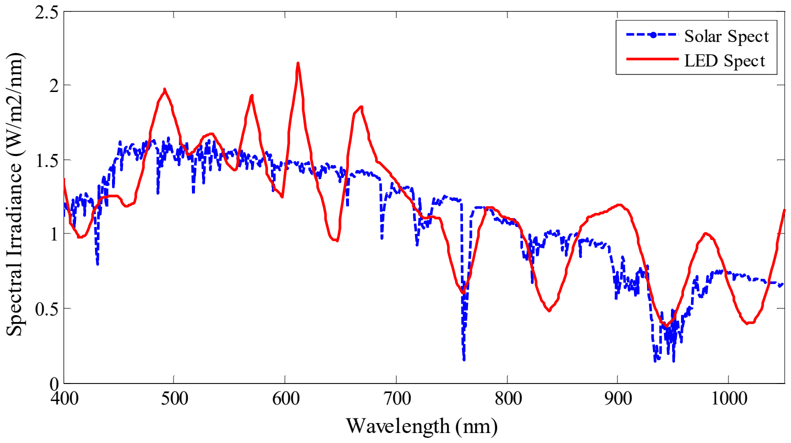


Fig. 8: LED spectrum and AM 1.5 using 29 LED in case 3

Table 5: Distribution of Irradiance Performance for case 3

Wavelength (nm)	Proportion of total irradiance (%)	Spectral match
400-500	21.4	1.16
500-600	17.9	0.90
600-700	19.8	1.07
700-800	12.8	0.86
800-900	11.9	0.95
900-1100	15.9	1.00

Table 6: Comparison of the present design with the previous works

	Proposed design		(Watjanatepin, 2017)		(Bliss *et al*., 2009)	(Presciutti *et al*., 2014)	
Wavelength (nm)	% of Irradiance	SM	% of Irradiance	SM	SM	% of Irradiance	SM
400-500	21.4	1.16	22.61	1.229	1.86	10.7	0.58
500-600	17.9	0.90	27.8	1.397	1.31	14.4	0.72
600-700	19.8	1.07	16.95	0.921	0.84	15.2	0.83
700-800	12.8	0.86	12.65	0.849	0.44	12.2	0.82
800-900	11.9	0.95	10.03	0.802	0.47	24.2	1.98
900-1100	15.9	1.00	9.96	0.626	0.75	23.3	1.45
Total	Class A		Class B		Class C	Class C	

irradiance is approximately 24%. The simulation classification is class B and spectral ratio is 0.0609.

Case 3, carried out using 63 different LED wavelengths. The best combination achieved by using 29 types of LED as adopted in Fig. 8. The spectral match and the proportion of total irradiance are cleared in Table 5. So, the final simulator classification is class A and spectral ratio is 0.024.

DISCUSSION

Table 6 shows the comparison between the present results of LED based solar simulator using GA with the previous works. It depicted that (Watjanatepin, 2017) achieved solar simulator with class varying from A to C in different wavelength bands by using different types of LED. The overall class of solar simulator is B. In (Bliss *et al*., 2009) and (Presciutti *et al*., 2014) the class achieved is C.

Plyta, (2015) designed a solar simulator based on light emitting diode with different combination which are 18, 20, 22, 24, 26, 28, 30 and 32, in each case spectral ratio is0.18, 0.18, 0.18, 0.18, 0.18, 0.19, 0.21 and 0.27 respectively with interval 20 nm and class AAA was achieved. In the present study spectral ratio achieved in the tested three cases are 0.0549, 0.0609 and 0.024 respectively with an interval of 1 nm.

The proposed study agrees with the results obtained by (Plyta, 2015) with a small deviation in simulation parameters which are total number of LEDs, optimization parameters and interval used. The results obtained here were better than the results obtained by (Watjanatepin, 2017), (Bliss *et al*., 2009) and (Presciutti *et al*., 2014). In the proposed method the simulator is classified as class A while the previous studies achieved are class B, C and C.

CONCLUSION

LED light sources were used to produce a solar simulator due to their improved capability compared to other sources. The aim of this study was to achieve a close spectral match to AM1.5 solar spectrum from 400 nm to 1100 nm. AM 1.5 solar spectrum needs to be acquired. GA as an optimization technique was chosen to solve the optimization problem and determine how many combinations of LED are chosen by GA to accurately represent the theoretical spectrum.

29 types of LED from 63 different wavelengths results in a satisfactory class B spectral mismatch of 25% across the range specified by the standards. The results show that the great potential LEDs offer as light sources in solar simulators leads to minimize the spectral mismatch error and improve the measurement accuracy.

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