A low-voltage boost converter using a forward converter with integrated Meissner oscillator

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A low-voltage boost converter using a forward converter with integrated Meissner oscillator

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Abstract. This paper describes a novel boost converter to be used with energy harvesters that provide only low output voltages. The device is self-supplied from electric power delivered to its input. With peak power conversion efficiencies above 30% at start-up voltages down to 10 mV this circuit sets best values in comparison with the state-of-the-art. This is achieved by the novel combination of a Meissner oscillator, used as stand-alone in most low-voltage step-up converters today, with a forward converter usually applied in high power systems.

1. Introduction

Depending on the application scenario, generators used for energy harvesting may deliver relatively low output voltages that are variable under a variable ambient power input. This is the case for thermoelectric energy harvesting, as shown e.g. in [1] where a low temperature difference of appr. 1 K generates output voltages of only a few 10 mV at a mid-size thermoelectric generator. Similar conditions exist for photovoltaic cells under low-light conditions or biofuel cells [2,8]. For these generators it is mandatory to use an electronic boost converter to raise the low delivered voltage up to a higher voltage for the supply of an embedded system. The requirements for such a step-up converter are very different from the state-of-the-art defined by various - even low voltage - off-the-shelf components: A step-up converter used in conjunction with energy harvesting should be self-starting from input voltages as low as possible without using any auxiliary power, provide a suitable step-up ratio and exhibit an acceptable efficiency of power conversion. Also, the input and output impedance may have to be adjusted for an optimal load matching or for an optimal voltage step-up ratio.

2. A brief review on low-voltage step-up converters

The parameters start-up voltage and self-supply together with the used circuit concept are important criteria for comparing different step-up converters. Exploring low-voltage step-up converters is still a topic of active ongoing research with only few devices being commercially available. These converters have in parts impressive start-up voltages as low as 20 mV [3]. An early circuit from the mid 1970s uses a Meissner oscillator with junction field effect transistors (JFETs) instead of bipolar junction transistors (see Fig. 1) [4]. This combination is favourable with respect to three important criteria: (1) JFETs provide a conducting channel with zero gate voltage thus enabling the onset of oscillations at low voltages. (2) The self-resonance of a Meissner oscillator does not require any auxiliary power for start-up and (3) a favourable transition of the oscillation from a linear into a non-linear regime can be accomplished by a suitable feedback circuitry, as shown especially in [5].

The latter effect helps to reduce internal losses and therefore to increase power conversion efficiency. Consequently, the Meissner oscillator, is used today in the majority of low-voltage step-up converters, sometimes with only minimal modifications of the type and number of transistors or the design of the feedback circuitry [5-8]. Start-up voltages as low as 6 mV have been achieved with a purely JFET-based Meissner oscillator [6], however with the drawback of large and bulky transformers. An early modular combination of a Meissner oscillator with a standard boost converter is presented in [5]: There, the Meissner oscillator serves as a start-up circuit providing the supply voltage for a separate, inductor-based step-up converter from an input voltage of 300 mV. A fusion of both converters is presented in [7], with the Meissner oscillator and the boost converter sharing the same transformer. The start-up voltage of this circuit is 70 mV.

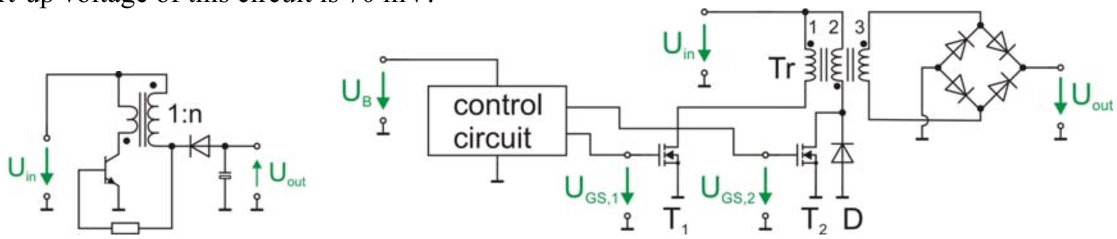

Figure 1. Basic circuit of a Meissner oscillator (left) and a forward converter (right)

3. Design concept

The low-voltage step-up converter developed within this study uses, as far as the authors know for the first time, the combination of a self-resonant Meissner oscillator and a self-resonant forward converter. This concept was chosen for several reasons. (1) A stand-alone Meissner oscillator will only draw an intermittent input current in its nonlinear operation regime, as the feedback circuit is continuously disrupting and re-establishing the current flow through its transistor. Therefore, the magnetic core of the transformer is biased in one direction with the danger of non-optimal use or even magnetic saturation. Also, the connected generator will only be loaded in an intermittent fashion, which may be detrimental and non-efficient. Both effects are not present in a forward converter (see Fig. 1) that is using a transformer with two input windings that are driven in an alternating way. (2) A Meissner oscillator starts at low input voltages but may operate inefficiently at low voltage levels. The Meissner oscillator , however, is able to work as a kick-off starter circuit for a more efficient forward converter, which would not start operation from such low input voltages. (3) An appropriate design of the feedback circuitry will allow to draw power not only from the output winding of the transformer but also from the feedback winding without compromising the self-oscillation of all circuits. As shown within this work such a behavior will increase the power conversion efficiency of the whole converter.
Two versions of the designed step-up converter, "design A" and "design B", are presented in Fig. 2. In both circuits a Meissner oscillator is formed by connecting an array of five p-channel JFETs T_1 to T_5 to input winding 2 and feedback winding 1 of a transformer. Following the design concept presented in [5] the low end of the feedback winding is connected to ground by an RC tank in design A. As an improvement to this concept the low end of the feedback winding is connected to the output capacitor C_{out} via a parallel circuit of a capacitor C_F and a Schottky diode D_F in design B. The forward converter is realized by adding one p-channel MOSFET T_6 and one n-channel MOSFET T_7. While the drain and source of the PMOS transistor T_6 are connected in parallel to the JFET array, the NMOS transistor T_7 is connected to an additional input winding 3 (see also Fig. 1). Output power is drawn from the transformer through winding 4, using a simple one-way rectifier (Schottky diode D_R). With the connection scheme shown in Fig. 2 the feedback winding 1 is capable to deliver a common drive signal for all transistors, without the need of a separately powered control circuit (see Fig. 2). The gates of the JFET array are directly connected to the feedback winding, whereas the MOSFET gates are connected to the feedback winding by a common high-pass filter constituted by R_G and C_G.
The operation principle for design A is described in the following: At low input voltages the Meissner oscillator starts operation first. If the input voltage is high enough it undergoes a transition from its lin-

ear into a non-linear operation regime. The details of this start-up phase are described in [5] for a similar circuit and will not be repeated here. During start-up the gate-source diode of the JFET array acts as a rectifier for the AC signal present at the feedback winding 1. In consequence, a positive DC voltage U_F eventually builds up at C_F. This growing DC voltage shifts the operational set-point at the gates of the JFET array into the blocking region and eventually enforces the nonlinear operation of the Meissner oscillator. The bleeding resistor R_F prevents the build-up of a DC voltage at C_F that is large enough to keep the AC signal at the JFET gates in the blocking regime. In this case the JFETs would no longer be turned on and oscillation would stop.

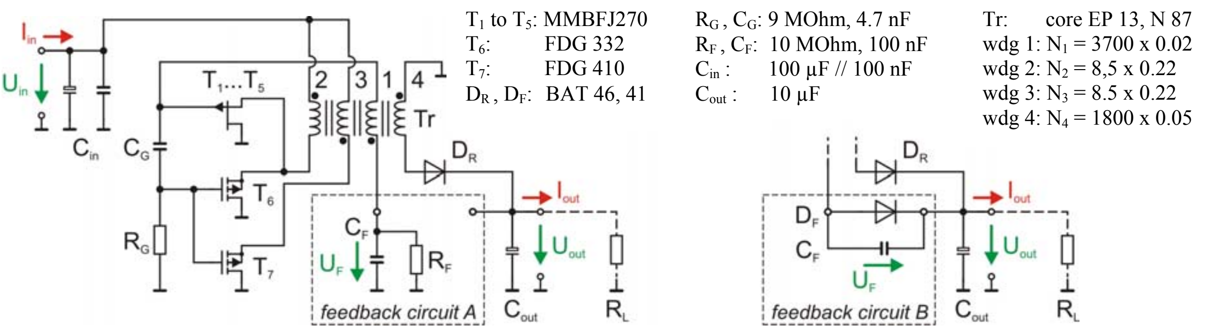

Figure 2. Meissner-forward converter: design A (left) and modifications for design B (right)

During the start-up phase the amplitude of the feedback signal at winding 1 is gradually increasing. As soon as the signal amplitude exceeds the threshold voltages of the MOSFET transistors, they start to turn on and off in an alternating way, such setting the forward conversion into operation. These MOSFETs exhibit a much lower on-resistance than the JFET array. Hence, the input currents and AC voltages at the input, feedback and output windings of the transformer are abruptly increased. The rectified output voltage will also increase up to an operational set-point defined by input voltage U_{in} and load resistance R_L.

Contrary to the circuit presented in [5] p-channel JFETs are used within this work. A drawback of such transistors is their much higher channel resistance compared to equivalent n-channel JFETs. This is compensated by connecting several transistors in parallel. The advantage of using p-channel JFETs is, however, that the DC voltage at C_F is positive with respect to ground. Therefore, the charge accumulated at C_F can be easily forwarded to the output capacitor C_{out}, e.g. by connecting a diode between C_F and C_{out}. Also, as done in design B, the low end of C_F can be directly connected to C_{out}. Additionally a Schottky diode D_F is connected in parallel to C_F to allow for a fast build-up and a limit of U_F to its threshold voltage. The current through D_F and C_F is directly fed into the output capacitor with a net increase of the available output power. In design A, as in [5], power is dissipated in the bleeding resistor R_F instead. If the load resistance is too low, the start-up phase of the converter is prolonged or even completely prohibited at low input voltages. It is therefore advisable to monitor the state of the converter and to connect the load after full start-up only. This can be accomplished by monitoring either the voltage at the output or the voltage at the feedback capacitor.

4. Experimental

A printed circuit board was designed and manufactured to characterize the step-up converters shown in Fig 2. Access to several test points was provided together with various jumpers to change device settings, and pin sockets to exchange MOSFET transistors, transformer and feedback circuitry (Fig. 3). Transformers were wire-wound on a commercial coil winder. Different core sizes, types, and materials, as well as different winding ratios and numbers of windings were used to find a sufficient set of parameters. For all transformers the input windings 2 and 3 were fabricated first in a bifilar winding pattern using enamelled copper wire. On top of this layer, first the feedback winding and then the output winding were wire-wound. Layers of 25 µm thick adhesive tape were applied on top of all windings as flat surface for the next winding. The required low input voltages were provided by a custom-made power supply. A large electrolyte capacitor (4700 µF) was connected to the output of this power supply to average the delivered current for increasing the accuracy of current measurements. Multimeters were used to measure input vol-tage, input current and output voltage. The load resistance was changed with a switchable resistor box 10 equidistant values between 10 kOhm and 100 kOhm. For the output voltage range of the step-up converters (0.5....3 V) these resistance values generate the typical power requirements of an energy autonomous system (10...200 µW).

Figure 3. Test board (design A, B)

5. Results and Discussion

For both designs A and B the start-up of the Meissner oscillation did set in, under no-load conditions at the output, at an input voltage of appr. 6.2 mV. For input voltages up to appr. 10 mV the Meissner oscillator was not capable of initiating the start-up of the forward converter. For input voltages of 10 mV and above a gradual increase of the AC voltage at the feedback winding and of the DC voltage at C_F was observed, with a rapid on-set of forward conversion as soon as a certain DC threshold was reached. During this stepwise transition the AC feedback voltage changed shape from a sinusoidal over a distorted sinusoidal into a square-like waveform. For an input voltage of 10 mV and with the connected rectifier and a discharged output capacitor C_{out} the start-up procedure took appr. 25 seconds under no-load conditions. The output voltage was app. 360 mV at this point, i.e. together with the threshold voltage of the used diode D_F, the DC feedback voltage $U_F + U_{out}$ was appr. 500 mV.

Fig. 4 shows the most important characteristics of design B. Depending on the delivered output power and the available input voltage the step-up ratio varied between 50 and 136. For the respective maximal output power P_{out}, whose value varied between 15.6 µW for U_{in}=10 mV and 189.7 µW for U_{in}=30 mV, a fairly constant step-up ratio of 80 was reached. Under no-load condition much higher step-up ratios ranging between 618 and 792 could be achieved. However, at input voltages exceeding 19 mV clipping did set in, i.e. intermittent oscil-lations occurred under no load, due to a periodically too high DC part of the feedback voltage $U_F + U_{out}$. Such high step-up ratios under no-load can be used favourably to charge the output capacitor C_{out} with a high voltage that may then be used to kick-start a self-supplied boost converter requiring higher start-up voltages. This concept is realized in [5] and [9] with a much higher start-up voltage of 300 mV.

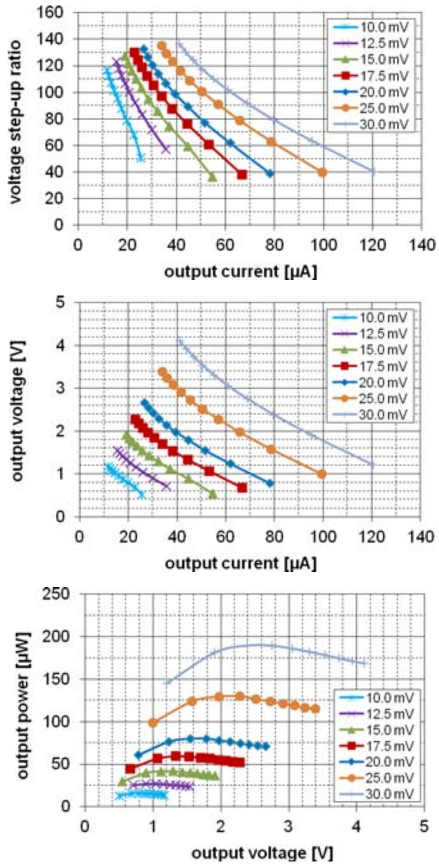

Figure 4. Measured data of design B: step-up ratio U_{out}/U_{in} and output voltage U_{out}, both vs. output current I_{out} and input voltage U_{in}, output power $P_{out}=U_{out}\cdot I_{out}$ vs. U_{in} and U_{out}.

As expected, output voltage and output power are highly depending on the input voltage as well as on each other. For the lowest input voltage (10 mV) the minimal values of U_{out} and P_{out} occurred at the same set point, with 0.509 V at 12.95 µW. For the highest input voltage (30 mV) the maximum output voltage and output power were 4.109 V at 168.9 µW and 189.8 µW at 2.386 V, respectively.

A comparison of the power conversion efficiencies P_{out}/P_{in} for design A and B (Fig. 5) shows the improvement obtained with design B. The maximal power conversion efficiency of design A does significantly depend on the input voltage and falls drastically from its highest values of 32% at 10 mV to only 14% at 20 mV. This is, for instance, also found in [6]. At input voltages slightly above 20 mV design A showed clipping under load, with a further, drastic reduction of power conversion efficiency and, overall, an unstable operation. The main reason for clipping is a too high feedback voltage at C_F. Design B avoids this problem by the measures discussed before. Power conversion efficiencies for design B were consistently higher than for design A. Also the efficiency values were stable in a much larger range of load currents and input voltages. Clipping was not observed with design B, for the tested ranges of output current and input voltage.

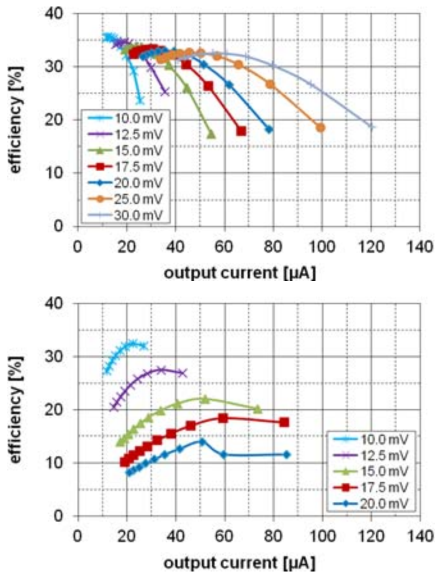

Figure 5. Power conversion efficiency P_{out}/P_{in} for design B (top) and design A (bottom) versus output current I_{out}.

6. Conclusion

A novel design of a low-voltage step-up converter was presented, using a combination of a Meissner oscillator and a forward converter. The realized circuit starts self-resonant operation as Meissner oscillator at an input voltage of 6.2 mV and forward conversion at 10 mV. In difference to the state-of-the-art that frequently uses Meissner oscillators alone the maximum power efficiency of an improved design presented within this work was almost constant. It exceeded 30% for a large range of input voltages. An input voltage between 20 and 25 mV is sufficient to supply a typical energy-autonomous embedded system with a power consumption of approximately 100 µW at a voltage of 2.2 V [10]. Future research will concentrate on optimization and miniaturization, and on an application in energy-autonomous systems.

7. Acknowledgement

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8. References

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