Design and Implementation of a on-board Device for Photovoltaic Panels monitoring

Lorenzo Ciani[1], Loredana Cristaldi[2], Marco Faifer[2], Massimo Lazzaroni[3] and Marco Rossi[2]

[1]Dipartimento di Ingegneria dell'Informazione - Università degli Studi di Firenze - Firenze, Italy
lorenzo.ciani@unifi.it
[2]Dipartimento di Elettrotecnica - Politecnico di Milano - Milano, Italy,
loredana.cristaldi@polimi.it - marco.faifer@polimi.it
[3]Dipartimento di Fisica - Università degli Studi di Milano - Milano (MI), Italy
massimo.lazzaroni@unimi.it

Abstract — **Nowadays the world energy infrastructure is subjected to a progressive transformation. In fact it is already possible to notice the growing number of distributed small generation units, based on different technologies, directly connected to the power grid. At present the energy that can be produced by the sun and wind seem to be the most promising renewable energy sources. The use of the solar energy requires to optimize the efficiency of the converting chain and to maintain the performances of the system. These requirements highlight the need to equip photovoltaic (PV) plants with efficient condition monitoring tools. In this paper a hardware solution for monitoring system that allows implementing algorithm devoted to check the dependability of the PV panels and to improve the overall system efficiency is presented.**

Keywords—measurement; reliability; diagnosis; testing; temperature measurement, voltage measurement, current measurement.

I. Introduction

It is well known that PV plants are one of the most useful and easy-to-implement system for the use of renewable energy sources. However, systems based on photovoltaic conversion are characterized by low conversion efficiency against costs of installation which normally provide an economic return in twenty years. These considerations highlight the need to maintain high efficiency of the plant; this condition is possible only through both the use of optimized conversion algorithms and the use of proper maintenance strategies [1] - [8].

Currently, photovoltaic systems are monitored through monitoring apparatus which extract information devoted to the assessment of the overall performance of the system.

In previous works the authors have been demonstrated as the working point of a grid-connected plant (denotes as Maximum Power Point – MPP) is a key indicator for monitoring the efficiency of the plant itself. MPP is normally determined by means of dedicated optimization algorithms.

As just shown in [8], MPP can be used to evaluate the opacification due to the soiling of the panel surface but MPP variation is even a symptom of malfunction due to breakdown of the panel cells.

In order to verify the status of the PV panel using strategy based on the panel performances (*e.g.* approach based on MPP), the measurement of electrical and physical quantities measured on the PV panel are strictly required. Voltage, current and temperature can be used both for maintenance policy ([5], [8]), diagnosis algorithm definition ([1], [3] and, in particular, if the solar radiation is known or acquired, improve the conversion efficiency using MPP tracker based on the model of the panel ([9], [10]).

Starting from these considerations, the aim of this paper is to propose a low-cost on board monitoring device that allows both to identify any malfunctions and, if used with devoted conversion system, to achieve optimal conversion conditions.

The paper is organized as follows. In Section II the system design is presented and deeply discussed. In Section III the reliability analysis is implemented, the characterization tests are described in Section IV and conclusions are presented in Section V.

II. System Design

In order to assure the monitoring system requirement highlight above, a board able to measure the physical and electrical quantities has been designed.

The proposed board measures PV panel voltage, PV panel current and the temperature of the PV panel. The board is also equipped with an RS485 bus. The bus is necessary because allow to connect the board with other boards or the industrial network devoted to manage the plant in which the PV panel is installed. As far as the temperature measurement different approach has been presented in literature [11], [12]. However, in actual application a simple approach have to be preferred in order to obtain a cost effective board. For sake of simplicity only the more important functions are here discussed (Section II.*a* through II.*c*) and the complete schematic is not depicted. In Section II.*d* further detail concerning data communication and microcontroller will be presented. The board layout as implemented is also reported (Section II.*e*). It is important at this point to remember that the board is designed in order to implement a diagnostic tool that helps to improve all aspects concerning the system reliability [13].

A. Current Measurement

Current measurement is performed by a Hall-Effect Sensor. In particular, the used device consists of a precise, low-offset, linear Hall sensor circuit with a copper conduction path located near the surface of the die. The internal resistance of this path is very low (1.2 mΩ typical), providing in this way low power loss, that is very important for actual application. The current flowing through the copper conduction path generates a magnetic field which is sensed by the integrated Hall IC and converted into a proportional voltage. Device accuracy is optimized through the close proximity of the magnetic signal to the Hall transducer. Finally, a proportional voltage is generated by a low-offset, chopper-stabilized BiCMOS Hall IC. Further interesting characteristic of the selected device is the availability in surface mount release (SMD). The output of the sensor is *ratiometric*, *i.e.* the device gain and offsets are proportional to the supply voltage. This feature is very useful in actual application where the voltage proportional to the current is acquired by an A/D converter that can derive their LSB from a reference voltage input (or, in industrial application, from the supply voltage) and if the reference voltage varies, then the LSB varies proportionally. In actual case both the current sensor ACS712 output and the LSB of the A/D converter track any variations in the reference voltage source. Therefore, reference voltage variations will not be a source of error in the analog to digital conversion (ADC) of the voltage proportional to the measured current.

The output voltage *vs* input current is described by the following equation [14]:

$$V = aI + b. \tag{1}$$

that it is the equation of a straight line with slope and y intercept respectively:

$$\begin{cases} a = 0.1 \\ b = 2.5 \end{cases} \tag{2}$$

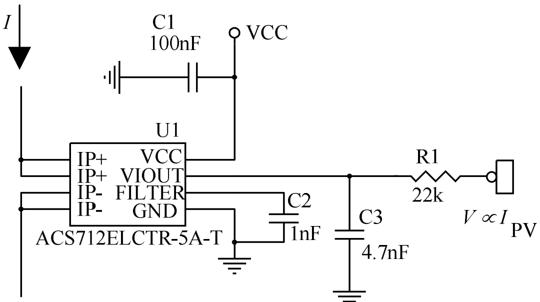


Figure 1. Current measurement circuit. The output voltage is proportional to the input current (plus a constant as described by equation (1).

The sensitivity is 100 mV/A as the slope coefficient in the previous equation highlight. The circuit for current measurement is depicted in Figure 1.

B. *Voltage Measurement*

The PV voltage can be measured by different approach. However, considering the actual application it is important to use a simple solution. Isolation, in fact it is not necessary and this fact allows us to design a very simple circuit for voltage measurement. The circuit for voltage measurement is depicted in Figure 2.

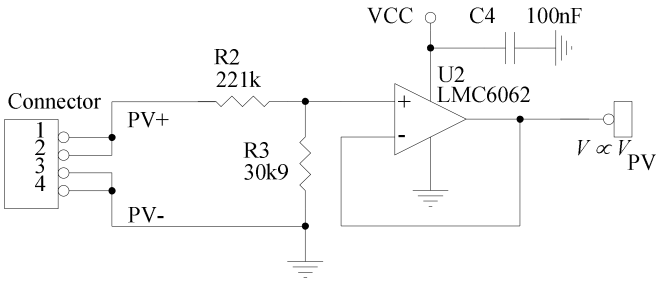


Figure 2. Adopted circuit for PV voltage measurement.

C. *Temperature Measurement*

Temperature measurement is performed by silicon temperature sensor. The used temperature sensor is the TC1047A from Microchip [15], [16]. It is well known that integrated Circuit sensors measure temperature by monitoring the voltage across a diode. The device uses a bipolar temperature sensing diode that is built from a substrate of a CMOS IC. The bipolar diode is created from a PNP transistor which is formed by combining the appropriate P and N junctions.

The transfer function of the device is linear [15] and the output voltage is related to the temperature by the following equation:

$$V_{out} = m \cdot T_a + q \tag{3}$$

where the slope coefficient m is 10 mV/V and the y-intercept coefficient q is 500 mV as depicted in Figure 3.

The PV panel temperature can be so evaluated starting from (3) in the following way:

$$T_{PV} = \frac{V_{out}(\mathrm{mV}) - 500(\mathrm{mV})}{10(\mathrm{mV}/°\mathrm{C})} \tag{4}$$

where T_a is the rear PV panel temperature in °C and V_{out} is the sensor output voltage in millivolt.

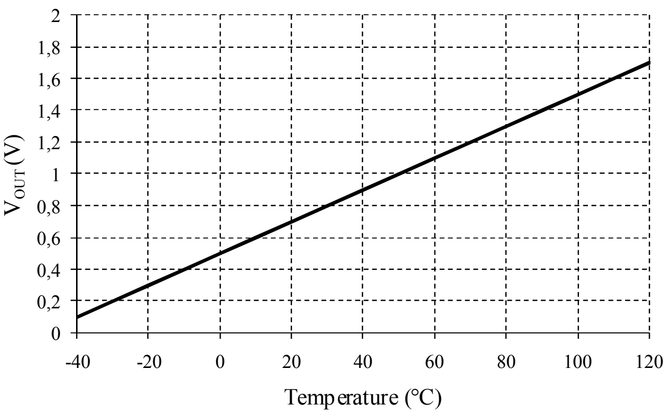


Figure 3. Transfer function of the temperature sensor [15].

The circuit for temperature measurement is show in Figure 4. The voltage proportional to the temperature is filtered before to be read from the A/D converter.

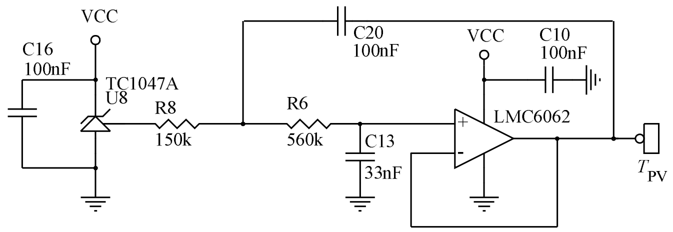


Figure 4. Adopted circuit for temperature measurement.

D. *Microcontroller and data communication*

The board is supervised by a low range Flash Microcontroller with Extreme Low-Power Management (XLP) Technology: the PIC16F1825 from Microchip [17]. In order to manage all the board function the following features are necessary: 3 analog input for voltage, current and temperature measurement, RX and TX (and Enable) in order to implement an RS485 bus. The bus is necessary in order to connect the board with other boards or the industrial network devoted to manage the plant in which the PV panel is installed. If different board have to be connected on the same bus it is necessary to implement an optical isolation between boards. The RS485 transceiver (ISL81487 from Maxim) is so used with optical isolation devices (such as the HCPL0601 optical isolator from AVAGO). The analog input are implemented by a 10-bit A/D converter with $V_{FS} = 5$V. LSB for this converter is:

$$LSB = \frac{V_{FS}}{2^n} = \frac{5}{2^{10}} = \frac{5}{1024} = 4.88 \text{ mV} \tag{5}$$

The sampling frequency can changed within a range. The source of the conversion clock is software selectable via three bits (the ADCS bits) of a devoted register (ADCON1 register). It is however necessary to highlight that in actual application high rate of sampling frequency are not necessary.

E. *Board Layout*

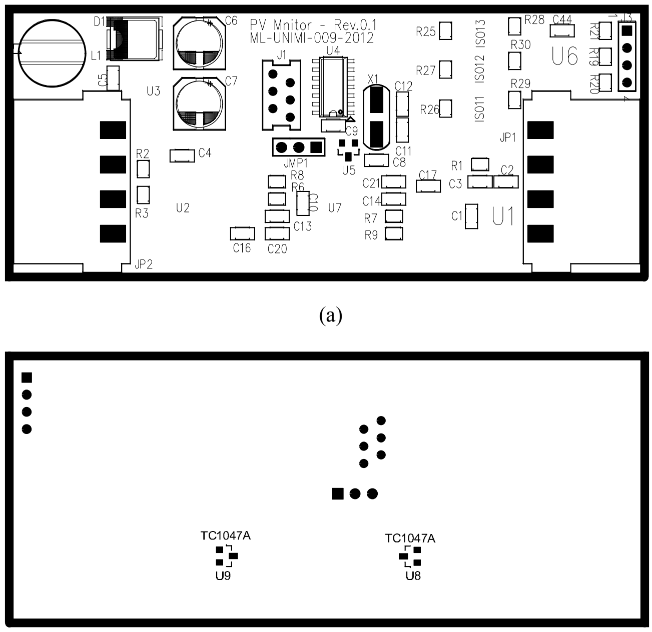
The designed board is represented in Figure 5. In particular in Figure 5.a is reported the silkscreen of the top (component side) where component are placed. In Figure 5.b is shown the silkscreen bottom where the two temperature sensor are placed. In this way the temperature sensor can be put directly in contact with the rear of the PV panel without the necessity of wire for connections.

III. Reliability Analisys

Since reliability is so crucial to a successful system design, it is important to quantify it. This is not as straightforward as measuring voltage, current or temperature. There is no method for directly measuring the absolute value of reliability of a circuit. There is no "reliability meter" that can be correlated to a circuit and give a real-time readout.

Instead, the reliability assessment must be made either by some kind of prediction or by a measurement made over a considerable period of time.

Therefore an estimation of the reliability performance represents a fundamental step before the final development of the system under examination.



(a)

(b)

Figure 5. Layout of the designed board. In (a) the silkscreen top is depicted wheras in (b) the silkscreen bottom (mirrored).

Reliability analysis has been made according to the database MIL-HDBK-217-FN2 (Mode I case 3) [18]. As hypothesis we assumed:

- series functional configuration for the whole system;
- operative temperature of 40° C;
- operative environment *GF* - Ground Fixed, fixes non weather protected environment, characterized by thermal and mechanical stresses directly influenced by the natural climatic conditions.
- Duty Cycle equal to 100% (24/24 hours);
- independent failures: the failure of any one component is statistically independent of the failure or success of any other;
- constant failure rate: even if very few failure mechanisms strictly satisfy a "constant rate" type occurrence law, the dispersion of many failure mechanisms, although they are cumulative and therefore increasing with time, is such that they can be deemed to be constant over the considered time interval. Furthermore, the increasing number and diversity of components, even on a single board, will be close to a constant. For these reasons, the assumption of a constant failure rate is still the most relevant approach for estimating the predicted reliability of a system.

Based on this assumption the MTBF and the failure rate of the whole system can be calculated by Part Stress method. It provides additional generic scaling factors intended to account for the reliability degradation effects of usage stresses such as power, voltage, and temperature. Stress factors may be used earlier in the design process through component derating guidelines, which establish stress rules for components in a particular circuit application. MTBF has been estimated equal to 250.380 hours with a corresponding failure rate of about 3,99 failures/10^6 hours.

Figure 7 shows the plots of subsystem and system MTBF Vs temperature. From a climatic-environmental point of view, the most critical sub-systems are the PV panel current measurement system, the microcontroller section and the temperature measurement system.

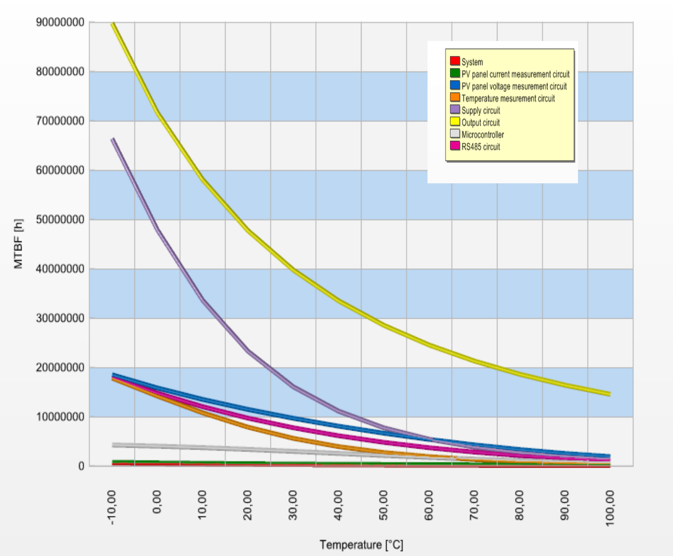


Figure 6. System MTBF vs temperature.

It can be observed that the trend plotted in Figure 6 highlights the negative effect that temperature has on the life of the system [19]. Therefore, based on the reliability prediction results, several environmental test are carried out in order to verify that our design is robust enough to survive and operate in its operative environment. These tests are mandatory in order to know if hardware will eventually fail and it's important to know which section, as above described, of the hardware fails first. Starting from these results, it is possible to modify the system design in order to eventually make it more reliable, regardless of how severe the service environment will be. Environmental testing not only confirms quality through such tests as simulation testing and product life testing, such activity also could be defined as a fundamental prerequisite to quality assurance.

According to [20] the proposed measurement device can be assimilated to the family devices operating in "*Outdoor, protected*" environment that corresponds to equipment that are partially covered to protect them from direct rain, sun, wind-blown dust, ice, fungus, and radiation to the cold night sky, etc. From this classification, it has been possible to select the test severity and duration properly. In fact, if the selected stress level is too high, the equipment under test might be overstressed and the failure mechanism might be different from failures of the product under normal use condition. In particular, three different environmental tests were carried out:

- dry heat test;
- cold test;
- thermal cycling test.

The object of this test sequence is to determine the performance characteristics of the proposed PV monitoring device to show (within reasonable constraints of cost and time) that the component is capable of maintaining this performance after exposure to the simulated service natural environmental conditions for which it is intended to be applicable [20].

The dry heat test allows to determine the ability of the device under examination to be used, transported or stored at high temperature. In this case a temperature of 75°C and a test duration of 24 hours has been chosen in according to the cited Standard [20].

The second phase is the cold test carried out in order to validate the correct functioning of the device to operate, transported or stored at low temperature. The system has been exposed to -20°C during 24 hours [20].

The final test is the thermal cycling test. This kind of test is conducted to determine the ability of components withstand mechanical stresses induced by alternating high and low temperature extremes. By means of this test it is also possible to demonstrate the readiness of the hardware to operate in the intended cyclic environment. The thermal cycling test profile is shown in Figure 7.

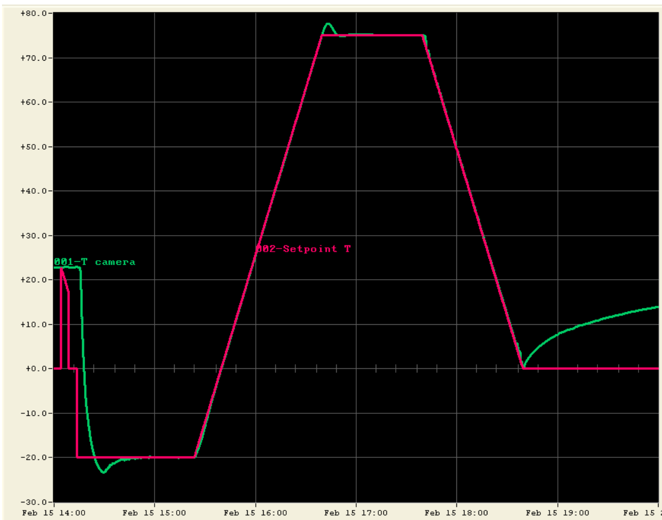


Figure 7. Fitted Thermal cycling test profile.

The rate of change of temperature between the low (-20°C) and high (+75°C) extremes was about 100 °C/h and the component temperature was remained stable at each extreme for a period of 1 hour (dwell time). The cycle time was selected equal to 4 hours and the number of performed cycles was equal to 50.

In compliance to the cited Standard [20] a first visual inspection has been carried out. It has shown that mechanical and welding damages have not found.

IV. CHARACTERIZATION TESTS

Characterization tests of the developed PV monitoring system are carried out before and after the environmental test sequence.

The devices used for the developed board are in compliance with the selected range of temperature summarized in the following table.

Table I – Components temperature limits

Device	T_{min} (°C)	T_{max} (°C)
ACS712	- 40	+ 85
PIC16F1825	- 40	+ 125
LMC6062	- 40	+ 85
LM2675	- 40	+ 125
HCPL0601	- 40	+ 85
TC1047A	- 40	+ 125

Two different experimental setups have been used. The first one was used in order to perform Voltage and Current characterization. In the second one the section devoted to the temperature measurement has been tested.

In order to verify the effects of the applied thermal cycling test on the functions of the designed board voltage, current and temperature characteristics have been evaluated before and after the environmental test sequence.

The voltage is measured by the circuit shown in Figure 2. The output of this circuit is acquired by the 10 bit ADC of the microcontroller. The measured values are reported in Figure 8. In the same figure the reference values are measured by a 6½ Digit Fluke 8845A multimeter. The good fit between the two characteristics is shown in Figure 8 where the two chracteristics are pratically overlapped. In the same figure are also reported the two equations of the linear interpolated line.

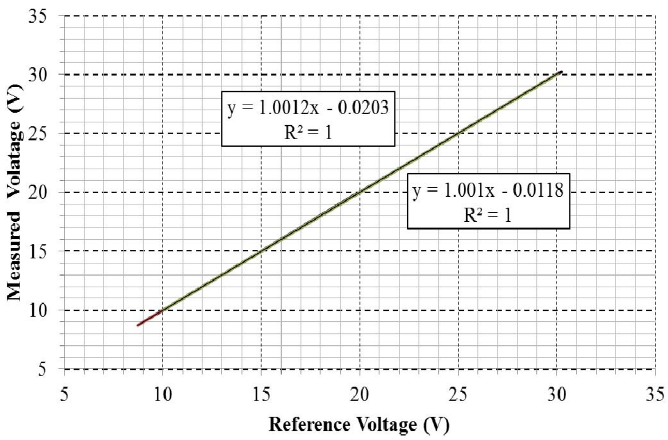


Figure 8. Fitted line plot of the Voltage. The voltages have been evaluated before and after the thermal cycling test. The good fit is shwon in figure where the two chracteristics are pratically overlapped.

In the following Figure 9 the current characteristics are depicted. Here it is possible to highlight that a little change in offset results after the thermal cycling test is occurred. However the gain isnot pratically changed. It is important to noted that the ADC when used for current measurement is not used over all its range (0 – 5V).

The experimentally evaluated equation for current transducer is the equation of a straight line (see Eq.(1)) with slope and y intercept respectively:

$$\begin{cases} a = 0.0996 \\ b = 2.4938 \end{cases} \quad (5)$$

After the termal cycle the slope and y intercept are:

$$\begin{cases} a = 0.1012 \\ b = 2.4968 \end{cases} \quad (6)$$

In the following Figure 10 the error is reported. The lines denoted as *Typ*, *Min* and *Max* represent the maximum error allowed taking into consideration the manufaturer specification. Points denoted as *Actual Before* are the errors evaluated respect the theoretical expeted values if the sensor operate with typical transfer function as described by Eqs (1) and (2). The points denoted as *Actual After* are the same errors but evaluated after the thermal cycle.

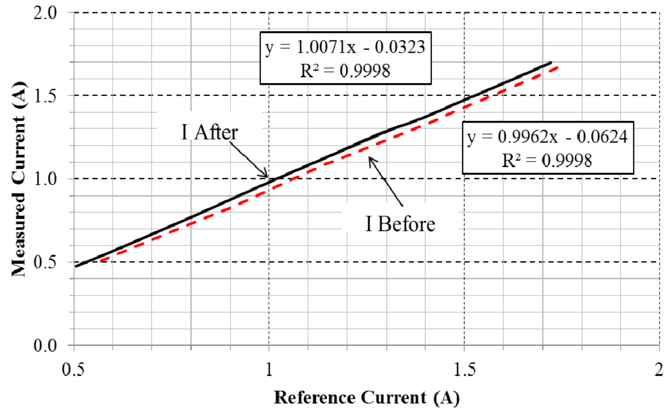


Figure 9. Fitted line plot of the Current.

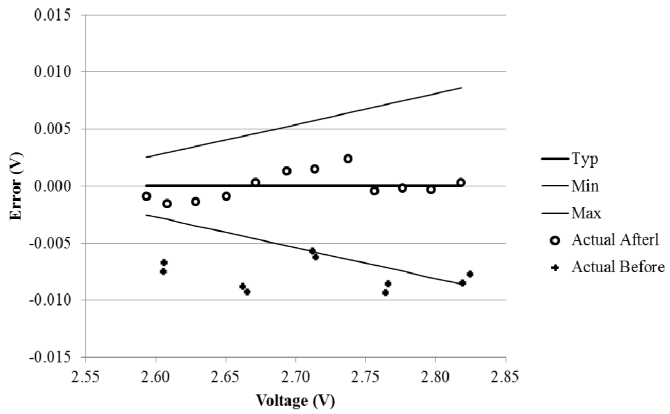


Figure 10. Errors in current measurement.

The aging has not significately modifyed both the gain and offset of the system respect to the nominal condition, only an offset reduction can be noticed. In a way, such reduction is related to the test ageing effects that lead the compontents to the optimal perfomances phase in which the manufacturer defines the functional specifications. This aspect will be object of future works. However, as can be noticed in Figure 10 the errors evaluated for the sensor after the thermal cycle are well inside the manufacturer specification.

In Figure 11 the errors in temperature measurement are depicted. The experimental activity lead to conclude that temperature measurements present an error of about 2 % for positive temperature. Instead, if negative temperature measurements are performed the error rise quite rapidly up to about 15 %. The difference between the value obtained before and after thermal cycle are not significative.

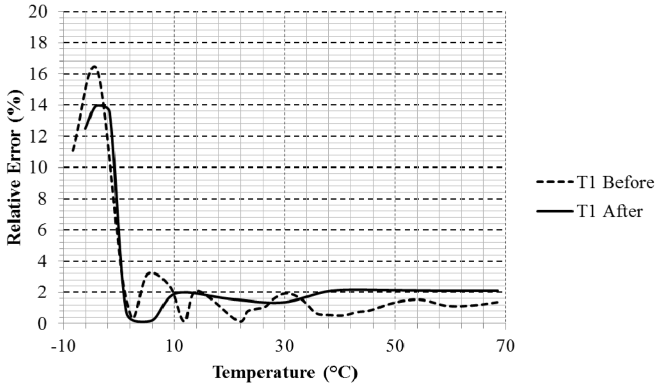


Figure 11. Fitted line plot of the Temperature for Sensor 1 (U8 in Figure 6.b). Reference values are obtained by a termocouple located near the board inside the climatic chambre and it is denoted as Temperature on x-axis.

V. Conclusions

Monitoring and control of photovoltaic systems is essential to allow a reliable functioning and to obtain the maximum yield of the whole solar plant.

In this paper a board devoted to the photovoltaic panels monitoring is proposed. The board is able to measure PV panel voltage, current and temperature and to exchange the measured data to the plant monitoring system. Moreover it has been designed in order to implement a diagnostic tool that helps to improve all aspects concerning the system reliability and efficiency. For this reason a detailed reliability analysis of the proposed device has been carried out and several environmental tests have been implemented in order to verify the real condition of use in the field of application.

Finally, the characterization of the measurement section of the board has been carried out. In order to qualify the board in different environmental conditions, a climatic test sequence on the prototype has been done and the condition of the board after these tests, mainly thermal cycling, has been tested and discussed. The analysis highlights a good agreement between the reference values defined during the design phase and those evaluated before the thermal test. The effects of the thermal test have not introduced significantly modification of the system features.

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