Towards a fully LED-based solar simulator - spectral mismatch considerations

TOWARDS A FULLY LED-BASED SOLAR SIMULATOR – SPECTRAL MISMATCH CONSIDERATIONS

Foteini Plyta, Thomas R. Betts and Ralph Gottschalg
Centre for Renewable Energy Systems Technology (CREST)
School of Electronic, Electrical and Systems Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK
Tel: +44 1509635323, Email: F.Plyta2@lboro.ac.uk

ABSTRACT: LED solar simulators have a high potential for high quality characterisation of solar cells. One of the main challenges is to achieve a close spectral match to the AM1.5 solar spectrum from 350nm to 1300nm. The main sources of measurement uncertainty are the spectral mismatch, the non-uniformity of light and the reference cell. The spectral mismatch can increase the measurement uncertainty significantly. In order to minimize a major uncertainty factor a close spectral match needs to be acquired. It will be shown that the usage of LEDs, which are narrow wavelength emitting light sources, can improve the measurement accuracy of the solar simulator by accurately matching the solar spectrum. The process of choosing the best combination of wavelengths and the LED population per wavelength is a complex, dual optimization problem. This paper evaluates the optimisation algorithms chosen and examines the influence of different fitness functions in acquiring a Class A+ spectral match.
Keywords: Light Emitting Diodes (LEDs), Solar Simulator, Characterisation, Spectral match.

1 INTRODUCTION

It is being argued that LEDs are excellent candidates as light sources in solar simulators as they have the potential to result in a Class AAA LED system, regarding the IEC standards [1]. It will be shown that one of the many advantages in using LEDs as main light sources in a solar simulator is their capability to achieve a close spectral match to the AM1.5 solar spectrum, which improves the measurement accuracy of the solar simulator. They could also be regulated to meet any other desired AM as long as realistic intensities are required. Their effectiveness in achieving variable light intensities and variable output spectra provides more flexibility in reproducing realistic environmental conditions in the solar simulator [2]. Minimising the uncertainties introduced due to spectral mismatch improves the overall measurement accuracy of the solar simulator and can improve the characterisation of multi-junction solar cells and the energy yield prediction in general. In order to match the current of different stacked cells, the spectral output of the solar simulator needs to be adjusted to the spectral response of each junction. Also, the elimination of the spectral mismatch under various spectra provides more accurate measurements which lead to a precise energy yield prediction of various PV technologies.

According to the IEC standards [1], a Class AAA solar simulator needs to match the AM1.5 solar spectrum between 400nm and 1100nm in 6 bins. The first 5 bins are 100nm wide and the last bin is 200nm wide. The spectral match in each interval needs to be between 0.75 and 1.25 to meet the Class A i.e. the spectral mismatch can be up to 25%. Also, the non-uniformity and the temporal stability need to be less than or equal to 2% to reach Class A. This paper focuses on the spectral match Classification. However, a wider spectral range from 350nm to 1300nm was chosen to account for the spectral response of different PV technologies.

Identifying which LEDs should be used to better match the solar spectrum is a very complex dual optimisation problem. Elaborate optimisation algorithms needed to be identified and used to better solve the problem. Those algorithms are the genetic algorithm and CVX which is an open source modelling package for convex optimisation used in Matlab. The chi-squared is used as the error criterion. Different fitness functions were used to determine their influence to acquiring a Class A+ spectral match between 0.9 and 1.1, i.e. 10% mismatch. The comparison between the results obtained by the different fitness functions will determine the wavelengths of LEDs and the quantities of each wavelength that need to be used to best match the AM1.5 solar spectrum. It will also be shown how this result compares to the spectra of other types of lamps.

2 SIMULATION SET-UP

2.1 Choice of LEDs

LEDs offer many advantages when used as light sources in solar simulators. They are narrow wavelength emitting light sources with a specific central wavelength, FWHM (Full Width at Half Maximum) and maximum power output. Their intensity distribution is described by a Gaussian distribution.

A selection of LEDs available on the market was chosen to set the initial wavelengths that cover the 350nm-1300nm spectral range. Figure 1 shows the FWHM and radiant flux distribution of those LEDs.

It can be observed that there is a wide range of LEDs with different characteristics depending mainly on the material of their dies. The 500nm-600nm visible range can also be represented by the usage of warm white LEDs which have a broader power distribution with a peak around that area. It can be observed in Figure 1 that the availability of LEDs in the 1100nm to 1300nm range is very limited. They all come in a variety of power outputs. Some of them are really powerful due to the usage of multiple dies that construct the chip.

The cost and wavelength availability of the LEDs does not allow for the usage of an infinite number of them to best fit the AM1.5 solar spectrum. Therefore, the best combination of wavelengths and the number of LEDs for each wavelength needs to be determined. The goal is to find the minimum number of different wavelengths (i.e. LED types) that best match the AM1.5 solar spectrum allowing for a spectral mismatch of 10% instead of 25% specified in the standards [1]. This problem is a complex dual optimisation problem. The first objective is to determine the best overall combination of wavelengths out of the overall range of them and the second objective is to calculate the best possible agreement for a given set of LED types. The number of possible wavelength combinations increases exponentially with the number of available LEDs as it can be seen in Figure 2. It becomes clear that this problem cannot be solved analytically as it is computationally intensive and time consuming. Therefore, the usage of optimisation algorithms is crucial to reach a close to optimum solution.

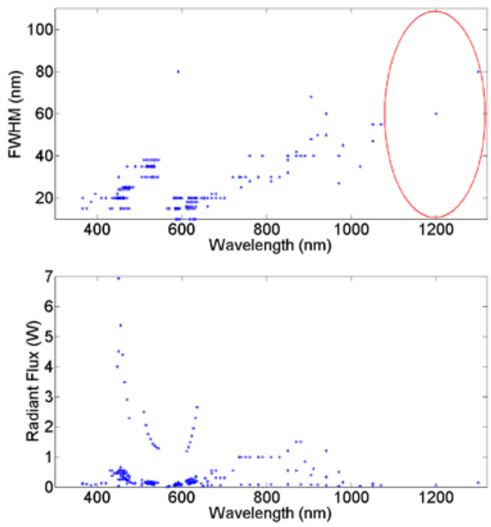

Figure 1: The FWHM and radiant flux distribution of different off the shelf LEDs across the 350nm-1300nm spectral range.

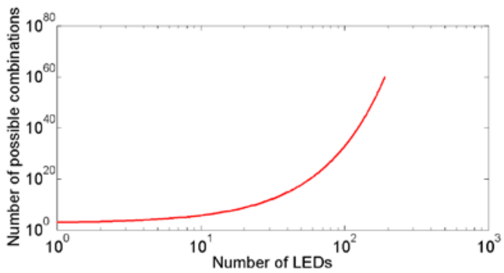

Figure 2: The number of possible combinations increases exponentially with the number of LEDs.

2.2 Optimisation algorithms

The main objective is to minimize the difference between the theoretical AM1.5 solar spectrum and the spectrum constructed by the LEDs in order to achieve a 10% spectral mismatch by using as fewer LEDs as possible. The standards take into account the 400nm-1100nm wavelength range and specify a Class A spectral match if it is within the 0.75-1.25 range, i.e. up to 25% mismatch for 5 different 100nm bins and a 200nm bin. The optimisation process described in this paper calculates the spectral mismatch across the 350nm-1300nm wavelength range. Two different optimisation techniques need to be followed to solve different aspects of the problem. The first one is the determination of the best combination of wavelengths and the second one is the determination of the number of LEDs per wavelength for a given set of wavelengths. They both depend on each other. The first optimisation method chooses a combination of LEDs for every iteration and then the second optimisation method determines how many of those LEDs should be used and what the best possible fit to the target spectrum could be.

The accuracy of the result depends on the precision of the algorithm used. Therefore, a robust optimisation method should be used to determine the optimum solution. The optimisation method chosen for the first objective is the genetic algorithm while the optimisation method chosen for the second objective is the cvx, an open source modelling package for convex optimisation in Matlab with the chi-squared as the error criterion. These algorithms were chosen for their speed, accuracy and reliability.

The genetic algorithm is an optimisation method which uses techniques of biological evolution to converge to an optimal solution. It starts off with an initial population and through means of natural selection such as mutation and crossover it creates new solutions called offspring which perform better until a satisfactory solution is obtained. The criterion that determines which solutions are better is called a fitness function. The fitness function is calculated for each individual of a population and the fittest survive. Different fitness functions were used to determine their influence on the result. These are the spectral ratio as specified by the standards, the spectral ratio in 100nm intervals across the 350nm to 1300nm spectral range and the error value of chi-squared. Therefore, the genetic algorithm will try to minimise the difference between the two spectra, the solar and the one synthesized by the LEDs, giving priority to the solutions that have the best fitness function.

The spectral ratio is defined as the ratio between the spectral response of the LEDs and that of the AM1.5 across the specified bin. The error value of chi-squared is used for fitting and it minimises the sum of the squares of the difference between the actual value of the solar spectrum and the value predicted by the synthesis of the LEDs' wavelengths. Therefore,

$$\underline{e} = \underline{SRth} - \underline{La}$$

where, $\underline{e} = \begin{bmatrix} e(1) \\ e(2) \\ \vdots \\ e(N) \end{bmatrix}$, $\underline{SR_{th}} = \begin{bmatrix} SR_{th}(1) \\ SR_{th}(2) \\ \vdots \\ SSR_{th}(N) \end{bmatrix}$,

$\underline{L} = \begin{bmatrix} L_1(1) & L_2(1) & \cdots & L_N(1) \\ L_1(2) & L_2(2) & \cdots & L_N(2) \\ \vdots & \vdots & & \vdots \\ L_1(N) & L_2(N) & \cdots & L_N(N) \end{bmatrix}$ and $\underline{a} = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_N \end{bmatrix}$

All the components are expressed in the form of matrices. The error is e and expresses the difference between the theoretical and the modelled spectrum. SR_{th} is the theoretical AM1.5 solar spectrum, L is the spectrum of all the LEDs combined and L_1, L_2,.., L_N are the spectra of each individual LED. N is the number of different LED types used and a is a matrix that contains the quantities of each LED to be used, i.e. how many times an LED should be used to best match the solar spectrum. The least squares calculation of the error is as follows:

$$J = \underline{e}^T\underline{e} = (SRth - La)^T(SRth - La) = SRth^T SRth - SRth^T La - a^T L^T SRth + a^T L^T La = SRth^T SRth + a^T L^T La - 2a^T L^T SRth$$

The above equation expresses mathematically the error criterion for this problem.

3 RESULTS

Three different fitness functions were used in the genetic algorithm to determine which one would give the most reliable results. These are the spectral ratio in 100nm intervals across the 350nm to 1300nm spectral range, the spectral ratio as specified by the standards, and the error value of chi-squared.

The spectral ratio calculated in 100nm bins over the 350nm to 1300nm spectral range did not result in Class A+ due to the lack of a wide variety of LEDs in the range between 1100nm and 1300nm. The algorithm was trying to give priority to solutions that would have the best spectral match in 100nm bins. However, the 1200nm to 1300nm range could never be reduced enough to give a Class A+ spectral match due to the poor availability of LEDs in that range. As a result, the algorithm always ended in worse Classifications than the desired A+ when that fitness function was used and therefore that method was not considered further.

Then the spectral ratio in bins specified by the standards was used as a fitness function. The spectral ratio had a value between 0.056 and 0.059, i.e. 5.6% to 5.9% mismatch when 24 to 30 different wavelengths were used to match the solar spectrum which meets the desirable criterion of Class A+ spectral mismatch better than 10%. However, the area between 1100nm and 1300nm was discarded by the algorithm since it was not set in its fitness function. As a result the genetic algorithm prioritised the solutions that resulted in good spectral match up to 1100nm as this allowed it to use less LEDs and still return a result within the specifications of the fitness function. This can be seen in Figure 4.

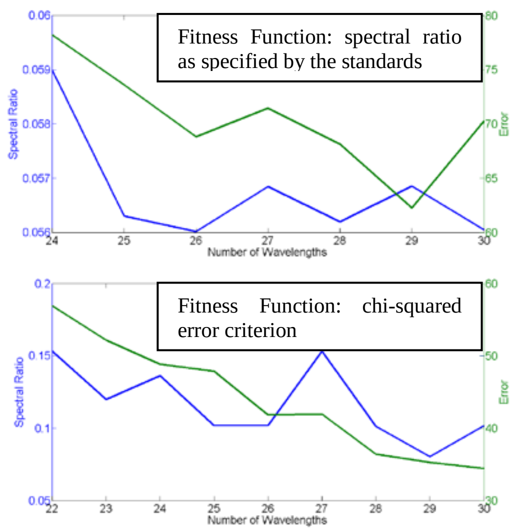

Figure 3: Spectral ratio and chi-squared error for different numbers of wavelengths, for different fitness functions.

The third fitness function considered was the chi-squared error. This proved to be the best fitness function of the three since it was the only one returning results that included LEDs across the entire specified range of 350nm to 1300nm. However, the Classification is A+ only for the bins specified by the standards and not for the 1100nm to 1300nm range which is again due to the lack of availability of LEDs in that range.

Those results can be observed in Figure 3 which shows the variation of the spectral ratio and the error criterion for different numbers of wavelengths. The upper graph refers to the fitness function determined by the spectral ratio specified by the standards and the bottom graph refers to the fitness function determined by the chi-squared error. It can be observed that in the first case the value of the spectral ratio is almost the same for all cases whereas the error increases as the number of wavelengths decreases but does not follow a clear increasing trend, which is within the calculation error of the genetic algorithm. The spectral ratio stability is believed to be a result of the genetic algorithm trying to minimise the difference between the spectra and always overshooting in the same areas to do so. On the other hand when the error criterion is used as a fitness function it increases when the number of wavelengths used decreases showing that the spectra difference will always be smaller when more LEDs are used. However, the spectral ratio as calculated by the standards does not follow a trend showing that it can be Class A+ even if a smaller number of wavelengths is used since the algorithm might overshoot some of them resulting in a smaller spectral ratio.

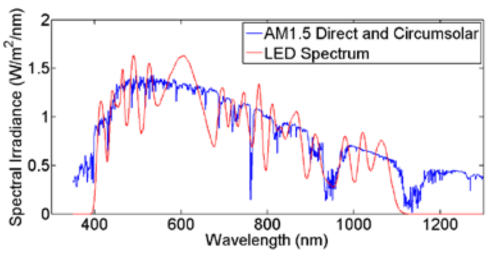

Figure 4: Spectral match for 26 different wavelengths when the fitness function is the spectral ratio specified by the standards. The 1100nm to 1300nm range is not taken into account by the genetic algorithm.

Once the error criterion fitness function was determined to be the best, the result using 26 different wavelengths was adapted as it showed a smaller spectral ratio than other solutions and at the same time the chi-squared error was not too elevated when compared to other numbers of wavelengths. The spectral mismatch can be shown in Figure 5 and is equal to 10.1%.

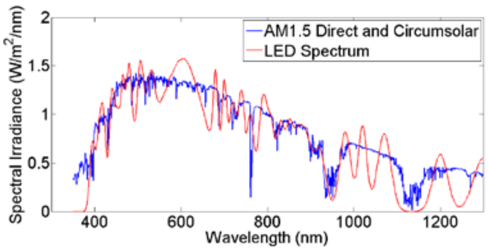

Figure 5: Spectral match for 26 different wavelengths when the fitness function is the error criterion.

The LEDs chosen for this simulation had the smallest FWHM among the ones of the same central wavelength available. The same simulation was conducted using the LEDs with the highest FWHM and the result can be seen in Figure 6. The higher FWHM offers a match better coverage of the spectrum.

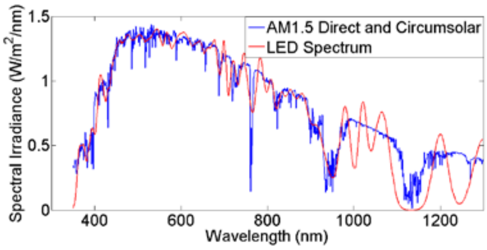

Figure 6: Spectral match for 26 different wavelengths using LEDs of higher FWHM.

However, the value of the spectral ratio was in the range of 10% as before due to the 900-1100nm spectral range which seems to determine the spectral ratio in all cases. The range between 1200nm and 1300nm still does not result in a Class A+ spectral match due to the lack of available LEDs in that range. However, LEDs still offer a better spectral match when compared to other light sources. Their spectrum was compared to the spectra of the light sources of two Class A+ solar simulators available in our lab. Figure 7 shows that the LEDs, whose spectrum is represented in red, cover the solar spectrum very accurately and better than the other light sources in the range up to 1000nm whereas solar simulator 2 offers a better coverage in the range between 1000nm to 1300nm.

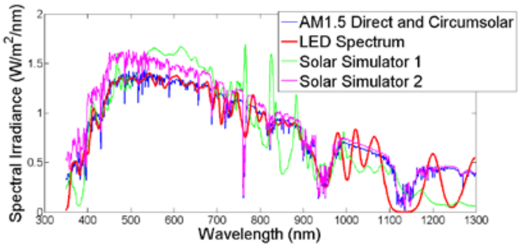

Figure 7: The LED spectrum compared to the spectra of two solar simulators available in our labs.

4 CONCLUSIONS

The spectral mismatch error and the significance to minimise it was addressed in this paper by creating an experimental spectrum of Class A over the 350nm to 1300nm. LEDs were used as light sources to produce the experimental spectrum due to their improved capabilities compared to other light sources. Elaborate optimisation techniques were chosen to solve the dual optimisation problem of how many wavelengths and how many LEDs per wavelength need to be used to accurately represent the theoretical spectrum. Different fitness functions were tested for their accuracy.

It was shown that the best fitness function is the chi-squared error criterion since it offers a solution that minimises the difference between the theoretical and the LED spectra across the entire spectral range of interest. A selection of 26 wavelengths results in a satisfactory class A+ spectral mismatch of 10% across the range specified by the standards and at the same time it covers the range between 1100nm and 1300nm as accurately as the availability of LEDs permits. The comparison with other light sources shows that LEDs offer a better spectral match. This shows the great potential LEDs offer as light sources in solar simulators to minimise the spectral mismatch error and improve their measurement accuracy.

4 REFERENCES

[1] IEC 60904-9 Ed.2, "Photovoltaic devices – Part 9: Solar simulator performance requirements," 2007.
[2] M.Bliss, T. R. Betts and R. Gottschalg, "Advantages in using LEDs as the main light source in solar simulators for measuring PV device characteristics – art. No. 704807," *Reliability of Photovoltaic Cells, Modules, Components, and Systems*, col.7048, pp. 4807-4807, 2008.