

An Automatic Thermal Cycling based Test Platform for Thermoelectric Generator Testing

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Abstract—Thermoelectric (TE) modules are solid-state devices that convert directly thermal energy in electrical energy. However, they can undergo performance degradation due to thermal cycling. In the present study, a control-based test platform that is capable to apply specific thermal cycling pattern at periodic intervals is presented in order to evaluate performance degradation that influence the TE module lifetime. Using this test platform, some parameters and the figure of merit ZT of a commercial TE module are measured before and after thermal cycling application. An important feature of the proposed platform is that the applied thermal cycling is bipolar, that is, it is possible to apply positive or negative temperature difference and, through this, performance degradation would be observed after only 548 thermal cycles much lower than previous works.

Index Terms—Thermal cycling; experimental platform; performance degradation evaluation.

I. INTRODUCTION

Thermoelectric (TE) modules are solid-state devices used in the direct conversion between thermal energy and electrical energy [1][2][3][4][5]. A TE module can either operate in an electrical power generation configuration, which a temperature gradient generates a electrical potential difference that, in this case, the TE module can be denominated Thermoelectric Generator (TEG), or in a thermal power generation configuration, which an electrical energy generates a temperature gradient that, in this case, the TE module can be denominated Thermoelectric Cooler (TEC). The higher is the temperature gradient $\Delta T = T_H - T_C$ on the hot and cold sides of the TEG (see Figure 1), the higher is the resulted electric voltage V_S , where this relation is given by the $V_S = \alpha \Delta T$, where α is the Seebeck coefficient. Taking TEC into consideration, the higher is the electrical current I applied into this, the higher is temperature gradient ΔT produced by the heat flow produced, Q_p , where this relation is given by the $Q_p = \pi I$, where π is the Peltier coefficient.

Thermoelectric conversion efficiency is limited accordingly to the intrinsic materials [6][7][8] that the TE modules are

composed of. However, that material can suffer degradation as a result of subjecting it to thermal stress and, consequently, thermoelectric conversion efficiency also can be degraded [6][9]. In summary, the performance of TE modules may present degradation according to the thermal cycling they are subjected [6]. In order to evaluate and to accelerate the performance degradation of TE modules, thermal cycling controlled by test platform are used.

With respect to previous test platform for thermal cycling, Park *et. al* [6] proposes a test platform where the temperature of only a side of the TEG-under-test is controlled and, as a result, the achieved temperature varies positively on that side, while the other side is fixed in 20°C. In this test platform, the TEG-under-test is sandwiched between a heat spreader and water cooling block and performance degradation was observed after 2,000 thermal cycles. In other test platform, the temperature of one side of the TEG-under-test is controlled but the temperature of the other side is maintained in room temperature $\approx 23^\circ\text{C}$ [1]. Using this test platform, performance degradation was observed between 10,000 and 45,000 thermal cycles.

As can be observed in these works, only one side of the TEG is allowed to change its temperature and this does not correspond to a real situation when TEG is placed in an uncontrolled temperature environmental. In this way, a test platform that is possible to set both T_H and T_C in an economical and effective way is welcome and turn to be very useful to perform empirical testing on TEG.

This paper presents a test platform for TEG performance degradation evaluation which is based on a scheme that the TEG-under-test is sandwiched between two TEC which both are driven by a PID-based actuator controlled by a PC. An important feature of the proposed platform is that the applied thermal cycling is bipolar, that is, it is possible to apply positive or negative temperature difference because the symmetrical scheme used, that is, while a TEG-under-test side

is hot, the other side is cold or vice-versa (the latter is cold, the former is hot). For both side, the maximum achieved temperature is 85°C and the minimum was -5°C . Also, performance degradation in a commercial TE module has been observed after 548 thermal cycles much lower than previous works.

II. THERMOELECTRIC MODULE

Thermoelectric (TE) modules are devices that convert temperature differences directly into electrical energy and vice-versa and are made of semiconductor pairs connected electrically in series and thermally in parallel. These semiconductor pairs consist of n- and p-type thermoelectric materials (typically Bi_2Te_3 -alloys for moderm commercial modules) [1] and are disposed between two ceramic plates [3][10][11], as shown in Figure 1.

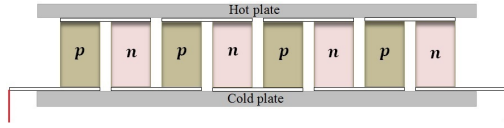


Fig. 1. Thermoelectric Module.

Basically, the operation of a TE module involves some effects, namely, Peltier, Joule, Fourier and Seebeck, that are associated with various energy transport mechanisms and phenomenon [12]. Equations (1) and (2) show the relationship between these effects, where n is the number of internal p-n pairs [12].

$$Q_H = n\alpha T_H I + K\Delta T - \frac{1}{2}I^2 R \quad (1)$$

$$Q_C = n\alpha T_C I + K\Delta T + \frac{1}{2}I^2 R \quad (2)$$

where Q_H and Q_C are the heat input to the TE module and heat output from the TE module, respectively, T_H is the temperature on the hot side of the TE module, T_C is the temperature on the cold side, $\Delta T = T_H - T_C$, α is the Seebeck coefficient, K is the thermal conductance, I is the current owing into the TE module, and R is the TE electrical resistance.

From Equations (1) and (2), the first term, $n\alpha T_H I$, represents the Peltier and Seebeck effects relationship that validates the reversibility presented by the TE module. The second one, $K\Delta T$, represents the Fourier effect and express the heat conduction, and the third term, $\frac{1}{2}I^2 R$, is the Joule heating effect. The Joule heat is distributed throughout the TE module, so $\frac{1}{2}$ of the heat goes towards the cold side, and $\frac{1}{2}$ of the heat goes towards the hot side.

III. PROPOSED TEST PLATFORM FOR TEG TESTING

The complete block diagram of the proposed test platform for TEG performance degradation evaluation is shown in Figure 2. It is composed of a PC computer, a data acquisition system (DAQ), and the test platform apparatus developed in

this work. A LabVIEWTM-based Virtual Instrument (VI) runs independently two PID controllers (PID_1 and PID_2) that control the thermoelectric coolers, TEC_1 and TEC_2 , in order to maintain their temperatures in the user-defined setpoints. The feedback paths to the controllers are performed by two K -type thermocouple TP_1 and TP_2 which were chosen for their sensitivity and their operation range. The TEG-under-Test is sandwiched by TEC_1 and TEC_2 as well as by heat reservoirs, as shown in Figure 2, in order to create a heat storage that allows a soft changing of temperature. The actuators for both TEC_1 and TEC_2 are carried out by two electronic power drives. In both ends of the apparatus, a heat sink is attached to a fan cooler in order to reject the heat flow on the opposite plate of the TECs. In order to reduce the thermal contact resistance, all plates and sides are connected thermally by a thin layer of thermal grease.

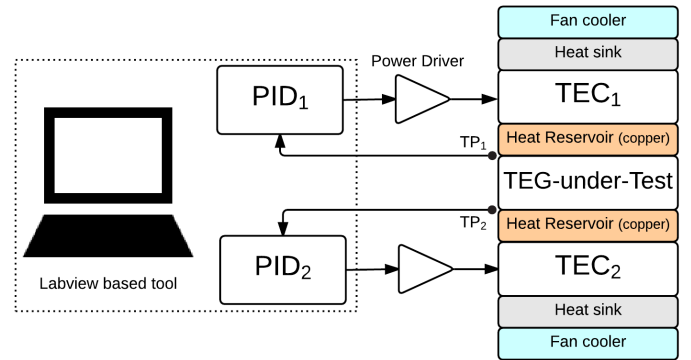


Fig. 2. Block Diagram of the Proposed TEG Test Platform.

As can be seen in Figure 2, from the TEG-Under-Test upward or downward the test platform is symmetrical. In this way, any TEC can generate T_H or T_C to be applied to the TEG-Under-Test, then the test platform is capable to produce positive $\Delta T > 0$, as shown in Figure 3(a), and negative $\Delta T < 0$, as shown in Figure 3(b), consequently generating heat flowing up-down and down-up, respectively. Figure 4 shows an ideal thermal cycling that can be obtained by the platform.

A. Thermal cycling Generation

In order to generate thermal cycling, the designed VI has to be configured properly setting up T_H , T_C , the cycle period T and the number of thermoelectric cycles, as shown in Figure 5. The produced ΔT is positive in $\frac{1}{2}T$ and ΔT is negative in the next $\frac{1}{2}T$ as shown in Figure 4. As a result, it is generated thermal cycling periods where the temperatures on both sides are inverted frequently resulting in stress in the thermoelectric material structure. With these applied thermal shocks, it has been possible to degrade the TEG-under-test in a shorter period of time when compared to other platforms as those presented in [9][1][6]. A picture of the experimental TEG test platform is shown in Figure 6.

The TE module used to operate as TEC and TEG was a commercial thermoelectric module made of Bi_2Te_3 . Specifi-

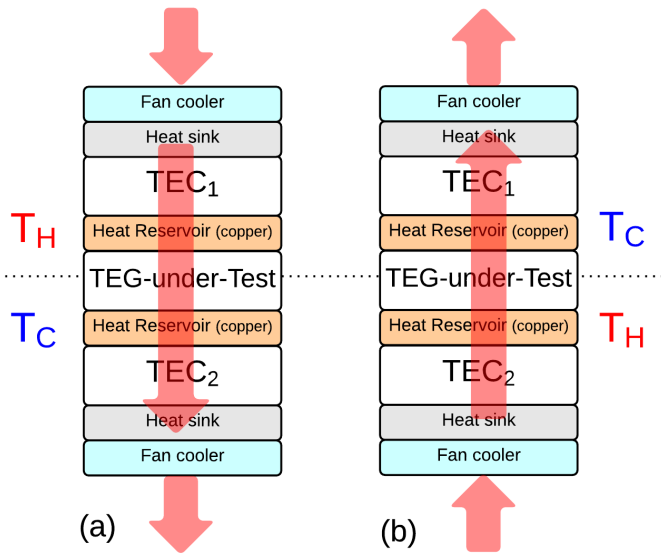


Fig. 3. Symmetrical Operation of the TEG Test Platform.

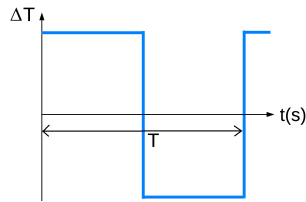


Fig. 4. Ideal Thermal Cycling aimed of the proposed platform.

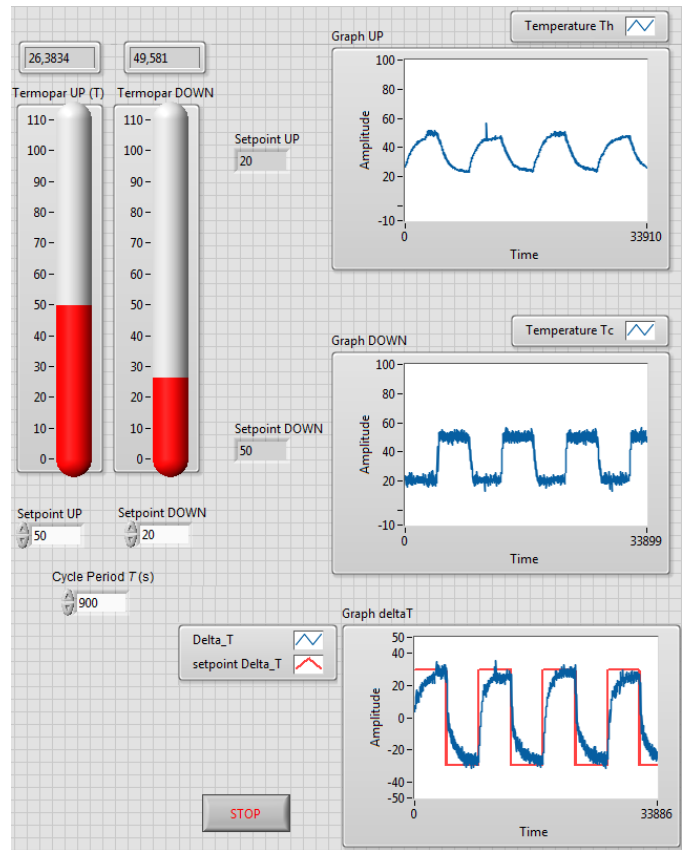


Fig. 5. Virtual Instrument.

cally, it was the model TEG1-241-1.0-1.2 from Everredtronics that presents the specifications given in Table I.

TABLE I
THERMOELECTRIC MODULE SPECIFICATIONS.

Specification	Value
Number of Thermocouples (pn junctions)	127
Dimensions	40 mm x 40 mm x 3,3 mm
T_{max}	235 °C
I_{max}	2.8 A
R_{in}	10.1 Ω

IV. EXPERIMENTAL RESULTS

In order to validate the proposed TEG test platform, it was carried out some experiments with a specified thermal cycling curve to evaluate some TEG parameters.

A. Specification of thermal cycling

In order to realise the experiments, the TECs temperature setpoints were set in 20°C and 40°C. The defined thermal cycling period was 900 seconds (15 minutes) meanings that an inversion of TECs temperature setpoints occur in each 450 seconds (7.5 minutes). The resulted thermal cycling curve

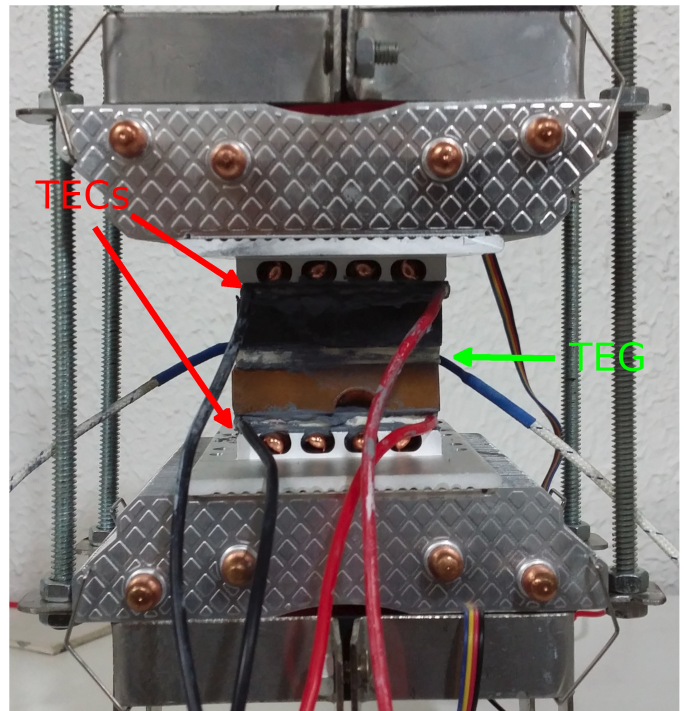


Fig. 6. Experimental TEG test platform.

is shown in Figure 7 where can be observed the temperatures measured in both sides of TEG-under-Test. The thermal cycling pattern applied on the TEG-under-test is shown in Figure 8 where ΔT is $+20^\circ\text{C}$ and -20°C after each half-cycle.

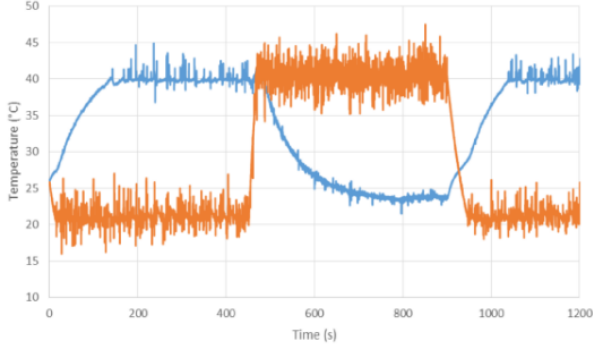


Fig. 7. Measured temperatures in both TEG-under-Test sides.

The chosen specification of the thermal cycling ΔT was defined based on environmental range which are often applied on thermoelectric-based energy harvesting system.

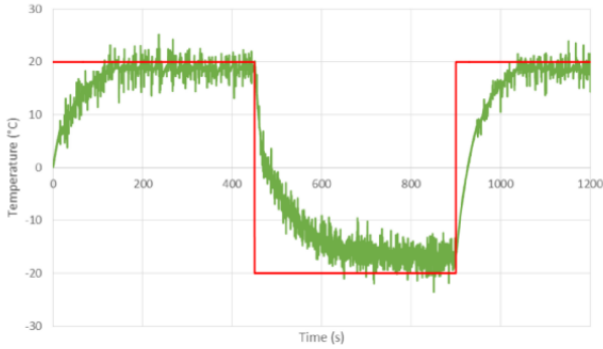


Fig. 8. Thermal Cycling.

B. Measuring and Calculations of thermoelectric parameters

In order to evaluate the parameters and the figure of merit ZT of the TEG, the Harman's method, proposed by T. C. Harman in 1958, was used. This method was chosen based on studies that compare it to other methods as described in [1] where the Harman's method presented satisfactory results for TEG manufacturers.

The Harman's Method is based on coexistence of two voltages: the Seebeck voltage (V_S) and resistive voltage (V_R). For that, an electric current I_T is applied in the TEG-under-test and when the sides of the TEG are on steady state, a total voltage (V_T) is generated by the sum of V_S and V_R voltages. In practice, to obtain V_S and V_R voltages the measurements are made as shown in Figure 9.

In Figure 9(a), I_T is applied at a period $t = t_{off} - t_{on}$ that is the time needed to achieve the maximum value of the total voltage (V_T) and in Figure 9(b) are presented the values of the V_T , V_S and V_R . At the instant that I_T is applied, only V_R is

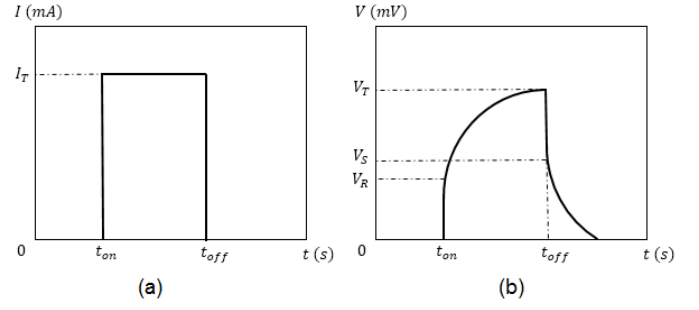


Fig. 9. Principles of Harman's Method.

presented on the TEG and when the V achieves its maximum value, V_R is added to V_S to produce V_T , as a result. When I_T is cut off, $V_R = 0$ and the only voltage produced is V_S produced by the last difference of the temperature measured. With the voltages and temperature difference values, these values are applied into the following equations for calculations of the TEG parameters:

$$R_{in} = V_R / I_T \quad (3)$$

$$\alpha = \frac{V_S}{\Delta T} \quad (4)$$

$$\rho = R_{in} \left(\frac{A}{L} \right) \quad (5)$$

$$\lambda = \left(\alpha \frac{IT}{\Delta T} \right) \left(\frac{A}{L} \right) \quad (6)$$

where R_{in} is the inner resistance, α is the Seebeck coefficient, λ is the thermal conductivity, ρ is the electricity conductivity of the TEG-under-measurement.

For the application of Harman's method, $I_T = 10\text{mA}$ and $t = 70$ seconds and the current curve was as shown in Figure 10. The measurement process based on Harman's method was performed 30 times for precision considerations. In Figure 11 is presented a voltage signal produced by the TEG that was used by the application of Harman's method.

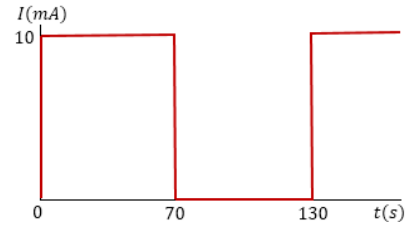


Fig. 10. Current Flow Cycle.

In order to evaluate the TEG-under-Test degradation, it is submitted to Harman's method before the thermal cycling and after a defined number of thermal cycling. The measured average voltages before thermal cycling were $V_T = 8.39\text{mV}$, $V_S = 6.48\text{mV}$, $V_R = 1.90\text{mV}$ and the average difference of temperature $\Delta T = 0.22^\circ\text{C}$.

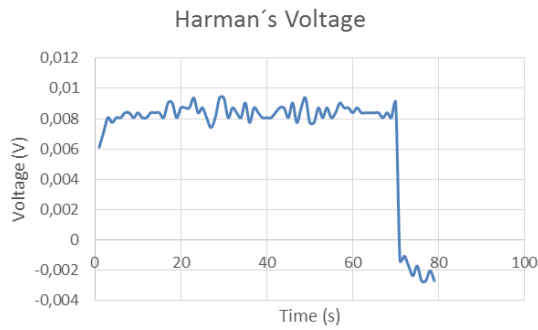


Fig. 11. Voltage Measured on Hardmans Method.

The standard TE performance metric is the non-dimensional figure of merit, ZT , which depends on the thermal conductivity λ , the electrical conductivity ρ and Seebeck coefficient (α), and is given by [1]:

$$Z\bar{T} = \frac{\rho\alpha^2}{\lambda}\bar{T} \quad (7)$$

where \bar{T} is the average temperature of the module (taken as the mean temperature of the hot and cold plates).

In this way, before thermal cycling, the TEG-under-Test parameters are calculated using Equation 3, 4, 5, 6 and 7 and the results are shown on Table II.

TABLE II
PARAMETERS BEFORE THERMAL CYCLING.

Inner resistance (R_{in})	1.69 Ω
Seebeck coefficient (α)	30.8mV/K
Thermal conductivity (λ)	2.16K.mm/mW
Electricity conductivity (ρ)	0.368 Ω /mm
Figure of Merit (ZT)	89.4 · 10 ⁻³

After 548 thermal cycling (about 137 hours), the TEG-under-test parameters have presented the values shown in Table III because the measured voltages were $V_T = 7.97mV$, $V_S = 6.21mV$ and $V_R = 1.76V$ and the difference of temperature was $\Delta T = 0.21^\circ C$.

TABLE III
PARAMETERS AFTER THERMAL CYCLING.

Inner resistance (R_{in})	1.85 Ω
Seebeck coefficient (α)	29.6mV/K
Thermal conductivity (λ)	1.97K.mm/mW
Electricity conductivity (ρ)	0.404 Ω /mm
Figure of Merit (ZT)	72.6 · 10 ⁻³

By comparing the values of Table II and III, it can be seen a variation on TEG-under-test parameters. The inner resistance increase 9.8%, the Seebeck coefficient reduces 3.9%, whereas his variation depends on Seebeck voltage, the thermal conductivity reduced 8.6% and the electric conductivity decrease

9.6%. The non-dimensional parameter ZT decreased 18.7% when compared to its value before thermal cycling.

V. CONCLUSION

In this paper, it was proposed a complete TEG test platform that shows to be capable to apply specified thermal cycling pattern in a thermoelectric generator under test. The proposed platform is composed of a PC computer and the test platform apparatus that is controlled by a LabVIEW™-based PID control system. As experimental procedure a TEG-under-test parameters are evaluated before and after thermal cycling by the Harman's Method. Experimental results have shown the applicability and efficiency of the proposed TEG test platform.

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