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DEVELOPMENT OF SMART PIC-BASED ELECTRONIC EQUIPMENT FOR MANAGING AND MONITORING ENERGY PRODUCTION OF PHOTOVOLTAIC PLAN WITH WIRELESS TRANSMISSION UNIT

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ABSTRACT

Aim of this paper is to present a PIC-based low-cost monitoring system for domestic PV plant, able to detect environmental and electrical parameters for controlling energy production and its proper functioning. Thereby the designed equipment can guarantee, by sending alarm signal to a data/receiving viewing device, quick detection in case of system's malfunction or productivity's drops. In fact realized system is able to transmit by wireless ZigBee module, the PIC processed data about PV plant's status and productivity to a remote device, touch screen display or PC, for viewing the information to the user.

Keywords: photovoltaic plant, monitoring, electronic equipment, wireless communication.

INTRODUCTION

Electronic systems for measuring and monitoring the energy produced by a photovoltaic plan are fundamental in order to know the plan's status and to optimize its productivity and thus for determining the economic convenience of the made investment. For this purpose, electronic equipments allow to detect environmental and electrical parameters of PV plan in order to control energy production and the proper functioning thereby to guarantee quick detection of any failures or system's malfunctions (thus avoiding drops or holes of productivity). These measurements can be performed by energy meters upstream (DC side) or downstream (ac side) of the inverter or by means of electronic sensors and devices positioned at single PV panel or string level, depending on the PV plan's size and the degree of desired accuracy in the measurement of produced electrical energy (Visconti *et al.* , 2015). Even for PV plan of small size (a few kW) typically for domestic use, a continuous monitoring is essential for optimizing the productivity giving the possibility, to the common user owner of the plant, to be informed in real time on the energy production and consequently to be able to intervene quickly in case of malfunctions or reduced unjustified energy production (shading of solar modules, public power grid failures, damages due to climatic events) (Bialasiewicz, 2008).

Photovoltaic systems can be connected to the electricity distribution network (grid connected) or directly to isolated users (stand-alone) in order to assure them the availability of electricity. The PV plants connected to the network have the feature of working in interchange mode with the power grid; practically, in daylight hours, the electrical utilities use the electricity produced by own PV plan and in case of overproduction the difference is sold and put in external power grid; whereas when the solar radiation there isn't or it is not sufficient because users require more energy than the PV system is able to provide, the electric network will ensure the supplying of the required energy. Solar energy is available everywhere but in some circumstances and locations it is necessary to optimize the dimensions of plants, thereby avoiding large surfaces of PV modules installed on the ground, preferring modules located on solar trackers in order to increase the efficiency by at least 35% (Visconti *et al*. , 2015).

In this work, we have designed and developed a simple and smart remote monitoring system specifically for single phase PV plants of small sizes, up to 6kW power. It performs the detection of ac current and voltage signals provided by inverter thus ensuring the possibility to install the electronic control equipment even after the PV plant's realization being independent from technology or specified devices used to build the PV facility. The designed apparatus detects ac current and voltage from the inverter and then calculates, by means of dedicated firmware running on XAP2b microprocessor, instantaneous and average power levels and energy generated from PV plant (Kopacz *et al*., 2014). In this way, the user can evaluate the PV plan's performances, any reduction or holes of productivity due to shading by comparison with light sensor signal or can rapidly reveal any damages in case of theft or vandalism events thus enabling rapid intervention by means of sms and e-mail sending directly to the technicians (Sanchez-Pacheco *et al.* 2014). For PV installations with several inverters, the designed system is able to acquire the electrical parameters provided from each inverter and to process them for a proper management of the whole large PV plant.

In Figure-1 is shown a block diagram of a PV grid-connected plan with the designed control equipment inserted after the inverter in order to detect ac current and voltage signals and process them through a smart PIC-based electronic board. The realized system is also able to transmit the processed data about status and productivity of PV plant, using ZigBee technology, to a remote device able to show these information to a common user (for example using a touch screen display with ZigBee receiving module or PC with USB receiving module and data viewing application) (Guerriero *et al*., 2014).

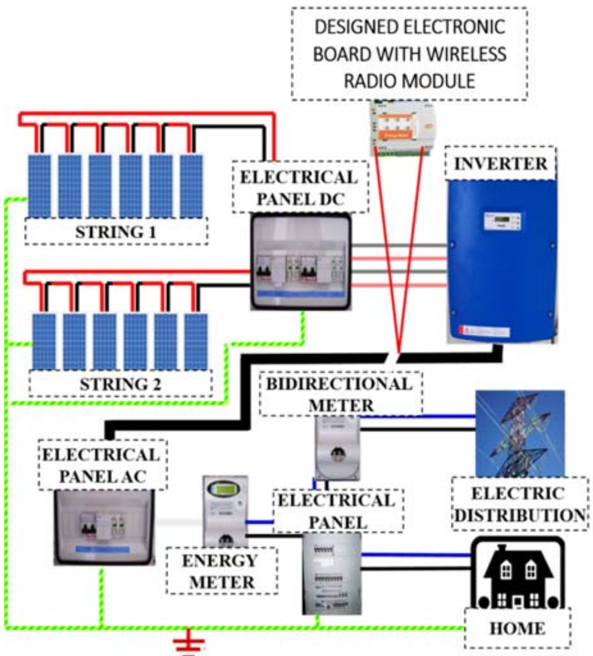

Figure-1. Block diagram of a grid-connected photovoltaic system connected to the mains and home utilities, managed and monitored by designed electronic equipment inserted after DC/AC converter (inverter).

BLOCK DIAGRAMS OF DESIGNED EQUIPMENT: SENSING CIRCUIT, ACQUISITION/PROCESSING UNIT AND DATA TRANSCEIVER

The designed electronic system consists of two main blocks: the first one has to be interfaced to the DC/ac inverter in order to detect and process by PIC ac voltage and current signals generated by the PV plant and then, by means of ZigBee Radio Module, to transmit these data to a remote viewing device. The second circuital block allows the remote control, from the end user or plant's owner, by means data receiving and their viewing for productivity monitoring.

Figure-2 shows a block diagram of the data acquisition circuit, which consists of a Voltage sensing circuit for detecting ac voltage (220V effective value, 50Hz ac) generated by the inverter and for its conditioning in order to obtain a suitable signal V for radio module input (1.2V ac maximum voltage). For providing adequate galvanic isolation between the low-voltage embedded systems and the mains from inverter, an isolation transformer is placed in series with inverter outputs.

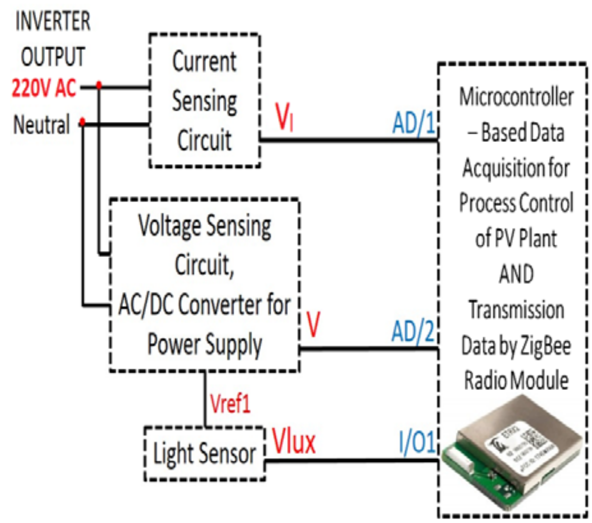

Figure-2. Data acquisition (ac voltage and current) from inverter output and their processing/transmission with designed electronic equipment.

From ac voltage by means of a ac/DC converter, we obtain 5V DC power supply for powering the transmitting radio module and the LEM current transducer used in the current sensing circuit. This last circuital block takes care of detecting the ac current generated by photovoltaic string using LEM HAIS 100-pe current sensor. Thus the current sensing circuit provides an output voltage V_I, proportional to measure current, proper to be connected to the input of processing / transmission unit.

The designed electronic apparatus also includes the use of a brightness sensor to avoid false alarms caused by reduced or total absence of solar irradiation due to sun's covering.

The ETRX2 radio module, shown in Figure-2, has the function of processing the input data (ac voltage and current) for the calculation of generated power and energy and of managing the wireless transmission of PV plant's data to remote viewing devices. For easy wireless network development, ETRX2 radio device carries the Telegesis AT Command line interface which allows quick integration of meshing radio technology without complex programming or RF design experience (see Ref. ETRX2 ZIGBEE module product manual).

Figure-3 shows the electronic device for remote data receiving which involves the use of a ZigBee radio module for the receiving of sent parameters from the master board and the data viewing on a LCD display in

ARPN Journal of Engineering and Applied Sciences

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order to provide, to PV plant's owner, a simple and useful graphical interface (Rashidi *et al.*, 2011). Alternatively the designed equipment can include the use of a USB device, with a ZigBee Radio Module embedded inside, for data visualization on PC through proper application which allows to store data on PV plant's productivity and to make a data's deeper analysis (Guerriero *et al*., 2014).

The Telegesis ETRX2 USB device is a high performance, low power 2.4GHz ISM band transceiver in a USB Stick form factor. Based on Embers EM250, it complies with the IEEE 802.15.4 standard, providing a low cost effective method of adding ZigBee capability to any device which employs USB connector.

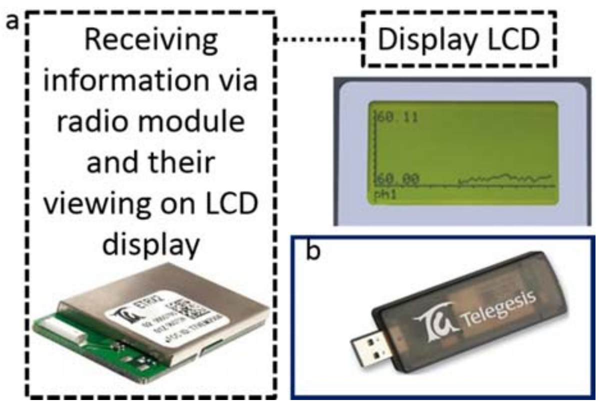

Figure-3. Data receiving block of PV plan status by Radio Module and their viewing on LCD display (a) or by USB Radio Module for data displaying on PC. (b)

CIRCUITAL SCHEMES FOR SENSORS SIGNAL CONDITIONING AND POWER SUPPLY GENERATION

The realized energy meter is able to measure power and energy produced by PV plant detecting ac voltage and current signals downstream of the inverter. The schematic shown in Figure-4 is relative to the acquisition circuit of voltage signal from inverter (green box) in order to make it suitable for analog input of the radio module. The signal in fact, taken directly from the 220V AC line, is suitably treated by resistive voltage divider (high precision resistor R1-R2), which provides a sinusoidal waveform with a peak value (originally about 220V*√2) approximately equal to 1.15V proper to be connected to analog input A/D1 of ETRX2 radio module.

The obtained signal has sinusoidal waveform; for this reason it is used a diode D3, directly polarized, to allow the pass only of the sinusoid's positive half-wave. From ac signal, it was obtained the DC supply voltage V_{REF1} (5V) needed for both current transducer and signal comparator used in Light sensor conditioning circuit (orange box). Moreover, reducing the 5V DC voltage through the diodes (D4, D5, D6), it is obtained the power supply voltage V_{REF2} = 3V (red box) suitable for powering the ZigBee radio module (DC supply voltage range 2.1 - 3.6V).

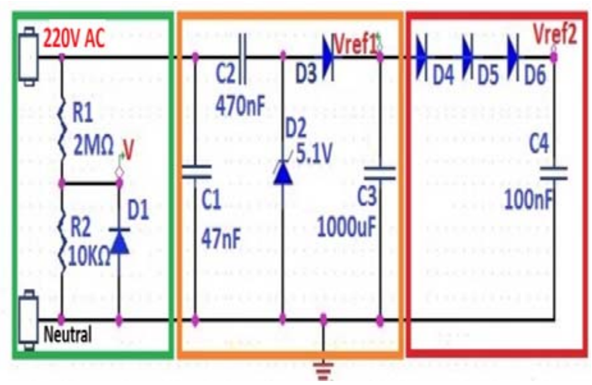

Figure-4. Voltage sensing and AC/DC conversion circuits. Green box: voltage divider for acquiring ac output voltage from inverter. Orange box: DC power supply generation for current transformer and light sensor (Vref1). Red box: DC supply voltage for transceiver Radio Module (Vref2).

The current sensing circuit (shown in Figure-5) involves the use of a Hall effect current transducer (LEM HAIS 400-p) for current signal (I_P) acquisition; the output voltage V_{OUT}, proportional to the detected ac current I_P, through the resistive voltage divider acquires a suitable value (V_I) to be connected to analog input A/D2 of ETRX2 radio module. The functional relationship between output voltage V_{OUT} and the ac input current I_P is the following:

$$VOUT = VREF \pm (0.625 * IP/IPN) \quad \text{with } IPN = 400A$$

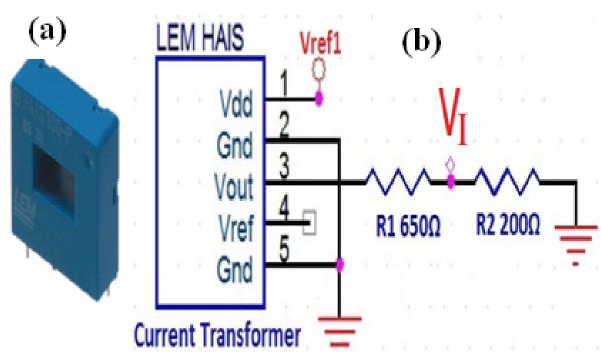

Figure-5. Viewing of LEM HAIS 400-P current transducer (a) and relative current sensing circuit (b) for obtaining V_I voltage proportional to ac input current and adapted for radio module input by voltage divider.

By means of a brightness sensor, photodiode D1 in Figure-6, the circuital block is able to detect and recognize situations of sunlight's reduced level or partial

 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

shading of the photovoltaic strings that determine a reduced energy production. In such cases, the circuit provides this information to PIC's digital input (Vlux equal to 0 logic level) and the control system will not generate an alarm condition since the low productivity is due to a reduced solar radiation. A variable resistor R2 provides the ability to change the minimum brightness level below which the digital output Vlux is enabled. A LM311 comparator performs the comparison between light level voltage and a threshold voltage V_{COMP} providing, as output, the logic level Vlux. The LM311 output stage consists of an open collector BJT; in case of low level output, the BJT works in saturation region and thus the LM311's output voltage is equal to 0,2V = $V_{SAT\ BJT}$ (Vlux at low logic level), while in case of high-level output, the final stage's BJT goes to interdiction (opened switch) and by the push-pull resistance R5, it is obtained VOUT = Vlux = Vref2.

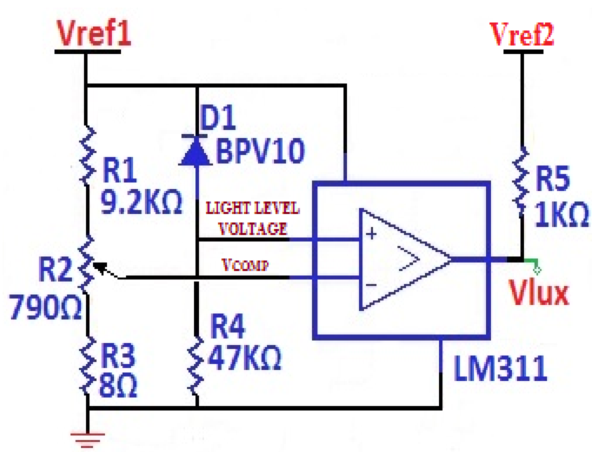

Figure-6. Acquisition circuit of Light sensor signal (photodiode D1) and its comparison with proper threshold level in order to get digital Vlux applied as input to PIC on ZigBee ETRX2 Radio Module.

ZIGBEE RADIO MODULE FOR WIRELESS TRANSMISSION DATA

The Telegesis ETRX2 module, shown in Figure-7a, used in both data transmitting and receiving units, is a 2.4GHz transceiver based on EM250 single chip Ember, with ZigBee / IEEE 802.15.4 protocol (see Ref. Datasheet EM250 Single-Chip ZigBee/802.15.4 Solution). In figure 7b are shown its block diagram with the different building logic modules and the external pinout that allows an easy access to embedded PIC's inputs (see Ref. ETRX2 ZIGBEE module product manual). The ETRX2 ZigBee device presents 12 general-purpose I/O lines and 2 analogue inputs; all 17 GPIO pins of the EM250 chip, with XAP2b microprocessor embedded, are accessible. In particular, we used two analog inputs (A/D1 - A/D2) for ac current/voltage signals acquisition (pins 9-10), a digital input (I/O1) for connecting the lighting sensor circuit's output (pin 25) and the required pins for PIC programming done by means of Insight USB link. The ETRX2 module provides the possibility of programming via AT commands which give the needed tools for set up and management of a wireless mesh network, allowing an easy access to low-level functionality of ZigBee stack for both Router/Coordinator and data receiving end devices (Rashidi *et al*., 2011).

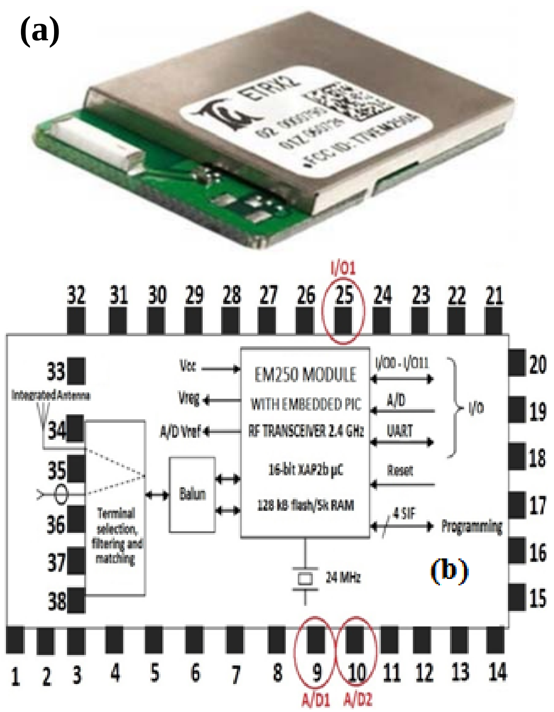

Figure-7. Viewing of ETRX2 ZigBee Radio Module (a) and its block diagram with pinout description (b) in order to connect it with designed electronic board.

The EM250 chip needs an external high-frequency 24MHz crystal oscillator with accuracy of ±40ppm. The PIC's ADC is a first-order sigma-delta converter with maximum sampling frequency of 1MHz, programmable resolution (up to 12 equivalent bits) and conversion time small up to 32 µs; in our application, A/D conversions are triggered by interrupts, occurring with a frequency of 500 or 1000 Hz.

Since the proposed setup performs current-voltage measurements downstream of the inverter, the inputs of both A/D converter channels are 50 Hz sinewaves; then the transferred energy E is estimated as the numerical integral of the current-voltage (I*V) products. Hence, in order to accurately detect ac current/voltage signals and to estimate properly the energy (E) values, a minimum sampling frequency of at least 500 samples/s on each ADC channel (i.e., at least 10 samples for each sinewave period) is needed.

VOL. 10, NO 20, NOVEMBER, 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Obviously we have verified, on the basis of the technical specifications reported on PIC's datasheet and dedicated processing tests carried out with our experimental setup, that the XAP2b microprocessor (a 16-bit Harvard architecture processor with separate program and data buses) has adequate processing power in order to sustain real time operations; as reported in the following paragraph, PIC's mathematical processing consists of two A/D conversions, one multiplication, one addition and one division (this last surely a floating point operation).

FIRMWARE DEVELOPMENT AND PIC PROGRAMMING USING DEDICATED BOARD FOR ETRX2 RADIO MODULE

In order to make possible, through the ZigBee radio module, the network's making, data processing and management of data communication between the transmitting and receiving modules, the XAP2b microcontroller, on board of the same ETRX2 radio module, has been programmed. By means of Insight USB Link, a serial RS 232/USB interface shown in the insert of Figure-8, the PC is connected to the Development Breakout Board (shown in Figure-8) and therefore to memory bus and to PIC embedded on ETRX2 Radio Module thereby making possible the loading of dedicated firmware on the same PIC. The Insight USB Link, being managed from command line via PC, is a cheap technical solution but very useful for laboratory testing and programming of prototypes; it is provided with LEDs suitable to verify the correct operation of the tested device (by detecting errors/malfunctions or read/write actions) during its use.

Figure-8. Breakout Board for connecting the ZigBee Radio Module to PC in order to test its electrical behavior and for programming the embedded microcontroller with proper firmware; in the insert the InSight USB Link cable for connection to PC.

The operations concerning the network's making, management of AD/1 and AD/2 input signals and their processing will be done automatically by PIC on ZigBee radio module after its programming with dedicated software; this will allow then to develop a dedicated application for the management of PV plant's electrical parameters and for processed data's communication between processing/transmitting board and receiving unit.

In Figure-9 is shown the flow chart of the realized firmware for management of the energy meter's functionalities (Vergura *et al*., 2009). An interrupt, with time interval of repetition equal to 2ms (also settable to 1ms in case of higher accuracy), starts the processing of AD/1 and AD/2 analogue inputs (relative to ac current and voltage respectively) in order to calculate power (P = AD/1 * AD/2) and energy generated by PV plant. For energy's calculation, a variable Ei acts as adder of the generated and each time calculated power, so as to communicate to the user the value of generated energy E updated at that time.

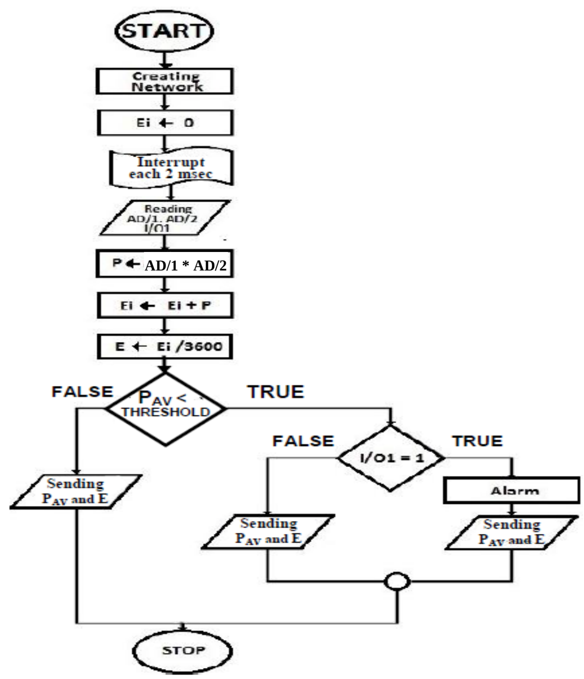

Figure-9. Flow chart of firmware, implemented in the programmed PIC, which provides instantaneous and average power values and produced energy by processing of ac current and voltage signals.

The main purpose of the designed control system is to alert the PV plant's owner or manager in the event of sudden unjustified production's reduction. For this reason, the calculated average power value P_{AV} (obtained as the average of ten instantaneous power values for each sinewave period at sampling rate of 500 samples/s), through PIC processing, is compared with a variable threshold value (dependent on time of day and level of solar radiation). In the case where the average power value P_{AV} is lower than threshold value, then consequently the system will be considered in low productivity condition

VOL. 10, NO 20, NOVEMBER, 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

and it is required to send the PV plant’s data to the receiving radio module and the activation of a sound alarm to make known the user about the malfunction condition.

The logic level Vlux (from comparator's output in Light sensor circuit) applied to I/O1 input of ETRX2 radio module provides, to the control system, the information on solar radiation level and thus allows to discriminate a real situation of low productivity (by sending an alarm message to the receiver module) from an event of low solar radiation.

ELECTRICAL TESTING BY MEANS OF EXPERIMENTAL SETUP FOR DATA ACQUISITION AND TRANSMISSION

For the functional testing of the designed control device, a PC is connected to dedicated Development Board with Telegesis ZigBee Radio Module on board, in order to curry out functioning tests by AT commands. By means of the AT commands, it is allowed the mesh network’s creation and management as well as the access to the low-level physical parameters (i.e. the choice of communication channel and power level of transmitted radio signal). In Figure-10 is shown the development board, connected to the PC by means of RS232 serial port, with aboard the ETRX2 radio module with transmitting function while in Figure-11 shows the Telegesis ETRX2USB device connected to PC’s USB port. This device includes inside a ZigBee radio module with data receiving function from transmitting board and RS232/USB adapter for PC data acquisition. After making the connection between development board and PC through the serial port and installed the ETRX2-USB adapter key, to AD/1 and AD/2 inputs of the development board are connected the conditioning circuit’s outputs of ac current and voltage signals downstream of the inverter. These input data are processed by PIC on ETRX2 module and processing results (average power P_{AV} and produced energy values) are sent to data receiving unit (ETR-X2 USB connected to PC) for PC displaying of the same data.

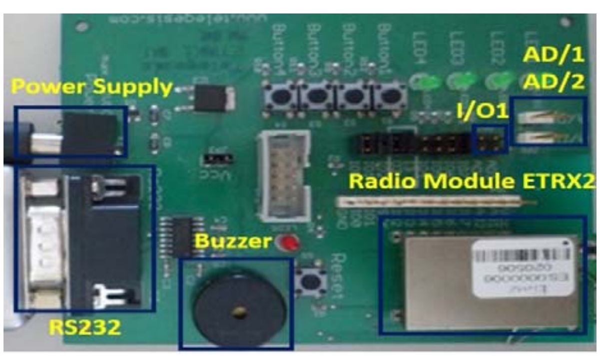

Figure-10. Development board for electrical testing of ETRX2 Radio Module, for creating a mesh network and communication test between transmitting ZigBee Module and USB receiving module on PC.

Figure-11. Telegesis ETRX2USB device connected to PC’s USB port for data receiving from transmitting board. The device includes inside a ZigBee receiving module and RS232/USB adapter for data acquisition from PC.

Finally the electrical circuits previously described (shown in the figures from 4 to 6) were produced on a single breadboard (shown in the insert of Figure-12) in order to carry out the final testing for verifying the proper functioning of the entire designed electronic equipment. Figure-12 shows the laboratory experimental setup with power supply generators, measurement instruments and the assembled prototype (shown under testing in the insert) which includes DC power supplies generation (Vref1, Vref2), detection/conditioning circuits of ac current/voltage signals from inverter and sensing circuit of lighting level.

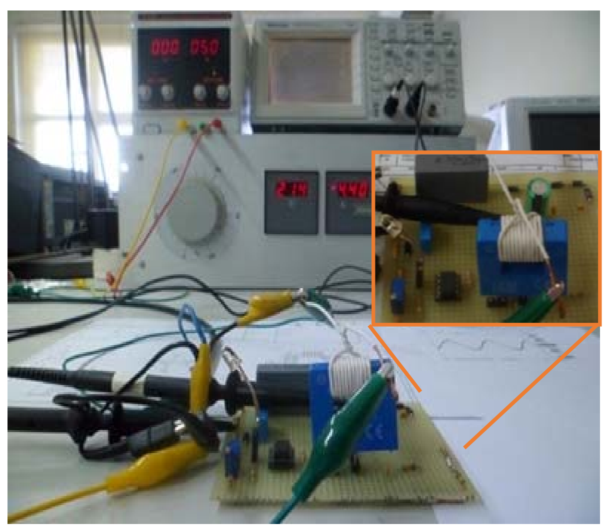

Figure-12. Laboratory experimental setup for testing of designed electronic board, which includes DC power supplies generation (Vref1, Vref2), detection/conditioning of ac current/voltage signals from inverter and sensing circuit of light level. In the insert shown a top view of the realized prototype during testing operation.

During the laboratory tests, it was verified the correct functioning of the realized monitoring device through reading values of the different voltages (ac

VOL. 10, NO 20, NOVEMBER, 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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voltage and current signals, power supply voltages Vref1 and Vref2 and digital signal Vlux). By means of the oscilloscope, the reading of the output voltage from current transducer LEM HAIS 400P was carried out during normal functioning of the PV plant in different daylight hours. Figure-13(a) shows the time-dependent waveform of voltage signal V_I (referred to detected ac current) after conditioning circuit operation as applied to PIC inputs (input data to the radio module). On the second channel of the oscilloscope (waveform shown in Figure-13b), can be observed the oscillogram relative to voltage signal obtained from the ac voltage sensing circuit after the resistive divider.

In conclusion, some considerations regarding the achievable measurement accuracy that depends on inverter ac outputs' precision, on ac signals conditioning, on ADC sampling rate and ADC resolution. From experimental results, we estimate an accuracy, concerning instantaneous ac power, average power value P_{AV} and produced energy E, of the order of one percent due to noise, supply fluctuations and low sampling rate.

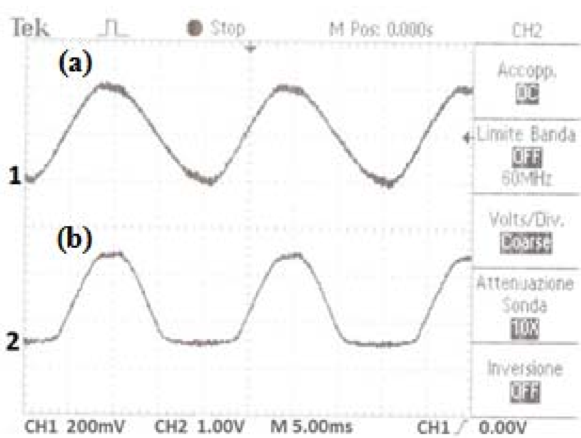

Figure-13. Oscilloscope detection of ac current (channel 1 shown in Figure-a) and voltage signals (channel 2 shown in Figure-b) after operation of respective conditioning circuits as applied to PIC inputs.

In order to display and monitor data related to energy production of domestic PV plant, we have developed a PC application capable of showing, as graphs or histograms in the time domain, the sent values of produced average power P_{AV} and energy E as numerical integral of the current-voltage (I*V) products. In such way, the user will have under control, from own PC, the monitored PV plant thus ensuring its proper functioning and quick intervention in case of productivity drop or sudden failure. In Figure-14, a screenshot of PC application (Figure-14b) and some typical graphs, obtained by means of PC application, related to detected PV plant's data (Figures 14c and 14d) are shown.

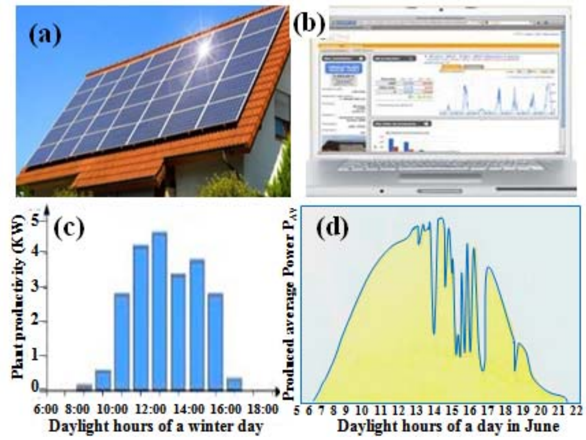

Figure-14. A domestic PV plant on house's sloping roof (a), a screenshot of PC application (b) and typical graphs related to detected PV plant's data (histogram of produced power in Figure-c and time-domain plot of P_{AV} in Figure-d).

CONCLUSIONS

In conclusion, we have designed and tested a PIC-based, simple and smart monitoring system for domestic photovoltaic plants, able to control the energy production and proper functioning by detecting ac current and voltage values downstream the inverter and lighting level on PV string. Thereby the realized equipment is able, by sending via wireless communication the PIC processed data to a receiving device, to keep informed the PV plant's owner or manager on its functioning and productivity and to alert him in case of sudden unjustified power production's drop determined by PIC comparison with a variable threshold power value (Visconti *et al*., 2015).

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