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Efficient Boost Converter for Thermoelectric Energy Harvesting

J.-M. Gruber, S. Mathis
Institute of Embedded Systems (InES),
Zurich University of Applied Sciences (ZHAW)
Winterthur, Switzerland
gruj@zhaw.ch

Abstract

This paper presents a new boost converter for thermoelectric energy harvesting. The output voltage is regulated at 3.6 V for use with embedded systems. The booster reaches high efficiency at low input voltages of few 10 mV. A first prototype operates at about 15 mV input voltage with an efficiency of 45%. At 120 mV input voltage the efficiency increases to 74%. Using a 30x30mm sized low cost thermoelectric generator (TEG) in combination with the new developed booster, enough energy can be harvested to power an embedded wireless sensor.

Key words: DC-DC converter, thermal energy harvesting, low input voltage, thermoelectric generator, TEG, boost converter

Thermal Energy Harvesting

In environments with heat waste, thermoelectric generators (TEG) can be used to convert thermal energy in electrical energy. Typical applications are heat radiators or pipes with hot fluids. Also heat from mechanical or electrical equipment is a potential energy source, e.g. industrial drives. The conversion process is based on the Seebeck effect. The output voltage is proportional to the temperature difference.

Motivation

Small TEGs provide an output voltage of a few 10 mV at small temperature differences. A boost converter is needed to convert the voltage into a usable voltage level for sensors and embedded systems. It should be able to start up and operate efficiently at these low voltages. Under these conditions, commercial available boost converters operate with low efficiency or don't operate [1,2,3].

Goal of this work is to realize a boost converter which can directly start and operate at high efficiency from several 10 mV. In order to supply sensors and electronics, the output voltage is adjustable up to 3.6 V. Costs are comparable to commercial available solutions.

Booster Layout

Fig. 1 shows the simplified block diagram of the booster. The TEG input is on the left and the regulated output voltage on the right side.

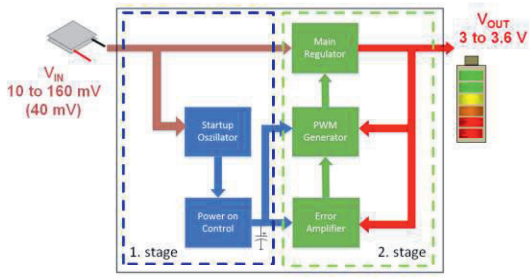

Fig. 1 Simplified block diagram of the developed boost converter

The converter has two separated stages. The first stage is used to start up the converter from low input voltages. The first stage starts charging an intermediate capacitor. When the capacitor is charged, the collected energy is used to activate the second stage. The second stage operates with high efficiency and provides a regulated output voltage of 3.6 V.

Startup

The first stage is a startup circuit for cold start. It operates at an input voltage of about 36 mV. The startup circuit is a self-resonant oscillator connected to a voltage doubler. It is shown

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simplified in Fig. 2. The TEG is connected at the V_{IN} node and the energy collected from the TEG is stored in the capacitor C_1 at the output.

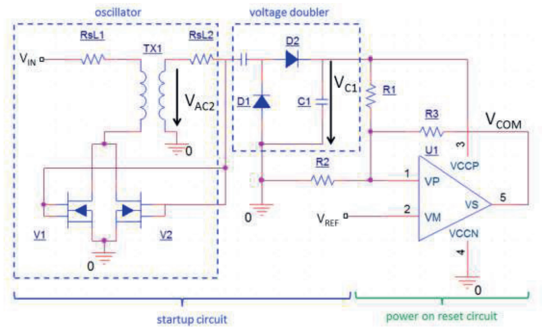

Fig. 2 First stage consisting of self-resonant oscillator, voltage doubler and power on reset

A coupled inductor in conjunction with two transistors builds an oscillator. The use of depletion FETs allows the converter to start from input voltages below the threshold voltage of enhancement FETs because conduction occurs at zero voltage. The parasitic gate capacitors of V_1 and V_2 and the secondary coil winding of TX1 form a series resonant circuit with a resonance frequency f_R according to (1)

$$f_R = \frac{1}{2\pi\sqrt{L_2 * C_{gtot}}} \qquad (1)$$

Where L_2 is the secondary inductance of TX1 and C_{gtot} represents the sum of the gate capacitors of V_1 and V_2. Due to oscillation, an alternating voltage V_{AC2} is formed on the secondary winding. On the one hand V_{AC2} is fed back to V_1 and V_2 to sustain the oscillation and on the other V_{AC2} is rectified by the voltage doubler to charge the intermediate capacitor C_1.

The coupled inductor is realized by a transformer with a secondary inductance of 75 mH. RsL1 and RsL2 are the winding resistance of the primary and secondary coil in the simulation. While C_1 is charged through the startup circuit, the power on reset circuit on the right side in Fig. 2 senses the voltage V_{C1}. The power on reset circuit consists of a shunt voltage reference V_{REF} and a comparator U_1 with three external resistors. With the voltage reference set to 1.25 V the trip points for V_{C1} become V_{TH+} = 2.8 V and V_{TH-} = 1.9V. The comparator output is low while C_1 is charged but switches into high state as soon as V_{C1} reaches 2.8 V.

The startup circuit is optimized for low input voltages. Thus the overall efficiency of the startup circuit is about 9.5 %.

The startup circuit needs 73.1 seconds to charge a 10 µF capacitor to 2.8 V with a measured output power of average 5.6 µW. Although the startup circuit is not suitable for high efficiency conversion, it collects enough energy to start the second stage.

High Efficiency

When the voltage on the intermediate capacitor C_1 reaches 2.8 V, the power on reset circuit activates the second stage. It consists of the main converter, a triangle wave generator, comparator and an error amplifier (Fig. 3). By turning on the main regulator control blocks, a pulse width modulated (PWM) signal is generated on the N-FET V_1, which turns on the main regulator, current flows through the inductor L and thus charges the output capacitor C_{OUT} to 3.6 V.

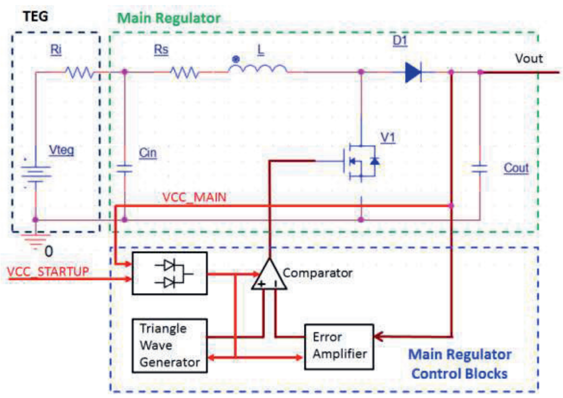

Fig. 3 Second stage with main regulator, control blocks and TEG on the left side

An error amplifier in voltage controlled mode is used for the output voltage regulation. The relaxation oscillator with a switching capacitor of 100 pF generates the triangle wave signal. The triangle wave signal is compared with the error amplifier output to form the PWM signal. Due to high a voltage gain up to 200, the converters duty cycle had to be equal 99% or more in continuous conduction mode. Instead, the converter works in discontinuous conduction mode with a maximum duty cycle limited to 66%. Thereby the converter sets the closed loop input voltage approximately to 50 % of the open loop TEG voltage if the output is loaded.

The new boost converter is tuned to operate in optimum efficiency with an evaluated TEG at low temperature differences. Internal resistance of the TEG is about 0.85 Ω. This combination starts harvesting energy at 1.5 K temperature difference. At 3 K, the open loop output voltage on the TEG becomes 78 mV. Due to low TEG internal resistance, an input current of more than 44 mA must flow through the converter to achieve maximum power transfer between TEG and converter. In simulation of the main converter, a switching frequency of 5 kHz on V_1 in combination with an inductor L of 36 µH performed best in terms of overall efficiency.

For the inductor, simulation results with series resistances of 20 mΩ or less showed good results. At 40 mV input voltage, peak switching currents on the inductor up to 130 mA at full load are required. The TEG is not able to deliver the peak current directly. Input buffering capacitors are used. To reduce converter complexity and costs, a schottky diode D1 is used for rectification. Fig. 4 shows the component losses by performing a transient simulation of the main regulator. The TEG open loop voltage V_{TEG} is set to 78 mV to simulate a temperature difference of 3 K. C_{IN} and C_{OUT} are pre-charged according to in- and output voltage. The output voltage of the converter is fixed at 3.6 V using a DC source.

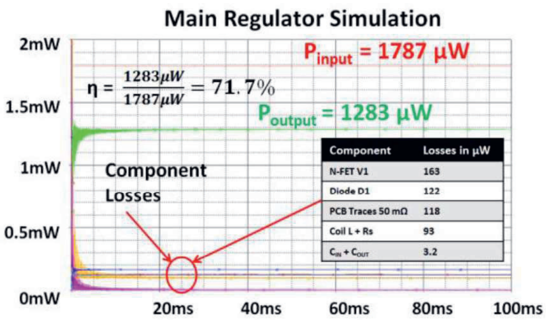

Fig. 4 Simulation results and component losses at 40 mV input voltage (3K on the TEG)

The simulated converter efficiency is about 71 % at 40 mV input voltage. Most of the losses are caused by V_1 and D_1, especially due to switch node ringing when turning off V_1. For simulation, a PCB copper trace resistance of 50 mΩ has been assumed. According to Fig. 4 this resistance already causes 118 µW or 7% losses. Keeping PCB traces in the main regulator paths as short as possible reduces losses.

The real converter efficiency is lower compared to simulation. Supplying all control blocks including switching of V_1 causes losses of 50.4 µW. This drops the converter efficiency down to 68%.

Prototype

The prototype PCB outlines measures 55x60 mm with a total height of 25mm due to two 1500 µF capacitors (Fig. 5).

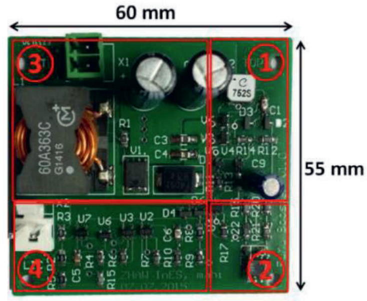

Fig. 5 Converter prototype assembled on a PCB

The converter is made of discrete components and functional blocks are arranged into four different blocks. In block 1 the startup oscillator with the voltage doubler and intermediate capacitor is shown. Block 2 contains the power on reset circuit which activates the main regulator as soon as the intermediate capacitor is charged to 2.8 V. The components of the main regulator in block 3 are kept close to each other to reduce copper trace resistance. Main regulator control blocks such as error amplifier and PWM generator are located at the bottom in block 4.

Prototype Results

The converter was tested using a 30x30mm TEG with an internal resistance of 0.85 Ω and Seebeck coefficient of 26 mV/K. It was mounted between a labor hot plate and heat sink. In Fig. 6 the startup and operation of the developed converter is shown.

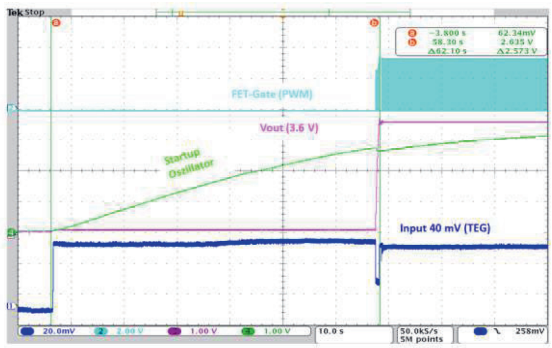

Fig. 6 Startup of the converter from TEG with 40 mV input voltage

After reaching a stable output voltage of approximately 40 mV (CH1, dark blue) on the TEG, the converter was connected. Immediately the startup oscillator starts charging the intermediate capacitor (CH4, green). To power the control blocks during main regulator startup, the capacitor on the developed prototype was increased from 10 µF to 47 µF. At 2.8 V the second stage is activated through the power on reset circuit which enables the PWM generator (CH4, light blue) to start conversion on the main regulator.

Charging the output capacitors to 3.6 V (CH3, red) causes a short voltage drop on the input voltage. Approximately one minute elapsed until 3.6 V was measured at the output. Although no load was connected, the input voltage is slightly lower compared to the startup phase due to main regulator control block supply.

Comparison of Different Combinations

The developed booster in combination with TEG 071-150-22 (30x30 mm) and TEG 049-150-30 (25x25 mm) is compared against other combinations with commercial available converters. Three boost converters in total, LTC3108, ECT310 and BQ25504 are tested with different types of TEGs at temperature differences from 3 to 15 K on the TEG. The results of the measurements are shown in Fig. 7. On the LTC3108 and ECT310 the TEG internal resistance is important for maximum power transfer. While the ECT310 requires a TEG with less than 2 Ω [1], the LTC3108 equivalent input impedance depends on input voltage while VOUT is charging [2]. A TEG with an internal resistance of 6.6 Ω and Seebeck coefficient of 56 mV/K was chosen and a transformer ratio of 1:20 on the LTC3108. On the BQ25504, the TEG impedance does not matter because of maximum power point tracking [3]. For all measurements, the output voltage of the converters was set to 3.3 V.

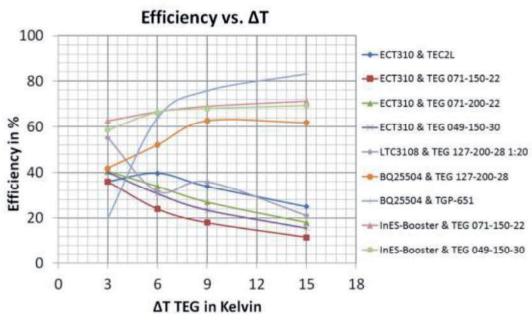

Fig. 7 Efficiency comparison of different combinations

At a temperature difference of 3 K, a combination efficiency of 62% was achieved with the developed converter while delivering 802 µW at the output. Similar results were measured on the LTC3108, about 55% with constant output power of 719 µW. With increased temperature difference, the efficiency on the LTC3108 and ECT310 drops due to output voltage limitation on the transformer. In contrast, the efficiency on the developed converter and BQ25504 increases with higher input voltage because conversion takes place according to boost instead of flyback topology.

Conclusion

A solution is presented for thermoelectric energy harvesting at very low input voltages. The new developed boost converter reaches high efficiency at 15 mV input voltage. The converter can start directly from a small TEG with 36 mV input while delivering a regulated output voltage of 3.6 V. A prototype has been realized and tested. At 3 K temperature difference on a small TEG the prototype reached an efficiency of 62 % while delivering 802 µW of power.

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