Low-cost solar Radiation Sensing Transducer for Photovoltaic Systems

S. GAGLIANO, D. NERI, N. PITRONE, N. SAVALLI, G. TINA
D.I.E.E.S.
University of Catania
V. le A. Doria 6, 95125 Catania
ITALY
gtina@diees.unict.it http://idrilab.diees.unict.it

Abstract: - Measurements of solar irradiance are critical for evaluating solar energy potential in a given location and for calculating the efficiency of a solar system (Photovoltaic and solar thermal).

In order to maximize the energy collected by a given Photovoltaic System tracking the position of the sun in order to expose a solar panel to the maximum radiation level at any given time is needed: to do so the maximum insulation direction must be determined. On this regard it is worth to investigate a low-cost solar radiation sensing transducer, which consists of a structure of green light emitting diodes: this device should be designed not only to individuate the direction corresponding to maximum insulation, in order to every timed expose the solar panel to maximum radiation, but also to measure the beam and the diffuse solar radiation. In this paper some preliminary experimental results regarding testing and calibration of a prototype developed in the Idrilab laboratory in Catania (Italy) are reported.

Key-Words: - Photovoltaic System, Tracking System, Solar Radiation, Diffuse solar radiation, Sensing transducer, low-cost.

1 Introduction

Private investors and electric utilities intending to develop photovoltaic generation systems need solar energy resource data, both to evaluate the economic feasibility of solar facilities and to facilitate their location.

Colle et al. [1] have shown that uncertainty in life cycle savings for solar thermal and Photovoltaic Systems (PVS) are linearly correlated with uncertainty in solar resource data. In planning PV systems and control their operation the solar radiation components (Direct and Diffuse ones) and the status of the sun must be determined.

In particular, to know the total irradiance whatever is the tilt angle processing the Diffuse and the Direct irradiance data is necessary, as these components vary in a different way with the inclination θ.

Furthermore, the knowledge of the sun position permits to expose a solar panel to maximum radiation at any time.

In the literature, different techniques have been recently shown to produce significantly better measurement of solar energy resource, classified as:

- dynamic system [2].
- static system [3], [4], [5], [6], [7], [8], [9].

However the dynamic system, due to the maintenance requirement tends to be more expensive than the static one, on the other hand not appropriate maintenance can lead to low reliability and insufficient precision.

Those techniques have been developed for two different objectives: to measure the solar radiation components [2, 3, 5], and to track the sun position [4, 6, 7, 8, 9]. The detectors of the solar radiation can be solar cells [4, 7], thermo resistors or thermistors [9], green light emitting diodes (LED) [3, 5, 8], phototransistors [6].

In [2] a solar instrument with a rotating shadow band pyranometer has been developed: it performs the function of a pyranometer, a pyrheliometer and a sun tracker.

In [4] the authors propose an electronic detector which consists of 5 solar cells in one package, made in MEMS technology. In [7] an electronic differential detector has been proposed: it consists of five solar cells in one package, with their planes oriented at 90°. It is interesting to observe the system developed in [3]: it is an integrated device (called the BF3) that uses an array of photodiodes with a unique computer-generated shading pattern to measure the incident solar radiation.

In [8] the radiation-to-electrical-voltage transducer consists of a LED. In [9] the position and the “status” of the Sun are detected by light-dependent resistors LDRs. In particular, in [8] eight LED’s are positioned on a semicircular support, in [9] a rosette of nine LDRs has been realized. It can be recognized that the static systems are generally used for both the objectives: to measure the solar radiation components and to detect the status of the sun.

The purpose of this paper is to present a low-cost solar radiation sensing transducer, designed in order to obtain both the objectives: to measure the solar radiation components and to observe the status of the sun. The system is a static one and consists of green LEDs to perform accurate field measurement of the global, direct and diffuse solar irradiance. On the base of a suitable elaboration of the signals supplied by the LEDs it is possible to individuate the sun direction corresponding to maximum insulation, in order to expose the solar panel to maximum radiation.

2 Solar radiation data for optimal photovoltaic system operation

The choice of a proper location is the first and the most important step in solar system design procedure. Even the most carefully planned solar system doesn't work satisfactory if the location wasn't properly chosen. It is critical that the modules are exposed to sunlight without shadowing at least from 9 am to 3 pm; therefore, the properties and the values of solar insolation should be studied. The modules have to be fixed with proper tilt angle allowing an efficient operation of the system. Understanding the motion of the Sun is essential for a proper design of solar systems and for the choice of the proper location of solar collectors or photovoltaic modules, which is needed in planning and operation of PVS.

Furthermore, to know the sun position permits to individuate the direction corresponding to maximum insulation to expose a solar panel to maximum radiation at any time, which is the main purpose of a solar tracking PVS.

Planning of PVS: just one solar radiation sensor, instead of two, would allow us to make some measurements of beam and diffuse components of the solar radiation; this characteristic is crucial, in fact, very often the only set of radiation data available to predict energy production of a PVS, in a given site, refers to the global radiation on horizontal surface and also, when the diffuse component is available, it has been calculated by means of simple experimental expressions that calculate the diffuse components as a function of the clearness index K_T. On the other hand a long term campaign of measurement of both components could be very useful to evaluate the energy performances of system based on tracking systems. Indeed, the smaller is the diffuse component, compared to the beam one, the more economical advantageous is the system equipped with a tracking system (e.g. concentrating PVS).

Operation of PVS: to be sure that a PV plant is working well, monitoring the primary energy, that is the solar radiation, is needed. Automatic data acquisition systems are currently used for both monitoring system performance and control of its operation. The obtained information can be used to evaluate the plant efficiency during long periods and to optimize future systems in terms of performance and reliability [10]. Several data acquisition systems have been developed for their use in a wide variety of applications, which include measuring, acquisition and processing environmental variables [11–13]. In [14] an automatic, low-cost data acquisition system for monitoring PV solar plants has been developed using a novel procedure based on virtual instrumentation. It measures and displays graphics of solar radiation, room temperature and numerical values of the more usual PV system variables. To calculate the efficiency of the PV field the solar radiation that reaches the PV array should of course be measured. If the PV panels have a tilt angle different from zero, one or more pyranometers parallel to the arrays have to be installed.

In this case, an instrument that can measure both the solar radiation components could be very useful. In fact, known the beam and diffuse components, by means of straight calculations it is possible to evaluate the radiation that strikes a surface, whatever inclination it has.

Most major PVSs undergo some monitoring for at least a few years after their installation. Such monitoring can have several goals:

- to ensure that the system is operating properly,
- to assess the performance of system components, pinpoint faulty devices or devices operating below their nominal performance,
- to permit the calibration of design and simulation tools,
- to reveal improvements to the design and to increase the understanding of the designer.

Despite its usefulness, monitoring is often overlooked. In [15] the authors reported numerous examples of improper monitoring. The main reasons for that are:

- some important variables, as diffuse irradiance in plane, were simply not monitored;
- improper connections of some sensors to the data logger;
- improper calibration of an instrument;
- wrong handling of data file.

3 Solar radiation measurement

The instruments that make measurement of Direct and Diffuse components of solar radiation are usually expensive and require considerable attention.

The direct normal solar radiation component has generally been measured by a *Pyrheliometer* on a sun-following tracker, the Global Horizontal radiation by a *Pyranometer* with a horizontal sensor, the Diffuse component by a shaded *Pyranometer* under a tracking ball.

There are two types of pyranometer detectors:

- thermopile Detectors: 1st Class, Expensive, Flat Spectral Response, "Slow"
- photoelectric Detectors: Fast, Low-Cost, with Reduced Spectral Response (Fig. 1).

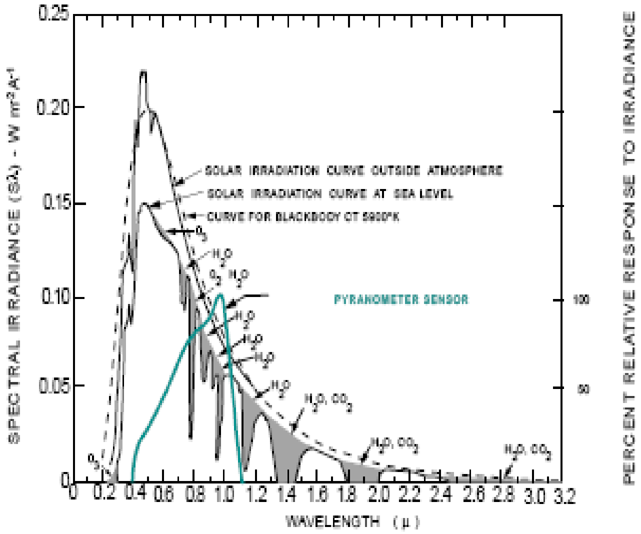


Fig. 1 Silicon Photovoltaic Pyranometer spectral response, as a function of the energy distribution in the solar spectrum.

Table 1 Pyranometer Basic Characteristics

	Photodiode	**Thermopyle**	**Photo-voltaic**
Electro-magnetic Spectrum [nm]	400-1100	335-2200	400-700
Cosine response	±3% (0° to ±70° incident angle); ±10% (±70° to ±85° incident angle)	Maximum deviation from the ideal cosine-response: up to 80° angle of incidence (with respect to 1000 W/m2 irradiance at normal incidence, 0°)	±80°
Response Time	50 ms	<15 s	10µs
Operating Temp. [°C]	-40÷65	-40÷80	-40÷65

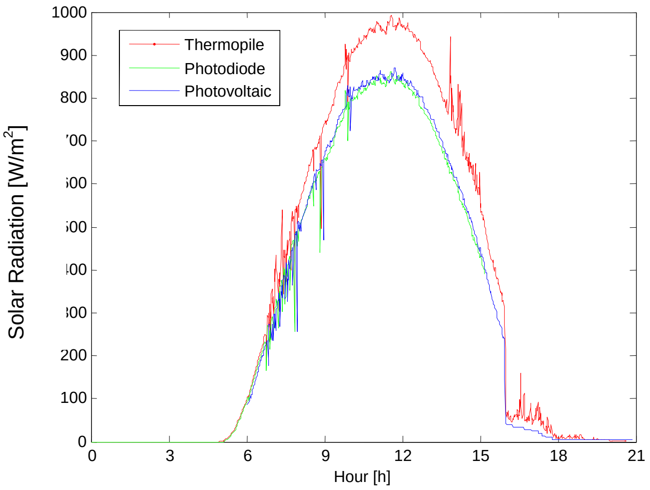


Fig. 2 Solar Radiation Measurement using different Detectors: Thermopile, Photodiode and Photovoltaic.

The pyranometers specifications can be observed in Table1.

In Figure 2 the difference of the responses given by the following three solar radiation detectors can be observed:

- Thermopile Pyranometer
- Photodiode Pyranometer
- Photovoltaic Irradiation Sensor

It can be seen that the outputs between the photoelectric pyranometers (Photodiode and Photovoltaic) are very similar, whereas the thermopile output is significantly higher. This is related with the electromagnetic spectrum of the pyranometers (Table 1): the thermopile pyranometer electromagnetic spectrum range is larger than the other ones.

It is important to observe that the pyranometer shows a measurement error that is known if it is installed on a horizontal plane [16], but normally it is installed on the same plane of the PV modules that are in most cases tilted with respect to the horizontal plane.

Another important application of solar radiation measurement system is tracking the position of the sun.

For many years, several energy companies and research institutions have been performing solar tracking for improving the efficiency of solar energy production.

A variety of techniques of solar energy production used have proven that up to 30% more solar energy can be collected with a solar tracker than with a fixed PVS [5].

The cost of such systems is however still very prohibitive for the average consumer or for a small-scale application. In [8] the authors show a system for academic institutions. The solar trackers currently available are generally not programmable for location flexibility. In [17] a solar tracker based on an arrangement of auxiliary bifacial solar cell is described. There are two types of automatic trackers for small and medium Solar Panels: with electronic control and with electromechanical control [18].

In this paper a low-cost solar radiation sensing transducer consisting of green LEDs has been developed, not only to individuate the direction corresponding to maximum insulation to expose a solar panel to maximum radiation at any time but also to measure the beam and diffuse solar radiation.

4 System Description

The WSR1 sensor is actually a component of a Multisensor system developed at the University of Catania, Idrilab Laboratories [19], in which many transducers play a fundamental role for the characterization of the WSR1, for enabling a cross check and for completely monitoring and planning the photovoltaic system.

The preliminary experimental prototype is the two axis tracking system depicted in Fig. 3.

Fig. 3 Two axis tracking system

In order to derive the sun direction, corresponding to maximum insulation, and to obtain the global and diffuse irradiance, the multisensor system is composed of ten transducers, as depicted in Figure 4.

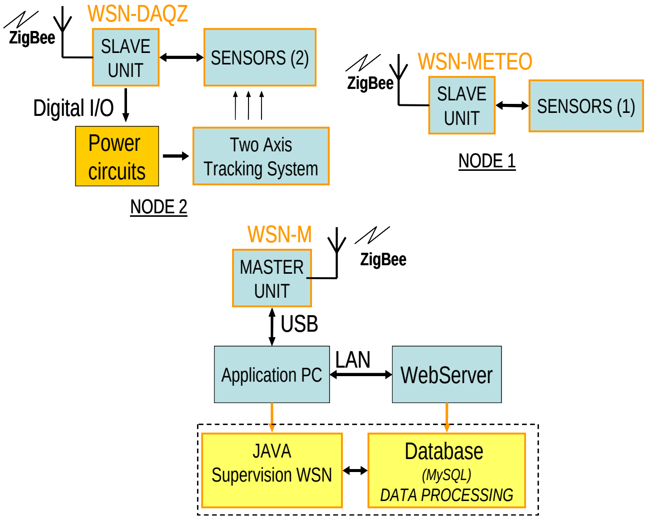


Fig. 4 Functional description of the system

These are part of two separate nodes, suitably located on the roof of the Idrilab-building (DIEES, University of Catania), and both composed of five different transducers. In particular, Node1 is equipped with the following sensors:

- Wind speed (wind cups and magnetic switch)
- Wind direction (wind vane and potentiometer)
- Pyranometer (photodiode)
- Pyranometer (thermopile, Kipp & Zonen - CM11)
- Temperature (band gap)
- Relative Humidity (capacitive polymeric)

whereas the Node2 is equipped with the following transducers:

- Wsr9 (rosette of nine photodiodes, shown in Figure 4)
- Photovoltaic Irradiation Sensor (photovoltaic cell, anchored to the panel plane)
- Inclinometer (capacitive)
- Rotational Potentiometer (resistive)
- Surface Temperature of Panel (resistive)

The photodiode in the rosette sensor is a high speed and high sensitive PIN photodiode in a miniature flat plastic package. Due to its waterclear epoxy the device is sensitive to visible and infrared radiation. The large active area combined with a flat case gives a high sensitivity at a wide viewing angle. In particular its main specifications are:

- Large radiant sensitive area ($A=7.5\ mm^2$)
- Wide angle of half sensitivity $\varphi = \pm 65°$
- High photo sensitivity
- Fast response times
- Small junction capacitance
- Suitable for visible and near infrared radiation

The range of Spectral Bandwidth is 600±1050 [nm], comparable with the electromagnetic spectrum of the Photodiode Pyranometer (Table 1).

All data from Node1 Node2 are sequentially wireless transmitted (ISM, 2.4 GHz) to the Web-server located at the Idrilab laboratories through the WSNmeteo and WSNdaq modules respectively, developed by WiSNAM [20].

Such modules are versatile and equipped with ADC converter for Sensors' analogical signal acquisition, Real Time Counter RTC for the data and hour management, one day data logging capacity, chip for the energy consumption analysis and an interface for the serial communication with other systems.

The sampling time is 5 seconds, whereas a refreshing time of 1 minute is fixed to transmit averaged data from almost sensors, except for the WSR9 transducers. For these latter sensors raw data are transmitted (12 samples in a minute).

In [9] the position and "status" of the Sun are detected by a rosette (Fig. 5) of nine light-dependent resistors (LDRs), for rotation, and three aligned LDRs for inclination, arranged in a suitable plastic supports.

In this paper the position and "status" of the Sun are estimated by processing the data gathered from the rosette of nine high speed and high sensitive PIN photodiodes.

The conditioning circuit adopted for each sensor is depicted in Figure 6.

The rosette is composed by nine sensors, and a shading cylindrical support with 2 inches diameter. This support permits to have evident grudges. As the Sun moves, its direct light will interest a different set of the sensors arrays with consequent variable intensity, as shown in Figure 7.

Finally, a Java-based tool located on the application PC allows for both to store the data in a relational Database (MySQL) and to implement the compensation procedure which allows for working at different latitudes.

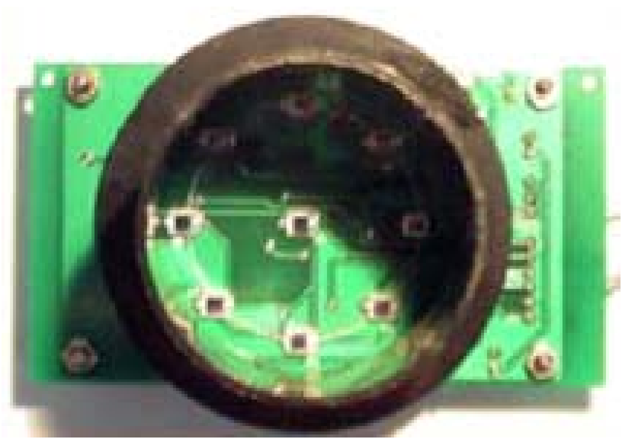


Fig. 5 Rosette of nine photodiodes

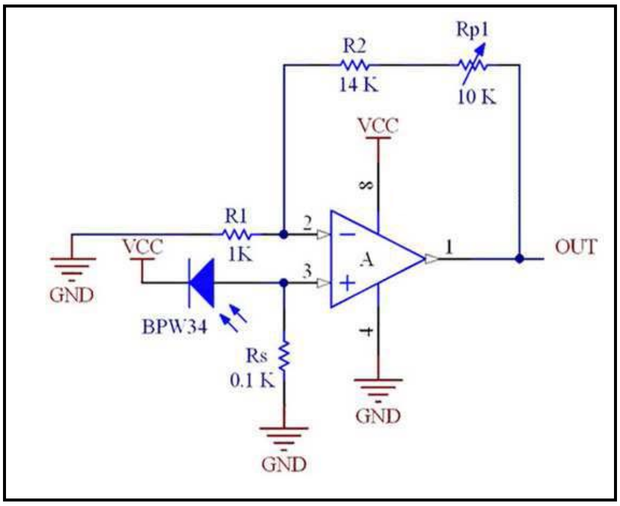


Fig. 6 Conditioning circuit for each single photodiode.

Then, the Wsr9 sensor permits to obtain the azimuth angle variation, the sun height and the global and diffuse irradiance, through suitable data processing procedures.

5 Experimental Results

Among the preliminary experimental tests already performed, particular attention has been devoted to the characterization of the behaviour of the light dependent sensors in the rosette configuration. After executing the system setup, the signals coming from those sensors have been gathered through a Data acquisition board and a supervising unit, realized in the LabView environment at IDRILAB Laboratory. (Catania, Sicily, Italy, latitude 37°3' and longitude 15°8'). The position and "status" of the Sun are estimated by processing the data gathered from the rosette of nine high speed and high sensitive PIN photodiodes, named S1÷S9.

Data gathered at the site for a particular day (4th May, 2008,) are reported in Fig. 8 a) and b).

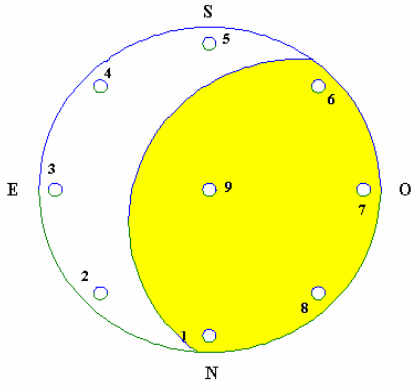
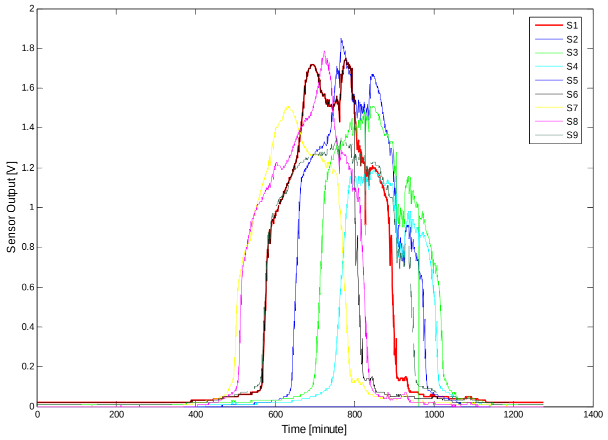
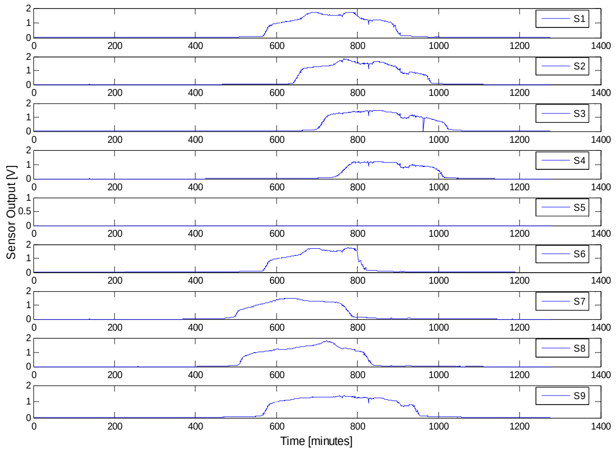


Fig. 7 Numbering and orientation of the rosette (The shadow condition refers to the day 4th May 2008, 9:00 a.m.)



a)



b)

Fig. 8 Voltage output from the nine sensors S1÷S9: a) sensor outputs,. b) sequence outputs.

In particular, in Fig. 8 a) the variations of the output of the nine sensors due to the variations of the irradiance are displayed, whereas in fig. 8 b) it is worth noting the sequence of the output from each sensor due to the position and the shadowing effect of the shading cylindrical support. This shifted outputs are in accordance with both the positions of the sensors in the rosette and the positions of the rosette respect with the direction north-south.

As we can see sensor 5 is always in shadow state, according to the position of the rosette and the movement of the sun and related shadow conditions. The data has been compared with the ones recorded by the meteorological station for the solar radiation and reported in Fig. 9; the signal coming from the pyranometer has been divided by 600 to bring the signals comparable. Indeed, the comparison is only qualitative in this case, because at this first step of the analysis, the calibration of the measuring system is the chosen target.

Finally, it is important to measure the global and the diffuse radiation.

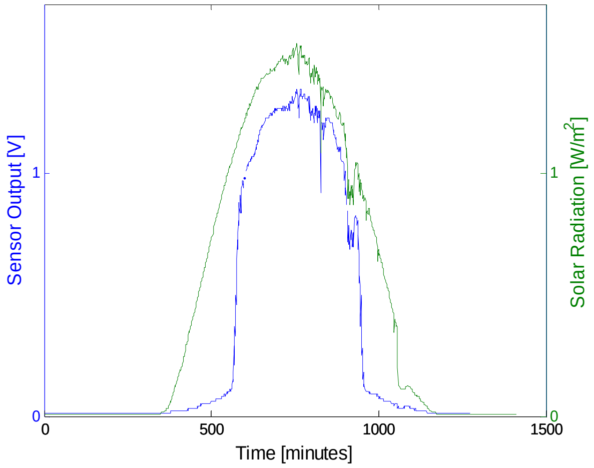


Fig.9 Comparison between the voltages output from the Sensor 9 and the Solar Radiation Recorded by Thermopyle Pyranometer

When the sun moves the PIN photodiodes change to light state to shadow state. During this change the PIN photodiode output is recorded every minute. Figure 10 is a plot of the outputs of two PIN photodiodes (Photodiode 1 and Photodiode 2), with different conditions: no shadow state and shadow state. The data have been recorded the 4th May 2008.

The beam normal irradiance (D_n) should be obtained from the difference between the global (G_h) and diffuse irradiance (D_h) values, divided by the cosine of the solar zenith angle (Z) at that instant. G_h is measured from the photodiode that is lighted and D_h is measured from the photodiode that, at the same instant, is shadowed. Since cos(Z) can be calculated as a function of site latitude, longitude, time and date, D_n can be easily computed.

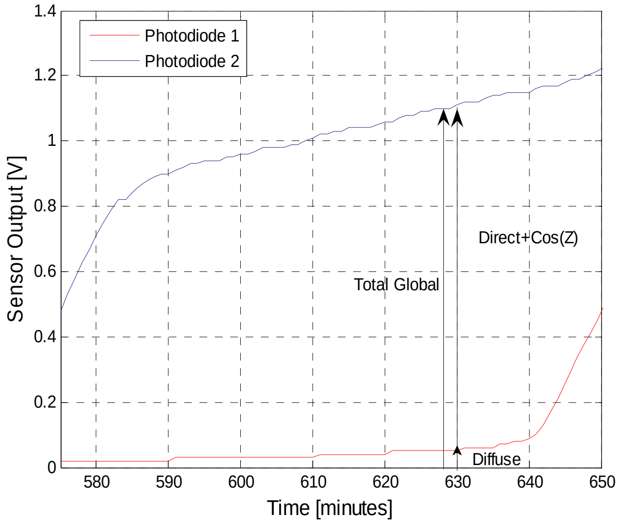


Fig. 10 Voltage output between two different PIN photodiodes, in different light conditions: shadow (Red line) and no shadow (Blue line)

4 Conclusion

A new low-cost solar radiation sensing transducer is proposed to individuate the direction corresponding to maximum insulation and to measure the solar radiation components.

The solar radiation sensing transducer is actually a component of a Multisensor system developed at the University of Catania, Idrilab Laboratories for the complete monitoring and planning of a photovoltaic system.

The position and "status" of the Sun and the global and diffuse components of solar radiation are estimated by processing the data gathered from the rosette of nine high speed and high sensitive PIN photodiodes. The present analysis shows some preliminary experimental results to validate the developed system. In particular the preliminary experimental tests has been devoted to the characterization of light dependent sensors behaviour in the rosette configuration.

A qualitative comparison between the system output with a thermopile solar detector (Kipp & Zonen CM11) global output has been presented.

Finally, the comparison between the voltage output coming from two different PIN photodiodes in different light conditions (shadow and no shadow state) gives the diffuse and global irradiance ratio (R). This value has been compared with the one obtained by the Clear Sky Model.

References:

[1] Colle S, De Abreu, SL, Ruther R., Uncertainty in economic analysis of solar water heating and photovoltaic systems, *Solar Energy*, Vol. 70 Issue 2, 2001, pp. 131-142.

[2] Kern E. C. Jr., Russell M. C., Rotating shadow band pyranometer irradiance monitoring for photovoltaic generation estimation, *IEEE*, 1991??????

[3] Wood J., Muneer T., Kubie J., Evaluation of a New Photodiode Sensor for Measuring Global and Diffuse Irradiance, and Sunshine Duration, *Journal of Solar Energy Engineering*, Vol. 125, 2003, pp. 43-48.

[4] Milea P. L., Oltu O., Dragulinescu M., Dascalu M., Optimizing solar panel energetic efficiency using an automatic tracking microdetector, *Proceedings of WSEAS International Conference on RENEWABLE ENERGY SOURCES (RES 07)*, 2007.

[5] http://wattsun.com/resources.html.

[6] A.Tognoni, Pannelli fotovoltaici : tecnologie e sistemi di puntamento, *M.S. Degree Thesis*, Pisa, 2005/2006 (in Italian).

[7] O. Oltu, P.L. Milea, M. Dragulinescu, E. Franti, Solar Panel Energetic Efficiency Optimization Method, based on an specific detector and orientation microsystem, *Semiconductor Conference, 2007. CAS 2007. International* Vol. 1 pp. 127-130.

[8] S. Lakeou, E. Ososanya, Ben O. Latigo, W. Mahmoud, G. Karanga, W. Oshumare, Design of a Low-cost Digital Controller for a Solar Tracking Photo-Voltaic (PV) Module and Wind Turbine Combination System, *21st European Photovoltaic Solar Energy Conference*, 4-8 September 2006, Dresden, Germany.

[9] S. Gagliano, N. Savalli, G. Tina and N. Pitrone, Two-axis sun tracking system: design and simulation, *Eurosun 2006*, Glasgow, June 2006.

[10] Blaesser G., PV system measurements and monitoring, the European experience, *Solar Energy Mater Solar Cells*, Vol. 47 (1-4), 1997, pp. 167–76.

[11] Wilson A, Pearsal N, Hill R., Installation and operation of the first city center PV monitoring station in the UK, *Solar Energy*, Vol. 59, 1997, pp. 19–26.

[12] Mukaro R, Carelse XF, Olumekor L., First performance analysis of a silicon-cell microcontroller based solar radiation monitoring system, *Solar Energy*, Vol. 63, 1998, pp. 313–21.

[13] Mukaro R, Carelse XF, A microcontroller-based data acquisition system for solar radiation and environmental monitoring, *IEEE Trans Instr Meas*, Vol. 48, 1999, pp. 1232–8.

[14] N. Forero, J. Hernàndez, G. Gordillo, Development of a monitoring system for a PV solar plant, *Energy Conversion and Management* Vol. 47, 2006, pp. 2329–2336.

[15] D. Thevenard, M. Ross, G. Howell, A Checklist for PV System Monitoring, CETC Number 1998-15-51/1998-04-07.

[16] J. A. Duffie and W. A. Beckman, Solar Engineering of Thermal Processes, *University of Wisconsin-Madison*, Ed.: John Wiley & Sons, 1991.

[17] Poulek V., Libra M., A very simple solar tracker for space and terrestrial applications, *Solar Energy Materials and Solar Cells*, Vol. 60, 2000, pp. 99-103.

[18] Libra M., Poulek V., Bifacial PV Modules in Solar Trackers and Concentrators Physical Methods in Agriculture, *Proceedings in International Conference, Kluwer Academic/Plenum Publishers*, New York, A., Prague, 2001.

[19] http://idrilab.diees.unict.it

[20] http://www.wisnam.com