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Transient response of a thermoelectric generator to load steps under constant heat flux

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HIGHLIGHTS

- The MPP of a TEG operated under constant heat flux is different from the MPP of a TEG operated under constant ΔT.
- The transient response of a TEG adopts different shapes depending on the current and next operating point.
- The operating point during transients is found by looking at the curves for constant ΔT.
- Thermal transients have an impact on the MPP tracking accuracy of some MPPT algorithms.

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ABSTRACT

Most waste heat recovery applications involve a heat source that provides a limited heat flux that can be converted into electricity by a thermoelectric generator (TEG). When a TEG is used under limited or constant heat flux conditions the temperature difference across the device cannot be considered constant and will change depending on the electrical current generated by the TEG. This phenomenon is induced by the Peltier effect, which works against power generation and deviates the optimum operating point from the commonly known maximum power point (MPP). This point, dictated by the *maximum power transfer theorem*, is achieved when the source equivalent series resistance and the load resistance are equal, in conditions of constant temperature difference. Hence maximum power point tracking (MPPT) algorithms that regulate the TEG at half of the instantaneous open-circuit voltage are optimized only for applications where the TEG operates under constant temperature difference but are not ideal for constant heat flux conditions. Hill climbing MPPT methods, e.g., perturb-and-observe (P&O) or incremental conductance (IC), can reach the MPP more accurately if the sampling time is extended to the thermal time constant of the system.

This article presents an analysis of the transient electrical and thermal response of a TEG to a load change. This investigation results fundamental to the design of MPPT algorithms such P&O or IC for TEGs operating under constant heat flux. A step-up (boost) dc-dc converter controlled by P&O is used to demonstrate the effects of the sampling time over of the transient response and hence the tracking performance of the MPPT algorithm.

1. Introduction

Thermoelectric generators (TEGs) are solid-state devices that convert thermal energy into electrical energy exploiting the Seebeck effect. TEGs do not have any moving parts; they are small, compact in size and very robust. The use of TEGs is not widely extended due to their low efficiency, around 5%. Thermoelectric technology gained more commercial success in cooling applications where thermoelectric devices are used as heat pumps [1].

TEGs have been used in the past in applications where only thermal energy was available e.g., in space or remote applications, as in the *Voyager* mission. More recently researchers have proposed applications of TEGs to generate electricity from waste heat [2] that otherwise would be lost in the environment. Some examples are energy generation from a combustion chamber [3], biomass cooking stove [4], wood burning stove [5,6] or gas stove [7,8]. Other applications can be found in the automotive sector where the heat sources are the exhaust [9–11] or a catalytic combustor [12]. In these applications proper thermal

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management is required and some applications using heat pipes have been developed [13]. TEGs can also be connected in series and in parallel to adjust the overall output voltage and current of the TEG module [14]. In most of the referenced applications the heat source can provide only a limited amount of thermal energy. The temperature gradient developing across the TEG system depends on the thermal resistance of the heat exchangers and the TEG devices.

It is commonly accepted in literature [15,16] that the MPP of a TEG operating under constant temperature difference can be found from the *maximum power transfer theorem* which states that the generated power is maximised when the external electrical load is matched to the TEG's internal resistance, *i.e.* $R_{source} = R_{load}$. Under these conditions the load voltage settles at half of the open-circuit voltage, *i.e.* $V_{load} = 0.5{\cdot}V_{oc}$ or, defining a new parameter, $\beta = V_{load}/V_{oc} = 0.5$. However, in real applications the temperature gradient across the TEGs is never constant. It varies with the thermal power available and with the effective thermal resistance of the TEG devices. In fact, the heat flux through the TEG from the hot to the cold side changes with the load current generated by the TEG according to the Peltier effect, considered parasitic in power generation. This effectively means that the thermal resistance of the TEG device varies with the electrical current that it generates. Eq. (1) represents the sum of powers at the hot side of a TEG in power generation mode and thermal steady-state conditions.

$$Q_H = K\Delta T + \alpha T_H I - \frac{1}{2}RI^2 \tag{1}$$

where Q_H is the heat flux absorbed by the TEG at the hot side, $K\Delta T$ is the thermal conduction term, $\alpha T_H I$ is the heat transfer from the hot side due to the Peltier effect and $0.5{\cdot}RI^2$ is the heat flowing back to the hot side due to internal Joule heating. This equation is obtained solving the one-dimensional heat conduction equation for thermoelectric generators [17,18]. The Thomson effect, which describes the variation of the Seebeck coefficient α with average temperature is here neglected due to its small contribution compared to the other terms [19].

Substituting $T_H = T_C + \Delta T$, being ΔT the temperature across the TEG, into Eq. (1) we obtain Eq. (2).

$$\Delta T = \frac{Q_H + \frac{1}{2}RI^2 - \alpha T_C I}{K + \alpha I} \tag{2}$$

As shown in Eq. (2), there is an amount of heat that flows from the hot to the cold side that depends on the current through the TEG and it contributes to the decrease of temperature between the TEG faces as compared to an open-circuit situation, when the current through the TEG is equal to zero. This is due to the Peltier effect. It also shows that there is a contribution from the internal Joule heating, but this contribution is smaller than the Petier effect [18]. If Q_H is maintained constant ΔT is maximum when no current is generated by the TEG. ΔT progressively decreases with an increase in electrical current. In order to maintain a constant temperature difference across the TEG device while the output current is increased, extra thermal energy must be transferred into the system to compensate for the Peltier effect contribution. This is not possible with limited heat sources.

There are many applications where the amount of heat is limited and therefore it is not possible to maintain a constant temperature across the TEG while the TEG current varies. Previous studies [20–26] have shown that under these conditions the maximum power delivered by the TEG is not produced when $R_{TEG} = R_{load}$. The optimum external load is related to the figure of merit ZT as shown in Eq. (3):

$$\frac{R_{load}}{R_{TEG}} = \sqrt{1 + Z\overline{T}} \tag{3}$$

whose parameters vary with the average temperature of the TEG device and therefore it is not possible to establish a fixed value for the optimum load when the temperature across the TEG varies.

Recent studies have shown that the MPP of TEGs operating under constant heat flux is found when $\beta > 0.5$. Montecucco et al. [26] supports this argument through the use of theoretical simulations confirmed by the work of Min [27]. These studies also show that the ratio at which the MPP is achieved changes with the amount of heat flux through the TEG.

Maximum power point tracking (MPPT) systems use DC-DC converters to operate the TEG at the MPP. This is achieved by controlling the input current or voltage of the converter so that the TEG operates at the MPP.

Some of the most common MPPT techniques used, like P&O or IC, change the operating point of the TEG by monitoring (sampling) the output power of the device until the MPP is reached. The dynamic response of the system must be taken into consideration so that the MPPT algorithm measures the correct steady-state value of power, otherwise the power converter will not be able to track the correct MPP.

Traditional MPPT algorithms like P&O or IC operate using sampling times that are several orders of magnitude shorter than the thermal time constants of TEG systems. The thermal time constant of a TEG system is defined in this paper as the time required for the system to change 63.2% the total difference between the initial and final temperature across the TEG plates when a load step change is applied at its terminals. The thermal time constant depends on the thermal resistance and the thermal capacitance of the different elements in the system, such as heat exchangers, thermoelectric device and the interfaces between these elements. A practical MPPT development is sensitive to the size and thermal time response of the system in use, hence the MPPT response parameters might need to be tuned to the particular system where it is used to achieve optimal performance.

Changing the operating point of a TEG at fast frequencies (compared to the thermal time constant of the system) will not allow for temperature changes across the TEG, which would be equivalent to operate at constant ΔT between consecutive samples. Without allowing the TEG system to reach steady-state conditions it is not possible to track the MPP under constant input heat flux.

In this paper the results of a study into the transient response of the TEG using power curves, obtained under conditions of constant heat flux and constant ΔT, are presented. The behaviour is then verified using experimental data. The effects of the dynamic response are shown using a boost (step-up) converter controlled by a microcontroller that implements a P&O algorithm.

2. Dynamic response

This section presents an analysis of the dynamic response of a TEG operated under constant heat flux conditions. Nonetheless, the electrical characteristic curves for constant temperature difference are also fundamental to aid the behaviour of the TEG in a thermally dynamic environment.

Any change in the operation conditions of a TEG operating under constant heat flux will occur at constant temperature. This is because the temperature of the system will not change instantaneously when the operating condition is changed. This effect is only valid at the moment the load change is applied. The temperature across the TEG will then change until the system reaches a new steady-state condition. This change in temperature is due to the Peltier effect that changes the effective thermal resistance of the TEG. The new steady-state condition corresponds to the crossover point between the constant heat flux power curve and the constant temperature power curve obtained at the new temperature difference across the TEG. For this reason it is important to inspect both types of curves in order to understand the transient response of the TEG. These transitions will be explained with the aid of Figs. 1 and 2.

It has been shown in [26] that the maximum power point of a TEG operating under constant heat flux corresponds to a point where $\beta > 0.5$. Fig. 1 shows the “Power and Voltage vs Current” curve of the

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