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Study of TEG When Connected in Series and Parallel Combinations Along With a DC-DC Converter

Faiz Mohd Siddiqui* and V.K.Maurya
Department of Electrical Engineering,
BBD University, Lucknow, U.P., India.
*faizsabri38@gmail.com

Abstract

The usage of thermoelectric generators (TEGs) for recovering useful energy from waste heat has increased abruptly in recent years with applications ranging from microwatts to KW. The thermoelectric modules can be connected in series and/or parallel (forming an array) to provide a large voltage. Most of the TEG systems are subject to temperature mismatch due to operating conditions. Variations in the electro-thermal performance and mechanical clamping pressure of individual TEG modules are also sufficient to cause a significant mismatch. Hence, when operating each TEG in the array will have a different electrical operating point at which maximum energy can be extracted and problems of decreased power output arise. The work here analyses the impact of thermal imbalance on the power produced at module and system level in a TEG array. Experimental results clearly illustrate the issue and a theoretical model is presented to quantify the impact. The authors believe the experimental results presented in this paper are the first to validate a rigorous examination of the impact of mismatched operating temperatures on the power output of an array of thermoelectric generators.

A DC-DC converter is included to provide suitable and stable voltage supply for in-car electronics. In a single-stage system, a string of series connected TE couples is used as the TEG module, and the module output is connected to the input of a DC-DC converter. The converter appears as a load to the TEG module. The TE couples must be piled up to a number so that the open circuit voltage of the TEG module is at an appropriate position in the input range of the converter.

Keywords – Mismatch, Variability, Clamping, Validate, Array, Converter, Couple, Piled.

Introduction

The use of TEGs to recover waste heat energy has increased rapidly in recent years with applications in fields such as remote sensing , automotive , stove, geothermal, space systems and industrial power plants . Thermo electrics are lately also combined to PV, solar thermal or thermo photovoltaic systems. The power requirements depend strongly on the application, but span the range from microwatts to kilowatts In systems where more than a few Watts are needed, several thermoelectric modules are deployed in arrays with series and/or parallel interconnections in order to provide the required power level (Ferre *et al.,* 2013).

The method of interconnection of the TEGs is usually determined by the voltage and/or current required. The TEG can be electrically modeled as a voltage source in series with an internal resistance, as shown in Fig. 1. The values of both the voltage produced and the internal resistance vary with temperature. The Peltier effect acts to pump heat from one side of the TEG to the other according to the current flowing through the device. As a consequence, the effective thermal resistance of the TEG depends to a certain extent on the magnitude of the current flowing in the external circuit (Crane *et al.,* 2012) In a thermoelectric generator the Peltier effect is considered to be parasitic and unwanted. Low electrical current will lead to a reduced thermal conductance and high electrical current will lead to an increased thermal conductance (low thermal resistance; high heat pumping). If the TEG is electrically short circuited, the TEG will have the highest possible thermal conductance. This condition is normally avoided because it leads to a very inefficient thermal circuit with a large amount of heat energy being transferred from the 'hot' to the 'cold' side with no benefit in electrical power generation. For a given thermal operating point the electrical power delivered by the TEG varies according to the current drawn by the electrical load. To maximise the power produced by the TEG, the electrical load impedance should equal the TEG's internal resistance (this is known as the "Maximum Power Transfer Theorem"). The Maximum Power Point (MPP), the point at which the TEG delivers the maximum possible power to the external load for a given temperature) is given by half the open circuit voltage, VOC=2, or by half of the short circuit current, ISC=2. Maximum power point tracking (MPPT) electronic converters are typically employed to maximise the power extracted (Hatzikraniotis *et al.,* 2009) This leads to the formation of what is called a distributed MPPT subsystem in which each TEG array's electrical operating point is controlled independently, in a similar way as for photovoltaic systems (Crane *et al.,* 2012.). The primary motivation for this approach is that in most TEG systems the individual thermoelectric modules are subject to temperature mismatch. Examples of situations where this mismatch occurs directly include thermal variability as found in exhaust gas systems or where the thermal conductivity of the mechanical system is poorly controlled. Variability of the electro-thermal performance of individual TEG modules is also sufficient to cause a significant mismatch. The mechanical clamping force the TEG is subjected to indirectly contributes to similar variation in electrical operating point, due to changes associated with the thermal contact resistance which is partially pressure dependent (Kaibe *et al.,* 2008). Consequently, when in operation each TEG in the array will have a different maximum power point. This maximum power point is the electrical operating point at which maximum energy can be extracted from the TEG. The normal operating condition for a TEG is to ensure that the load impedance is equal to (or greater) than the internal resistance, so that thermal conductance does not decrease the thermal to electrical conversion efficiency of the overall system. Ideally each TEG should be independently electronically controlled (Kaibe *et al.,* 2008) but this would greatly increase the number and complexity of the MPPT power electronic converters needed and adversely affect the cost of implementing the system. The work presented in this article deal with the issues related to thermally unbalanced TEGs connected in series and parallel, in a structured and rigorous way. It provides a way to predict the thermal and electrical behaviour of the system when several TEG devices are electrically connected in series or parallel, under balanced or unbalanced thermal conditions along with the combination of a DC-DC converter Experimental results taken from an operating thermoelectric generating system using multiple thermally unbalanced TEGs confirm the theoretical analysis and provide a figure relative to the magnitude of power lost due to temperature mismatch. The results presented are discussed and a comparison between series and parallel connection of TEG arrays is provided, to assist in some design decisions related to thermoelectric systems. The experimental work we have conducted that simulation models (Xiao *et al.,* 2012) currently in use should be updated to include additional physical effects that were previously assumed not to have an impact.(Crane *et al.,* 2012)

Figure 1 below shows the Thermo electric generator coupling modules connected to one and another in series this shows the characteristic features with respect to the generation of voltage. The p- and n-type semiconductors which make up the thermoelectric module are arranged in series electrically, and in parallel thermally, as shown in Fig. 1. The voltage from each of the element is added such that a device comprising many such elements produces a large usable voltage. Each p- and n-pair is referred to as thermocouple.

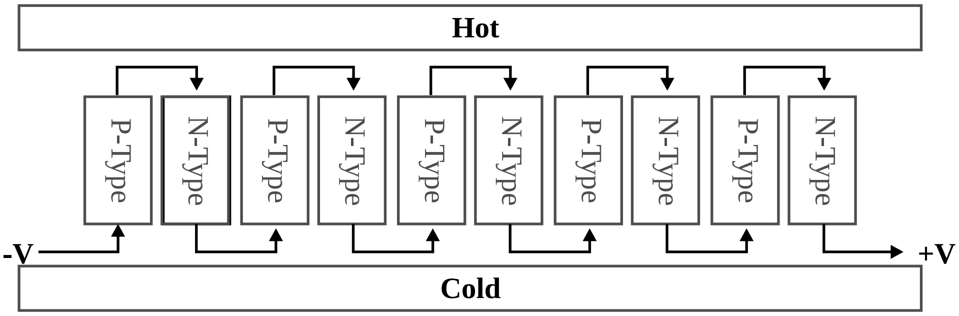


Figure 1: Arrangement of thermoelectric module

The magnitude of output voltage depends upon the material which is used as a thermoelectric module thereby providing the Seebeck effect. Bismuth Telluride BiTe and Lead Telluride PbTe are semiconductor materials that give satisfactory results can account for a voltage of up to 30V when used at a high temperature difference. An output curve is obtained where the voltage generation with respect to current is shown in the figure.2 below. Here a combination of 449 couples of module is used to generate a voltage at a temperature of 230 Celsius. The size of the couple used is 55*65 mm2. The blue straight line in Fig.2 symbolizes the voltage versus current (V–I) characteristic, while the red curved line is the power curve (P–I) for the device. The open-circuit voltage V OC is the voltage when no current is used by the load, while the short- circuit current ISC is the current when the TEG's terminals are shorted together. The max power point lies at the point when load ¼ ISC=2 or V load ¼ V OC=2 and is made when the equivalent electrical load resistance in the external circuit connected to the TEG exactly equals the internal electrical resistance Rint of the TEG (Hatzikraniotis *et al.*, 2009). Rint is the inverse slope of the V–I line and the absolute value is dependent on the temperature at which the TEG is operating and hence does not have a fixed value. When the TEG is operated to the left of the maximum power point as shown in Fig. 2, reduced current flows through the TEG and the effective thermal conductivity of the TEG (which depends also on the current flow, due to the parasitic Peltier effect) decreases. Under this condition the thermal energy conducted via the TEG is less than that at the maximum power point and hence a lower thermal load is imposed on the overall system. This has advantage in most circumstances since it leads to increased thermal efficiency of the system. When the TEG is operated to the right of the max power point the thermal conductivity then increases and the thermal energy conducted via the TEG is greater than that which flows at the maximum power point. Operation in the region to the right ton Fig. 2 leads to reduced thermal efficiency of the system. For the module data shown in Fig. 2, the maximum power is approximately 13:2 W with a corresponding output voltage of 16.5 V (being half of the open-circuit voltage of 33 V). Thermoelectric generator output curves at DT =230 c

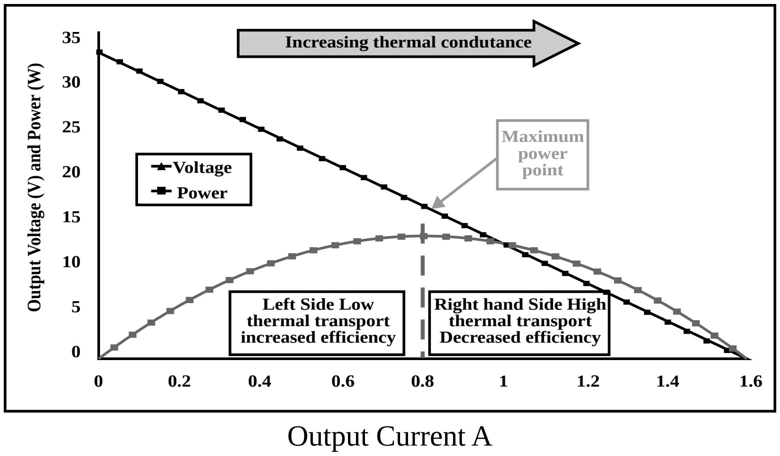


Figure 2 : V-I Charastenstics

Configuration of TEG in series and parallel Array

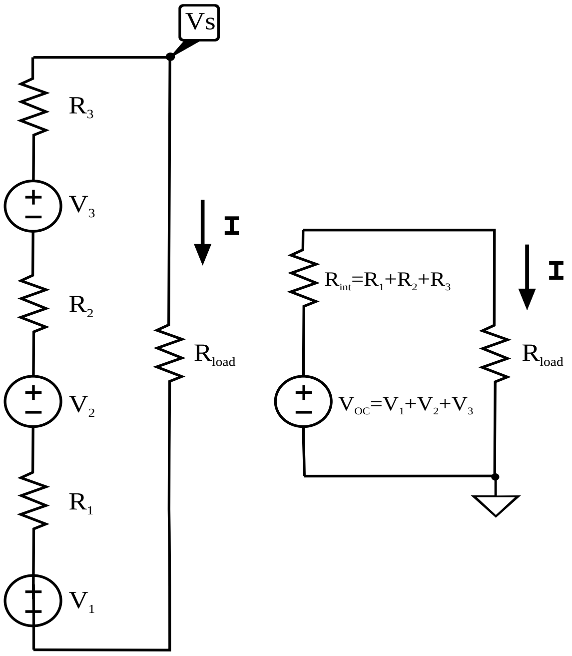
In practical thermoelectric systems, several thermoelectric modules are often deployed in arrays with series inter connection of the TEGs is usually determined by the voltage and/or current required.

Series Array Configuration

Fig. 3 shows the series connection of three TEGs, each of them represented by a voltage source V 1;...; 3 in series with an internal resistance R1;...;3. Under ideal operating conditions, each module within the array will experience an equal DT and therefore all modules will produce an equal output voltage VOC and the array will be in a balanced thermal condition. In this case the MPP is at 3VOC=2 and the overall l array resistance is 3Rint. However, actual thermal operating conditions in a practical system might be such that each TEG may experience a different DT and therefore their voltages and internal resistances will not be equal. In this case VOC = V1 + V2+ V3 and the current flowing into the load is

$$I = \frac{V_{oc} - V_s}{R_1 + R_2 + R_3}$$

Where V_s is the voltage at the array's terminals.



(a) **(b)**

Figure 3: An array of three TEG modules electrically connected in series

Parallel array configuration

Fig. 4 shows three TEGs in a parallel configuration. For ideal operating conditions, the TEG modules in the array operate at the same DT. Hence each TEG produces the same voltage and operates at maximum power, with $I_1 = I_2 = I_3$.

Under non-ideal thermal conditions the different temperature gradient across each TEG unit will lead to a mismatch in the currents magnitude:

$$I_1 = \frac{V_1 - V_P}{R_1} \qquad I_2 = \frac{V_2 - V_P}{R_2} \qquad I_3 = - I_1 - I_2 \tag{2}$$

Where V_p is the voltage at the arrays terminals.

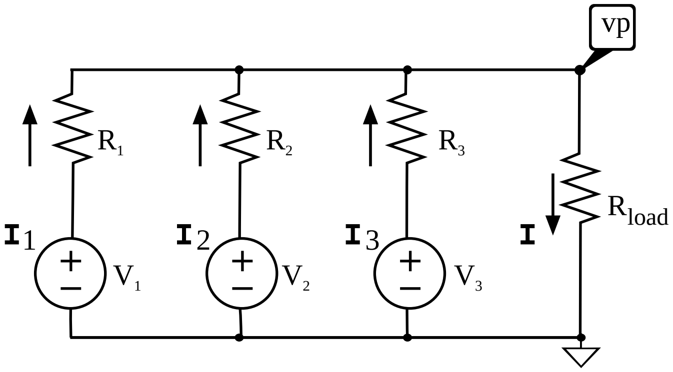


Figure 4: An array of three modules electrically connected in series

Single Stage Topology of DC- DC Converter

Most of the TEG systems utilized nowadays is single-stage conversion system. A DC-DC converter is usually included to provide appropriate and stable voltage supply for in-car electronics. In a single-stage system, a string of series connected TE couples is used as the TEG module, and the module output is connected to the input of a DC-DC converter. The converter appears as a load to the TEG module. The TE couples must be piled up to a number so that the open circuit voltage of the TEG module is at an appropriate position in the input range of the converter. However, with the population of hybrid electric vehicles, higher output voltage is required from the conversion system when it comes to automotive applications, such as charging the batteries. Under this circumstance, the limitations of the traditional single-stage conversion system is straight-forward. Firstly, the internal resistance of TEG module climbs up as the number of series connected TE couples increases to reach a certain voltage level. However, the input resistance of DC-DC converter is usually around 1 Ohm, or even lower. The unmatched resistances tend to severely degrade the overall efficiency of the system. Secondly, the single-stage topology is in itself unreliable. If one of the TE couples in the long string fails to function, the entire device would fail, which might lead to more serious results of vehicle failure (Champier *et al.*, 2011).

Proposed Multi-Section Multi-Stage Topology

The DC-DC conversion network proposed in this paper is a multi-section multi-level network based on TEGs. A general topology of the network is shown in Figure.5. According to the need of specific applications, parameters of the network can be customized, such as the number of conversion levels and conversion locations, the amount of TEG modules at each location, and so on.

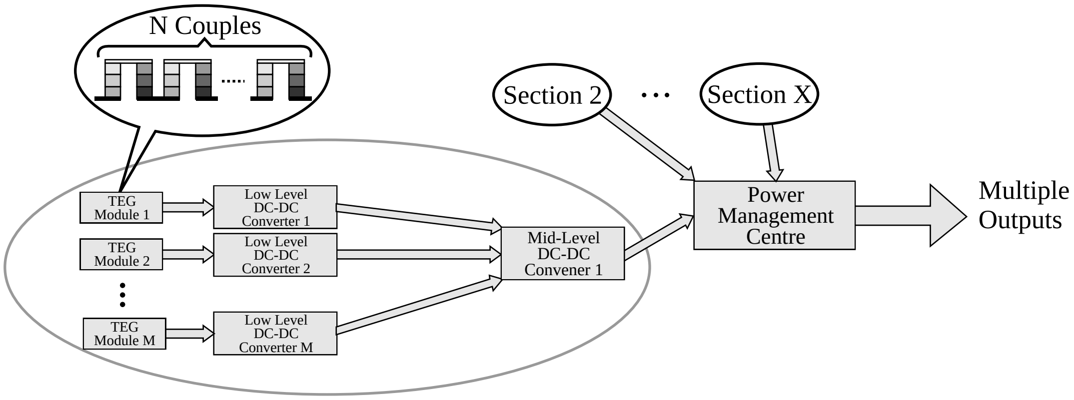


Figure 5: TEG based DC-DC Conversion Topology

At each conversion location, TEG modules are placed in parallel. Each module is a string that consists of a number of serially connected TE couples. A relatively small voltage with a large current is obtainable with TEG. However, many applications require higher and more stable voltage supplies than the output level of TEGs, hence, DC-DC converter is a necessity for TEG as a power supply method. For initial boost, the output of each TEG module is forwarded to a low level DC-DC converter. The outputs of all low level DC-DC converters in the same conversion location are then forwarded to a mid-level DC-DC converter for further voltage boost. There is a power management center with multiple outputs which mainly consists of a high level DC-DC converter. The power management center is in charge of collecting outputs from all mid-level converters, and producing stable power supply for various electronics on vehicles. The merit of this topology is at least three-folded. First of all, this network topology enables high utilization of waste heat by distribution of as many as possible energy harvesting devices around the vehicle body. The TEG modules at different locations could be designed to target differently properties. For instance, TE materials can be specifically selected for a particular location to best suit the available amount of heat energy density and temperature gradient. Secondly, the parallelization of TEG modules serves as a fault tolerant mechanism that increases the reliability of the whole network. Moreover, the parallelization of TEG modules also contributes to compromising the pursuit of high utilization of waste heat and low level impedance matching.

Experimental setup

As per according to the DC-DC converter topology for efficient power management there is a need for connection of the TEG modules in series and parallel configurations. Now, in order to characterize the performance of the thermoelectric devices in multiple connection configurations and with different temperature gradients, the measurement system presented in has been used. This test apparatus provides accurate and repeatable measurements and is able to independently control the mechanical load and the temperature difference across each of the four TEG channels that can be used at the same time. Fig. 7 illustrates the schematic of one channel. The TEG device is sandwiched between a hot block and a cold block. The former contains a high-temperature high-power heater powered by a DC power supply, while the latter is water-cooled by a chilled unit. The output of the TEG can be connected to an electronic load or to any other desired load. A load cell measures the mechanical pressure over the TEG and thermocouple sensors are fitted through the copper blocks touching the TEGs' hot and cold faces, in order to obtain precise temperature measurements. A data logger unit is used to record temperature and mechanical pressure measurements from the test fixture and all the instruments are fully programmable and operated from a laptop PC running an Agilent VEE Pro program. VEE Pro is a graphical programming tool for automated control of laboratory equipment. Maintaining the temperature difference across the thermoelectric device to the desired value it is possible to obtain an accurate electrical characterization of the TEG under test, sweeping the load at different values, all at the same temperature difference. All the data provided was obtained using three identical TEG devices by European Thermodynamics Ltd. (product code: GM250-127-14-10). Every test was performed imposing 1.25 MPa of mechanical pressure onto each TEG, which corresponds to 200 kg on a surface of 40 * 40 mm^2.

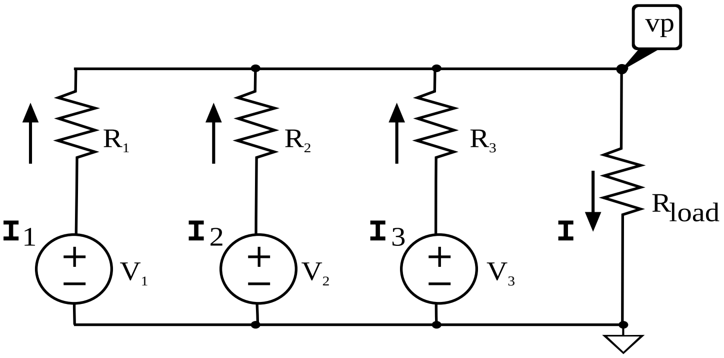


Figure 7: Array of TEG modules connected in Parallel

Individual TEG characterization

The individual electrical characteristic of each of the three TEGs is achieved at three different thermal operating points: ?T = 100. C,150. C and 200. C. Fig. 7 shows the resulting performance curves for TEG# 2. Table 1 lists the performance data of the three TEGs, together with the maximum deviation between the three devices, which stands at less than 5% for what concerns power production. Next, using a similar technique to that explained in, a mathematical characterization has been developed in order to be able to calculate any voltage and power as a function of the current load and temperature difference. Referring to Fig. 1, it can be written that

$$V_{load} = V_{oc} - R_{intl}l_{oad} \tag{3}$$

The open-circuit voltage is proportional to the Seebeck coefficient, which is not constant but varies depending on the Thomson coefficient (Jing et al., 1996). In order to account for the variation of V OC and Rint with DT, a 2nd-order polynomial curve fitting technique has been used, as shown in Fig. 8 for TEG# 2. Hence the Eq. (3) can be now written as

$$V_{load} = (a\mathrm{D}T^2 + b\mathrm{D}T + c) - (d\mathrm{D}T^2 + e\mathrm{D}T + f)I_{load} \tag{4}$$

Where a; b; c; d; e and f are constant coefficients, different for each TEG. Table 2 lists the a; . . . ; f parameters for the three TEGs used in the experiments (Montecucco et al., 2013). If a TEG producing half the voltage and double the amount of current was to be used, then the coefficients a; b; c would need to be halved and d; e; f divided by 4.Using Eq.(4) it is possible to replicate the electrical characteristics of the TEGs used, after obtaining the necessary parameters from the experimental data. Fig. 9 shows the resulting 'mathematical' electrical characterization for TEG# 2. As it can also be appreciated from a comparison with Fig. 8, the average deviation between the mathematically derived values and the experimental data is always less than 1.5%. This means that it is now possible to independently predict the output from each of the three TEGs with high confidence, even when they are at different thermal operating points.

Experimental Results

An analysis is presented to explain behavior during the open-circuit condition and to predict the at-load maximum power point and associated thermal behavior.

Series array configuration

The three TEGs were connected electrically in series into an array whose electrical characterization was performed with TEG# 1 at 100 C, TEG# 2 at 150 C and TEG# 3 at 200 C. The results obtained from the array of TEGs are shown in Fig.9

The maximum power that can be extracted (18.22 W) is less than the sum of powers that could be produced by the array if the TEGs were individually connected. From Table 1 this value can be calculated as 3.43 W (TEG# 1) 6.8 W (TEG# 2) 9.84 W (TEG# 3) ¼ 20.07 W. This means that when under the selected temperature-mismatched condition the three thermoelectric devices produced 9.22% less power. It must be noted that the wiring and connectors used for the series connection of the TEGs contribute to additional electrical resistance which in turns decreases the total output power from the TEG array. It can be noted that the MPP is found when the array's terminals voltage is at half of the open-circuit value. This result confirms the fact that an array of TEGs in series can be simplified to a voltage source, whose value is the sum of the individual TEGs' open-circuit voltages (from Table 1, 4.84V +7.23V + 9.2V = 21.27V), and an internal resistance equal to the sum of the individual internal resistances, as already described in previous section. This confirms that a MPPT (Lovatt *et al.,* 2008) converter using the fractional open-circuit voltage method is still able to obtain the MPP of a mismatched array. It is of great interest to understand the operating point for each module relative to its V–I curve, while series-connected in the (mismatched) array. The current is the same in each TEG and, from Fig. 9, is found to be 1:72 A. Reference to Fig. 7 shows that TEG# 1 (100 C) is working on the right-hand side of its power P–I curve (orange coloured); this means that it is working on a less efficient thermal operating point with higher Peltier effect (hence higher effective thermal conductivity) which leads to a decrease in temperature difference across it, thus amplifying the mismatched condition. TEG# 2 (150 C) works very close to its MPP, while TEG# 3 (200 C) works on the left-hand side of its power curve (in purple); this corresponds to working in a more efficient operating point which leads to an increase in the temperature gradient across it (Montecucco *et al.*, 2014).

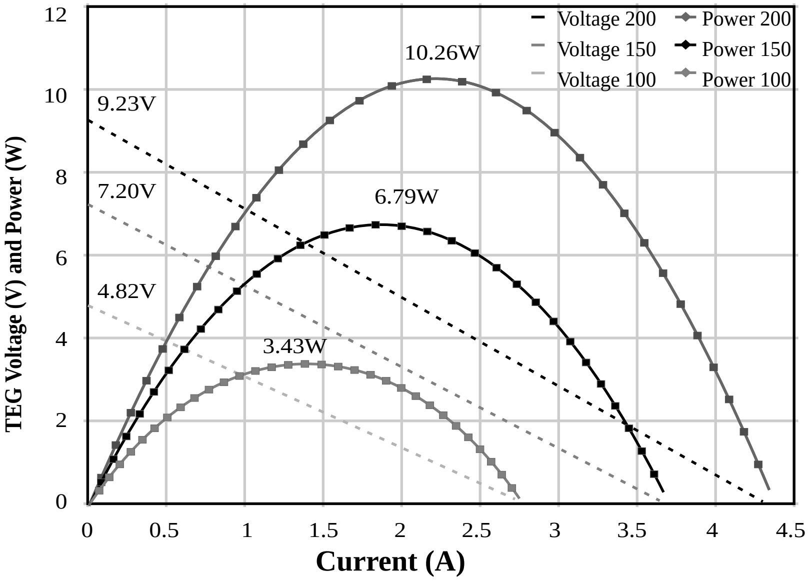


Figure 8: Curve fitting technique

Table 1: Performance characteristics of three Thermo electric modules used here

DT (^{0}C)	TEG#1			TEG# 2			TEG# 3			Deviation		
	R_{int} (W)	V_{oc} (V)	P_{max} (W)	R_{int} (W)	V_{oc} (V)	P_{max} (W)	R_{int} (W)	V_{oc} (V)	P_{max} (W)	R_{int} (%)	V_{oc} (%)	P_{max} (%)
100	1.73	4.84	3.43	1.73	4.87	3.44	1.80	4.87	3.33	3.80	0.7	3.2
150	1.94	7.22	6.79	1.94	7.23	6.80	2.01	7.21	6.57	3.6	0.2	3.4
200	2.11	9.25	10.26	2.10	9.25	10.30	2.17	9.20	9.84	3.3	0.5	4.5

Parallel array configuration

Here three TEGs are connected in parallel combination controlling them would lead to a temperature mismatch as it is clear from the schematic experimental diagram The current going from TEG# 3 to TEG# 2, I32, was 0:95 A while the current going from TEG# 2 to TEG# 1, I21, was 1:10 A. The difference with the results of Eq.(7) stands around 10%, which can be attributed to the difficulty in reading the multimeter during the transient, to the frequency response of the multimeter itself and to the thermal effects occurring during the transient from open circuit to short-circuit. As in the previous procedure for the series array, it is relevant to establish the operating point of each TEG with reference to its P-I curve. In this case of parallel electrical connection of the modules would decrease the temperature mismatch and increase the array electrical efficiency (Ferrari *et al.*, 2007). At the same time, reducing the temperature gradient across the TEG at highest temperature difference could prove unwanted because output power increases exponentially with temperature difference. This situation has not been studied in this work and will be researched in the future to better understand its advantages and disadvantages. From the electrical connection point of view, the parallel-connected array has lower voltage and higher current, which leads to higher I2R losses (Joule heating) in the wiring and MPPT converter, thus further decreasing the overall system electrical efficiency. System cost in parallel connection is adversely affected because of the need for high-current inductors in the Switch-Mode Power Supplies (SMPS), and possibly more complicated SMPS topologies in case that high-step up is required. Especially in low-temperature applications a higher open-circuit voltage is preferred because it calls for a simpler and more efficient power converter. When designing a thermoelectric generating system a balance must be found between the number of MPPT converters and the number of TEGs connected into an array controlled by one of those power converters. This work ultimately suggests that the connection of thermoelectric devices in series yields a more efficient system at lower cost, compared to parallel connection. This is true considering both non-uniform temperature distributions, as researched in this paper, and the aforementioned considerations related to Joule losses and size and cost of wiring and electronic components. Future work will investigate solutions to diminish the negative impact of thermo-mechanic mismatches on the thermal and electrical efficiency of interconnected TEG array (Montecucco *et al.,* 2012).

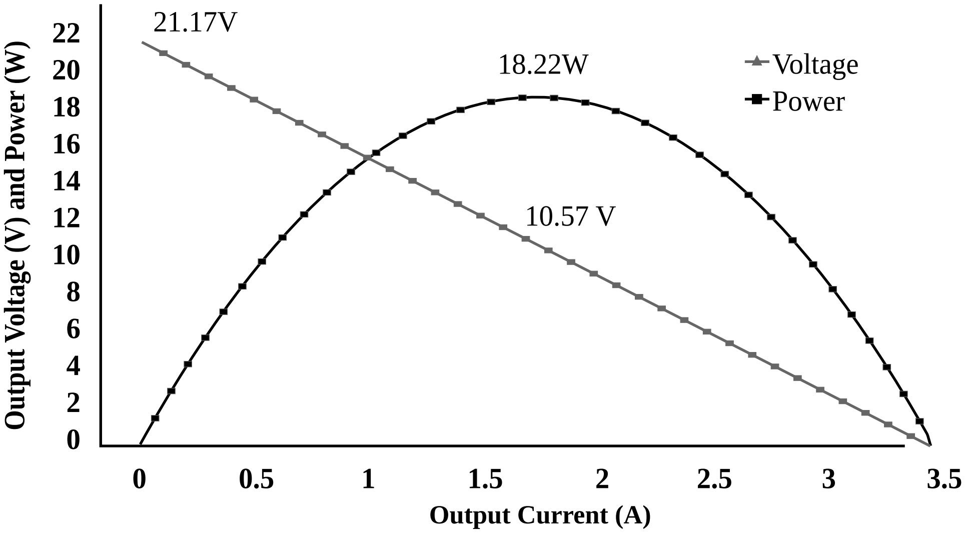


Figure 9: Electrical characteristics of three TEG connected in series with a temperature mismatch at 100 C, 150 C, 200C

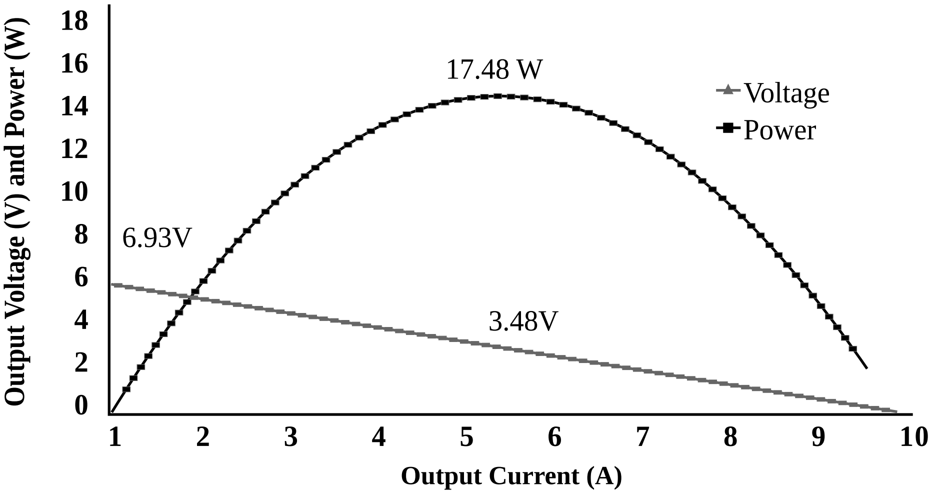


Figure 10: An array of three TEGs in parallel configurations under the mismatched temperature of TEG#1 =100C, TEG#2 =150C, TEG#3 =200C

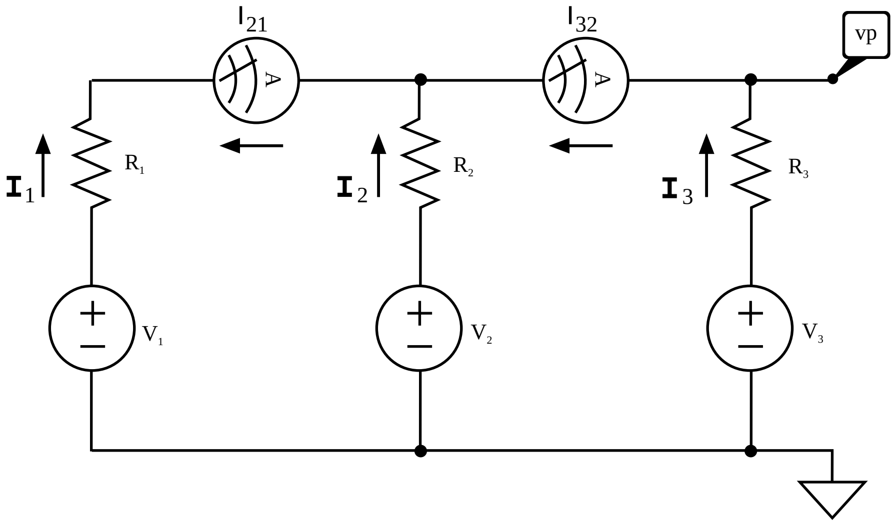


Figure 11: Circuit diagram of the experimental set up used to measure the instantaneous current flowing after the parallel connection of mismatched thermoelectric devices.

Conclusions

This work describes the electro-thermal effects occurring in arrays of thermoelectric generators connected in series and in parallel along with a DC-DC converter, when the individual devices are exposed to non-uniform temperature gradients. Experimental data are presented to show that such problem can impact the performance of a thermoelectric system, and a theoretical analysis is presented to justify the results and to calculate expected performance. The experimental results show that the power lost by mismatched conditions (temperature, mechanical load, manufacturing tolerances, aging) can be significant, and it is lower in the series connected array. This work provided both a mathematical formulation (achievable from experimental characterization) and electrical circuit equations that together can be used to predict the output electrical power in any temperature mismatch situation. This work analyzed arrays of three TEGs; however the results and the circuit equations can easily be adapted for a higher number of TEGs. In commercial systems that are currently under development for energy scavenging from vehicle exhaust gases there are arrays which are subject to different temperatures. There is a need for multiple power converters; however this is insufficient to guarantee that the maximum possible power will actually be achieved. Simulation models currently in use should be updated to include the additional physical effects due to temperature imbalance, otherwise risking over-estimating total power production. The presented results suggest that series electrical connection enables more of the available power to be captured and that Joule heating losses in wiring and the electronics are minimized. In the practical case where thermal–mechanical imbalances may be expected, a balance must be found between the number and cost of MPPT converters in a distributed system, and the expected power loss due to mismatched conditions.

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