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Piezoelectric Transformers for Ultra-low Voltage Energy Harvesting Applications

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Abstract

This work shows the possibility to exploit piezoelectric transformers (PTs) for implementing step-up oscillators for ultra-low DC voltage energy harvesting (EH) applications. Oscillation is achieved by coupling a common source stage made up of n-channel JFETs with a piezoelectric transformer acting like a high gain notch filter. A voltage doubler is used to store energy in a capacitor. A mathematical model of the whole system is developed and matches experimental measurements. The minimum activation voltage is 73 mV. This value decreases if higher mechanical quality factors of piezoelectric transformers are provided along with a corresponding design of the input stage.

Keywords: Energy Harvesting, Piezoelectric Transformers, Step-up oscillator.

1. Introduction

Step-up oscillators, suitable for systems kick-start (Fig. (1a)), activating with DC voltages of few tens mV exploiting magnetic transformers (MTs) coupled with depletion-mode or junction FETs have been used to harvest energy from low voltage sources such as TEGs and to store energy in a battery or in a capacitor [1,2,3]. However, magnetic components are usually not easily miniaturized and suffer from core saturation and losses. Mechanical resonators, instead, can be integrated via MEMS based implementations and have much higher quality factors [4].

Up to now, piezoelectric transformers (PTs) have been widely used in high-voltage applications such as inverters for LCD backlight, or for ultra-compact mobile battery chargers [5]. For the first time, we report a step-up oscillator circuit based on a PT suitable for ultra-low voltage Enegy Harvesting (EH) applications. We also propose an analytical model of the system based on equivalent electromechanical circuits that validates the followed approach.

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2. Piezoelectric Transformers

PTs are resonant devices that exploit the direct and inverse piezoelectric effect of specific ceramic materials. Generally, PTs have a distributed network as equivalent circuit, but when driven at a frequency near one of their mechanical resonances, a lumped equivalent circuit [6] can be used to describe their operation.

Fig. 1b shows the equivalent electromechanical circuit of a PT driven at a resonant frequency together with the system architecture: C_{d1} is the input electrical capacitance (tens of nF), and generally is the highest capacitance for multi-layer transformers; the capacitance C_M is related to the Young's modulus, the resistor R_M is related to the mechanical quality factor Q of the device (typically Q>500 for commercial PTs), the inductor L_M accounts for the vibrating mass; N is the equivalent turn ratio of the ideal magnetic transformer and is related to the force ratio from input to output; C_{d2} is the electrical output capacitance, and is usually much lower than C_{d1}, typically few pF in cm-sized devices, since the distance between the electrodes is generally higher.

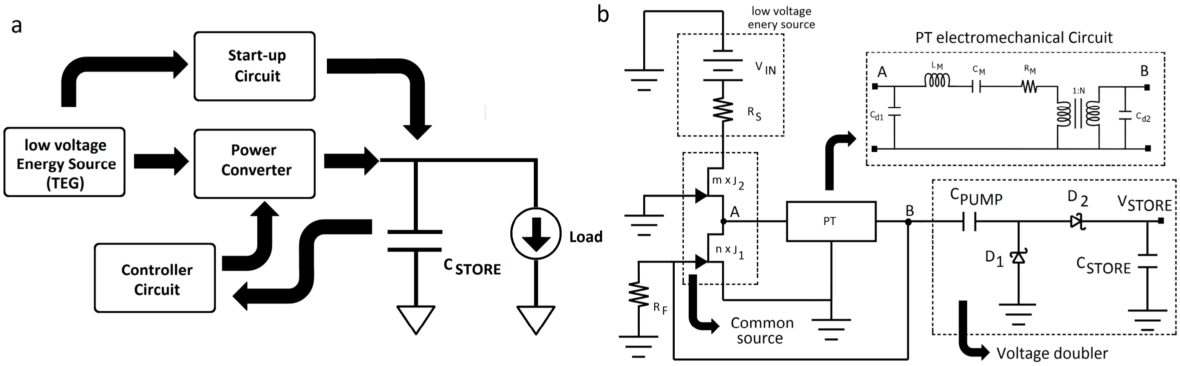

Fig. 1: (a) System kick-start. A conventional power converter cannot start operating with input voltages lower than the devices' threshold voltage. A start-up oscillator can be used to pump low voltages to sufficiently high levels suitable to control the power devices. Once the main converter has been turned on, it can efficiently perform power conversion. The primary target of a step-up oscillator is the lowest possibile start-up voltage and not necessarily the efficiency. (b): Circuit schematic. A very high resistance R_F (> 140MΩ) is introduced to avoid turn-on of the gate to source pn junction, that would cause the loss of the transistor effect.

The PT used in our experiment is the SMMTF55P4S80 by Steiner & Martin's Piezo and was characterized with the admittance circle method.

3. Behavior of the system

The schematic of the circuit is reported in Fig. 1b. The whole system can be divided into four blocks: the low voltage energy source V_{IN} with its series resistance R_S, a common source stage made up of n amplifier JFETs (J201 from Fairchild Semiconductors) and m load JFETs, the PT, a voltage doubler composed of a pump capacitor C_{PUMP} = 470pF, BAS70 Schottky diodes, and a storage capacitor of 4.7μF.

The PT voltage transfer function is shown in (1):

$$A_{VPT}(s) = \frac{V_B}{V_A} = N \cdot \omega_{s,el}^2 \frac{C_{eq} / C_{OUT,N^2}}{s^2 + \left(\omega_{s,el} / Q_{el}\right)s + \omega_{s,el}^2} \tag{1}$$

where $\omega_{s,el}=(L_M C_{eq})^{-1}$ is the electric resonance pulsation, $C_{OUT,N^2}=N^2 \cdot C_{OUT}$, $C_{eq}=C_M \cdot C_{OUT,N^2}/(C_M+C_{OUT,N^2})$ ($\approx 0.96 C_M$), and $C_{OUT}=C_{d2}+C_G+2C_D$ is the overall small signal capacitance seen at the PT output, being C_G the load effect of the JFET J_1 and the capacitance C_D associated to the diodes of the voltage doubler. The device behaves like an extremely high Q second order system: in the vicinity of the resonance (where the phase shift is 90 degrees), the phase has a very steep slope. As stated before, PTs have very high quality factors compared to MTs. This means that