



## WIRELESS ENERGY MONITORING SYSTEM OF PHOTOVOLTAIC PLANTS WITH SMART ANTI-THEFT SOLUTION INTEGRATED WITH CONTROL UNIT OF HOUSEHOLD ELECTRICAL CONSUMPTION

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*Submitted: Jan. 17, 2016*

*Accepted: Apr. 5, 2016*

*Published: June 1, 2016*

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*Abstract - This paper describes an intelligent system for monitoring photovoltaic plants, detecting thefts or malfunctions and optimizing energy production by algorithm to drive solar trackers. Sensing/processing board detects environmental parameters and calculates produced power/energy for monitoring efficiency while anti-theft system reveals any critical condition. Designed board controls biaxial trackers calculating sun position and following solar orbit to optimize energy production. Monitoring and anti-tampering systems communicate with PC or remote stations by wireless modules. Finally, wireless monitoring system of household facilities measures absorbed currents viewing consumption values on web-page. Depending on light/presence sensors, system can switch on/off monitored facilities obtaining energy savings.*

**Index terms:** Wireless monitoring of PV plants, Anti-theft system, PIC signals processing, Solar trackers, Household energy savings.

## I. INTRODUCTION

Technicians and engineers which manage plants, not only photovoltaic (PV) power plants but also, i.e. lighting plants are increasingly geared towards the improvement of customer service. New technologies and tele-control systems contribute to achieve this goal. In addition to get an effective solution in the prevention of faults and their quick correction, these new electronic systems constitute an excellent tool for cost control. Monitoring and control systems of PV plants, however, must be easy to use, quick to install and efficient. In the world of alternative energies, the need for a careful management of security and remote control of PV plants is becoming more pressing, especially when it concerns large photovoltaic systems often characterized by a lack of control being installed away from inhabited areas. In addition a PV plant is remunerated according to energy production, whereby it is fundamental to guarantee its monitoring by a tele-control system:

1. To keep the plant safe from thefts.
2. To be promptly advised as soon as there is an unjustified reduction of the energy production.
3. To view easily the acquired data, also remotely by internet network in an area dedicated to under-control plant.

Telecontrol systems use a monitoring software and integrate the capabilities of remote monitoring and fault reporting or tampering with user-friendly technologies (sms, email, web) [1,2]. All acquired information are stored locally on memory device and periodically sent to a server. Data and statistics can be easily available in graphic form on a web portal or directly accessible on site. Usually, various functional alarms are also implemented, which are managed by sms/e-mail to promptly initiate the needed maintenance.

In addition, there are different techniques for obtaining the maximum energy production from a PV plant; the main system that maximizes the efficiency is the solar tracker, an electro-mechanical device which is able to favorably move to solar rays the PV panels. The main purpose of a tracker is to maximize the efficiency of the device hosted on board [3,4]. In a PV field, the modules installed on a tracker are usually arranged geometrically on a single panel/string in order to avoid the use of a tracker for each module.

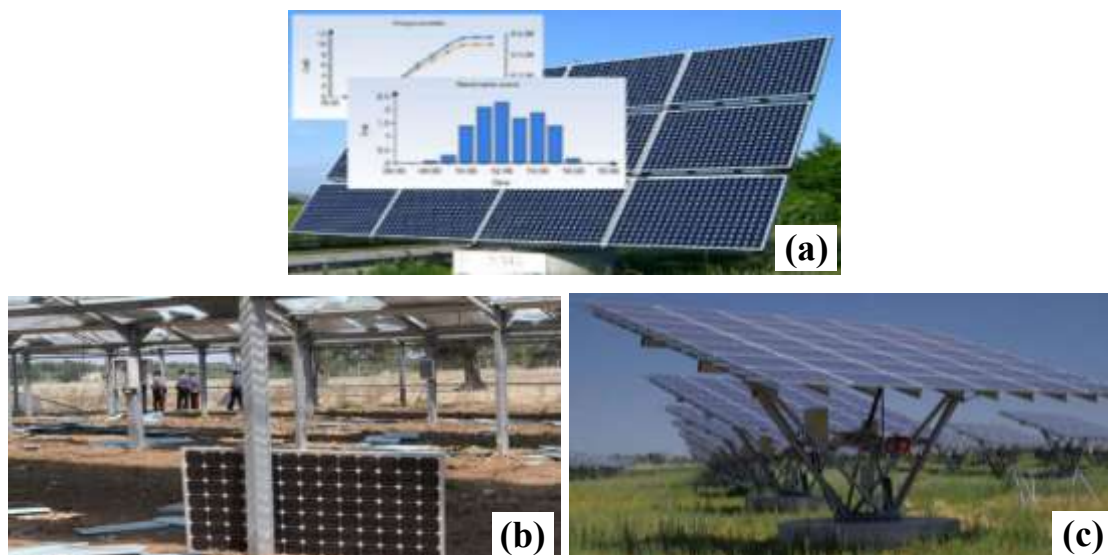


Figure 1 Example of PV string and screenshots of graphs or histograms obtained by monitoring software (a); Police intervention after theft of PV panels and consequent visible damages (b); PV plant with bi-axial solar trackers driven by the realized control equipment.

Regarding monitoring systems of operation or productivity related to the PV-solar thermal or wind plants, as well as power consumption optimization of household facilities, several research works have been conducted. Prieto et al [5] presented a wireless sensor network (WSN), powered with all other components from the same PV panels, for real-time monitoring of efficiency, features, failures and weaknesses from a single cell up to the whole plant. Ng et al [6] assessed the effects of the solar radiation on diversely oriented surfaces and optimum tilts for solar absorbers. Bertoldo et al [7] designed a WSN for anti-theft alarm system; each node was installed under each PV string and equipped with an accelerometer sensor for detecting a minimum displacement of PV panel from its steady position. Ando et al [8] realized a solution for automatic estimation of efficiency losses of PV modules and related causes based on a WSN that allows to monitor efficiency, to provide data useful to investigate on causes of efficiency losses and to detect events related to attempts of theft. Han et al [9] presented a smart home energy management system, based on ZigBee and PLC, for managing energy consumption and generation by renewable source. At last, Boonsong et al [10] presented a wireless monitoring system of household consumption based on RFID and WSN technologies.

## II. PROGRAMMABLE SYSTEMS FOR REMOTE MONITORING OF PV PLANT, PANEL ANTI-THEFT AND DRIVING OF SOLAR TRACKERS

The designed monitoring system, using dedicated sensors, RS232/RS485 connections and/or WiFi radio modules, ensures high efficiency and functionality by communication from/to a

supervision center located on plant (local management) or in remote location (web management). Given the continuous growth of PV installations, it has been identified the need to design and implement a PIC-based system able to acquire voltage and current from many PV strings, to measure environmental parameters such as temperature and solar radiation and to calculate average power and energy produced by the plant, so that the power production can be monitored, both locally and remotely [11]. The control board CS097, despite having all current and voltage transducers installed on itself, was designed with the smallest possible size. The functions of acquisition, power calculation and communication with external devices are managed and executed by on-board microcontroller. The acquired and processed data are transmitted to connected PC via RS485 interface or to remote stations by radio modules [12-17].

Parallel to the development of PV market, has also grown the annoying problem of solar panels theft, mainly because of their relatively high cost and location of these plants, usually placed in remote and poorly protected sites. In order to prevent the theft of PV panels, many companies have stepped forward on the anti-tampering systems market, proposing many alternatives. The proposed system, composed of CS083 and CS088 electronic boards, is an alarm system which indicates a dangerous situation when electrical continuity between the PV modules is interrupted or string voltage presents a not-justified rapid variation due to bypassed solar panels. Such electronic system provides a control over PV strings voltage both during the day, distinguishing in this case a condition of maximum solar radiation from a condition of partial or full shading, and at night during which there is no exposure to light. Evaluating detected values of the string voltage, the system is able to establish, with the help of a programmed PIC, if there is a critical situation due to a sudden drop of electrical potential, thus generating an alarm condition, or if the lowering of string voltage was caused by a decrease of solar radiation. In this situation, it was observed that shape of string voltage curve is characterized by a progressive, and not sudden, reduction, index of a correct operation of the PV plant and not a critical condition of theft [7,8].

With the aim of maximizing the efficiency of a PV plant, the control board CS012 has been created. In particular, an algorithm, implemented in a biaxial solar tracker, can instantly calculate the sun position at the latitude and longitude of the installation site. The algorithm can drive up to two engines which are able to change the position of a solar panel, in order to increase its efficiency, for tracking the sun in its movement from east to west (azimuth motion) and in its elevation up to solar noon (tilt motion) [18]. The whole system is adaptable to various types of structures as it involves a cycle of self-learning of the structure and thus

adaptation of calculations to the tracker on which it is installed. The block diagram of a PV plant with designed remote control/monitoring system, the alarm anti-theft device and the solar trackers is illustrated in Figure 2.

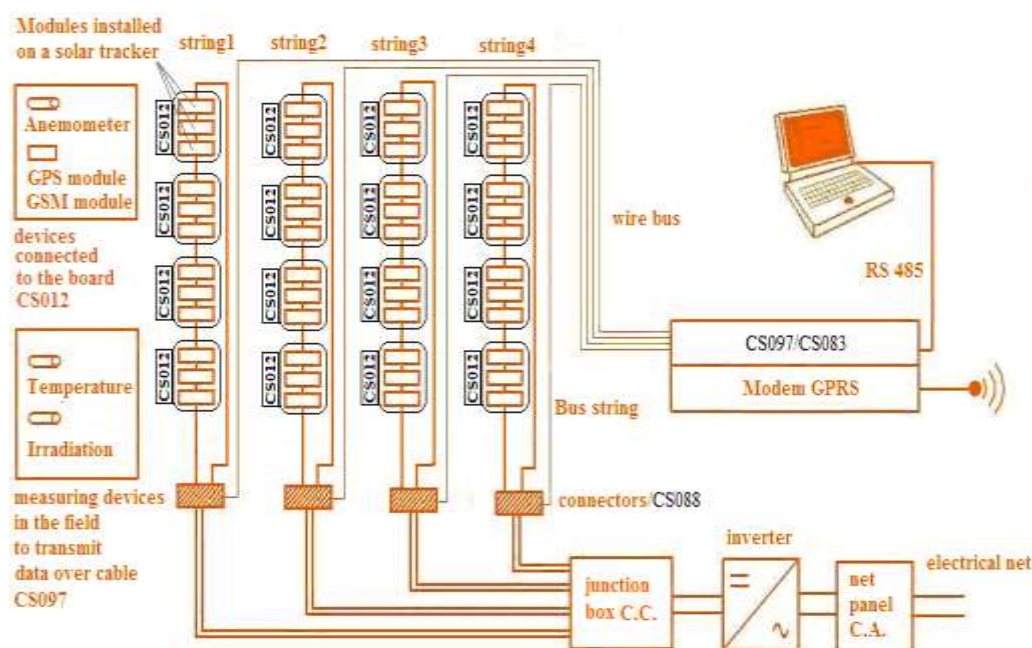


Figure 2 Block diagram of a photovoltaic system with remote control (CS097), alarm system (CS083-CS088) and solar trackers (CS012).

The CS097 sensing/processing (S/P) electronic board is capable of controlling up to four photovoltaic strings, acquiring current and voltage from each of them. Current and voltage transducers detect currents not exceeding 20 amperes and voltages lower than 1000 V. Since this electronic board is not a real measuring instrument but only a device to control the trend of electrical parameters, it shall not require great accuracy for data acquisition; however, acquired data have a maximum error of 1% compared to real values. Galvanic isolation is provided between the input current/voltage DC signals and detecting/acquisition and processing circuits. CS097 S/P board also detects two signals from temperature sensor and pyranometer positioned near the PV field in order to evaluate the expected energy starting from the information on panel temperature and solar energy that actually reaches the solar panel. Since the supervision center can be located on PV plant or in remote location, CS097 board is equipped with RS232-RS485 outputs and/or GSM/WiFi radio module. Aside from connection in real time, it's always possible to consult the historical archives of monitored data on a daily, weekly, monthly basis [19-22].

In addition to the acquisition/processing unit of electrical and environmental parameters, it's possible to install the anti-tampering system, consisting of CS083 and CS088 boards. CS083 board is the basic element for data acquisition, processing and generation of any alarm signal

in presence of a critical condition. The PIC runs a set of inputs, including signals from the CS088 acquisition board connected to the PV strings. This board has the function of transduction: voltage signal from PV string is translated and adapted in voltage values suitable to be interpreted and processed by the PIC-based CS083 board [7,8,23].

In addition, the CS012 board drives two motors (tilt and azimuth engines) capable of orienting a PV string for tracking the sun in its movement from east to west (the azimuth motion) and in its elevation up to solar noon (tilt motion). Using an anemometer, the whole structure is protected from sudden gusts of wind, disabling the panel's movement. It is connected to a GPS position detector that provides the latitude and longitude of the installation place of the structure and to GSM/WiFi communication modules to transmit any alarms or system malfunctions [3,4,24].

At last, the realized system has been integrated with a designed unit for the reduction/optimization of power consumption in domestic environment. The designed board can be connected to ac outputs of PV plant's inverter and remotely accessing to web page by means of WiFi module, the user will monitor, in real time, not only the PV energy production but also the consumption and energy needs of household appliances for obtaining better systems integration and consequently higher energy savings [25]. The realized unit is capable to monitor real-time the energy consumption of one or more electrical loads (appliances, lighting units) and their operation mode directly from PC or wirelessly via tablet or smartphone. Moreover to PCB's digital inputs are connected presence and/or brightness sensors for avoiding energy waste in case the room lighting is not necessary because there aren't people inside or simply the natural daylight is sufficient (Figure 3).

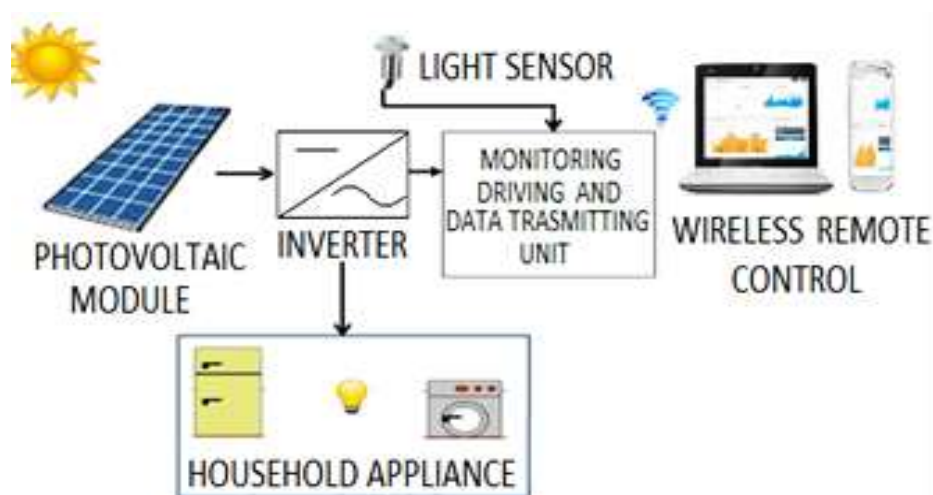


Figure 3 Remote wireless monitoring, by means of tablet/smartphone connected to internet web page, of electrical energy produced from domestic PV plant and its integration with household appliances.

a. Block diagram of data Acquisition Board

In Figure 4 is shown the block diagram of CS097 S/P board; the heart is a microcontroller Microchip PIC16F887A which, suitably programmed, performs different tasks independently. Essentially, it manages input and output lines according to the program (firmware) implemented in it. CS097 board is also provided with RS-485 and RS-232 interfacings and with communication port for MPLAB REAL ICE, respectively to transfer out the outgoing data from PIC16F887A and to program its MCU. The microcontroller will handle input signals from temperature and radiation sensors and the outputs of four current transducers and four voltage transducers installed on the same board.

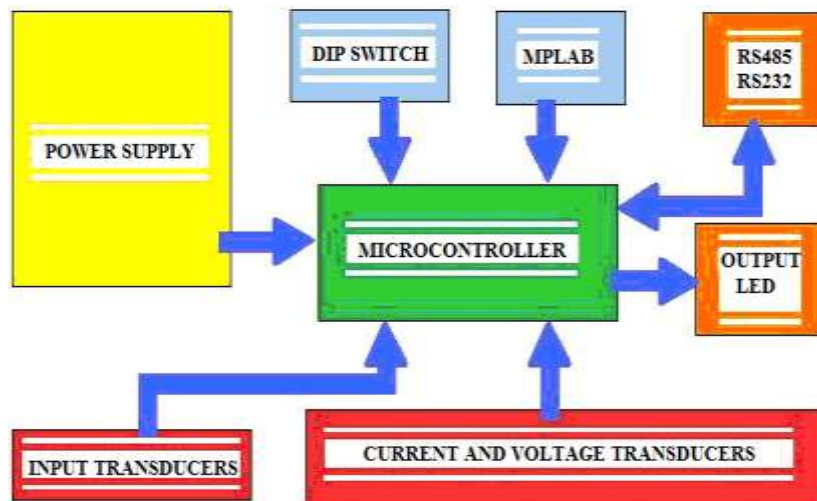


Figure 4 Block diagram of data acquisition board CS097.

A DIP switch will allow the technician, when the board will be installed in the PV plant, to configure the CS097 with the right parameters related to the specified plant. Two led show the execution of any instruction by the microcontroller. The CS083 block diagram is similar to that of CS097 electronic board.

b. Block diagram of the transduction board

The CS088 electronic board was designed and built for detecting DC voltage and current values generated from PV strings. Aboard the CS088 transduction device, therefore have been used two current transducers and two voltage dividers, suitably sized to receive input voltages from 0 to 1000V (maximum voltage produced by a string) and to reduce this values to  $0 \div 0,2V$  range. Downstream of the voltage dividers are in fact installed opto-couplers with input voltage range  $-0,2 \div 0,2 V$ . The output signals of CS088 electronic board, before sending to the PIC of CS083 processing board, are filtered by RC circuits specifically designed to reduce the noise. The Figure 5 shows the block diagram of transduction board CS088.

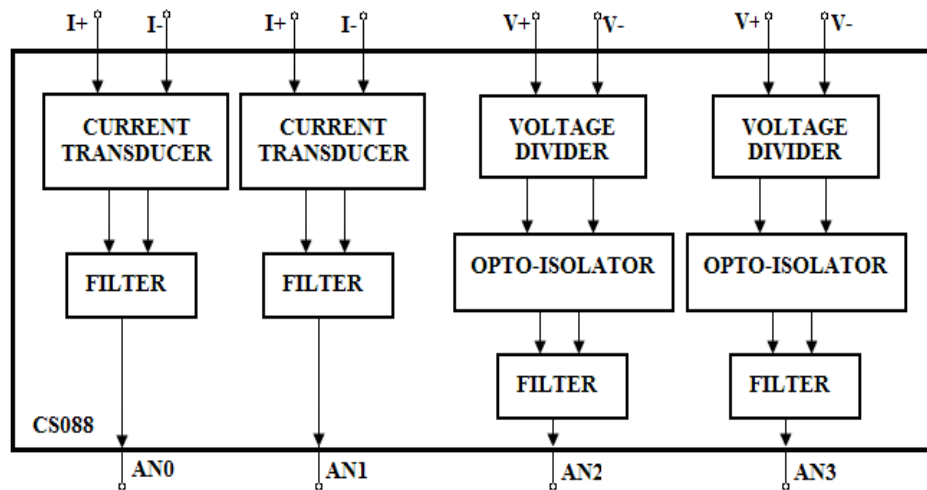


Figure 5 Block diagram of transduction board CS088.

c. Circuital sections of designed transduction and data acquisition boards

As shown in Figure 6, the voltage transducers are simply linear opto-couplers connected downstream of voltage dividers, necessary to reduce the maximum range of input voltage (0 to 1000V) to values accepted from opto-coupler (0 ÷ 0,2 V). The opto-coupler is an electronic component that allows to transfer a signal between two circuits keeping the galvanic isolation between them: it is made usually optically coupling a LED with a photosensitive element. The brightness variations of LED related to the input signal are detected by photosensitive element obtaining the information transfer from one circuit to another without being electrical continuity. The opto-couplers are used in all cases in which, for reasons of safety or circuital specifications, it is necessary to keep electrically separated two circuits, for example in case of digital control systems from the power section, in the input circuits of PLC and in some switching power supplies.

The resistors R4 and R5 were calculated taking into account the power dissipation given the wide range of transduction from 1000 V to 0.2 V. The other side of opto-coupler is galvanically isolated from voltage supplied by PV string and it is connected to input AN1 of A/D converter, through a low pass filter. The low pass filter, whose task is to eliminate any fast changes of the signal or possible noise superimposed on the useful signal, is designed to have a cutoff frequency of 15Hz.

Also the output signals from the four current transducers pass through the RC low pass filters with a cutoff frequency of about 15 Hz (Figure 7). The used Hall effect current transducers, model LEM HP 20 Amperes, present within a copper conductive path ensuring galvanic isolation between primary and secondary circuit.



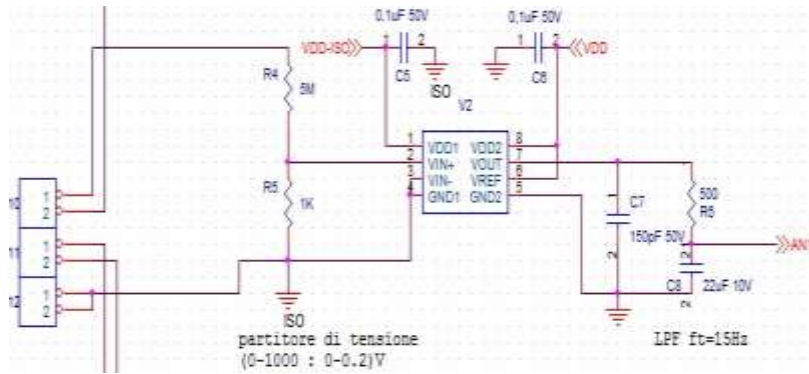


Figure 6 Circuitual schemes of voltage transducer and interfacing with PIC input.

The current applied to input, flowing through this copper path, generates a magnetic field that is sensed by Hall sensor and converted into a voltage proportional to detected current. In this way, the downstream electronic board will process voltage signal concerning high current generated by PV string.

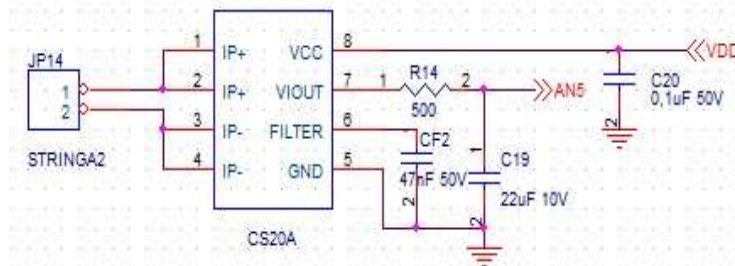


Figure 7 Circuit diagram related to the interfacing between the current transducer and the PIC.

The JP7-CH0 and JP6-CH1 inputs in Figure 8 are used to interface the CS097 board with any other device, such as temperature sensors and pyranometer. The analogue signals from sensors are converted into digital signals by the U6 IC A/D converter. The communication between the ADC and microcontroller on the CS097 board is implemented through the PIC16F887 SPI serial interface.

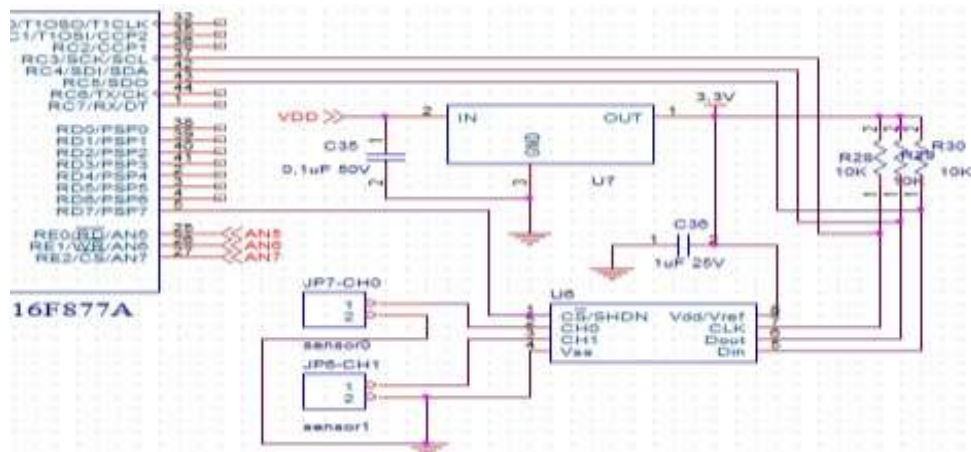


Figure 8 Circuitual scheme relative to the interfacing between the temperature sensor, pyranometer and the PIC.

With regard to the digital output for alarm signal, a output pin of the PIC is used in order to report any alarm conditions when it is led to the high logic level. In this case, the PIC digital output, through a resistor suitably sized, biases the base of transistor BJT bringing it into saturation. So the current, flowing into BJT ON, determines the lighting of a green LED and the switching of a relay which normally operates in open mode. The relay has the task of activating the alarm signal when it receives from PIC the input relative to the tampering of controlled system (in this application the monitored PV plant), by switching itself from the normally open state to the closed state and so doing trigger the alarm signal.

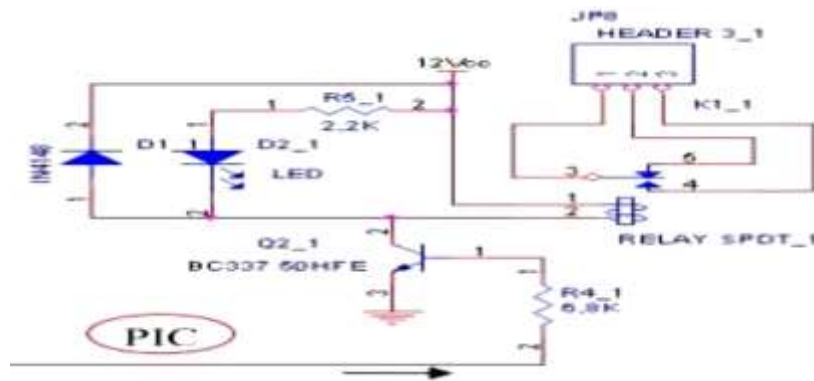


Figure 9 Circuitual section of CS097 acquisition/processing board relative to digital output of the PIC for signalling any alarm conditions concerning the PV plant operation.

d. The driving board of solar trackers

A simplified block diagram of the electronic system that implements biaxial solar tracker is shown in Figure 10. A picture of CS012 electronic board, the heart of system, is shown in Figure 11 and its simplified block diagram in Figure 12. The realized board drives two motors (tilt and azimuth engines) capable of orienting a PV panel/string for tracking the sun in its movement from east to west (azimuth motion) and in its elevation up to solar noon (tilt motion). Using an anemometer, the whole structure is protected from sudden gusts of wind, disabling the panel's movement. CS012 board is connected to a GPS detector that provides latitude and longitude of installation place and to a GSM/WiFi communication module that transmits alarms or system malfunctions. The board's heart is the Microchip PIC16F876 in which the algorithm for calculating the sun position is implemented. The board is also equipped with a stabilized power supply circuit, the RS485 data port to interface it with an external PC (in order to program the PIC using MPLAB programmer), four configurable limit switch inputs and two power outputs in order to drive the engines [26].

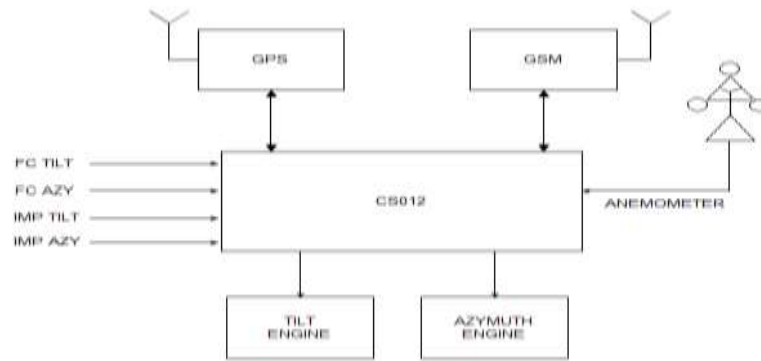


Figure 10 The block diagram of realized solar tracker driving unit.

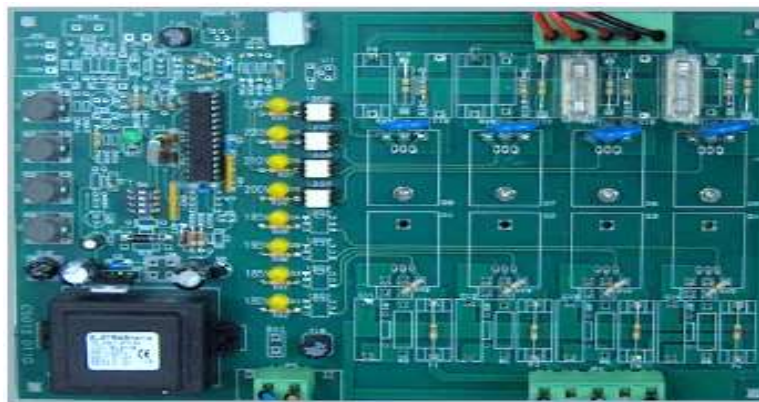


Figure 11 The electronic board CS012 implemented in SMD technology.

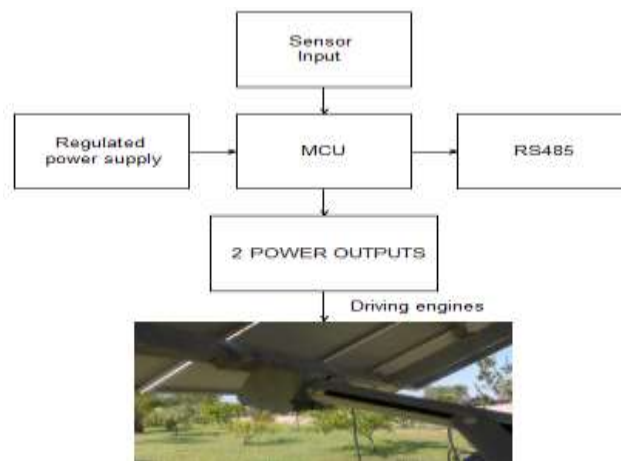


Figure 12 Block diagram of CS012 electronic board.

### III. DEVELOPMENT OF THE FIRMWARES

In this section, we have analyzed the firmware algorithms implemented in CS097 data acquisition board, in the CS083 alarm anti-theft unit and in CS012 electronic control/driving board of the solar trackers; for developing the firmwares, we used the C language and development environment Microchip MPLAB IDE. The tool used for programming and debugging microcontroller’s firmware is Microchip MPLAB Real ICE In-Circuit Debugger and Programmer.

a. Firmware development of data acquisition board

In Figure 13 is shown the block diagram of the firmware implemented in the data acquisition board CS097 for monitoring the PV plant. As soon as power is supplied to the board, the firmware initializes the state variables and prepares the device for signals acquisition, their processing and transmission of processed data. After this operation, through a loop, signals are read from voltage and current transducers connected to analogue inputs of the PIC. These signals are filtered through a digital filter F.I.R. (*Finite Impulse Response*) designed specially, by Matlab software, for reducing noise present on the electrical signals. Once that 30 samples of current and voltage are acquired, with a given sample rate and filtered, the algorithm proceeds with the calculation of produced power/energy. The solar radiation and PV panel temperature are detected in order to check if the monitored plant is working properly; if the plant performance is satisfactory, the acquired and processed data are sent wirelessly to a remote station, otherwise a warning signal is generated and sent to the technicians for activating quickly a maintenance operation.

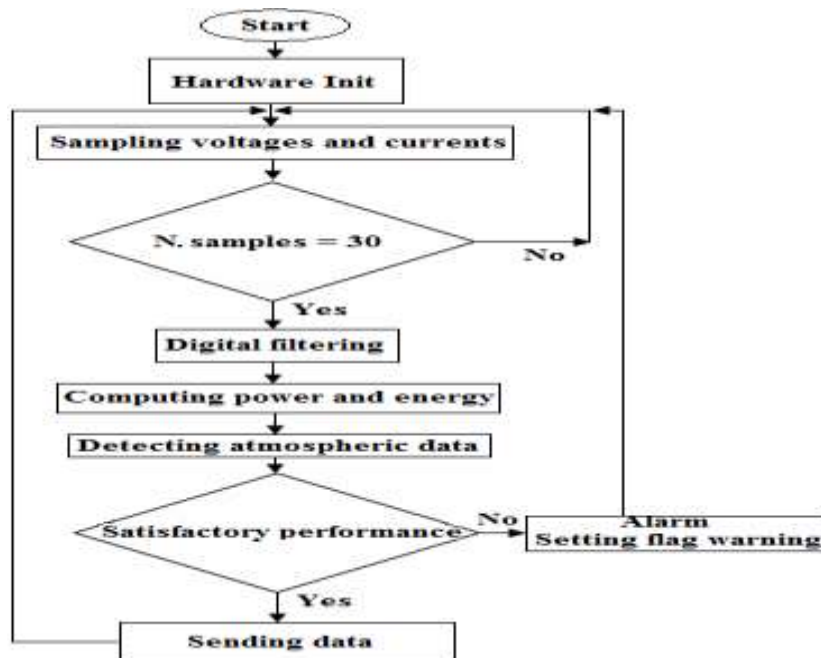


Figure 13 Block diagram of firmware for data acquisition board CS097.

b. Design of the digital filter

A stringent specification is required for the digital filter with the smallest possible transition region; thus the designed filter will be close to ideal one as possible. The purpose of filtering is to eliminate frequency components above 15 Hz as efficiently as possible. For these reasons, we used a rectangular window filter; the disadvantage of this filter type is the high

over-elongation peak which results in poorer accuracy. The low pass digital filter dampens the higher frequency components of input signal by means of frequency by frequency product between input signal spectrum and transfer function. This may seem like a problem because the microcontroller does not work with the Fourier transform of the sampled signal, but only with a sequence of samples, that is the digital signal expressed in the time domain. To overcome this obstacle, it is necessary to think exclusively in time domain; thus PIC acquires the signal samples on every sampling period, keeps them temporarily in memory until they reach a suitable numbers ( $M$ ) for easily processing with the impulsive response of the filter previously saved in the memory. The specifications of the designed filter are:  $M=18$ ,  $p = f_p/f_{\text{sampling}} = 15\text{Hz}/100\text{Hz} = 0.15$ , rectangular window. By running the code created by MATLAB 7.6, the impulsive filter response is obtained together with a filter's graphical representation in time and frequency domain as shown in Figure 14. The developed digital filter provides clearly oppressive performances already at frequencies greater than 21Hz so being able to eliminate rapid changes in time-domain signal attributable to noisy phenomena.

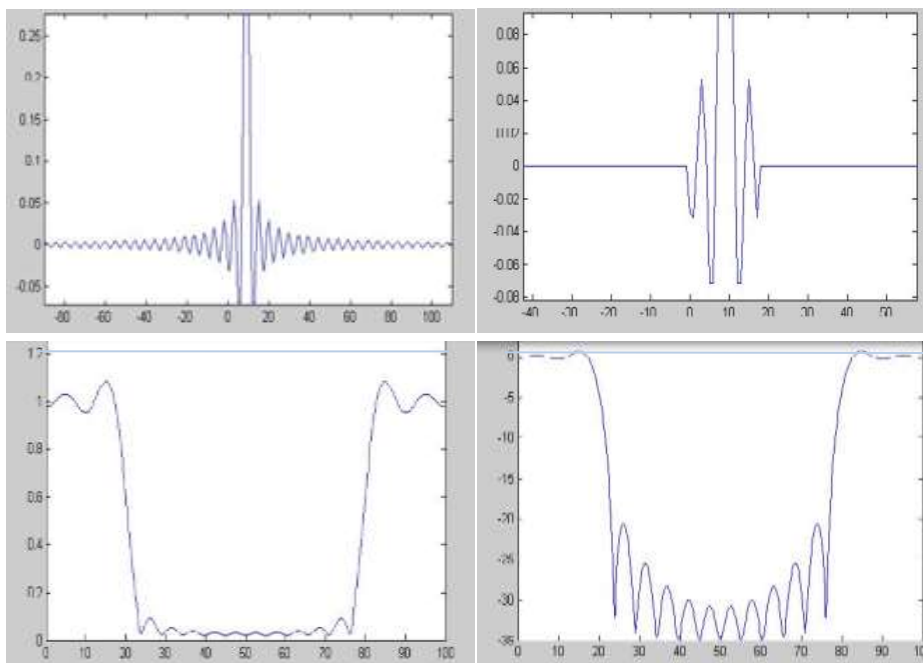


Figure 14 Clockwise: Ideal filter's impulsive response; real filter's impulse response; frequency response of the real filter, in decibels and in amplitude.

### c. Firmware development of alarm anti-theft system

In Figure 15 is shown the block diagram of implemented firmware in the PIC of CS083 board. The programmed PIC reads the voltage values detected from PV strings under control and compares them with a threshold value  $V_{\text{THR}}$  (determined on the basis of results obtained after

careful analysis of the functioning of PV modules in the two different temporal conditions and depending on PV panel model and size of the PV string) in order to determine night or day condition. Then the different functioning mode depending on the temporal condition (night or day) can start; if the read value is below the  $V_{THR}$  voltage, the system interprets it as absence of solar radiation, activating the nightly mode of analysis and action. In this case, the PIC calculates  $Z_{STR}$  string impedance and compares it with  $Z_{STRTYPICAL}$  typical impedance of the PV string; if  $Z_{STR}$  impedance is different from  $Z_{STRTYPICAL}$ , then the PIC activates an alarm output. If the comparison indicates a value above the threshold voltage, the modules surely work in lighting conditions, even partial, so it is possible to initialize the part of program that manages the day operating mode. In this case, the microcontroller runs an algorithm that evaluates the rate of change in the string tension rather than its lowering, since the string voltage levels during the hours of solar irradiation are very high (hundreds of Volts) and the deactivation of just a single module would result in a negligible voltage drop not easy to identify.

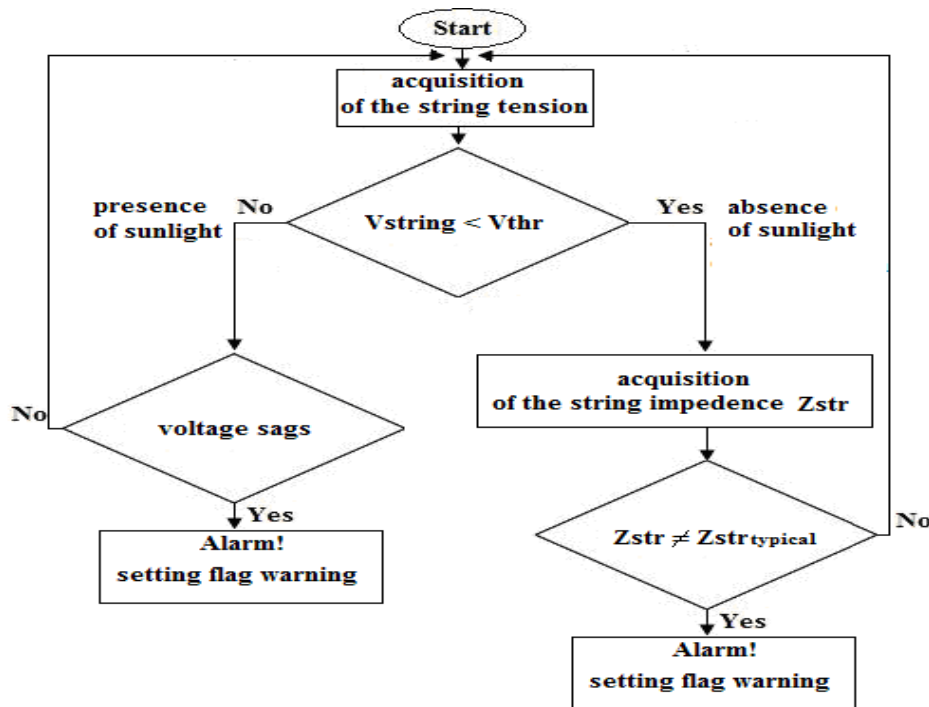


Figure 15 Block diagram of firmware for alarms control boards CS083-CS088.

d. Firmware development for the solar tracker system

In this section is reported the flow chart (see Figure 16) relative to PIC's operations of electronic board that drives the engines of the solar tracking system. After preliminary phase of GPS coordinates acquisition (latitude and longitude of the installation site) and self-learning of the structure parameters, there's the acquisition of current time and check if it is

greater or less than sunrise time. The process continues with the calculation of daily parameters such as solar declination, equation of time, etc., necessary for calculation of  $\alpha$  (sun's height) and  $\gamma$  (azimuth angle) angles relative to sun position. Then there is the execution phase of two engines and the check if sunset time is reached. If so, before returning to the acquisition time step, there is the east positioning of the PV structure.

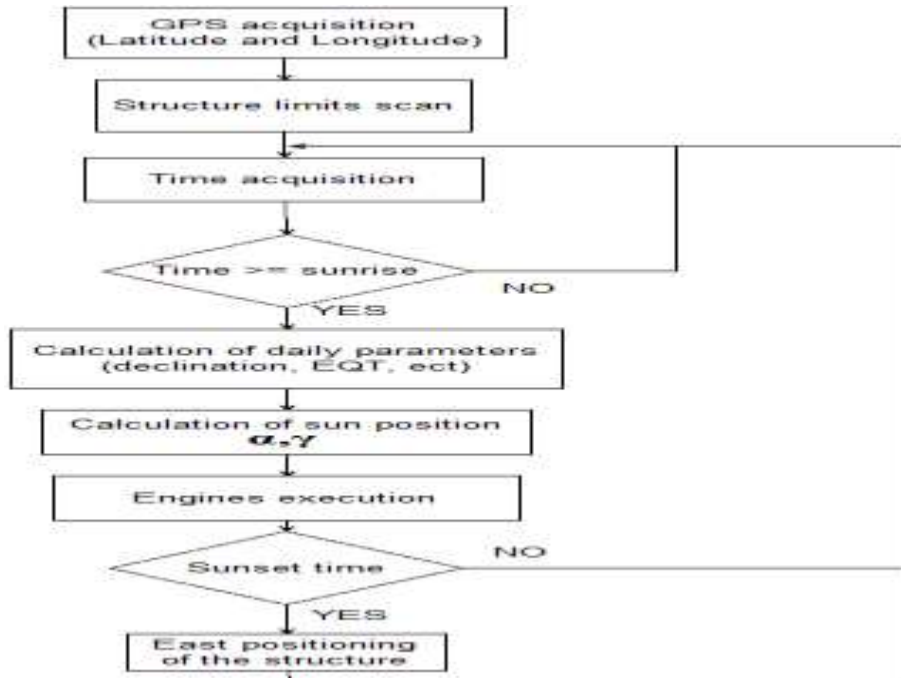


Figure 16 The flow chart of solar tracking system.

e. Calculation of the sun position

The sun position, in a reference system, relatively to a point on Earth is given by solar height angle  $\alpha$  (formed by solar rays direction with the horizontal plane) and azimuth angle  $\gamma$  (between projection on the horizontal plane of solar rays and the south); this last can vary between  $0^\circ$  and  $\pm 180^\circ$  and is positive if projection falls to east (before solar noon) and negative if projection falls to west (after noon). These two angles depend on declination of solar rays  $\delta$ , latitude  $\varphi$  and hour angle  $\omega$ . The declination  $\delta$  is the angle formed by solar rays inclination and the equatorial plane; the latitude  $\varphi$  is the angle between the line joining the observation point and equatorial plane whereas hour angle  $\omega$  is the angle between the projection of the line joining the centers of gravity of the sun and the Earth on the equatorial plane and the reference (Greenwich) meridian. Thus the instantaneous sun position is determined by following formulas:

$$\text{Solar angle (or solar height or Tilt): } \alpha = \arcsin(\sin\delta \cdot \sin\varphi + \cos\delta \cdot \cos\varphi \cdot \cos\omega) \quad (1)$$

$$\text{Azimuth angle: } \cos\gamma = [\sin\alpha \cdot \sin\varphi - \sin\delta] / (\cos\alpha \cdot \cos\varphi) \quad (2)$$

In order to calculate the sun position on a day  $n$  at hour  $h$  is necessary to know the latitude and longitude of the installation site of PV plant; these data have to be inserted from technicians or acquired from GPS unit for configuring the system so that it is able to track rightly sun orbital every moment of any day of the year.

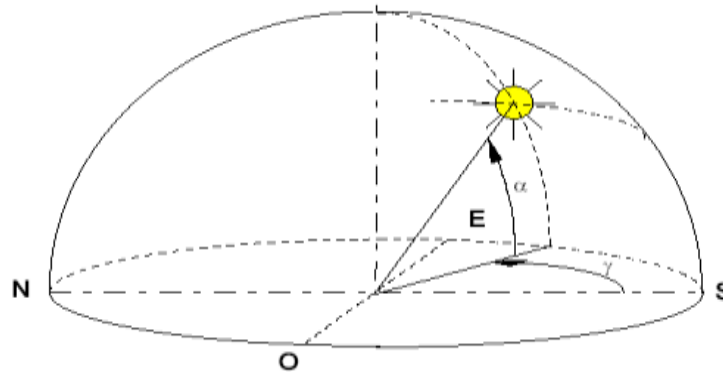


Figure 17 Solar height angle ( $\alpha$ ) and azimuth angle ( $\gamma$ ) .

#### IV. WIFI MODULE FOR MONITORING THE HOUSEHOLD ELECTRICAL CONSUMPTION AND DESIGN OF WEB PAGE FOR INTERNET REMOTE CONTROL

With the aim of reduction of household energy waste, the designed system has also the functionality of wireless monitoring of household appliances and facilities by using the *Open Picus FlyPort WiFi* module, chosen after careful research having required and necessary technical features and being cheaper and simpler to use respect to other similar devices. Also it is open source and without additional development costs allowing us to reduce the necessary time and costs; the Microchip certified TCP/IP stack is already loaded in the embedded PIC and so you don't need to set and load the data relative to WiFi communication protocol. *Open Picus FlyPort* board is powered by DC 5V supply voltage while PIC and embedded WiFi module need power supply of 3.3V got by using LT1117 voltage regulator. Thereby user needs only to be connected to home WiFi network and through a web browser to access the realized web page for adjusting the operation mode of controlled household facilities or simply viewing how much is consuming each monitored electrical load.

In the figures 18 and 19 are shown the *Open Picus FlyPort* board and its block diagram with the Microchip 24FJ256GA106 PIC and Wi-Fi Microchip MRF24WB0MA chip. This smart board can be used in several applications (wireless sensors network, Internet of Things, data communication security and automation); in our work, the PIC reads data from connected sensors and the processed data are sent to a remote web server by email or to web server located in memory of the PIC itself.





Figure 18 Open Picus FlyPort board with embedded the WiFi module.

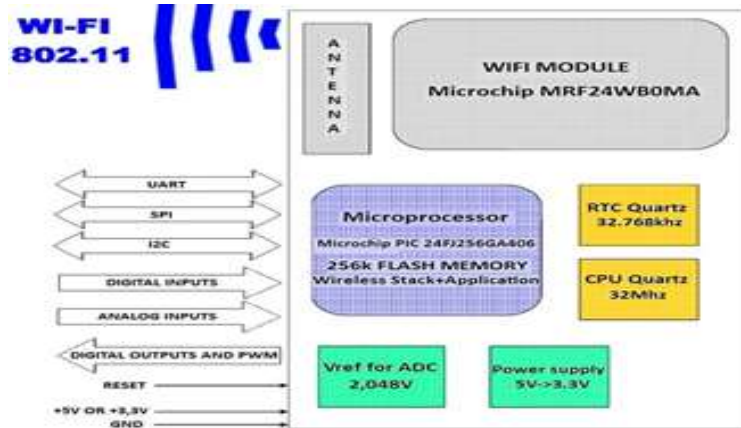


Figure 19 Block diagram of Open Picus FlyPort board with Microchip PIC 24FJ256GA106 and WiFi MRF24WB0MA chip.

The Microchip MRF24WB0MA chip, whose block diagram is shown in figure 20, is a low-power transceiver compatible with standard WiFi 802.11 b/g/n, connected to PIC by UART interface with integrated a PCB antenna with RF distance range of 400m. All RF and base band components and the 802.11 medium access control (MAC) layer are embedded into the WiFi module thereby creating a simple and convenient technical solution to add the WiFi connectivity to the designed electronic control system.

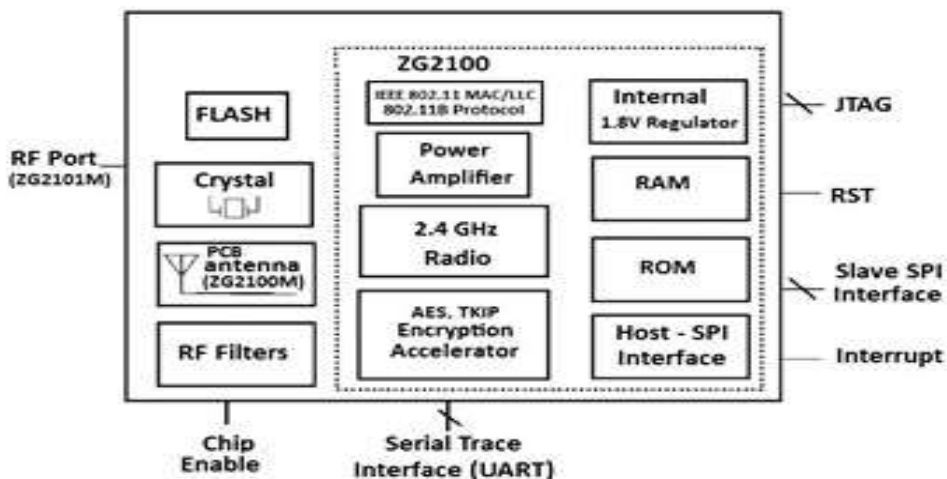


Figure 20 Block diagram of the WiFi Microchip MRF24WB0MA module embedded into the Open Picus FlyPort board.

Open-Picus FlyPort board is a stand-alone system; it incorporates the TCP/IP stack to control WiFi module and can be programmed in order to make proper actions as control of devices or actuators, reading of digital and analog inputs, communication with external devices through UART, I2C or SPI serial mode.

In figure 21 is shown a screenshot of web page realized with dedicated NVU software; two buttons are used to turn on/off the electrical loads connected to monitoring/driving board while two LEDs display the loads' state (on/off) and other two LEDs the logic level of digital inputs (infrared presence/movement detector or lighting sensors). By processing of absorbed current data, real-time calculation and viewing of the instantaneous active power (W) and total consumed energy (Wh) from monitored loads (in our laboratory tests, traditional lamps or LEDs) are performed. Many functions of household appliances or lighting facilities can be set from web page; in conclusion, by logging on to web page via a PC or tablet / smartphone, the user will monitor domestic energy consumption and regulate the operation of lighting systems for energy savings and user satisfaction for the better quality of life.



Figure 21 Screenshot of realized web page in order to switch on/off the connected electrical loads and view, after current data processing, instantaneous active power (W) and overall consumed energy (Wh).

## V. LAYOUT AND ASSEMBLING OF THE ELECTRONIC BOARDS

Using a dedicated program, OrCAD Capture, starting from schematics, the components of designed boards were positioned in order to use in the best way the available space. The connectors are positioned on the side of board to facilitate links with the external devices (PV strings, temperature and solar radiation sensors, pyranometer, communication ports, PC for data storage, radio modules, power supply, etc.). In Figure 22 is illustrated the layout of the PCB CS097 with routed links; sections related to 230V power supply has tracks greater than

the rest of circuit to avoid overheating damage. After making all the routine checks to ensure that each step was successful, without having left out any part from board or tracks that overlap, Gerber files were generated necessary for SMT-based PCB realization.

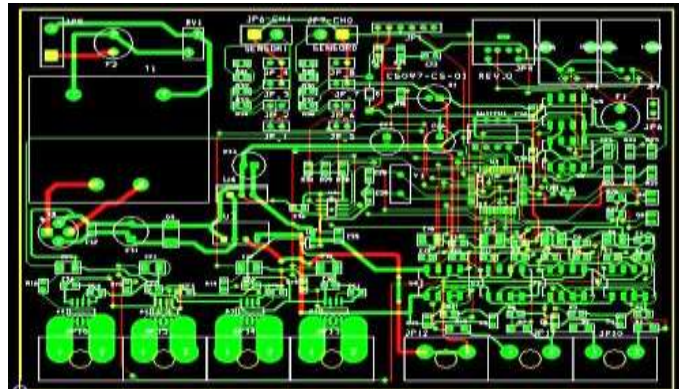


Figure 22 The master of the board CS097 after routing traces.

Figure 23 shows the realized CS097 PCB composed mostly of SMT components (before mounting of them) whereas the finished CS097 S/P board is shown in figure 24 after mounting of the SMT and through hole components.

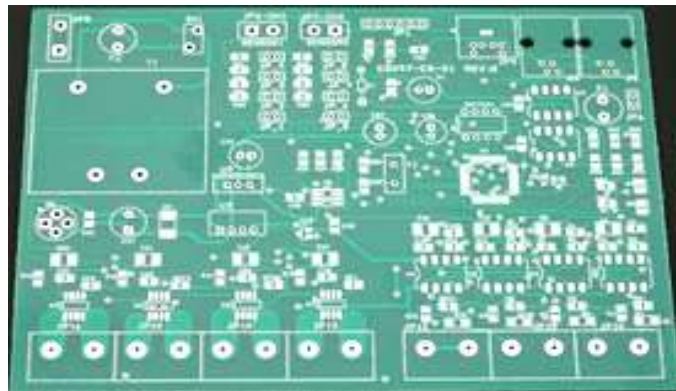


Figure 23 Designed Printed Circuit Board CS097 before mounting of the SMT components.



Figure 24 Photo of the CS097 realized electronic board, for acquisition / processing of PV plant data, after the mounting of SMT and through hole components.

In Figure 25 is shown an example of the manufactured control panels (marketed by Cavalera company) with embedded the anti-theft circuitual section, the conductive bar for parallel connection of PV strings, the blocking diodes and fuses for protection of PV strings.

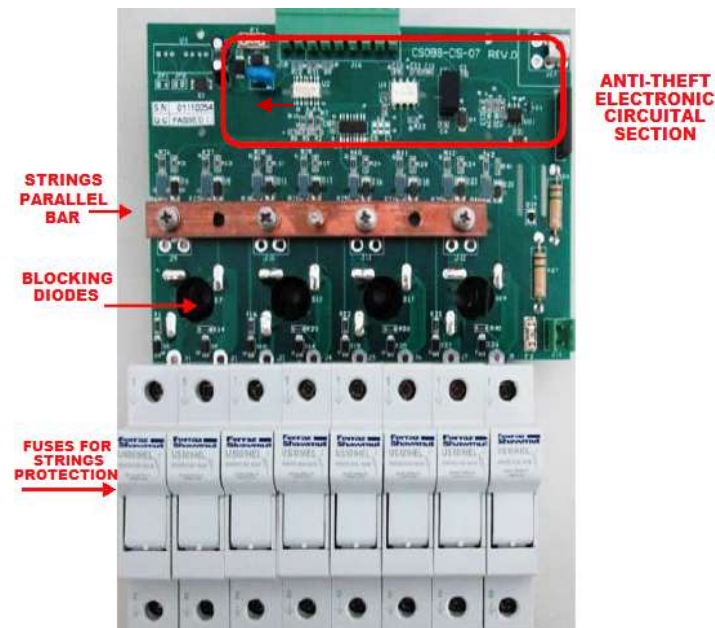


Figure 25 Photo of realized completed board installed on field with anti-theft circuitual section, the conductive bar for parallel connection of PV strings, blocking diodes and fuses for protection of PV strings.

## VI. EXPERIMENTAL TESTING AND RESULTS

In this section we present the experimental results of electrical tests carried out on field by using the designed and manufactured electronic systems.

After performing the electrical testing of S/P CS097 PCB, the first on-field test has concerned the monitoring of grid connected PV plant installed on the roof of Cavalera company (shown in Figure 26a). This three-phase PV system has three inverters Fronius IG30, one for each phase and string; regarding division of PV modules into strings, two inverters detect DC current/voltage of two PV strings, each consisting of twenty PV modules manufactured by Helios Technology (model H1540 135W) and the third inverter operates on string of eighteen PV modules. The monitoring experimental tests were carried out in different conditions of solar irradiation, so as to analyze the plant operation in both day and night modes. As shown in Figure 26b, the complete system, equipped with transduction/ acquisition and processing boards, is connected to PV string consisting of 18 modules, after disconnecting it electrically from downstream circuit through the corresponding protection breaker placed in the string control panel.

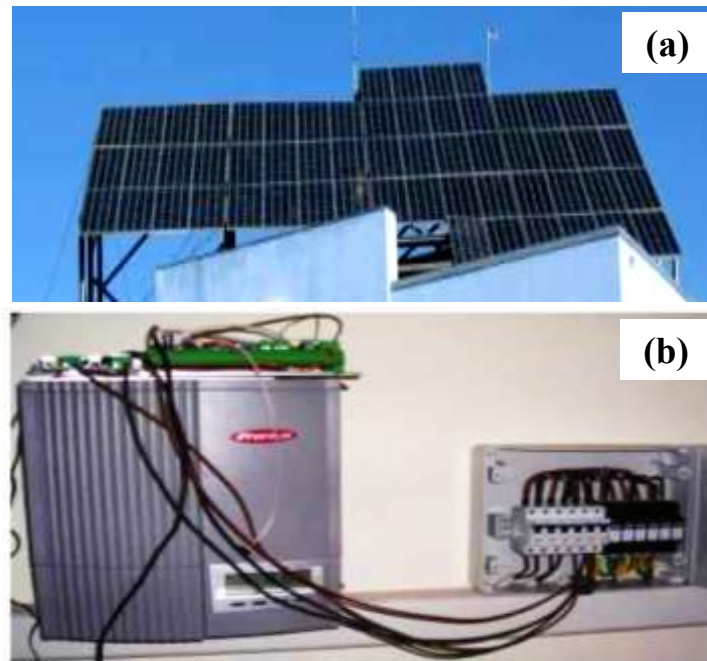


Figure 26 Photo of the monitored PV plant installed on the roof of Cavalera company (a); experimental setup with CS097 S/P electronic board and alarm anti-theft electronic unit connected to PV string (b).

Figure 27 shows an enlargement of the curve relative to DC voltage samples (one each two seconds) acquired from PV string during a short time interval of the morning with light irradiation variable due to fast sun covering for the clouds. The detected voltage generated by the string increases progressively, with enhancing solar radiation, varying in the range [270-310] V in this short interval of ten minutes. In order to verify correct operation of acquisition board of DC voltage/current values, with the aid of high precision calibrated voltage meter, simultaneously, voltage values supplied by PV string have been measured and recorded, and then compared with those detected by acquisition board, finding out a difference less than 1%.



Figure 27 Plot, as function of time, relative to DC voltage samples acquired from PV string during a short time interval of the morning.

Figure 28 shows the time-domain diagrams of the instantaneous power (Figure 28a) and total energy (Figure 28b) detected on a PV string, during three consecutive days with different climatic conditions, using the CS097 data acquisition/processing board. The continuous variations of PV plant's calculated power in Figure 28a are due to changes in the weather conditions while the night-time is obviously characterized by no power and energy production. As it can be seen from the second graph (Figure 28b), the total energy produced by the PV string during each day is greater in the third day characterized by a clear sky.

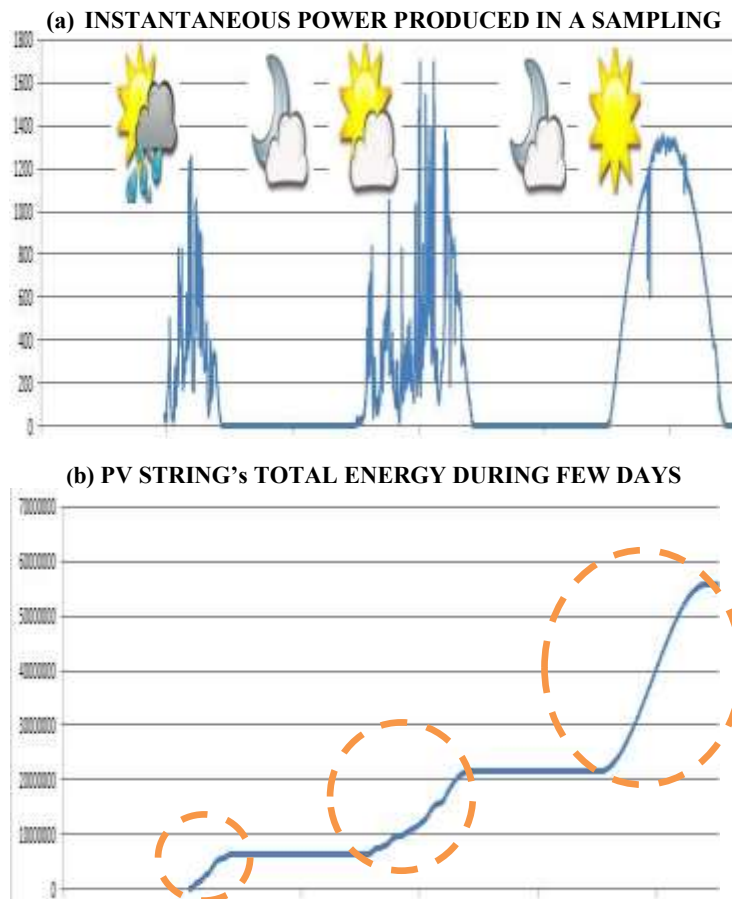


Figure 28 Time-domain plots of the instantaneous power (a) and total energy produced by a photovoltaic string (b) after acquisition and PIC processing of PV string voltages, during three days with different climatic conditions using the S/P CS097 designed board.

To verify the correct operation of monitoring system of household facilities, several tests were carried out each time building a proper experimental setup. In a functional test, it was verified the managing, through the web page, of digital outputs and analog inputs monitoring the energy consumption of a common bulb, reporting the acquired data on the web page properly designed. In the experimental setup, a Cascade transformer 230VAC - 24VAC and a 40W incandescent lamp were connected to the realized PCB.

After opening the web page, by clicking on channel 1 (see Figure 21), the connected lamp is turned on (also LED D5 on PCB as shown in figure 29). Then the ACS712 current transducer provides, to analog input AN1 of the PIC, the values of absorbed current for calculating and viewing, on web page, of active power (W) and energy (Wh) consumed from load lamp for each minute. In figure 30, the flow chart concerning executed operations and calculations in this test is shown. Clicking again on channel 1 after an hour of monitoring, the 40W lamp is turned off by stopping energy counting to value of 38.30Wh with an error of 4.25%. The same test was carried out by connecting the 40W lamp on second channel and clicking channel 2 on web page. In this case, after an hour, calculated value of used energy was 38.20Wh with an error of 4.5%; the obtained results are consistent with a 4% measuring error of ACS current transducer as reported in its datasheet. In addition, by means of webpage, the user can remotely turn on/off managed facilities or in automatic mode, depending on lighting/presence sensors connected to digital inputs, for obtaining, in both cases, energy savings.

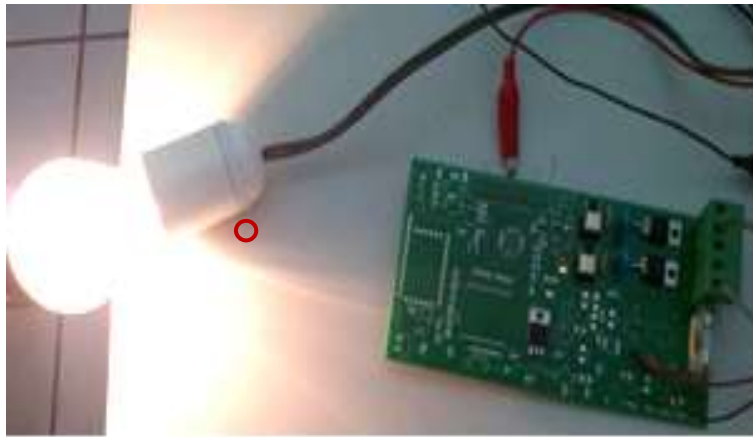


Figure 29 40W incandescent lamp connected to driving/monitoring board (D5 LED ON in the red circle) during first functional test.

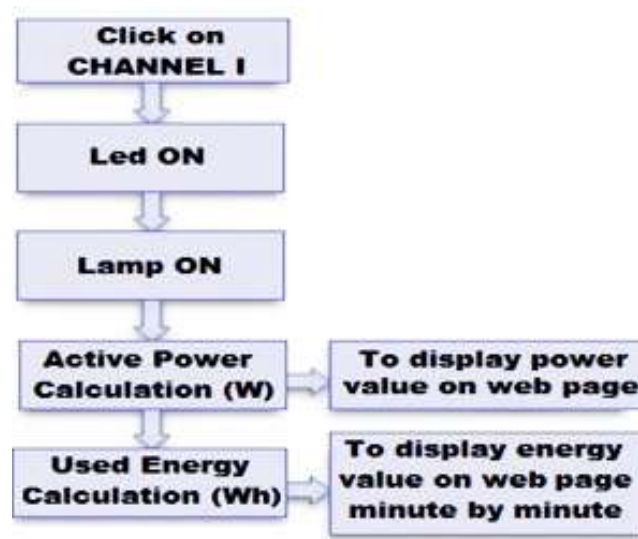


Figure 30 Flow-chart concerning executed operations and calculations in the functional test.

Figure 31 shows the results of on field experimental tests of the alarm anti-theft equipment based on CS083-CS088 electronic boards. The aim of the tests was to verify whether the designed board was able to identify the critical condition, typical of theft of one or more modules. For this purpose, the test was conducted mainly during the dark hours because these are the most critical hours for thefts. In order to verify that the system was able to detect critical alarm situation, a condition of theft was recreated, first shorting only one PV module then two PV modules. Thus the negative voltage signal produced from PV string was detected by electronic boards and then processed by PC for simple and clear viewing. From acquired voltage samples, we noted that during the first attempted theft of only one module, there is a voltage lowering (in absolute value) measured by the board, then the return to normal operation when the short circuit is removed. The difference between the voltage level before and after the theft is even more pronounced during the second test with the short circuit of two PV modules (as shown in Figure 31).

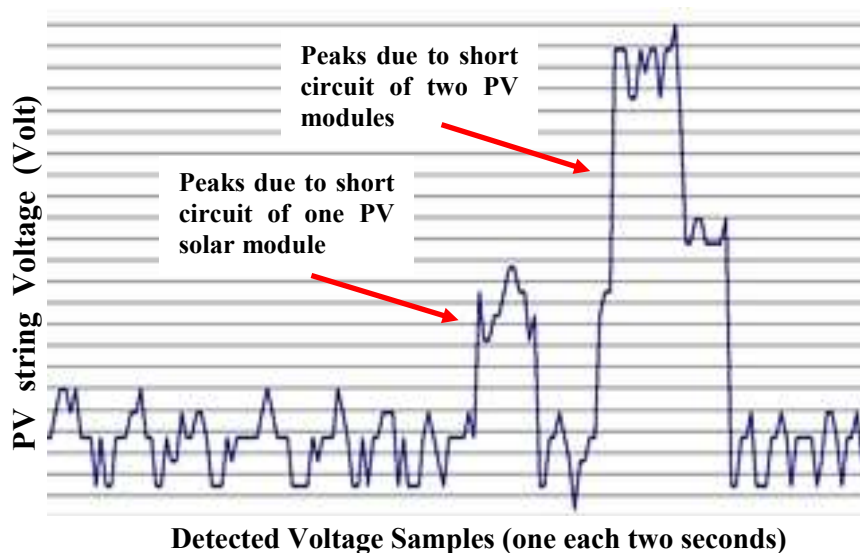


Figure 31 Testing of the alarm anti-theft system CS083-CS088, showing time-domain diagram of the detected string tension developed during the simulation of a robbery.

In conclusion, the complete electrical control panel of PV system is shown in figure 32 including the circuital section to perform the parallel of the strings and the blocking diodes used to isolate the strings between them ensuring that, in case of a short circuit or shading, the other strings continue to work without problems avoiding a reverse current in the inactive string. Moreover in the electrical panel, a fuse, for general applications and of appropriate size, protects each string and downstream equipment from any overloads or over-currents while a voltage discharger protects the system against any over-voltages. Instead the



intelligent control section includes (on the top in figure 32) the monitoring CS097 S/P board and the anti-theft CS083/CS088 electrical boards (both electronic units can be powered by 12V DC supply voltage or through the ac 230V rms mains voltage).



Figure 32 Photo of designed and realized control panel of PV plants including the circuitual sections of parallel connection, strings protection, detection and processing of PV plant parameters and alarm anti-theft.

## VII. CONCLUSIONS

According to the obtained results, the following conclusions have been drawn:

1. A control system has been designed in order to monitor, both locally or remotely, a PV plant, to detect any theft or malfunction and to optimize energy production by efficient algorithm for driving the biaxial solar trackers.
2. The designed system is integrated with a wireless unit to monitor and control operation of household facilities.
3. A sensing/processing board detects environmental parameters, temperature and solar radiation, and calculates the produced PV power and energy for monitoring efficiency and electricity production.
4. An Alarm anti-theft board detects a critical condition in case of electrical continuity loss or not-justified rapid variation of PV string voltage or in case of a measured string impedance different from the typical one, so activating an alarm output. The designed system has dual operation mode that makes it capable of auto-adapting itself distinguishing between day and night.

5. Finally a programmable driving board controls biaxial solar trackers and instantly calculates the sun position at latitude and longitude of installation site so following the solar orbit for increasing the PV plant productivity.
6. Plant owner or technicians can access to the realized webpage with simple and user-friendly interface to monitor/control operation state of household appliances and for viewing the energy production/consumption data. Thus, the constant monitoring allows to promptly intervene in case of sudden malfunction or unjustified high consumption of the monitored electrical loads.

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