Biblid: 1821-4487 (2019) 23; 3; p 124-127
UDK: 551.524.7

Original Scientific Paper
Originalni naučni rad

TEMPERATURE MODEL OF A PHOTOVOLTAIC MODULE

TEMPERATURNI MODEL FOTONAPONSKOG MODULA

Matúš BILČÍK, Monika BOŽIKOVÁ, Martin MALÍNEK, Peter HLAVÁČ, Petr KOTOULEK
Faculty of Engineering, Department of Physics, Slovak University of Agriculture in Nitra,
Tr. A. Hlinku 2, SK - 949 76 Nitra, Slovak Republic
e-mail: bilcikmatus@gmail.com

ABSTRACT

The primary purpose of this study is to create a thermal model of a photovoltaic module which is usable under real climatic conditions in the Central Europe region. The system for temperature measurements of the photovoltaic module was designed and built at the Department of Physics SUA in Nitra. The climate data utilized in the present study were obtained from a weather station. The measurements were performed during the summer on PV modules. The results obtained indicate that the response of the module temperature is dynamic with changes in irradiance and module temperature, particularly during the periods of fluctuating irradiance. Mathematical descriptions of the obtained time-temperature and time-irradiance relations were made on the basis of the experimental results obtained. A second-degree polynomial function was established for every graphical relation obtained with relatively high coefficients of determination. The temperature model of PV modules was generated after fitting the experimental results to real dependencies and correlation analysis values.

Key words: *external factor, relation, solar system, energy.*

REZIME

Primarni cilj ovog rada je kreiranje termalng modela fotonaponskog modula koji je upotrebljiv u pravim klimatskim uslovima u regionu Centralne Evrope. Sistem za merenje temperature fotonaponskog modula je projektovan i napravljen na Departmanu za fiziku, Slovačkog poljoprivrednog univerziteta u Nitri, Slovačka. Klimatski podaci prikazani u radu su izmereni stanicom za prognozu i praćenje vremenskih uslova. Merenja su obavljena tokom leta sa PV modulom. Dobijeni rezultati pokazuju da je odziv temperature modula dinamičan sa promenama zračenja i temperature modula, posebno u periodima fluktuirajućeg zračenja. Na osnovu dobijenih eksperimentalnih rezultata napravljeni su matematički modeli dobijenih odnosa temperaturnog zračenja i vremena. Polinomna funkcija drugog stepena je definisana za svaki grafički odnos, sa relativno visokim koeficijentima determinacije. Temperaturni model PV modula nastao je nakon prilagođavanja eksperimentalnih rezultata sa stvarnim zavisnostima i vrednostima korelacione analize.

Ključne reči: *spoljni uticaj, relacija, solarni sistem, energija.*

INTRODUCTION

One of the most important renewable energy is solar energy due to its availability and cheap energy resources. Photovoltaic cells are devices which directly convert solar energy into electrical energy (Chander et al., 2015). The possibilities of photovoltaic system application were described in publications by Čorba et al. (2009) and Milićević et al. (2012). The PV module operating temperature is dependent on many factors: solar radiation, ambient temperature, wind speed and direction, module material composition and mounting structure. These dependencies have been argued by Amstrong (2010), Bilčík and Božiková (2018), Malínek et al. (2018) and Libra et al. (2017). A number of factor exert effects on the PV cell energy production, but temperature is of paramount importance. Amstrong (2010), Jones (2001), Duffie (1980), Schott (1985) and Servant (1985) studied the effects of the PV module operating temperature on the output efficiency, reporting that increasing temperature decreases the amount of power available. Therefore, the present paper deals with the analysis of photovoltaic module temperature. Experiments under real climatic conditions were conducted including the photovoltaic system located in the area of CULS in the Czech Republic. The temperature of photovoltaic modules was detected using a fully autonomous measuring system with 24 temperature sensors. The climatic data were collected from a weather station which located near the photovoltaic system.

MATERIAL AND METHOD

A system for measuring temperature, i.e. one of the most important external factors, was designed and constructed for the purpose of the study. The system consists of B&R components and operates fully automatically. It is run by a software, which was programmed in the Automation Studio.

Fig. 1 Measuring system

The PV module consists of several components made of different materials. It was necessary to measure the temperature of the individual components of the PV module. The measuring system features 24 temperature sensors. The accuracy of these sensors is ± 0.75 %. The thermal camera Fluke TiR1 was used for detecting temperature changes on the PV module surface. The measurements performed indicate that different parts of the PV module exhibit different temperatures (Figure 2).

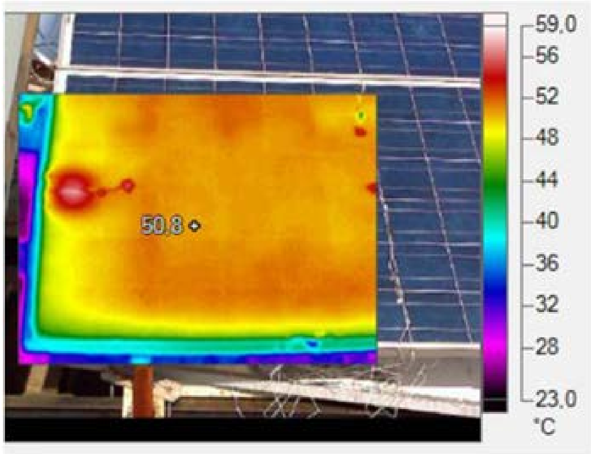

Fig. 2 Identification of temperature changes using the thermal camera Fluke TiR1

Climatic data were obtained from a weather station in the area of CULS. The weather station measures ambient temperature, humidity, air pressure, rainfall, wind velocity, wind direction and solar radiation. Ambient temperature was measured using the sensor HMP45C manufactured by Vaisala, Inc. The measurement accuracy of the sensor HMP45C was ± 0.5 °C. The solar radiation was detected using the pyranometer CM11 (Kipp & Zonen).

Fig. 3 Weather station in the CULS area in Prague

The main experiment was carried out on the polycrystalline PV module (Table 1). Polycrystalline solar modules tend to have slightly lower heat tolerance than monocrystalline solar modules. This technically means that they perform slightly worse than monocrystalline solar modules at high temperatures. Heat can affect the performance of solar modules and shorten their lifespans. The efficiency of polycrystalline-based solar modules is typically (13 – 16) %, in our case the efficiency of solar module was 14 %.

Tab. 2 Technical parameters of the PV module

Brand	Yingli Solar
Module type	YL230P-29b
Rated maximum power	230 W
Rated voltage	29.5 V
Rated current	7.8 A
Size	(1590 x 990 x 45) mm

RESULTS AND DISCUSSION

The experimental results are presented in graphical dependencies, especially the time-temperature and solar radiation relations via temperature dependencies. The following parameters were measured: temperature of the PV cells active part, temperature of no active white part of the PV module and temperature of the PV module frame. The thermal camera was used to determine differences between the upside and downside temperatures of the PV module, so the temperatures were measured on both the upside and downside of the PV module.

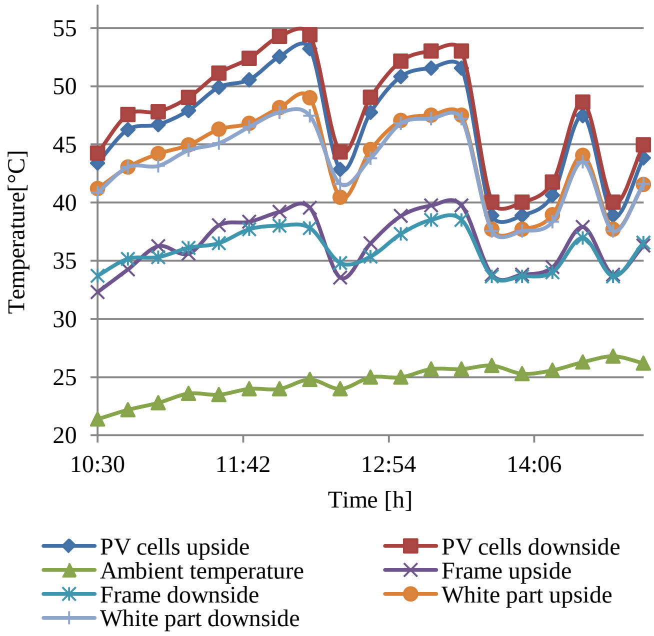

Fig. 4 Time-temperature dependencies of the PV module different parts and ambient temperature – real curves

Figure 4 shows changes in the temperatures of the PV module individual parts. The graphical relation in Figure 4 represents a certain deviation from the expected trend of temperature, which is consistent with the theoretical models presented in the literature (Amstrong (2010), Jones (2001), Duffie (1980), Schott (1985), Servant (1985)). The primary purpose of this paper is to create a simplified mathematical model for temperature and solar radiation which could be used for predicting the operational parameters of PV modules. From the mathematical description perspective, it was necessary to smooth out extreme parts of the time-temperature graphical dependences, so a fitting procedure was applied. The fitting procedure eliminates extremes of graphical dependencies which did not correspond to the assumed trend of the graphs. This procedure was used for all the measured dependencies.

Tab. 1 Table of statistical coefficients for the time-temperature relations

Part of PV module	Coefficients of the regression equation A	B	C	Coefficients of determinations
PV cells	-1035.7	1101.4	-240.06	0.97
Frame	-642.8	699.13	-149.84	0.97
White part	-814.68	865.29	-181.27	0.98

The following objective of this research was to identify the effect of ambient temperature on the temperature of different parts of the PV module through correlation analysis of all graphical dependencies. The correlation coefficients were found in the range from 0.32 to 0.7. A correlation coefficient of 0.34 was found for the correlation between the ambient temperature and the temperature of the PV cells, which indicates a middle-degree correlation. The temperature of the PV module frame and ambient temperature correlate significantly with a correlation coefficient of 0.7. Moreover, the correlation between the temperature of the PV module and white area was identified as mild with a correlation coefficient 0.32. On the basis of the results obtained, the influence of ambient temperature on the temperature of the individual parts of the PV module is evident. This result is new because all the mathematical models arguedd in the literature (Amstrong (2010), Jones (2001), Duffie (1980), Schott (1985), Servant (1985)) assume the constant temperature of all PV module parts which is contrary to the results obtained under real conditions. Figure 6 show the fluctuations in the intensity of sunshine due to cloudiness change. These fluctuations also affected the temperature of the PV cells. These extremes were inappropriate for creating a mathematical model, so fitting procedure was applied.

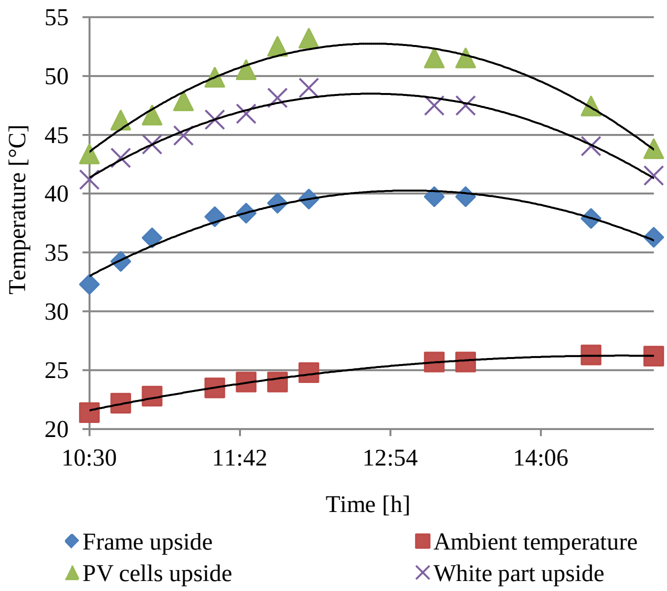

Fig. 5 Time-temperature dependencies of the PV module different parts and ambient temperature after the fitting procedure and regression analysis

The next step of graphical dependency processing was a regression analysis. The regression analysis allowed the selection of the most appropriate graphical dependence. On the basis of the descriptive characteristics (coefficients of regression equation, coefficients of determination etc.) of graphical dependencies, a second-degree polynomial function was created, which is represented by the following regression equation (1):

$$T = At^2 + Bt + C \qquad (1)$$

Where T – is the temperature of the PV module part, t – is time. Coefficients of the regression equation and coefficients of determinations are presented in Table 2. Consequently, a polynomial function for the time-temperature relations was obtained, in contrast to mainly linear or exponential graphical dependencies by Amstrong (2010), Jones (2001), Duffie (1980), Schott (1985), Servant (1985).

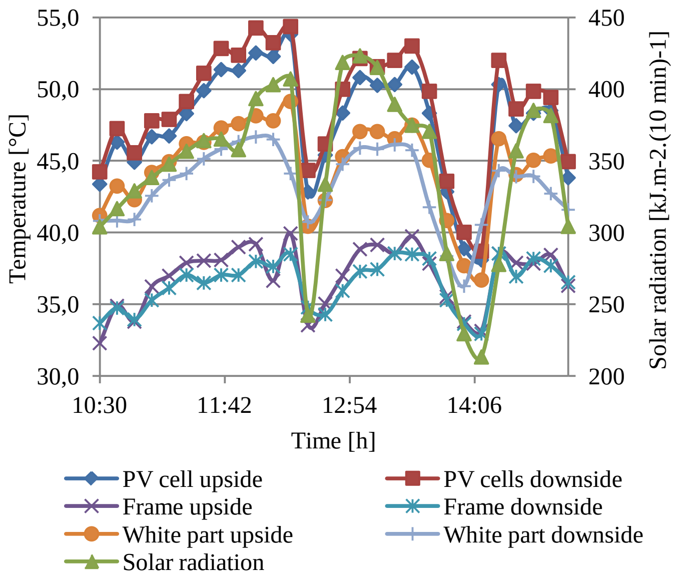

Fig. 6 Time-temperature and solar radiation dependencies – real curves

After applying the fitting procedure, graphs with smooth curves were obtained (Fig. 7.) and a regression analysis was for regression equations, i.e. the second-degree polynomial function. These functions are generally represented by a regression equation (2).

$$I = Et^2 + Ft + G \qquad (2)$$

where I – is solar radiation, t – is time. Table 3 shows the coefficients of this regression equation and the coefficients of determinations. Determination coefficients are relatively high, ranging from 0.8 to 0.92. A second-degree polynomial function was chosen not only from the mathematical perspective, but also from the physical theory perspective that predicts the polynomial progress of temperature in relation to the culmination of the sun's intensity.

Tab. 3 Table of statistical coefficients for time relations of solar radiation

	Coefficients of the regression equation			
Part of PV module	E	F	G	Coefficients of determinations
PV cells	-844.75	909.13	-192.33	0.8
Frame	-590.66	645.21	-135.68	0.92
White part	-542.29	577.58	-105.98	0.82

A basic correlation analysis was performed to evaluate graphical dependencies as in previous cases. The correlation coefficients for the correlation between the temperature of the PV module different parts and the solar radiation intensity were in the range of 0.69 - 0.89, indicating a high-degree correlation. The result of the measurements and statistical evaluation are consistent with those reported in the literature, confirming that the intensity of solar radiation significantly affects the temperature of the PV module.

$$T_C = T_a + \alpha G_T(1 + \beta T_a)(1 - \gamma v_W)(1 - 1.053\eta_c) \qquad (3)$$

Equation 3 presents a temperature model by Servant. This model incorporates parameters such as ambient temperature, solar radiation, module electrical efficiency and constant wind velocity with value 1 ms^{-1}. The values of constants are α = 0.0138, β = 0.031 and γ = 0.042.

$$T_C = T_a + \frac{G_T}{G_{NOCT}}\left(T_{c,NOCT} - T_{a,NOCT}\right)\left(1 - \frac{\eta_c}{\tau\alpha}\right) \qquad (4)$$

The temperature model by Davis, Dougherty and Fanney is showed in Equation 4. The coefficient NOCT (nominal operating cell temperature) is incorporated in the model and defined as the temperature of a device at the conditions of the nominal terrestrial environment: solar radiation flux 800 $W.m^{-2}$, ambient temperature 20 °C, average wind speed 1 $m.s^{-1}$, zero electrical load (i.e. open circuit), and free-standing mounting frame oriented ''normal to solar noon''.

Both the equations predict the temperature of the PV cell with a linear trend. However, Equations 1 and 2 represents second-degree polynomial functions, which are superior because the culmination of sun intensity has a polynomial trend too.

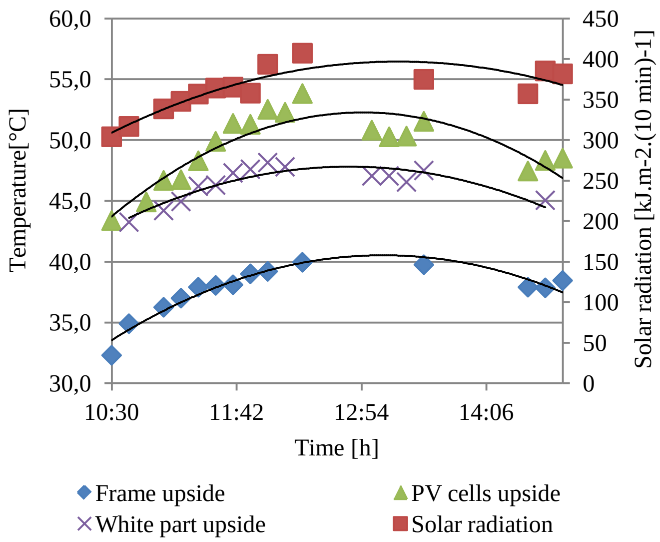

Fig. 7 Time-temperature dependencies of the PV module different parts and solar radiation after the fitting procedure and regression analysis

CONCLUSION

The results obtained are in good agreement with those reported in the literature (Amstrong (2010), Jones (2001), Duffie (1980), Schott (1985), Servant (1985)). On the basis of the PV module temperature and solar radiation intensity measurements performed, it is evident that the reaction of the PV module temperature is dynamic under real conditions. The temperature changes in the PV module different parts, for the Central Europe region, were characterized by second-degree polynomial functions (determined by the regression analysis of the experimental data and the application of the fitting proper procedure). The correlation analysis confirmed a significant influence of solar radiation intensity on the temperature of polycrystalline PV modules, as well as a partial influence of ambient temperature on the PV module temperature. The temperature of the PV module depends on the material of PV module components.

ACKNOWLEDGEMENT: This paper was supported by the project KEGA 017-SPU 4/2017 - Multimedia textbook of physics for engineers, Ministry of Education, Science, Research, and Sport of the Slovakia and was co-funded by the European Community within the project no 26220220180: Building Research Centre „AgroBioTech"

REFERENCES

Amstrong, S., Hurley, W.G:A thermal model for photovoltaic panels under varying atmospheric conditions. Applied Thermal Engineering, 30, 2010. 1488-1495

Bilčík, M., Božiková, M: Wind speed and the selected time temperature dependencies for photovoltaic module In: Physics – Applications and Inovations. SUA in Nitra, 2018.

Čorba, Z., Kalić, V., Milićević, D: Photovoltaics systems in Agriculture. Journal on Processing and Energy in Agriculture, 13 (4), 2009. 328 – 331.

Duffie, J.A., Beckman, W.A: Solar Engineering of Thermal Processes. John Wiley & Sons, New York, 1980.

Chander, S., Purohit, A., Sharma, A., Arvind, Nehra, S. P., Dhaka, M. S: A study on photovoltaic parameters of mono-crystalline silicon solar cell with cell temperature. Energy Reports, 1, 2015. 104-109

Jones, A.D., Underwood, C.P: A thermal model for photovoltaic systems. Solar Energy 70 (4), 2001. 349-359.

Libra, M., Poulek, V., Kouřím, P: Temperature changes of I-V characteristics on photovoltaic cells as consequence of the Fermi energy level shift. In Research in Agricultural Engineering, 2017, vol. 63, no. 1, pp. 10–15.

Malínek, M., Bilčík, M., Božiková, M., Petrović, A., Kotoulek, P., Hlaváč, P: 2018. The selected time temperature and wind speed dependencies for photovoltaic module. Journal on Processing and Energy in Agriculture, 22 (2), 2018, 82-84. National Society of Processing and Energy in Agriculture, Novi Sad. ISSN 1821-4487

Milićević, D., Popadić, B., Dumnić, B., Čorba, Z., Kalić, V: Possibility of solar potential utilization in Republic of Serbia – practical example. Journal on Processing and Energy in Agriculture, 16 (3), 2012. 109 – 112

Servant JM: Calculation of the cell temperature for photovoltaic modules from climatic data. In: Bilgen E, Hollands KGT, editors. Proceedings of the 9th biennial congress of ISES – Intersol 85, Montreal, Canada, extended abstracts, 1985. p. 370.

Schott T: Operation temperatures of PV modules. In: Proceedings of the sixth E.C. photovoltaic solar energy conference, London, UK, April 15–19; 1985. p.392–6.

Received: 19. 02. 2019. Accepted: 22. 07. 2019.