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FRONT-SURFACE SOILING MEASUREMENT DEVICE FOR PHOTOVOLTAIC MODULES

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Abstract. *Every year, significant investments are directed to re-search institutes and other organizations around the world that are engaged in improving the efficiency of solar cells. The decrease in the efficiency of photovoltaic modules is largely caused by surface contamination and depends significantly on the re-gion where they are installed. In some locations, performance losses can be substantial. The construction of utility-scale PV plants requires vast land areas. Therefore, it is not advisable to build them in urban are-as or on agriculturally valuable lands. Utility-scale PV plants are usually built on unprofitable or barren lands such as semi-desert, desert areas, where access to water is limited. These are plots of land that are not in demand for agriculture or other constructions, but such regions are characterized by a large num-ber of sunny days a year. It takes a lot of water to clean the surfaces of the PV modules at the station. But in desert areas, the cost of water consumption can be equal to the price of fuel. To find a balance between the soiling losses in PV system and its surface cleaning costs, a device is required that monitors these pa-rameters and notifies when cleaning is needed – specifically, when energy losses outweigh the expenses. This paper describes a developed device for measuring soiling losses in PV module. The operating principle of the device is based on the phenomenon of diffuse light reflection from the surface of PV module. Exper-iments have proved that the developed device can be used to monitor the soiling losses in PV systems.*

Keywords: *photovoltaic systems, photovoltaic module contamination, soiling measurement, light source, reflection, solar simulator.*

ПРИСТРІЙ ДЛЯ ВИМІРЮВАННЯ ЗАБРУДНЕННЯ ЛИЦЕВОЇ ПОВЕРХНІ ФОТОВОЛЬТАЇЧНИХ МОДУЛІВ

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Анотація. *Щороку значні інвестиції спрямовуються в науково-дослідні інститути та інші організації по всьому світу, які займаються підвищенням ефективності сонячних елементів. Зниження ефективності фотоелектричних модулів (ФЕМ) значною мірою пов'язане із забрудненням їхньої поверхні та залежить від регіону, в якому вони встановлені. У деяких місцях втрати продуктивності можуть бути суттєвими. Для будівництва великих фотоелектричних станцій (ФЕС) потрібні значні земельні ділянки. Тому недоцільно розміщувати їх у містах або на* *прибуткових сільськогосподарських угіддях. Зазвичай великі ФЕС будують на нерентабельних або непридатних для сільського господарства землях — таких як напівпустельні або пустельні регіони, де доступ до води обмежений. Це території, які не використовуються для ведення сільського господарства або будівництва. Такі регіони також характеризуються великою кількістю сонячних днів на рік. Для очищення поверхонь фотогальванічних модулів на станції необхідна значна кількість технічної води. Однак у посушливих регіонах вартість води може зрівнятися з ціною палива. Щоб знайти баланс між втратою потужності ФЕС та витратами на очищення поверхні модулів, необхідним є пристрій, який здійснюватиме моніторинг цих параметрів та сигналізуватиме про необхідність очищення, коли втрати енергії перевищують витрати на обслуговування. У цій роботі описано розроблений пристрій для вимірювання втрат потужності ФЕМ через забруднення їхньої лицьової поверхні. Принцип роботи пристрою базується на явищі дифузного відбиття світла від поверхні модуля. Проведені експерименти підтвердили, що розроблений пристрій цілком придатний для моніторингу забруднення ФЕС.*

Ключові слова: *фотоелектричні системи, забруднення поверхні модулів, вимірювання забруднення, джерело світла, відбиття, симулятор сонячного світла.*

List of abbreviations and symbols used:

PV – photovoltaic

VAC - volt ampere characteristic

LED - light emitting diode

USB - universal serial bus

Introduction. The accumulation of contaminants on the front surface of photovoltaic modules reduces the solar irradiance incident on the solar cells, thereby diminishing the overall electricity output of solar power plants [1–5]. In this regard, it becomes necessary to determine the effect of surface contamination on the power generation by PV module. To clean the frontal surface of PV modules from contaminants, a special maintenance is required, which leads to additional time and financial costs. In recent years, there has been a significant increase in both the implementation of devices that monitor soiling-related losses and the elaboration of various methods for their direct use in PV systems [6–11].

A traditional method for determining energy losses associated with PV modules contamination is well-known. It is based on comparing the values of short-circuit currents of two identical reference modules located next to PV station modules with the same tilt angles. One of the reference PV modules is periodically cleaned, and the other is in a dirty state, as are the PV station modules. The reduction of short-circuit currents associated with surface contamination is defined as the ratio of the output currents of the compared reference modules [12–14]. The drawback of this method is that the difference in inclination or azimuth angles (for example, by 0.5 °) of clean and soiled PV modules do not allow us to obtain accurate values of the measurement due to the difference in the amount of solar energy converted by each module during the day [15].

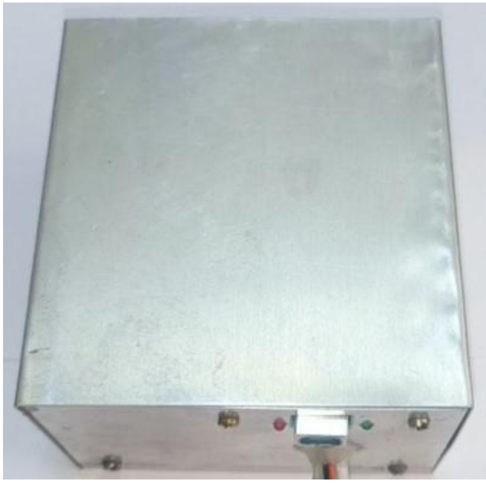
In another work, a device using microscopic imaging was developed that makes it possible to assess the degree of modules contamination based on a comparative analysis of images of a soiled surface obtained using the device's camera [16,17]. The disadvantage of this method is that a separate device must be mounted to each array of modules of a PV system, which leads to additional financial costs.

The purpose of this paper is to develop a device for determining power losses in PV modules caused by soiling of their front surface.

Operating principle of the device. The device operates based on the principle of diffuse light reflection from the PV module surface (Fig. 1). To determine the degree of contamination of PV module, the device, with the optical side where the hemispherical reflector is located, is tightly affixed to the measurement places of the frontal surface of the PV module. In the upper part of the hemispherical reflector, a light source is located perpendicular to the frontal surface of PV module and a photodetector is located at a certain angle to it, which detects the reflected light. The light source consists of 7 LEDs tightly mounted in a circle with each other. The LEDs were chosen so that they emit ranges of white light: IR, red, yellow, green, blue, UV, and even white light itself.

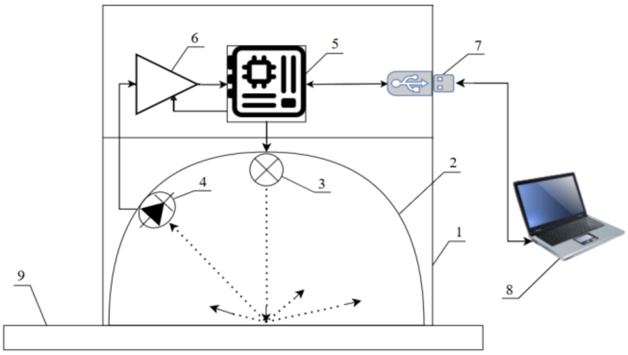
To make measurements, a laptop is connected to the USB interface of the device and data can be exchanged between the device and the laptop via any “terminal” utility. When the corresponding command is sent from the laptop, the control unit turns on and off the LEDs sequentially for a short time and when light hits the surface of PV module, the light is reflected in different directions and part of the reflected light reaches the photodetector. The signal from the photodetector is amplified, converted into a digital signal on the control unit and transmitted to a laptop to display and storage data for further analysis. The measured values of the device are displayed on the computer screen as a dimensionless value depending on the intensity of the reflected light. As soiling particles accumulate on the surface of the PV module, the reflective characteristics of the surface change and, as a result, the intensity of light registered by the photodetector also changes, and consequently the readings of the device too. This makes it possible to establish a relationship between the power loss of

PV module and contamination. The device is powered via a USB interface connected to a laptop. In future versions of the device, to facilitate the measurement process, the possibility of connecting a Bluetooth module to the device's USB interface is being considered so that measurements can be taken via an Android application.



a) the appearance of the device

b) the appearance from the optical side



c) block diagram of the device

Fig. 1. On (a) and (b) the external views of the device are shown. In (c) the block diagram of the device: 1 - housing, 2 - hemispherical reflector, 3 - light source, 4 - photodetector, 5 - control unit, 6 - amplifier, 7 - USB interface, 8 - laptop, 9 – reference PV module

The experimental part. Two identical 4 W monocrystalline modules were selected for the measurements. The surfaces of the modules were cleaned of dirt and measurements were carried out using the developed device in certain places of each module. After that, VAC of the modules was measured using a Sciencetech solar radiation simulator (UHE-NL-250) [18–20] at the Physical-Technical Institute of Uzbekistan. The solar simulator could illuminate a surface area of 25x25 cm, so the dimensions of both modules were chosen not exceeding these limits (module size: 20x20 cm).

Both modules were installed in close proximity on the heliopolygon (solar testing site) of the Physical-Technical Institute. The modules were oriented southward, and the angle of inclination coincided with the geographical latitude of Tashkent. Then they were left on the heliopolygon for contamination in a natural way. Periodically, one module was cleaned, while the other remained dirty. After each cleaning, the device was used to measure both modules in certain places (Fig. 2). At the beginning of each month, the VACs of both modules were measured on a solar simulator and then reinstalled in their places at the Institute's heliopolygon (Fig.3).

Fig. 2. Carrying out measurements by the device

Fig. 3. Measuring VAC of modules using the Sciencetech solar radiation simulator (UHE-NL-250)

Initially, the experiments were conducted during the day. Due to the fact that the photodetector is highly sensitive to sunlight, the measurement results varied when the intensity of solar radiation changed. Although, during the measurements, the device was tightly affixed to the front surface of the PV module, the back side of the module also allowed solar radiation to pass through. Therefore, the experimental results were unsuitable for analysis.

In the next stage, we have resumed the experiment, but now the experiments were conducted after sunset. The measurement results are shown in Fig. 4. It can be seen from Fig. 4 that the light reflection curves from green to white light have the same appearance (profile), but with a shift along the vertical axis. To simplify data analysis, reflections of the green LED light are selected for further calculations. The use of a monochromatic green light source with a wavelength of 530 nm is justified by the findings reported in [21], where it was shown that the impact of surface soiling on the electrical performance of solar cells can be accurately assessed using optical transmission measurements within the 500–600 nm spectral range, which corresponds to the emission bands of green and yellow LEDs [22]. Although our approach relies on analyzing reflected light rather than transmitted light, we consider this assumption valid for the purposes of our study. Nevertheless, further investigation is needed to verify whether this approach is also appropriate when applied to reflected light.

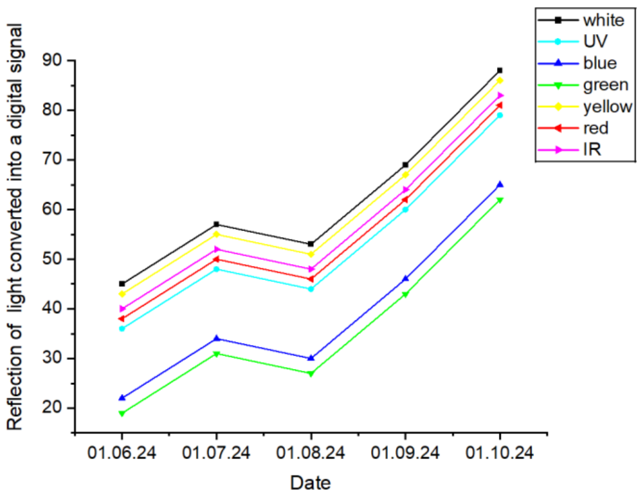


Fig. 4. The data obtained using the device from 01.06.2024-01.10.2024. The vertical axis shows the device readings

Analysis of the results. To find the relationship between reflected light (which was recorded by the device), the amount of which is related to the surface contamination level and power losses (measured using a solar simulator), a graph was plotted using previously obtained results (Fig. 5).

The vertical axis shows the power loss values of PV module measured on a solar simulator, the lower horizontal axis shows the device readings, and the upper horizontal axis shows the soiling losses. The graph shows that the correlation between them is linear.

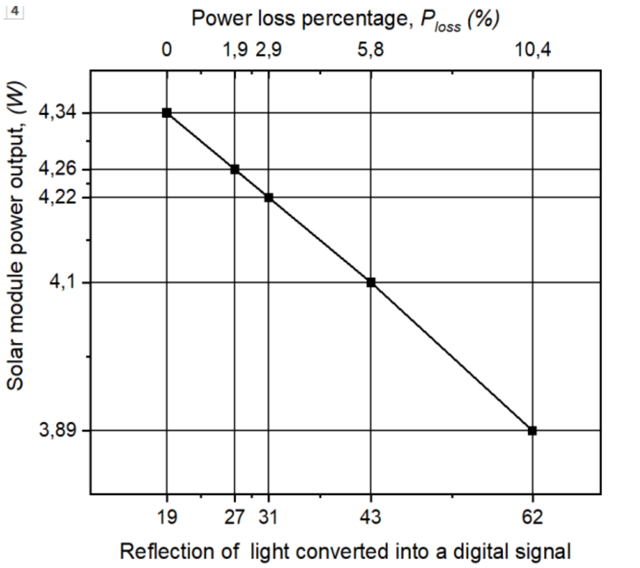


Fig. 5. The relationship between reflected green light and the soiling losses of PV module

As mentioned above, at the beginning of the experiment, the power (P_C) of the cleaned PV module was measured, then the power of an identical module, but with a soiled surface (P_D), was measured over several months. To determine the power loss (P_{loss}), the measured values were substituted into the following formula:

$$P_{loss} = \frac{P_C - P_D}{P_C} \cdot 100\%. \qquad (1)$$

The relationship between PV module power losses (P_{loss}) and the degree of contamination is determined using the following formula:

$$k_{loss} = \frac{I_n - I_{n-1}}{P_{loss}} \qquad (2)$$

where k_{loss} is a coefficient that indicates how many units the device readings change, corresponding to a 1% drop in power of PV module, and I_n and I_{n-1} are the device readings. Substituting the corresponding values from the graph in Fig. 3 into formula (2), we obtain: $k_{loss} = 62\text{-}19/10.4 \approx 4$.

The calculations show that each increase in the instrument readings by an average of 4 units corresponds to a 1% reduction in PV module power. This dependence is determined for monocrystalline PV module and may differ for different types of PV technologies. Therefore, k_{loss} of the PV module (it is recommended to use PV module similar to modules on PV system) that is planned to be used for monitoring soiling losses of PV system must be calculated. After that, it can be installed in the same plane as the PV system and monitored using the device.

Conclusions. Experiments have shown that the developed device, based on the principle of diffuse light reflection from the surface of PV module, can be used to determine power losses of a PV system caused by soiling.

The device can be used to assess the degree of erosion on the front surface of the PV module over several years. This can be evaluated by determining how closely the device readings match the original values recorded before field installation.

The device can be used to evaluate the effectiveness of different PV surface cleaning methods under field conditions.

The proposed method does not require maintaining a permanently clean reference PV module, as is done in a traditional soiling station [12], thereby eliminating continuous maintenance staffing and avoiding unnecessary water consumption.

Compared with the Mars Soiling Sensor^{TM} [16], this device does not employ any microscopic digital camera or optical lenses, which makes it structurally simpler and less expensive than other optical analogues.

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