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Uninterrupted thermoelectric energy harvesting using temperature-sensor-based maximum power point tracking system

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ABSTRACT

In this paper, a thermoelectric generator (TEG) energy harvesting system with a temperature-sensor-based maximum power point tracking (MPPT) method is presented. Conventional MPPT algorithms for photovoltaic cells may not be suitable for thermoelectric power generation because a significant amount of time is required for TEG systems to reach a steady state. Moreover, complexity and additional power consumption in conventional circuits and periodic disconnection of power source are not desirable for low-power energy harvesting applications. The proposed system can track the varying maximum power point (MPP) with a simple and inexpensive temperature-sensor-based circuit without instantaneous power measurement or TEG disconnection. This system uses TEG's open circuit voltage (OCV) characteristic with respect to temperature gradient to generate a proper reference voltage signal, i.e., half of the TEG's OCV. The power converter controller maintains the TEG output voltage at the reference level so that the maximum power can be extracted for the given temperature condition. This feedforward MPPT scheme is inherently stable and can be implemented without any complex microcontroller circuit. The proposed system has been validated analytically and experimentally, and shows a maximum power tracking error of 1.15%.

1. Introduction

Recently, investigation into sustainable alternative energy sources has been significantly expanded. In addition to the large-scale renewable energy systems using wind turbines and photovoltaic (PV) panels, the harvesting of small energy from various free energy sources, such as vibrations from a bridge, waste heat from internal combustion engines and brick kilns, and electricity from biological molecules, has been investigated in regard to direct power generation for low-power loads or system efficiency improvement through energy recovery [1,2]. Among these approaches, heat energy harvesting via thermoelectric generators (TEGs) converts thermal energy to electrical energy without any mechanical moving part. It is small, light, reliable, eco-friendly, and promising for applications such as automotive waste heat recovery and wireless sensor network power supply due to its long lifetime and high reliability [3–6]. Although it has suffered from low efficiency and high cost, the feasibility of TEG as an energy source is being improved by recent research progress in areas such as material efficiency [7–9] and energy harvesting system development [10,11].

While most research efforts have focused on enhancing thermoelectric material properties, power conditioning circuits optimized for TEG systems have not been investigated extensively. Many studies have suggested optimal electrical load matching conditions for maximized power generation, and utilized maximum power point tracking (MPPT) techniques originally developed for PV systems, such as Perturb and Observe (P&O) and Incremental Conductance (IC) [12–14]. Although maximizing the energy harvest from TEGs by means of an MPPT technique is essential for TEG applications to compensate the TEG's low conversion efficiency, conventional MPPT techniques for PV systems may not be optimal for TEG systems. Unlike a PV system, a TEG system requires a certain amount of time to reach a steady-state; hence, fast perturbations on output power in P&O and IC algorithms could lead to off-MPP operations due to the inaccurate instantaneous TEG power measurement. Moreover, these hill climbing techniques rely on fast measurements and complex computation, which in turn require additional hardware and software that consume measurable amount of power. The fractional voltage technique that samples the open circuit voltage (OCV) of the TEG while in operation is also widely used [15–17]. But, it also suffers from the large

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system time constant that is required to sample precise OCV for the given temperature differential. Furthermore, a microcontroller and analog switch are required to disconnect the TEG from the circuit and sample OCV, which can be costly and troublesome especially in low-power TEG systems.

In this paper, a temperature-sensor-based MPPT technique is proposed for TEG energy harvesting systems. The proposed system can track variations of MPP that are due to temperature changes with a simple and inexpensive temperature-sensor-based circuitry that can avoid the disadvantages of conventional techniques, such as current measurement, source disconnection, and power perturbation. Instead, TEG's OCV characteristic with respect to temperature difference between source and environment is built into the circuit; then a proper command voltage signal – i.e., half of the TEG's OCV for the given temperature differential – is generated. The command is used by a hysteresis controller to generate a gate signal for the power converter to harvest power from the TEG at the MPP of the given temperature condition without perturbation or interruption. The proposed MPPT circuitry can be implemented with a minimal number of discrete parts and without any complex microcontroller system. Moreover, the system is inherently stable because it operates based on the feedforward model without any instantaneous power feedback loop. The proposed scheme has been validated analytically and experimentally, and demonstrated successful performance.

2. TEG energy harvesting

2.1. Thermal model of thermoelectric module

Thermoelectric modules directly generate electricity proportional to the temperature difference applied across the legs. A typical schematic of a TEG system and its thermal circuit model is shown in Fig. 1. The heat flow in the system can be represented by the following two energy conservation equations.

$$\dot{Q}_H = \dot{Q}_{Cond} + \dot{Q}_{Peltier} - \dot{Q}_{JH} = \frac{T_S - T_H}{\Psi_H} \quad (1)$$

$$\dot{Q}_C = \dot{Q}_{Cond} + \dot{Q}_{Peltier} + \dot{Q}_{JH} = \frac{T_C - T_\infty}{\Psi_C} \quad (2)$$

where $\dot{Q}_H$ and $\dot{Q}_C$ denote the amount of heat transfer at the hot and cold surfaces of the thermoelectric module, $\dot{Q}_{Cond}$, $\dot{Q}_{Peltier}$, and $\dot{Q}_{JH}$ are heat conduction, Peltier heating/cooling, and Joule heating inside the thermoelectric material, respectively. ψ_H and ψ_C are the thermal resistance of the hot and cold sides. T_S, T_H, T_C, and T_∞ are the temperatures of the heat source, hot surface, cold surface, and ambient air, respectively. The energy conservation equations can be further expanded as

$$\dot{Q}_H = K(T_H - T_C) + \alpha I_{TEG} T_H - \frac{1}{2} I_{TEG}^2 R_{\mathrm{int}} \quad (3)$$

$$\dot{Q}_C = K(T_H - T_C) + \alpha I_{TEG} T_C + \frac{1}{2} I_{TEG}^2 R_{\mathrm{int}} \quad (4)$$

where K is the thermal conductance of TEG material, α is the Seebeck coefficient of TEG material, I_{TEG} is the TEG output current, and R_{int} is the internal electrical resistance of the TEG material [18]. The Seebeck coefficient and the internal resistance have been shown to be nearly constant over the operating range of the TEG [15]. The output power of the TEG module will be given as

$$P = \dot{Q}_H - \dot{Q}_C \quad (5)$$

Because $\dot{Q}_{Peltier}$ and $\dot{Q}_{JH}$ are functions of the TEG output current as can be seen in (3) and (4), the TEG output power will vary as the output current changes even with a constant temperature difference between T_H and T_C. Furthermore, T_H and T_C will also change with the amount of output current for the given source and ambient temperatures T_S and T_∞, because $\dot{Q}_H$ and $\dot{Q}_C$ are functions of the output current. So far, many thermoelectric system analyses have assumed that change of temperatures by electrical current is negligible, and have used a conventional maximum power output condition ($R_{int} = R_{ext}$). Several researchers addressed the inaccuracy of this approach in real applications and suggested new optimum operation conditions [18–21].

2.2. Electrical model and maximum power point

The electrical power converted from the thermal power by TEG will be given as

$$P = V_{TEG} I_{TEG} \quad (6)$$

where V_{TEG} and I_{TEG} are the voltage and current at TEG's output terminals, respectively. Taking into account the thermal factors described in Section 2.1, the TEG can be modeled as a dependent voltage source V_S with an internal resistance R_{int}, as shown in Fig. 2. The external resistance R_{ext} represents the electrical load that draws power from TEG.

The TEG will operate at a point on the V–I curve or power curve. It can also be associated with the load resistance seen by the TEG. In the conventional system model where the internal voltage V_s is constant and independent of output current, it can be analytically derived that the MPP occurs when $R_{int} = R_{ext}$ [15]. However, it has been shown that this impedance-matched MPP condition is valid only when the temperatures at both ends of the thermoelectric legs are kept constant [22,23]. This assumption cannot hold in practical applications, because temperatures at both ends of the

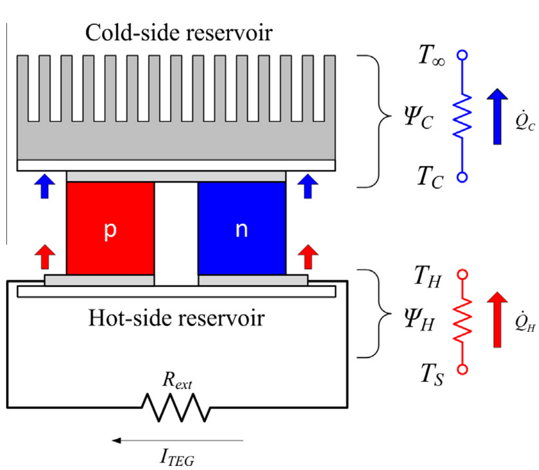

Fig. 1. Schematic and thermal circuit model of a typical thermoelectric module.

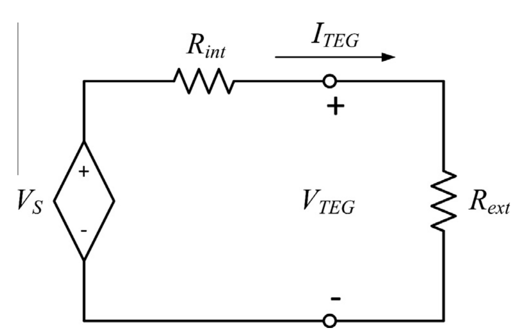

Fig. 2. Electrical equivalent circuit of TEG system.