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THE INFLUENCE OF DUST AND TEMPERATURE ON THE EFFICIENCY OF SOLAR PHOTOVOLTAIC MODULES

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At present, the use of solar photovoltaic (PV) modules plays an important role in the field of utilization of solar energy and transformation of this energy into electricity. The main characteristic of PV modules is the work efficiency. It strongly depends on external influences such as the degree of contamination on the glass surface and the operating temperature of the PV modules. Accumulation of dust particles on the surface of PV modules has a very negative effect on their efficiency. At high ambient temperatures, solar PV modules heat up, and the efficiency of modules is reduced. This problem is very substantial for the countries with high temperature conditions and dusty climate. In this paper, the influence of dust and temperature on the efficiency of solar PV modules is investigated. The new-type economically viable system for cleaning and cooling PV modules is used during the experiments. The conducted experimental studies under actual operating conditions during the rainiest period of the year in Yerevan, have shown that due to the cleaning of dust, the efficiency of PV modules is increasing on average by 6.7%. Due to rapid cooling by water in two minutes, the efficiency of PV modules is increased by 2.5%. To improve the operation efficiency, the PV modules must be cooled periodically, taking into consideration the quantity of the consumed water in order to get the maximal economic effect.

Keywords: solar, photovoltaic, module, efficiency, cleaning, cooling, temperature.

Introduction. The photovoltaic (PV) conversion is the main technology for transformation of solar radiation into electric energy. One of the most important characteristics of PV converter modules is the efficiency, which determines the amount of electricity generated. The efficiency of PV converters depends on the internal electro-physical parameters of semiconductor solar cells, which are generally made of silicon. It is also highly dependent on external influences, such as the degree of contamination on the glass surface of the PV module and the ambient temperature.

The accumulation of dust particles on the surface of PV modules has a very negative effect on their efficiency, as in the presence of dust, the solar rays do not

penetrate into the solar cells [1]. The presence of dust can reduce the efficiency of solar modules by more than 35% [2]. At the real operating conditions, the PV modules are heated due to the absorption of solar rays and influence of ambient temperature. As it is known, in solar photovoltaic systems, most of the energy is not converted into electric energy but is converted into thermal energy, which increases the operating temperature of silicon solar cells. With heating, the efficiency of solar cells decreases by about 0.5% with each 1°C increase in temperature, which is an inherent characteristic of solar cells [3]. On bright sunny days, at high ambient temperatures (30...50 °C), the temperature of solar cells can reach 100°C. In this case, the efficiency of the cells is reduced by 40%.

The influence of dust and temperature on the efficiency of solar PV modules is especially acute in countries with high temperature conditions, dry and dusty climates. To address this problem, different cleaning and cooling systems of solar PV modules are investigated, developed, and employed [1,2,4-6]. The main disadvantages of these systems are the high cost and shadowing effect. Due to the high cost of the cooling systems, the cost per watt of the gained power by cooling exceeds the average cost per watt for the PV module [7]. To reduce the operation temperatures of PV modules new hybrid PV and thermal modules are investigated and developed [8, 9]. These systems clean and cool the PV modules by different methods and techniques.

In this paper, the influence of dust and temperature on the efficiency of PV modules under real operating conditions, during the rainiest period of the year in Yerevan (Armenia), is investigated. The experiments are conducted in open air conditions in the research laboratory of National Polytechnic University of Armenia. Two identical PV modules are investigated: one was cleaned and cooled and the other used as the reference module. To clean and cool the module, a new automated cleaning and cooling system of PV modules was developed and used.

Dependence of efficiency of solar cells on the dust and temperature. The thermal dependence of the mono/poly-crystalline Si solar cells is defined as [10]

$$\eta = \eta_0 [1 - \beta(T - T_0)], \quad (1)$$

where η_0 is the reference efficiency of the solar cell, which is measured under standard test conditions (STC), β - the temperature coefficient, T - the operating temperature of the solar cell (°C), T_0 - the reference temperature of the solar cell. Typically, the solar cells are rated at $T_0 = 25^\circ\text{C}$ under illumination of 1 kW/m^2 (STC). As it follows from formula (1), the efficiency of PV module is decreasing linearly by increasing the operating temperature T of the solar cell.

The values of η_0 and β are generally given by the PV manufacturer. However, they can be obtained from flash tests in which the electrical output of the PV module is measured at two different temperatures for a given solar radiation flux. The temperature coefficient β is different for different types of solar cells. For the most common mono-crystalline and poly-crystalline silicon solar cells $\beta = 0.005 / ^\circ\text{C}$ and $\beta = 0.0045 / ^\circ\text{C}$ respectively [10].

The efficiency of a solar cell is determined as the fraction of maximum power which is converted to electricity and the incident power of solar radiation and is defined as:

$$\eta = \frac{P_m}{P_{in}} = \frac{P_m}{AP_{sun}} = \frac{I_m V_m}{AP_{sun}}, \quad (2)$$

where P_m is the maximum power which is converted into electricity (W); P_{in} - the incident power of solar radiation (W); A - the surface area of PV modules (m^2); P_{sun} - the solar radiant power per unit area (W/m^2); I_m - the maximum current (A) and V_m (V) - the maximum voltage at maximum power point. Current I_m is directly proportional to the number of incident photons or solar light intensity. Thus, when the PV module is covered by dust layer, due to the “blocking” of light, the I_m is decreasing and the efficiency of the PV module is also decreasing.

A PV modul automated cleaning and cooling system. In order to assess the impact of dust on the characteristics of solar PV modules a new automatic water cleaning system has been used, the structure of which is shown in Fig. 1. It consists of a water sprayer (1) with holes, located at the top of the solar module. The water jet is evenly distributed on the surface of the photoelectric module. The operation of the system is automatically controlled by an electronic control unit (4). Upon receiving the signal from the dust and temperature sensors (3), the electromagnetic valve (5) opens or closes the water flow.

Fig. 1. The structure of the PV module cleaning and cooling system:
1 – water sprayer, 2 – PV module, 3 – dust and temperature sensors, 4 - electronic control unit, 5 – electromagnetic valve

The minimum dust threshold level was determined experimentally, as a result of which the sensor transmits a signal to the electronic control unit. When it senses the dust and the increased temperature, the water valve is turned on and water flows on the surface of the solar module.

Measurement results. Two identical PV modules are tested under the open air condition. The modules placed nearby and tilted at 30° are tested (Fig. 2). The modules are made of 60 polycrystalline solar cells with the maximum power of 275 W. One PV module (left) was cleaned and cooled periodically, before the measurements and the other (right) was used as the reference module.

*Fig. 2. Tested PV modules and the Seaward measuring system:
From the left – the module with cleaning and cooling system; from the right – the
reference module*

The parameters of the PV modules were measured using the SEAWARD PV200 measuring system. The intensity of the solar radiation, the panel temperature and the ambient temperature, was measured using a Solar Survey 200R, which was attached to the solar panel (Fig. 2). The measurements were conducted in Yerevan, for about a month, from April 23 to May 14 2021.

To measure the influence of the dust on the efficiency of the PV modules, each day, at 12:00, the PV module equipped with a cleaning system (Fig. 2, left) was cleaned. As a result of cleaning by water, the temperature of the PV module was decreased. Then, the temperature of cleaned module was increased and after 15 min, it was equal to the temperature of the reference module. So, the efficiencies of the cleaned and reference modules were measured at the moment, when the temperatures of the two modules were equal. The results of measurements are presented in Fig. 3. It can be seen, that the efficiency of the cleaned module is more than the efficiency of the reference module.

The average value of the ambient temperature during the measurement period was 28.1 °C and the average temperature of PV modules was 48.6 °C.

Fig. 3. Efficiencies of the cleaned and reference PV modules

The difference of efficiencies of the cleaned and reference modules is calculated:

$$\Delta\eta_{av} = \frac{\sum_{i=1}^n \Delta\eta}{n} = 6.7\% .$$

It can be seen from Fig. 3 that in 23.04.21 the efficiencies of the cleaned and reference modules are almost the same. This is described by the heavy rain seven days before. But in four days, in 27.04.21 the efficiency was increased significantly by cleaning the dust. After that, the difference of efficiencies changes due to the influence of precipitation availability of dust in atmosphere. Note, that the period of the conducted experiments is the most rainy period in Armenia. There were six rainy days during the period of the experiments. Thus, it can be concluded that the effect of cleaning of PV modules will be more during summer months, which are generally dry, hot and dusty in Armenia.

The influence of temperature on the efficiency of PV modules is conducted with the use of one module (Fig. 2, left), equipped with a cleaning and cooling system. The PV module was cleaned, and the influence of temperature on the efficiency was investigated. The efficiency of the hot module was measured and after that the module was cooled by water for two minutes, and the efficiency was measured again, after cooling it. In 10 to 15 minutes, the temperature of the PV module was increased to the maximum value. As an example, the results of the measurements, conducted in 23.04.21 are presented in Fig. 4. It can be seen from the figure, that due to cooling, the temperature of the PV module is decreased from 64.77 °C to 33.64 °C, and the efficiency

is increased from 13.54% to 16%. But without cooling, the temperature is increasing again rapidly (in about 15 *min*) up to the temperature of reference module and a new cooling procedure is required.

Fig. 4. The efficiency change after periodically cooling the PV module

Thus, the efficiency of the PV module increases significantly by cooling. Note that the ambient temperature in Yerevan, on the day of this experiments (in 23.04.21), was 32 °C. During the hot summer period, the cooling will be more important to improve the efficiency of PV modules. Since the PV module, after the cooling process is heated up very quickly, due to the influence of the elevated ambient temperature, the cooling process must be repeated periodically. The duration between the two cooling processes must be optimized to minimize the water consumption and to get maximal economic effect.

Conclusions

1. Due to the cleaning of photovoltaic (PV) modules once a day, during the rainy period in Yerevan, the efficiency of PV modules is increases on average by 6.7%. The increase in the efficiency of modules will be more during the summer months, which are generally dry, hot and dusty in Armenia.
2. Due to cooling with a duration of 2 minutes, the efficiency of the PV module increases by about 2.5%. The efficiency of the PV module will increase more due to cooling during the hot summer period.
3. After cooling the PV module is heated up to the temperature of the reference module quickly (in 10...15 *min*). The cooling process must be conducted

periodically, and the periods must be optimized to minimize the water consumption and to get maximal economic effect.

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**ՓՈՇՈՒ ԵՎ ՋԵՐՄԱՍՏԻՃԱՆԻ ԱՁԴԵՑՈՒԹՅՈՒՆԸ ԱՐԵՎԱՅԻՆ
ՖՈՏՈԷԼԵԿՏՐԱԿԱՆ ՄՈԴՈՒԼՆԵՐԻ ԱՐԴՅՈՒՆԱՎԵՏՈՒԹՅԱՆ ՎՐԱ**

Ռ.Ռ. Վարդանյան, Ն.Կ. Բադալյան

Ներկայումս արեգակնային ֆոտոռելեկտրական (ՖԷ) մոդուլների կիրառումը կարևոր դեր է խաղում արևային էներգիայի օգտագործման և այդ էներգիան էլեկտրաէներգիայի վերածելու ոլորտում: ՖԷ մոդուլների հիմնական բնութագիրը աշխատանքի արդյունավետությունն է: Այն խիստ կերպով կախված է արտաքին ազդեցություններից, ինչպիսիք են ապակու մակերևույթի աղտոտման աստիճանը և ՖԷ մոդուլների աշխատանքային ջերմաստիճանը: ՖԷ մոդուլների մակերեսին փոշու մասնիկների կուտակումը խիստ բացասաբար է ազդում դրանց արդյունավետության վրա: Շրջակա միջավայրի բարձր ջերմաստիճանների դեպքում արևային ՖԷ մոդուլները տաքանում են, և մոդուլների արդյունավետությունը նվազում է: Այս խնդիրը շատ էական է բարձր ջերմաստիճանների պայմաններում և փոշոտ կլիմա ունեցող երկրների համար: Ուսումնասիրվել է փոշու և ջերմաստիճանի ազդեցությունը արևային ՖԷ մոդուլների արդյունավետության վրա: Փորձերի ընթացքում օգտագործվել է ՖԷ մոդուլների մաքրման և հովացման տնտեսապես կենսունակ նոր տիպի համակարգ: Երևան քաղաքում իրական աշխատանքային պայմաններում անձրևների շրջանում կատարված փորձնական ուսումնասիրությունները ցույց են տվել, որ փոշու մաքրման արդյունքում ՖԷ մոդուլների արդյունավետությունը միջին հաշվով աճում է 6,7% -ով: Ջրի միջոցով արագ հովացման հետևանքով երկու թույլի ընթացքում ՖԷ մոդուլի արդյունավետությունն աճում է 2,5% -ով: ՖԷ մոդուլների արդյունավետությունը բարելավելու համար պետք է մոդուլները պարբերաբար սառեցվեն՝ հաշվի առնելով օգտագործվող ջրի քանակությունը, ապահովելու համար առավելագույն տնտեսական արդյունավետություն:

Առանցքային բաներ. արեգակնային, ֆոտոռելեկտրական, մոդուլ, արդյունավետություն, մաքրում, հովացում, ջերմաստիճան:

**ВЛИЯНИЕ ПЫЛИ И ТЕМПЕРАТУРЫ НА ЭФФЕКТИВНОСТЬ
СОЛНЕЧНЫХ ФОТОЭЛЕКТРИЧЕСКИХ МОДУЛЕЙ**

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В настоящее время солнечные фотоэлектрические (ФЭ) модули играют важную роль в области использования солнечной энергии и преобразования этой энергии в электричество. Основная характеристика ФЭ модулей - эффективность работы. Эффективность сильно зависит от внешних воздействий, таких как степень загрязнения поверхности стекла и рабочая температура ФЭ модулей. Накопление частиц пыли на поверхности ФЭ модулей негативно сказывается на их эффективности. При высоких температурах окружающей среды солнечные ФЭ модули нагреваются, и эффективность модулей снижается. Эта проблема весьма актуальна для стран с высокими температурами

и пыльным климатом. В данной статье исследуется влияние пыли и температуры на эффективность солнечных ФЭ модулей. В экспериментах используется экономически эффективная система очистки и охлаждения ФЭ модулей нового типа. Проведенные экспериментальные исследования в реальных условиях эксплуатации показали, что за счет очистки от пыли эффективность фотоэлектрических модулей увеличивается в среднем на 6,7% в самый дождливый период года в Ереване. За счет быстрого охлаждения водой в течение двух минут эффективность ФЭ модулей увеличивается на 2,5%. Для повышения эффективности работы ФЭ модули необходимо периодически охлаждать с учетом количества потребляемой воды, чтобы получить максимальный экономический эффект.

Ключевые слова: солнечная энергия, фотоэлектричество, модуль, эффективность, очистка, охлаждение, температура.