Solar Simulator for Photovoltaic Devices Based on the Electrodeless Sulfur Lamp

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Abstract—**At the present time, there has been an active growth in the use of solar energy, which is the most affordable renewable energy source for us. In this regard, there is a need for testing of photovoltaic cells and solar panels used to collect solar energy. In laboratory conditions, when testing photovoltaic panels, it is necessary to use solar simulators, which have very close parameters to solar radiation. The most important components of solar imitators are artificial light sources. Within this work, the reference spectral distribution of sunlight in the visible optical range at the level of AM 1.5G was shown, as defined in ASTM G173-03. The goal of this work is to determine the output characteristics (spectral match and spatial non-uniformity of irradiance) of the solar simulator based on ASTM E927-10 standard in the interval of 400 nm - 700 nm. As a light source of the solar simulator, a powerful electrodeless sulfur lamp with microwave excitation is used which has a continuous quasi-solar spectrum of optical radiation with a maximum at 510 nm and is very close to the solar spectrum in the visible range.**

Keywords—solar simulator; photovoltaic device; sunlight; electrodeless sulfur lamp; wavelength

I. INTRODUCTION

Photoelectric conversion of solar energy into electrical energy is a very actual task today [1]. This is due primarily to the depletion of fossil reserves on Earth, which led to the need to use renewable energy sources. Recently, a number of problems related to the further development of photoelectric devices have been identified. This increase in the initial efficiency of solar cells (increasing efficiency and increasing radiation resistance), reducing the weight and cost of solar panels (SP), as well as increasing their service life.

During the testing phase, it is necessary to determine the values of photoelectric devices, such as current-voltage characteristic (VCC), short-circuit current, idling voltage, efficiency and maximum power in real climatic conditions. Photovoltaic (PV) modules are usually evaluated under standard test conditions (STC) with a cell temperature of 25° C, an illumination of 1000 W/m^2 and a global (G) air mass spectrum (AM) of 1.5 [2].

Improvement of PV technology is impossible without improving the methods of testing the parameters of photocells, which are a key factor in the research and production of solar panels. However, laboratory tests should be close to real operating conditions. Measurements can be carried out under natural sunlight in an open space or in a closed laboratory environment using a solar simulator. In the first case, it is impossible to obtain the same conditions (intensity and spectral distribution of solar radiation, geographic location, climatic and weather conditions, atmospheric composition, altitude, time and seasonal periods) for research. The second option is more efficient due to the simplicity, reproducibility and reliability of the measurements.

The simulator of solar radiation is an artificial source of radiation that provides a spectral and optical composition similar to the intensity of sunlight, and an optical forming system that directs the flow into the working zone [3]. The main purpose of these devices, in our case, is to check the photocells and PV modules in controlled laboratory conditions.

The purpose of this work is to study electrodeless sulfur lamps with microwave excitation as a simulator of solar radiation for testing PV cells and solar panels.

II. SOLAR SPECTRUM AND AIR MASS

Simulators of solar radiation create a flux of pulsed or continuous optical radiation. Ideally, simulators should, with the best approximation, reproduce all the parameters of solar radiation - flux density, parallelism of rays, stability in time, uniformity of illumination and spectral composition.

The sun is the largest source of energy on Earth and supplies 99.98% of the total energy of our planet (the rest energy is geothermal). The temperature of the Sun on its surface-the photosphere-is 5773 K, the color temperature of the solar radiation is 5081 K. The energy density of the solar radiation, which reaches the atmosphere of the Earth, averages 1.367 kW/m². This value is called the solar constant ($E_{C_\perp}$).

Because of the large distance between the Sun and the Earth, solar radiation, which reaches the upper boundary of the atmosphere, falls in the form of almost parallel rays. This radiation includes ultraviolet radiation (UV), visible light and infrared radiation (IR). The maximum radiation intensity falls on the visible spectrum range (λ = 380-780 nm), where the Sun emits 45% of its total energy, the UV radiation ($\lambda \le 380$ nm) accounts for 9% and in the IR spectral region ($\lambda \ge 780$ nm) about 46% of the total energy is emitted [4]. Every second the Sun emits to the Earth an energy of about 10^{18} $\mathrm{W \cdot s}$.

When passing through the atmosphere, part of the solar radiation reaches the surface of the Earth, and a part is scattered by gas molecules, aerosol particles, water droplets and ice crystals (Fig. 1). These processes greatly influence the spectrum of radiation that reaches the earth's surface. The spectral composition and flux density of solar radiation at the Earth's surface vary depending on the length of the optical path of light rays in the atmosphere. The length of this path is characterized by a quantity called the optical atmospheric mass and is related to the angle θ (the angle of the Sun's height above the horizon) by the formula

$$m = 1/\sin\theta \, . \tag{1}$$

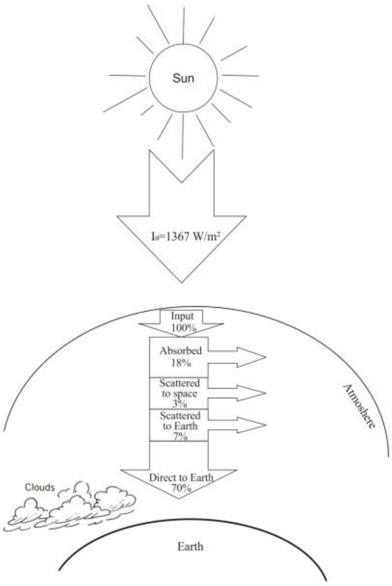

Fig. 1. Typical clear sky absorption and scattering of incident solar energy.

The indicator of the atmospheric effect on the intensity of solar radiation reaching the earth's surface is determined by the "atmospheric mass" (AM) [5]. If the Sun is at the zenith, then $m = 1$ (AM 1), but this is not synonymous with a sunny afternoon, and when it is away from the zenith the optical atmospheric mass increases. At AM 1, the radiation intensity is approximately 1000 W/m^2. Further, as the angle $\theta = 48.2°$ is increased, the air mass increases (approximately per second) and corresponds to AM 1.5 with an intensity equal to 964 W/m^2. The AM 2 spectrum is realized at an angle $\theta = 60°$. In this case, the flux density of solar radiation is 840 W/m^2, which roughly coincides with the average radiation intensity on Earth (835 W/m^2).

The flux of solar energy on the surface of the Earth for medium latitudes changes during the day from sunrise to noon in the range from 32.88 W/m^2 to 1233 W/m^2 on a clear day and from 19.2 mW/m^2 to 822 W/m^2 on a cloudy day. This affects the efficiency of PV inverters.

Spectrum AM 0 determines the operation of solar cells on space vehicles (with an intensity of 1353 W/m^2).

AM for any level of the earth's surface at any time of the day can be determined by the formula [5]:

$$AM = \frac{y}{y_0} \frac{1}{\sin\theta} \, , \tag{2}$$

where y - atmospheric pressure, y_0 - normal atmospheric pressure (101.3 kPa), θ - the angle of the Sun's height above the horizon of the globe.

III. STANDARDS FOR SOLAR SIMULATION

In connection with the above, it is very important to have uniform standards for solar radiation simulators that are used in testing photovoltaic devices with different operating conditions. Solar simulators can simulate natural sunlight of two types: space radiation (AM 0) and terrestrial radiation (AM 1D (Direct), AM 1G (Global), AM 1.5 D, AM 1.5G, AM 2D and AM 2G). The spectral irradiance values, as indicated in the standard tables ASTM G173-03 [6] for the reference spectra of the solar spectrum, are shown in Fig. 2. To classify systems of solar simulators, this standard is limited to wavelengths from 400 to 1100 nm. The total illumination of the AM 1.5G spectrum is obtained by integrating it and is equal to 759 W/m^2.

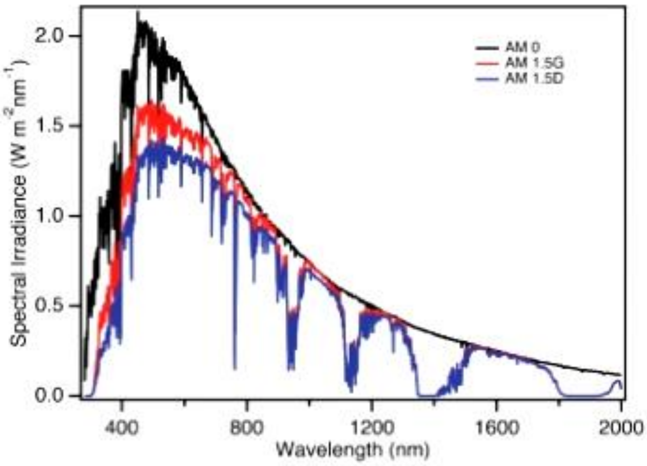

Fig. 2. AM 0, AM 1.5D and AM 1.5G reference spectra from the ASTM G 173-3 standard.

A large number of standards operate in the field of photoelectric measurements. Among them are the standards ASTM E 927-10 [3], JIS (Japanese Industrial Standard) C 8912 [7] and IEC (International Electrotechnical Commission) 60904-9 [8], for solar modeling of terrestrial photoelectric tests, which are used to estimate the VCC and tests for influence of radiation. According to ASTM E927 (Standard Specification for Solar Simulation for Ground Photovoltaic Testing) and IEC 60904-9, the simulated characteristics of solar simulators are defined as: Class A, Class B and Class C [3]. This classification defines three main criteria: spectral match to all intervals of wavelengths, spatial non-uniformity of irradiance in the test area and temporal instability of irradiance. These criteria are presented in Table 1.

TABLE I. CLASSIFICATIONS OF SIMULATOR PERFORMANCE

Class	Characteristics		
	Spectral Match	*Spatial Non-uniformity, %*	*Temporal Instability, %*
Class A	0.75-1.25	2	2
Class B	0.6-1.4	5	5
Class C	0.4-2.0	10	10

In accordance with these criteria, the highest class is designated as class A, and the lowest class is designated as class C.

Spectral match is necessary to ensure uniform compliance with natural light and test conditions.

Finding the spectral matching of the light source in accordance with the standard spectrum (AM 1.5G) is the main parameter for the quantitative analysis of the solar simulator. For its determination, the 400 nm-1100 nm interval is divided into six wavelength sub-bands (standard ASTM E927-05 [3] (Table 2)). Each of these intervals contributes a certain percentage to the total integrated illumination. To determine the spectral matching of the solar simulator, it is necessary to integrate the spectral density of energy illumination over the wavelength intervals defined in Table 2, and also to obtain the total irradiance. The results of integration in each of the wavelength intervals are normalized to the total irradiance and the ratio of its percentage contribution to the spectrum of the simulator is calculated to a similar percentage contribution to the standard solar radiation spectrum [9]

$$SM = \frac{Actual\ Percentage\ of\ Irradiance}{Required\ Percentage\ of\ Irradiance}. \qquad (3)$$

TABLE II. SPECTRAL DISTRIBUTION OF RADIANCE PERFORMANCE REQUIREMENTS

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

The limits of the deviation of spectral irradiance for classes A, B and C are given in Table. 1.

For laboratory research, solar simulators are used in accordance with the standards of the solar spectrum. To achieve these requirements, various artificial light sources are selected and used, depending on the application conditions (space or terrestrial use) and the type of solar simulator (pulsed or continuous).

IV. REQUIREMENTS AT SOLAR SIMULATORS FOR THE TEST OF PHOTOVOLTAIC DEVICES

PV panels have a wide viewing angle and should be positioned so as to obtain the maximum amount of solar radiation energy. In this case, the panels can be either fixed or tracking.

The effectiveness of the spectral sensitivity of the panels is different. Traditional photovoltaic semiconductor materials (silicon and germanium) used in the manufacture of solar panels are mainly sensitive to the visible and near infrared spectral regions, from about 400 to 1100 nm (fig.3). However, depending on the state of the sky, a significant amount of energy can come from the ultraviolet region of the spectrum - with a wavelength of up to 400 nm, and also from near infrared radiation with a wavelength of more than 1100 nm. Therefore, modern solar cells have a multilayer structure and combine several compounds (for example, GaInP/AlGaAs/Ge based solar cells (fig. 3)) to use much more available solar energy.

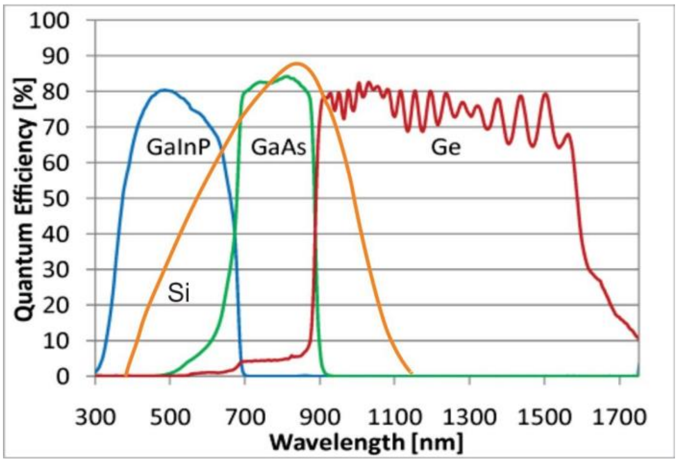

Fig. 3. The external quantum efficiency of the different types of PV solar cells

From all of the above, we can formulate the requirements for simulators of solar radiation, which are used to test solar cells and PV panels, namely:

- spectral distribution of radiation energy in the wavelength range (200-2500) nm, close to the distribution of solar radiation;
- the radiation flux density at the level of 1340 ... 1440 W/m^2 (for space purposes) and 750 ... 850 W/m^2 (for terrestrial use) with an error of simulating no more than 10% of the nominal values;
- dimensions of the light spot, corresponding to the dimensions of the test field;
- spatial non-uniformity and temporal instability of irradiance no more than 10%.

For effective operation of PV cell, radiation of a certain spectral composition and color temperature is necessary.

V. INVESTIGATIONS OF THE ELECTRODELESS SULFUR LAMP AS SOLAR SIMULATOR

An investigation of the influence of the composition of the emission spectrum of a solar simulator on the basis of an electrodeless sulfur lamp with microwave excitation on the conversion efficiency of optical energy into electrical energy consisted primarily in analyzing the spectral matching of the output spectrum of the solar imitator with the standard solar spectrum (AM 1.5G) and the impact of the emission spectrum to the VCC of solar panels. The spectral characteristics of the solar simulator were determined experimentally with the help of the LR-1 spectrometer (ASEQ Instruments, Canada). The object of the study was a PV module based on polycrystalline silicon AB-60P with a power of 260 W (ABiSOLAR, Taiwan). The idling voltage and the short-circuit current were measured with an ARPA 106 digital multimeter.

The spectral characteristic of an electrodeless sulfur lamp is shown in Fig. 3. In the same figure, for comparison, the standard solar spectrum AM 1.5G is presented.

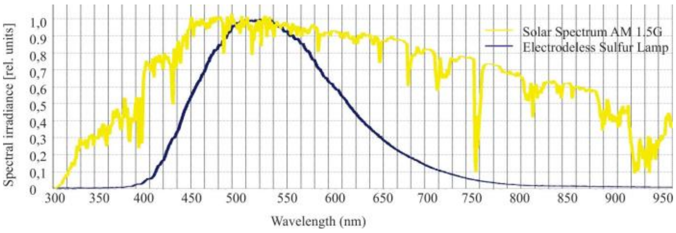

Fig. 4. Spectral profile of sulfur source compared to that of the sun.

As can be seen, from Fig. 4, the spectral characteristic of an electrodeless sulfur lamp has a continuous emission spectrum close to the spectrum of solar radiation in the visible region [10]. In Table. 3 shows the characteristics of lamps that are used in simulators of solar radiation and the parameters of a sulfur lamp with microwave excitation.

TABLE I. CHARACTERISTICS OF THE LIGHT SOURCES FOR SOLAR SIMULATION

Characteristics	**Light Sources**		
	Halogen lamp KG-220-10000	***Gas discharge xenon lamp OSRAM XBO 10000***	***Electrodeless Sulfur Lamp LG PSF1831A***
Power consumption, kW	10	10	1,85
Light output, lm/W	26	50	101
Luminous flux, lm	260 000	500 000	186 000
Color Temperature, K	3200	6000	5500
Operating time, h	2000	500	60000

Based on the requirements for simulating solar radiation, when comparing the parameters of an electrodeless sulfur lamp with microwave excitation and similar parameters of other light sources used in such devices, it can be seen that the sulfur lamp is more efficient and has a considerable work life. This allows us to consider it as a promising source for use in solar radiation simulators when testing PV cells and SP, as well as providing modeling of various modes of operation in laboratory conditions [11].

When finding the spectral match, Equation (3) can be rewritten as:

$$SM = \frac{Actual\ Irradiance\ in\ the\ Interval}{Required\ Irradiance\ in\ the\ Interval}\,. \qquad (4)$$

The spectral match of the electrodeless sulfur lamp can be obtained by simulation in Scilab program.

VI. RESULTS

In this paper, we found the spectral match of a solar simulator based on an electrodeless sulfur lamp with microwave excitation for each wavelength band using the Scilab program. From the calculations performed by the program, it is clear that the spectral match of class A was obtained only in the middle part of the visible region of the spectrum. The general spectral match of the solar simulator based on the electrodeless sulfur lamp is class C because of poor spectral matching in the IR region of wavelengths. To improve the spectral matching in this area, it is proposed to introduce additional substances (for example, $CaBr_2$) into a quartz bulb with sulfur and an inert gas (Ar), or to create a hybrid solar simulator based on sulfur and halogen lamps.

When illuminated by a light flux of a solar simulator on the basis of an electrodeless sulfur lamp with microwave excitation of the PV module surface, a maximum electric power value of about 35 W was observed.

VII. CONCLUSIONS

It was established that a solar simulator with an electrodeless sulfur lamp with microwave excitation as a light source satisfies to a class A specification in the visible region. In addition, it is shown that the output optical radiation of an electrodeless sulfur lamp has a continuous quasi-solar spectrum close to the spectrum of the Sun in the wavelength interval, where the spectral sensitivity of the PV devices is most effective. In addition, the development of such a simulator is advisable in terms of the considerable longevity of its lifetime. At the end of the lifetime of the electrodeless sulfur lamp, the light flux is reduced by no more than 10%, which can not be said of a similar simulator with a xenon arc lamp or other light sources.

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