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Efficiency Evaluation of Cleaning a Photovoltaic Panel Surface from Snow and Ice by Supplying Electrical Energy to Its Outputs

Alim Arifov*, Eskender Bekirov*, Marlen Asanov*‡

*Electrical Energy and Electrical Engineering Department, V.I. Vernadsky Crimean Federal University, Prospekt Vernadskogo 4 , Simferopol, Republic of Crimea, 295007

(arifov.alim@inbox.ru, bekirov.e.a@cfuv.ru, asanov.m.m@cfuv.ru)

‡ Corresponding Author; Marlen Asanov, Electrical Energy and Electrical Engineering Department, V.I. Vernadsky Crimean Federal University, Prospekt Vernadskogo 4 , Simferopol, Republic of Crimea, 295007, Tel: +73 652 545 036, Fax: +73 652 545 246, asanov.m.m@cfuv.ru

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Abstract- Energy generated by a photovoltaic panel directly depends on the amount of solar radiation falling on its surface. In the winter season, perhaps the main factor that affects a panel operation is the soiling of snow and ice on its surface. It decreases a panel's efficiency and reduces the reliability and durability of its work. The authors reviewed the existing methods that are used to clean panels surface. Noted the great interest and attention paid by researchers to the considered problem. The authors analyzed a panel cleaning method based on the supply of electric power to its outputs. A number of experiments, both indoor and outdoor, were carried out to evaluate the effectiveness of the method. In the indoor experiment, the panels were pre-cooled. In the outdoor experiment, the panel was pre-coated with ice and dry snow. The methodology used in the experiments is to change the magnitude of the current supplied to the panel outputs and fix the power spent on heating, the heating time, and the maximum temperature of the panel surface. The results of the outdoor experiment showed that a panel with about 50% of its surface covered by melted snow and ice could generate electricity at the same time as it releases heat to completely clean its surface. The energy spent for cleaning the photovoltaic panel surface is 30% less than the amount of energy generated by the panel after it has been cleaned.

Keywords Soiling on a photovoltaic panel; snow and ice removal; heating method; reverse current; outdoor experiment.

1. Introduction

Researchers are constantly facing a major problem of increasing photocells efficiency [1, 2]. One of the factors affecting the amount of energy generated by photovoltaic cells is the presence of dust and snow on a panel surface. Soiling reduce the amount of solar radiation falling on photocells surface and, as a result, negatively affect their operation [3–7].

Studies at desert in Oman show that soiling reduces electric power generation by 4.8%, 18.1%, and 38.1% after one, three, and five weeks of operation, respectively [8]. Changes in the power generation of photovoltaic panels located in the territory of Santiago, Chile were in the range of 0.13% - 0.56% per day. A similar annual index turned out to be dependent on the type of photovoltaic panels: 1.29% for polycrystalline, 1.74% for monocrystalline and 2.77% for thin film systems [9]. When analyzing panels operation in Palestine during the year, the loss of electric power generation varied from 0.79% in December to 3.67% in August [10]. Other studies report changes in daily electric power generation of 0.32% in dry and 0.02% in rainy periods [11]. This index can reach 6% per day in summer for rooftop systems located at 8 degrees to the horizon [12]. Sea salt together with dust and dirt soiling on panels surface can have a negative impact on panels efficiency [13]. It leads to significant financial losses, which are estimated at 3-5 billion euros per year in the most optimistic scenario [14].

Snow and ice cover can cause moisture to enter a photovoltaic panel perimeter, causing electrochemical corrosion. It can cause destruction, delamination and failure of photovoltaic panels. Large snow loads can also lead to deformation of a panel protective frame (Fig. 1, a), cracking of a panel protective glass (Fig. 1, b), or subsidence of a photovoltaic system mounting table (Fig. 1, c). In addition, when a panel is partially shaded, f.e. by snow cover, point heating of a panel cells occurs (Fig. 1, d). While non-shaded cells supply energy to this area, it greatly affects the efficiency of the entire string of series-connected panel cells.

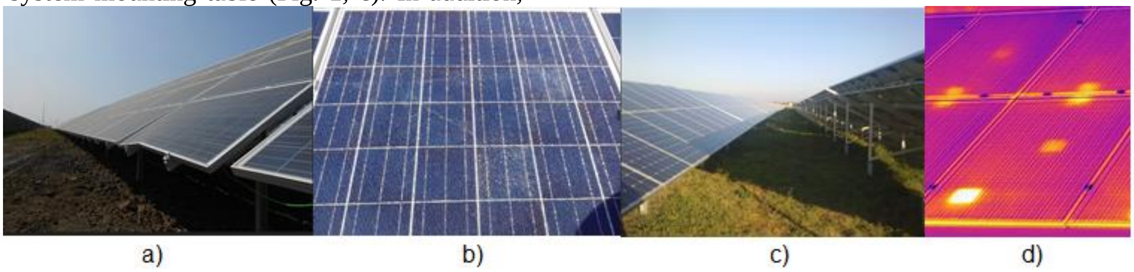

Fig. 1. Examples of the different damages of photovoltaic panels: a) deformation of a panel protective frame; b) cracking of a panel protective glass: c) subsidence of a photovoltaic system mounting table; d) point heating of a panel cells

Devices based on two measurement methods are used to register soiling on panel surface. One measures a panel characteristics such as current or power at its output. Other is based on an optical analysis of the reflection or transmission of light due to the accumulation of soling on the sensor surface [15].

There are a number of methods for cleaning a panel surface from dust and dirt.

A variety of robots with brushes using water or not can be used for this purpose. Activation and control can be carried out automatically [16].

The Heliotex system sprays water onto panels surface to clean them. The system can be programmed at a request of a user. Compressed air also can be used to blow panels [16].

Dust particles can be removed electrostatically. It can only be done in dry weather for dry surfaces. Positive and negative electrodes were embedded in the protective coating of the panel. They were placed alternating each other and parallel to the ground. When a single-phase rectangular voltage was applied to the electrodes, dust particles were attracted one by one to the electrodes and rolled down from the panel under the action of gravity. The high efficiency of the method is noted: up to 90% of the accumulated dust was cleaned in less than 2 minutes [17].

Another way to clean dust from a panel surface is to place the mechanism that creates vibration on a panel's backside. Dust rolls off a surface under the action of the generated mechanical vibrations [16].

In general, the methods of cleaning a panel surface from snow can be divided into active and passive ones.

One of the passive methods is based on heating a panel by reflecting light onto its rear surface. Under a panel the special box is installed, which focuses the solar radiation, directing it to a panel. However, this method requires a significant amount of time to remove snow [18].

Another way to remove snow from a panel passively is to use a special coating on its surface instead of or together with a protective glass. Special coatings have irregularities that prevent the formation and sticking of snow and ice. The size of the irregularities must be smaller than the size of the particles to be removed. These coatings are divided into the following categories: photocatalytic hydrophilic surface; superhydrophobic or ultrahydrophobic surface; microstructured or nanostructured surface. A manufacturer in a factory can produce special coatings. At the same time, a consumer himself can complete the preparation of special coatings by applying an attached special liquid [19-21].

Active methods involve the energy spending for cleaning panels from snow.

The simplest method of cleaning a panel surface is manual (mechanical) snow removal. It is simple, but the effectiveness of this method is very low. In addition, removing ice or frozen snow from a panel by applying pressure to a surface can damage a glass surface of a photovoltaic panel.

The box with an electric heater inside is proposed to install on a panel's backside to clean its surface. The air heated by the heater is used to melt snow and ice [18].

Another method of surface cleaning is to directly heat photovoltaic cells by applying a reverse voltage to them. Both positive [21] and negative [18] voltage is applied to the output of a photocell.

In the first case [21], HQST Solar Panel SQ150-PC photocells with an area of about 0.076 m^2 were placed in a freezer. An alternating voltage source together with a clamping circuit was used to heat the photocells. The temperature of the photocells rose from -10 C to 4 C within 20 minutes. The current and voltage values were 1.01–1.18 A and 26.3–27.1 V, respectively. Experiments with the use of snow were not carried out.

Two methods for heating a panel surface were investigated in another paper [18]. In the first method, carbon film heaters were attached to the back of the panel and covered about 80% of its surface. They were supplied with alternating voltage. The heaters were covered with insulating material in two layers to reduce heat loss. In the second method, reverse voltage was supplied to the panel from a DC source. In this case, the back of the panel was not insulated. The experiments were conducted in Ontario, Canada in the winter of 2016 and 2017. The panels were placed outdoors at 30, 45 and 55 degrees to the ground (only one panel was installed at 45 degrees to the ground to test the second method). Polycrystalline silicon panels were used with a maximum power of 70 W and an area of about 0.66 m^2. The heating power in the first method was 180 W/m^2, in the second method it was 235 W/m^2. The energy required to melt the snow was calculated depending on the mass of snow per unit area of the panel. Studies showed that the time it took to clear snow from a panel was highly dependent on the angle of its inclination. The time of cleaning ranged from several minutes (for a panel with an angle of 55) to 34 minutes (for a panel with an angle of 30). When panel was heated with reverse voltage, the time of cleaning was about 7 minutes.

2. Methodology of the Experiment

To clean a surface of photovoltaic panels over a large area, for example, in a solar power plant, the most promising, from the authors' point of view, is the method of heating by voltage supplied to panels output. Manual cleaning, as described above, is not effective. All other methods require significant changes in the design of photovoltaic panels. The purpose of this work is to study the effectiveness of the chosen method of photovoltaic panels surface cleaning from snow.

Two identical photovoltaic panels were used for the experiment. Their characteristics are presented in Table 1.

Table 1. Characteristics of photovoltaic panels used for the experiments

Parameter name	PV 1 panel № 011-2023-8
	PV 2 panel № 011-2023-9
Maximum power, W	20
Maximum voltage, V	17.1
Rated current, A	1.17
Open circuit voltage, V	21.5
Short circuit current, A	1.25
Surface area, m^2	0.175

The Element 305DB laboratory DC power source, the Fluke 87 multimeter with thermometer function, and the Velleman HPS-40 oscilloscope were used.

A number of experimental studies were carried out. The contacts of the power source were connected directly to the panel output. A temperature sensor was mounted on the front surface of the panel. The panel was 100% covered.

Three values of the current supplied to the panel outputs were chosen. They correspond to relatively average values of the heating time and the power spent for heating the panel. At lower values, the panel heats up very slowly, at higher values - quickly.

At first, experiments were carried out with the panel with an initial surface temperature of +10 C. The chosen maximum value of the current was pre-set on the laboratory power source. The supply voltage was smoothly increased with a resolution of 1 V until the current set value in the circuit was reached. The voltage, the heating time and the maximum temperature of the panel surface were measured at the current set value. The experiment was repeated for two other values of the current supplied to the panel outputs.

After that, the panel was cooled to a temperature of -5 C. The experiment was repeated according to the method described above with the set current applied at three different values.

The results obtained are presented in Table 2 and in Fig. 2 and 3. Figures 2 and 3 show the results averaged over two panels.

3. Results and Discussion

With an increase in the set values of current, and, consequently, power, the maximum temperature of the panel surface increases (see fig. 2). The heating time also increases.

Figure 3 shows the dependencies that allow us to analyze the effect of the initial temperature of the panel surface on the heating process.

As can be seen from Fig. 3, more power is required to achieve the set values of the current supplied for heating at a lower initial temperature of the panel surface. However, the power consumption per unit temperature change is practically independent on the initial temperature of the panel surface. This parameter increases more with an increase in the set values of the current supplied for heating.

In turn, the rate of the panel surface heating strongly depends on its initial temperature. As the initial temperature of the panel surface decreases, the heating rate also decreases. However, changing the set values of the current supplied for heating has practically no effect on the heating rate, especially at low initial values of the panel surface temperature.

4. Additional Outdoor Experiment and Its Results

In addition to the experiments described above, the outdoor experiment was carried out to study the cleaning of a photovoltaic panel surface from snow and ice. The experiment was carried out on February 10, 2023 in Simferopol located at 44°N. On the experiment day the air temperature in the sun was -4 °C, the cloudiness was zero. For the experiment, one PV1 panel was taken and placed at an angle of 30.7 degrees to the ground. It corresponds to the angle at which panels are located at solar power plants in the region. The influence of a panel tilt angle was not studied in this work, although the authors of [15] pointed out how important its value is. It can be additionally noted that a panel tilt angle affects the following:

1. The height of a snow cover on a panel surface.

2. The rate of water removal from a panel surface during snow melting.

3. Time spent for snow and ice melting.

4. Sliding of melted snow masses under the action of its own gravity.

5. The amount of spent electrical energy.

Table 2. The results of the indoor experiment with panels having different initial surface temperatures

Panel surface initial temperature, C	Current maximum set value, A	Voltage value, V	Maximum panel surface temperature, C	Heating time to reach the maximum panel surface temperature, min	Power consumption for heating the panel, W
+10	1	23.5	26	6	23.5
		23.5	27	6	23.5
	1.25	24.1	30	8	30.1
		24	31	9	30
	2	25.5	35	10	51
		25.5	36	11	51
-5	1	25.1	13	10	25.1
		25.2	12	10	25.2
	1.25	25.8	16	12	32.2
		25.9	17	12	32.3
	2	27.7	23	15	55.4
		27.5	22	16	55

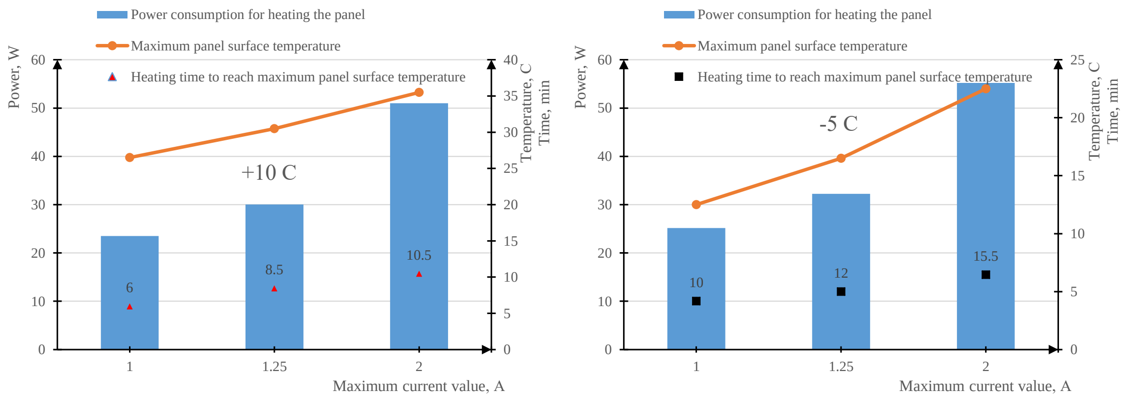

Fig. 2. The diagrams of power, temperature and time dependencies on current maximum set value for panels that have different initial surface temperatures.

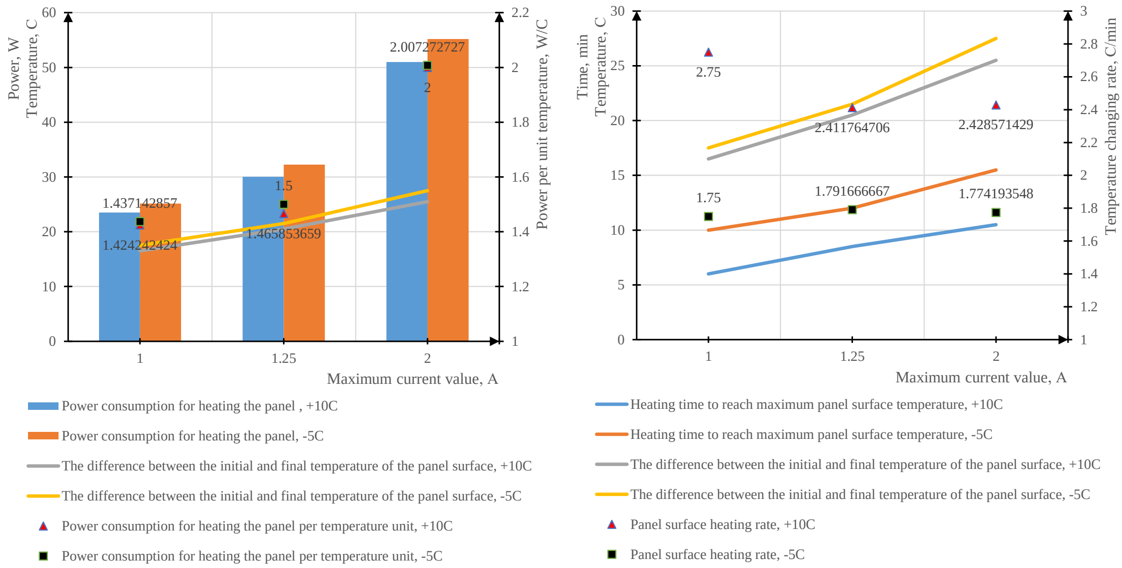

Fig. 3. The diagrams showing the difference between heating parameters of panels that have different initial surface temperatures.

The surface of the panel was preliminarily doused with water, which later froze to increase adhesion. Subsequently, the panel was evenly covered with a layer of a dry snow with a thickness of 32-35 millimeters.

The experimental procedure was similar to that described above. The maximum value of the current was set to be equal to 2.0 A. With a resolution of 0.5 V, the voltage was increased until the maximum set value of the current in the circuit was reached. When the current reached 2 A, the voltage level was 27.5 V.

The experiment started at 10:27 Periodic monitoring of the snow masses melting dynamics on the panel surface is shown in Fig. 4.

During the experiment, it was found that the snow did not slide off the panel surface under the influence of its own weight, but slowly melted starting from the bottom edge and along the sides. Authors assume that it happened for either the insufficient weight of the snow or the insufficient angle of the panel to the ground. At 11:20, i.e. after 53 min from the beginning of the experiment (Fig. 4, c), the panel was disconnected from the power source. As a result of measuring the panel characteristics, it was found that the open circuit voltage was 22.7 V, and the short circuit current was 0.87 A, while 50% of the panel surface was still covered with melted snow masses.

At 11:22, the load was connected to the photovoltaic panel through the PWM circuit of the "Solar charge controller PWM" (model: W88-C). The load was an incandescent lamp with a supply voltage of 12 V and a power of 20 W. During the autonomous operation of the photovoltaic system in the generator mode for the connected load, the panel was cleared from snow masses by 100% at 11:45, i.e. after 1 hour 16 minutes from the beginning of the experiment. A DC wattmeter was connected to the electrical circuit between the controller and the photovoltaic panel to calculate the useful generated electrical energy. At 16:10 the photovoltaic system was turned off due to the end of the generation process. The results of the experiment are presented in Table 3.

a) b) c)

Fig. 4. The dynamics of ice and snow melting on the photovoltaic panel surface: a) 10:27 (initial); b) 10:47 (after 20 min); c) 11:20 (after 53 min).

Table 3. The results of the outdoor experiment showing the effectiveness of the panel heating

Time spent on cleaning the panel surface by 50%, min	Amount of electrical energy spent on cleaning the panel surface by 50%, W*h	Operating time of the panel in generator mode until the surface is completely cleaned by 100%, min	Total operating time of the panel in generator mode from the moment the heating is turned off until the end of the generation cycle, min	Amount of generated electrical energy from the moment the heating is turned off until the end of the generation cycle, W* h
53 (from 10:27 to 11:20)	49	23 (from 11:22 to 11:45)	288 (from 11:22 to 16:10)	71

The experiment shows that a pre-melted thin layer of snow covering about 50% of the surface allows the photovoltaic panel to operate, including due to scattered radiation falling on its surface. Further heating of the panel does not make sense, because at this stage the panel can already generate electrical energy while continuing to generate heat until its own surface is completely cleaned.

Table 3 shows that the amount of electrical energy generated by the panel after its cleaning is 30% more than the amount of energy spent on heating it. This amount can be even higher if the heating process is carried out early in the morning. Then, the process of generating electrical energy by the panel will be much longer.

About 4.5 Wh of energy was spent on a heating the investigated panel with an area of 0.175 m^2 by 20 C during the indoor experiment. The heating time was 8 min. In [21], heating the panel with an area of about 0.076 m^2 by 20 degrees took 20 minutes and 9.5 Wh of energy.

49 Wh of energy was spent in the outdoor experiment for cleaning the panel surface with an area of 0.175 m^2, located at an angle of 30.7 degrees to the horizon, from about 1.53 kg of snow. It is about 32 Wh per kg of snow or 280 Wh per m^2 of panel surface. Here, the energy generated by the panel after cleaning 50% of its surface was not taken into account. In [18], where the method of heating the panel with carbon film heaters attached to its back was analyzed, the energy was calculated to clear snow from the system with an area of 16.3 m^2, located at an angle of 30 degrees to the horizon from 55.5 kg of snow. It was equal to 4.9 kWh. It is about 88.3 Wh per kg of snow or 300 Wh per m^2 of panel surface.

The analyzed method of a photovoltaic panel surface cleaning from snow and ice, according to the authors' point of view, has a number of significant advantages:

- does not require any changes in the structure of panels themselves. If it is necessary to heat panels at a solar power plant, it is enough to follow the developed algorithm and equip it with such automation system elements as a thermal relay, a minimum current relay and a microcontroller;

- relatively small heating time and energy consumption for heating panels;

- does not affect the characteristics of photocells themselves.

As for the last statement, it should be noted that the photovoltaic panels surface temperature during heating process while conducting the experiments did not exceed +36 C (see Table 2). In normal operation, the permissible nominal temperature of the panel surface declared by the manufacturer is +45 C. It follows that the artificial heating of the photovoltaic panel to the above temperatures will not affect its performance. It distinguishes positively the analyzed method from all the others, especially from the method using mechanical removal of snow and ice from a panel surface.

The speed of cleaning a photovoltaic panel is directly dependent on the duration of a snowfall, taking into account the following atmospheric and design features and factors:

1. Height of snow cover.
2. Weight of snow cover.
3. Density of snow cover.
4. Ice formations on a surface of a photovoltaic panel.
5. The angle of a photovoltaic panel relative to the horizon.
6. Surface temperature of a photovoltaic panel (ambient temperature).

5. Conclusion

The paper analyzes methods for cleaning photovoltaic panels from snow and ice in order to increase their efficiency in winter. It is concluded that the most promising is the method in which a direct current is applied to the outputs of a photovoltaic panel.

A number of experiments were carried out with two identical photovoltaic panels. The panels were totally covered. The surface temperature of the panels was -5 C and +10 C. The current supplied to the panel outputs was set to three values. The supply voltage was smoothly increased until the set current was reached. The experiments showed that the power consumed for heating the panel per unit of temperature change is practically independent on the initial temperature of the panel surface. This parameter increases with an increase in the set values of the current supplied for heating. In addition, changing the set values of the current supplied for heating has practically no effect on the heating rate, especially at low initial values of the panel surface temperature.

The outdoor experiment on cleaning the photovoltaic panel surface from snow and ice demonstrated the effectiveness of the chosen method. It showed that the amount of electrical energy generated by the panel is 30% higher than the amount of energy spent on its heating.

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