International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 4 Issue 04, April-2015

Thermo-Solar Plant Managing and Monitoring by Electronic Programmable Device with Touch-Screen Interface and Local or Remote Control Possibility

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***Abstract* — This paper describes a programmable electronic equipment for controlling the environmental parameters and managing the electrical functions of a thermo-solar plant. The control unit acquires data from analog sensors, processes these information and commands external actuation devices in order to optimize plant performances improving efficiency and energy saving. The designed electronic system has a touch-screen display for graphical interface with users, which makes device programming and managing operations easier. In addition to, the system is accessible via PC terminal on site by RS232 serial cable and from Android-based mobile devices connected to internet network for remote monitoring, since control unit is connected to a modem/router device with an RS485/Ethernet adapter.**

***Keywords* - Thermosolar ; sensor; mobile device; PIC; monitoring.**

I. INTRODUCTION

Today a great number of thermo-solar plants are installed in order to obtain energy saving by production of hot water usable for sanitary circuit or space heating. In this context, aim of this work is the design of an electronic system for physical parameters control (water temperature, solar collector's fluid temperature, solar radiation level, etc..) in order to monitor and consequently optimize thermo-solar plant functioning. In particular, the designed control unit is able to control actuation systems for opening/closing of electric valves and enabling/disabling of auxiliary heating systems (gas boilers, wood boilers, etc..) and to manage a set of visual/audible feedbacks for faults reporting, request of maintenance intervention in order to monitor the plant's status [1] [2].

The main innovations introduced by the designed electronic equipment regard on the possibilities:

- to monitor and program the device functionality by means of a touch-screen graphical display that also allows to plant's owner or manager to check the correct operation and quickly reveal any fault;
- to manage and view locally the plant functioning by serial connection to PC with terminal role;
- to access to control system, for remotely viewing and monitoring actions, by Android-based mobile devices, through RS485/Ethernet adapter and modem/router device connected to internet network.

II. LOCAL OR REMOTE MONITORING OF THERMO-SOLAR PLANT BY MEANS OF DESIGNED CONTROL SYSTEM

A thermo-solar plant can be composed by several components according to application context and functionality needed by user. In figure 1 is shown a solar collector heating system with forced circulation, integrated by an auxiliary gas boiler heating system, managed by designed control unit. A thermo-solar system uses a solar panel that receives solar energy, transforms it into thermal energy by heating a vector fluid and then transfers it to the water contained in a storage tank, by circulating the heated fluid into an heat exchanger inside the tank. The vector fluid is slid by electric pump, only if fluid's temperature in the panel is higher than water's temperature in storage tank. The circulation is managed by electronic sensors that compares vector fluid's temperature (TS1) with water's temperature (TS2) into the tank.

In the system scheme of figure 1 are present: a temperature sensor TS1 for detection of vector fluid's temperature in solar collector; a temperature sensor TS2 for detection of water's temperature in the tank; a light sensor LS1 for verification of solar radiation conditions; an electric valve R1 for enabling/disabling the forced circulation pump; a relay switch R2 for enabling/disabling the auxiliary gas boiler; the heat exchanger for thermal energy transfer [3].

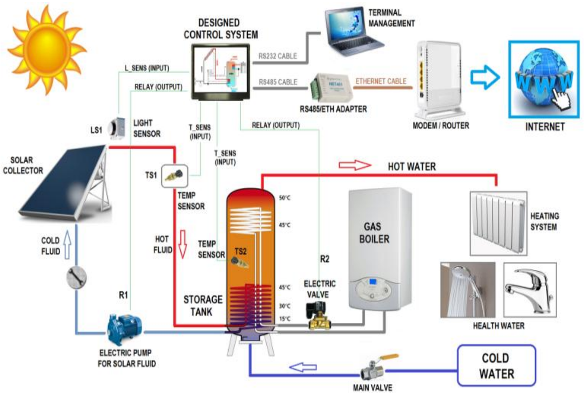


Fig. 1. Block diagram of a generic thermosolar plant managed by the designed electronic control unit interfaced with PC for local control or connected to internet network for remote access by Android-based mobile devices.

The designed control system presents some innovations with respect to traditional monitoring systems of energy production facilities. First of all, it is provided with a touch-screen graphical color display, which allows to make all user's interventions for device programming or managing easy and quick. Moreover, the system can be managed locally via PC terminal through RS232 serial cable for extraordinary or periodic control interventions, device maintenance or faults detection (figure 2a). Moreover, the control system is connected to internet network by means of a modem/router device plugged in a RS485/Ethernet adapter; in this way, it's possible for user to manage remotely all plant's operating functions through a suitable application on Android-based mobile devices (figures 2b, 2c) or different kinds of electronic equipment provided with an internet connection [4] [5] [6] [7].

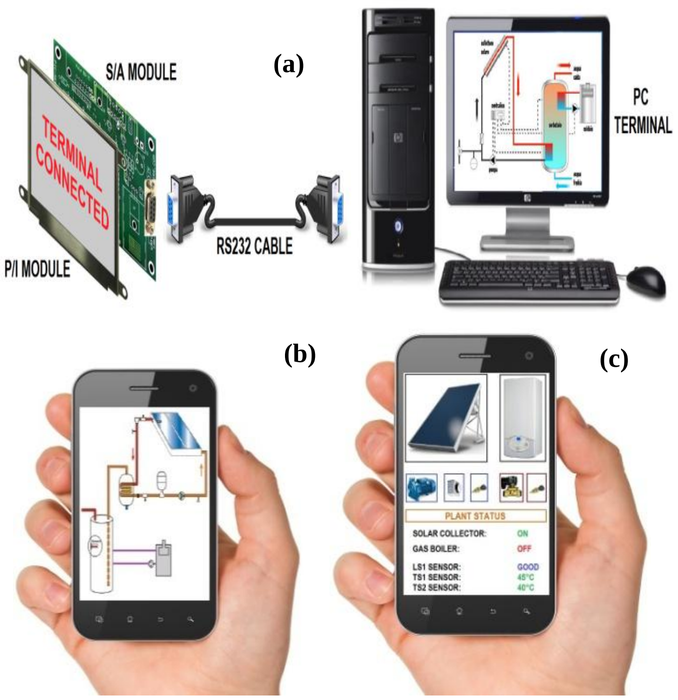


Fig. 2. Connection of designed monitoring system, by RS232 cable, to PC for local managing (a) and two images of mobile device's display that show different applications for plant's remote control (b,c).

III. HARDWARE STRUCTURE OF CONTROL UNIT: DESIGNED ELECTRONIC BOARD INTEGRATED WITH BOLYMIN BE635 DISPLAY EMBEDDED SYSTEM

The electronic control unit for management of thermo-solar plants is thought with general purpose logic, so that it can manage several facility's types piloting different actuators and detecting fluid temperatures by any type of sensing device. The operation mode of system's inputs (sensors) and outputs (relay switch) will follow the general purpose logic, adapting to features of a specific plant thanks to PIC's programmability. It was used a PIC32 microcontroller, with RS485 interface for serial communication, installed on a Bolymin BE635 embedded system, which consists of an electronic board carrying on PIC32MX575F512L and all connection pins for its programming and using. The BE635 system has a 3.5" TFT LCD 320x240 pixels touch screen color display controlled by PIC. In figure 3a is shown the back of BE635 module with the control and driving electronic board, whereas in figure 3b is shown the other face with the 3.5'' TFT LCD display.

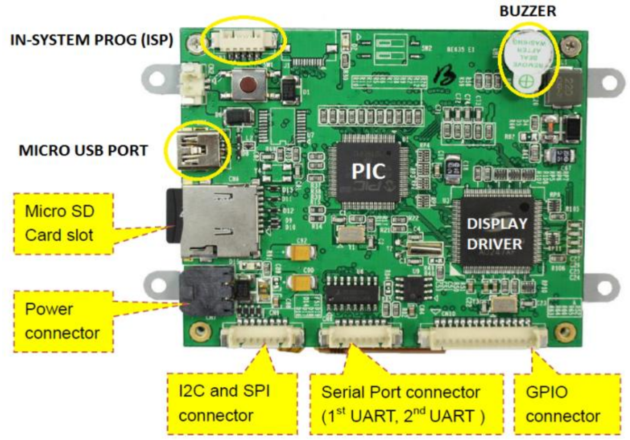


Fig. 3a. Bolymin BE635 display embedded system for user-friendly interface useful for plant manager: back view with electronic control and driving board

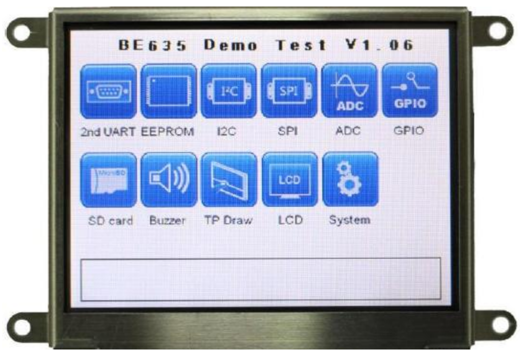


Fig. 3b. Bolymin BE635 display embedded system for user-friendly monitoring of plant functioning: front view with 3.5'' TFT LCD display

So, this device plays the dual role of brain and graphical interface of the control unit. Another board, plugged to BE635 embedded system through appropriate connectors, will contain the circuit sections of temperature sensing, detected signals conditioning and actuation of the external devices connected to it through power relays. Figure 4 shows a block diagram of this designed sensing/actuation (S/A) module [8].

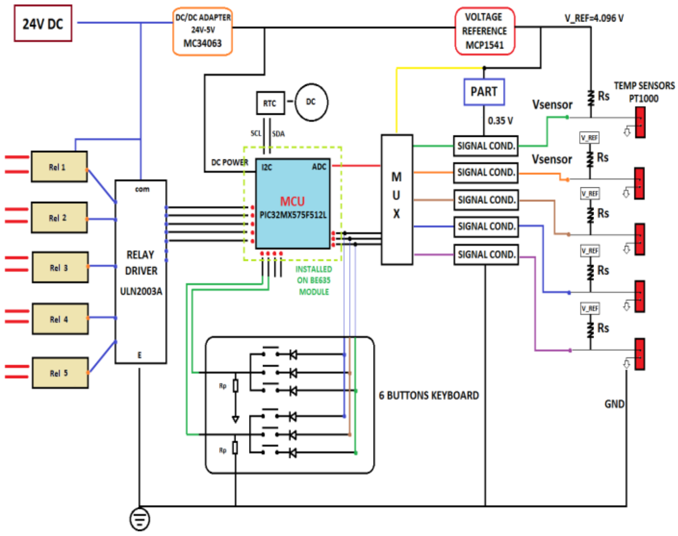


Fig. 4. Block diagram of the designed electronic sensing/actuation module

The power relays are controlled by 24V DC voltage; each relay has a coil's pin connected to 24V and the other pin connected to one of the five outputs of a driver (ULN2003A) powered by 24V DC voltage too. The five driver's input pins are connected to five PIC's logic outputs; when these outputs are high (5V), the corresponding output pins of the driver will reach 0V, creating the potential difference on the coil required to activate the relays. However, when the PIC's outputs are low, the corresponding output pins of the driver are at about 24V, leaving the relays deactivated.

The sensing part of the designed board is composed by five PT1000 temperature sensors, thermo-resistors that change their resistance with temperature (from 687.3Ω at T=-79°C to 2839.7Ω at T=599°C with ΔR=4Ω for each degree). Such probes, connected to the power supply in voltage divider configuration (see figure 4), generate a variable voltage Vsensor in according to temperature; Vsensor is connected to the analog input pin of microcontroller's ADC for subsequent conversion and processing. Being only one the ADC's analog input, it was used a multiplexer managed by three logic output pins of PIC, in order to execute, by software, cycles of interrogation of the five sensors, one at a time.

On low cost versions of the designed system, without touch-screen display, will be installed a keypad with six buttons for functionalities' management, interrogated, in order to save needed PIC's pins, by means of the cycles performed by MUX control pins thanks to matrix configuration of the buttons. The MCU is installed on BE635 module while the other components are installed on S/A designed board and interconnected to PIC by the connectors on BE635 device.

IV. DESIGN OF DC POWER SUPPLY, SIGNAL ACQUISITION CIRCUIT AND ACTUATORS SECTIONS

The 24V DC industrial voltage for supplying the control unit must have some minimum requirements in terms of output current. Each supplied component, in fact, has its own current absorption that contributes to the overall consumption. In figure 5 is shown a block diagram of the different circuital sections with indication of each current needs.

A first contribution to the total consumption is the Ir current needed for the actuation section, composed by the ULN2003A driver and the five relays. Each relay absorbs in the worst case 20mA, so, if all five relays are activated (worst case), the current Ir reaches the maximum value of 100mA. Even the ULN2003A driver has its absorption, about 24mA, therefore the total current absorption Ir is 124mA (150mA for safety). A second contribution is the $I_{DC/DC}$ current, absorbed by DC/DC 24/5V MC34063 adapter; it supplies BE635 system, which has a maximum current consumption of about 220mA (250 mA in order to have a quiet cover margin).

The DC/DC 24V-5V MC34063 adapter doesn't constitute a stable voltage reference for power supply of sensing circuit due to ripple and fluctuations of the 5V output voltage. Such oscillations, even if minimum (mV), would vary the current in T-sensor circuital branches, which is already very small for design parameters, so worsening the resolution. For this reason, it was decided to install a stabilized voltage reference, the Microchip MCP1541, able to provide a 4.096V stabilized output voltage powered by 5V input voltage from MC34063.

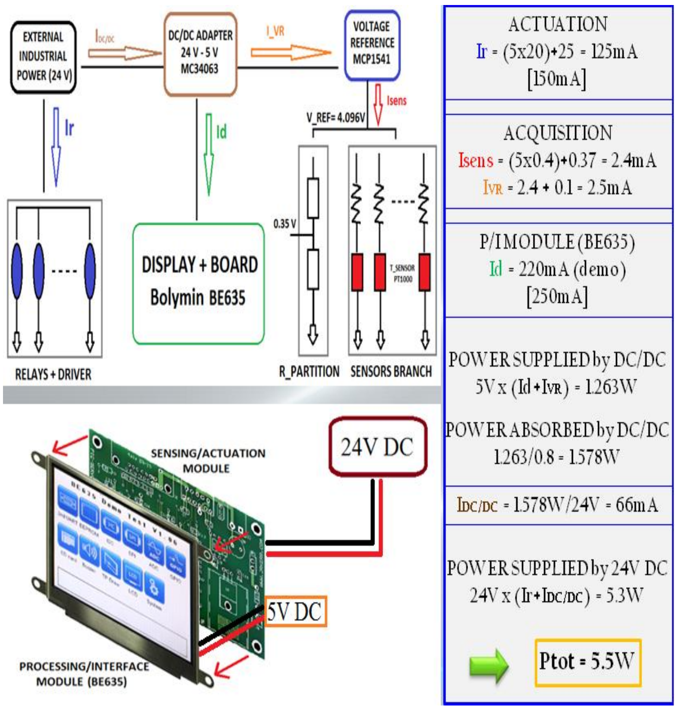


Fig. 5. Current absorption of different sections of the control unit in order to evaluate the technical specifications of DC power supplies; on the right side, viewing of supply current needed for each circuital section.

The MCP1541 IC is capable of delivering a maximum current of 20mA, a sufficient value considering that each voltage divider branch absorbs in the worst case 0.4mA (lowest resistance value of T-sensors), for a total consumption of 2mA for all five branches.

About signal conditioning of the temperature sensors, an amplifier stage with LM358N operational amplifier (op-amp) amplifies the voltage Vsensor got from PT1000 probe, in order to obtain the whole analog range (0-5V) at the input of the PIC's ADC in order to optimize the temperature detection resolution. The amplifier stage is necessary because the read current that flows through temperature sensors must be lower than a threshold value, as shown in figure 6, otherwise the sensor heating for Joule effect would degrade the accuracy in temperature detection.

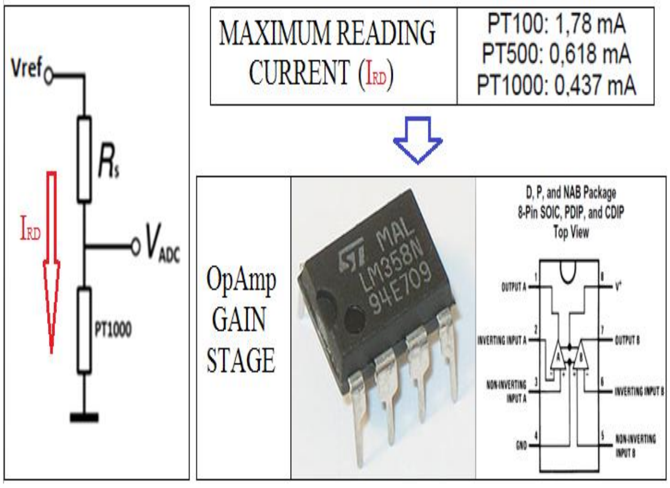


Fig. 6. Maximum value of read current for PT temperature sensors and operational amplifier IC used for designed gain stage

Figure 7 shows the designed acquisition circuit: the stabilized generator MCP1541 supplies each voltage-divider branch on which the probe PT1000 is located. The gain stage amplifies the value read on the probe (Vsensor) and shifts it in the amplified range 0-5V thanks to the connection of R1 resistance to a voltage (Vpart) obtained by another voltage divider. This divider is also powered by the 4.096V stable voltage reference which avoids the risk of unexpected fluctuations; Vpart voltage is supplied to the terminal of R1 resistor by a further LM358N op-amp in voltage buffer configuration. With this method, the gain stage's output goes to a voltage value Vout regulated by the following law:

$$Vout = Vsensor\ (1 + R2/R1) - Vpart\ (R2/R1)$$

The maximum current ISENS (see the figure 5) supplied from IC MCP1541 is the sum of contributions from the five voltage-divider branches with PT1000 T-sensor and from the single voltage divider branch for Vpart generation (0.35V) and so it reaches a value equal to Isens = 2.4mA. This value must be added to the absorption of the MCP1541 device for its supply, equal to 0.1mA, for a total of I_VR = 2.5mA.

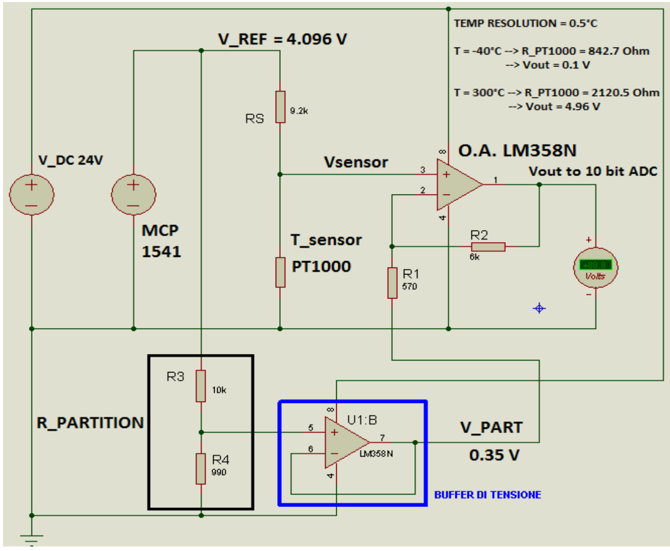


Fig. 7. Software simulation of designed signal acquisition circuit powered by not-stabilized 5V and 24V DC voltages and stabilized 4.096V DC reference voltage V_REF in order to avoid resolution loss.

The Isens current can be supplied by MCP1541 voltage reference, because the manufacturer claims that the maximum payable current is 20mA. Considering that the MC34063 DC/DC adapter has a power efficiency of 80%, it results that the total current necessary to supply MC34063 DC/DC adapter is **IDC/DC** = 66 mA (see figure 5). Adding to the IDC/DC the Ir current (150mA) absorbed by the actuation section, the 24V DC supply voltage must provide a total current of 220 mA, for a power dissipation of 24V*0.22A = 5.3W. Ultimately, a final comment on the current consumption of the eight operational amplifiers (used in the sensing section) supplied between 24V and ground. The LM358 datasheet shows a maximum supply current of 2mA; each LM358 IC actually contains two op-amps in the package, so our board will need four ICs. Therefore the total supply current absorption is 8mA and this results in a total power of 24V*0.008A=192mW. Finally, the external 24V DC power supply must be able to deliver a power of 5.5 W (rounded up) in order to meet the specifications of the designed control unit.

RS	T (°C)	Rpt (ohm)	I pt (mA)	Vout (V)	ΔV step		R1	R2	R3	R4
9.2k	-40	842,7	0,408	0,0789478			570	6k	10k	990
9.2k	-39	846,7	0,408	0,0961624	0,0172146					
9.2k	0	1000	0,402	0,745817						
9.2k	1	1003,9	0,402	0,76209	0,016273					
9.2k	299	2117	0,362	4,94812						
9.2k	300	2120,5	0,362	4,95998	0,01186					

MINIMUM Vout VARIATION = 11mV
(WORST CASE for Rpt=2120.5 ohm)

OBTAINED RESOLUTION = 0.5°C
(10 bit ADC >>> ΔV_{STEP} = 4.9mV

Fig. 8. Vout voltage values from conditioning circuit (applied to ADC's input) for different PT1000 values and resulting temperature resolution obtained with the 10 bit ADC embedded inside PIC.

Thanks to the accuracy of MCP1541voltage reference and consequently of Vsensor and Vpart voltage values, from simulations of the designed circuits it results an output's (Vout) minimum variation of 11mV/°C; the 10-bit ADC of the microcontroller has an amplitude of each quantization interval of 4.9 mV, obtaining a resolution in temperature detection of 0.5 °C, as shown in the table of figure 8. Finally, figure 9 shows the designed circuit for the actuation section, with the power relays switch managed by relay driver ULN2003A IC controlled by the PIC's output pins.

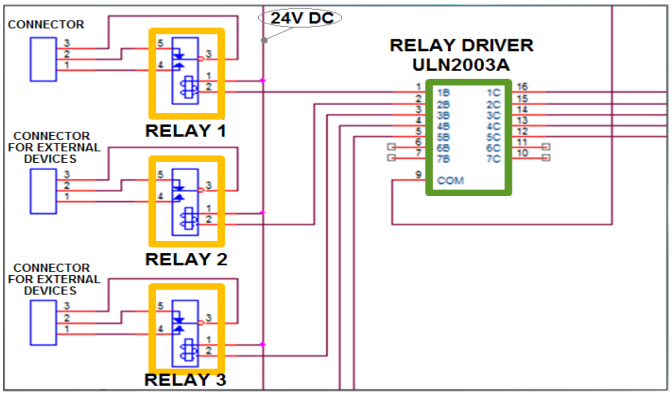


Fig. 9. Designed actuation circuit with relay driver IC ULN2003A and 24V DC power relays, realized with OrCad Capture software.

Circuital scheme of figure 9 contains the power relays N4100F 24V DC and the IC relay driver ULN2003A illustrated in figure 10 together with their pin's connection schemes.

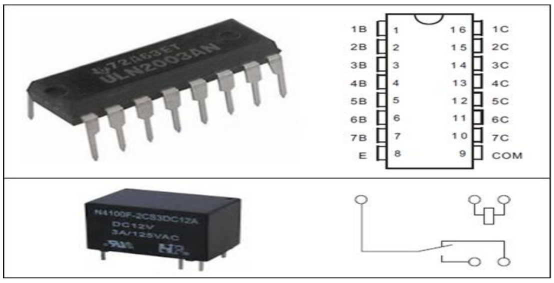


Fig. 10. Relay driver IC ULN2003A and N4100F 24V DC power relay with their pin's connection schemes

V. CONTROL UNIT REALIZATION AND TESTING: INTERFACING OF SENSING/ACTUATION PROTOTYPE MODULE WITH PROCESSING/INTERFACE BE635 DISPLAY SYSTEM

After completing the simulation and design stages, a prototype of the sensing/actuation (S/A) board, shown in figure 11, was realized in order to verify the correct operation for the designed system and the communication with processing/interface (P/I) module. For prototype realization, using a single-side breadboard, the components used in electrical scheme were installed trying to obtain an efficient use of space on the basis of needed electrical connections.

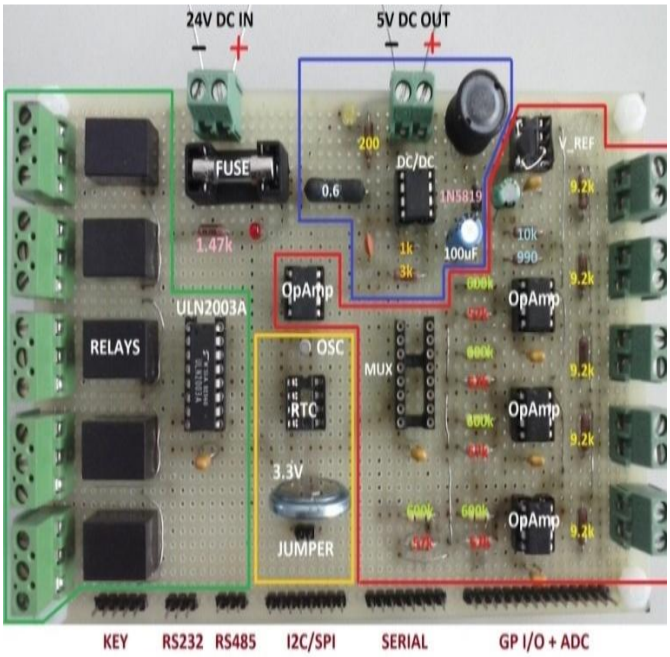


Figure 11. Realized prototype of the sensing/actuation module with graphical indication (coloured boxes) of different circuital sections.

In order to allow the association between the prototype view and the relative circuital section, in figure 11 the different functional areas have been graphically indicated; in the red section is enclosed the sensing/conditioning circuit, in the blue section the DC/DC converter, in the green box the actuation circuit and in the orange box is shown the real time clock. Finally, in the upper left is shown the power supply 24V DC connector with protection fuse and down several strip-line connectors for interfacing with BE635 P/I module.

After the realization of proper connection and power supply cables, the two modules (S/A and P/I boards) were connected in order to verify the correct behavior of the following functions: operation mode of programmed PIC by specified firmware, multiplexer logical addressing for selection of the desired T-sensor, correctness of voltage values provided by the selected sensor, A/D conversion executed by the microcontroller, transmission of the actuation commands between the two modules and relative switching of the relays, system response after connection of PT1000 temperature sensors. Figure 12 shows the experimental setup realized for the electrical testings of the system functionalities: S/A module is connected through the realized cable to P/I module, directly supplied with 5V DC voltage by S/A board.

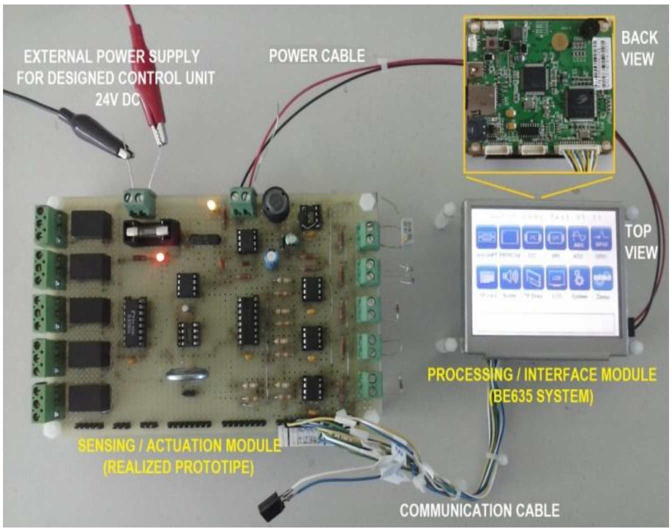
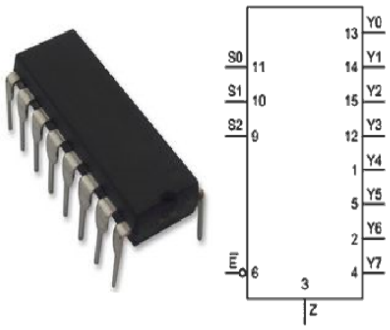


Figure 12. Laboratory experimental setup for electrical testing of sensing/actuation and processing/interface modules and of their communication for viewing on display of temperature values detected by PT1000 sensors.

Bolymin BE635 embedded system (P/I module) is provided with a pre-loaded test firmware that makes possible to test the device functionalities using the touch-screen interface. In particular, the user can view the voltage levels detected by PIC's ADC and can set and control the logical levels (low or high) present on GPIO pins, selecting the suitable test applications in the main menu on the screen (blue buttons in figure 12). Therefore, multiplexer has been addressed (figure 13) with different logical words created through GPIO pins test application and consequently the voltage values corresponding to the selected sensor has been read through ADC test application.



Input				Channel ON
E	S2	S1	S0	
L	L	L	L	Y0 to Z
L	L	L	H	Y1 to Z
L	L	H	L	Y2 to Z
L	L	H	H	Y3 to Z
L	H	L	L	Y4 to Z
L	H	L	H	Y5 to Z
L	H	H	L	Y6 to Z
L	H	H	H	Y7 to Z
H	X	X	X	switches off

Figure 13. Multiplexer 74HC4051 IC for sensors' cyclic addressing with corresponding connections diagram and table of addressing logical words

Figure 14 shows the screenshot of GPIO test application with switches for multiplexer addressing (a) and two screenshots of ADC test application with the detection of the voltage values from temperature sensor input with address 000 (variable potentiometer, figure 14b) and from input with address 001 (2kΩ resistor, figure 14c).

Instead, figure 15 shows the experimental setup for testing of actuation section's switching functionality, managed by graphical application installed on P/I module (BE635 system). For signaling of correct switching operation, each power relays has been connected to a LED, following the circuital scheme shown in upper right of figure 15.

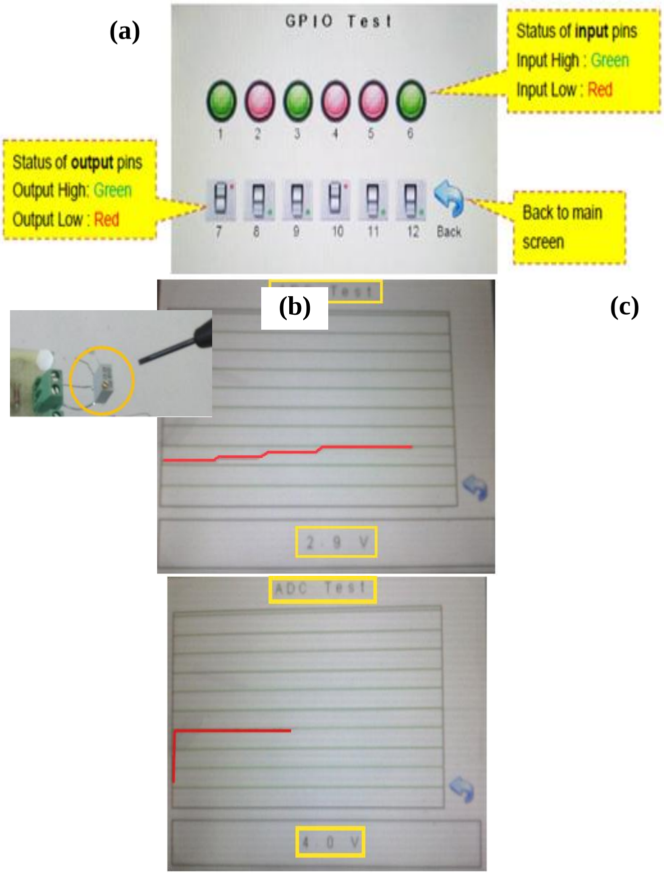


Figure 14. Functional testing using BE635 touch-screen display: screenshot of GPIO pins management application for multiplexer addressing (figure a) and of ADC test application with voltage values detected on variable potentiometer with 000 address (figure b) and on 2kΩ resistor with 001 address (figure c).

As shown in figure 15, the obtained results have confirmed the proper functioning of actuation section; in fact, moving to ON position the correct graphical switch on touch-screen display (in the green box in figure 15), the related LED turns ON as expected, reporting the correct switching of the corresponding power relay. In the final version of the control system, GPIO pin's state will be controlled by microcontroller through firmware execution; thanks to GPIO test application on BE635 P/I module we have verified that designed circuital schemes and realized physical connections were error-free.

ISSN: 2278-0181
Vol. 4 Issue 04, April-2015

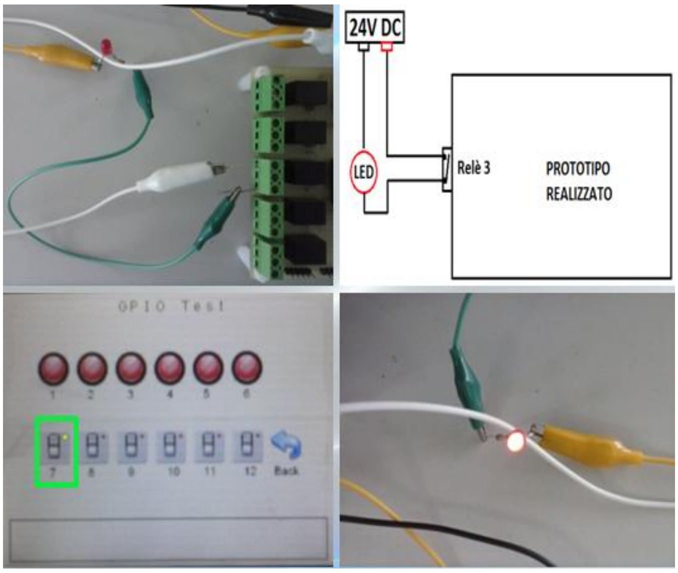


Figure 15. Testing of switching functionality of the power relays installed on sensing/actuation prototype board by means of switching commands sent through touch-screen display on processing/interface module.

As final test for monitoring apparatus, a real PT1000 temperature sensor has been connected to the first sensor input of the realized S/A module, as shown in figure 16. Sensor resistance changes according to external temperature, generating a variable voltage value across it.

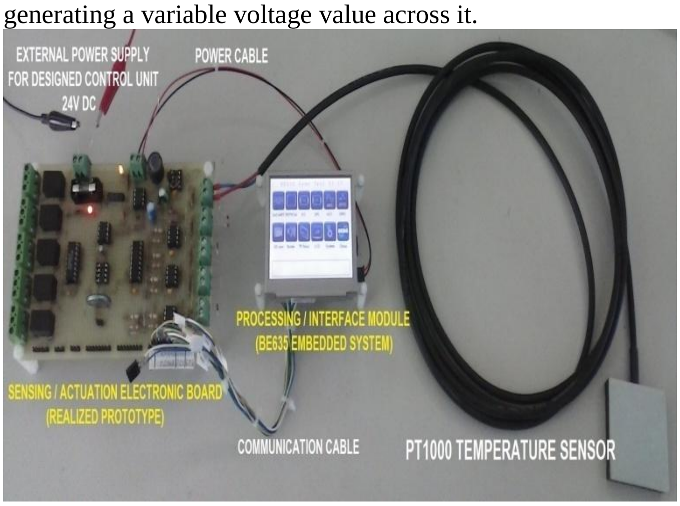


Figure 16. Laboratory experimental setup for electrical testing of sensing/actuation and processing/interface modules and of their communication for representation on display of temperature detected by PT1000 sensor.

After proper conditioning, this voltage signal is sent, by correct addressing of multiplexer 74HC4051 IC, to microcontroller's ADC input for voltage detection and subsequent visualization through ADC test application, as shown in figure 17. Environmental temperature has been preliminarily detected through laboratory digital equipment (figure 17a); at 18.2°C PT1000 sensor exhibits a resistance value equal to 1070.2Ω and so the voltage value expected at gain stage's output was about 1.03V, as shown in software simulation reported in figure 17b.

Figure 17c shows the voltage value actually detected by microcontroller and displayed on P/I module through ADC test application; this value is consistent with the expected one.

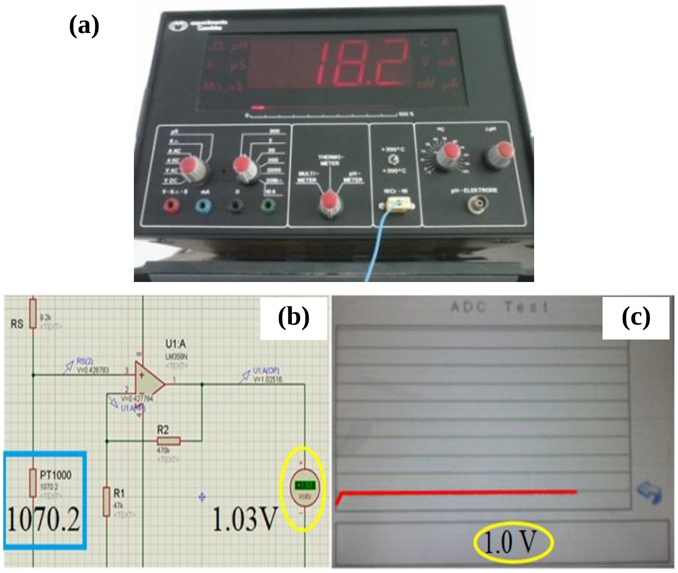


Figure 17. Environmental temperature detected by laboratory digital instrumentation (a), software simulation of the expected voltage value at gain stage output (b) and real voltage value detection read on P/I module through ADC test application (c).

In the final version of the control system, the voltage values detected by PIC's ADC will be related to the corresponding temperature by firmware programming, in order to make the system able to manage thermo-solar plant on the basis of acquired data.

In conclusion, successfully verified the proper interaction between designed S/A board and P/I BE635 module, the future work will regard on the realization of the SMT-based PCB for S/A board (figure 18), the implementation of the final apparatus with proper packaging and the microcontroller programming with dedicated firmware for thermo-solar plant's managing.

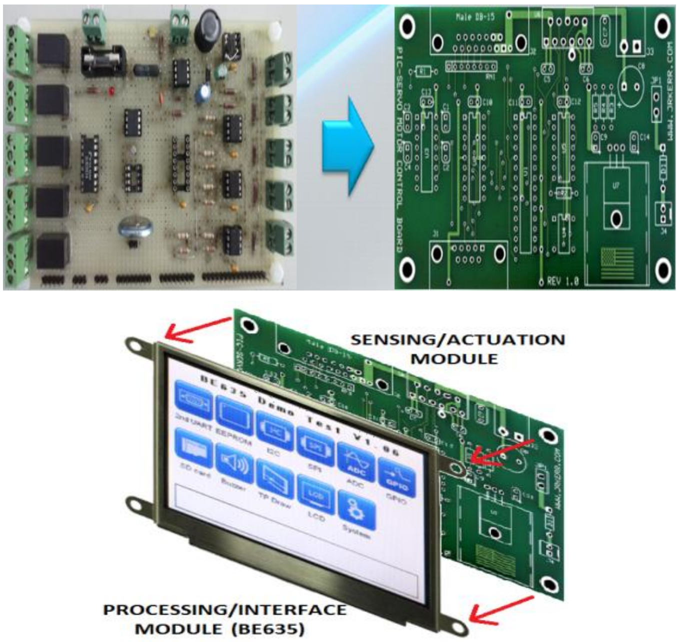


Figure 18. PCB realization for the S/A prototype module in order to obtain the final structure of the control system after proper packaging.

These operations will make possible the test of designed control unit on field for the management of a real thermo-solar plant, in order to verify the proper functioning of the implemented control system and the consequent energy saving for the user.

VI. Conclusion

Aim of this work was the design, realization and testing of a programmable and flexible control system for thermo-solar plant's control and management, in order to maximize its efficiency and energy saving. This system has been thought with some innovative characteristics, such as a graphical touch-screen interface and the possibility of being accessible both locally and remotely.

The hardware structure of this system has been conceived with a modular architecture, composed by two different blocks: one with processing and interface tasks and the other one with sensing and actuation functions. For the first module it was chosen the Bolymin BE635 embedded system, while the second one has been designed and realized in prototype form. After a first electrical testing, the two blocks have been interconnected in order to verify the proper functioning and data/commands exchanging.

Starting only from a concept, it was realized and tested, although in prototype form, the complete hardware structure of the control system. This work's state makes possible any future operation on designed system, with the aim of implementing the final apparatus.

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