Energy Conversion and Management 108 (2016) 355–365

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A simple maximum power point tracker for thermoelectric generators

Alexandros Paraskevas, Eftichios Koutroulis *

School of Electronic and Computer Engineering, Technical University of Crete, Chania GR-73100, Greece

ARTICLE INFO

Article history:
Received 7 July 2015
Accepted 10 November 2015
Available online 7 December 2015

Keywords:
Thermoelectric generator
Maximum Power Point Tracking
Boost converter
Energy harvesting

ABSTRACT

ThermoElectric Generators (TEGs) are capable to harvest the ambient thermal energy for power-supplying sensors, actuators, biomedical devices etc. in the μW up to several hundreds of Watts range. In this paper, a Maximum Power Point Tracking (MPPT) method for TEG elements is proposed, which is based on controlling a power converter such that it operates on a pre-programmed locus of operating points close to the MPPs of the power–voltage curves of the TEG power source. Compared to the past-proposed MPPT methods for TEGs, the technique presented in this paper has the advantage of operational and design simplicity. Thus, its implementation using off-the-shelf microelectronic components with low-power consumption characteristics is enabled, without being required to employ specialized integrated circuits or signal processing units of high development cost. Experimental results are presented, which demonstrate that for MPP power levels of the TEG source in the range of 1–17 mW, the average deviation of the power produced by the proposed system from the MPP power of the TEG source is 1.87%.

1. Introduction

The application of energy harvesting technologies has emerged during the last years for satisfying the power-supply requirements of power-autonomous devices, by scavenging the mechanical, waste heat, biological etc. energy, which is available in their surrounding environment [1]. The harvested energy is then interfaced to a microelectronic energy management system for conversion to a form suitable for power-supplying the target electronic load. Among the energy harvesting alternatives, the ThermoElectric Generators (TEGs) comprise multiple semiconductor thermocouples (e.g. constructed using Bismuth Telluride with *p*- and *n*-doping), which are capable to generate electric energy when subject to a temperature difference across their hot and cold sides [2]. The TEGs feature high reliability, do not contain moving parts [3] and exhibit compactness, long-lifetime and low-weight features. Thus, they are suitable for installation on surfaces where thermal flows are developed (e.g. human body, pipes of hot liquids, combustion engines, vehicle exhausts etc.). The TEG devices are capable to power supply, in the μW up to several hundreds of Watts range, medical devices, wearable and wireless sensors, remote actuators, interplanetary space flight systems etc. (e.g. [4–8]).

A generalized block diagram of a thermoelectric energy harvesting system is illustrated in Fig. 1(a). The TEG power source is connected to a DC/DC power converter, which interfaces the generated power to the system load or an energy storage unit (rechargeable battery or super-capacitor) [9]. An example of the power–voltage characteristic of a TEG module is depicted in Fig. 1(b), indicating that the TEG power source exhibits a point where the generated power is maximized (i.e. Maximum Power Point, MPP). The necessary condition that must be satisfied by a Maximum Power Point Tracking (MPPT) process for maximizing the power generated by the TEG source, is the following:

$$\frac{\partial P_{TEG}}{\partial V_{TEG}} = 0 \quad (1)$$

where P_{TEG} (W), V_{TEG} (V) is the TEG output power and voltage, respectively.

A wide variety of techniques have been proposed in the past for performing the MPPT process in TEG-based energy harvesting systems, as analyzed in the following.

The Perturbation and Observation (P&O) or hill-climbing MPPT technique is based on the result of comparison of successive measurements of the TEG output power [10,11], which are performed before and after, respectively, the duty cycle of the power converter has been perturbed. The Incremental-Conductance (InC) algorithm is based on the principle that at the MPP of the TEG generator, it holds that [11]:

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* Corresponding author. Tel.: +30 28210 37233; fax: +30 28210 37542.
E-mail address: efkout@electronics.tuc.gr (E. Koutroulis).

http://dx.doi.org/10.1016/j.enconman.2015.11.027
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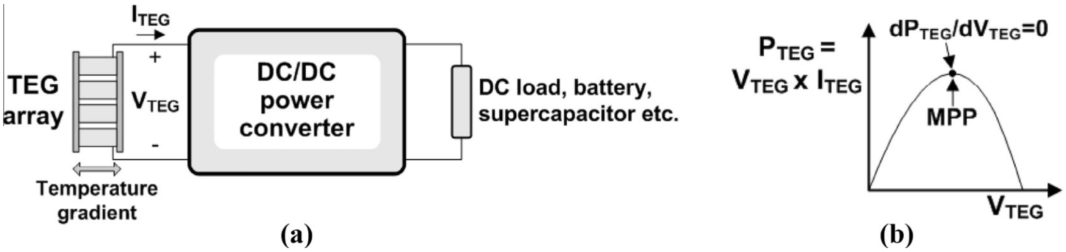

Fig. 1. A thermoelectric energy harvesting system: (a) a generalized block diagram and (b) an example of the power–voltage characteristic of a TEG module.

$$\frac{\partial P_{TEG}}{\partial V_{TEG}} = 0 \Rightarrow \frac{\partial (I_{TEG} \cdot V_{TEG})}{\partial V_{TEG}} = I_{TEG} + \frac{\partial I_{TEG}}{\partial V_{TEG}} V_{TEG} = 0 \Rightarrow \frac{\partial I_{TEG}}{\partial V_{TEG}} = -\frac{I_{TEG}}{V_{TEG}} \tag{2}$$

where I_{TEG} (A) is the TEG output current.

Thus, by measuring and comparing the values on the two sides of (2), the TEG operating point is progressively moved to the MPP. A voltage-trend detection circuit has been designed in [12], where the gradient of a Boost-converter output power is detected by measuring the corresponding output voltage, thus achieving a low-power implementation of the hill-climbing MPPT approach. The MPPT efficiency of the P&O and InC algorithms is affected by circuit noise, as well as by the accuracy of calculating the TEG output power or current gradient. As discussed in [11], increasing the perturbation step results in a high steady-state oscillation around the MPP, which reduces the TEG power production. On the other hand, increasing the accuracy of the power or gradient measurements, increases the complexity and power consumption of the MPPT control unit. This operational characteristic is especially crucial in low-power TEG applications where the power production of the TEG source and the power consumption of the control-unit are of the same order of magnitude.

For performing the MPPT process in [13,14], the TEG power source is periodically disconnected from the power converter in order to measure its open-circuit voltage, $V_{TEG,oc} = V_{TEG}|_{I_{TEG}=0}$. Then, SEPIC- and Boost-type DC/DC power converters, respectively, are controlled such that the TEG source operates at $V_{TEG,oc}/2$, which corresponds to the MPP. This technique is usually referred to as the "fractional open-circuit voltage" (FOCV) MPPT method. Similarly, in the "fractional short-circuit current" (FSCC) MPPT method, the TEG source is periodically set to operate under a short-circuit condition and the corresponding short-circuit output current, $I_{TEG,sc}$, is measured (i.e. $I_{TEG,sc} = I_{TEG}|_{V_{TEG}=0}$) [11,15]. The power stage is then controlled such that the TEG output current is equal to the half of the previously measured short-circuit TEG current, thus achieving operation at the MPP. Despite their operational simplicity, the FOCV and FSCC MPPT methods are not able to track the short-term changes of the MPP, which occur between successive measurements of the open-circuit voltage or short-circuit current. Else, the sampling frequency of the open-circuit voltage or short-circuit current should be substantially increased, resulting in power loss, since the power production of the TEG device is suspended during the open-circuit voltage or short-circuit current measurements. In order to avoid interrupting the TEG source operation for measuring the open-circuit voltage, the FOCV technique has been implemented in [1] by employing a pair of temperature sensors for measuring the temperature gradient developed across the hot and cold sides, respectively, of the TEG source and estimating the corresponding open-circuit voltage of the TEG source. However, this approach has the disadvantage that the temperature sensors employed increase the cost of the MPPT system, especially in the case that the operating temperature range of the TEG source is high (e.g. in combustion engine applications).

A single-sensor MPPT approach for TEGs is proposed in [16]. The inductor current of a Boost-type DC/DC power converter is measured and used to estimate the MPP of the TEG power source by using a model of the power converter according to the state-space averaging technique. In order to apply this method, a Digital Signal Processing (DSP) unit must be employed for performing the calculations dictated by the power converter model during the MPPT process.

In another class of TEG MPPT techniques, the internal resistance of TEGs is considered approximately constant over the entire span of operating temperature gradients [17]. Based on this operating principle, the input impedance of a Boost-type DC/DC converter operating in the discontinuous-conduction mode, R_{in}, is tuned in [17] to match the TEG series-resistance [i.e. "Impedance Matching" (ImpM) MPPT method], such that the TEG source always operates at the MPP. The input impedance tuning is implemented by selecting the switching frequency, f_s and ON-time, t_1, of the converter power switch, given the value of the power converter inductance, L, as follows:

$$R_{in} = \frac{2 \cdot L}{t_1^2 \cdot f_s} \tag{3}$$

A similar approach has also been employed in [18]. The ImpM method has the following disadvantages: (i) the efficiency of the MPPT process is affected by the accuracy of setting the inductance, incorporated in the power converter, to the desired value (due to inductance value tolerance, as well as its variation with the operating temperature), (ii) it does not enable tuning the inductance and switching frequency to the appropriate values, which would optimize the power converter performance in terms of metrics such as the power conversion efficiency and cost and (iii) the power converter operation in the discontinuous-conduction mode is not desirable at higher power levels, since power semiconductors of a high current rating would be required in that case.

The Extremum Seeking Control (ESC) MPPT technique, which is proposed in [19], is based on the implementation of a feedback control loop, where a sinusoidal perturbation is applied to the duty cycle of the DC/DC converter control signal, resulting in a perturbation of the TEG-generated power. Then, the output power of the TEG source is measured and the resulting signal is demodulated, indicating the gradient of the TEG power–voltage curve at the corresponding operating point. This information is used to derive the new duty-cycle perturbation, which will force the TEG operating point to move toward the MPP of the TEG source, where condition (1) holds. The disadvantage of the ESC MPPT method is that in order to operate successfully, the values of multiple parameters of the control loop must be properly adjusted.

In this paper, an alternative MPPT method for TEG devices is proposed, which is based on controlling a power converter such that it operates on a preprogrammed locus of operating points, which reside close to the MPPs of the power–voltage curves of