

Combined Solar Simulator for Testing Photovoltaic Devices

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Abstract— The paper discusses a combined solar simulator, consisting of an electrodeless sulfur lamp with microwave excitation and a halogen lamp. It is shown that the emission spectrum of such a design of the combined solar simulator is closest to the spectral distribution of solar radiation in the wavelength range of 400 ... 1100 nm and has an increased service life compared to the solar simulator based on a xenon arc lamp. The spectral irradiance data of the solar simulator based on ASTM E927-10 in the wavelength range of 400 ... 700 nm have been measured. An excellent correspondence has been found between the observed results and existing spectral distribution of sunlight in the visible optical range at the level of AM 1.5G in according to standard ASTM G173-03.

Keywords— solar simulator, photovoltaic (PV) cells, microwave excitation, sulfur lamp, halogen lamp

I. INTRODUCTION

Recently, there has been a significant increase in researchers' and developers' interest of the problems of direct conversion of solar energy into electrical energy, primarily with the help of photoelectric converters (photovoltaic (PV) cells), which are the basis for solar panels [1–3]. This is due to the urgent need of searching an alternative, environmentally friendly, renewable energy sources that can replace traditional energy sources.

Expansion of the production of solar panels requires testing of their parameters in conditions close to real operating conditions. Testing of solar panels is carried out in natural sunlight in open space or in closed laboratory conditions using a simulator of solar radiation (SSR) [4]. In the first case, especially problematic is the creation of the same conditions for testing solar panels, including the intensity and spectral distribution of solar radiation, geographic location, climatic and weather conditions, atmospheric composition, altitude change, time and seasonal periods. The second option is more efficient due to simplicity, reproducibility, and reliability of measurements, but it requires the development of SSR which can satisfy all the requirements.

At present in the field of PV measurements, there are standards of the International Electrotechnical Commission (IEC), as well as ASTM, IEEE, JIS and others [5], which impose a number of requirements to the SSR [6–8], such as:

power density, uniformity and the output beam stability (not exceeding 10 %), spectral and angular energy distribution of the Sun in Space (AM 0, total irradiance $1366,1 \text{ W}\cdot\text{m}^{-2}$ [9]) and terrestrial (AM 1.5G, solar zenith angle 48.19° and irradiation with an integrated power density of $1000,4 \text{ W}\cdot\text{m}^{-2}$ [10]) conditions (fig. 1).

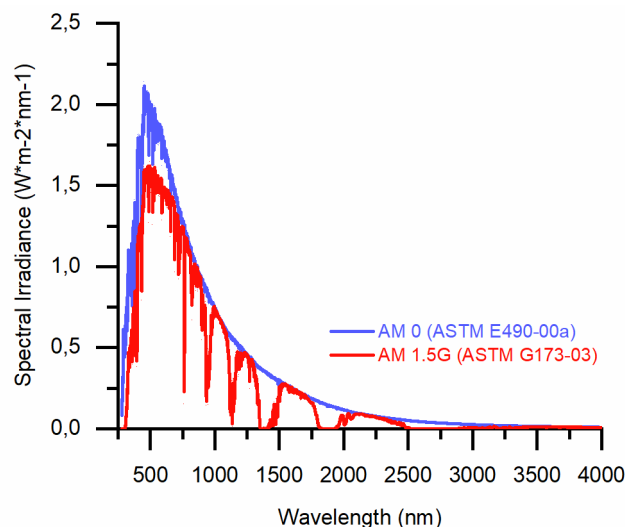


Fig. 1. AM 0 and AM 1.5G reference spectra from the ASTM G 173-3 standard [9, 10]

Therefore, there is a task associated with the need to develop high-quality SSRs that most accurately recreate the spectral distribution of the energy of the Sun's radiation under terrestrial conditions [11]. The emergence of new sources of optical radiation, such as LEDs and electrodeless lamps with microwave excitation, can improve the performance of solar simulators [12–18].

The purpose of this paper is to study the spectral match of the total irradiance of a combined SSR based on the electrodeless sulfur lamp with microwave excitation and the halogen lamp with a spectrum close to a Sun's radiation for terrestrial testing of PV cells and solar panels.

II. II. STANDARD SOLAR SPECTRA AND REQUIREMENTS TO SOLAR SIMULATOR

The radiation source of most to solar radiation simulators for the extraterrestrial atmosphere (AM 0) is a high-pressure xenon lamp with a short arc (steady-state simulator), or with a long arc (pulse simulator).

Fig. 2 shows the AM 1.5 G spectrum (green curve), the xenon lamp spectrum and its corrected spectrum using interference optical filters [19].

As is can be seen from the Fig. 2 (blue curve) the traditional spectrum of the xenon lamp has maximal energy emission in the region of the IR radiation, therefore, to improve the spectral characteristics, corrective optical filters are used (see Fig. 2, red curve) [19].

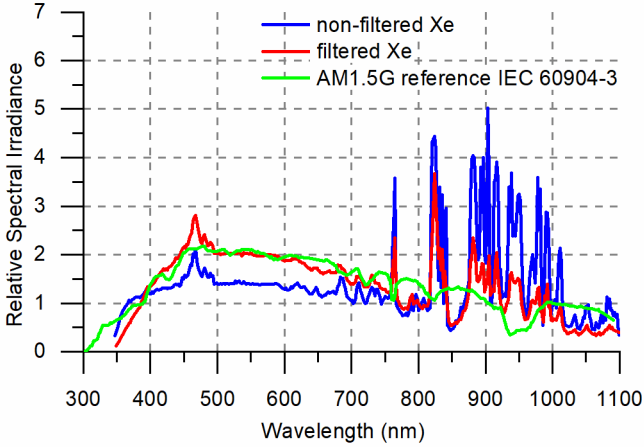


Fig. 2. The spectral distribution of irradiance of the high-pressure xenon lamp, the xenon lamp solar simulator equipped with a standard AM 1.5 filter, the solar spectrum of AM 1.5G defined in standard IEC 904-3 [20]

Simulating the spectral distribution of sunlight at AM 1.5G [10] is a difficult task. This is that the intensity and spectrum of solar irradiance on the surface of the Earth are irregular, depending on many factors: the height of the sun above the horizon, altitude and the state of the atmosphere. The Sun's height above the horizon determines the optical path length of the rays in the atmosphere and is characterized by an atmospheric mass equal to $m = 1$ with normal incidence ($\alpha = 90^\circ$, conditions AM 1), $m = 1.5$ ($\alpha = 48,2^\circ$, conditions AM 1.5), $m = 2$ ($\alpha = 30^\circ$, conditions AM 2). Passing through the atmosphere, solar radiation is selectively absorbed by water vapor, ozone, carbon dioxide, oxygen, etc., and is also scattered by aerosols and gas molecules (Rayleigh scattering).

As a result, the intensity and the solar spectrum under natural conditions differ significantly from standard terrestrial conditions. Fig. 3 shows the reference solar spectrum and accepted average level of the AM 1.5 spectrum [20]. It also shows the upper and lower limits for the spectral distribution of irradiance of the SSR meeting Class A.

The spectral distribution of the irradiance of the simulators of the terrestrial spectrum of the Sun is very different from the standard AM 1.5 spectrum. In addition, such devices are very complex and expensive, even for testing individual PV cells. It is extremely difficult to satisfy these requirements in the case of photovoltaics tests of the PV cells and solar panels while ensuring the required flow uniformity over the area corresponding to the overall dimensions of the PV devices. Therefore, in practice, the SSR based on quartz tungsten

halogen (QTH) lamp is widely used. Such simulators are stable, simple, convenient to use, have low cost. However, as it can be seen from Fig. 3 (dashed curve), the spectral composition of their radiation differs significantly from the standard AM 1.5 spectrum, which can lead to significant errors in the determination of the photovoltaic parameters of the PV cells and the solar panels.

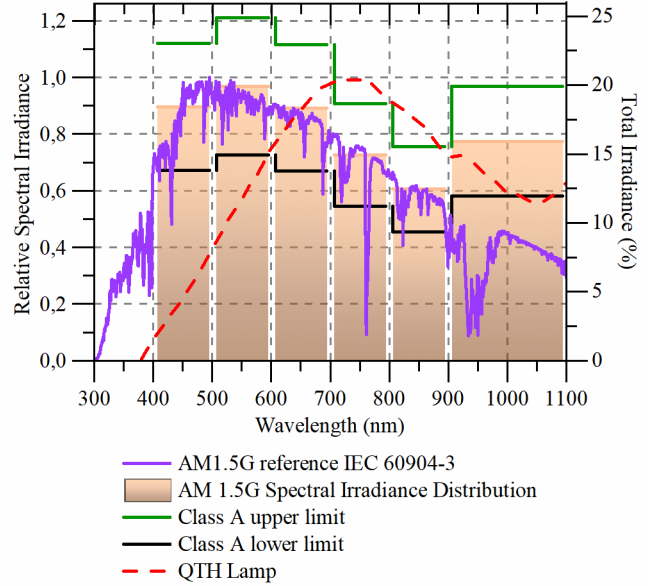


Fig. 3. The spectral distribution of solar radiation for standard conditions at AM 1.5, upper and lower levels of the spectral distribution of irradiance of Class A simulator meeting IEC-904-9 standard [6], the spectrum of a quartz tungsten halogen lamp

It is known that the error in determining the short-circuit current of the PV cells is associated with the difference in the spectral distributions of the radiation energy of the SSR and the Sun can be found from

$$\delta = \frac{J_{SCSSR} - J_{SCSun}}{J_{SCSun}} = \frac{\int_0^\infty E_{Sun\lambda} \cdot S'_{PV} d\lambda \cdot \int_0^\infty E_{SSR\lambda} \cdot S_{PV} d\lambda}{\int_0^\infty E_{Sun\lambda} \cdot S_{PV} d\lambda \cdot \int_0^\infty E_{SSR\lambda} \cdot S'_{PV} d\lambda} - 1, \quad (1)$$

where $J_{SCSSR} \cdot J_{SCSun}$ – the short-circuit current of the tested PV cell measured with used the SSR and standard solar radiation; $E_{Sun\lambda}$, $E_{SSR\lambda}$ – the spectral density of the flux of standard solar and simulated irradiance; S'_{PV} , S_{PV} – the relative spectral sensitivity of the reference and tested PV cells, respectively [21].

Analysis of equation (1) shows that the error in determining the short-circuit current of the PV cell δ is zero in two cases:

- 1) $E_{Sun\lambda}(\lambda) = E_{SSR\lambda}(\lambda)$ – the case of the solar simulator that accurately recreates the spectral distribution of solar irradiance;
- 2) $E_{Sun\lambda}(\lambda) \neq E_{SSR\lambda}(\lambda)$, if $S'_{PV} = S_{PV}$ – the spectral sensitivity of the tested PV cell exactly corresponds to the spectral sensitivity of the reference PV cell, which is used to adjust the SSR to standard conditions.

In such cases, if $E_{Sun\lambda}(\lambda) \neq E_{SSR\lambda}(\lambda)$ and $S'_{PV} \neq S_{PV}$ the error δ in determining the short-circuit current increases more with the greater degree of difference between the Sun and the SSRs spectra, as well as the spectral sensitivities of the reference and tested PV cells.

As a result, to minimize the error in determining the incident light power in natural conditions and to set up the SSR it is necessary to use the reference PV cell that has a spectral irradiance distribution similar to that of the PV cell of the tested solar panels. In accordance with (1), the measurement error decreases significantly.

III. INVESTIGATIONS OF THE COMBINED SOLAR SIMULATOR

The definition of the spectral match of the light source as regard to the standard spectrum of the Sun is the main parameter for the quantitative determination of the quality of the SSR. To determine it, the region from 300 nm to 1400 nm is divided into wavelength intervals ([7] (see Table I)).

TABLE I. SPECTRAL DISTRIBUTION OF RADIANCE PERFORMANCE REQUIREMENTS

Percentage of Total Irradiance	Wavelength, nm						
	300-400	400-500	500-600	600-700	700-800	800-900	900-1100-1400
AM 1.5G, %	–	18.4	19.9	18.4	14.9	12.5	15.9

As it is shown in Fig. 4, each of these intervals contributes a certain percentage to the total integrated irradiance for the AM 1.5 G spectrum, which is 759.26 W/m² in the wavelength range from 400 to 1100 nm.

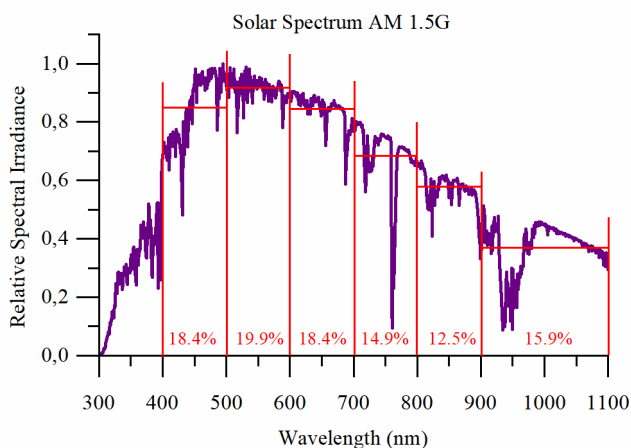


Fig. 4. IEC-904-9 standard solar spectrum irradiance distribution

In modern SSR, electrodeless lamps with microwave excitation are already used (for example, [18]). This electrodeless light source has lifetime of the light emitter > 20,000 h. The several spectra available, from energy-saving Class C (140 lm/W) to high-end Class A (70 lm/W). The electrodeless lamp has a quartz bulb is filled with a composition comprising an inert gas Ag and an active component being an antimony or bismuth halide with additional active components.

The study of the composition of the combined SSR irradiance spectrum based on the halogen lamp and electrodeless sulfur lamp with microwave excitation consisted in analyzing the spectral match of its output beam with the standard solar spectrum (AM 1.5G). The spectral distribution of the irradiance of the SSR was determined experimentally using a USB spectrometer based on a TOSHIBA TCD1304DG linear image sensor CCD (charge coupled device) for measurements in the wavelength range of 300 ... 1000 nm and spectral resolution < 1 nm.

The spectral irradiance of the halogen lamp and electrodeless sulfur lamp with microwave excitation are shown in Fig. 5. In the same figure, for comparison, the standard solar spectrum AM 1.5G is presented.

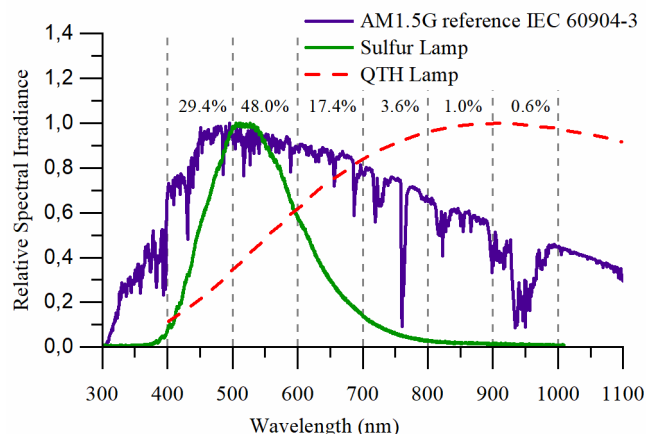


Fig. 5. The reference spectrum of solar radiation, the output spectra of lamps and the spectral distribution of irradiance in percentage for the electrodeless sulfur lamp with microwave excitation

As it can be seen, the spectral irradiance of the electrodeless sulfur lamp with microwave excitation has a continuous emission spectrum close to the spectrum of solar radiation in the visible region. At the same time, a large proportion of the spectral distribution of the radiation power of the electrodeless sulfur lamp with microwave excitation falls in the wavelength range of 400 ... 600 nm [22]. Table II shows the characteristics of the halogen lamp and parameters of the electrodeless sulfur lamp with microwave excitation, the main advantage of which is a long service life.

TABLE II. CHARACTERISTICS OF THE LIGHT SOURCES FOR SOLAR SIMULATION

Characteristics	Light Sources	
	Halogen lamp KG-220-10000	Electrodeless Sulfur Lamp LG PSF1831A
Power consumption, kW	10	1.85
Light output, lm/W	26	101
Luminous flux, lm	260 000	186 000
Color Temperature, K	3200	5500
Operating time, h	2000	60000

Fig. 6 shows the emission spectrum of the combined SSR based on the electrodeless sulfur lamp with microwave excitation and the halogen lamp with filament temperature $T = 3200$ K, as well as the spectral power distribution of the irradiance in the intervals of the wavelength ranges in accordance with the requirements of the standard [6], which should not exceed 2%.

To quantify the quality of the combined SSR and to determine its class (A, B, or C), the deviation of the spectral irradiance from the standard solar spectrum in each of the wavelength subranges is considered and presented in Fig. 7.

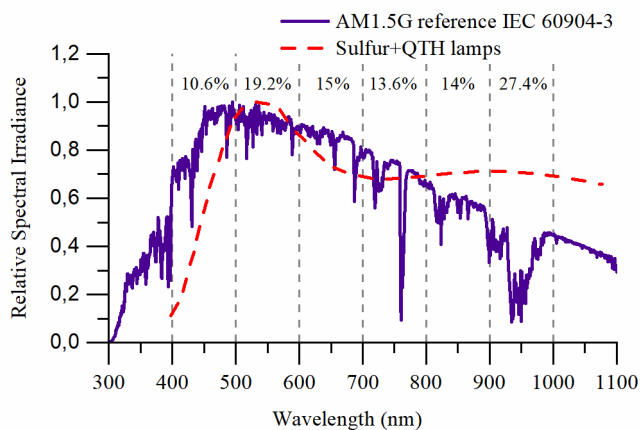


Fig. 6. The spectrum of solar radiation and the total emission spectrum of the SSR, and its spectral distribution of irradiance in percentage

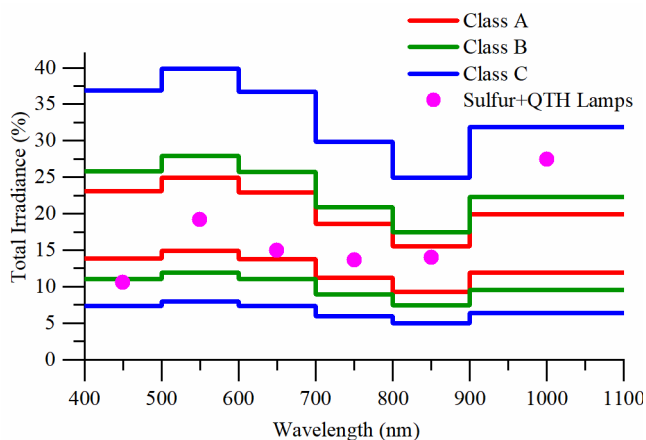


Fig. 7. The spectral distribution of the irradiance for the combined spectrum of SSR in accordance with the requirements of the standard [6]

As it can be seen from this figure, in the four central subranges of wavelengths (500 ... 900 nm), the class of the combined SSR corresponds to A and only in the extreme subranges – the Class C (400 ... 500 nm and 900 ... 1100 nm).

Fig. 8 is given spectral irradiance of combined SSR and spectral response of silicon and perovskite solar cells, which are the most effective today.

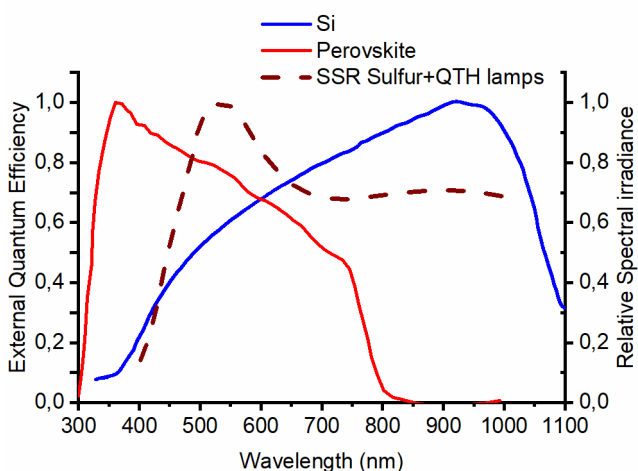


Fig. 8. Relative spectral irradiance of solar simulator and spectral response of Si and Perovskite solar cells

Since the most used material for the PV cell is silicon, which has the best conversion efficiency of solar energy in the field of visible and near infrared radiation, the use of combined SSR based on the halogen lamp and electrodeless sulfur lamp with microwave excitation is promising for photoelectric testing.

IV. CONCLUSIONS

Thus, the implementation of the combined SSR based on the electrodeless sulfur lamp with microwave excitation and the halogen lamp in the wavelength range of 400 ... 1100 nm, taking into account international standards, allows us to achieve an improvement in the spectral match of the irradiance of such the simulator with reference solar radiation. As a result, the spectrum of the combined SSR corresponds to Class A in the wavelength range from 500 nm to 900 nm and only in the extreme ranges 400 ... 500 nm and 900 ... 1100 nm is Class C, compared with the spectrum of the electrodeless sulfur lamp with microwave excitation, which has the spectral match Class A only in the range of 600 ... 700 nm. Since the spectral sensitivity of PV devices is the most effective in the field of visible and near infrared radiation, the use of the combined SSR for photoelectric testing is very promising. In addition, the development of such the simulator is appropriate from the point of view of increasing the durability of its service life (more than 100 times), and by the end of the service life of the electrodeless sulfur lamp with microwave excitation, the luminous flux is reduced by no more than 10%, the same cannot be said about the equivalent xenon arc lamp solar simulator (by 20%) or LED solar simulator (by 30%).

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