TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
CHEMISTRY | CHEMIA
1-Ch/2016

10.4467/2353737XCT.16.045.5307

TADEUSZ KOMOROWICZ, KRZYSZTOF NEUPAUER, KATARZYNA SABAT*,
ANETA GŁUSZEK**

LABORATORY TESTS OF PHOTOVOLTAIC MODULES FORMED OF MULTICRYSTALLINE SILICON CELLS

BADANIA LABORATORYJNE MODUŁÓW FOTOWOLTAICZNYCH ZBUDOWANYCH Z POLIKRYSTALICZNYCH OGNIW KRZEMOWYCH

A b s t r a c t

The paper presents the results of laboratory tests of both a photovoltaic module formed of 36 multicrystalline silicon cells and a four-module generator, in the form of voltage-current characteristic curves. An analysis of the obtained data is conducted as well.

Keywords: photovoltaics, multicrystalline silicon cells, voltage-current characteristic curves

S t r e s z c z e n i e

W artykule przedstawiono wyniki badań laboratoryjnych zarówno modułu fotowoltaicznego zbudowanego z 36 polikrystalicznych ogniw krzemowych i czteromodułowego generatora, w formie charakterystyk prądowo-napięciowych. Przeprowadzono również analizę otrzymanych wyników.

Słowa kluczowe: fotowoltaika, polikrystaliczne ogniwa krzemowe, charakterystyki prądowo-napięciowe

* Ph.D. Eng. Tadeusz Komorowicz, Ph.D. Eng. Krzysztof Neupaper, M.Sc. Eng. Katarzyna Sabat, Chair of Chemical and Process Engineering, Faculty of Chemical Engineering and Technology, Cracow University of Technology.

** Ph.D. Eng. Aneta Głuszek, Office of Technical Inspection (UDT) – Warsaw.

1. Introduction

According to the "20–20–20 targets" in European Union, by the year 2020, all EU countries should meet at least 20% of their energy needs with renewable energy, the energy efficiency should be improved by 20%, and thereby the reduction of CO_2 emissions, in comparison to the year 1990, should be decreased by 20% [1, 2, 3]. The Sun is a source of energy on the Earth. Radiation power outside the Earth's atmosphere is equal to 1337 W/m^2 (the solar constant) [4]. Passing through the Earth's atmosphere, it reduces to 1000 W/m^2. Photovoltaics, converting solar energy into electric energy, is one of the renewable energy sources.

The basic elements of photovoltaic equipment are photovoltaic cells. The most popular are silicon cells [4]. There are three types of silicon cells:
– monocrystalline,
– poly- or multicrystalline,
– amorphous.

Monocrystalline solar cells, also known as Czochralski or CZ-pulled cells (abbreviation: CZ-Si), are pulled, in a high temperature process, from a crystal (round) and cut into sheets approximately 0.3 mm thick. Pseudo-square wafers are created by sawing the round silicon sheets. The global market share of this type of cells was approximately 30% in 2010 [4]. Monocrystalline silicon cells are the most expensive cells and reach the highest efficiency of about 20%.

Poly- or multicrystalline silicon cells (abbreviation: poly-Si) are poured from a Si melt into a mould. Then, the material is cut from rectangular blocks into 0.3 mm thick wafers. Multicrystalline cells reached a global market share of about 50% in 2010 [4]. The energy expended in the manufacturing process is lower than that of monocrystalline cells. Therefore, the energy payback period is shorter, but the efficiency of cells is lower – about 15%.

Amorphous silicon cells (abbreviation: a-Si) belong to the group of thin film cells. They are produced as a silicon steam precipitate on a glass substrate. The layer thickness does not exceed 0.5 μm. The global market share of amorphous silicon cells was about 5% in 2010 [4]. Less energy is expended when manufacturing them than in the case of monocrystalline cells. The efficiency of amorphous cells ranges from 5 to 10%. The largest surface area, in order to obtain an energy unit, is therefore required compared to other kinds of cells.

The voltage of individual solar cell ranges from 0.5 to 0.6 volt. Therefore, for the standard low voltage range of 6–24 volts, many cells are connected together in series. By doing this, one obtains a solar module or a solar panel that can consist of 12-42 solar cells. When building larger photovoltaic systems (PV systems), many solar modules are connected together in series and in parallel to make a solar generator.

The Chair of Chemical and Process Engineering at the Cracow University of Technology has been involved in the research of renewable energy sources. Photovoltaics is one of their branches. In the Chair, there are laboratory stands for testing modules and generators [5].

The results of laboratory tests of a solar module consisting of 36 multicrystalline silicon cells, and a solar generator formed of four modules combined in series and in parallel, are presented in this paper in the form of current-voltage characteristic curves. An analysis of the obtained data is conducted as well.

2. Description of laboratory tests

2.1. Description of test stations

The first photovoltaic test station is equipped with a single photovoltaic module (Fig. 1). The second station consists of a set of 4 modules forming a current generator (Fig. 2). All of the modules are identical. Each module consists of 36 multicrystalline rectangular silicon cells (310×364 mm) connected in series, arranged in six rows containing 6 cells each (Fig. 3). The modules are illuminated with separate incandescent lamps with an adjustable light intensity. The measurements of light intensity can be carried out using a luxmeter.

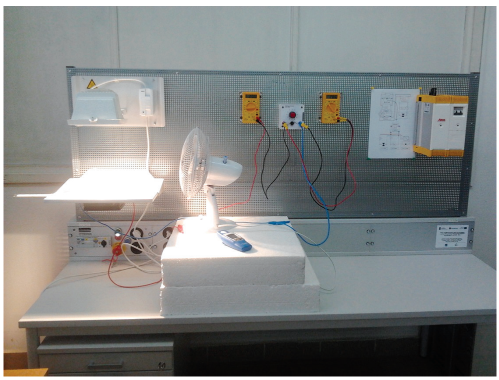

Fig. 1. The photovoltaic test station equipped with a single photovoltaic module

The modules in the generator can be connected either in series or in parallel. It is also possible to make a serial-parallel connection. A serial connection consists in the connection of a "+" electrode of one module with a "–" electrode of the next module, while a parallel connection consists in connecting a "+" electrode of one module with a "+" electrode of another module, and connecting the "–" electrodes in a similar way. A serial-parallel connection consists in a serial connection of 2×2 modules and a parallel connection of the 2 rows.

Fig. 2. The photovoltaic test station equipped with four photovoltaic modules

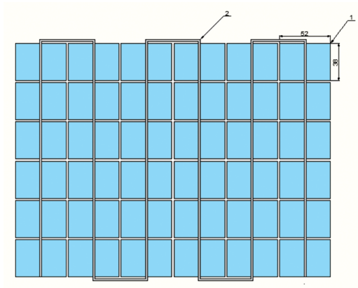

Fig. 3. Scheme of connection of cells in the tested photovoltaic modules,
1 – an individual cell, 2 – connection of cells

2.2. Methodology of measurements

The two basic quantities used in photovoltaics are [6]:
- open circuit voltage – the highest voltage of a voltage source;
- short circuit current – the strongest current in an electric circuit.

The basic parameters of a photovoltaic module are obtained by examining its voltage-current characteristics [6]. In order to obtain these characteristics, the electric system presented in Fig. 4 was applied.

In the first photovoltaic station, the following measurements were carried out:

A. The measurements of open circuit voltage and short circuit current at a temperature of 22°C and in the functions of:
   - the radiation power (in the range from 4 to 540 W/m^2, 14 measurement points); the angle of module inclination equal to 0° (the angle of radiation insistence equal to 90°); no shading;
   - the angle of module inclination (from 0° to 90°, with an interval of 10°); the radiation power 550 W/m^2, no shading;
   - the ratio of module shading in the range from 0 to 5/6 (fraction), with an interval of 1/6 (fraction) in two ways: from left to right and from top to bottom (Fig. 3); the radiation power 550 W/m^2; the module inclination angle 0°.

The temperature was measured on the module surface (see a thermometer in Fig. 1). In order to keep a constant temperature during the measurements, fans were applied (Fig. 1, 2). “No shading” means that the whole module surface was illuminated. It was easy to receive a shading interval of 1/6 to shadow the individual rows (Fig. 3).

B. Tests of voltage-current characteristics (Fig. 4) of the module at different values of radiation power (160, 300 and 520 W/m^2) with a change of electric resistance from 0 to 970 Ω; the module inclination angle 0°; no shading.

In the second photovoltaic station, the above measurements were repeated for each individual module and the following voltage-current characteristics were tested:
- separately for the serial and parallel connections of modules 1 and 2,
- separately for the serial and parallel connections of modules 1, 2 and 3,
- separately for the serial and parallel connections of modules 1, 2, 3 and 4,

– for combined connection – a parallel connection of two separate serial connections of the modules 1 and 2 and the modules 3 and 4.

In electrical measurements, a digital multi-meter was used. The accuracy of the individual measurements were:

± (0.8% + 5 Digit) for voltage measurements,

± (1.2% + 5 Digit) for current measurements below 200 mA,

± (2.0% + 5 Digit) for current measurements above 200 mA.

For testing the stand, it was possible to measure the radiation power with a luxmeter using an approximate conversion factor: 100 lux ≈ 1 W/m^2. The luxmeter accuracy was ± (4% + 50 Digits).

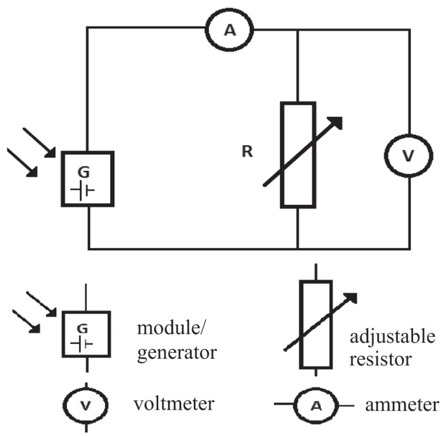

Fig. 4. Diagram of a voltage-current characteristics measurement station

3. Test results

The results are presented in the form of graphs. Each measurement point in the graphs represents a mean value of three results of measurements, which differ no more than 5%.

The following graphs present the results obtained in the test photovoltaic station equipped with a single module:

– the effect of radiation power on the open circuit voltage (Fig. 5),
– the effect of radiation power on the short circuit current (Fig. 6),
– the effect of the module inclination angle on the open circuit voltage (Fig. 7),
– the effect of the module inclination angle on the short circuit current (Fig. 8),
– the effect of the shading ratio of the module on the open circuit voltage (Fig. 9),
– the effect of the shading ratio of the module on the short circuit current (Fig. 10),
– the voltage-current characteristics and the power vs. voltage for three values of radiation power (Fig. 11),
– the voltage-current characteristics and the power vs. the voltage, and the module efficiency vs. the voltage for radiation power equal to 300 W/m^2 (Fig. 12).

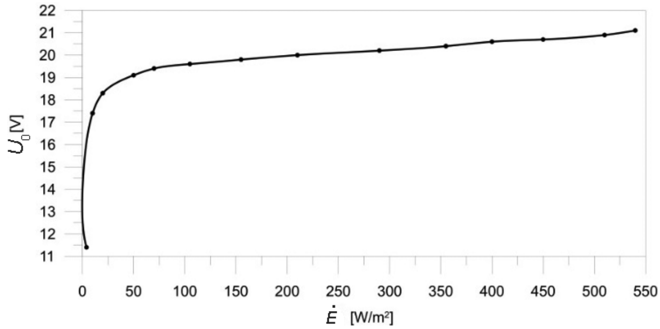

Fig. 5. The effect of radiation power on the open circuit voltage

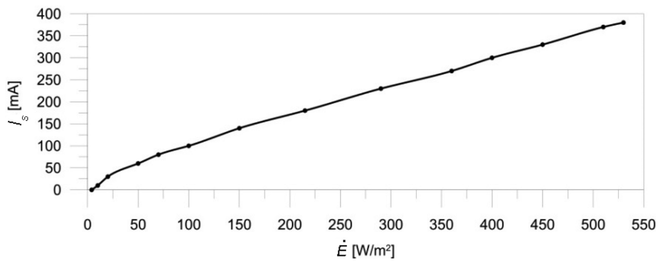

Fig. 6. The effect of radiation power on the short circuit current

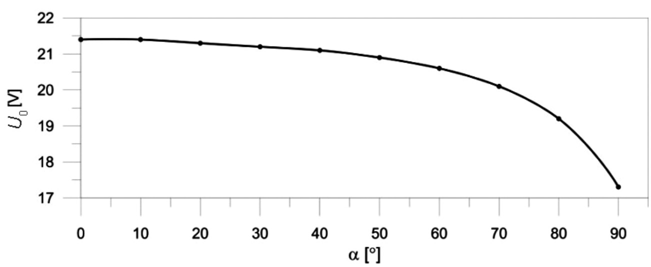

Fig. 7. The effect of the module inclination angle on the open circuit voltage

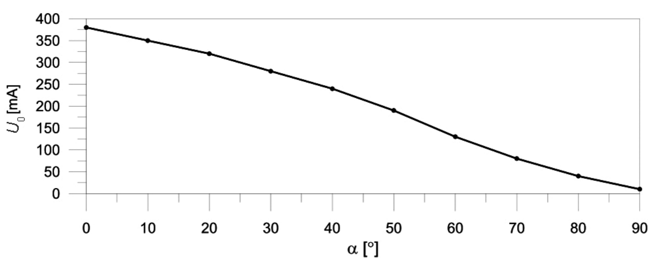

Fig. 8. The effect of the module inclination angle on the short circuit current

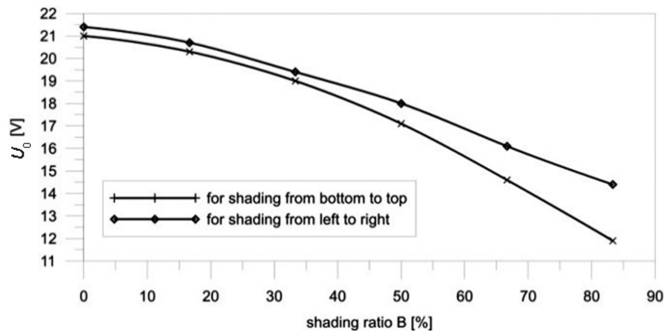

Fig. 9. The effect of the shading ratio of the module on the open circuit voltage

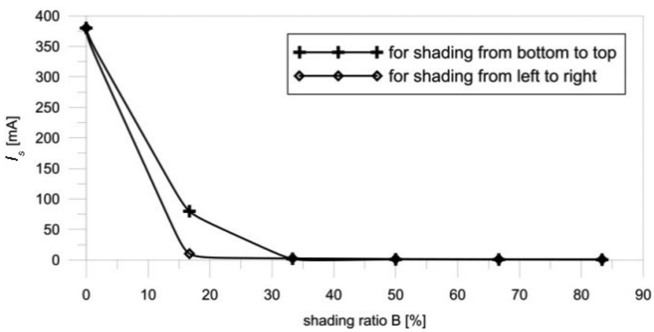

Fig. 10. The effect of the shading ratio of the module on the short circuit current

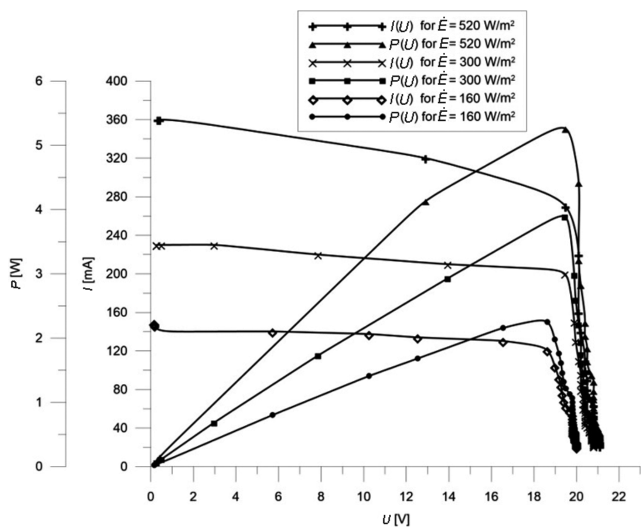

Fig. 11. The voltage-current characteristics and the power vs. the voltage for three values of radiation power

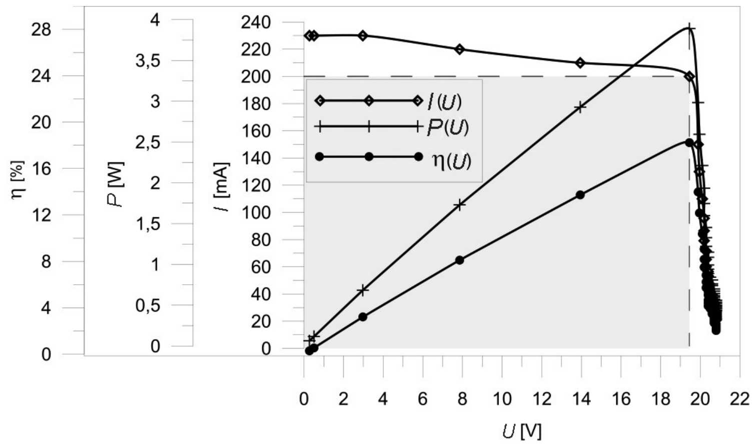

Fig. 12. The voltage-current characteristics and the power vs. the voltage, and the module efficiency vs. the voltage for radiation power equal to 300 W/m²

In Fig. 12, the point (200 mA, 18,7 V) corresponding to the maximum efficiency is the Maximum Power Point. The ratio of the shaded area to the area of rectangle 230 mA×21 V is a filling factor FF. The filling factor is a measure of correctness of the module operation. In the case of an ideal module, FF = 1. In the case of the tested module, FF = 0,774.

On the other hand, the following exemplary graphs present the results obtained in the tests of photovoltaic station equipped with four modules:

– the voltage-current characteristics of individual modules 1, 2, 3, 4 and in case of serial connections 1+2, 1+2+3 and 1+2+3+4 at radiation power equal to 640 W/m² (Fig. 13);
– the voltage-current characteristics of individual modules 1, 2, 3, 4 and in case of parallel connection 1+2+3+4 at radiation power equal to 150 W/m² (Fig. 14).

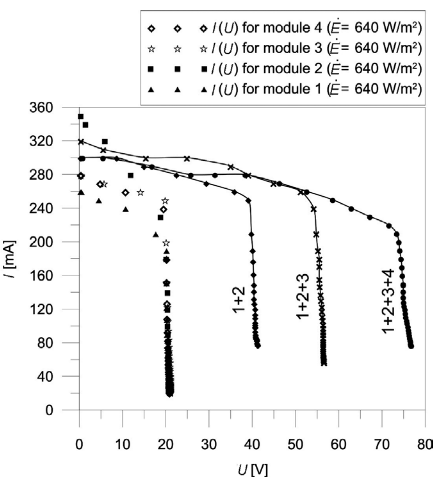

Fig. 13. Voltage-current characteristics of individual modules 1, 2, 3, 4 and in case of serial connections 1+2, 1+2+3 and 1+2+3+4 at radiation power equal to 640 W/m²

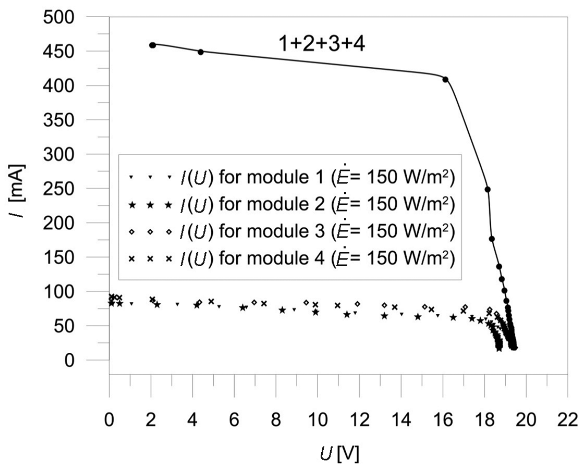

Fig. 14. Voltage-current characteristics of individual modules 1, 2, 3, 4 and in case of parallel connection 1+2+3+4 at radiation power equal to 150 W/m^2

3. Conclusions

The results of measurements lead to the following conclusions:

- The photovoltaic cell has approximately a constant open circuit voltage. An increase in radiation power results in a slight increase of open circuit voltage, whereas a considerable, approximately linear, increase in the short circuit current (Fig. 5, 6).
- An increase in the module inclination angle results in both a decrease in the open circuit voltage and a fast decrease in the short circuit current, in comparison to the perpendicular angle of the radiation incidence (Fig. 7, 8).
- An increase of the shading ratio of the module results in a slight decrease in the open circuit voltage and in a fast decrease of the short circuit current (Fig 9, 10). A shading ratio of 15–30% decreases the short circuit current almost to 0, depending on the method of shading.
- An increase of radiation power results in a higher current at the same voltage, which results in a larger module power (Fig. 11).
- The filling factor for the tested modules is relatively high (Fig. 12). The closer the value of the filling factor is to 1, the closer the voltage-current characteristics are to that of an ideal cell.
- In the case of serial connections of the modules, theoretically, their total voltage should be the sum of the voltages of individual modules. In the case of a parallel connection, theoretically, their total current should be the sum of the currents of individual modules. Small deviations from this rule observed in practice – Figs. 13 and 14 respectively – result from some differences in the individual characteristics of the modules.
- A similarity of characteristics of various technical devices can be observed. The voltage-current characteristics of a photovoltaic module and the characteristics of a centrifugal pump are analogous (Fig. 12, 15): the module voltage corresponds with the pressure generated by the pump, whereas the module current corresponds with the pump capacity. On the other hand, the radiation power (module characteristics) corresponds with the rotational speed (pump characteristics). The courses of power and efficiency are similar in both cases.

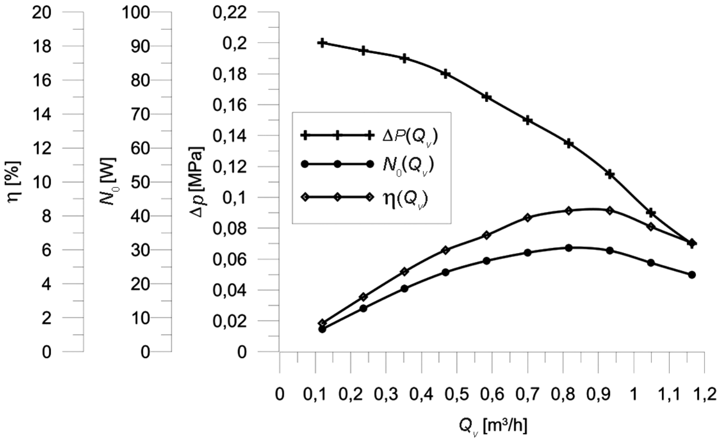

Fig. 15. An exemplary centrifugal pump characteristics received in laboratory tests: the pressure, the power and the pump efficiency vs. the pump capacity

The tested station can be successfully applied for research in the photovoltaic field.

References

[1] Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community, Document 32009L0029.

[2] Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020 ("Effort Sharing Decision").

[3] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC ("Renewable energy Directive").

[4] Luque A., Hegedus S., *Handbook of Photovoltaic Science and Engineering*, 2nd Edition, John Wiley & Sons Ltd., New Jersey 2011.

[5] Głuszek A., Pater S., Neupauer K., *Renewable Energy Sources – Laboratory Exercises*, Wydawnictwo Politechniki Krakowskiej, Kraków 2014.

[6] Kirchensteiner W., *Solar Power Laboratory, Experimental Manual Off-grid and On-grid Technology*, Dr. Ing. Paul Christiani GmbH & Co. KG, Konstanz 2010.