ULTRA-LOW INPUT VOLTAGE DC-DC CONVERTER FOR MICRO ENERGY HARVESTING

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Abstract: Sensor nodes and other ultra-low power devices can be powered with micro energy harvesting. In case of low environmental power thermo generators, solar cells, inductive generators or radio frequency (RF) energy harvesting circuits provide an extremely low output voltage that needs to be increased to generate a suitable power supply. This paper presents a DC-DC converter that starts operation at 6 mV and 490 nW input power without needing a higher start-up voltage to achieve over 1 V unloaded DC output voltage. The circuit reaches an efficiency of 18 % and the results are experimentally verified by building a prototype.

Keywords: Ultra-low input voltage DC-DC converter, micro energy harvesting.

INTRODUCTION

Micro energy harvesting power sources get more and more interesting for supplying ultra-low power sensor circuits instead of batteries. Especially the option to seal off the whole device makes it attractive for many monitoring and industry applications [1]. In the majority of cases the harvesters have an irregular release of energy and a low output voltage [2]. Therefore they mostly have a build in power regulation that scales up the voltage making it suitable for the following application [3] [4]. Those converters cannot start up below a certain input voltage [5]. In order to cover a broader field of applications a DC-DC converter is required that starts operation at an input level below the commercial available devices like ECT 100 from EnOcean ($\leq$ 44 µW and 11 mV).

We therefore suggest using an ultra-low start-up voltage oscillator with a high gain to obtain a preferably hight output voltage. In addition an efficient rectifier circuit is required that can handle the low current flow. The design presented within this article is capable of converting ultra-low voltage while challenging efficiency.

CIRCUIT DESIGN
Oscillator Circuit

For the oscillator circuit as shown in Fig. 1 seven cascaded print transformers (Block VB 0.35/2/6) are used to improve the voltage gain at the gate of the JFET. The low impedance windings are connected in parallel and the high impedance windings in series. A JFET (BF862) is chosen because it is conducting at a zero gate voltage and has a low gate threshold voltage as compared to a MOSFET.
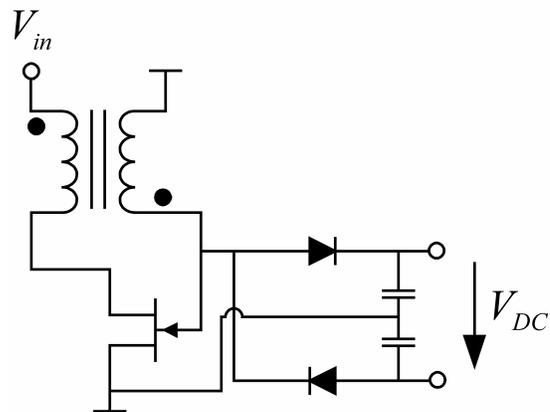

Fig. 1: Schematic of the DC-DC converter containing an oscillator and a voltage doubler circuit.

Rectifier Circuit

In this section three different types of rectifiers are presented. The first one consists of a half-wave rectifier with a 1N4148 fast switching diode. As shown in Fig. 2 the positive half-wave of the oscillator is below 0.7 V and a full-wave rectifier would not lead to a higher voltage due to the threshold voltage of the diode and the leakage current of further diodes. The second circuit is a voltage doubler configuration, as shown in Fig. 1, built with a HSMS2862 double Schottky diode that has a 50 % lower turn-on voltage than 1N4148 and a low series resistance of 5 Ω. To examine the influence of leakage current of an HSMS-2862 diode a third circuit was tested, containing te same circuit configuration like the first rectifier but with an HSMS-286B single diode.
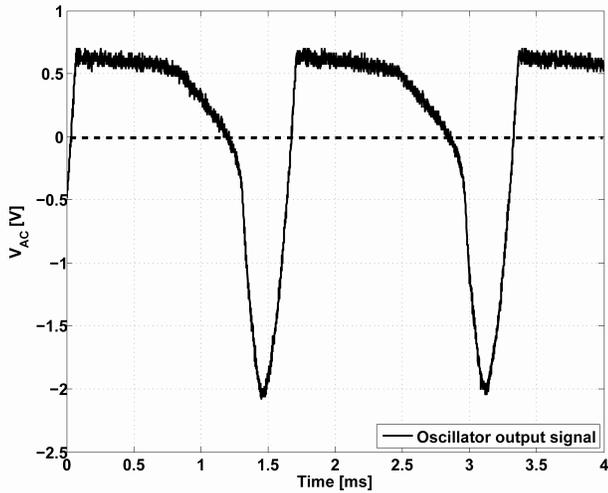
Fig. 2: Oscillator output signal at 6 mV DC input voltage.

Fig. 3: Behaviour of two rectifier circuits at different loads.

EXPERIMENTAL RESULTS
Measurement Setup

Input and output voltages were measured with a high-resistance voltmeter (Keithley 6514) due to its high sensitivity. Measuring the input power by using an ampere-meter with few Ohm resistance influences the oscillator circuit resulting in a higher start-up voltage. Therefore, the input current measurement was done with a 25 cm piece of constantan wire with two soldered connectors on each end whereby the voltage drop over this piece was measured. To calibrate the measurement and determine the exact resistance of the constantan a 4 wire measurement with a Keithley 2400 Source Meter was done. All devices were controlled over a GPIB interface with LabView to achieve a fast automated measurement.

Output Voltage and Efficiency

The measurement results of the input voltage V_{in} compared with the DC output voltage V_{DC} are shown in Fig. 3. For a load of 5 MΩ the starting voltage for the oscillator is 6 mV for the one-diode rectifier circuit with the 1N4148 diode and 7 mV for two-diode rectifier circuit with the HSMS2862 diode. The diagrams for 5 MΩ load are crossing at an input of 15 mV. The circuit with a 1N4148 diode achieves a higher output voltage on open circuit and from 15 mV on when loaded. Below 15 mV input voltage the HSMS2862 diode is preferable.
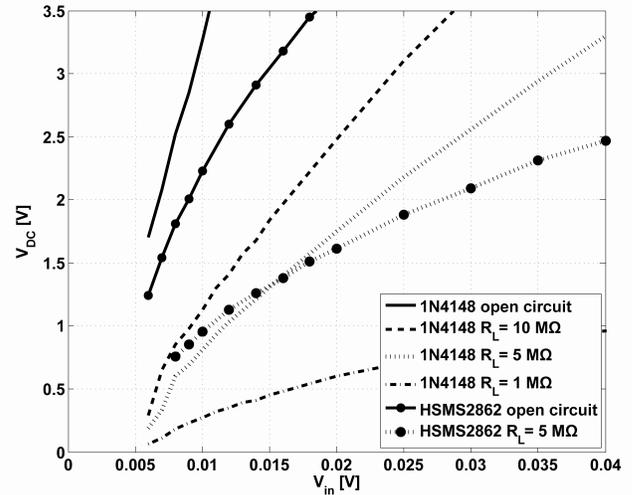
The breakdown voltage of the HSMS2862 diode is 7 V and therefore unsuitable for high input voltage. Furthermore, as shown in Fig. 4, the input power required by HSMS circuit is always lower than 1N4148 circuit. Due to the very low saturation current (50 nA) of the HSMS2862 diode the overall efficiency is more than 12 % and higher than the efficiency of the 1N4148 circuit shown in Fig. 5. For higher input levels the span between the efficiencies becomes smaller.
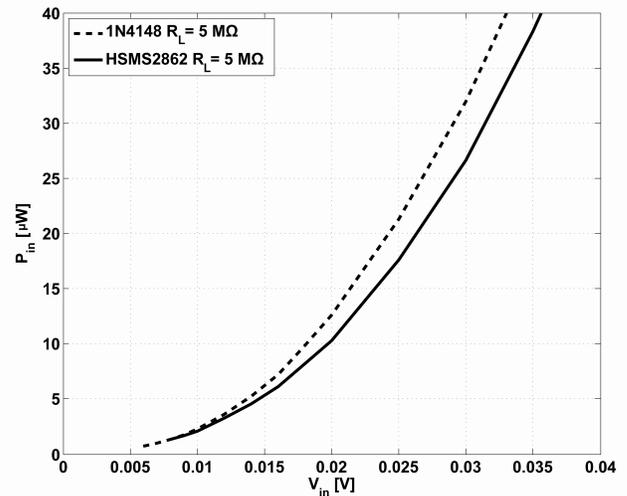

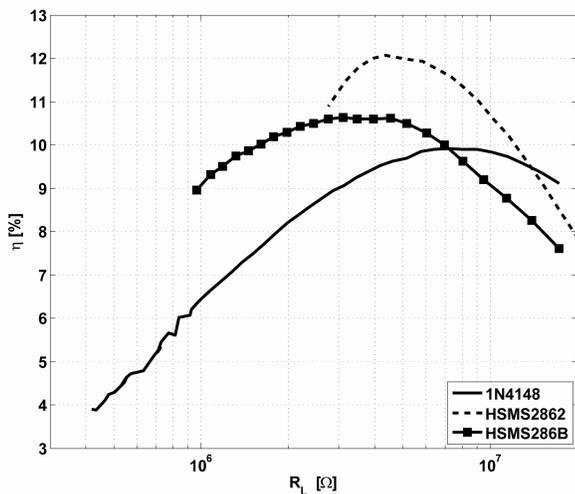Fig. 4: Measured power consumption of the converter comparing two types of rectifierss at a load of 5 MΩ.

Fig. 5: Measured overall efficiency of the DC-DC converter with seven transformers comparing three types of rectifiers by varying the output load.
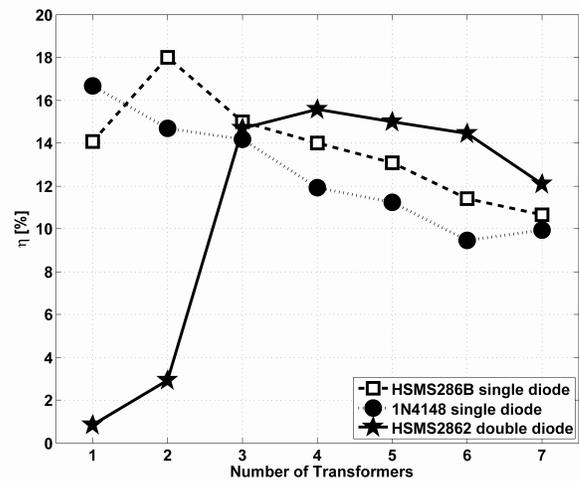

Fig. 6: Measured system efficiency of the DC-DC converter comparing three types of rectifiers by varying the number of transformers.

Optimum Input Voltage

Previous test measurements have revealed, that the system efectiveness of the DC-DC converter achieves best results at low input voltages just over the start-up voltage. To determine the optimum input voltage for the system by testing all rectifiers the efficiency is measured while altering the input level. The results in Table 1 demonstrate that the oscillator circuit with seven cascaded transformers reaches the highest efficiency for all rectifiers at an input voltage of 12 mV.

Variying number of Transformers

In order to analyse the influence of the winding ratio in the oscillator circuit the ratio has been altered by consecutively cascading the transformers. The input and output voltage and the input power were measured. The results in Table 2 show that with increasing winding ratio the minimum input power required for an oscillation decreases dramatically.

Table 1: System efficiency with different rectifier circuits and input voltage levels.

V_{in} [mV]	η [%] 1N4148	η [%] HSMS286B	η [%] HSMS2862
7	8.28	9.53	10.37
12	9.93	9.65	12.07
17	8.04	8.12	9.53

Loading a 100 µF Capacitance

To clarify that the developed circuit is suitable for supplying a microcontroller it is needed to provide appropriate voltage amplification and to transfer enough charge to an energy storage. Therefore, a 100 µF capacitor is connected to the output of the voltage doubler rectifier with a HSMS-2862 diode and the system is supplied with 12 mV input voltage. The capacitor voltage has been measured by using an automated LabView measurement setup. As shown in Fig. 7 the circuit is able to charge the capacitor to 1 V in less than 10 minutes. An another interesting result is apparent from the fact that the capacitor is connected directly without any series resistor. The oscillator shows no oscillation breakdown at all in the first moment of the charging procedure where the output current is maximum.

Table 2: Start-up voltage, input power and oscillator output voltage measurement with an altering number of transformers in the oscillator circuit.

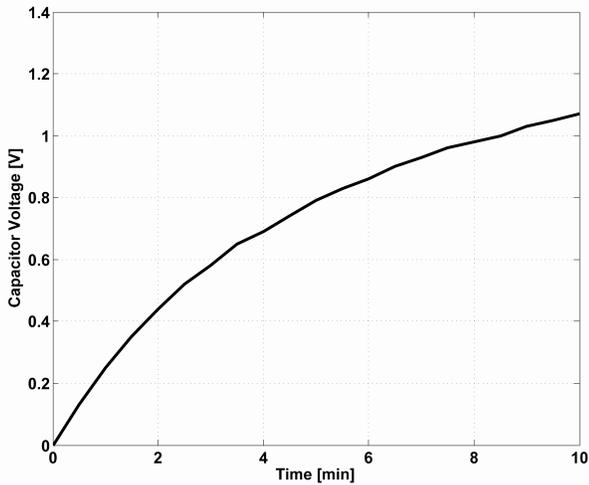| Number of Transformers	$V_{in,min}$ [mV]	$P_{in,min}$ [µW]	$V_{out\,(p-p)}$ [V]
1	62	42.2	39.2
2	28	10.6	16.1
3	18	4.68	10.1
4	13	2.47	6.3
5	10	1.7	5
6	8	1.13	3.8
7	6	0.49	2.7

Fig. 7: 100 µF capacitor charged by the circuit with HSMS-2862 diodes at an input voltage of 12 mV.

CONCLUSION

The main improvement of the presented oscillator is its reduced start-up voltage of 6 mV. To accomplish this purpose it was necessary to increase the voltage gain of the transformer. The DC-DC converter circuit presented in this paper starts operating at 6 mV and 82 µA input to achieve an unloaded DC output voltage of more than 1 V. The circuit reaches an efficiency of more than 18 % with two transformers and a HSMS-286B diode. A prototype of the converter has been implemented with discrete components. This circuit was able to load a 100 µF capacitance within 10 minutes to over 1 V with an input voltage of 12 mV DC and a power consumption of 2.7 µW.

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