MODELLING OF PHOTOVOLTAIC MODULE CONVECTIVE HEAT TRANSFER COEFFICIENT

MARTIN MALINEK¹, PETR KOTOULEK¹, ANA PETROVIC¹, TOMAS REGRUT¹, MONIKA BOZIKOVA¹, PETER HLAVAC¹, VLADIMIR CVIKLOVIC², MARTIN OLEJAR²

¹Department of Physics
²Department of Electrical Engineering, Automation and Informatics
Slovak University of Agriculture in Nitra
Tr. A. Hlinku 2, 949 76 Nitra
SLOVAK REPUBLIC
Monika.Bozikova@uniag.sk

Abstract: In this article are presented facts from photovoltaic theory and practise. The amount of energy produced by PV system is influenced by many internal and external factors. One of the most important factors is temperature which has significant influence on PV system energy production. The temperature of PV module is affected by emissivity, absorptivity of cell surface and convective heat transfer coefficient. In the text are presented parameters of real PV system installed on RES laboratory roof in Slovak University of Agriculture in Nitra. Measured parameters by PV systems were used for verification of mathematical model for time temperature relation. The main aim was modelling of convective heat transfer coefficient dependence on temperature and wind speed. There were compared time relations of measured and modelled convective heat transfer coefficient.

Key Words: photovoltaic module, mathematical model, temperature, convective heat transfer coefficient, relation

INTRODUCTION

The PV system is one of the most important ways for conversion of solar energy into electric energy. The photovoltaic system consists from photovoltaic modules or panels. Basic design component of photovoltaic panel is photovoltaic cell. From physical point of view the operation principle of photovoltaic cell is based on photovoltaic effect. The usage of PV system depends on many technical and physical factors such as: solar irradiation, azimuth angle of sunlit surfaces orientation, the angle of surface inclination which is dazzled, local climate and temperature conditions. All mentioned conditions have significant influence on PV cell energy production, but one of the most important factors is temperature. Temperature of PV cells is important parameter for assessing the long term performance of PV module systems and their annual amounts of electrical energy production. This temperature depends on many parameters such as the thermal properties of materials used in PV module encapsulation, types of PV cells, configuration of PV modules installation and climatic conditions of the locality. Typically, PV module efficiency strongly depends on its cells operating temperature. Increasing cell temperatures during operation generally deteriorates the performance of the PV module in electricity generation. The analysis of photovoltaic panel temperature and power output was presented in literature (Marc et al. 2012). They created simulation of electric and thermal model of PV modules and they verify theoretical results in real operation conditions.

The thermal model of photovoltaic system and combined model of energy transfer processes was presented by authors (Jones and Underwood 2001). They showed that the response of the module temperature is dynamic with changes in irradiance and the accurate module temperature, particularly during periods of fluctuating irradiance. Based on the previous facts were made experiments in real climatic conditions with localization in central Europe region.

MATERIALS AND METHODS
The photovoltaic system is located on the RES laboratory roof in Nitra in the campus of the Slovak University of Agriculture. The PV panels were installed fixed PV system which consists from 6 photovoltaic modules made from monocrystalline silicon. Every photovoltaic module contains six photovoltaic cells STP040S – 12/Rb developed by SUNTECH. The PV cells are used in the combined serial-parallel connection. The total efficiency of photovoltaic modules is 12.6%. Optimal operating voltage is 17.6 V and optimal current is 2.56 A. Maximum power is 45 Wp (1000 W/m²) and operating temperature is from -40 °C to +85 °C. Active surface of measured PV cells is 1.95 m². Block scheme of PV systems is shown on Figure 1.

The technical and physical parameters were monitored for 24 hours a day and time interval between measurements was 10 s. Monitored parameters and their measurement uncertainties were: ambient temperature (± 0.5 K), module temperature (± 0.5 K), solar irradiance (± 2 W/m²), electric current (± 10 mA), electric voltage (± 0.0075 V). As the main aim of the research were observed temperature characteristics of photovoltaic module and relation between temperature and power output of PV system in real climatic conditions located in central Europe region.

The temperatures were measured by calibrated digital temperature sensors DS18B20. Communication between control microprocessor and sensors was realized by 1-wire protocol. Standard accuracy is ± 0.5 °C in temperature range from -10 °C to + 85 °C. Accuracy is better than 0.25 °C in temperature range from –10 °C to 100 °C. The temperature sensors were additionally calibrated for this range.

For battery charging was used TriStar TM controller TS-45. The controller operates in one mode at the time. Rated solar current of the controller was up to 45 A and system voltage was set to 24 V in our case. Accuracy of the voltage measurement was lower than 0.1% (± 50 mV). Modbus communication protocol was used. Communication was realized on the RS-232C physical layer.

System was loaded by bulbs, which were switched by the module Load Control. Output current of system and battery voltage was measured by this module. Converter resolution was 12-bit. The sine wave inverter AJ1300 from producer Studer was used. Maximum output apparent power was 1300 VA and efficiency was up to 9%. Input voltage was optimally 24 V. Inverter output voltage is sine waveform with effective value 230 V/50 Hz, it is generated by the PWM principle with passive filtration.
The measurement system was controlled by the single-chip microcontroller modules. Data were loaded by the program in Labview via USB port and measurement results were saved in Matlab.

Temperature model of photovoltaic module

From the literature are known two types of photovoltaic module temperature models. First type of model was described by Schott (1985) for steady state conditions, but for real climatic conditions is better non-steady state temperature model, which was presented by Jones and Underwood (2000). We assume that the thermal energy exchange in PV module with its environment is realised by three heat transfer ways – conduction, convection and radiation. The most significant are two ways of heat transfer – convection and conduction which are applied on the front and back surfaces of photovoltaic module.

The resulting rate of temperature changes can be expressed by equation:

\[ C_{PV} \frac{dT_{mod}}{d\tau} = q_{LW} + q_{SW} + q_{conv} - P \]  

(1)

where \( C_{PV} \) - is heat capacity of photovoltaic module, \( q_{LW} \) - is heat flux per unit area of PV module surface which characterizes long wave electromagnetic energy exchange, \( q_{SW} \) - is heat flux per unit area of PV module surface which characterizes short wave electromagnetic energy exchange, \( q_{conv} \) - is the total convective energy exchange from photovoltaic module to surface, \( P \) - is DC electrical power generated by PV modules. The solution of differential equation (1) could be obtained by Euler method of integration and temperature of PV module at time step \((\tau + 1)\) could be described by equation (2) (Jones and Underwood 2001)

\[ T_{mod}(\tau + 1) = T_{mod}(\tau) + \text{step} \frac{dT_{mod}}{d\tau} . \]  

(2)

The temperature of PV module was obtained as solution of differential equation (1) and could be described by next formula (3):

\[ T_{mod}(\tau) = \int_{\tau_0}^{\tau} C_{mod} \left[ \alpha \Phi S_{mod} - h_c S_{mod} (T_{mod} - T_{amb}) - P \right] d\tau \]  

(3)

where \( \sigma \) - is Stefan-Boltzman constant and \( \varepsilon \) - is emissivity, \( \alpha \) - is the absorptivity of cell surface, \( \Phi \) - is the total incident irradiance on module surface and \( S_{mod} \) - is the area of surface, \( h_c \) – is heat transfer coefficient, \( T_{mod} \) – is temperature of PV module, \( T_{amb} \) – is ambient temperature (Jones and Underwood 2001).

RESULTS AND DISCUSSION

Collected energy from PV system was approximately equal to supplied energy during the measurement. Therefore, battery voltage was regulated to 26 V. Constant battery voltage is controlled by the program in Labview. The basic role of load control module is regulation output power. System is based on the industrial single-chip microcontroller C8051F340, which is manufactured by Silicon Laboratories. All-important parameters was monitored and saved to the file. Namely they are: cells output voltage, cells output current, battery voltage and load current. These data are very important for energy relationship evaluation.

Days without wind were selected for measurements. Selected value of global solar radiation intensity was 760 W/m². Ambient air temperatures were selected in range from 5 °C to 18 °C during the measurement and the temperature of PV module was from 6 °C to 33.5 °C. Selected day for measurement of PV system parameters was 19.03.2015.

The temperature of PV module is influenced by many factors. Very important factor is emissivity \( \varepsilon \). Normal range of emissivity for objects goes from 0.1 to 0.95 and typical value of glass emissivity is 0.85. The total emissivity depends on emissivity of surface of ground, emissivity of PV module and emissivity of the sky but in our case was used emissivity of the glass because it represents the frontal surface of PV panel (Green 1995). In generally the emissivity range for PV module is (0.85 – 0.91) according to the external conditions.
The next important factor that has an effect on the PV module temperature is absorptivity of cell surface $\alpha$ which is defined by formula (4) (Santbergen and van Zolingen 2007). The absorptivity of cell surface depends on the extinction coefficient $k$ and wavelength $\lambda$.

$$\alpha = \frac{4\pi k}{\lambda}$$  \hspace{1cm} (4)

The values of extinction coefficient $k$ are presented in literature (Green 1995). The absorption coefficient depends on the material and also on the wavelength of light which is being absorbed. Semiconductor materials have a sharp edge in their absorption coefficient, since light which has energy below the band gap does not have sufficient energy to excite an electron into the conduction band from the valence band. Consequently this light is not absorbed. The relations of cell surface absorptivity $\alpha$ for crystalline silicon and wavelength is known from literature (Santbergen and van Zolingen 2007). In our case was used constant absorptivity which is simplification for the calculation of values during the day. For silicone modules with antireflection coating it is 0.7 (Jones and Underwood 2001).

Figure 2 Relation between coefficient of convective heat transfer, temperature and wind speed

![Figure 2](image1.png)

Figure 3 The time dependence of convective heat transfer coefficient obtained from measured parameters of PV system

![Figure 3](image2.png)
The last factor which has effect on PV module temperature is coefficient of convective heat transfer $h_c$, which was examined. It depends on the physical situation for example it contains wind conditions, free convection and forced convection. The values of heat transfer coefficients for different wind speed are presented in literature (Schott 1985). In generally it can be approximated as a linear function of wind speed. In our case was modelled relation between coefficients of convective heat transfer $h_c$, temperature of PV module in the temperature range from 0 °C to 20 °C and wind speed in the range 0 m.s$^{-1}$ to 20 m/s. Final relation is showed on Figure 2. From Figure 2 is evident that temperature dependence of convective heat transfer coefficient $h_c$ has nonlinear shape. The time dependence obtained from measured values is shown on Figure 3 and the same relation obtained by mathematical model application is presented on Figure 4. In the measured relation – Figure 3 are some variations from mathematical model, mainly in time range from 7:30 h to 10 h and in (13–14) h and also in (15–16) h.

The variations of convective heat transfer coefficient were caused mainly by temporary cloudiness and also by chemtrials smog which had significant influence on the solar radiation intensity. In the statistical evaluation were not included extreme measured values in mentioned time ranges. The statistical evaluation of the results showed, that measured values of convective heat transfer coefficient co-vary with modelled values with correlation coefficient of 0.9862.

CONCLUSION

Solar energy is one of the most popular types from group of renewable energy sources. The PV systems usage depends on many factors. From the technical and physical point of view most relevant factors are: solar irradiation, azimuth angle of sunlit surfaces orientation, the angle of surface inclination which is dazzled, local climate and temperature conditions. All mentioned factors were examined on photovoltaic solar system installed on the roof RES laboratory of SUA in Nitra. Presented article is focused on mathematical model which describes dependence between temperature of photovoltaic module and factors as: emissivity, absorptivity of cell surface and convective heat transfer coefficient. Main attention was oriented on modelling of convective heat transfer coefficient dependence on temperature and wind speed. In the second part of results were compared time relations of measured and modelled convective heat transfer coefficient. Both results were in good agreement which was proved by correlation coefficient. Obtained results showed that temperature is one of the most influencing factors.

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The impact of external factors on the photovoltaic cell efficiency in real conditions of micro-region Nitra, VEGA1/0696/11.
REFERENCES


