THE TIME-TEMPERATURE DEPENDENCIES OF POLYCRYSTALLINE PHOTOVOLTAIC MODULE DIFFERENT PARTS

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Abstract
The main aim of this research is creation of thermal model for photovoltaic module which is usable in real climatic conditions with localization in Central Europe region. The measuring system for temperature measurement of the photovoltaic module was designed and built at Department of Physics Slovak University of Agriculture in Nitra. Climate characteristics were measured by weather station. The measurements were done during the summer on photovoltaic module. From obtained results is clear that the response of the module temperature is dynamic with irradiance changes, particularly during periods of irradiance fluctuating. Based on the previous facts were made mathematical descriptions of obtained time-temperature and time-irradiance relations. For every graphical relation was obtained polynomial function of the second degree with relatively high coefficients of determination. Temperature model of photovoltaic module was obtained after application of fitting procedure to real dependencies and correlation analysis.

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

INTRODUCTION

Solar energy can be directly converted into electrical energy by photovoltaic cells. Photovoltaic have a lot of applications. These applications described author's (*Olejár et al., 2015; Milićević et al., 2012*). The usage of PV system depends on many factors as: solar radiation, ambient temperature, wind speed, material of PV module, composition and mounting structure. Mentioned factors were described by the authors (*Amstrong & Hurley , 2010; Bilčík & Božiková, 2018; Malínek et al., 2018; Libra et al., 2017*). The temperature of PV module especially the temperature of PV cells is important parameter for assessing the long term performance of PV system and its energy production. The authors (*Amstrong & Hurley, 2010; Jones & Underwood, 2001*) reported that PV module efficiency strongly depends on its cells operating temperature. The increasing cell´s temperature has negative influence on the electric power production of PV module (*Duffie & Beckman, 1980; Schott, 1985, Servant, 1985; Cviklovič & Olejár, 2013*). However, in real operating conditions, the temperature measurement of a photovoltaic cell is relatively difficult, so it is more appropriate to measure the surface temperature of PV module active and passive parts. Based on presented facts the main aim of this research was to identify real time-temperature dependencies of the polycrystalline PV module different parts. The next aim of this work is creating the simplified mathematical model for temperature and solar radiation which could be used for prediction operational parameters of PV module. For these measurements was designed and created fully autonomous measuring system with 24 temperature sensors. The measurements were performed on the photovoltaic system, which is located in area of CULS in Czech Republic. The climate parameters were measured by weather station which was located near the PV system.

MATERIALS AND METHODS

For temperature measurement was designed and constructed the measuring system (Fig.1). The measuring system contains these components: 24 temperature sensors with accuracy ± 0.75 %, control module, communication module, measuring module (B&R, Austria), It works fully automatically. The control software of the measuring system was programmed in Automation Studio. The position of the temperature sensors was chosen according to the temperature changes of the PV module different parts. The temperature changes were detected by the thermovision using the termocamera Fluke TiR1 (Fluke, USA) (Fig. 2).

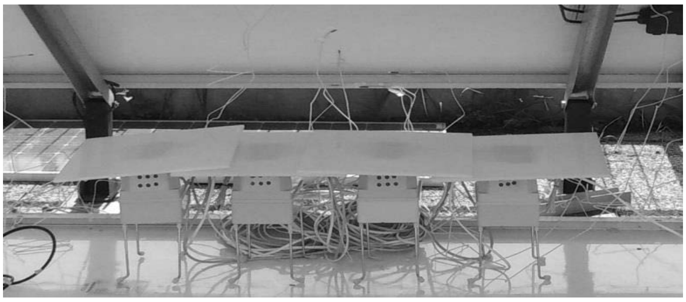

Fig. 1 Measuring system

This weather station measures quantity as: ambient temperature, humidity, air pressure, rainfall, wind velocity, wind direction and global solar radiation. Ambient temperature was measured by sensor HMP45C with accuracy ± 0.5 °C (Vaisala, Inc., Germany). The intensity of solar radiation was detected by pyranometer CM11 with accuracy < 10 $W \cdot m^{-2}$ (Kipp & Zonen, Holland).

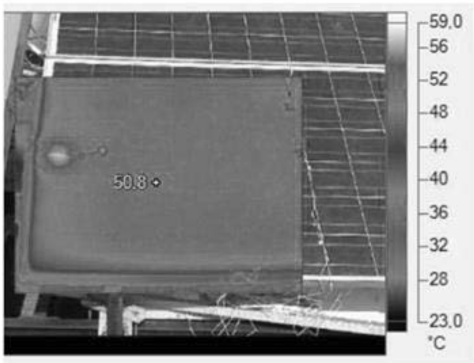

Fig. 2 Identification of temperature changes by termocamera Fluke TiR1

The measurements were performed on the polycrystalline PV module (Yingli Solar, China). The technical parameters of this PV module are presented in Tab. 1. The efficiency of the polycrystalline PV module was 14 %.

Tab. 1 Technical parameters of PV module

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

RESULTS AND DISCUSSION

At the first were detected the temperature changes by the thermocamera (Fig. 2). These measurements identified differences between upside and downside temperatures of PV module, so the temperatures were measured on the upside parts of PV module and also on downside of PV module. The results of experiments are presented as graphical dependencies. Especially, the time-temperature relations and the relations of global solar radiation intensity in the same time range were identified. The temperature was measured of PV module active part, no active white part of PV module and also in the frame of PV module. The graphical relation on Fig. 3 represents a certain deviation from the expected trend of temperature, which is known from the theoretical models presented in literature (*Amstrong & Hurley, 2010; Jones & Underwood, 2001; Duffie & Beckman, 1980; Schott, 1985; Servant, 1985*).

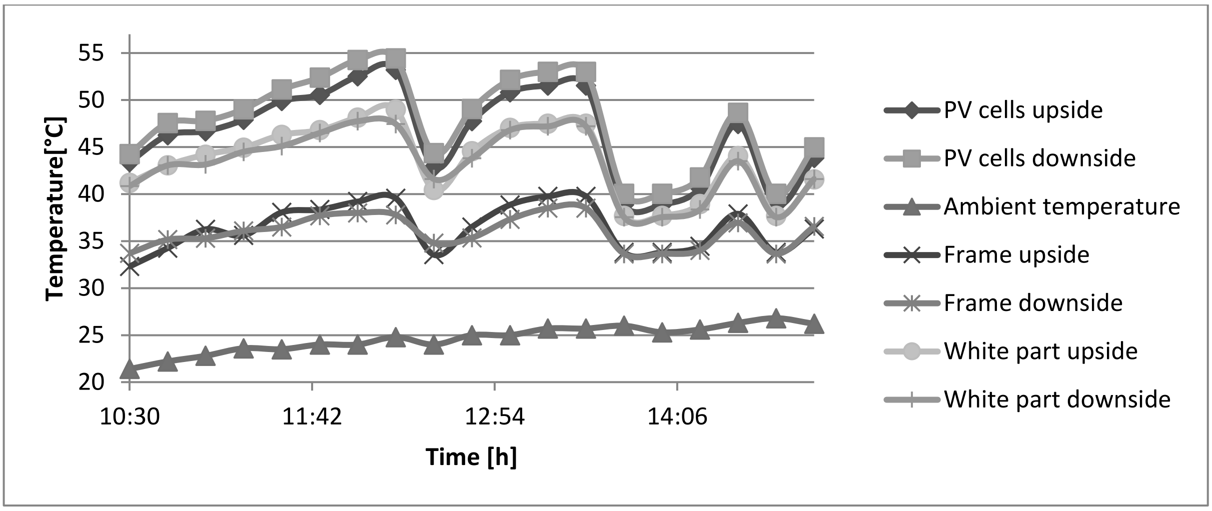

Fig. 3 The time-temperature dependencies of PV module different parts and ambient temperature – real curves

The fitting procedure was applied on the graphical dependences, because from the mathematical point of view it was necessary to smooth out extreme parts of the time-temperature graphical dependences. It eliminates extremes of graphical dependencies which did not correspond to the assumed trend of the graphs.

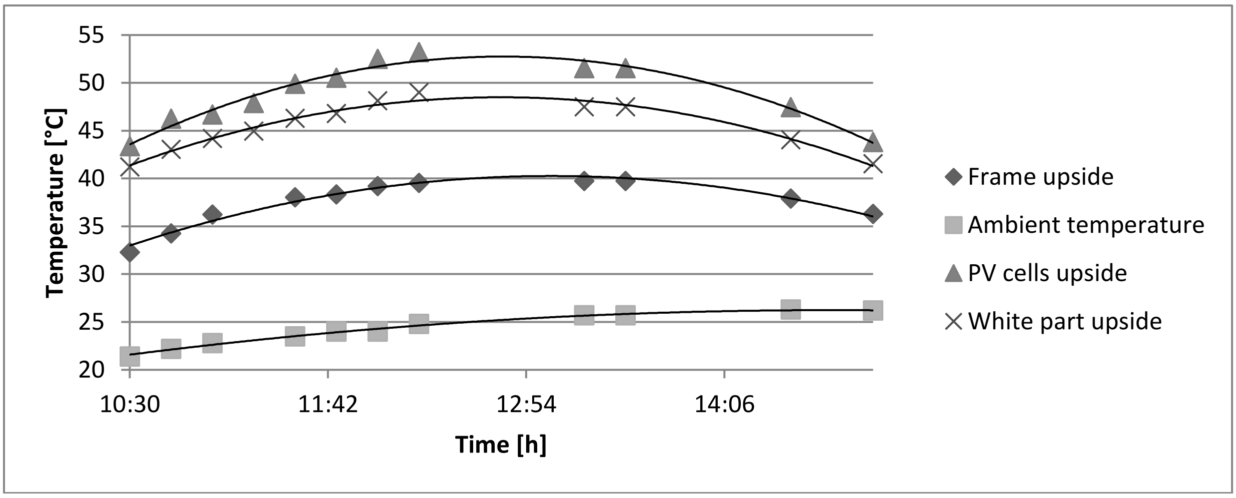

Fig. 4 The time-temperature dependencies of PV module different parts and ambient temperature after fitting procedure and regression analysis

The next step of graphical dependencies processing was regression analysis. The regression analysis allowed the selection of the most appropriate graphical dependence. Based on the descriptive characteristics (coefficients of regression equation, coefficients of determination etc.) of graphical dependencies were selected in all cases the second degree polynomial functions, which are represented by the regression equation (1).

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

Where T – is the temperature of PV module part, t – is time. Coefficients of the regression equation and coefficients of determinations are presented in Tab. 2. In our case was obtained polynomial function for time-temperature relations, but in literature (*Amstrong & Hurley, 2010; Jones & Underwood, 2001; Duffie & Beckman, 1980; Schott, 1985; Servant, 1985*). are presented mainly linear or exponential graphical dependencies.

Tab. 2 Table of statistical coefficients for time-temperature relations

Part of PV module	A	B	C	Coefficients of determinations	Coefficient of correlation	Degree of correlation
PV cells	-1035.7	1101.4	-240.06	0.97	0.34	mild
Frame	-642.8	699.13	-149.84	0.97	0.7	high
White part	-814.68	865.29	-181.27	0.98	0.32	mild

The next part of this research was identifying the influence of the ambient temperature on the temperature of different parts of PV module, so there was performed correlation analysis on all graphical dependencies. The results of correlation analysis are presented in Tab. 2 as coefficients of correlations and degree of correlation. The correlation coefficients were found in the range from 0.32 to 0.7. Especially, the correlation coefficient of 0.34 was found for correlation between the ambient temperature and the temperature of the PV cells, which means middle degree of correlation. The temperature of the PV module frame and ambient temperature correlate on the high degree with a correlation coefficient 0.7 and for the correlation between the temperature of PV module and white area was identified a mild correlation degree with correlation coefficient 0.32. Based on presented results is clear the influence of ambient temperature on the temperature of individual parts of the PV module. This result is new because all known mathematical models presented in literature (*Amstrong & Hurley, 2010; Jones & Underwood, 2001; Duffie & Beckman, 1980; Schott, 1985; Servant, 1985*). assume the constant temperature of all PV module parts which is contrary to the results obtained under real conditions. In the next part of results are presented the time-temperature and solar radiation dependencies. Fig. 6 shows the fluctuations in the intensity of sunshine due to cloudiness change. These fluctuations also affected temperature of PV cells. These extremes were inappropriate for creating of a mathematical model, so fitting procedure was applied.

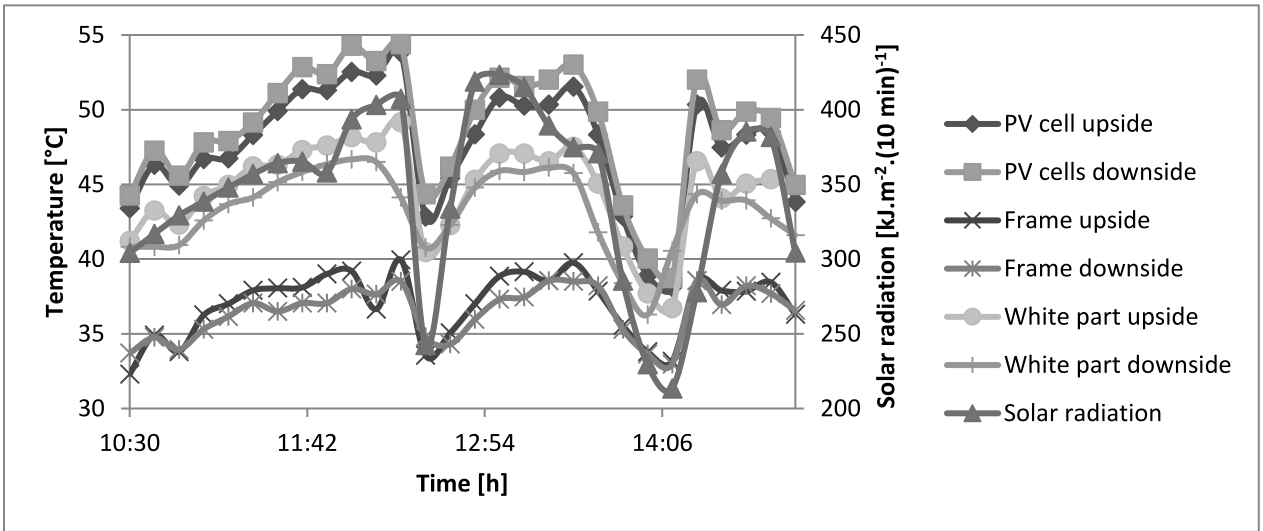

Fig. 5 The time-temperature and solar radiation dependencies – real curves

After fitting procedure were created graphs with smooth curves (Fig. 7.) and by using of regression analysis were chosen model regression equations. The model relations can be described by the polynomial function of second degree (Equation 2).

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

Where I – is the solar radiation, t – is the time. Tab. 3 presents the coefficients of this regression equation and the coefficients of determinations. Determination coefficients are relatively very high, they are from range R^2 = (0.8 – 0.92). The polynomial function of second degree was chosen correctly, not only from the mathematical point of view, but also from the physical theoretical point of view. It predicts the polynomial progress of temperature relation during the culmination of the sun's intensity.

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

Part of PV module	E	F	G	Coefficients of determinations	Coefficient of correlation	Degree of correlation
PV cells	-844.75	909.13	-192.33	0.8	0.8	high
Frame	-590.66	645.21	-135.68	0.92	0.89	high
White part	-542.29	577.58	-105.98	0.82	0.69	high

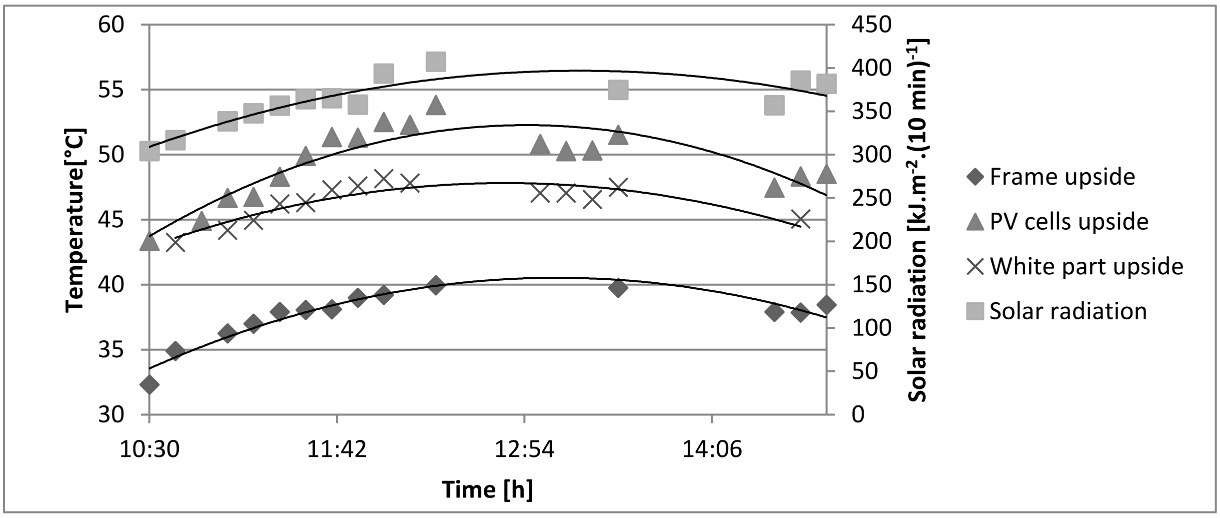

Fig. 6 The time-temperature dependencies of PV module different parts and solar radiation after fitting procedure and regression analysis

A basic correlation analysis was performed for evaluation of graphical dependencies as in previous cases. The correlation between the temperature of PV module different parts and the solar radiation intensity was high with correlation coefficients in range (0.69 - 0.89). The results of the measurement and statistical evaluation of the measured data confirmed from the literature well-known fact, that the intensity of solar radiation most significantly affects the temperature of the PV module.

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

The Equation (3) presents temperature model by (*Servant, 1985*) and Equation (6) present temperature model by (*Schott, 1985*). The models for PV module temperature T_m contain physical quantities as ambient temperature T_a , global solar radiation G_T, module electrical efficiency η_c and constant wind velocity v_w with value 1 m·s^{-1}. The parameters in Equations (3) and (6) have values α = 0.0138, β = 0.031, γ = 0.042 and a, b (Eq. 4, 5) are coefficients of empirical functions of PV and ground emissivities ε_{PV}, ε_g and a cloudiness factor, $\varepsilon_{c.}$

$$a = 208\varepsilon_{PV} + 297.14\varepsilon_a - 594.3\varepsilon_g \quad (4)$$

$$b = 6\varepsilon_{PV} + \varepsilon_a - 2\varepsilon_g \quad (5)$$

$$T_m = T_a + \frac{(\alpha - \eta_c).G_T + (a + bT_a)}{17.8 + 2.1v_w} \quad (6)$$

Equations (3) and (6) predict temperature of PV module with the linear trend. From presented results is clear that there is high correlation between the intensity of solar radiation and temperature of PV module different parts. From the physical theory is known fact that the culmination of sun intensity has polynomial trend too. It was the main reason for usage the polynomial functions of second degree.

CONCLUSIONS

Results obtained by PV module temperature measurements and measurements of solar radiation intensity confirmed that the reaction of PV module temperature is dynamic in real conditions. This fact is clear for periods where are detected changes of solar radiation intensity which were affected by the cloudiness. The next result is that temperature changes of PV module different parts can be characterized by polynomial function of the second degree. This result was determined by regression analysis of experimental data and by application of the fitting procedure. The significant influence of solar radiation intensity and partial influence of ambient temperature to temperature of polycrystalline PV module was confirmed by correlation analysis. From results is evident, that the temperature of PV module depends on the material of PV module components. The obtained results are in good agreement with the literature (*Amstrong & Hurley, 2010; Jones & Underwood, 2001; Duffie & Beckman, 1980*).

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