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Variability of photovoltaic panels efficiency depending on the value of the angle of their inclination relative to the horizon

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Abstract. The objective of this paper was to determine the relationship between the efficiency of photovoltaic panels and the value of the angle of their inclination relative to the horizon. For the purpose of experimental research have been done tests on the photovoltaic modules made of monocrystalline, polycrystalline and amorphous silicon. The experiment consisted of measurement of the voltage and current generated by photovoltaic panels at a known value of solar radiation and a specified resistance value determined by using resistor with variable value of resistance and known value of the angle of their inclination relative to the horizon.

Symbols used in formulas

P_{ideal}	– power of ideal photovoltaic cell, W
V_{oc}	– open circuit voltage, V
I_{sc}	– short circuit current, A
FF	– fill factor, -
$\eta_{\max}$	– efficiency of photovoltaic cell, -
$P_{\max}$	– maximum power of real photovoltaic cell, W
q	– power of solar radiation, W
q_{r}	– solar irradiance, W/m^2
A	– active area of photovoltaic cell, m^2

1 Principle of operation of photovoltaic cells

Photovoltaic cells produce electricity through direct conversion of solar radiation energy. The conversion of solar radiation is caused by the occurrence of the internal photoelectric effect in the interior of a photovoltaic cell - changes in the electron energy due to absorption of energy of photon beam incident on the solar module [1-4]. The principle of operation of photovoltaic cell is shown in Fig. 1.

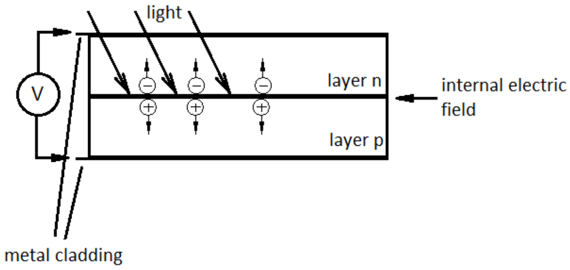

Fig. 1. Scheme and principle of operation of photovoltaic cell.

In PV module is used internal photoelectric effect involving the passage of electrons to the corresponding energy levels and the formation of excess charge carriers inside the solid - in case of silicon cells, this effect occurs within the crystal lattice of silicon at the interface "p"-"n", at the junction of layers with excess of electrons and holes (positive electrical charge carriers). Theory of bands is used to describe the phenomenon of internal photoelectric effect - according to this theory in material are energy levels which are "allowed" and "not allowed" for electrons. The photoelectric effect, described in accordance with the theory of bands, occurs in all semiconductors, but its intensity and wavelength range, which cause radiation, depends on the composition of the semiconductor.

Silicon, of which are made most of currently used photovoltaic cells, is intrinsic semiconductor and has a relatively high value of the conductivity at temperatures close to room temperature. In order to increase the conductivity of the crystal structure of the silicon are added small amounts of the appropriate elements (arsenic, phosphorus, aluminum, gallium). The "p"-type semiconductors, in which occurs a deficiency of electrons, are obtained by the use of acceptor, trivalent, dopant, "n"-type semiconductors, characterized by an excess of electrons, are obtained by applying a donor, pentavalent, dopants. At the interface between "n"-type semiconductor and the "p"-type semiconductor is created "p"-"n" junction [5]. By the diffusion of electrical charges is created barrier layer consisting of charge carriers with opposite sign, with a thickness of several mean free paths of electron. After reaching the "p"-"n" junction by a photon with sufficiently high energy, at least the energy of band gap, is formed in the potential difference - as a result of electron transfer to a segment of "n"-type semiconductor.

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If a "p"-"n" junction is connected to the resistor, the circuit is closed and occurs a flow of electric current.

2 Construction of silicon photovoltaic cells

The first monocrystalline and polycrystalline silicon solar cells were produced in thick layer technology - thickness of plates of silicon in modules of this type amounts to 200 ÷ 400 microns. Photovoltaic panel predominantly consists of the 36 or 40 interconnected cells as a single module allows to obtain a voltage of 0.5 ÷ 0.6 volts and a current of about 0.3 amperes. The cells, which are made of monocrystalline silicon, take the shape of a square with bevelled vertices, have uniform color, and their production relies on cutting them from a single crystal of silicon [6-8]. Polycrystalline cells take the shape of squares, and they do not have a uniform color. Silicon wafers in modules made in the thick layer technology are placed between two panes made from tempered glass with a thickness of 3 ÷ 5 mm and a reduced content of iron oxide. In order to create an electrical circuit individual links are joined using silver tape and adhered to the bottom of the glass. The whole structure is surrounded by the aluminum frame and rubber pads are mounted around pane as an additional sealing of the photovoltaic module [9]. Thin film cells are made of amorphous silicon dusted with a thickness of several micrometers onto a substrate made of e.g. glass. During the manufacturing process to the silicon layer are connected electrodes and the whole system is covered with a layer of solar glass with reduced content of iron oxide.

3 Characteristic parameters of photovoltaic cells

Photovoltaic cells are characterized by short circuit current I_{sc}, open circuit voltage V_{oc} and the values of voltage and current during the generation of the maximum power of cell, indicated by symbols V_{max} and I_{max} [10]. The values of these parameters can be read in the approximate manner by using the current-voltage and power-voltage characteristic for the photovoltaic module. The current-voltage and power-voltage characteristics created based on tests prepared for this paper are presented in Fig. 2 and Fig. 3.

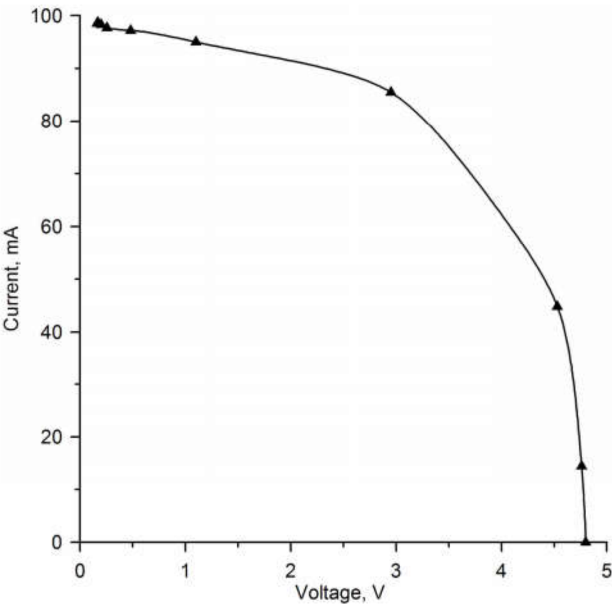

Fig. 2. Current-voltage characteristics of the photovoltaic cell.

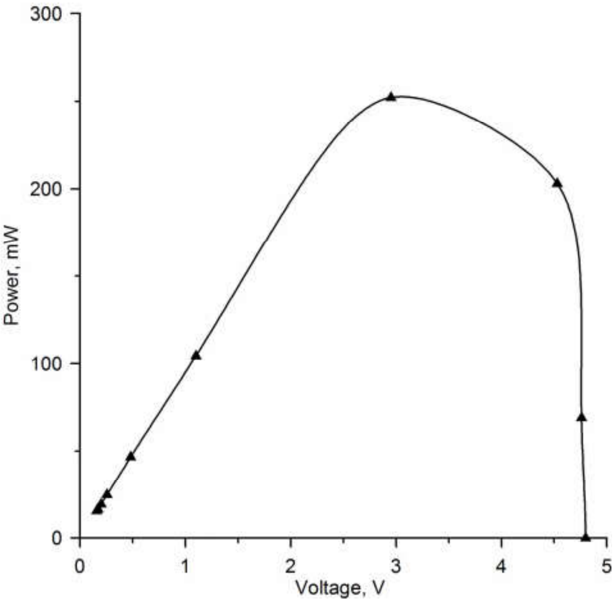

Fig. 3. Power-voltage characteristic of the photovoltaic cell.

Short circuit current I_{sc} is the value of the maximum current that will flow through tight contacts of photovoltaic cell, between which the voltage value is equal to zero. The value of short circuit current is related to the construction of the photovoltaic cell and the material from which it is made. Open circuit voltage V_{oc} is the maximum value of the potential difference that can be produced by a lighted photocell, which is not connected to the load. Maximum power point defines a pair of parameters (current and voltage) for which the real cell generates the maximum possible value of power at given conditions - it is equal to the largest rectangle designated under the current-voltage characteristics for the coordinates (I_{max}, V_{max}). The value of maximum power of real cell is defined by the formula:

$$P_{max}=V_{max}I_{max} \tag{1}$$

and is less than the maximum power of the ideal cell, which is defined by the equation:

$$P_{\mathrm{ideal}}=V_{\mathrm{oc}}I_{\mathrm{sc}}. \tag{2}$$

The relationship between the maximum power of the real cell and the maximum power of the ideal cell determines the fill factor *FF*. The coefficient can be expressed by using the formula:

$$FF=P_{\mathrm{max}}/P_{\mathrm{ideal}}=(V_{\mathrm{max}}I_{\mathrm{max}})/(V_{\mathrm{oc}}I_{\mathrm{sc}}) \tag{3}$$

The fill factor *FF* reaches the greater value, the more shape of the current-voltage characteristic of real photovoltaic cell is similar to the shape of the characteristic of the ideal cell. The value of fill factor of currently used silicon photovoltaic cells amounts in most cases 0.6 to 0.82.

Efficiency of the photovoltaic cell is a very important parameter because it largely depends on it how effectively will be processed solar energy. Efficiency of the module is defined as the ratio of the photovoltaic cell power to the sunlight radiation power operating on active area of the photovoltaic module. It can be expressed by using the formula:

$$\eta_{max}=P_{\mathrm{max}}/q \tag{4}$$

4 Measuring system

In order to determine efficiency of tested photovoltaic panels and changes of its value depending on the angle of inclination of modules relative to the horizon has been built measuring system (shown in Fig. 4) allowing the movement of cells and change of angle of their inclination. The research position consists of a rectangular frame with installed photovoltaic panels, the frame is placed on wheels and had two elements allowing to the change of the angle of inclination of the photovoltaic modules. On the frame has been installed three photovoltaic panels: polycrystalline with a power of 250 W_p, amorphous with a power of 120 W_p and monocrystalline with a power of 250 W_p. In order to determine the current-voltage characteristics and power-voltage characteristics of each panel to the position was attached a variable resistance resistor.

Fig. 4. Measuring system.

5 Determination of the efficiency of photovoltaic modules

In order to calculate the efficiency of photovoltaic cells should be determined the ratio of the maximum power generated by the photovoltaic cell on the conditions occurring at the time of measurement to the solar radiation power [11, 12], which can be expressed as the product of the intensity of solar radiation incident on the cell surface and the active surface area:

$$\eta_{max}=(V_{\mathrm{max}}I_{\mathrm{max}})/(q_rA) \tag{5}$$

Efficiency of the cell is determined for each series of measurements by performing calculations for a known value of solar radiation incident on the active surface of the panel and voltage and current value corresponding to the maximum power achieved in the measurement series.

6 Results

Tests using previously described photovoltaic modules were made in the spring. On the basis of the collected measurements were plotted current-voltage characteristics of examined photovoltaic panels. The characteristics of individual modules were collected in order to compare their charts depending on angle of inclination of panels relative to the horizon. Characteristics obtained for the amorphous photovoltaic cell are shown in Fig. 5, for the monocrystalline photovoltaic cell in Fig. 6 and for the polycrystalline photovoltaic cell in Fig. 7.

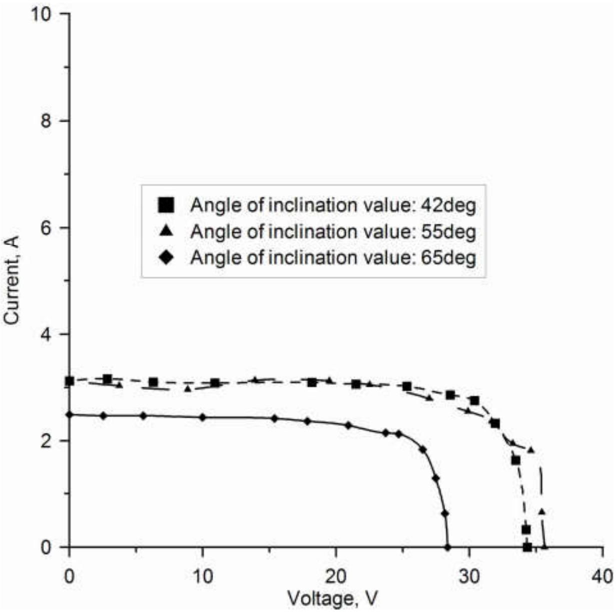

Fig. 5. Current-voltage characteristics obtained for the amorphous photovoltaic cell.

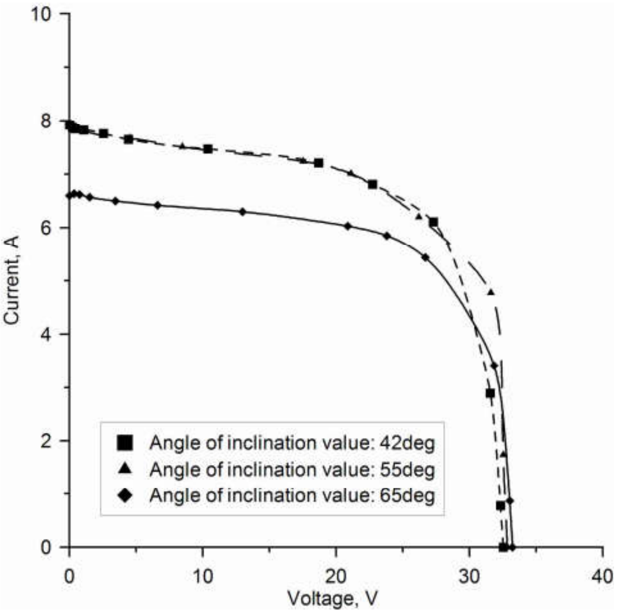

Fig. 6. Current-voltage characteristics obtained for the monocrystalline photovoltaic cell.

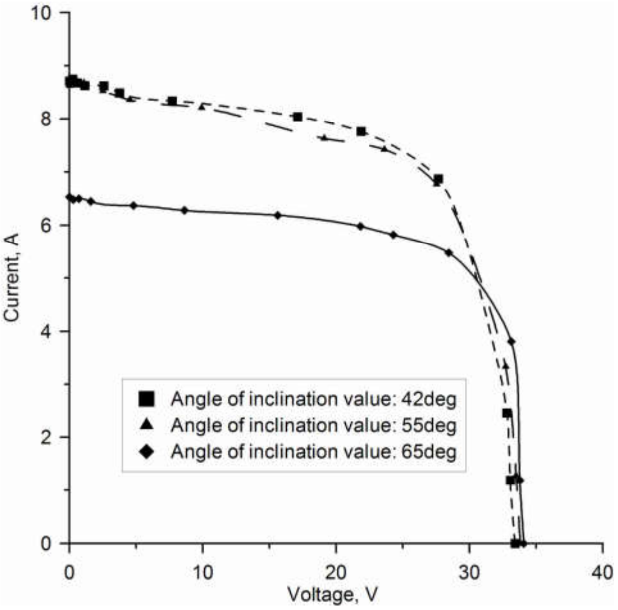

Fig. 7. Current voltage characteristics obtained for the polycrystalline photovoltaic cell.

In order to determine the efficiency of photovoltaic modules for each series of measurements were assigned maximum power points of characteristics, followed by a calculation based on the equation (5). During the calculation were used values of the active surface area of examined photovoltaic modules from their documentation and the average values of solar radiation measured by the pyranometer during each series of measurements. For each data set was also determined filling factor value. The results, with including absolute errors, which takes into account the uncertainty of used sensors, are presented in Table 1.

Table 1. Efficiency values for tested photovoltaic panels and values of fill factor for each measurement series.

	Mono-crystalline PV panel	Poly-crystalline PV panel	Amorphous PV panel
Efficiency of the panel for the angle of inclination of 65,0°	(16,145 ±0,161) %	(15,359 ±0,154) %	(6,287 ±0,063) %
Efficiency of the panel for the angle of inclination of 55,0°	(17,155 ±0,172) %	(16,423 ±0,164) %	(7,803 ±0,078) %
Efficiency of the panel for the angle of inclination of 42,0°	(16,011 ±0,160) %	(16,156 ±0,162) %	(7,488 ±0,075) %
Value of fill factor for the angle of inclination of 65,0°	(66,421 ±1,328) %	(67,563 ±1,351) %	(72,757 ±1,455) %
Value of fill factor for the angle of inclination of 55,0°	(63,428 ±1,268) %	(61,904 ±1,238) %	(67,496 ±1,350) %
Value of fill factor for the angle of inclination of 42,0°	(65,294 ±1,306) %	(62,771 ±1,255) %	(79,026 ±1,580) %

Conclusions

By comparing data collected in table Tab. 1 may be noted that, for studied angles of inclination, selected from the most commonly used in Poland inclination angles of photovoltaic panels, modules achieve maximum efficiency at an angle of inclination of 55°. The obtained value of the angle of inclination of panels relative to the horizon is consistent with the experiences of companies that use and assemble the photovoltaic panels on Polish territory - they prescribe use of inclination angles of modules of 35-45° in summer and 65° in winter. Measurements were made in the spring, so that the obtained value of an optimal angle of inclination of panels which fall within the scope between these values allows to be considered that the outcome of the research is realistic. It should also be noted that changes in the efficiency of each module are only about one order of magnitude greater than the differences resulting from the uncertainty of measurement for used sensors. This is mainly due to the participation of the scattered radiation in the total radiation at about 40-50% and also because the surface structure of the solar panels is adapted to absorb the maximum amount of the radiation regardless of the angle of incidence on the surface of the module. Due to such small dependence between the efficiency of solar panels and angle of inclination relative to the horizon can be bring up within the reasonableness of use, at least in the case of installations of low and medium power, the construction of the variable angle of inclination at the time of day and year, as well as the lag systems, which additionally reduce the net production of electricity through the energy to power the actuators that change the setting of panels and controllers directing the operation of the entire system.

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