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Application of crystalline silicon solar cells in photovoltaic modules

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ABSTRACT

Purpose: The aim of the paper is to determinate basic electrical properties of solar cells, made of them photovoltaic module and analysis of its main electrical parameters.

Design/methodology/approach: In this study, several methods were used: current – voltage characteristic to determinate basic electrical properties of 36 monocrystalline silicon solar cells, soft soldering technique to bond solar cells . Photovoltaic module was produced from 31 solar cells with the largest short-circuit current, which were joined in series.

Findings: In order to obtain a device producing an electrical current with a higher current and voltage level, solar cells were connected in a photovoltaic module and then protected from damages derived from external factors. In series connection solar cell with the lowest current determines the current flowing in the PV module. Taking this fact into account the analysis of photovoltaic module construction was performed.

Practical implications: Because of low operating cost and simplicity of photovoltaic installation, photovoltaic technology is perfectly suitable for supplying objects which are beyond powers network range as well as connected to it. In many cases, they are less costly option than a direct extension of the power network.

Originality/value: Protecting the environment from degradation due to pollution, which has source in conventional power industry, as well as diminishing resources of fossil fuels, tend to increase development of renewable energy production such as photovoltaic technology.

Keywords: Photovoltaic; Monocrystalline silicon; Solar cells; Photovoltaic module

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PROPERTIES

1. Introduction

Ozone hole, greenhouse effect and acid rain are one of the most significant contemporary ecological problems, which threaten life and health. They are effects of mass combustion of fossil fuel such as: coal and crude oil. The key to solve this problem is development of renewable energy technology [1-7].

One of the most interesting technology of renewable energy to produce electrical energy is photovoltaic technology. Because of low operating cost and simplicity of photovoltaic installation, photovoltaic technology is perfectly suitable for supplying objects which are beyond powers network range as well as connected to it. In many cases, they are less costly option than a direct extension of the power network [5-8].

Photovoltaic effect utilization to produce electrical energy is also important due to depletion of traditional energy stocks like coal, crude oil, uranium or natural gas. In Figure 1 world energy resources are shown [2-4, 9].

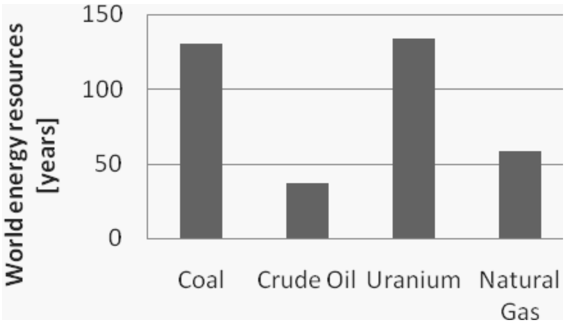

Fig. 1. World energy resources [9]

Achievements in the field of traditional silicon materials (mono- and polycrystalline) offer improved efficiency silicon solar cells and reduce their manufacturing costs. Mono- and polycrystalline silicon cells represent more than 90% of the photovoltaic industry, which is now one of the fastest growing industries. This development is a result of advances in materials and technology, and programs aimed at dissemination of photovoltaic [4-6, 10].

The potential of photovoltaics is also perceived by the European Union. In order to empower position of renewable energy sources a SET Plan (Strategic Energy Technology), which includes initiatives of renewable energy sources was created. The initiative aims to support the development of photovoltaic technology. Main goal is to achieve 12% share in electricity production (285 TWh) in Europe by 2020. According to the most optimistic projections by 2100 photovoltaics will be the most important source of energy.

Because a single solar cell can only produce a limited amount of power photovoltaic panels are used in commercial applications that are packaged interconnected assemblies of solar cells. Electrical connections are made in series to achieve a desired amount of current [11].

In order to obtain higher voltage solar cells are connected in series. The overall voltage of series connection is the algebraic sum of voltages of all elements of the system. In this connection, the weakest link determines the quality of the entire chain, which means that the current of PV module depends on the weakest link in the series (Fig. 2). If even a solar cell is shadowed, for example by power poles, wires, trees, leaves, dust, bird droppings, the voltage on the cell changes direction and polarization of such a link becomes a burden to the other [12-14]. In practice, the complete elimination of shading is not possible, therefore, PV modules are protected against damage using a shunt diodes, called bypass, which during normal operation are reversed biased, and do not cause any power loss (Fig. 3). In case of shading photovoltaic cells diodes are forward biased and current generated by the rest of the solar cells start to flow through bypass diode, "bypassing" the shaded cells. The ideal would be to bypass all the photovoltaic cell, but this would apply only in aerospace engineering. In practice, bypass diodes is usually connected in a group of 15-20 solar cells [12, 13, 16].

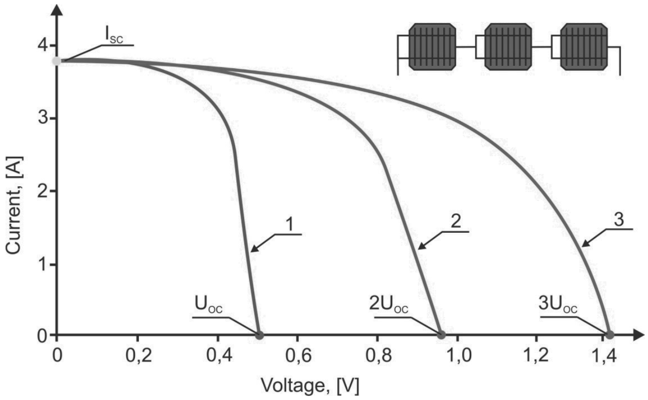

Fig. 2. Effect of serial connection of photovoltaic cells on the current - voltage characteristics, where: U_{OC} – open circuit voltage, 1,2,3-current - voltage characteristics of: 1- single solar cell, 2-two solar cells connected in series, 3-three solar cells connected in series [13-15]

To increase the value of current, photovoltaic cells are connected in parallel. With this combination, the current value is the algebraic sum of the individual currents of each component. In Figure 4 effect of parallel connection of three identical PV cells on the current - voltage characteristics is shown [13].

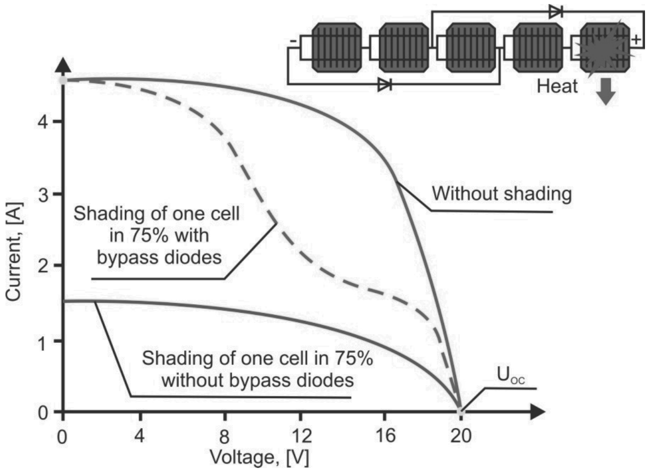

Fig. 3. Effect of bypass diodes on the current - voltage characteristics of partially shaded photovoltaic module [9-11]

In a parallel connection in the case of a shaded photovoltaic cells can also become a burden for others. However, placing the serial diode D_S in each branch contains a number of cells connected in series, prevents this phenomenon (Fig. 5). In the case of a shading diode D_S is reversed biased, the branch is not damaged, but did not produce any energy [13,15].

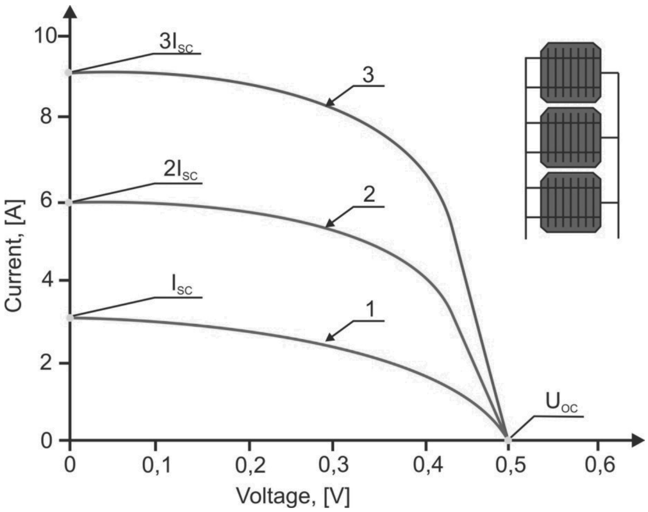

Fig. 4. Effect of parallel connection of three identical PV cells on the current - voltage characteristics, where: I_{SC} – short-circuit current, 1, 2, 3-current - voltage characteristics of: 1- single solar cell, 2-two solar cells connected in parallel, 3-three solar cells connected in parallel [13-15]

In a parallel connection in the case of a shaded photovoltaic cells can also become a burden for others. However, placing the serial diode D_S in each branch contains a number of cells connected in series, prevents this phenomenon (Fig. 5). In the case of a shading diode D_S is reversed biased, the branch is not damaged, but did not produce any energy [13, 15].

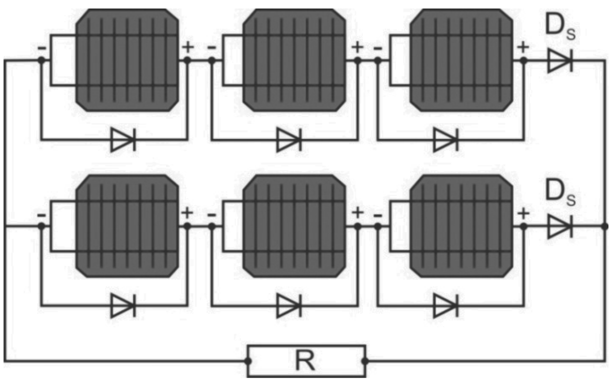

Fig. 5. Security in case of parallel connection of solar cells [15]

To protect against damage, pollution and environmental impact and give adequate mechanical rigidity connected photovoltaic cells are subjected to lamination. Lamination method depends on the type PV module manufacturing technology of solar cell [14, 16, 17].

Photovoltaic module must be resistant to transportation, installation, mechanical stress, humidity and temperature changes, so should be equipped with a solid, rigid frame (Fig. 6) [12, 14].

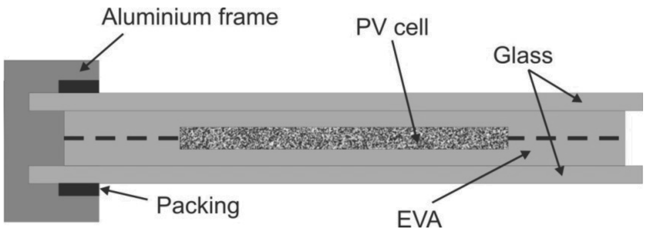

Fig. 6. Standard enclosure of solar module [19]

Housing solar module must be subjected to encapsulation. There are three basic types of enclosure (encapsulation) of photovoltaic modules [12, 14]:

- EVA (octane ethylene - vinyl),
- Teflon (fluorocarbon polymer material),
- Cast rubber.

The first series-produced monocrystalline silicon solar cells have the shape of a circle. They were obtained directly from slicing a cylindrical single crystal silicon. Currently, round cell is cut in half to form a semicircle, or cut into squares to increase the area of module covered by solar cells. The optimum fill is this one in which the cells cover 90% of the PV module. Due to the thermal expansion a certain area of the photovoltaic module must remain free [3, 12, 14, 18].

The basic advantages of photovoltaic cells made of silicon are [2, 6, 18]:

- Good efficiency of solar cells in series production (up to 22%),
- Excellent efficiency above 24%, obtained in laboratory scale,
- The possibility to use the experience from the very well-developed electronics industry,
- Unlimited amount of base material,
- Simplicity and very good stability,
- Good compliance with environmental requirements.

The fundamental defects of silicon photovoltaic cells are [2,20]:

- Necessity to apply a thick absorber area (> 100 microns) to obtain high efficiency,
- Application of large amounts of expensive high-purity silicon, which is the main factor behind the high cost of production,
- Difficult in disposing compounds arising from manufacturing solar cells.

The main purpose of the research was to determine basic electrical properties of solar cells, made of them PV module and analysis main electrical parameters of this module.

2. Experimental

2.1. Material

In order to determine the basic electrical properties of photovoltaic cells (Solartec) made of monocrystalline silicon, their current - voltage characteristics were measured under standard spectrum AM 1.5 at the temperature of cell 25°C. Measurement was done for 36 photovoltaic cells with dimensions of 29.4 mm x 12.3 mm (Fig. 7).

Open circuit voltage (U_{OC}), short-circuit current (I_{SC}), the module maximum power (P_m), current and voltage at the point of maximum power (I_{max}, U_{max}), fill factor (FF) and efficiency of the photovoltaic test cell (E_{ff}) were determined from current-voltage characteristics. Table 1 summarizes main electrical properties of measured photovoltaic cells.

In Figure 8 current- voltage characteristics of solar cells with the highest and the lowest: open circuit voltage and short-circuit current are shown.

a) b)

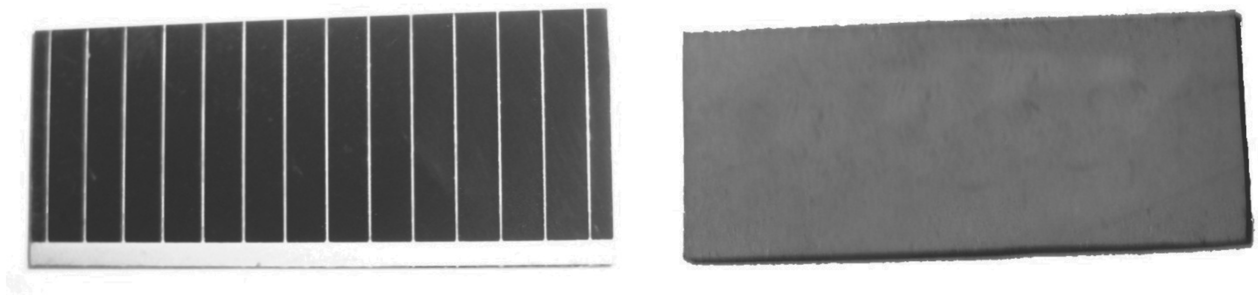

Fig. 7. Monocrystalline silicon solar cells a) front surface, b) back surface

a) b)

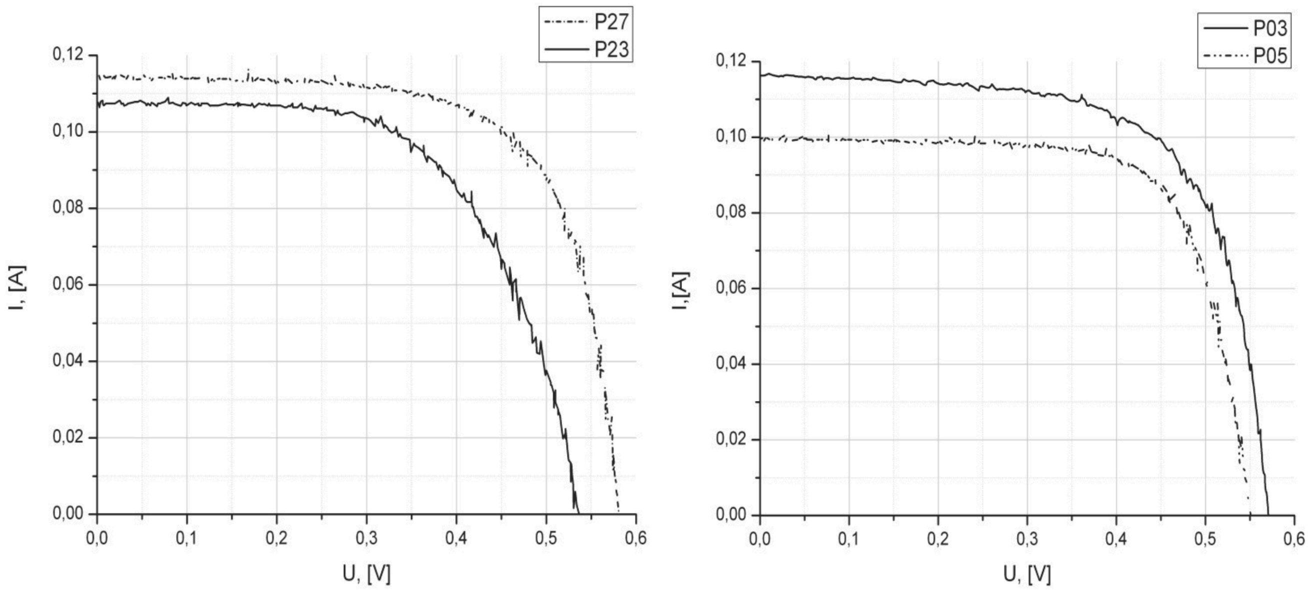

Fig. 8. Current-voltage characteristics of solar cells with the highest and the lowest a) open circuit voltage, b) short-circuit current

Table 1.
Electrical properties of silicon solar cells

Cell number	U_{oc} [mV]	I_{sc} [mA]	I_{max} [mA]	U_{max} [mV]	P_m [mW]	FF	E_{ff} [%]
P01	575.45	100.92	83.15	460.76	38.31	0.66	10.59
P02	578.01	100.72	81.87	470.01	38.48	0.66	10.64
P03	570.65	116.54	101.16	442.36	44.75	0.67	12.37
P04	573.67	114.24	94.69	461.94	43.74	0.67	12.10
P05	550.81	99.63	87.13	451.44	39.33	0.72	10.88
P06	565.4	112.73	93.69	410.22	38.43	0.60	10.63
P07	572.25	112.88	96.9	449.28	43.54	0.67	12.04
P08	571.6	111.73	95.36	463.17	44.17	0.69	12.21
P09	566.42	112.9	106.19	466.1	49.50	0.77	13.69
P10	548.27	101	92.13	446.78	41.16	0.74	11.38
P11	567.46	113.66	94.65	460.17	43.56	0.68	12.04
P12	557.11	114.58	95.94	432.72	41.52	0.65	11.48
P13	574.32	112.51	99.11	440.89	43.70	0.68	12.08
P14	569.42	113.08	93.9	460.65	43.26	0.67	11.96
P15	578.01	114.72	97.87	470.01	46.00	0.69	12.72
P16	570.66	114.83	97.22	466.16	45.32	0.69	12.53
P17	563.56	115.46	96.5	458.2	44.22	0.68	12.23
P18	569.09	113.95	96.72	465.55	45.03	0.69	12.45
P19	570.14	112.68	90.49	447.05	40.45	0.63	11.19
P20	563.42	113.84	98.71	439.46	43.38	0.68	12.00
P21	565.71	114.8	96.52	447.84	43.23	0.67	11.95
P22	577.25	115.5	93.86	471.77	44.28	0.66	12.24
P23	581.12	114.33	98.07	460.66	45.18	0.68	12.49
P24	568.41	111.6	93.64	455.68	42.67	0.67	11.80
P25	561.13	100.51	86.57	456.64	39.53	0.70	10.93
P26	559.16	110.01	92.02	430.45	39.61	0.64	10.95
P27	536.34	107.47	82.86	409.23	33.91	0.59	9.38
P28	569.59	99.51	82.6	445.9	36.83	0.65	10.19
P29	545.77	104.4	83.97	397.22	33.35	0.59	9.22
P30	572.31	109.58	94.47	452.18	42.72	0.68	11.81
P31	574.74	110.63	95.12	461.21	43.87	0.69	12.13
P32	560.04	111.86	94.75	421.26	39.91	0.64	11.04
P33	574.75	110.3	100.08	435.63	43.60	0.69	12.06
P34	554.95	109.11	87.08	491.27	42.78	0.71	11.83
P35	573.36	108.43	87.81	422.55	37.10	0.60	10.26
P36	575.83	111.2	95.09	462.82	44.01	0.69	12.17

2.2. Research methodology

In order to obtain a device producing an electrical current with a higher current and voltage level, solar cells are connected in a photovoltaic module and then protected from damages derived from external factors. Taking this fact into account the analysis photovoltaic module construction was performed.

In series connection solar cell with the lowest current determines the current flowing in the PV module, and therefore in its construction 31 of 36 solar cells with the largest short-circuit current were used. Five photovoltaic cells of lowest short-circuit current were rejected. In order to obtain the maximum voltage produced by a solar module photovoltaic cells were connected in series.

Output voltage of solar cells connected in series is the sum of the individual voltage of photovoltaic cells:

$$U_{OC(M)} = \sum_{i=1}^{n} U_{OC(i)} \tag{1}$$

where:
$U_{OC(M)}$ - the output voltage generated by the photovoltaic module,
n - number of cells in the PV module,
$U_{OC(i)}$-voltage of a single solar cell.

Substituting the appropriate values into equation (1) the total value of the output voltage of the photovoltaic module was calculated (17.58 V).

Current of photovoltaic module is determined by the weakest link:

$$I_{SC(M)} = min\ (I_{SC(Pi)},\ \ldots\ ,I_{SC(P36)}) \tag{2}$$

where:
$I_{SC(M)}$ - current generated from photovoltaic module,
$I_{SC(Pi)}$- current of a single solar cell.

Short-circuit current of the photovoltaic module is: $I_{SC(M)}=101\ mA$.

Photovoltaic cells were connected in series (Fig. 9) using the tape "Torpedo" of dimensions 0.13 mm x 2.54 mm (Fig. 10).

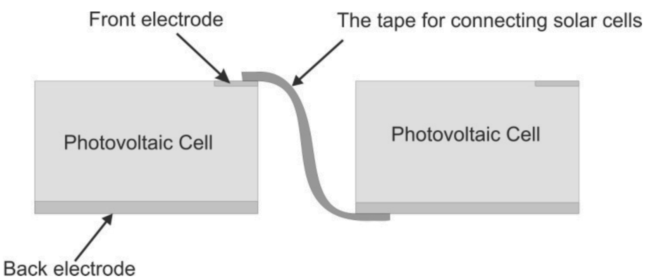

Fig. 9. Diagram of a serial connection of photovoltaic cells

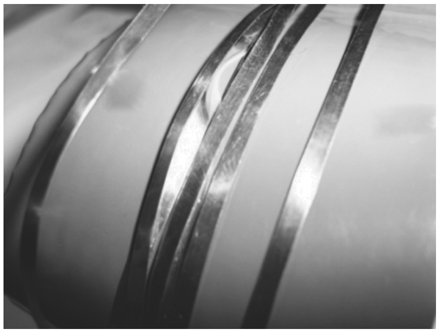

Fig. 10. Tape "Torpedo" for connecting photovoltaic cells

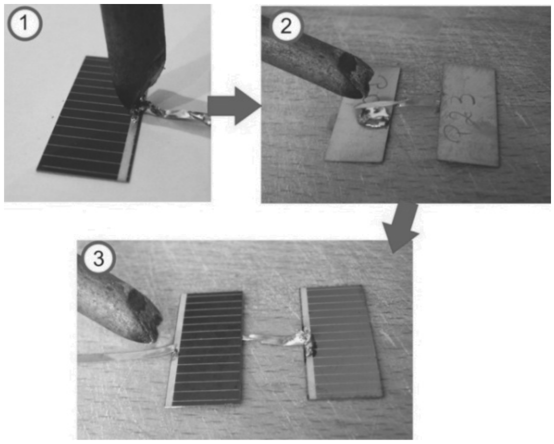

Fig. 11. Implementation stages of the photovoltaic module

In Figure 11 implementation stages of the photovoltaic module is shown. The tape for connecting cells was soldered to the surface of solar cells. Next, the back surface of photovoltaic cells was attached to the acrylic glass with double-sided tape to prevent movement of cells inside the frame. In order to protect the photovoltaic cells against external factors, front of the solar module is protected with a layer of acrylic glass. Both layers were combined with synthetic glue, and then reinforced with electrical tape. In Figure 12 ready photovoltaic module is shown.

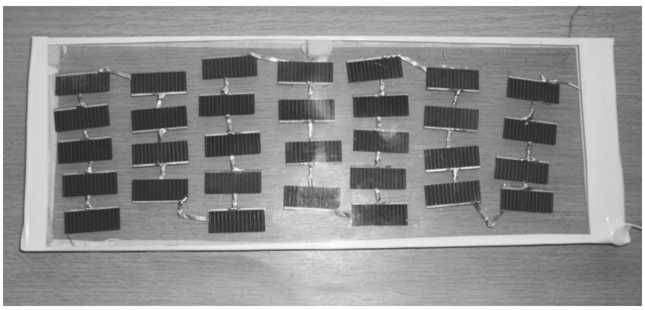

Fig. 12. Complete PV module

3. Results

Electric properties of photovoltaic module were studied. The main electric properties of PV module are presented in Table 2. In Figure 13 current - voltage characteristics of the PV module is shown.

Table 2.
Electric properties of photovoltaic module

Parameter	Value
I_{SC} [mA]	101
U_{SC} [V]	17.58
I_{max} [mA]	84
U_{max} [V]	12.93
P_M [W]	1.08
E_{ff} [%]	9.7
FF [%]	61

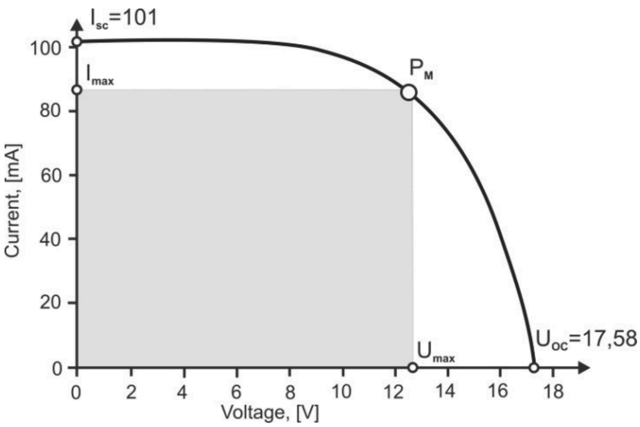

Fig. 13. The determinate current - voltage characteristics of the PV module

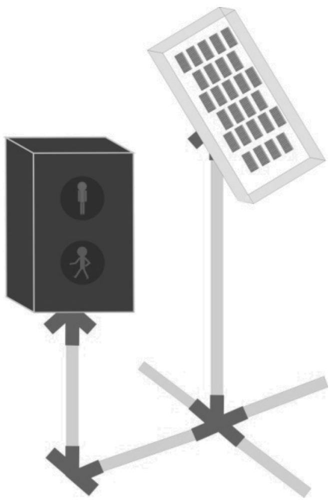

Fig. 14. Photovoltaic system: light signalling-pedestrian crossing

In order to assess the proper operation of the photovoltaic module electrical properties were measured. Measurements were made under natural conditions in the spring day in clear weather.

Voltage measurements were made by plugging the multimeter in parallel at the output of the photovoltaic module. Current measurement was performed by connecting multimeter in series with load.

The design module was used in demonstration photovoltaic system: light signalling-pedestrian crossing. Photovoltaic system (Fig. 14) is consisted of: photovoltaic module, step-down converter, battery pack, astable generator and enclosure. Due to the unstable conditions of illumination and in order to protect battery against overcharging and discharging step-down converter was used. In order to enable the working of PV system during night and day battery pack was used. Astable generator changes the colour of light signalling.

4. Conclusions

On the base of measured current-voltage characteristics of 36 solar cells 31 of them were used to build solar module demonstrating open circuit voltage of 17.58 V and short circuit current of 101 mA and fill factor at average level of 61%. Taking into account the conditions of implementation of PV module results can be considered satisfactory.

Based on the results obtained from measurements of voltage and current of the photovoltaic module found that they are slightly smaller than the characteristic value. This may be due to the fact that measurements were not performed under ideal conditions, as well as losses arising on cable connections and individual items.

In this work photovoltaic system: light signalling-pedestrian crossing was built. Design photovoltaic system shows the practical use of renewable energy source which is the sun.

Acknowledgements

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