TESTING THERMOELECTRIC GENERATORS

Application Note n. 2901
by Thermoelectric Conversion Systems Limited (TCS)

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THERMOELECTRIC CONVERSION SYSTEMS

Introduction

Testing the performance of thermoelectric devices in not straightforward for a variety of reasons, in particular:

- it involves precise measures of temperature and heat
- there are no recognised standards
- the electrical operating point has profound influence over the thermal conditions and *vice versa*

Several manufacturers and research groups have each developed their proprietary test system resulting from particular needs, budgets and specifications. Many of these systems are described in the scientific literature and it is not the scope of this application note to provide an exhaustive description of them. This document focuses on the description of the techniques employed by TCS to test thermoelectric generators. TCS offers fully automated (optionally customised) thermo-mechanical test rigs and dynamic electronic loads specifically designed for thermoelectric power generators.

Test Considerations

There are some general rules that should be followed when dealing with TEGs:

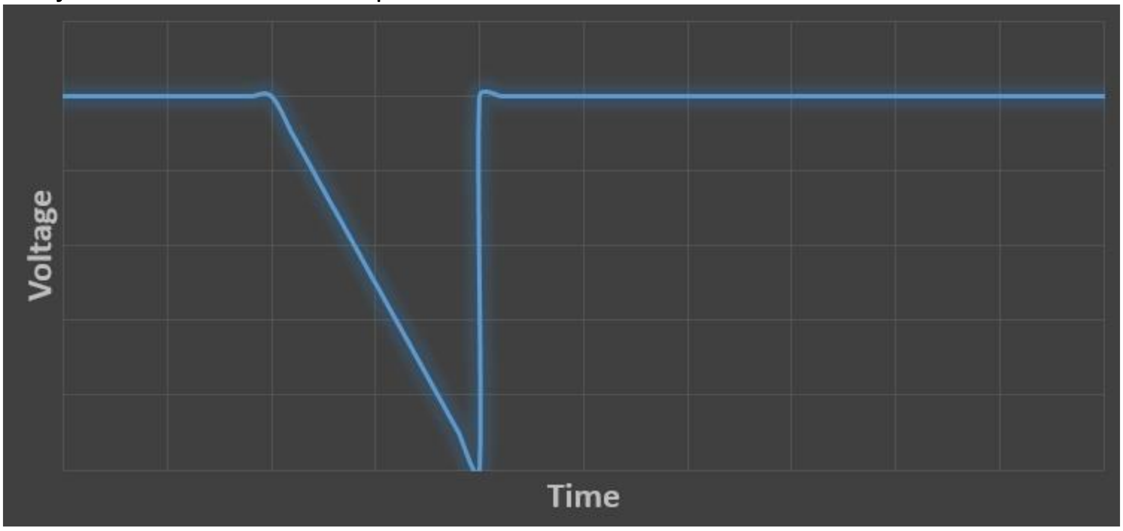
- contact resistances influence the performance and should be minimised. This leads to two important rules:
    - Use sufficiently high values (1 to 1.5 MPa) of mechanical load compression.
    - Use suitable thermally conductive material in the space between different bodies to minimise air voids. Optimum performance is obtained after cycling the device to high temperature to reduce thermal resistances.
- Temperatures across the TEG should be measured by high-precision thermocouples in direct contact with the faces of the TEG.
- when loading the thermoelectric device and drawing current, the device itself may expand and contract depending on the heat flux. A continuously updating pressure-compensation system is required to maintain a fixed pressure.
- thermocouples should be calibrated prior to installation in the test system and offsets included in the logging program.
- ensure a constant temperature cold side to minimise the impact of increased average temperature influencing the efficiency and power measurements.
- In constant thermal power operating modes, a characterisation of the test system losses should be done.
- thermal interface blocks should be sized appropriately to the Thermoelectric device under test, and they should be insulated to reduce losses to atmosphere under high temperatures, or when testing under 'constant power' regime.

Test under Constant Temperature Difference

The aim of this test is to obtain a number of current-voltage points on the electrical load characteristic of the TEG, when the temperature difference across the TEG is maintained at a chosen level. The series of equivalent resistive loads is successively applied to the terminals of the thermoelectric generators and measurements are obtained when –per each load point– the temperature difference is constant.
An electronic load controlled in current (CC) or voltage (CV) mode is usually connected to the terminals of the TEG. The test starts from open-circuit (OC) when the load is in CV mode, and from short-circuit (SC) when the load is in CC mode.
This test can be performed in two ways –“fast” and “slow” – each with its own advantages. Both test procedures are described below.

“Fast” I-V Scan at Constant Temperature Difference

It is well known that the effective thermal resistance of a thermoelectric device varies depending on the current flowing through it. This is due to the Peltier effect, which is parasitic in power generation mode. In particular, the effective thermal resistance reduces considerably with the load current. However, it can be experimentally demonstrated that when the load current is varied for less than 100 msec the impact on the thermal operating point is practically negligible.
The “Fast” I-V method relies on this basis. The test system first stabilises the temperatures across the TEG with the electronic load in open-circuit condition. Next, it triggers the electronic load to successively set and measures a series of current-voltage points. It is of fundamental importance that the load scan is executed as quickly (less than 100 msec as a guideline) as possible to minimise thermal effects. The figure below shows how the voltage at the TEG terminals is quickly ramped down from OC to SC and back to OC.
The advantage of this technique is that it produces an I-V trace extremely quickly. In order to do this, a fast-settling electronic load and measurement unit is required. TCS offers the RO3, a dynamic electronic load specifically designed for TEGs, able to perform fast I-V scans with adjustable number of load points.



"Slow" I-V Scan at Constant Temperature Difference

The "Slow" method is more accurate, as every load point is measured with the system in steady-state at the desired temperature difference.

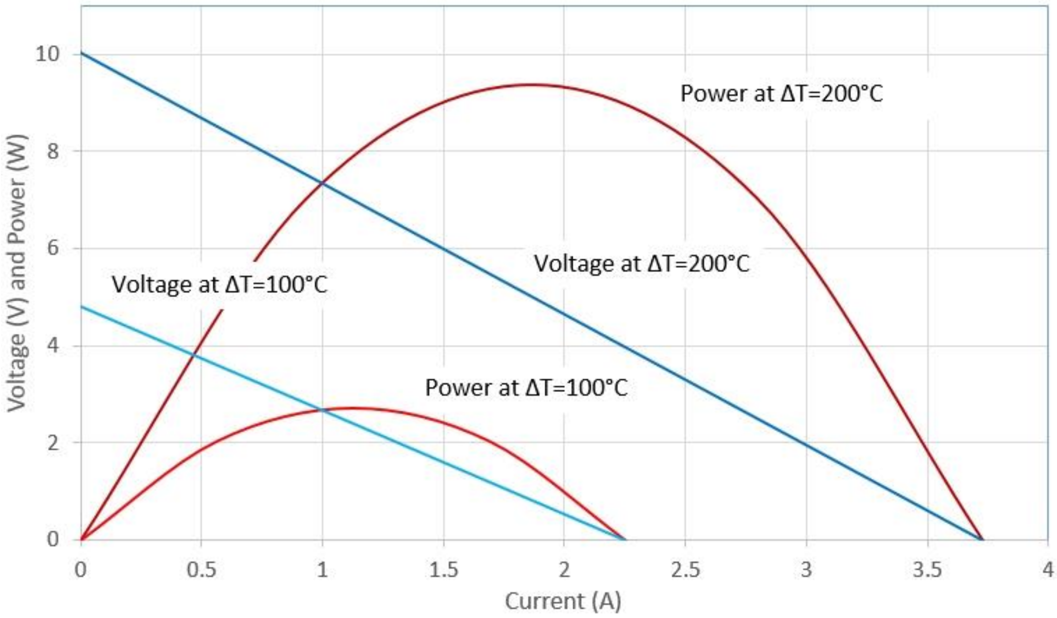
The scan can be started with the load in OC or in SC. The temperatures are adjusted to bring the TEG to the set temperature difference. When this is reached and maintained data are measured. The next load point is then set at the TEG's terminals. As a consequence the temperature difference will either increase (moving to lower current) or decrease (towards higher current). Therefore the thermal power through the TEG needs to be adjusted to account for the change in effective thermal resistance of the TEG. When testing from OC to SC the thermal power required to maintain the same temperature difference needs to be progressively increased to account for a decrease in TEG thermal resistance.

A new measurement is taken after the temperature difference is re-adjusted. The same procedure is followed for each required electrical load point until OC (starting from SC) or SC is reached.

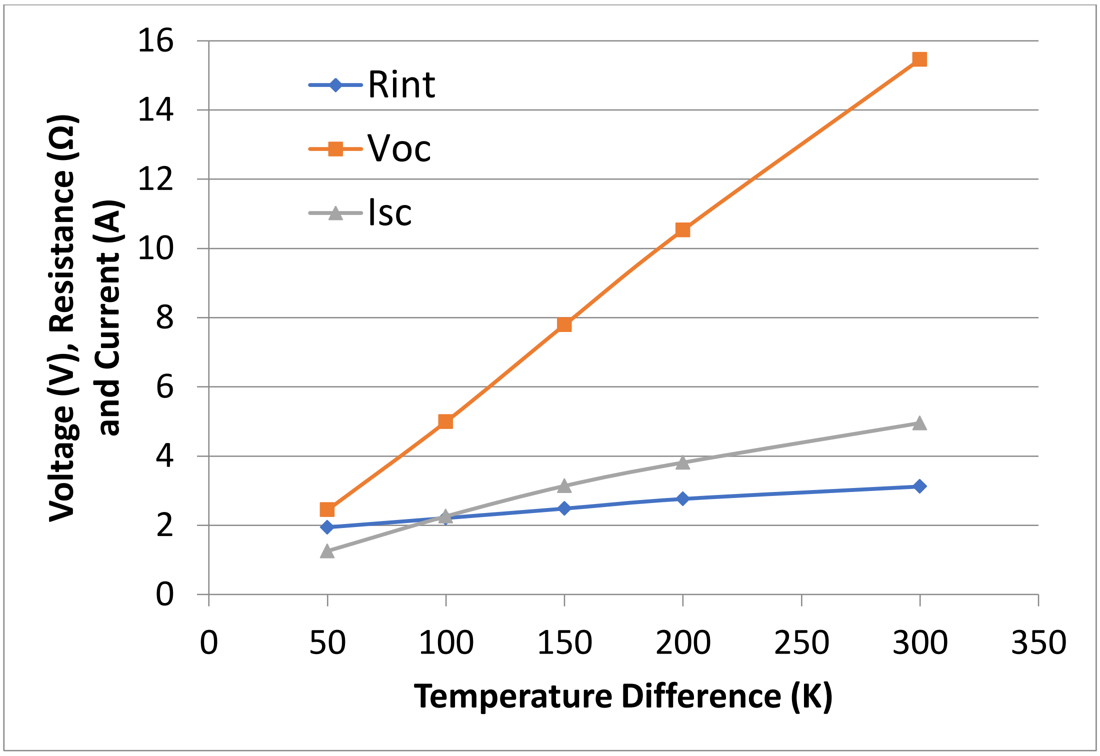
The "Slow" scan takes longer because the temperature difference is adjusted for each electrical load point, however, optimal accuracy is guaranteed by measuring all data points at the same temperature difference. The time required to obtain a complete I-V trace depends on the desired number of electrical points, on the thermal masses of the system that set the thermal time constant of the system, and on the response speed of the temperature controller of the test system.

What information is obtained by I-V Scans at Constant Temperature Difference

In most practical TEG systems the temperature difference is not constant and continuously varies depending on availability of heat from the source, e.g., automotive exhaust gas. For this reason constant temperature difference plots do not offer useful information about the quantity of electrical power that can be extracted by a TEG system. Nonetheless they offer useful information about the variation of important parameters –like open-circuit voltage, short-circuit current and internal resistance– with temperature and temperature difference.



The figure above shows the electrical characterisation of the monTEG™ device offered by TCS for two temperature differences –100 and 200 degrees–. In the plot, voltage and power are plotted on the vertical axis versus the current on the horizontal axis. In a similar representation the voltage is on the x-axis. The slope of the I-V lines represents the internal resistance of the TEG. It can be noted that the two blue lines are tilted at different angles, signifying a change in internal resistance. The OC voltage and SC current also vary with ΔT. These variations with temperature can be seen in the figure below, where Voc, Isc and Rint are plotted against the temperature difference.



If the test system is capable of either a) eliminating heat losses, b) measuring heat losses, or c) measuring heat flux accurately, then this test method can also offer information about the efficiency of the power generation at each load point as

$$\eta = \frac{P_{electrical}}{P_{thermal}}$$

and the thermal resistance as

$$R_{th} = \frac{\Delta T}{P_{thermal}}$$

As previously mentioned, R_{th} varies with the generated current, hence the effective R_{th} can be calculated at each point using the P_{th} that is required to maintain the set ΔT with that particular electrical load.

Test under Constant Heat

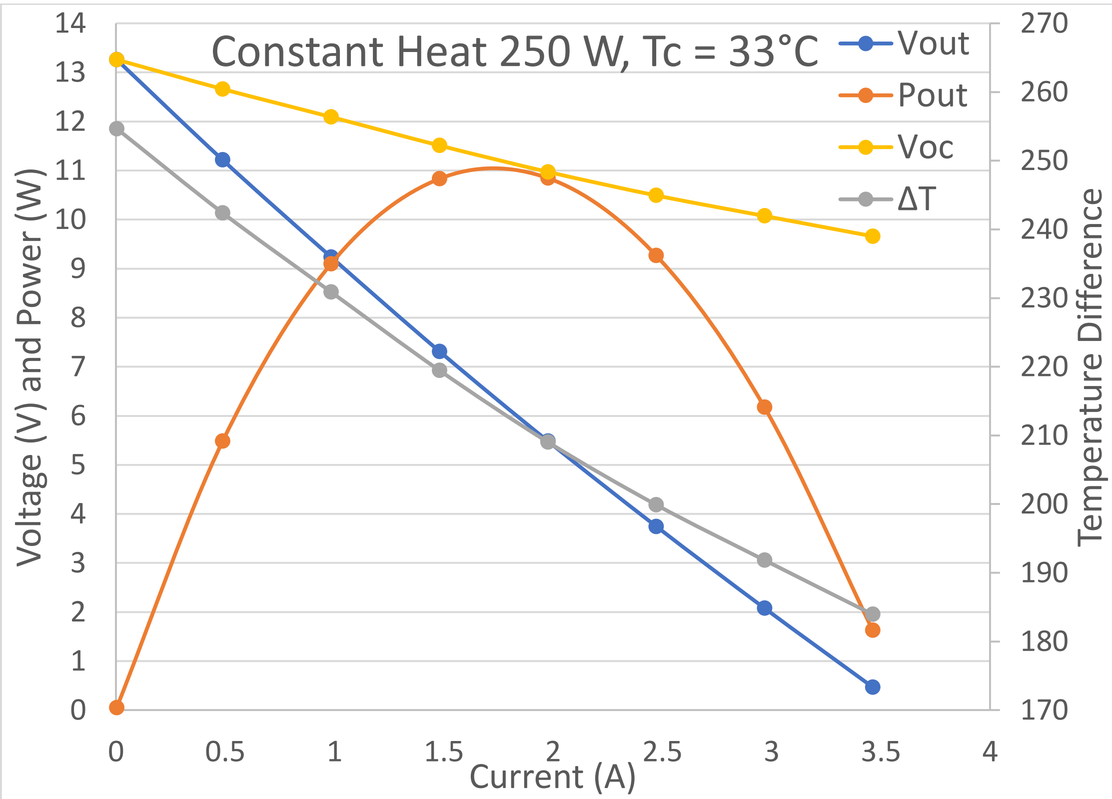
In most practical applications thermal energy available from the heat source is limited, at any moment in time. As a consequence, and considering the variable effective thermal resistance of the TEG, it is practically useful to use the TEG electrical characteristic for constant heat.

The constant heat test requires the system to reach steady-state for each load point. This takes around 30 min, depending on the test system, therefore the overall test length can increase significantly with the number of load points.

The procedure is similar to the slow constant temperature difference test. The test starts either at OC or SC and the load parameter (voltage or current) is progressively decreased. After each load step the controller needs to establish when the system has reached steady-state, afterwards it proceeds to take measurements and follow on to the next load point.

The figure below shows the voltage, power (on the left vertical axis) and temperature difference (on the right vertical axis) plotted versus the current, for a constant heat of 250 W, with the cold side temperature at 33˚C.

It is important to note that during the test from OC to SC the temperature difference varies significantly (more than 70 degrees in the case below), therefore the test system needs to account for heat losses compensation to ensure that constant heat flux is maintained towards the TEG hot side.



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