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Design and experimental investigation of a low-voltage thermoelectric energy harvesting system for wireless sensor nodes

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ABSTRACT

A thermoelectric energy harvesting system designed to harvest tens of microwatts to several milliwatts from low-voltage thermoelectric generators is presented in this paper. The proposed system is based-on a two-stage boost scheme with self-startup ability. A maximum power point tracking technique based on the open-circuit voltage is adopted in the boost converter for high efficiency. Experimental results indicate that the proposed system can harvest thermoelectric energy and run a microcontroller unit and a wireless sensor node under low input voltage and power with high efficiency. The harvest system and wireless sensor node can be self-powered with minimum thermoelectric open-circuit voltage as 62 mV and input power of 84 μW. With a self-startup scheme, the proposed system can self-start with a 20 mV input voltage. Low power designs are applied in the system to reduce the quiescent dissipation power. It results in better performance considering the conversion efficiency and self-startup ability compared to commercial boost systems used for thermal energy harvesting.

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1. Introduction

Thermoelectric generators (TEGs) are usually applied to convert thermal energy into electrical energy, provided that a temperature difference existed between the hot side and the cold side of the TEGs, exploiting the Seebeck effect. Applications of the thermoelectric generators have been explored on vehicle exhaust heat recovery, geothermal, power stations, and woodstoves [1–4]. Kempf and Zhang [1] investigated a high-temperature thermoelectric generator that converted engine exhaust waste heat into electricity and found that both the optimal TEG design and the fuel efficiency increase were highly dependent on the thermal conductivity of the heat exchanger material. Stevens [2] investigated ground-air thermoelectric generators operating between the air and ground temperatures. It was shown that a finned prototype produced power at an average rate of 1046 μW. Yazawa et al. [3] showed that thermoelectric generators could add 4–6% to the overall system efficiency for advanced supercritical steam turbines. Sornek et al. [4] exhibited the high potential of using thermoelectric generators to provide self-sufficient operation of stove fireplaces. Different designs of heat exchanger configurations and TEG modules were tested and compared. The maximum obtained power can reach 6 W. However, the relatively low efficiency of thermoelectric generator compared with typical conversion systems restricts their applications in large-scale [5]. Promising applications of the thermoelectric generators would like to be in small-scale applications for example the "self-powered" wireless sensor networks (WSNs).

WSNs have found more and more applications in recent years. However, one issue in the applications of WSNs is the power supply for wireless sensor nodes. Due to the limited battery capacity, to replace a large number of batteries for WSN nodes is inconvenient and sometimes impractical. Energy harvesting technologies with ambient energy offer a solution to solve this problem. Various kinds of ambient energy sources have been considered for energy harvesting [6,7]. Challenges and potentials of the renewable power sources including piezoelectric, solar, thermoelectric, wind and RF energy were evaluated and it was demonstrated that renewable power sources were able to generate sufficient power for remote sensors [6]. Electromagnetic, kinetic, thermoelectric and airflow-based energy sources were identified as potential energy sources within buildings and the available energy was measured [7]. Within these ambient energy sources, thermoelectric energy is an attractive solution [8,9]. A thermoelectric energy harvester powered wireless sensor networks designed for building energy management applications was built and tested [8]. Their tests demonstrated that the proposed thermoelectric generator could

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effectively power WSN module when the prototype was placed on a typical wall-mount heater. Applications of thermoelectric generators for wearable wireless sensors were also shown [9]. Their thermoelectric harvesting systems provided power about 280 μW to operate wearable wireless sensors.

The magnitude of the TEG's open-circuit voltage is directly proportional to the temperature difference. It should be noted that, in natural convection environment, the temperature gradient cannot be kept at a significant level due to the homogenization process between the hot and cold junction. Therefore, in these applications of TEGs, the temperature difference is usually small and the output voltage can be in range of 20–400 mV. Therefore, boost converters are usually used to boost the voltage for use. Moreover, TEGs are often employed in environments with time-varying temperature differences. Therefore, it is necessary to control the converters with a maximum power point tracking (MPPT) algorithm to enhance the converter efficiency. Another important issue of the converter system is the ability to self-start. The system should be able to self-start when the thermal gradient becomes high enough for harvesting energy.

Designs of energy harvesting circuits from low-voltage TEGs have been investigated intensively in recent years [10–17]. Efficiency and self-startup ability are two main considered issues. Carlson et al. [10] presented a DC-DC converter that can boost a small input voltage of 20 mV to an output voltage of 1 V with high efficiency. However, a switched capacitor circuit should be used to generate a 600 mV voltage to start up the converter. Paraskevas and Koutroulis [11] proposed a MPPT method for TEG elements by controlling a power converter with the use of low-cost and off-the-shelf microelectronic components for high efficiency. However, the power consumption of the control unit they used was as high as 5.13 mW. Guan et al. [12] designed and investigated a boost converter for low voltage thermoelectric generator with MPPT scheme; however, the power consumption of the converter and microcontroller was still higher than 200 μW and the converter did not have the self-startup ability. Ramadass and Chandrakasan [13] tried to solve the start-up problem of the boost converter by applying a mechanically assisted startup circuit, which enabled operation of the boost system from an input voltage as low as 35 mV. However, the start-up mechanism will not work when there is no mechanical energy input. Im et al. [14] used a dual-mode converter to solve the start-up problem. The converter runs in transformer oscillation mode at low input voltage and in normal boost converter mode when input voltage exceeds a threshold value. However, the converter efficiencies are low with a peak efficiency of 61% and the maximum input voltage is constrained by 300 mV. Teh and Mok [15] also addressed the start-up problem in their boost converter. A self-start oscillation mechanism depending on the mutual coupling between the two identical transformer coils was applied. However, the efficiencies of their converters are low at low input voltages under 200 mV.

There are some commercially available boost converters, which were designed for low-power energy harvesting systems. Texas Instruments released a low-power boost converter chip BQ25504 with battery management for energy harvesting [16]. However, it needs a minimum input voltage of 80 mV, which is relatively high for low-voltage TEGs. And the self-startup voltage of 330 mV is too high. LTC3108 from Linear Technology [17] can operate at very low input voltage (as low as 20 mV). However, it does not possess an MPPT technique and its efficiency is relatively low as no more than 40%.

In order to power the wireless sensor nodes, there are some more considerations in the design of power management circuits. The operating voltage of the wireless sensor nodes (usually higher than 1.8 V) requires high conversion ratio boost systems from low voltage. Moreover, during transmit/receive mode, wireless transmitter will consume a high current (more than 15 mA). The high conversion ratio and current requirements both pose challenges for the power management system. To improve efficiency at high conversion ratio, usually a multistage boost system is applied [8,18]. To supply a high current during transmitting, usually a supercapacitor or a rechargeable battery is applied as an energy storage element.

In this paper, a low-voltage thermoelectric energy harvesting and management system for powering wireless sensor nodes is presented. The proposed system adopts a two-stage boost scheme and is able to self-start at a very low input voltage. The efficiency of the system is investigated experimentally. This paper is organized as follows. In Section 2, the overview of the proposed system and low-power design techniques employed for the proposed system are described. The experimental results are given in Section 3. Finally, conclusions and discussions are presented in Section 4.

2. Energy harvesting and management system

The design and operation of the system including the converter, self-startup system and MCU are described in this section.

2.1. System diagram

A block diagram of the proposed TEG generator system is shown in Fig. 1. The thermoelectric generator can be modeled as a voltage source V_T in series with its internal resistance R_T. The internal resistance R_T is slightly changed depending on the temperature difference level [19]. There are basically two working modes in this system. One is the two-stage booster working mode which is the normal working mode. The other is the self-startup working mode.

2.2. Design and operation of the two-stage converter

In the two-stage booster working mode, the energy from input capacitor C_i is transferred to a temporary storage capacitor C_{tem} with a boosted voltage. The second-stage boost converter is used to boost the voltage on the capacitor C_{tem} to a final energy storage device, usually a supercapacitor or a rechargeable battery. A linear regulator is used to regulate the voltage on the energy storage device to a working voltage for the MCU and WSN node. As the voltage on the energy storage device may be much higher than the needed working voltage for the MCU and WSN node, the linear regulator can reduce the unnecessary power consumption due to the higher voltage.

As the BQ25504 chip can boost a low voltage (higher than 80 mV) to a battery voltage and possess the battery management functions, it is very suitable for working as a second stage converter. A high efficiency first-stage boost converter is needed to boost the ultra-low voltages from TEGs to a workable voltage V_{tem} for BQ25504, which is set as around 1 V in the proposed system. The topology of the first-stage boost converter is similar as in [12] and is shown in Fig. 2. Differently, a DCM working mode is applied to the first-stage boost converter to lower down the power consumption of the converter.

The first-stage booster mainly includes controlled on-off switches G_1, G_2 and S_2, and an inductor L. Switches G_1, G_2 and S_2 are all based on n-channel metal–oxide–semiconductor field-effect (NMOS) switches. To implement the impedance matching technique, the converter is periodically disconnected from the TEG element by a switch S_2 and the open-circuit voltage is measured during the disconnection period by the controller. The impedance matching scheme is implemented by keeping the voltage on the input capacitor C_i optimal.

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