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DETERMINATION OF PHYSICAL CHARACTERISTICS OF HORIZONTALLY POSITIONED SOLAR MODULE IN REAL CLIMATE CONDITIONS IN NIŠ, SERBIA

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Abstract.*The aim of this paper was to investigate the influence of solar radiation intensity, ambient temperature, wind speed and solar module temperature on the modules physical characteristics, in local climate conditions and for all seasons in Niš, Serbia. Twelve sunny days, for each month of the year, from the period September 2014 - June 2016 were selected. During each day meteorological parameters, solar module temperature and solar module output parameters were measured. The highest values of solar radiation intensity, ambient temperature and solar module temperature were measured in summer months, while the lowest values were in winter months. The maximal values of the output power were measured in summer months due to the high values of solar radiation intensity on the solar modules surface. A negative impact of high solar module temperature on the open circuit voltage, the output power, the fill factor and the efficiency was observed. In the winter months the local climatic conditions and air pollution have an adverse impact on the solar module efficiency and lead to a noticeable reduction of the efficiency.*

Key words: *photovoltaic modules, I–V characteristics, solar module temperature, efficiency*

1. INTRODUCTION

Meteorological parameters such as solar radiation intensity, ambient temperature, wind intensity, relative humidity and air pollution depend on the local meteorological conditions. It is found that under actual outdoor conditions performance of PV modules is quite different from that determined under the controlled laboratory conditions (Almonacid et al., 2009; Bücher,1993; IEA, 2011; Osterwald, 1986; Vikant and Chandel, 2013). Also,under different climate conditions PV characteristics are different. A strong seasonal variation in the PV characteristics of crystalline modules with low performance in summer and high performance in winter was reported (Aika et al., 2014;Carr and Pryor, 2004; Pantic et al., 2015a).

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Quality and performance of solar modules as functions of varying environmental parameters can be identified by their photovoltaic characteristics (I–V curves)(Buresch, 1998; Marwan, 2006; Pantic et al., 2015b;Pantic et al., 2016). The curve indicates the characteristic parameters of PV module at which it would work at peak efficiency.

The efficiency of PV modules as a function of climate conditions for specific locations in the world was studied by several authors (Fesharaki et al., 2011; Furushima et al., 2006; Kaldelis et al., 2014; Nordmann and Clavadetsher, 2003; Singh, 2013; Skoplaki and Palyvos, 2009). The solar module temperature, output power and electrical efficiency are site-dependent and affect the amount of energy that can be generated by the solar module.

Overall, it is very important to determine solar module characteristics for local meteorological conditions since they are significantly site-dependent. Therefore, the aim of this paper is to investigate the influence of solar radiation intensity, ambient temperature, wind speed and solar module temperature on the modules' physical characteristics, in local climate conditions and for all seasons in Niš, Serbia.

2. THEORY

Photovoltaic solar radiation conversion is the process of converting solar radiation energy into electrical energy. The photovoltaic conversion of solar radiation is based on the internal photoelectric effect in the *p-n* junction (under the influence of the solar radiation) and takes place in solar cells, which are made of semiconductor materials.

The solar cell in the electrical circuit is a source of direct current. Output parameters of solar cells are: short-circuit current I_{sc}, open-circuit voltage V_{oc}, maximum power current I_{mpp}, maximum power voltage V_{mpp}, maximum powerP_{mpp}, fill factor *FF* and efficiencyη.

The important characteristics of the solar cell are open circuit voltage (V_{oc}) and short circuit current (I_{sc}). Open circuit voltage is the maximum voltage at the ends of the solar cell in the open circuit. If the solar cell is short-circuited, short circuit current I_{sc}, which is proportional to the intensity of the incident solar radiation, will flow through the circuit.

Since the electric power *P* is equal to the product of voltage and current, in practice working resistance is chosen so that this product reaches the maximum value. Product $V \cdot I$ at some point of the solar cell characteristics is always smaller than the product $V_{oc} \cdot I_{sc}$. Therefore, for the optimal operating point, in which useful power is maximum power, that is $P_{mpp}=V_{mpp} \cdot I_{mpp}$, or $V_{mpp} \cdot I_{mpp}/V_{oc} \cdot I_{sc}$ is smaller than one. This relationship represents the fill factor of solar cells:

$$P_{mpp} = V_{mpp} \cdot I_{mpp} = F \cdot V_{oc} \cdot I_{sc} \tag{1}$$

$$F = \frac{V_{mpp} \cdot I_{mpp}}{I_{sc} \cdot V_{oc}} \tag{2}$$

The fill factor is a measure of how close the given solar cell is to the ideal one, that is, how big the influence of the serial resistance on the solar cell efficiency is. In good solar cells the fill factor ranges from 0.7–0.9.

The efficiency (rate of useful activity) of the solar cell is expressed by the relation of the used energy and the total energy of solar radiation energy incidence on the solar cell. Efficiency of the solar cell can be calculated in the following way:

$$\eta = \frac{I_{mpp} \cdot V_{mpp}}{I_s \cdot S} = \frac{F \cdot I_{sc} \cdot V_{oc}}{I_s \cdot S} \tag{3}$$

where V_{oc} and I_{sc} are voltage and current of the short circuit, I_s intensity of solar radiation and S is the surface of the solar cell. To increase the efficiency of the solar cell it is necessary to increase V_{oc} and I_{sc} and that FF is around one (Pavlovic et al., 2015).

2.1. Models for calculating solar module temperature, output power and efficiency

Module temperature modifies the PV system efficiency, output power and energy. It depends on the module encapsulating material, the irradiance level, ambient temperature, wind speed and the installation conditions. There are many relations expressing PV module temperature as a function of ambient temperature and solar radiation intensity.

A number of relations found in the literature modeled PV electrical power as a function of the module operating temperature and the basic environmental variables. Many of them are linear while others are more complex.

A problem of the efficiency reduction caused by the cell temperature increase has attracted the interest of many researchers resulting in numerous efforts of the quantitative interpretation.

From the numerous models in the literature, for calculating the solar module temperature, output power and efficiency, the most commonly and widely used are the following models.

Solar module temperature T_c

For calculating the solar module temperature (T_c) the following linear model is most commonly used:

$$T_c = T_a + G/G_{NOCT} \cdot (T_{NOCT} - 20) \tag{4}$$

where T_a is an ambient temperature (ºC), T_{NOCT} is a Nominal Cell Operating Temperature given by the manufacturer (ºC), G is a measured solar radiation intensity (W/m^2) and G_{NOCT} is a solar radiation intensity of 800W/m^2(Alonso and Balenzategui, 2004; Skoplaki and Palyvos, 2009).

Solar module output power P_{mpp}

For the output power calculation two models are usually used, the first one is linearly dependent while the second takes into account a nonlinear dependence of the output power on the solar radiation intensity and solar module temperature.

The first model for calculating the solar module output power is:

$$P_m = P_{m,STC} \cdot G/G_{STC} \cdot (1 - \gamma \cdot (T_c - 25)) \tag{5}$$

where P_m (W) is a calculated output power, $P_{m,STC}$ is a maximal rated power at STC and is given by manufacturer (W), G is a solar radiation intensity on the module plane (W/m^2), G_{STC} is a solar radiation intensity of 1000 W/m^2, γ is a maximum power correction factor for temperature and T_c is a solar module temperature (°C) (Fuentes et al., 2005; Almonacid et al., 2009).

The second model for calculating solar module power is developed in the National Renewable Energy Laboratory, Colorado, USA (Module Energy Rating – MER):

$$P_{max}=P_{max,ref}\cdot G_T/G_{Tref}\cdot[1+\alpha\cdot(T_c-T_{ref})]\,[1-\gamma\cdot(T_c-T_{ref})][1+\delta(\mathrm{T_c})\ln(G_T/G_{Tref})] \quad (6)$$

where P_{max} (W) is a calculated output power, $P_{max,ref}$ is a maximal rated power in the reference conditions (W), G_T is a solar radiation intensity on the module plane (W/m^2), G_{Tref} is a solar radiation intensity in the reference conditions, T_c is a solar module temperature (°C), T_{ref} is a temperature in the reference conditions (°C), α, γ - are correction factors for temperature, δ - is a correction factor for the irradiance(Marion et al., 1999; Skoplaki and Palyvos, 2009).

With regard to the wind's indirectly beneficial effect of lowering the operation temperature by forced convection and, thus, increasing the power output of the modules following relation can be used:

$$P_{max}= G_T\cdot(b_1 + b_2 \cdot G_T + b_3 \cdot T_\mathrm{a} + b_4V_f) \quad (7)$$

where P_{max} (W) is a calculated output power, G_T is a solar radiation intensity on the module plane (W/m^2), T_a is an ambient temperature (ºC), V_f is the free-stream local wind speed measured at a height of 10 m above ground, b_1, b_2, b_3, and b_4 are regression coefficients determined using solar radiation flux values above 500 W/m^2(Farmer, 1992; Skoplaki and Palyvos, 2009).

Solar module efficiency η

To this end and with regard to the most common crystalline silicon based applications, the following linear model for the cell efficiency is used:

$$\eta = \eta_{Tref}(1-\beta_\mathrm{ref}\cdot (T_c-T_{ref})) \quad (8)$$

where η_{Tref} is a module's efficiency at the reference temperature T_{ref}, β_{ref} is a temperature coefficient mainly determined by the cell material and temperature and T_c is a module operating temperature (Kaldelis et al., 2014, Skoplaki and Palyvos, 2009).

For calculating instantaneous efficiency, the following nonlinear model is used:

$$\eta = \eta_{Tref}(1-\beta_{ref}\cdot (T_c-T_{ref}) + \gamma\log_{10}G_T) \quad (9)$$

where η is an instantaneous efficiency, $\eta_{Tref}$is an efficiency in the reference conditions (%), $\beta_{ref}$is a temperature coefficient, $T_{ref}$is a temperature in the reference conditions (°C), T_c is a solar module temperature (°C), γ is a correction factor for the irradiance (Evans, 1981; Fesharaki et al., 2011; Notton et al., 2005;Skoplaki and Palyvos, 2009).

The wind speed is taken into account directly or indirectly through the forced convection coefficient component of U_L. For including the influence of windthe following relation for the efficiency can be used:

$$\eta = 0.94 - 0.0043(\overline{T_a} + \frac{\overline{G_T}}{(22{,}4+8.7\,\overline{V_w})} - 25) \pm 2.6\% \quad (10)$$

where η is efficiency, $\overline{T_a}$ is daily average ambient temperature (ºC), $\overline{G_T}$ is daily average solar radiation intensity on the module plane (W/m^2), $\overline{V_w}$ is daily average wind speed (CLEFS CEA,2004; Skoplaki and Palyvos, 2009).

3. EXPERIMENT

The experiment was done in the Solar Energy Laboratory of the Faculty of Sciences and Mathematics, University of Niš. In the experiment a horizontally positioned monocrystalline solar module, *Isofoton* ISF-60/12 power of 60W and the area of 0.514 m^2 was used, whose characteristics are listed in Table 1.

Table 1 Technical characteristics of the solar module ISF-60/12

Outside dimensions (size)	776 × 662 × 39.5 mm
Cell type	Si monocrystalline
Power of the module – P_{MPP}	60Wp
Module efficiency – η	11.2%
Maximum power current – I_{MPP}	3.47 A
Maximum power voltage – V_{MPP}	17.3V
Short circuit current – I_{sc}	3.73
Open circuit voltage – V_{oc}	21.6
NOCT (800W/m^2, 20°C, AM 1.5, 1m/s)	47°C
Fill Factor – *FF*	74.5%

For the measurement of the meteorological parameters an automatic weather station DAVIS Vantage Pro (USA) was used. The acquisition of the meteorological parameters was performed by the computer every ten minutes. The meteorological parameters continuously measured and recorded were: solar radiation intensity, ambient temperature, wind speed, etc. A meteorological weather station was placed in a close proximity of the solar module.

For the measurement of the solar module I-V characteristics a PV KLA and MINI-KLA devices (Ingenieurbüro Mencke & Tegtmeye, Germany) were used. These devices were also used for the measurement of solar modules open circuit voltage (V_{oc}), short circuit current (I_{sc}), maximum output power (P_{mpp}), nominal current (I_{mpp}), nominal voltage (V_{mpp}) and Fill factor (*FF*).

For the measurement of the solar module temperature a Pt-100 temperature sensor was placed in the middle of the back side of the solar module. Solar module temperature was recorded at a one minute interval.

The measurement results refer to 12 sunny days, for each month of the year, selected from the period September 2014 - June 2016. For each month a sunny day, mainly at the middle of the month, or close to it if it was not a sunny day, was selected to get results that represent the day with an average extraterrestrial solar irradiation of the month as referred in (Duffie and Beckman, 1991). For each day meteorological parameters (solar radiation, ambient temperature and wind), solar module temperature and solar module I/V characteristics were measured. In order to clearly notice the change in the measured parameter during the year, the presentation of the results of the measured parameters was divided into two parts: from January to June, referring to the first half of the year, and from July to December, referring to the second part of the year.

4. Results

Further on, the results for 12 sunny days, selected from the period September 2014 - June 2016 for the measured meteorological parameters, solar module temperature and measured electrical characteristics of the horizontal solar module in Niš, Serbia are given.

4.1. The results of the meteorological parameters measurements

Solar radiation intensity I_s

The results of the measurement of daily variations of the solar radiation reaching the horizontal surface during the year are shown in Figures 1 and 2.

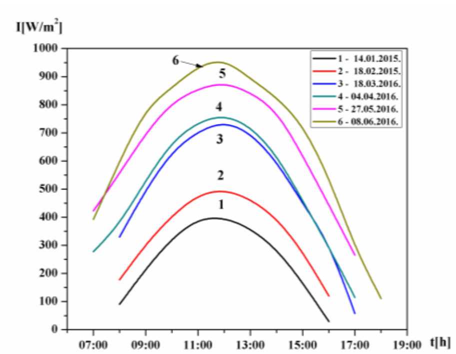

Fig. 1 The results of the measurement of daily variations of the solar radiation intensity reaching the horizontal surface in the period from January to June.

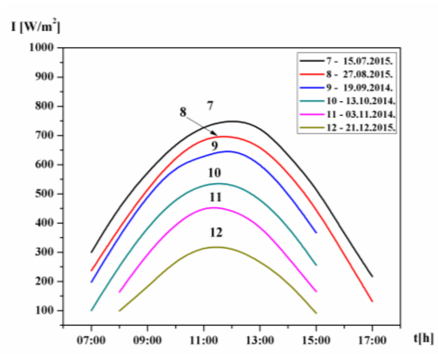

Fig. 2 The results of the measurement of daily variations of the solar radiation intensity reaching the horizontal surface in the period from July to December.

During a sunny day, the maximum values of the solar radiation intensity correspond to the solar noon. In the first half of the year (Fig. 1), the maximum value of the solar radiation intensity increased from 400 W/m^2 measured in January, to a value of 965 W/m^2 measured in June. In the second half of the year (Fig.2), the maximum value of the solar radiation intensity decreased from 755 W/m^2 measured in July, to a value of 321 W/m^2 measured in December. In the summer months the solar radiation intensity reaching the horizontal surface has the highest value, while in the winter months it has the smallest value. The values of the solar radiation intensity in spring and autumn are about the same.

Ambient temperature T_a

The results of the measurement of daily variations in the ambient temperature during the year are shown in Figures 3 and 4.

During the day, the ambient temperature rises from the lowest values in the early morning hours to the maximum values late in the afternoon. In the first half of the year a measured daily ambient temperature rises from the smallest daily values in February and January to the highest values in April, May and June. In the second half of the year a measured daily ambient temperature decreases from the highest value in August and July to the smallest value in December.

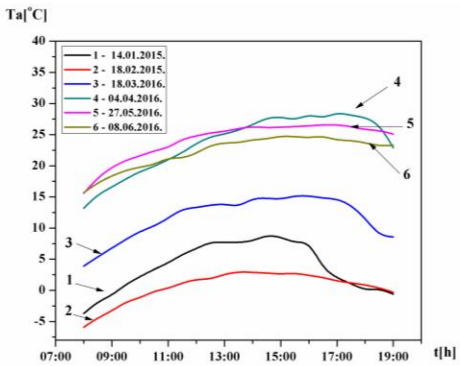

Fig. 3 The results of the measurement of daily variations in the ambient temperature in the period from January to June.

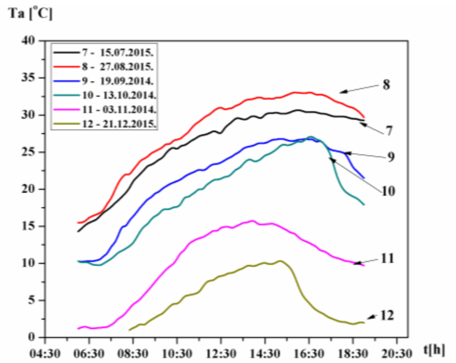

Fig. 4 The results of the measurement of daily variations in the ambient temperature in the period from July to December.

Figure 3 shows that the ambient temperature during the day in February was higher than the ambient temperature in January. Also, the ambient temperature in the afternoon in April was higher than the ambient temperature in the afternoon in May and June. Figure 4 shows that the ambient temperature during the day in August was higher than the ambient temperature in July. The warmest day was July with an ambient temperature over 30°C in the afternoon, and the coldest day was February with daily values of the ambient temperature below 4°C. The ambient temperature is the highest in summer and the lowest in winter, whereas in spring and autumn the ambient temperatures are about the same.

Wind speed (v)

The results of the measurement of daily variations of the wind speed during the year are shown in Table 2.

Table 2 The results of the measurement of daily variations of the wind speed during the year

	Wind speed *v* [m/s]											
Time	14.01. 2015.	18.02. 2015.	18.03. 2016.	04.04. 2016.	27.05. 2016.	08.06. 2016.	15.07. 2015.	27.08. 2015.	19.09. 2014.	13.10. 2014.	03.11. 2014.	21.12. 2015.
8:00 AM	0	0	0	0	0	0	0	0	0	0	0	0.4
9:00 AM	0	0	0	0	0	0	0	0	0	0	0	0.9
10:00 AM	0	0	0	0	0	0	0	0	0	0	0	0.4
11:00 AM	0	0.4	0	0	0.4	0	0	0	0	0	0	0
12:00 PM	0	0	0.4	0	0	0.4	0	0.4	0	0	0.4	0
1:00 PM	0	0	0.9	0	0	0	0.4	0	0	0	0.4	0
2:00 PM	0	0	0	0	0	0	0	0	0.4	0	2.2	0
3:00 PM	0	0.4	0	0	0	0	0	0.4	0	0	0.4	0
4:00 PM	0	0	0	0	0.4	0	0	0	0	0	0.9	0
5:00 PM	0	0	0	0	0	0	0	0	0	0	0	0
6:00 PM	0	0	0.9	0	0	0	0	0	0	0.4	0.4	0

Based on the results shown in Table 2, it can be seen that on the selected days in January, April and October there was no wind during the experiment. During the day in

February, May, June, July, August and September wind was registered only at times with the values of 0.4 m/s. During the day in March wind was registered at 12 AM, 1 PM and 6 PM with the values of 0.4 m/s, 0.9 m/s and 0.9 m/s, respectively. The day in November was windy, with a maximum wind speed of 2.2 m/s, measured at 2 PM.

Solar module temperature T_c

The results of the measurement of daily variations of the solar module temperature T_c during the year are shown in Figures 5 and 6.

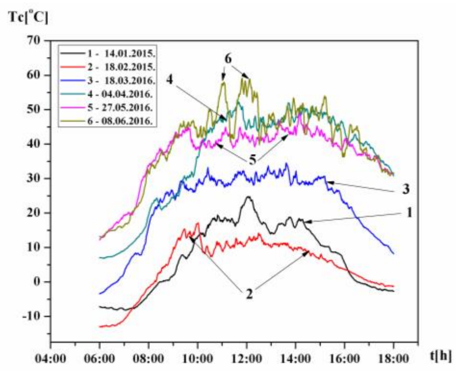

Fig. 5 The results of the measurement of daily variations of the solar module temperature T_c in the period from January to June.

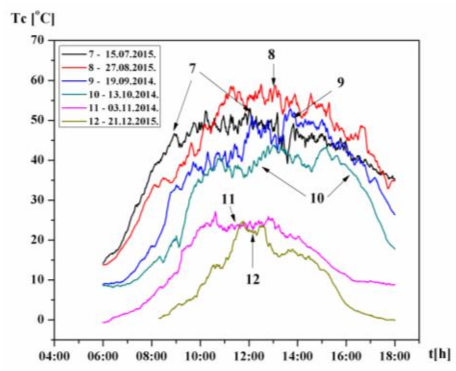

Fig. 6 The results of the measurement of daily variations of the solar module temperature T_c in the period from July to December.

When considering the change of the solar module temperature during the sunny day it can be seen that early in the morning (6 AM) the solar module temperature was the lowest and corresponded to the ambient temperature. Also, it can be seen that in the afternoon, the values of the solar module temperature are higher than the values in the morning, as a result of higher ambient temperatures in the afternoon than in the morning. The highest daily values of the solar module temperature were measured around solar noon.

Figure 5 shows that the highest values of the solar module temperature measured during the day in February and January were 17.2°C and 24.8°C, respectively, and in June was 59.2°C. Figure 6 shows that the highest values of the solar module temperature measured during the day in August and July were 59°C and 53°C, while in November and December they were 27.1°C and 24.8°C, respectively. The lowest measured solar module temperatures during the sunny day were in the cold winter months, and the highest were in the warm summer months.

The solar radiation intensity reaching modules' surface has a dominant influence on the solar module temperature. With the increase in the solar radiation intensity the solar module temperature increases. In addition, wind speed has a significant influence on the solar module temperature. Increase in the wind speed leads to a decrease of the solar module temperature due to the increased heat conduction.

4.2. The results of electrical parameters measurements

Short circuit current I_{sc}

The results of the measurement of the daily variations of short circuit current I_{sc} (A) of the horizontal solar module during the year, are shown in Figures 7 and 8.

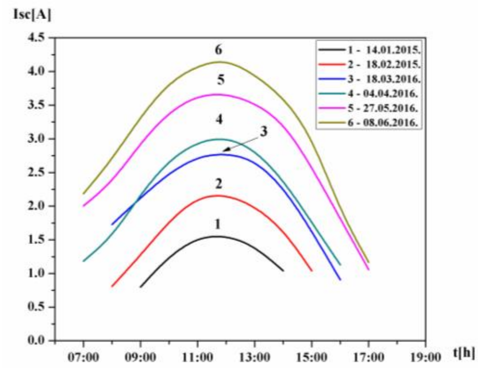

Fig.7 The results of the measurement of daily variations of short circuit current I_{sc} (A) of the horizontal solar module in the period from January to June.

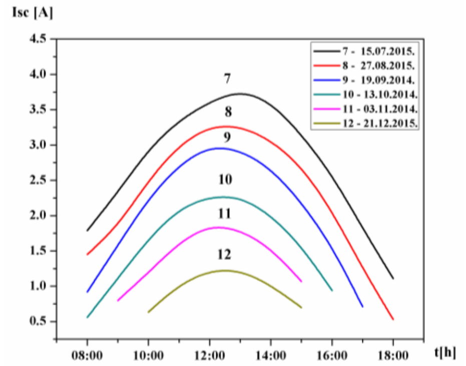

Fig. 8 The results of the measurement of daily variations of short circuit current I_{sc} (A) of the horizontal solar module in the period from July to December.

During the day, the short circuit current I_{sc} is changing in accordance with a change in the solar radiation intensity reaching the solar modules surface. A maximum measure value of the short circuit current I_{sc} corresponds to solar noon.

In Figure 7, it can be seen that the maximum measured value of the short circuit current, during a sunny day, increases from the smallest daily value in January (1.57 A) to the largest daily values in May and June (3.7A and 4.3A). This increase in the daily values of short circuit current is in accordance with the increase in the solar radiation intensity reaching the horizontal surface in the first half of the year. In the second half of the year, a reduction in the daily values of the short circuit current is observed (Figure 8), corresponding to the reduction in the intensity of solar radiation reaching the horizontal surface. The maximum value of the short circuit current was measured in June (4.3 A) and the smallest was in December (1.21 A).

Open circuit voltage V_{oc}

The results of the measurement of daily variations of open circuit voltage V_{oc} (V) of the horizontal solar module during the year are shown in Figures 9 and 10.

In Figure 9, it can be seen that the open circuit voltage of the horizontal solar module has the greatest value in the morning, after which the voltage decreases. The values of the open circuit voltage were less in the evening than in the morning, as a result of the higher ambient temperature and solar module temperature in the evening than in the morning. The open circuit voltage of the horizontal solar module decreases from the maximum daily values measured in February (22.1 V) to the smallest daily value measured in June (18.6 V) and April (19.1 V).

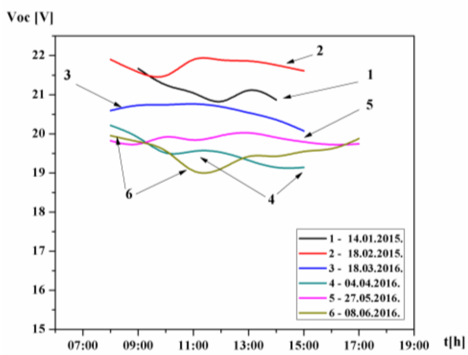

Fig. 9 The results of the measurement of daily variations of open circuit voltage V_{oc} (V) of the horizontal solar module in the period from January to June.

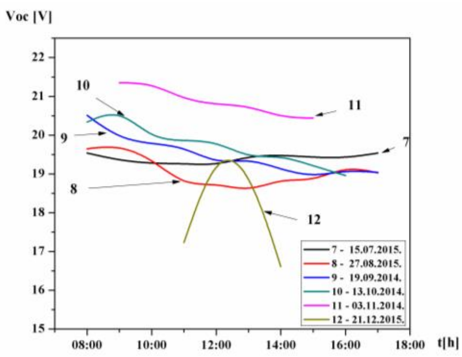

Fig. 10 The results of the measurement of daily variations of open circuit voltage V_{oc} (V) of the horizontal solar module in the period from July to December.

In Figure 10, it can be seen that the open-circuit voltage of the horizontal solar module increases from the smallest measured daily values in August (18.5 V) to the highest measured daily values in November (21.4 V). In the period from July to December, during the sunny day, the open-circuit voltage has the greatest value in the morning, after which the voltage decreases. The biggest daily change in the open-circuit voltage was measured on a sunny day in December, and the smallest was measured in July.

With the increase in solar module temperature there is an increase in the thermal vibration of the atoms in crystal lattice, of the materials used to produce solar cells, which in turn impedes a directed movement of the free carriers of charge resulting in an open circuit voltage decrease. The curves representing daily change of the open circuit voltage have a minimum corresponding to the solar noon and the maximal solar module temperature which can be seen in Figures 9 and 10.

Maximum power P_{mpp}

The results of the measurement of the daily variations of maximum power P_{mpp} (W) of the horizontal solar module during the year are shown in Figures 11 and 12.

During a sunny day the maximum measured power of the horizontal solar module corresponds to the solar noon. Figure 11 shows that the solar modules measured maximum power increases from January (22.12 W) to June (48.63 W). In May, the value of the maximum power was similar to those measured in June (46.84 W), and in March (38.75 W) was similar to the measured one in April (37.68 W). In Figure 12, it can be seen that the maximum power of the horizontal solar module decreases from July (42.72 W) to December (19.33 W). Although the maximal values of the power were measured in the summer months, due to the high values of solar radiation intensity on the solar modules surface, the output power would be even higher if the solar module temperatures were lower.

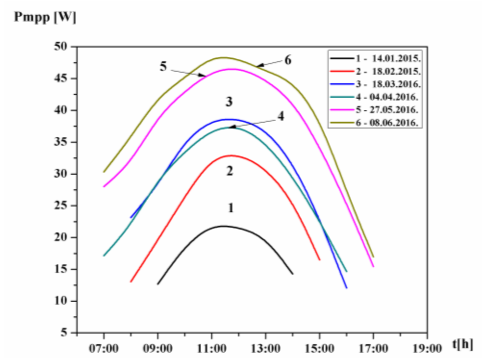

Fig. 11 The results of the measurement of daily variations of maximum power P_{mpp} (W) of the horizontal solar module in the period from January to June.

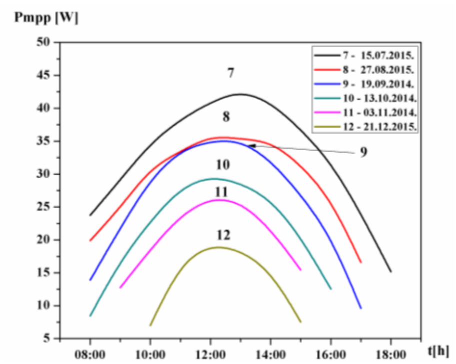

Fig. 12 The results of the measurement of daily variations of maximum power P_{mpp} (W) of the horizontal solar module in the period from July to December.

Fill factor FF

The results of the measurement of daily variations of fill factor *FF* (%) of the horizontal solar module during the year are shown in Figures 13 and 14.

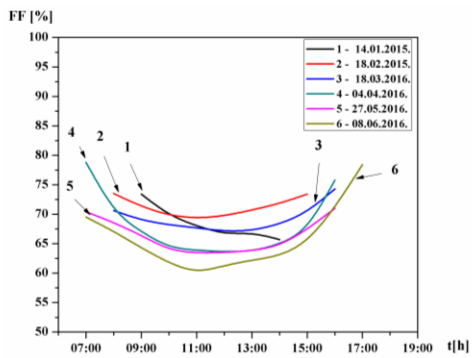

Fig. 13 The results of the measurement of daily variations of fill factor *FF* (%) of the horizontal solar module in the period from January to June.

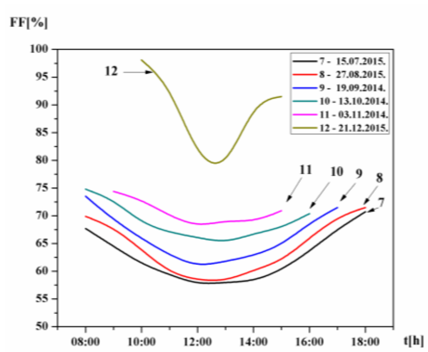

Fig. 14 The results of the measurement of daily variations of fill factor *FF* (%) of the horizontal solar module in the period from July to December.

Daily values of the fill factor were highest in the morning and late afternoon, while the minimum values corresponded to the solar noon. Figure 13 shows that the daily values of the fill factor were highest in February (the coldest day with the lowest solar module temperature), and the lowest in June (warm day with the highest solar module temperature). Figure 14 shows that the daily values of the fill factor increased from the smallest values in July to the highest values in December. With the increase in the solar module temperature the value of the fill factor reduces. The minimum daily values of the fill factor correspond to themaximum daily solar module temperature.

4.2.1. The solar module efficiency η

The results of the measurement of daily variations of the efficiency η (%) of the horizontal solar module during the year are shown in Figures 15 and 16.

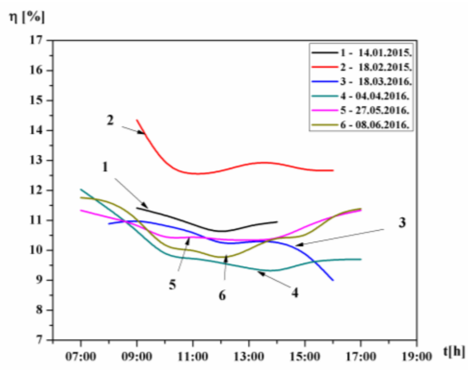

Fig. 15 The results of the measurement of daily variations of the efficiency η (%) of the horizontal solar module in the period from January to June.

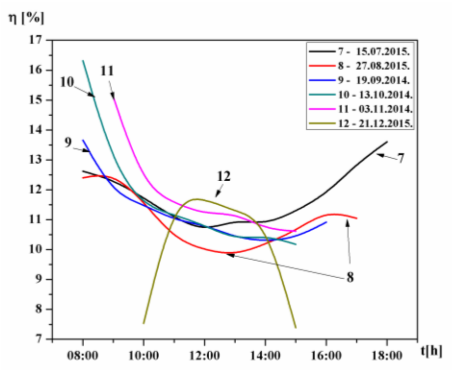

Fig. 16 The results of the measurement of daily variations of the efficiency η (%) of the horizontal solar module in the period from July to December.

The highest daily values of the horizontal solar module efficiency were early in the morning and late in the afternoon, while the minimum values corresponded to the solar noon. Early in the morning, the ambient temperature and the solar module temperature were the lowest, so that even with the lower values of the solar radiation intensity, the solar module efficiency was higher than later during the day. In the late afternoon, the temperature of the solar module decreased and an increase in the solar module efficiency was observed. Figure 15 shows that in April, May and June, the daily values of the solar module efficiency were less than in January and February. Figure 16 shows that solar module daily efficiency was the lowest in August, when the highest solar module temperatures and ambient temperatures were measured. This can be explained by the increase of the thermal vibration of atoms in crystal lattice due to high temperatures thus resulting in the efficiency decrease.

The exceptions were the days in January and December (curve 1 and 12) when a change in the efficiency deviates from the usual daily changes. This deviation can be explained by the specific local climate conditions in December and January: it is the heating season due to which the concentration of pollutants in the air is increased and the diffuse solar radiation is increased as well (due to the scattering of solar radiation on the particles of pollutants). Also, due to the low daily temperatures and high air humidity, in this period mist is present. Because of the local climate conditions and the fact that in winter the Sun is low on the horizon, the measured values of the solar radiation intensity are small (in January under 400 W/m^2 and in December below 300 W/m^2). Under these conditions a change in the daily efficiency is hard to predict and often deviates from the usual daily change.

4.3. Compliance with theoretical models

The experimentally obtained data of the solar module temperature are in good agreement with the calculated values obtained from Eq. 4. The best agreement between the calculated and the experimentally obtained values of solar module temperature was for summer months with high solar radiation intensity.

The experimentallyobtained data of the solar module output power are in better agreement with the linear model (Eq. 5) during the spring and autumn months when solar radiation intensity is moderate. On the contrary, the nonlinear model (Eq. 6) is more accurate for high solar radiation intensity and for the solar module temperatures higher than 25°C.

The efficiency calculated from experimental data (Eq.3) complies very well withthe efficiency values calculated from Eq. 8. On the contrary, the nonlinear model for calculating the solar module efficiency (Eq.9)overestimates the efficiency for all conditions.

5. Conclusion

Based on the previously presented results, the following can be concluded:

- Solar radiation intensity reaching thehorizontal surface is the highest in the summer months and the lowest in the winter months. In spring and autumn the solar radiation intensity values are about the same.
- The ambient temperature is the highest in summer and the lowest in winter. In spring and autumn, the ambient temperatures are about the same.
- The highest solar module temperatures were measured during the summer months when solar radiation intensity reaching the surface of the solar module is the highest. The highest daily value of the solar module temperature was measured in June (59.2°C). In February the highest daily value of the solar module temperature was 17.2°C.
- During a sunny day, the short circuit current increases with the increase in the solar radiation intensity reaching the solar modules surface.
- During a sunny day, the open circuit voltage decreases with the increase inthe solar module temperature due to the heating of the solar module under the influence of solar radiation reaching its surface. The highest values of the open circuit voltage were measured in the early morning hours and the smallest at noon. The highest daily values of the open circuit voltage were measured in cold winter months.
- The maximum values of the solar module power were measured during the summer months when the solar radiation intensity reaching the modules surface was the highest.
- With the increase in the solar radiation intensity and the solar module temperature the fill factor of the horizontal solar module decreased to a minimum value at solar noon, afterwards, with the decrease in the solar radiation intensity and the solar module temperature the values of the fill factor increased.
- During a sunny day, the highest daily values of the horizontal solar module efficiency were early in the morning and late in the afternoon. The minimum values of the efficiency corresponded to the solar noon and to the maximal solar module temperature.

- A negative impact of the high solar module temperature on the open circuit voltage, the fill factor and the efficiency was observed. This reduction inthe above mentioned parameters can be explained by the increase in the thermal vibration of the atoms in the crystal lattice of the solar cells, which impedes a directed movement of free carriers of charge.
- During the winter months the local climate conditions and the air pollution can have a negative impact on the solar module efficiency and can lead to a noticeable reduction of the solar module efficiency.
- For calculating solar module temperature, output power and efficiency in real climatic conditions in NišEquations 4, 6 and 8, respectively,can be used.

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ODREĐIVANJE FIZIČKIH KARAKTERISTIKA HORIZONTALNO POSTAVLJENOG SOLARNOG MODULA U REALNIM KLIMATSKIM USLOVIMA U NIŠU

Cilj ovog rada je da se ispita uticaj intenziteta sunčevog zračenja, temperature ambijenta, brzine vetra i temperature modula na fizičke karakteristike solarnog modula, u lokalnim klimatskim uslovima i svim godišnjim dobima u Nišu, Srbija. Izabrano je dvanaest sunčanih dana, za svaki mesec u godini, u periodu septembar 2014 - jun 2016. U toku svakog dana mereni su meteorološki parametri, temperatura solarnog modula i izlazni parametri solarnog modula. Najveće vrednosti intenziteta sunčevog zračenja, temperature ambijenta i temperature solarnog modula su izmerene u letnjim mesecima, a najmanje u zimskim mesecima. Najveća snaga solarnog modula izmerena je u letnjim mesecima jer je tada najveća vrednost intenziteta sunčevog zračenja koje dospeva na njegovu površinu. Uočen je negativan uticaj visoke temperature solarnog modula na napon otvorenog kola, snagu, fil faktor i efikasnost solarnog modula. U toku zimskih meseci lokalni klimatski uslovi i aerozagađenje nepovoljno utiču na efikasnost solarnog modula i dovode do njenog smanjenja.

Ključne reči: *fotonaponski moduli, strujno-naponske karakteristike, temperatura solarnog modula, efikasnost*