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A dual polarity, cold-starting interface circuit for heat storage energy harvesters

T.T. Toh*, S.W. Wright, M.E. Kiziroglou, P.D. Mitcheson, E.M. Yeatman

Department of Electrical and Electronic Engineering, Imperial College London, London SW7 2AZ, UK

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ABSTRACT

This paper describes the design and implementation of a power electronics interface for a heat storage thermoelectric energy harvesting system. As an example of its application, the energy harvester was designed to supply power to a duty cycled wireless strain gauge sensing system for aircraft applications that typically consumes 28.5 J per flight, with a peak power consumption of 100 mW at 3.3 V. The harvester, which will be mounted on the fuselage of an Airbus aircraft, generates a bipolar voltage due to a reversal in the polarity of the temperature difference across a thermoelectric generator at different parts of the flight cycle. For the target application, a peak generated voltage of ±1.2 V across a matched load is expected, which requires rectification and regulation. The interface circuit consists of a cold-starting rectifier topology, a low-dropout regulator and a maximum power point tracking boost converter with a battery charging module. A prototype of a new and cold-starting rectifier topology was implemented using an H-bridge configuration of off-the-shelf depletion- and enhancement-mode MOSFETs. For a temperature cycle of +24 °C to −27 °C and back, spanning 80 minutes, the interface circuit delivers 81 J into a secondary Li-ion battery from a total generated energy of 126 J. This corresponds to a measured average circuit efficiency of 64.3% for this example application.

1. Introduction

Aircraft electrical systems are becoming ever more complex and in the case of the Airbus A380, approximately 500 km of internal wiring is used [1]. Wireless solutions are therefore desirable within the aircraft industry. These wireless systems are conventionally powered by finite energy sources such as batteries, which will need periodic replacement with an associated cost. A better solution would be to create a wireless sensor network that is powered by a localised energy harvesting system. In this case, a power management circuit that interfaces the wireless sensor to the energy harvester is required, and one such system is described in this paper.

A recent approach to energy harvesting in an aircraft environment is to convert temporal temperature variations into spatial variations using a heat storage unit (HSU) containing a phase change material (PCM). A thermoelectric generator (TEG) then produces electrical energy from this temperature gradient. The HSU stores heat energy that flows between the TEG and the ambient and sustains a temperature difference ΔT across the TEG. There will be a periodic change in the polarity of ΔT due to the cyclic nature of the temperature. This is in contrast to conventional applications of TEGs where the ΔT is typically of a single polarity. Further details on heat storage thermoelectric energy harvesting can be found in [2–4] and a recent flight test application for this transduction method is reported in [5].

There are many publications on interface circuits for energy harvesting devices [6–9]; however, in this particular case, the focus is to describe a dual polarity, cold-starting interface circuit for heat storage energy harvesters. Therefore, only prior art involving TEGs that generate bipolar voltages is reviewed in this paper. This new approach to thermoelectric energy harvesting has been demonstrated on a systems level by Bailly et al. [10] and Samson et al. [11] using water as the PCM in both cases.

The device from [10] generated 34 J of electrical energy for a temperature profile that varied from +18 °C to −55 °C and back; however, the nature of the output power measurements, and hence energy harvested, was not reported. A brief description of a 0.35 μm CMOS interface that was simulated in PSpice indicated that synchronous rectification was used. The bias voltage for the synchronous rectifiers is provided by supercapacitors which, in their simulation, require 7 minutes of charging in order to reach 1 V.

* Corresponding author. Tel.: +44 7872608119.
E-mail address: tzern.toh@imperial.ac.uk (T.T. Toh).

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In [11], the device generated 22 J in a matched 39 Ω load, for a temperature variation of +20 °C to −35 °C and back. A description of the rectification stage in the power management circuitry was given in a prior publication [12], where Schottky diodes were used to rectify the generated TEG voltage.

A possible improvement to the interface electronics reported in [10–12] is to use a passive, cold-starting rectifier topology that does not require microcontroller-based polarity detection, gate drivers or diode-based rectifiers. Therefore, the aim of this paper is to describe, and explain in detail, the implementation of a prototype power electronic interface for a heat storage thermoelectric energy harvester that includes a cold-starting rectifier circuit, with the capability of extracting maximum power from the TEGs and using any excess generated power to charge a secondary Li-ion battery.

In order to experimentally evaluate a functional prototype, the interface electronics comprises only off-the-shelf components and, therefore, the efficiency of each circuit stage may be slightly compromised, compared with the possible performance using custom-designed electronics. The components were suitably chosen for operation over an extended temperature range of −40 °C to +85 °C.

2. Heat storage thermoelectric energy harvester

2.1. Device characteristics

The electrical equivalent circuit of a TEG is a DC voltage source with a series resistance R_{teg}. In this work two TEGs from Marlow Industries, the TG12-2.5-01L model, were connected electrically in series, resulting in a total equivalent internal resistance of 10 Ω. The choice and total number of TEGs was based on performance and on space constraints within the energy harvesting package, details of which can be found in [3].

Fig. 1 shows the results of experimental measurements in a climate chamber with a matched load of 10 Ω connected across the TEG terminals. The variables T_{in} and T_{out} represents the PCM temperature and climate chamber temperature respectively. The HSU has external dimensions 60 × 30 × 30 mm and an internal volume of 30 ml. Water was used as the PCM and only 23 ml of water was used to account for PCM expansion during phase change. The chamber temperature was varied in four stages, 1st stage: +24 °C to −21 °C; 2nd stage: held at −21 °C for 15 minutes; 3rd stage: −21 °C to −27 °C and finally, 4th stage: −27 °C to +22 °C, to simulate aircraft fuselage temperature variations during ascent, cruise and descent [13]. It was observed that the output voltage across a 10 Ω resistor, V_{teg}, changes polarity once due to the polarity reversal of the temperature gradient, and a peak voltage of 1.2 V was achieved at a $\Delta T = T_{in} - T_{out}$ of 27 °C.

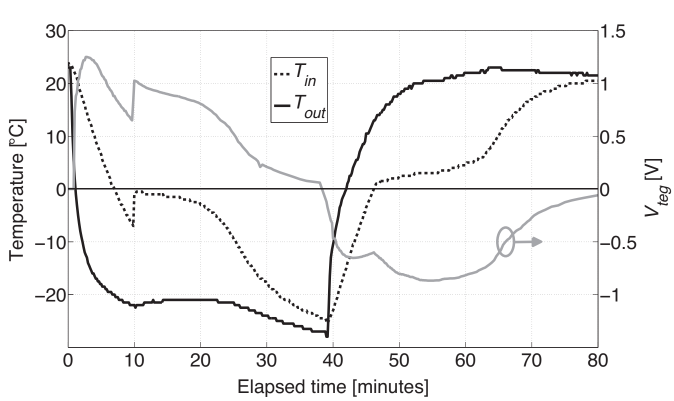

Fig. 1. Measurements of T_{in}, T_{out} and the voltage across a matched 10 Ω load. The right side axis is for V_{teg}, which is represented by the solid grey line.

2.2. Interface design requirements

The voltage profile in Fig. 1 shows two electrical characteristics of this method of thermoelectric energy harvesting. Firstly, the generated voltage is bipolar because ΔT changes polarity midway through the temperature cycle, and secondly, the generated voltage is typically low, in this case peaking at ±1 V. Therefore, some form of power management interface between the harvester and sensor node is required in order to rectify and step-up the generated TEG voltage and provide output voltage regulation. Additionally, it is desirable to store the excess energy in either a supercapacitor or rechargeable battery, which will be used to sustain operation of the interface electronics. The different stages required in the power electronic interface for this thermoelectric energy harvesting device are shown in Fig. 2.

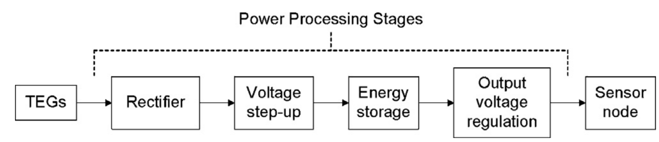

Fig. 2. Generic interface electronics topology for this application of a thermoelectric energy harvester.
Sources: Adapted from [14].

In the event that the aircraft is grounded for a long period, the energy storage element could become totally discharged. This means that the rectification stage must be able to cold-start, even if the energy storage element is depleted. This precludes using conventional active synchronous rectifiers that require gate drivers. Passive full-wave bridge rectifier circuits are not practical here due to the low generated voltage from the TEGs. Even if Schottky or germanium diodes are used, the TEGs will need to generate at least 0.5 V before the bridge conducts and at the peak ΔT, approximately half the generated voltage will be lost across the bridge. Such devices also have high reverse saturation currents, which are an undesirable feature. Another option is to use electromechanical latching relays to switch the conduction path depending on the polarity of the generated voltage. However, they are susceptible to contact bounce and require non-negligible energy to change state. Furthermore, such mechanical components are undesirable in aircraft systems.

Designing a rectifier circuit for this application is made simpler because the polarity of the TEG voltage, V_{teg}, can be determined beforehand by appropriate connection of the TEGs. Therefore, a set of normally-closed (NC) switches can be configured to provide a conduction path during the first half of the flight cycle where the ambient temperature is known to decrease. During the second half of the cycle, by which time there is enough energy available to operate the switches, the first set of NC switches will be opened and simultaneously, a second set of normally-opened (NO) switches will be closed to provide a conduction path for the opposing polarity of V_{teg}. This means a passive rectification path is present at the start of the temperature cycle without control signals and requiring no power. Using the energy harvested during the first half, a second set of switches can then be enabled during the second half of the flight cycle.

This is schematically shown in Fig. 3 as NO and NC switches in an H-bridge topology. The solid and dashed arrows indicate the conduction paths for the polarity of V_{teg} during the ascent and descent phases, and V_{rect} is the rectified TEG voltage.