DC-DC-CONVERTER WITH INPUT POLARITY DETECTOR FOR THERMOGENERATORS

Markus Pollak, Loreto Mateu, Peter Spies
Power Efficient Systems Department, Fraunhofer IIS, Nürnberg, Germany

Abstract: This paper presents a DC-DC converter, which automatically detects the polarity of its input voltage. Thus, the converter can work with both positive and negative input voltages. It is intended to be used by energy harvesting thermogenerators with output voltages below 300 mV where hot and cold side can exchange. A test design achieved an efficiency of 65 % for an input voltage of 200 mV and an output voltage of 2.5 V with an output power of 4 mW. This first design was built with discrete components, but can also be integrated on a chip with few external components (such as transformer and input/output capacitor).

Keywords: Thermogenerator, DC-DC converter, low input voltage, energy harvesting

INTRODUCTION

Thermogenerators based on the Seebeck effect provide in general low output voltages and relatively high output currents. Additionally, their output polarity is dependent on the direction of the applied temperature gradient. Thus, for using such transducers as energy harvesting generators a DC-DC converter for very low input voltages is most important. In a previous publication [1] such a design was shown with an efficiency of around 70 % at 200 mV input and 2 V output voltage. This design was further developed to work independently of its input voltage polarity for the use with thermogenerators with both positive and negative temperature gradients. This can be useful with changing environmental conditions like indoor and outdoor use.

DESIGN ASPECTS

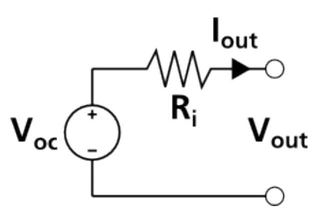

Fig. 1: Equivalent circuit of a thermogenerator

The proposed design in this paper is intended to be used in combination with thermogenerators based on the Seebeck effect. These energy transducers typically deliver a output voltage of around 50 mV per Kelvin temperature difference between top and bottom plate. Thus, the output voltage can be very low when used in energy harvesting applications, but at the same time currents of over 10 mA can be easily achieved. Fig. 1 shows the simplified equivalent circuit of a thermogenerator that fits very good to reality (a thermogenerator is a purely DC generator). However, the polarity of the voltage source can be positive or negative depending on its adjacent temperature gradient. Typically the internal resistance R_i is in the range of 10 Ω.

For supplying electronic devices from a thermogenerator it is required to connect a boost converter in between that can cope with very low input voltages. Another solution is to connect several thermogenerators in series like for example with solar cells to achieve more input voltage for the converter. But this would not only lead to size constraints - also the thermal behavior of the whole device would be changed. In this way the thermal resistance between hot and cold side would be lower and if a heat sink is used at the cold side it would be heated up more or a bigger one would have to be used. In the end a solution with a special DC-DC converter design is preferable. This design should start at low input voltages to prevent the use of an extra battery for start-up. Because of these criterias state-of-the-art DC-DC converters available as integrated circuit still can only be used inadequately due to their low efficiency (typically below 50 % at 0.5 V input voltage).

Another interesting capability of the converter would be that it can work with positive and negative input voltages due to the mentioned behavior of thermogenerators. For this task a circuit is proposed in this paper that ensures a high efficiency at very low input voltages. This way the boost converter can work even if the output polarity of the thermogenerator changes.

In the next chapter at first the design of the step-up converter is discussed, which is different to some degree from the previous design in [1].

LOW VOLTAGE DC-DC CONVERTER

Functionality and design changes

The design idea behind the DC-DC converter built up here is a "Meissner" oscillator circuit like in the previous design (see Fig.2). That means it is a self-oscillating circuit based on coupled inductors. An important difference to other structures is the combination of a low-threshold transistor with a low-ON-resistance transistor. In the previous design a JFET ("low" threshold voltage, but high ON-resistance) was parallel connected to a MOSFET (low ON-resistance, but high threshold voltage). In the new design (see Fig. 3) the JFET is exchanged by a MOS transistor. It has a threshold voltage of around zero Volts with an ON-resistance of 250 Ω.

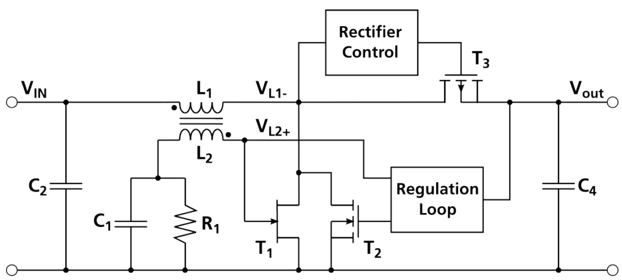

Fig. 2: Low voltage boost converter with coupled inductors from previous version

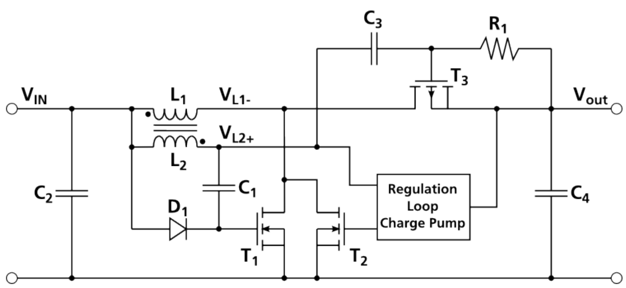

Fig.3: Low voltage boost converter with two parallel connected MOSFETs

The JFET used before led to a disadvantage - a lot of current is drawn out of the source below the start-up voltage, because the JFET is a normally-ON active element, that has a negative threshold voltage around -2 V. The MOSFET instead has a threshold at zero Volts and a much higher ON-resistance, thus the current around the start-up voltage is much less than with the JFET. This fact made it easier to build the polarity switching circuit discussed later on. The winding ratio of the transformer was additionally reduced to 1:4 (primary:secondary), still providing a start-up voltage of the converter itself at 110 mV.

Another change that has been made in the converter design concerns the regulation loop. In Fig. 4 again the former circuit part is shown [1]. In contrast in Fig. 5 the "new" approach can be seen.

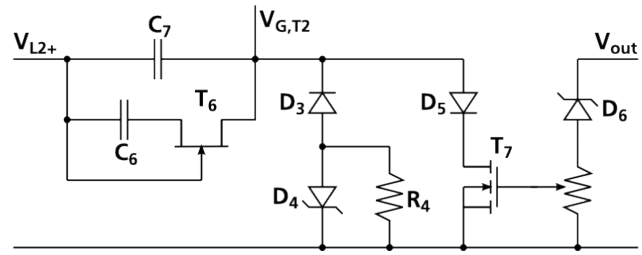

Fig. 4: Regulation loop of converter in [1]

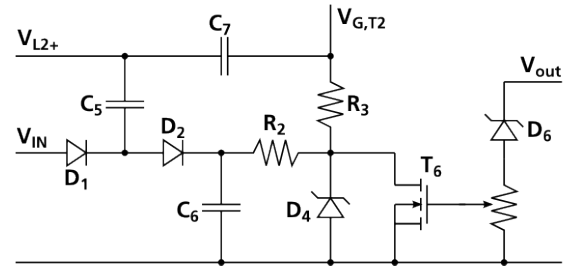

Fig. 5: Regulation loop of converter in this paper

The "starting aid" circuit (C_6 and T_6) has been exchanged by a simple charge pump consisting of Diodes D_1 and D_2 and the capacitors C_5 and C_6. That way a bias voltage for the low-ON-resistance transistor T_2 is generated the time after start-up where only T_1 is switching. That helps the converter getting into steady-state operation where T_2 is switching the main current over the inductor. The regulation of the output voltage itself is performed via transistor T_6 together with a Zener diode D_6 and a potentiometer that couples a part of the output voltage to the gate of T_7. This transistor controls the bias voltage for T_2 and basically the time it is switched ON. Thus a frequency modulation scheme is present in the same manner like in the "old" converter design (Fig. 2/4).

Another change which can be noticed from the design in Fig. 2 to the one in Fig. 3 is the control of the switching MOSFET T_3. The former inverter structure that uses V_{L1-} as input voltage has been exchanged by the capacitor C_3 connected to V_{L2+} and a resistor R_1. This has been done because of simplicity still eliminating a voltage drop loss using a diode instead of transistor T_3. Thus a high efficiency can be again reached (like in the former design), although the switching behavior of T_3 is only optimal for a fixed output voltage of the converter.

POLARITY INDEPENDENT DESIGN

Building Blocks

Fig. 6 shows the basic block diagram of the design developed for an input-polarity-independent DC-DC converter. The input signal first passes through a diode rectifier structure. The diodes can be short-circuited by switches to prevent losing efficiency from the forward voltage drop of the diodes. These switches are controlled by a comparator that compares the input voltage pins of V_{IN} and controls the switches inside the rectifier structure. For the comparator a dual voltage supply is provided by the positive output pin (V_{out}) of the converter and the negative output (compared to ground) from a charge pump. The input signal for the charge pump is the V_{L1-}-node of the primary inductor of the transformer – which would be also available if a commercial boost converter would be used. The negative supply rail for the comparator is generally needed because its input voltages can be negative compared ground potential. Additionally, this makes the design of the comparator easier, because it does not have to work close to the supply rails neither from the input side nor from the output side. The building blocks itself and their functionality are discussed in detail in the next subsection.

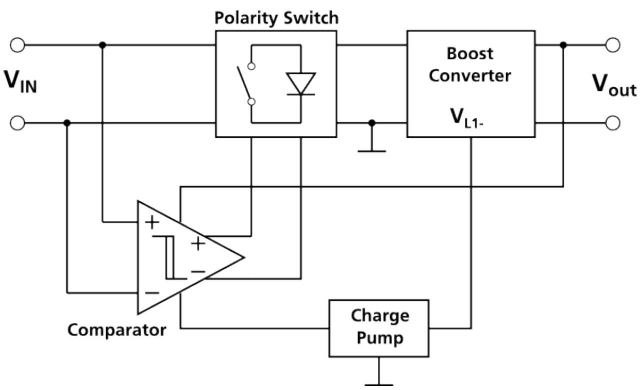

Fig. 6: Block diagram of proposed "bipolar" design

Polarity switching structure

As already mentioned, the structure for switching the input polarity is built like a diode rectifier bridge (see Fig. 7). The diodes are only active during start-up of the converter where still no supply voltage for the later on discussed comparator is present. Since standard schottky diodes have a significant voltage drop they act like resistors in the bridge structure in Fig. 7. That is the reason why the boost converter should draw as less current at start-up as possible to prevent having a too low voltage at its input. The former presented DC-DC converter in [1] was not suitable for this task, because the JFET (normally-ON active part) draws a lot of current out of the input of the converter before start-up.

As discussed before, also a charge pump is needed for creating a dual voltage supply for the comparator. This is shown in Fig. 8. It's a simple structure only built up with standard schottky diodes, but effective if the comparator does not need too much current. The charge pump uses the V_{L1-} signal (see Fig. 3) as input signal, shifting it (C_8 and D_{11}) and rectifying it (C_9 and D_{12}) afterwards.

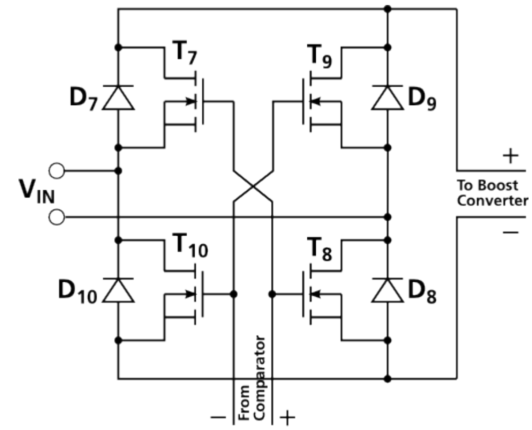

Fig. 7: Polarity switching circuit built similar to a rectifier bridge

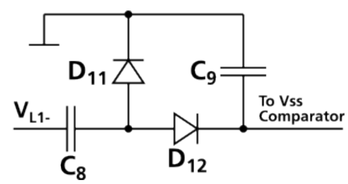

Fig. 8: Charge pump for the dual voltage supply of the comparator

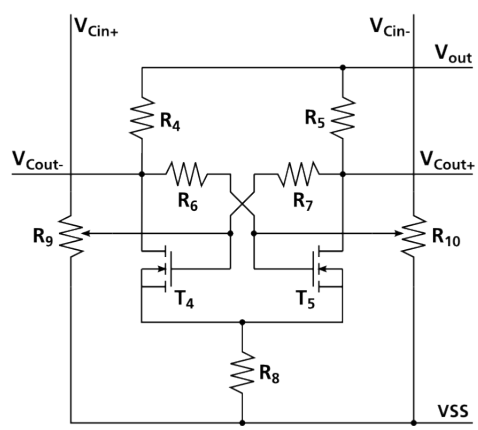

Fig. 9: Comparator design for detecting the input polarity and controlling the "rectifier" switches

The comparator structure (Fig. 9) is kept as simple as possible to have lowest possible current consumption and to make the whole design starting up at lowest input voltages. Of course, an alternative would be to use an integrated comparator since there are devices with extremely low current consumption below 1 µA on the market for low frequencies like in the application here. The comparator design in Fig. 9 is built up like a differential amplifier stage with a hysteresis established with the resistors R_6 and R_7. The transistors T_4 and T_5 have a threshold voltage of 0.2 Volts and an ON-resistance of around 500 Ω.

EXPERIMENTAL RESULTS

The complete "bipolar" boost converter approach was tested on a prototype board. The outline of the circuit itself is about 50 over 30 mm not including a big potentiometer for the output voltage adjustment.

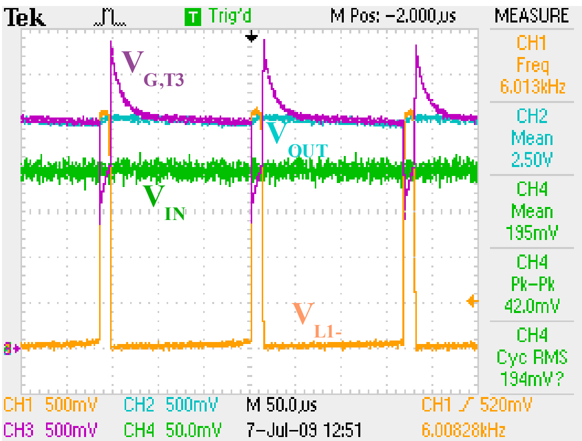

Fig. 10: Signals of the boost converter from Fig. 3 in steady-state operation

In Fig. 10 and 11 the circuit operation of the boost converter is shown at steady-state operation. The measurements were made at an input voltage of the system of 200 mV and an output voltage of 2.5 V. The output power was 3.85 mW with an input current of 29 mA. This resulted in a an efficiency of 66 %. Looking at V_{IN} - the input voltage of the boost converter after the rectifier structure - it can be noticed that the rectifier only creates a voltage drop of 5 mV. At the start-up voltage of 150 mV this voltage drop is around 40 mV, because only the rectifier diodes are working at that point. This voltage drop is of course low for Schottky diodes and could only be achieved using special devices with a high leakage current in reverse direction. But the measurements show that the leakage currents are not severely degrading the efficiency.

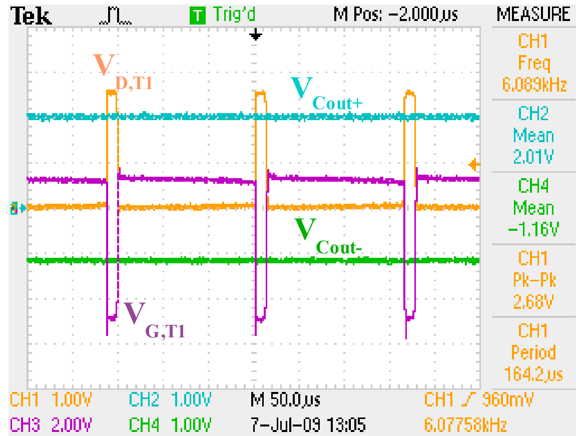

Fig. 11: Signals of the boost converter from Fig. 3 in steady-state operation

CONCLUSION

A step-up converter structure has been shown that can work efficiently at input voltages below 300 mV independently of its input voltage polarity. The system can start at an input voltage of 150 mV without the help of any energy storage elements.

REFERENCES

[1] M. Pollak, L. Mateu and P. Spies, Step-up DC-DC-Converter with Coupled Inductors for low Input Voltages, *PowerMEMS 2008 (Sendai, Japan 28–29 November 2007)*, pp. 145-148