DEVELOPMENT OF OUTDOOR PHOTOVOLTAIC MODULE MONITORING SYSTEM

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Key words: PV module, *I-V* curve measurement, outdoor monitoring

Abstract: Performance of photovoltaic (PV) modules is usually specified under standard test conditions (STC). But the performance of the modules under real field conditions can differ from the expectations derived from the results of STC tests due to variety of continuously different conditions. Therefore it is important to monitor PV modules' outdoor performance.

An automated computer-controlled monitoring system that is able to measure *I-V* curves of 16 PV modules in real-time has been developed and put in operation on the roof of Faculty of Electrical Engineering in Ljubljana. Beside the *I-V* curves the presented system also measures total and diffused solar irradiance, module temperature and other meteorological parameters. Selected measurement results are presented and discussed.

Razvoj sistema za merjenje fotonapetostnih modulov pri realnih vremenskih pogojih

Kjučne besede: PV modul, merjenje *I-U* karakteristik, meritve pri realnih vremenskih pogojih

Izvleček: Zmogljivost fotonapetostnih (photovoltaic - PV) modulov je običajno izmerjeno in deklarirano pri standardnih testnih pogojih (STC). Vendar so pogoji, pri katerih PV moduli običajno obratujejo, lahko zelo različni od pogojev pri STC. Zaradi tega lahko pride tudi do večjih razlik med pričakovanim energijskim donosom PV modulov glede na deklarirane parametre modulov ter dejanskim pridobljenim energijskim donosom. Zaradi tega je za natančnejše predvidevanje delovanja modulov potrebno meriti njihovo delovanje pri realnih zunanjih pogojih obratovanja.

V članku je prikazana zasnova in razvoj sistema za merjenje PV modulov pri realnih vremenskih pogojih, ki je postavljen na strehi Fakultete za elektrotehniko v Ljubljani. Razvit sistem omogoča avtomatično meritev *I-U* krivulj 16 PV modulov. Poleg *I-U* krivulj se sočasno merijo tudi globalno in difuzno sončno sevanje, temperature modulov, zraka ter ostali meteorološki parametri. Predstavljeni in ovrednoteni so značilni merilni rezultati.

1. Introduction

Performance of photovoltaic (PV) modules is determined by conversion efficiency of solar energy into electrical energy. The most important PV modules' performance parameters are STC efficiency (η_{STC}) and effective efficiency (η_{EFF}). The η_{STC} is determined as the maximal output power (P_{MPP_STC}) under standard test conditions (STC - solar irradiance 1000 W/m^2, AM 1.5 spectrum and module temperature 25 °C, wind speed 1 m/s) normalized to incident solar irradiance (G) of 1000 W/m^2 /1/ and η_{EFF} is calculated as a ratio of total available annual energy generated by a PV module (E_M), divided by annual solar energy the module receives (E_{SOL}):

$$\eta_{STC} = \frac{P_{MPP\_STC}}{1000\, W/m^2} \quad (1)$$

$$\eta_{EFF} = \frac{E_M}{E_{SOL}} = \frac{\int_{year} \eta\left(G, T_{PV}\right) \cdot G \cdot dt}{\int_{year} G dt} \quad (2)$$

Several procedures have been developed /2, 3, 4/ to asses PV modules' annual performance (effective conversion efficiency or energy yield) at a given location and installation by means of combining location specific data (irradiance, solar energy and air temperature) and PV module installation specific data (installation azimuth, inclination and mounting method) with PV module specific data (Figure 1).

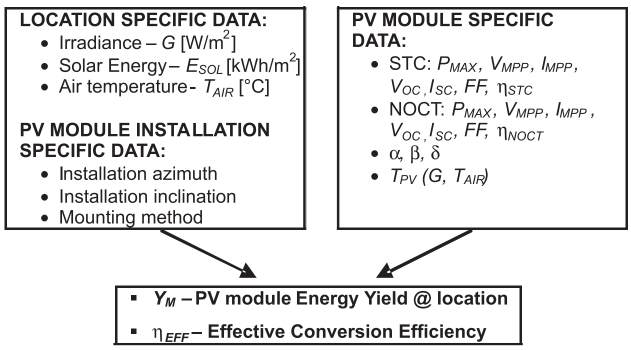

Fig. 1: *Input data needed to assess the PV module annual performance at specific location.*

The location specific data are normally measured by the local meteorological institute, whereas to obtain PV module specific data different approaches are possible. In the simplest approach one can use standard manufacturers' PV module parameters measured at the STC. Some PV module manufacturers also give module parameters measured at nominal operating conditions (NOCT - solar irradiance 800 W/m^2, AM 1.5 spectrum and 20 °C air temperature) /1/. Since performance of PV modules varies with solar irradiance, module temperature, solar spectrum, incident angle, etc., predicting PV module annual performance on the basis of module parameters measured at STC or NOCT can not guarantee accurate results. To be able to give a better daily or annual PV module performance prediction, its parameters have to be defined by outdoor monitoring at different times of the year, different weather conditions and at different mounting options (open rack mounting, building integrated).

For this purpose we have developed an outdoor PV monitoring system (Figure 2). The system has been in operation since 1st of January 2007. At the moment we are monitoring PV modules of the following technologies: poly-Si, mono-Si, back contact mono-Si, a-Si, CIGS, HIT, flexible single junction a-Si and flexible triple junction a-Si. The modules are either mounted on an open rack or integrated on a metal roof. The monitoring site is located on the roof of the Faculty of Electrical Engineering in Ljubljana (Slovenia), oriented south with an inclination angle of 30° (optimal for Ljubljana). To monitor integration of PV modules on building walls one module is also mounted on a metal wall oriented south and 90° inclined.

Fig. 2: *Outdoor PV module monitoring site located on the roof of the Faculty of Electrical Engineering in Ljubljana.*

First results acquired by the outdoor PV monitoring system have been reported elsewhere /5, 6/. We have found relatively large difference between outdoor monitoring results and the modules' performance at STC or NOCT. This confirms the need of continuous outdoor measuring of PV modules' at different conditions to accurately predict their long term performance. Similar conclusions have also been drawn by other authors /7, 8, 9, 10, 11, 12/.

2. Development of the outdoor PV monitoring system

The most important requirement of an outdoor PV monitoring system is that it is able to simultaneously measure several PV modules of different technologies with wide range of nominal powers. If new modules are added to the system it should be easily expandable. Each module should be completely characterized by *I-V* curve scanning from short to open-circuit conditions and its temperature needs to be measured as well. The *I-V* scan should be as fast as possible to assure stable weather conditions during the scan since sample and hold technique can not be applied. In addition, meteorological data (solar irradiances, air temperature, wind speed, etc.) need to be monitored. To minimize the measurement error due to long connection cables, the monitoring system should be located as close as possible to the monitored PV modules. This usually means that measurement instruments have to be located outdoors, which can lower measurement accuracy due to temperature and humidity variations. If a personal computer (PC), which controls the system, is situated indoors a long and reliable communication bus has to be implemented.

On the basis of those requirements we designed and built a microcontroller based outdoor PV monitoring system that is comprised of a PV measurement unit, a module switching unit, different irradiance and several temperature sensors and a commercially available weather station (Figure 3). PV measurement and switching units are controlled by a PC via RS-485 bus. Another RS-485 bus is used to connect remote weather sensors to the weather station display, which is connected to the PC with a RS-232 bus. A separated switching unit allows us to easily expand the system capacity by simply adding additional switching units, which can be connected to the same RS-485 bus. The monitoring system measures global and diffused irradiances on a horizontal surface, air temperature, wind speed, rain-fall, air pressure and humidity at chosen time intervals (every two minutes). The measurement time interval for *I-V* curves, PV modules' temperatures and irradiance in the plane of PV array (G_{POA}) is ten minutes. Entire monitoring system is controlled by monitoring software, developed in LabVIEW programming language, which runs on a PC. All the measured data is stored in an SQL database.

2.1 PV measurement unit

The main part of the whole PV monitoring system is the PV measurement unit (Figure 4), which enables 4-wire connection of the measured PV module /13/. The electronic load is a power MOS-FET controlled by a 14 bit D/A converter. Current of the module is measured as a voltage drop on a precise shunt resistor with a 24 bit A/D converter, which also acquires the module voltage, scaled by a precision voltage divider. The input current and voltage limits are 12 A and 100 V, respectively. The limits are sufficient to measure all commercially available PV modules on the market at the moment. The unit also has six inputs for different types of irradiance sensors. Four of them are voltage inputs (two with 24 mV and two with 120 mV input limits), while the rest are current inputs with 24 mA maximal current input. Specifications of the PV measurement unit are shown in Table 1. In addition to the current and voltage inputs, the measurement unit also features one-wire digital communication bus for connection of digital temperature sensors. The unit can be powered from the grid, in that situation it is connected to the measurement compu-

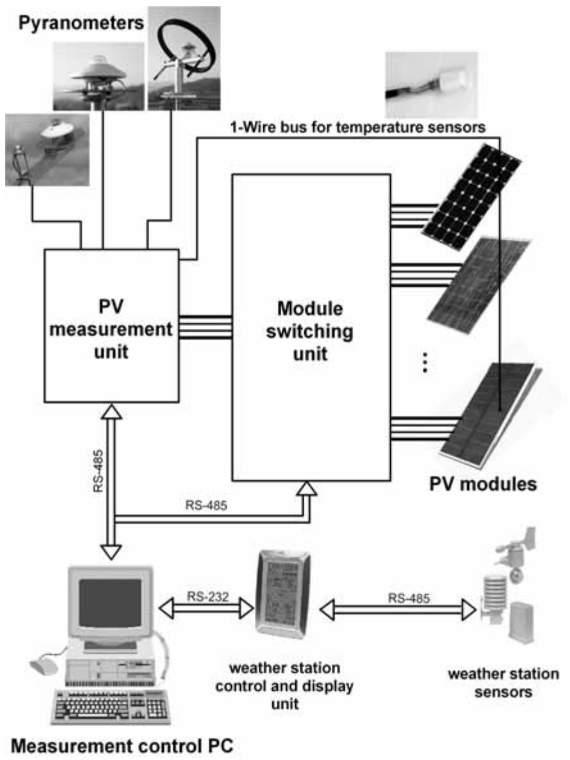

Fig. 3: *Block diagram of the PV monitoring system.*

ter via a RS-485 bus (as it is done at our monitoring system), or via USB connection, when using it as a portable PV module *I-V* curve measurement device.

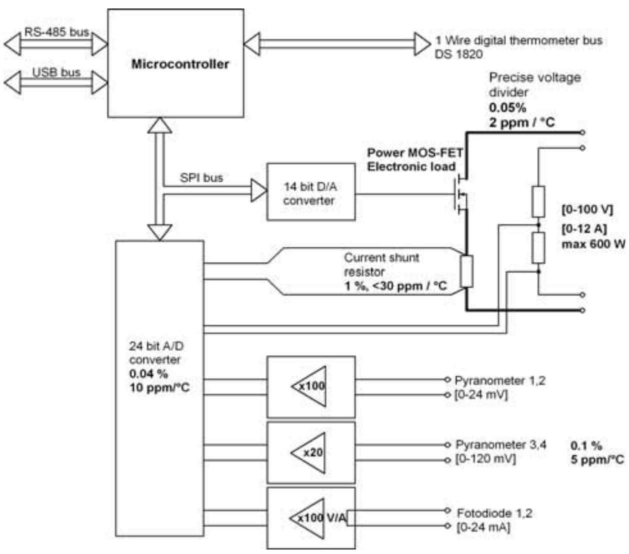

Fig. 4: *Block diagram of the PV measurement unit.*

2.2 Module switching unit

The purpose of the module switching unit in the designed PV measurement system is to enable arbitrary 4-wire connection of multiple PV modules to a single *I-V* measurement unit. In our case, the switching unit allows connecting up to 16 PV modules to the measurement unit. Similar to the PV measurement unit, the module switching unit can also be powered from the grid or from the USB bus power

Table 1: *Specifications of the developed PV measurement unit.*

Input Channel	Input range	Max. offset [0-60°C]	Max. error [0-60°C]
PV current input	0 ÷ 12 A	±0.5 mA	0.25%
PV voltage input	0 ÷ 100 V	±0.75 mV	0.1%
Pyranometer voltage input	0 ÷ 24 mV	±15 μV	0.25%
Pyranometer voltage input	0 ÷ 100 mV	±15 μV	0.3%
Reference cell current input	0 ÷ 24 mA	±0.15 μA	0.1%

supply (5 V) in case of using RS-485 or USB connection, respectively. Block diagram of the four point module switching unit is shown in Figure 5.

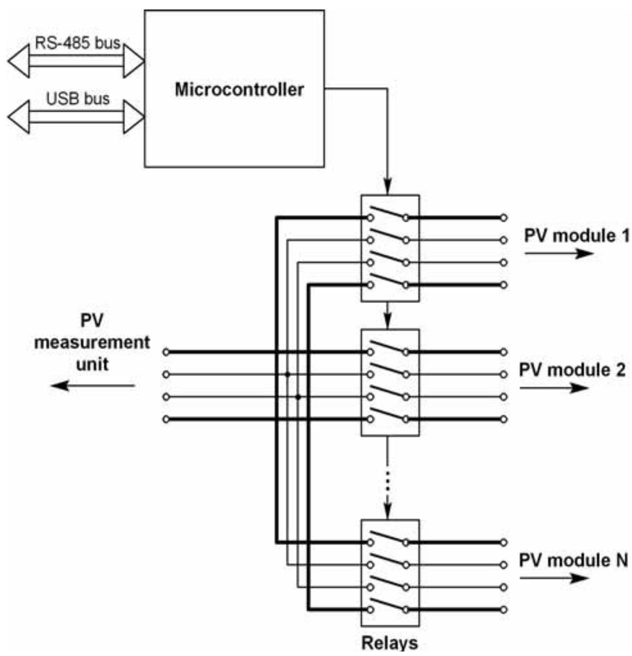

Fig. 5: *Block diagram of the 4-point module switching unit.*

2.3 Sensors

As local specific data we measure instant total solar irradiance in the plane of array, total and diffused irradiance on flat surface, module and air temperature, wind speed and direction, relative humidity, air pressure and rain-fall.

The total solar irradiance at the plane of array *(G_{POA})* is measured with two different types of irradiance sensors. One is a thermopile based pyranometer (*CMP 6*) /14/ and the other one is a pyranometer with a photodiode (*SP-Lite*)

/14/. The first one is more accurate but relatively slow and the second one has a fast response time, but it is less accurate. However, the measurements show that sudden irradiance changes do not contribute to the irradiation, so the difference in dynamic properties is not important. It is their spectral range that differs. While the *CMP 6* covers a broad spectral range, the *SP-Lite* is spectrally adopted to fit crystalline-Si PV modules. Such a combination allows us to accurately evaluate not only crystalline - Si PV module, but also PV modules from other technologies. Total and diffused irradiance on a horizontal surface is measured with two *CMP 6* pyranometers. For the diffused irradiance measurement a shadow ring /14/ is used in combination with the *CMP 6*.

We also monitor temperatures of each module (T_{PV}) by digital temperature sensors (*DS18B20*) /15/ glued on the back sheet of the PV modules. The temperature sensors are thermally connected to the back sheet of the module using a thermal conducting paste and shielded from the ambient temperature influence on the measurement of module temperature by polystyrene and silicon sealant.

For monitoring air temperature, wind speed and direction, relative humidity, air pressure and rain-fall a weather station WS3600 is used /16/.

Specifications for the pyranometers and the digital temperature sensors are shown in Table 2.

Table 2: *Specifications of the pyranometers and digital temperature sensors.*

Pyranometer with thermopile (Kipp&Zonen *CMP 6*)	
Measurement range	0 ÷ 2000 W/m^2
Spectral range	310 ÷ 2800 nm
Response time	18 s
Temperature range	-40 ÷ +80 °C
Directional error (at 80°)	2%
Pyranometer with photodiode (Kipp&Zonen *SP-Lite*)	
Measurement range	0 ÷ 2000 W/m^2
Spectral range	400 ÷ 1100 nm
Response time	< 1 s
Temperature range	-30 ÷ +70 °C
Directional error (at 80°)	5%
Digital temperature sensor (*DS18B20*)	
Measurement range	-55 ÷ +125 °C
Conversion time	0.75 s
Accuracy [-10 ÷ +85 °C]	±0.5 °C
Resolution	1/16 °C

2.4 Measurement control

The PV monitoring system is controlled by a LabVIEW based software, running on a standard PC, located indoors. The measurement sequence, which is shown in Figure 6, is executed every ten minutes. First the air temperature, wind speed, air pressure, humidity and PV modules' temperatures are measured. Then the solar irradiances are acquired. After that the system switches the first PV module to the PV measurement unit, which acquires its *I-V* curve. Then the system disconnects the PV module and calculates parameters of the measured PV module, which are together with the whole *I-V* curve and weather parameters stored to an SQL database. System switches to the next PV module and restarts the procedure with solar irradiance measurement until all PV modules are measured. The whole measurement procedure for 16 modules takes less than a minute. Between the measurement sequences the modules are kept in open-circuit conditions.

The user can compare G_{POA} irradiances measured by *SP-Lite* sensor prior and after *I-V* scanning and see whether the solar irradiance changed during the *I-V* scan. If the difference is too high, indicating unstable weather conditions, the *I-V* curve may be regarded as uncertain. The system also enables the user to manually select and measure individual PV modules at any time.

2.5 I-V curve measurement

The procedure of the PV module *I-V* curve acquisition starts with the measurements of the short and open circuit values of the curve. Using this information the optimal increment of the electronic load is set to measure the *I-V* curve with equidistant steps from shortcircuit to opencircuit conditions. Since the MOS-FET is highly non-linear, the step is adjusted from point to point during the *I-V* scan. Due to capacitive effects of the PV modules, the accuracy of the measured *I-V* curve strongly depends on the speed of the scan. *I-V* curves of the Sanyo HIT PV module /17/, measured at various acquisition times (t_{AP}) of each *I-V* point, are shown in Figure 7. From the study of different modules' behavior we conclude that t_{AP} should be at least 1 ms.

The total number of points per one *I-V* scan is adjustable up to 350 points, but we found a trade-off between total scan time and accuracy with around 70 points per *I-V* scan. To accurately determine the module's power at the maximal power point (P_{MPP}), the voltage (V_{MPP}) and the current (I_{MPP}) at the maximal power point, a fourth order polynomial interpolation is used. Since the electronic load is passive, the ideal opencircuit and shortcircuit circuit conditions cannot be achieved. Therefore, linear extrapolation is used to determine module's shortcircuit current (I_{SC}), opencircuit voltage (V_{OC}) as also the series and shunt resistances. From that parameters module's fill-factor (*FF*) and efficiency (η) is calculated by equations 3 and 4, respectively. G_{POA} represents measured total irradiance in plane of the measured PV module and *A* module area.

$$FF = \frac{I_{MPP} \cdot V_{MPP}}{I_{SC} \cdot V_{OC}} = \frac{P_{MPP}}{I_{SC} \cdot V_{OC}} \tag{3}$$

$$\eta = \frac{P_{MPP}}{G_{POA} \cdot A} \tag{4}$$

A screen shoot of the main measurement screen with a measured selected PV module's *I-V* curve, calculated *PV*

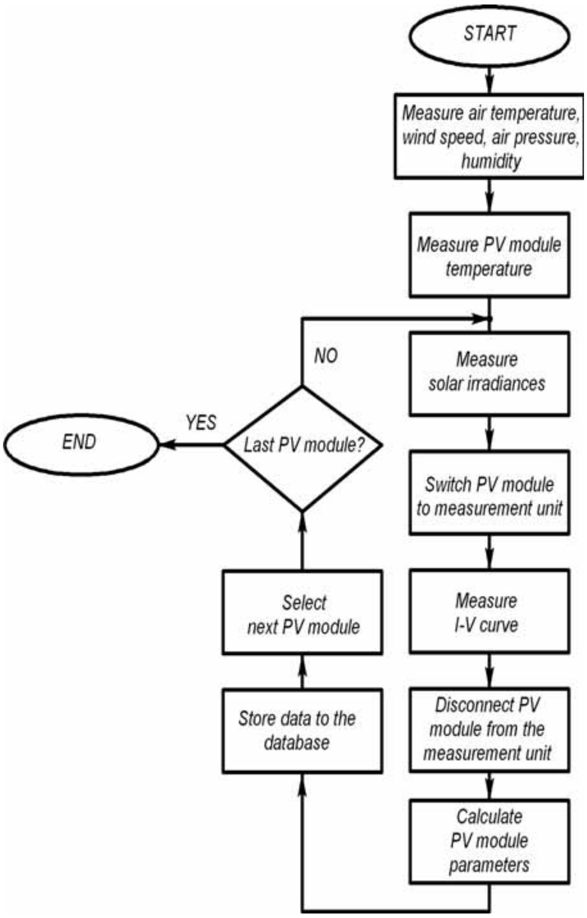

Fig. 6: *I-V measurement sequence block diagram.*

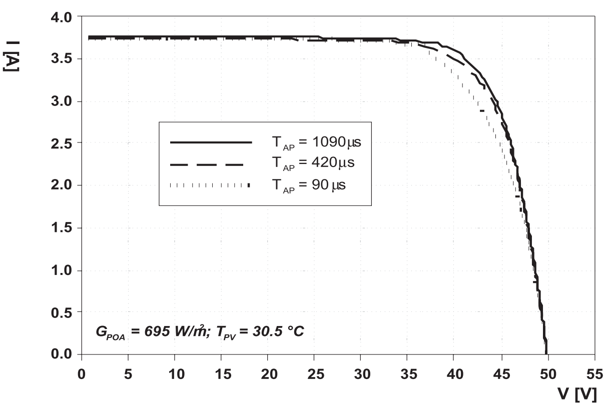

Fig. 7: *Measured I-V curves of the Sanyo HIT PV module at different t_{AP} (t_{AP} = 1090 µs – solid line, t_{AP} = 420 µs – dashed line and t_{AP} = 90 µs – dotted line).*

curve, irradiance and temperature data and from the *I-V* curve calculated PV module parameters is shown in Figure 8.

3. Measurement results

At our monitoring site we constantly monitor 16 different PV modules. Measured *I-V* curves of the Sanyo HIT PV module are shown as an example in Figure 9. The curves were measured in the afternoon of the 30th of March 2008

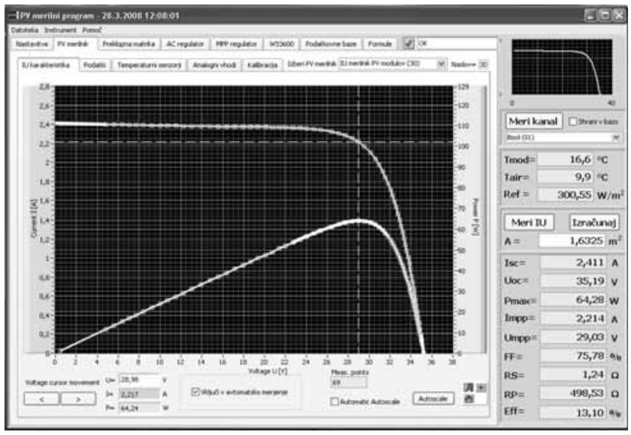

Fig. 8: *Screen shoot of the measurement software developed in program language LabVIEW.*

from noon till five o'clock under clear sky conditions with solar irradiance values ranging from 1015 W/m^2 to 265 W/m^2 and module temperature values ranging from 48 °C to 21 °C during the measurement period (see current in Figure 9).

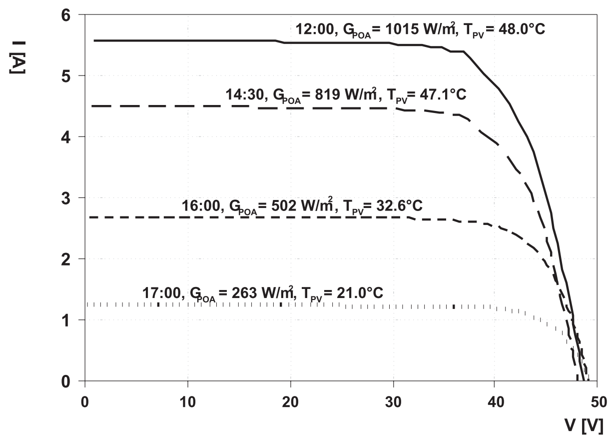

Fig. 9: *Measured I-V curves of a Sanyo HIT PV module on the 30th of March 2008.*

Measurements of solar irradiance on horizontal surface (Figure 10) for the selected day show cloudy and foggy conditions in the morning. That is noticed by almost the same values of total and diffused irradiance until 10:30. Afterwards the fog and clouds cleared out and it became a nice sunny afternoon, depicted by a large difference between the total and the diffused irradiance and a smooth curve of measured solar irradiances in the afternoon hours. Together with *I-V* curves and irradiances we measure module and air temperatures and wind speed. The measured parameters are shown in Figure 11. The 30th of March 2008 was a pretty calm day with wind speeds under 2 m/s and air temperatures up to 18 °C. Because of clear sky conditions in the afternoon, with G_{POA} up to 1000 W/m^2 and low wind speeds the HIT module heated up to almost 50 °C. In hot and clear-sky summer days module temperatures of up to 75 °C have been measured.

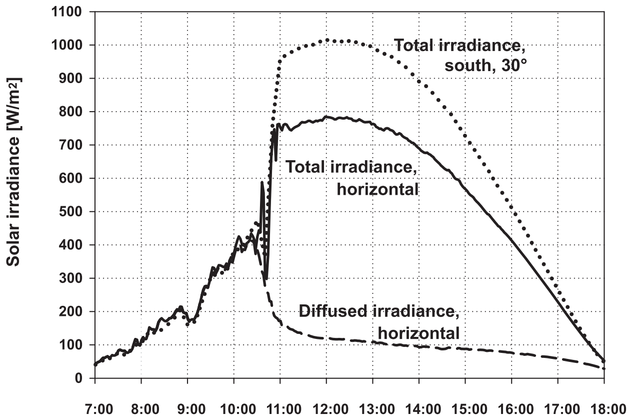

Fig. 10: *Total (solid line) and diffused solar irradiance (dashed line) on flat surface and total solar irradiance on plane of array (dotted line) on the 30th of March 2008.*

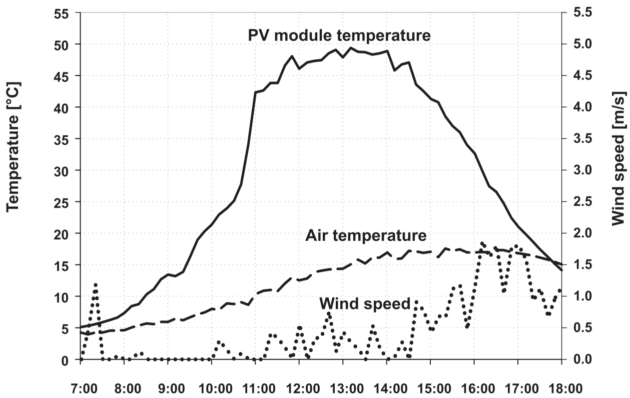

Fig. 11: *HIT PV module temperature (solid line), air temperature (dashed line) and wind speed (dotted line) on the 30th of March 2008.*

4. Conclusion

An outdoor PV monitoring system has been successfully developed and put into operation on the roof of Faculty of Electrical Engineering in Ljubljana. The monitoring system offers real-time measurement of PV modules' *I-V* curves together with their temperatures. Additionally we monitor the total and diffused irradiances on the horizontal plane and the total irradiance in the inclined plane of the PV modules. Meteorological parameters are monitored as well enabling us to accurately determine different short and long term module parameters. Longterm monitoring results are the basis for building and validating mathematical models of PV modules of different technologies and also the basis for study of PV modules' longterm stability.

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Prispelo (Arrived): 24.04.07 *Sprejeto (Accepted):* 28.5.08