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STEP-UP DC-DC-CONVERTER WITH COUPLED INDUCTORS FOR LOW INPUT VOLTAGES

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Abstract: Step-up dc-dc converters have to cope with extremely low input voltages when used in combination with energy harvesting sources like thermogenerators, inductive generators or solar cells. The presented dc-dc converter is characterized by a high efficiency, up to 70 % in the input voltage range between 200 mV and 500 mV, and a minimum start-up voltage of 70 mV. It can deliver an output power of about 5 mW with an input voltage of 300 mV and an input current of 3.5 mA for an output voltage of 2 V.

Key words: step-up converter, energy harvesting, low input voltage, high efficiency, thermogenerator

1. INTRODUCTION

Low-power energy autarkic systems can use energy harvesting power supplies instead of batteries as input voltage sources. The main advantage of energy harvesting power supplies over energy storage elements is that it is not necessary the charge or replacement of the input power supply. However, energy harvesting sources like inductive generators, solar cells and thermogenerators deliver very low input voltages for the DC-DC converters.

Commercial step-up DC-DC converter ICs are available with a minimum start-up voltage of 500 mV and a minimum input voltage of 300 mV after start-up with efficiencies of 20-40 % in this voltage range [1]. Therefore, there is a gap between the output voltage of the energy harvesting transducers to employ and the minimum required input voltage of the state-of-the-art voltage converters. The DC-DC converter presented in this paper achieves high efficiencies at input voltages lower than 300 mV and has a minimum start-up voltage of only 70 mV.

2. ENERGY HARVESTING POWER SUPPLIES

The power management design for an energy harvesting application requires a good knowledge of the equivalent electrical circuit of the energy harvesting transducer, as well as the levels of its output voltage and power.

The decision about which transducer to use in an energy harvesting system depends on which kind of energy is present in the environment. Solar cells are used for converting light energy, inductive generators for converting mechanical vibration and thermogenerators for converting temperature differences into electrical energy. Single junction Si solar cells produce voltages in the range of 500-600 mV in open circuit. For the case of inductive generators, the generated output power and voltage depends on the volume of the generator and on the mechanical input excitation. Amirtharajah et al. obtained 400 µW@180 mV with a mechanical excitation of 2 Hz and 2 cm of amplitude [1], Yuen et al. achieved 120 µW@900 µV with a mechanical excitation of 80Hz and 250 µm of amplitude with 2.3 cm^3 of volume [2] while Li et al. accomplished 10µW@2 V with a mechanical excitation of 64 Hz and 1 mm with 1cm^3 of volume [3].

Despite the fact that the energy harvesting power supplies presented in the previous paragraph can be employed with the designed step-up converter, the aim of the presented DC-DC converter is to use a standard thermogenerator, see Fig. 2, with an area not bigger than 40x40 mm and to use the human body as thermal energy source. Thermogenerators consist of several thermocouples comprising a p-type and n-type semiconductor connected electrically in series and thermally in parallel. The electrical connection allows adding the voltage obtained at each thermocouple due to the Seebeck effect. Therefore, the output voltage of the TEG is proportional to the number of thermocouples and to the temperature gradient between the cold and the hot side.

The open circuit output voltage of a thermogenerator V_{oc} is proportional 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.

$$V_{oc}= \alpha_m \Delta T \qquad (1)$$

The temperature difference between the human body and the environment can be considered in the range of 3-5 K. The Seebeck´s coefficient α_m of the selected thermogenerator, the Peltron module 128A1030, is 49 mV/K. Therefore, the input voltage of the DC-DC boost converter is in the range of 150-250 mV.

All the exposed energy harvesting power supplies are suitable for its use with the presented step-up converter due to their low output voltage and power.

3. DC-DC-CONVERTER

The power management unit presented in this section (see Fig. 1) consists basically in a synchronous step-up converter based on coupled inductors [4]. The challenge of building a boost converter with low input voltages is on one hand the impossibility of using conventional MOS transistors since their threshold voltage is higher than 500 mV and on the other hand the fact that transistors with a threshold voltage below 200 mV have a larger leakage current at zero gate-source voltage.

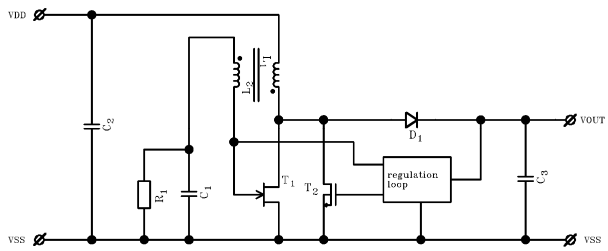

Fig. 1: Simplified schematic of the boost converter

Section 3.1 describes the main improvements of the designed boost converter over the standard boost converter design. Section 3.2 shows the schematic of the DC-DC converter and explains its operation. Next section is focused in the regulation loop and finally section 3.4 gives some efficiency measurements.

3.1 Design Considerations

The two main improvements of the presented step-up converter over the classical step-up converter are the transformer instead of the single coil and the parallel connection of transistors T_1 and T_2 [5].

In the presented design a transformer is needed because a secondary winding decreases the minimum input voltage. With input voltages below 500 mV, an active circuit for controlling the switching transistor cannot be built. Hence, the converter has to be self oscillating, which needs a secondary winding for driving the mentioned transistor.

The second improvement consists in the use of two switching transistors in parallel. One transistor is only employed for starting the converter and the other one is used during steady state operation. A junction field effect transistor, JFET T_1, is chosen as starting transistor because it is already conducting with a zero gate voltage and has also a low gate threshold voltage. Nevertheless, it can not be used as the main switching transistor since its on-resistance is generally in the order of some tens of Ohms which would produce high conduction losses and thus a decrease in the efficiency of the converter. Therefore, the NMOS transistor T_2 becomes the switching element after the start-up phase. The parallel connection of both transistors allows having a switch with low on resistance (5 Ω) during steady state and zero threshold gate voltage for start-up.

3.2 Circuit Operation

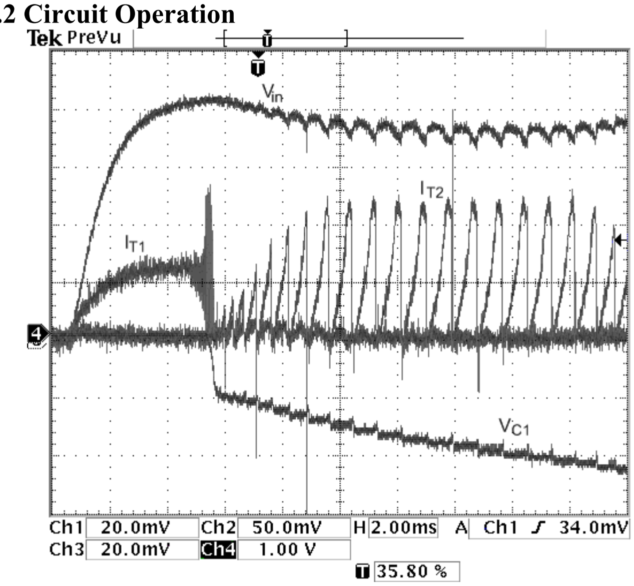

Fig. 2: Measured waveforms obtained during the start-up phase. Ch1 corresponds to IT2, Ch2 to Vin, Ch3 to IT1 and Ch4 to VC1.

Fig. 1 shows a block diagram of the designed converter. At startup, JFET T_1 conducts with positive input voltages. Fig. 2 and Fig. 3 show some waveforms of the circuit that have been measured in the start-up phase of the dc-dc converter.

When the supply voltage V_{in} is rising, the current over the JFET T_1 I_{T1} is increasing too. As the current on the primary winding of the transformer L_1 is rising, a small voltage is induced in the secondary winding, L_2. Because of the conducting pn-junction of the JFET, C_1 is charged to a slightly negative voltage. When V_{in} reaches its maximum value, the current over the inductor L_1 gets constant, the voltage over L_2 turns to zero and then the negative voltage stored on C_1, V_{C1}, is on the gate of T_1. If this voltage is near the pinch-off voltage of the JFET, the current through L_1 starts to decrease. The current decrease on L_1 induces a positive voltage over L_2 and therefore a negative voltage at the gate of T_1. The JFET T_1 now switches off. When the voltage pulses over the secondary winding are big enough, T_2 switches on. The dc voltage on the capacitor C_1 gets more and more negative so that, the JFET T_1 is not conducting anymore and only T_2 is switching.

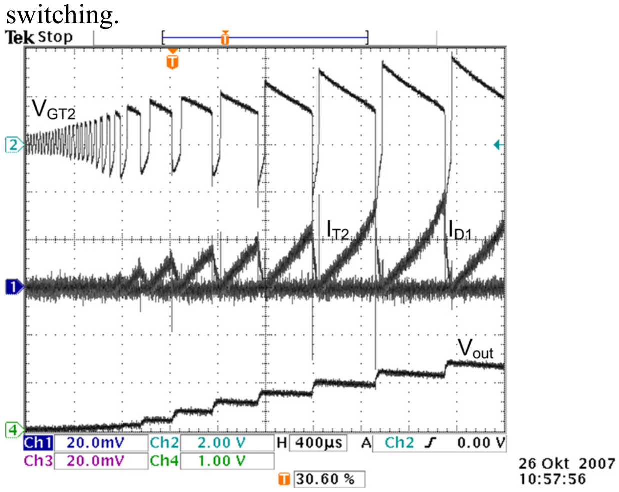

Fig. 3: Measured waveforms obtained during the start-up phase. Ch1 corresponds to I_{T2}, Ch2 to V_{reg}, Ch3 to I_{D1} and Ch4 to V_{out}.

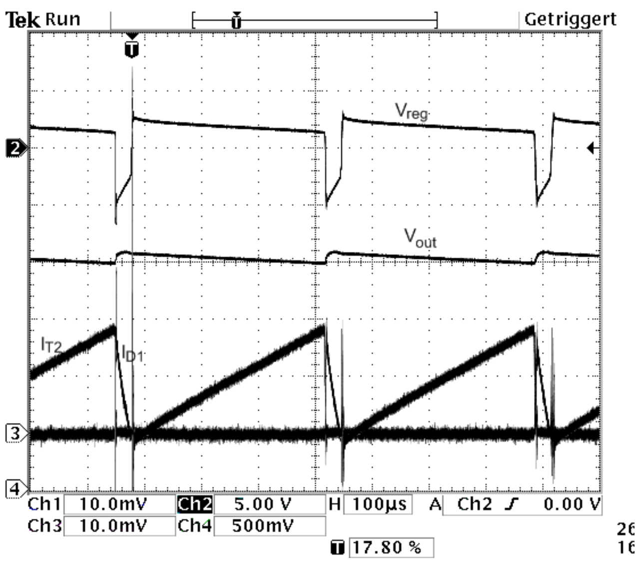

Fig. 4 Measured waveforms obtained during the steady-state phase. Ch1 corresponds to I_{T2}, Ch2 to V_{GT2}, Ch3 to I_{D1} and Ch4 to V_{out}

The voltage value on the gate of T_2, V_{reg}, modifies the value of the on-resistance of the NMOS transistor and therefore the time that it is switched on, keeping the switch off time almost constant. Thus, the value of V_{reg} regulates the output voltage of the converter, V_{out}, basically modifying the switching frequency of the converter.

The converter works in the boundary between continuous and discontinuous conduction mode, see I_{D1} and I_{T2} waveforms in Fig. 4, due to the self oscillation caused by the employment of the transformer.

The freewheeling diode D_1 (see Fig. 1) was replaced by a PMOS transistor which is switching on when the MOSFET T_2 is not conducting. The PMOS transistor is controlled by a simple inverter circuit connected to the drain of T_2. In that way the boost converter becomes a synchronous converter. This change causes a reduction on the forward voltage of the component and consequently an enhancement in efficiency of up to 5 %, depending on the output current of the converter.

3.3 Regulation Loop

The regulation loop circuit, see Fig. 4, is composed by a starting aid circuit, a MOSFET gate protection circuit and an output voltage regulation circuit.

The starting aid circuit consists of two capacitors connected in parallel: C_3 (22 nF) and C_4 (470 pF). C_3 is connected in series with a JFET T_3. At startup, the gate-source voltage on T_3 is 0 V and thus C_3 is connected in parallel to C_4. This parallel connection helps the converter to begin the oscillation at low input voltages. The turns ratio between the secondary inductor, L_2, and the primary inductor, L_1, is 17 in order to have a minimum start-up voltage of 70 mV and a low ohmic resistance of the primary winding that does not affect the efficiency of the converter. Nevertheless, this causes an excessive gate-source voltage of MOSFET T_2 which originates high switching losses. However, JFET T_3 is switched-off during steady state operation and therefore only capacitor C_4 (which has a lower capacitance than C_3) is active which motivates a reduction in the gate-source voltage of T_2. Hence, the parallel connection of capacitors C_4 and C_3, through T_3, accomplish a low start-up voltage and a reduction in the switching losses.

The MOSET gate protection circuit preserves T_2 against high gate-source voltages that can damage the transistor. The circuit consists of a signal diode D_2 and a zener diode D_3 with a breakdown voltage of 6.8 V. Resistor R_2 is connected in parallel to D_3 for starting up the converter.

The third circuit of the regulation loop is the output voltage regulator itself which consists of two diodes, D_4 and D_5, a transistor, T_4, and a potentiometer, R_4. This circuit controls the positive value of the gate-source-voltage of the switching MOSFET T_2. Because of its simplicity, it is not as accurate as a complex loop, but it has a very low current consumption, which is more important in the design of a converter to be employed in an energy harvesting system.

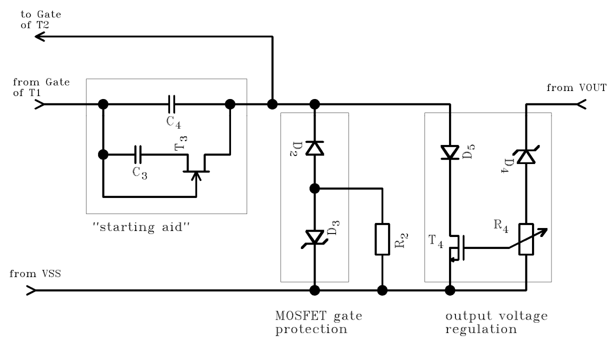

Fig. 5: Regulation loop circuit of the converter

3.4 Efficiency Measurement

Fig. 7 shows the efficiency of the converter versus the output current with different input voltages for an output voltage of 2 V and for an input voltage range of 200-500 mV. The boost converter has an efficiency of up to 68 % at a supply voltage of 200 mV and greater than 70 % for an input voltage range of 300-500 mV at an output voltage of 2 V. The minimum start-up voltage achieved is 70 mV.

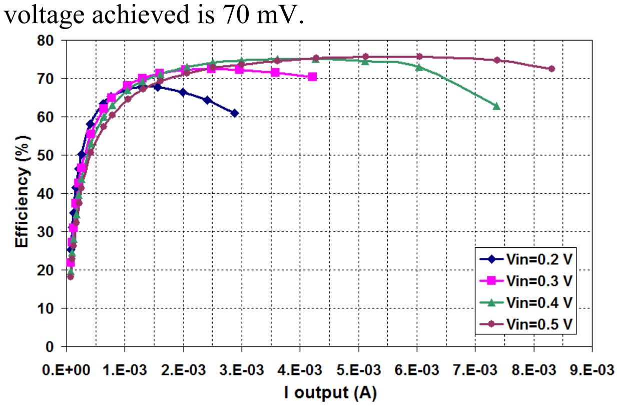

Fig.6: Efficiency vs. output current for different input supply voltages for an output voltage of 2 V.

4. APPLICATION

Fig. 5 shows a prototype board of the developed converter. Two different applications that use the designed step-up converter and are powered employing a thermogenerator that is heated by the hand are presented in this section. In the first application, the step-up converter powers some sensors and the low-power consumption transmitter module STM110 or STM1120 from EnOcean. The measured data is transmitted and displayed in a computer with a receiver RCM 120 connected.

In the second demonstrator, a LCD display is powered. The boost converter powers a temperature sensor and a low-power consumption microcontroller. The microcontroller controls the charge process of a capacitor that is also connected to the DC-DC converter in order to supply power to the display, which has a power consumption of 700 µW, when there is enough power stored in the capacitor.

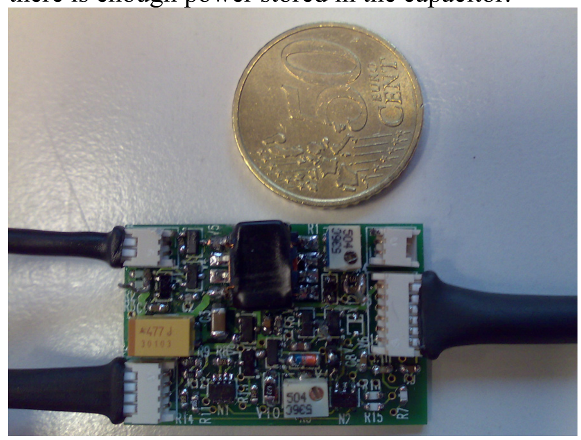

Fig.7: PCB of the DC-DC-Converter

5. CONCLUSION

A solution for up-converting extremely low voltages coming from energy harvesting power supplies like thermogenerators, inductive generators or solar cells is presented. The minimum start-up voltage achieved is 70 mV and for input voltages of 300-500 mV the efficiency is greater than 70 % for 2 V output voltage.

The DC-DC boost converter has been implemented with discrete components. However, currently an ASIC (application specific integrated circuit) is in development.

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