J Electr Eng Technol.2017; 12(2): 904-910
https://doi.org/10.5370/JEET.2017.12.2.904

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Temperature Measurement of Photovoltaic Modules Using Non-Contact Infrared System

Uglješa Jovanović[†], Dragan Mančić*, Igor Jovanović* and Zoran Petrušić*

Abstract – This paper presents temperature measurement of solar photovoltaic modules using the custom-made system composed of an infrared temperature sensor and a microcontroller. The obtained measurement results are processed, displayed and stored on a PC using the custom-made virtual instrument. The proposed system overcomes some of the problems related to the contact sensor application, and at the same time offers accurate readings and better flexibility. The proposed system is especially suitable for applications where the cost is a limiting factor in the choice of measuring system. The conducted analysis and the obtained results have shown an excellent accuracy of the proposed system in comparison to a high quality thermal imaging camera used as the reference instrument.

Keywords: Photovoltaic modules, Temperature measurement, Infrared temperature sensor, Thermal imaging camera

1. Introduction

The manufacturers of photovoltaic (PV) modules provide their electrical parameters only at the standard test conditions (STC). One of these parameters is the power that PV module delivers when it is illuminated with 1 kW/m^2 of luminous power, while the temperature of a PV cell is at 25°C. However, in reality, under environmental conditions these values vary significantly. With increase of a PV module temperature above the STC rated value, the PV module output current increases exponentially and the output voltage decreases linearly. This means that as the PV module becomes hotter the less power it produces than rated at STC [1-4]. The power drop of a monocrystalline PV module HYM260W [5], used to evaluate the proposed system is illustrated by Fig. 1.

Under the extreme summer conditions power deterioration of the HYM260W PV module can easily exceed 60-70 W, as shown in Fig. 1. Even if the ambient temperature is 25°C, temperature of PV modules can be much higher due to direct sun radiation which heats PV modules. This applies particularly to PV modules mounted on rooftops since they have far less air circulation beneath them and cools them [6].

In order to properly evaluate the power drop of the PV module caused by the temperature rise, it is essential to measure the temperature of a PV module accurately. The accurate measurement of a PV module temperature is a challenging process. Temperature measurement should be performed at the actual semiconductor junctions, but instead, it is usually measured at the backside surface of the PV module which inevitably leads to a small error due to temperature difference between semiconductor and backside surface [3, 7].

Conventional systems for temperature measurement of PV modules are based on contact temperature sensors [8, 9]. The majority of commercial sensors for this application are analog Pt100s or Pt1000s. However, the cost of a Pt100 sensor, made specifically for PV application, RTF4-5.0, is around 50$ [10] and the cost of a fairly good instrumentation system for Pt100 varies between 100$ and 500$. The costs significantly increase if it necessary to monitor temperature from more than one PV module. Furthermore, issues with wire resistances sometimes cannot be neglected. Rather than purchasing an expensive instrument, sometimes is more convenient to develop a low-cost custom-made system based on analog sensors such as a LM35 [9, 11] and a NTC thermistor [12], or a digital sensor like a DS18B20 [13-15]. These systems could cost up to 30$ but they suffer from accuracy issues if

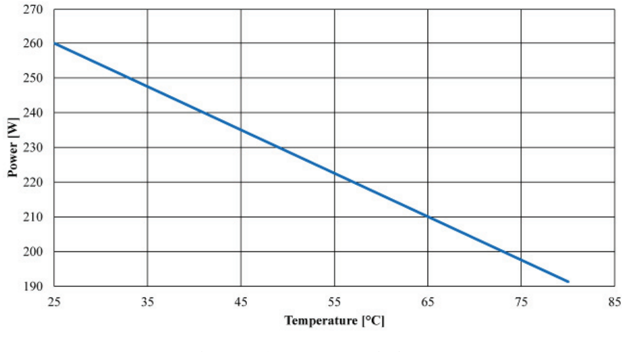


Fig. 1. Power drop of a PV module HYM260W [5]

[†] Corresponding Author: University of Niš, Faculty of Electronic Engineering, Serbia (ugljesa.jovanovic@elfak.ni.ac.rs)
* University of Niš, Faculty of Electronic Engineering, Serbia ({dragan.mancic, igor.jovanovic}@elfak.ni.ac.rs, zoran.petrusic@gmail.com)

Received: December 16, 2015; Accepted: October 24, 2016

the sensor is not properly thermally insulated [14]. Namely, if the sensor is not properly or with its entire surface coupled to the PV module, its readings will be inaccurate because it is not in thermal equilibrium. This means that the sensor readings will be lower than actual due to impact of ambient temperature [14]. However, thermal insulation of any temperature sensor is a challenging process and requires application of quality reference instrument. In addition, some low-cost systems require additional analog circuits such as amplifiers which makes the system more complex [12] and some sensors, such as an encapsulated DS18B20 and a NTC thermistor require calibration [12, 13] with application of a reference instrument. Moreover, any contact sensor, no matter how small it is, will disturb the measurement site and consequently introduce a small measurement error [16]. In addition, when coupled to the PV module, the contact temperature sensor cannot be easily moved over the surface of the PV module, which is sometimes necessary.

The non-contact method for temperature measurement based on infrared (IR) temperature sensors, represents more convenient solution since the sensor does not have to be physically coupled to a PV module [17]. If an IR sensor is compensated for ambient temperature then it would overcome all the issues of contact sensors.

This paper presents the development, realization and testing procedure of accurate, inexpensive system used for PV module temperature measurement. The proposed system is based on the non-contact method for temperature measurement using the IR sensor MLX90614. Based on the authors' knowledge, this method has not been previously investigated in a literature. A high quality thermal imaging camera Jenoptik Varioscan 3021ST with resolution better than ±0.3°C is used as the reference instrument for verification of the proposed system readings. It is shown that the difference between the corresponding measurements taken by the proposed system and the Varioscan 3021ST is less than ±0.5°C which is the range of Pt100 sensors [14].

A custom-made virtual instrument used to monitor operation of the proposed system is designed in LabVIEW.

2. System Design

The proposed system is rather simple and it is based on the IR sensor MLX90614ESF-ACF worth around 20$. The MLX90614 integrates IR thermopile sensors and a custom signal modulation chip in a single TO-39 package. It is capable of measuring object and ambient temperature independently. The MLX90614 is delivered factory calibrated with a digital output. Since the accuracy is specified when the sensor is in thermal equilibrium and under isothermal conditions, Melexis developed xCx series of sensors which internally measure the thermal gradients and the measured object temperature is compensated for them [18, 19]. All this makes the MLX90614 superior over specifically made Pt100s and any other contact sensor in terms of costs, accuracy and simplicity because it is cheaper than a specifically made Pt100, it is compensated for ambient temperature in contrast to contact sensors, it does not have to be calibrated and it requires less of additional electronics.

Ambient temperature is an important factor since it has a major impact on PV module temperature and therefore needs to be constantly monitored during the evaluation of the proposed system. For this application, a DS18B20 temperature sensor is employed.

The proposed system is built around a PIC18F4550 microcontroller (MCU) to which the MLX90614 is connected via I^2C bus while the DS18B20 is connected via 1-Wire bus. The system operation is pretty straightforward, upon obtaining the readings from both sensors, the MCU forwards them to the PC via built-in HID protocol. Virtual instrument, installed on the PC, acquires these results, handles their processing and then displays them. The acquired measurement results can optionally be saved in Excel file if the corresponding function in the virtual instrument is enabled. At the end of each measurement cycle the adjustable time delay is inserted, which has two roles. The first is to prevent the PC memory dumps and Windows crashes and the second is to control the pace of data acquisition. Photo of the proposed system is shown in Fig. 2.

In order to conduct measurements in a flexible manner both sensors are connected to the MCU via 2 m long cables. It should be noted that the proposed system, without DS18B20, can be realized with less than 30$ which is in the price range of majority of low-cost contact sensor

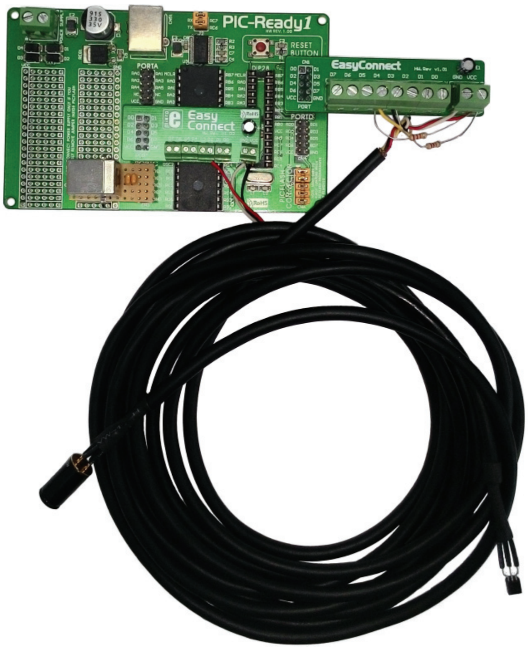
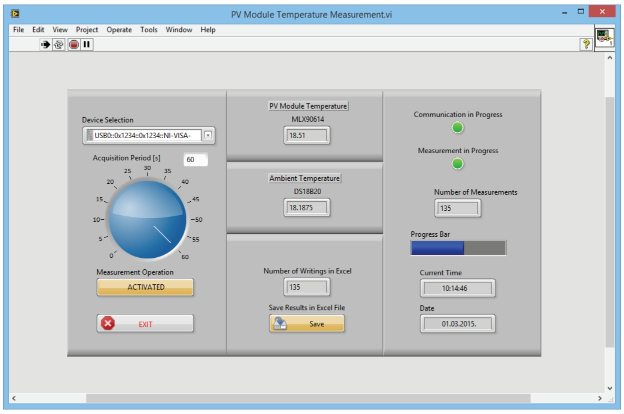


Fig. 2. Photo of the proposed system



Device Selection: USB0::0x1234::0x1234::NI-VISA-

Acquisition Period [s]: 60

Measurement Operation: ACTIVATED

PV Module Temperature
MLX90614: 18.51

Ambient Temperature
DS18B20: 18.1875

Number of Writings in Excel: 135

Save Results in Excel File

Communication in Progress

Measurement in Progress

Number of Measurements: 135

Current Time: 10:14:46

Date: 01.03.2015.

Fig. 3. Print screen of the virtual instrument front panel

based systems and it also represents the fraction of the costs of a Pt100 based system.

The suitable virtual instrument for the data acquisition is developed in LabVIEW. Print screen of the virtual instrument while the system is running is shown in Fig. 3.

3. Experimental Results and Discussion

As stated above, the MLX90614 is factory calibrated and on that basis the proposed system does not need to be calibrated. For the proper validation of the readings obtained using the proposed system, the high quality thermal imaging camera Jenoptik Varioscan 3021ST with the temperature resolution of 0.03°C is employed as the reference instrument, i.e. the measurements obtained from the proposed system are compared with the thermal imaging camera readings. The main reason for employment of this thermal imaging camera is because no sensor can provide as accurate measurements as the thermal imaging camera can. Thermal images taken by this camera are processed and analyzed using Irbis Professional software.

The experimentation is conducted on a 260 W monocrystalline PV module HYM260W with the nominal electrical parameters at the STC given in Table 1 [5].

Table 1. Nominal electrical parameters of HYM260W PV module at STC [5]

Optimum operation voltage	48 V
Optimum operation current	5.42 A
Open-circuit voltage	58.4 V
Open-circuit current	5.96 A
Maximum power at STC	260 W
Module efficiency	15.3 %
Temperature Coefficient	-0.48 %/°C

To thoroughly test the proposed system, evaluation measurements were conducted continuously in the laboratory over the several months while the readings were taken on every minute with the MLX90614 attached 2 cm away from the PV module at the right angle so it measures temperature from a specific measurement spot [20]. The MLX90614 is placed perpendicular to the PV module because then emissivity of the PV module backside is at its highest [21-23]. Additionally, by increasing the angle of incidence above 30°, the emissivity begins to drop hence the PV module temperature measurements are no longer accurate as when the MLX90614 is placed perpendicular. The measurements were also conducted outdoors under real-life environmental conditions. Both evaluation stages are conducted on the same 260 W monocrystalline PV module HYM260W. To validate the system readings, measurement series were conducted with the thermal imaging camera Varioscan 3021ST simultaneously measuring temperature of the same measurement spot as the MLX90614. The thermal imaging camera was synchronized with the proposed system, i.e. it was set to take photos at the same moment as the proposed system takes its readings. The photo of the experimentation setup is shown in Fig. 4.

Fig. 4. Photo of the experimentation setup

Before taking any measurements it was essential to adjust the proper emissivity of the thermal imaging camera and the MLX90614 for the backside of the PV module. The emissivity of the backside, made of white Tedlar, is calculated in the paper [24] and it is found to be 0.85, which is only 0.02 less than the value typical for the white Tedlar available in the literature. Therefore, the emissivity of the Varioscan 3021ST and the MLX90614 was set to 0.85.

In reality, when the PV module is not exposed to the sun radiation, i.e. when it is shaded, its temperature is almost equal to the ambient temperature. This means that the measured PV module temperature is confined by the ambient temperature, i.e. the PV module temperature and the ambient temperature are nearly the same. Under this condition the accuracy of the MLX90614 is the best. For this reason, during the laboratory evaluation the measurements were conducted in which the PV module was shaded and its temperature was confined by the constant adjustable ambient temperature. The results of this experiment, taken

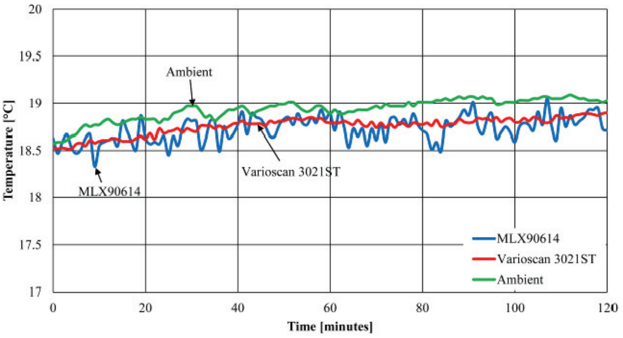


Fig. 5. Results of the laboratory evaluation

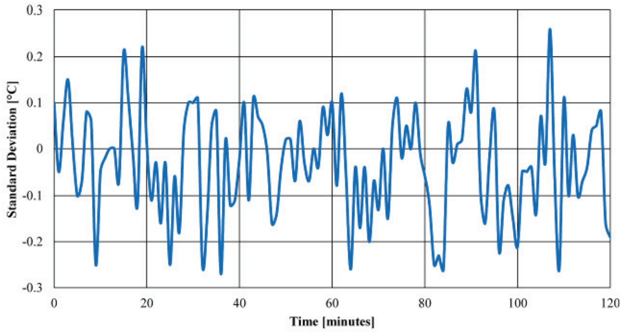


Fig. 6. Difference between the corresponding measurements

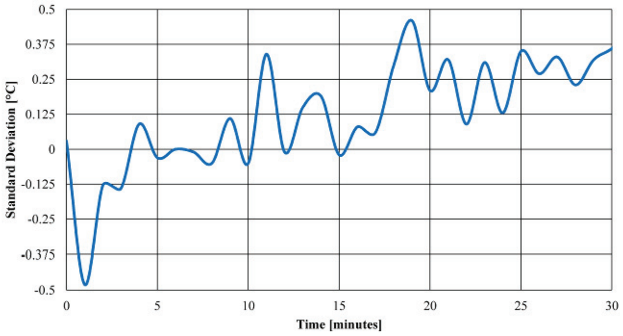


Fig. 7. Difference between the corresponding measurements when PV module temperature is 50°C

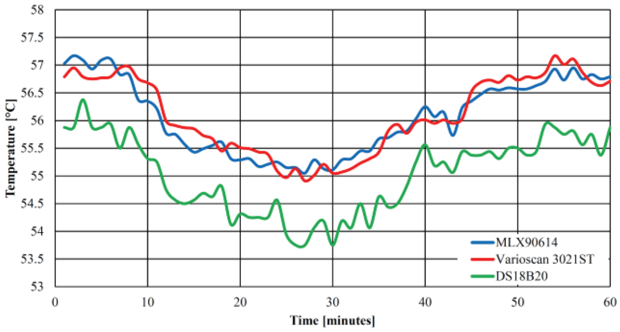


Fig. 8. Results of the outdoor experiment

during two successive hours, are presented in Fig. 5 with the readings taken on every minute.

Results presented in Fig. 5 clearly demonstrate an excellent accordance between corresponding measurements taken with the Varioscan 3021ST and those obtained by the proposed system. Fig. 6 gives the graphical representation of the difference between the corresponding measurements taken by the proposed system and the Varioscan 3021ST.

As one can observe from Fig. 6, the difference between the corresponding measurements is less than ±0.3°C. It should be noted that the realized system does not perform averaging or filtration of the measurements taken by the MLX90614 and the DS18B20.

Due to an intensive sun radiation and a lack of air circulation during summer periods, the difference between the ambient and the PV module temperatures can be quite severe and can go up to 55°C [25, 26]. As stated above, at such temperature difference the contact sensors must be thermally insulated or else their readings will be lower than actual [14]. In fact, the greater the difference between the PV module and the ambient temperature is the greater will be the error that contact sensors produce. As already mentioned, the MLX90614 overcomes these issues since it has ambient temperature compensation. In order to evaluate this, during the laboratory experiment several measurement series were conducted in which the PV module was heated up to 50°C using an industrial heater while the ambient temperature was 25°C. The graphical representation of the difference between the corresponding measurements taken by the proposed system and the Varioscan 3021ST when the PV module temperature was 50°C is shown in Fig. 7.

In order to evaluate the MLX90614 accuracy under environmental conditions, outdoor experimentation is performed on the same PV module implemented in a 3 kW PV power plant facing south with 30º of inclination during the spring of 2016. During this evaluation stage the DS18B20 was thermally insulated with 1 cm thick extruded polystyrene insulation block and was employed to measure PV module temperature 2.5 cm away from the MLX90614. The idea for this setup is to illustrate the difference between the measurements taken by the two measurement methods with similar prices since the DS18B20 is extensively used for PV module temperature measurement [13-15]. It should be noted that, thickness of the XPS insulation block has a massive impact on the DS18B20 accuracy [14]. Too thin XPS insulation block is insufficient to properly insulate the DS18B20 which is manifested as much lower readings than recorded with the Varioscan 3021ST. On the other hand, although it provides more accurate readings, too thick XPS block produced higher readings than recorded with the Varioscan 3021ST and heated up the PV cell. Results of the conducted experimentation showed that optimal thickness of the XPS insulation for the DS18B20 is 1 cm because the obtained readings were the most accurate. One hour measurements of the hottest period recorded during this experiment, when

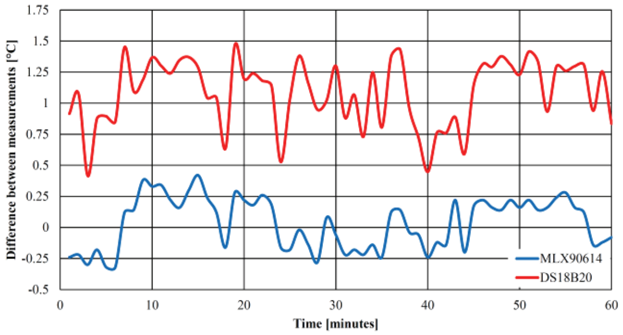


Fig. 9. Difference between the corresponding measurements

ambient temperature was around 25ºC, are shown in Fig. 8.

As can be seen from Fig. 8, the corresponding measurements taken by the MLX90614 and the Varioscan 3021ST are in nearly the same ratio as in case for laboratory experimentation. It should be noted that during this measurement there were few minor wind gusts, which together with few clouds caused the PV module temperature to slightly drop. However, the wind did not have an impact on the MLX90614 accuracy. Graphical representation of the difference between the corresponding measurements taken by the both sensors and the Varioscan 3021ST is shown in Fig. 9.

By viewing Fig. 9 it is evident that the difference between the corresponding measurements taken by the MLX90614 and the Varioscan 3021ST is less than ±0.5°C. However, the difference between the corresponding measurements taken by the DS18B20 and the Varioscan 3021ST is 1.5°C. This means that method based on the thermally insulated DS18B20 provides less accurate measurements in contrast to the method based on the MLX90614 while both of them are in the same price range.

4. Conclusion

In this paper the design, construction and testing of a precise, inexpensive instrumentation system for reliable temperature measurement of PV modules was presented. The realized system is based on the IR sensor MLX90614 and the microcontroller PIC18F4550. The thermal imaging camera Jenoptik Varioscan 3021ST was used as the reference instrument for the proper validation of measurement results obtained by the proposed system. According to the authors' knowledge and available literature, the application of an IR sensor, such as MLX90614, for the temperature measurement of PV modules is for the first time proposed in this paper. Proposed solution is more than one order of magnitude less expensive than the Pt100 based solution and it is in the price range of low-cost and less accurate solutions which require some sort of improvisation i.e. for the same amount of money the proposed solution offers better accuracy and flexibility.

IR sensor MLX90614 overcomes the problems of traditional contact sensors concerning the thermal insulation, immunity to ambient temperature and coupling to a PV module. Advantages of this sensor over contact sensors are clearly demonstrated during the outdoor experiment.

The custom-made virtual instrument conducts the communication initialization between the realized system and the PC, data acquisition and processing, visualization of measurement results and their storage.

The experimental results have demonstrated that the MLX90614 IR sensor has an excellent response time, i.e. it reacts almost instantaneously to any temperature change of the PV module.

During the experiments performed in the laboratory, it was demonstrated that the difference between the corresponding measurements taken by the proposed system and the reference instrument, i.e. thermal imaging camera is less than ±0.5°C which is the range of Pt100 sensors. Outdoor experiment under real-life conditions demonstrated superior accuracy of the proposed method over thermally insulated contact sensor and it also showed that the difference between the corresponding measurements taken by the proposed system and thermal imaging camera is still better than ±0.5°C.

Acknowledgements

The research presented in this paper is financed by the Ministry of Education, Science and Technological Development of the Republic of Serbia under the project TR33035.

References

[1] A. J. Carr and T. L. Pryor, "A comparison of the performance of different PV module types in temperate climates," *Solar Energy*, vol. 76, no. 1-3, pp. 285-294, 2004.

[2] Chen-Ching Ting and Wei-Shi Chao, "Measuring temperature dependence of photoelectric conversion efficiency with dye-sensitized solar cells," *Measurement*, vol. 43, pp. 1623-1627, 2010.

[3] Tom Markvart and Luis Castaner, *Solar Cells: Materials, Manufacture and Operation*, Elsevier, Oxford, Great Britain, 2005.

[4] Sang-Hoey Lee, Jae-Eon Kim and Han-Ju Cha, "Design and Implementation of Photovoltaic Power Conditioning System using a Current-based Maximum Power Point Tracking," *Journal of Electrical Engineering & Technology*, vol. 5, no. 4, pp. 606-613, 2010.

[5] HYM-260W Series Datasheet, Seasun, Changzhou Jiangsu, China, 2010.

[6] E. Skoplaki, A. G. Boudouvis and J. A. Palyvos, "A

simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting," *Solar Energy Materials & Solar Cells*, vol. 92, no. 11, pp. 1393-1402, 2008.

[7] E. Skoplaki, J. A. Palyvos, "Operating temperature of photovoltaic modules: A survey of pertinent correlations," *Renewable Energy*, vol. 34, no. 1, pp. 23-29, 2009.

[8] Stefan Krauter and Alexander Preiss, "Comparison of module temperature measurement methods," in Proceedings of the 34th IEEE Photovoltaic Specialists Conference (PVSC), Philadelphia USA, pp. 333-338, 2009.

[9] Vincent P. A. Lonij, Adria E. Brooks, James Greenberg, Sean Orsburn, Alexander D. Cronin and Gabe Torres, "Field performance measurements of new and traditional PV technologies," *in Proceedings of the World Renewable Energy Forum 2012*, Denver, USA, pp. 342-348, 2012.

[10] Platinum Silicone Patch Sensors (RTF4), Labfacility.

[11] Amal F. Abd El-Gawad, "Suggested Temperature Monitoring System for Distribution Transformers by Using Microcontroller Scheme," *Journal of Electrical Engineering & Technology*, vol. 10, no. 5, pp. 2099-2104, 2015.

[12] Rustu Eke, A. Sertap Kavasoglu and Nese Kavasoglu, "Design and implementation of a low-cost multichannel temperature measurement system for photovoltaic modules," *Measurement*, vol. 45, no. 6, pp. 1499-1509, 2012.

[13] Miguel Angel Martinez Bohorquez, Juan Manuel Enrique Gomez and Jose Manuel Andujar Marquez, "A new and inexpensive temperature-measuring system: Application to photovoltaic solar facilities," *Solar Energy*, vol. 83, no. 6, pp. 883-890, 2009.

[14] Marko Jankovec and Marko Topič, "Intercomparison of temperature sensors for outdoor monitoring of photovoltaic modules," *Journal of Solar Energy Engineering*, vol. 135, no. 3, SOL-12-1178, 2013.

[15] Hocine Belmili, Salah Med Ait Cheikh, Mourad Haddadi and Cherif Larbes, "Design and development of a data acquisition system for photovoltaic modules characterization," *Renewable Energy*, vol. 35, pp. 1484-1492, 2010.

[16] Jacob Fraden, Handbook of Modern Sensors: Physics, Designs, and Applications, Springer, New York, USA, 2010.

[17] Qingmin Li, Haoxi Cong, Jinyuan Xing, Bo Qi and Chengrong Li, "On-line Temperature Monitoring of the GIS Contacts Based on Infrared Sensing Technology," *Journal of Electrical Engineering & Technology*, vol. 9, no. 4, pp. 1385-1393, 2014.

[18] MLX90614 Datasheet, Rev 008, Melexis, Ieper, Belgium, 2013.

[19] Susan A. O'Shaughnessy, Martin Hebel, Steve Evett, Paul Colaizzi, "Developing a Wireless Infrared Thermometer with a Narrow Field of View," *Computers and Electronics in Agriculture*, vol. 76, no. 1, pp. 59-68, 2011.

[20] Klaus-Dieter Gruner, Principles of non-contact temperature measurement, Raytek 2003.

[21] Thermal imaging camera: a fast and reliable tool for testing solar panels, Flir, Technical note.

[22] T. Nunak, K. Rakrueangdet, N. Nunak and T. Suesut, "Thermal Image Resolution on Angular Emissivity Measurements using Infrared Thermography," *in Proceedings of the International MultiConference of Engineers and Computer Scientists (IMECS)*, Hong Kong, China, 2015.

[23] Pablo R. Muniz, Shirley P. N. Cani and Robson da S. Magalhaes, "Influence of Field of View of Thermal Imagers and Angle of View on Temperature Measurements by Infrared Thermovision," *IEEE Sensors Journal*, vol. 14, no. 3, pp. 729-733, 2014.

[24] Morgan D. Bazilian, Harry Kamalanathan, D. K. Prasad, "Thermographic analysis of a building integrated photovoltaic system," *Renewable Energy*, vol. 26, no. 3, pp. 449-461, 2012.

[25] Jurij Kurnik, Marko Jankovec, Kristijan Brecl and Marko Topič, "Outdoor testing of PV module temperature and performance under different mounting and operational conditions," *Solar Energy Materials & Solar Cells,* vol. 95, issue 1, pp. 373-376, 2011.

[26] Thomas Nordmann and Luzi Clavadetscher, "Understanding temperature effects on PV system performance," *in Proceedings of the 3^rd^ World Conference on Photovoltaic Energy Conversion*, Osaka, Japan, vol. 3, pp. 2243-2246, 2003.

Uglješa Jovanović received M.Sc. degree in Electronics at the University of Niš, Faculty of Electronic Engineering, in 2010. He is currently a research assistant at the Department of Electronics at the same faculty. His research areas are: embedded systems, electric current measurement, magnetic field measurement, radiation dosimeters and photovoltaic systems.

Dragan Mančić received Ph.D. degree in Electronics at the University of Niš, Faculty of Electronic Engineering, in 2002. He is currently a Full Professor at the Department of Electronics at the same faculty, where he lectures in thermal imaging, power electronics, alternative sources of energy and ultrasonic techniques. His research interests include thermography, power converters, and modeling and design of power ultrasonic and solar systems.

Igor Jovanović received M.Sc. degree in Electronics at the University of Niš, Faculty of Electronic Engineering, in 2008. He is currently a teaching assistant at the Department of Electronics at the same faculty. His research interests include the characterization of piezoelectric materials, modeling and design of power ultrasonic transducers.

Zoran Petrušić received M.Sc. degree in Electronics at the University of Niš, Faculty of Electronic Engineering, in 2010. He is currently with the Research Institute, Faculty of Electronic Engineering. His research interests are in the areas of measurement, diagnostic techniques for industrial electric systems, thermal imaging, and alternative sources of energy.