STEP-UP CONVERTERS FOR HUMAN BODY ENERGY HARVESTING THERMOGENERATORS

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Abstract: Two different approaches are presented for the challenge of the design of a low-input voltage converter to increase the voltage generated by a thermogenerator (TEG). One of the circuits employs a charge-pump in conjunction with a step-up converter whereas the other one is a step-up converter based on coupled inductors. The TEG makes use of the temperature gradient between the human body and the ambient (3-6 K) to generate a low output voltage that covers a range from 120 mV to 240 mV with a maximum output current of 18 mA.

Key Words: Thermogenerator, energy harvesting, step-up converter, low input voltage

1. INTRODUCTION

Energy harvesting transducers (kinetic, electromagnetic, electrostatic, thermogenerators, et cetera) can employ human body as their input energy to obtain electrical energy. The power management unit of an energy harvesting generator must be designed specifically for the kind of transducer employed. However, a common factor in all human body energy harvesting transducers is the low output power recovered.

The human body continuously radiates heat. Devices in direct contact to the human body can harvest this wasted energy by means of TEGs. This paper presents a TEG that makes use of the temperature gradient between the human body and the ambient (3-6K) to generate a low output power. Nowadays, there is a gap between the output of thermoelectrical energy transducers and the minimum required input voltage of state-of-the-art voltage converters like dc-dc boost regulators that is not lower than 300 mV [1]. Two different power management circuits are presented to increase the low output voltage of TEGs and be able to power supply a low power electronic device.

The structure of the paper is as follows. Section 2 describes the main constraints for the step-up converters related with the low output power obtained with thermoelectrical transducers. Section 3 introduces the first power management design which is a combination of a charge pump and a step-up converter. Section 4 presents the second power management circuit based on coupled inductors. Finally, Section 5 draws the main conclusions of the paper.

2. CIRCUITS CONSTRAINTS DUE TO THE USAGE OF THERMOGENERATORS

The power management design for an energy harvesting application requires a well knowledge of the equivalent electrical circuit of the energy harvesting transducer, as well as, its output voltage and current levels. The electrical part of the TEG equivalent circuit is composed by a voltage source, V_{oc}, and an internal resistance, R_m [2]. The value of V_{oc} is proportional to the temperature gradient, ΔT, between the hot and the cold junctions and to the Seebeck´s coefficient, α_m, of the thermoelectrical module, that is:

$$V_{oc}= \alpha_m \Delta T \tag{1}$$

Several thermogenerators were characterized in order to determine an optimum in terms of efficiency for the present application. The Peltrom thermoelectric module 128A1030 [3] was the selected one to be used as input source for the designed power management units. This TEG was characterized and the obtained measurements are presented in Fig. 1.

Fig. 1 shows the voltage as a function of current for different ΔT. The Seebeck´s coefficient for this thermoelectric module in open circuit is in the range of 40 mV/K. The value of the internal resistance, R_m, of the TEG was calculated for the different ΔT (see Fig. 1). The maximum power is obtained when the output load impedance connected to the TEG is equal to R_m.

In summary, the voltage source connected to the dc-dc converters is composed by a low voltage source in the range of approximately 100-250 mV and a resistor on the order of 10 Ω for the temperature gradients to be used.

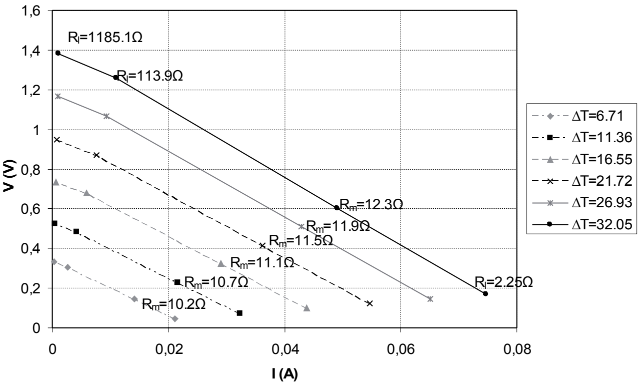

Fig. 1. Measured output voltage of the TEG as a function of current for different ΔT values. R_m is the internal resistance of the TEG and R_l is the value of the different resistive loads connected to the TEG.

3. POWER MANAGEMENT UNIT DESIGN BASED ON CHARGE-PUMP AND STEP-UP DC-DC CONVERTER

In energy harvesting generators, it is possible to employ a battery or a capacitor to store the energy that is not immediately consumed by the electronic load. However, an energy harvesting system must not be dependent on the energy storage element to be able to start its operation. Therefore, a start-up circuit to assure initial voltage conversion only employing a thermoelectric transducer is included in both designs presented.

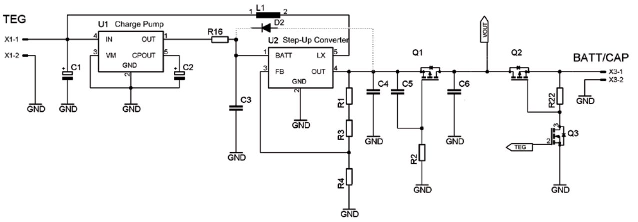

Fig. 2. Schematic of the power management unit composed by a charge-pump and a step-up converter.

The power management unit presented in this section (see Fig. 2) is designed to convert input voltages in the order of few hundreds of millivolts into 2 V and eventually to store the remaining energy into a storage element like a battery or a capacitor.

3.1 Starter Circuit

The start-up circuit consists of a charge- pump [4] in conjunction with a step-up DC-DC converter [5]. The charge-pump, *U1*, is employed as a starter circuit to increase the low input voltage generated by a TEG charging a high value capacitor, *C*2, to 1.8 V. Then, the step-up converter, *U2*, starts switching by means of this available start-up energy. Once the converter starts regulating and its output rises, the charge-pump is not needed anymore.

3.2 Main Circuit

Once the converter starts switching, the boost converter supplies its own control power by feeding the output voltage to the input of its switching circuitry by means of an internal diode of the step-up converter, *D2*, and the charge pump can be short-circuited by the inductor, *L1*, of the step-up converter. Thus, the step-up converter enters stand-alone operation mode and keeps supplying a regulated output even though the input voltage decreases below the 250 mV start-up voltage. Switching at an input voltage as low as 130 mV was recorded. The output voltage of the boost converter is 2 V. The efficiency of the converter is 60% for an input voltage of 300 mV and an input current of 10.33 mA and 40% for 130 mV and 8.45 mA.

Care must be taken in the choice of the values of the required energy storage elements, i.e. the capacitor of the charge-pump, *C2*, and the inductor of the step-up-converter, *L1*. A trade-off must be made when dimensioning the value of the charge-pump capacitor. A high value capacitance is required to provide the necessary start-up power of the next stage, while a lower value reduces the start-up time. Thus, the lowest but still functional value was selected. As the energy source is very restricted, current limitation issues are of no concern for the application. High inductor values may be employed by the step-up converter in order to reduce the minimal start-up voltage and to provide high efficiency as well. Thus a high value inductor was employed (*L1*=330 μH).

A PMOS transistor, *Q1*, is required to delay upon power-up the connection of the converter's output to the electrical load or the energy storage element since at first it can not deliver enough energy for the stand-alone operation and the load. The time delay is set by *C5* and *R2* and it is in the order of tens of milliseconds.

4. POWER MANAGEMENT UNIT DESIGN BASED ON COUPLED INDUCTORS

The power management unit presented in this section (see Fig. 3) consists basically in a synchronous step-up converter based on coupled inductors [6].

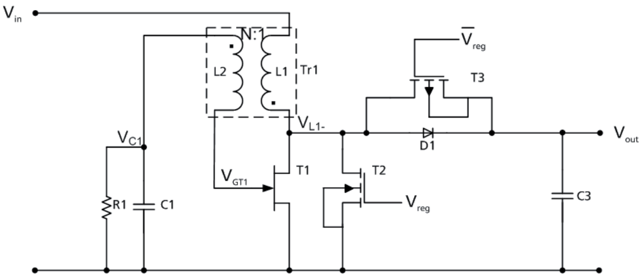

Fig. 3. Simplified schematic of the power management unit based on coupled inductors.

4.1 Starter Circuit

The N-channel FET, *T1*, is in on state with a zero gate voltage. Moreover, it takes some time to the TEG to provide a stable voltage at the input of the converter. Therefore, the current through the inductor *L1* and *T1* increases also slowly and induces a negative current in the secondary winding of the transformer, *L2*, that charges the capacitor *C1* with a small negative voltage because of the p-n junction connection to ground at the gate of *T1*. The current in the primary winding, *L1*, becomes constant when the input voltage becomes also constant. When the TEG provides a constant value, the current that flows through *L1* is also constant and a zero voltage appears on *L2*. Then, the gate of T1 is connected to *C1* making that the current flowing through *L1* decreases. Fig. 4 shows the waveforms obtained at different points of the circuit.

This switching cycle is repeated but with a constant voltage at the input which implies that an exponential response is obtained for the current that flows through *L1* with a time constant $\tau = L1/R$. *R* is the series equivalent resistance of the TEG and *T1*. τ is in the order of units of microseconds and therefore, a high negative voltage is induced in *L2* until the current flowing through *L1* reaches its maximum value. At this point, the gate of *T1* is connected to *C1*, switching the transistor off. This causes that the current flowing through *L1* decreases until it reaches a zero value that is when the cycle is repeated again. When the voltage over capacitor *C1* is lower than the threshold voltage of *T1*, this transistor is not switched on anymore and the NMOS transistor T2 becomes the switching transistor. The capacitor *C1* is charged more negatively and *C3* is charged via diode *D1*.

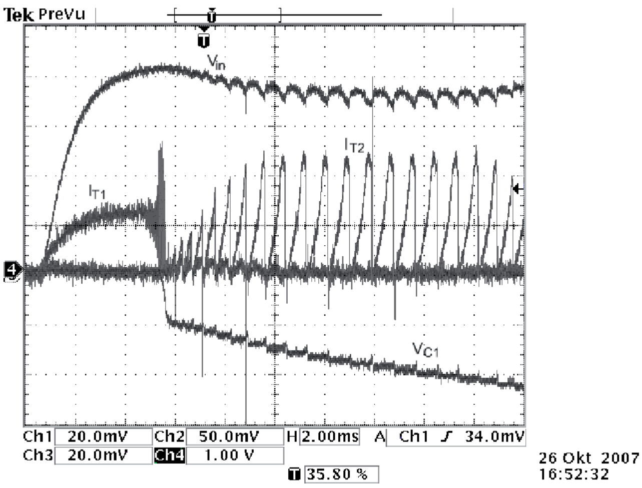

Fig. 4. Measured waveforms obtained during the start-up phase. Ch1 corresponds to I_{T2}, Ch2 to V_{in}, Ch3 to I_{T1} and Ch4 to V_{C1}.

4.2 Main Circuit

The main circuit (see Fig. 3) acts as a synchronous step-up converter with a feedback loop that allows regulating the output voltage with V_{reg} during steady state phase. Fig. 5 shows some waveforms obtained during steady state.

After the start-up phase, a NMOS transistor, *T2*, connected in parallel with T1 becomes the switching element. The parallel connection of both transistors allows having a switch with low on resistance during steady state and zero threshold gate voltage for start-up.

The value of V_{reg} modifies the value of the gate voltage on the NMOS transistor and thus, the value of its on resistance which modifies the time that *T2* is on, keeping the switch off time almost constant. Therefore, the value of V_{reg} regulates the output voltage of the converter basically modifying the switching frequency of the converter. The main circuit is a synchronous converter with a PMOS transistor *T3* in parallel with the diode *D1*. Therefore, when the main circuit starts regulating, the PMOS is switched which allows to reduce the drop voltage on the diode. The converter works in the boundary between continuous and discontinuous conduction mode, see I_{D1} and I_{T2} waveforms in Fig. 5 [7].

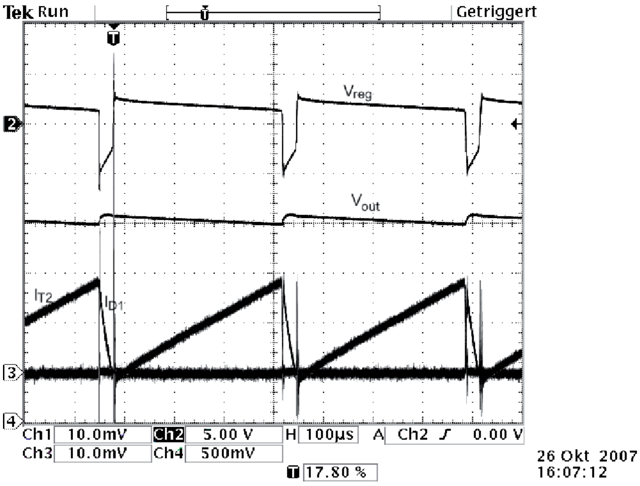

Fig. 5. *Measured waveforms obtained during the steady-state phase. Ch1 corresponds to I_{T2}, Ch2 to V_{GT2}, Ch3 to I_{D1} and Ch4 to V_{out}.*

Fig.6 shows the efficiency of the converter as a function of the load current for different values of the input voltage, V_{in}. The start-up voltage for this step-up converter is 116 mV.

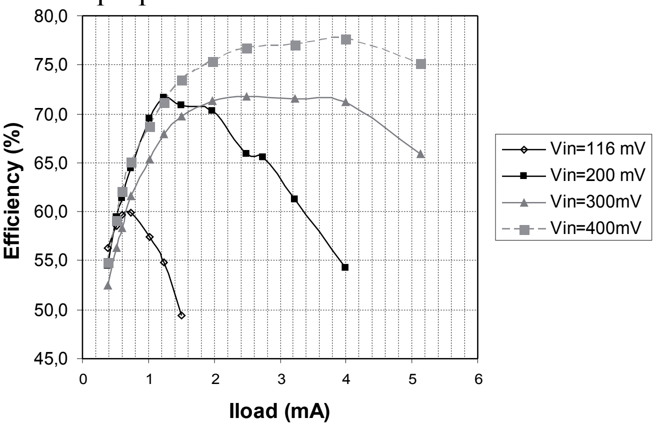

Fig. 6. Measured efficiency vs. load current for different input voltages.

5. CONCLUSIONS

Two different power management units to be used with TEGs as power supply source have been presented. The TEGs employ low temperature gradients (3-6 K).

The power management circuit with charge-pump and step-up converter has a lower efficiency and start-up voltage than the step-up converter based on coupled inductors. However, that solution it is easier and faster to implement.

The boost converter based on coupled inductors has efficiencies in the range of 70% for input voltages of 300 mV and a low start-up input voltage (116 mV) which makes it an appropriate power management solution to employ with TEGs.

The output power obtained with both step-up converters is enough to supply a low power communication module like the EnOcean transmitter module STM100 [8] and the nRF42E1 transceiver from Nordic [9].

ACKNOWLEDGEMENTS

The authors would like to thank Alexandre Jacquot, Nestor Lucas and Cosmin Codrea for their technical support and Fraunhofer IIS for founding the Nanotec project.

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