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A 12 mV start-up converter using piezoelectric transformer for energy harvesting applications

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Abstract. This paper presents a novel topology of start-up converter for sub 100 mV thermal energy harvesting based on an Armstrong oscillator topology using a piezoelectric transformer (PT) and a normally-on MOSFET. Based on a Rosen-type PT and off-the-shelf components, the proposed start-up topology begins to oscillate at 12 mV input voltage corresponding to a temperature gradient of 2°C and achieves 1 V output voltage with only 18 mV input voltage applied to the harvester.

1. Introduction

Energy harvesting devices are a key alternative to batteries to supply low-power devices. They allow those devices to be self-autonomous without need of maintenance and with longer lifetime. In particular, thermoelectric generators (TEG) provide a DC voltage by exploiting a gradient of temperature and constitute an interesting solution to supply devices consuming less than a few mW. However, in most applications, the TEG will only provide a voltage lower than the classical threshold voltage of semi-conductors (<100 mV) that cannot then be stepped-up by classical transistor-based converters. A cold-start circuit is required to start and charge a storage device at a sufficient voltage to allow another main converter to start and realize the optimized power extraction. The start-up converter power efficiency is therefore not the most important parameter due to its short working duration in the system and the focus in the design is put on optimization of minimum start-up voltage and voltage gain.

Resonant oscillator architectures and especially the Armstrong one have been used to start at voltages as low as 40 mV [1], [2] but they suffer from bulky magnetic transformers. Piezoelectric transformers (PT's) are a good alternative to magnetic ones as they present higher voltage gain and quality factor and limited electromagnetic radiation [3]. For exploiting PT properties in the cold-start context, the circuit proposed in [4] replaced the magnetic transformer by a piezoelectric one and used an architecture close to the half-bridge topology to obtain an inductor less converter that starts at 69 mV. Replacing a transistor with an inductance at the input allows them to decrease the start-up voltage to 32 mV.

This paper presents an alternate topology compared to [4] consisting in a self-start-up converter based on an Armstrong oscillator with a piezoelectric transformer. A biasing inductance is added at the input of the piezoelectric transformer to improve the performances. The converter has been realized experimentally

and characterized with a TEG. This converter starts with an input voltage of 12 mV and the output reaches 1 V for an input voltage of 18 mV. The paper first describes the architecture of the converter before presenting the results of the measurements.

2. Start-up converter topology based on piezoelectric transformer

2.1. Converter Topology

The schematic of the proposed converter is presented in Figure 1. The ideal voltage source V_{in} and the resistance R_t in series respectively represent the TEG harvester's open-circuit voltage and internal impedance. The piezoelectric transformer consists in the two electrode capacitances C_1 and C_2 , the RLC series branch representing the mechanical vibration and the ideal transformer characterizing the piezoelectric effect. The converter in itself is based on the Armstrong oscillator architecture where the magnetic transformer is replaced by a piezoelectric transformer. The active component is a depletion-mode MOSFET i.e. normally-on. The circuit works as a resonant oscillator. The inherent noise in the circuit is amplified and filtered by the PT. This signal is applied to the transistor and an AC current at the selected frequency appears at the primary branch of the circuit. The PT will further amplify the amplitude of the signal and, under particular conditions, an oscillating signal appears and its amplitude increases. This signal is rectified by the diode as soon as it reaches its threshold voltage. When loss and amplification are balanced, the amplitude stops increasing and the circuit is in steady-state.

At the beginning of operation, the transistor acts as a transconductance to amplify the feedback voltage applied at its gate. However, as contrary to a magnetic transformer, the two primary side branches of the piezoelectric transformer contain a capacitive part that prevent any DC current to flow through the transistor. Subsequently the transistor has no transconductance, cannot amplify the gate voltage and no oscillation appear in the circuit. In order to solve this issue, a biasing inductance L_{in} is added in parallel with C_1 in order to let a DC current flow through the FET during the start-up.

2.2. Start-up phase modelling

A small-signal analysis applied to the circuit in Figure 2 combined with the application of the Barkhausen criterion allows to find the free oscillation condition. The open-loop gain G_{OL} of the converter can be determined by opening the loop at the gate of the transistor. The Barkhausen criterion states that oscillation appears if the following conditions are respected:

$$|G_{OL}| > 1 \text{ and } \arg(G_{OL}) = 0 [2\pi] \quad (1)$$

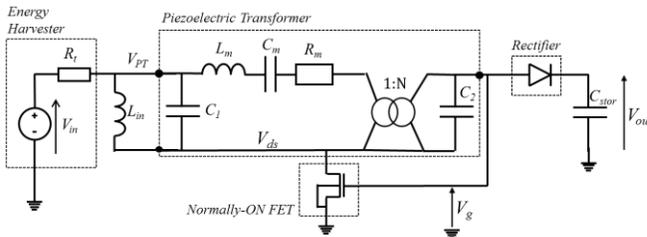


Figure 1. Circuit Schematic

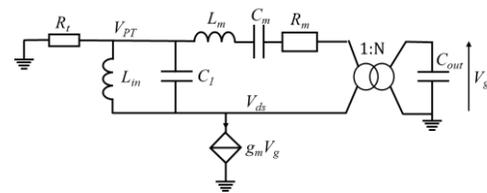


Figure 2. Small-signal equivalent circuit

The open-loop gain of the oscillator is characterized by the transconductance of the transistor, the input impedance of the piezoelectric transformer and its voltage gain. The current flowing through the FET is $i_{ds} = g_m V_g$. Thus the voltage at the input of the PT is expressed as:

$$V_{PT} - V_{ds} = g_m V_g Z_{in} \quad (2)$$

where $Z_{in} = \frac{Z_{PT} j\omega L_{in}}{Z_{PT} + j\omega L_{in}}$ and Z_{PT} is defined as $Z_{PT} = \frac{R_m + j\left(L_m\omega - \frac{1}{C_{eq}\omega}\right)}{1 + jC_1\omega\left(R_m + j\left(L_m\omega - \frac{1}{C_{eq}\omega}\right)\right)}$ and $C_{eq} = \frac{C_m \cdot N^2 \cdot C_{out}}{C_m + N^2 \cdot C_{out}}$

Finally, the open-loop gain is:

$$G_{OL} = G_{PT} \left(\frac{V_{PT} - V_{ds}}{V_g} \right) = \frac{-g_m}{Nj\omega C_{out} \left(1 + \left(\frac{1}{j\omega L_{in}} + jC_1\omega \right) \left(R_m + j\left(L_m\omega - \frac{1}{C_{eq}\omega} \right) \right) \right)} \quad (3)$$

Figure 3 shows the magnitude and phase of the input impedance Z_{in} , the voltage gain G_{PT} and the open-loop gain G_{OL} . Firstly, the addition of the inductance L_{in} modifies the resonance frequency of the input impedance. The oscillation frequency is defined as the one where the open-loop gain is equal to 0 according to (1). In this case, it happens close to the resonance frequency f_p of Z_{in} which is not a resonance for the PT voltage gain G_{PT} . As L_{in} increases, the oscillation frequency will be shifted away from the voltage gain resonance frequency thus reducing the voltage gain but the input impedance value Z_{in} will increase and so will do the input voltage $V_{PT} - V_{DS}$. A trade-off on the L_{in} value appears between the PT input voltage amplitude and the voltage gain of the PT.

3. Experimental Results

3.1. Setup description

The experimental setup is shown in Figure 4. The components were chosen to validate the model of the converter, and not in an approach of performances optimization. Their characteristics and references are summarized in table 1. The PT is a multi-layer Rosen-type PT with 55 kHz natural resonant frequency. Its output capacitance is small increasing the gain of the converter. The transistor consists in two identical depletion-mode MOSFET in parallel with a negative threshold voltage of -37 mV in order to let the current flowing at the beginning of operation. The rectifier is simply formed of a Schottky diode in series configuration. In order to test the circuit in real conditions, the measurements were realized with a TEG whose input resistance's value is 2.8 Ω . The TEG was combined to a controlled hot plate and a heat sink to create a temperature gradient and control the voltage provided by the TEG to the circuit.

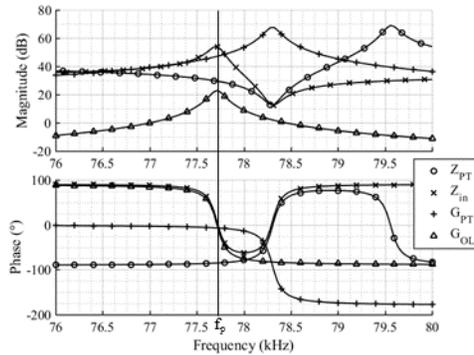


Figure 3. Magnitude and phase of the input impedance, the PT voltage gain and the total open-loop gain.

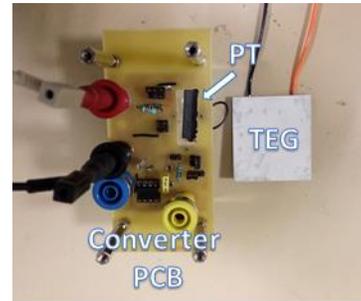


Figure 4. PCB of the proposed start-up converter.

Table 1. Values of the circuit parameters

PT SMMTF85P1S50	
C_1	90 nF
C_2	16 pF
R_m	0.9 Ω
L_m	1.61 mH
C_m	6 nF
N	45
Transistor ALD210800	
V_{th}	-37 mV
$\beta = \mu_0 \cdot C_{ox} \cdot W/L$	$22.4 \times 10^{-3} \text{ A/V}^2$
$C_{g,in}$	4.7 pF
Diode BAS70	
C_{diode}	2 pF
Forward Voltage V_F	0.41 V at $I_F=1 \text{ mA}$

3.2. Measurements

Measurements are realized with different values of the input inductance L_{in} . The quality factor of these inductances is equal to 35. In Figure 5 are represented the output voltages V_{out} against V_{in} for different input inductance values. For higher inductances, the circuit starts at smaller voltages but as soon as the circuit starts, smaller inductances achieve higher output voltages. Furthermore, the estimated temperature gradient was extracted from the open-circuit voltage and Seebeck coefficient of the TEG. For an inductance $L_{in} = 39 \mu\text{H}$, the circuit starts for $\Delta T = 2^\circ\text{C}$ which corresponds to an input voltage V_{in} of 12 mV. Furthermore, in this case, the output reaches 1 V for an input voltage slightly higher to 18 mV and an estimated $\Delta T = 3.3^\circ\text{C}$. Figure 6 represents the output voltage as a function of L_{in} . As expected, the higher the inductance is, the smaller is the output voltage and an optimum value exists for L_{in} that will lead to a maximum output voltage. This optimum value depends on the input voltage but in the studied range, it is between 15 and 20 μH .

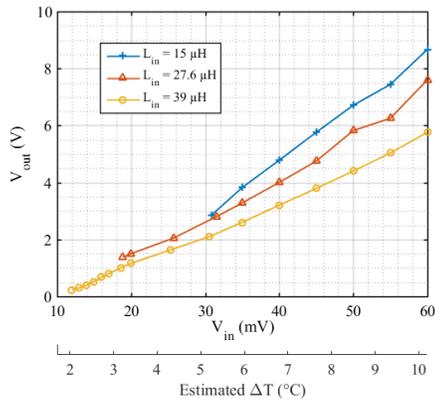


Figure 5. Voltage gain for different values of the biasing inductance as a function of the input voltage and ΔT

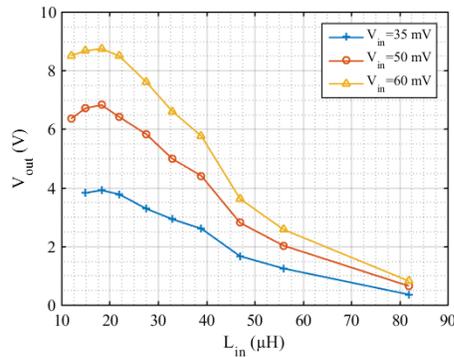


Figure 6. Evolution of the output voltage as a function of the biasing inductance.

Figure 7 represents the minimum input voltage to start-up the circuit as a function of the biasing inductance L_{in} . An optimum value of the biasing inductance exists also for the start-up voltage as expected from the modelling in 2.2. Its value is greater than the optimum value for maximising voltage gain. Secondly

we can see in Figure 8 that when the voltage increases from 0 V, the circuit starts at a specific voltage but if the voltage then decreases, the circuit will continue to operate at voltages lower than the start-up voltage leading to an hysteretic behavior. Furthermore, this figure shows the trade-off that needs to be made during the design of the circuit. If the critical aspect is the start-up voltage, high value inductances will allow to start and work at smaller voltages. On the other hand, if the minimum input voltage provided by the harvester is higher, a smaller value inductance will increase the voltage gain.

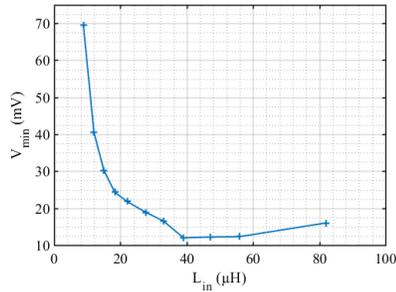


Figure 7. Minimum input start-up voltage of the circuit as a function of L_{in}

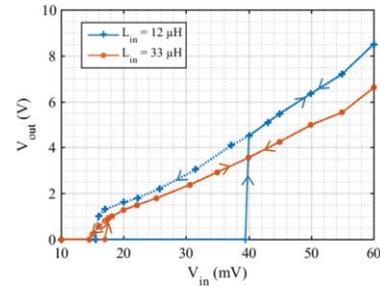


Figure 8. Hysteresis behaviour of the voltage gain

4. Conclusion

This paper presents a start-up converter with a new biasing scheme based on the Armstrong oscillator architecture with a piezoelectric transformer to achieve lower start-up input voltages. The circuit starts at voltages as low as 12 mV and can reach an output of 1 V for voltages as low as 18 mV once oscillation has started. The circuit was tested with a TEG and starts with a temperature gradient of only 2°C applied to the harvester. Compared to other start-up converters using piezoelectric transformers [4], this circuit achieves the lowest start-up voltage and highest voltage gain for similar piezoelectric transformer characteristics thanks to the proposed biasing scheme.

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