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Abstract. This paper reports on an innovative power management circuit for piezoelectric and electret-based mechanical energy harvesters able to self-start and to power battery-free Wireless Sensor Nodes (WSN) from scratch without any initial energy. The key elements of this circuit are a depletion-mode MOSFET combined with self-powered Schmitt triggers that enable to switch between (i) a non-optimized passive diode-bridge-capacitor configuration to start the system and (ii) an active power conversion path to maximize the energy extraction from mechanical energy harvesters. A discrete circuit implementing this architecture is presented and its operation is validated on simple piezoelectric and electret-based devices. An ASIC, based on the same architecture, has finally been designed, fabricated and validated.

1. Introduction

Mechanical Energy Harvesting is an increasing field of research since the 2000s whose main objective is to develop autonomous wireless sensors powered by ambient vibrations, stress, strains or shocks… The output power of piezoelectric and electret-based mechanical energy harvesters (EH) is generally in the 10μW-100μW range and their high AC output voltages are not compatible with standard electronic circuits requirements (3V-DC supply source needed). As a consequence, a power management circuit (PMC) is essential to turn the EH raw output into a viable supply source for wireless sensors.

In fact, two main types of PMCs can be employed to achieve this electrical conversion:

-   Passive PMCs (e.g. diode bridge rectifier + storage capacitor) that do not require power to operate, but which suffer from a non optimal energy extraction resulting in a low usable output power (figure 1a).

-   Active PMCs that have high conversion efficiencies, and which enable to implement nonlinear techniques such as SSHI (Synchronized Switch Harvesting on Inductor), SECE (Synchronous Electric Charge Extraction) [1] to increase the extraction of energy from the energy harvester [2]. Figure 1b shows an example of such a circuit: a flyback converter driven by a control circuit. Unfortunately, this type of circuit must be powered to operate, for example by a rechargeable battery which stores the harvested energy while supplying the electronic functions: the power balance (harvested power – PMC power consumption) is generally much larger than the output power obtained with a passive PMC.

Yet, energy harvesting has the great benefit of enabling the deployment of battery-free devices compatible with harsh environments (e.g. high temperatures) and with a theoretical unlimited lifetime. But, a problem arises when starting an energy harvesting system from scratch, without battery and any initial energy: the active PMC cannot be powered and the power converter (e.g. flyback converter) cannot be controlled. The

solution we propose consists in switching between the passive and the active PMCs as soon as enough energy has been stored in a startup capacitor C_s to power the control circuit.
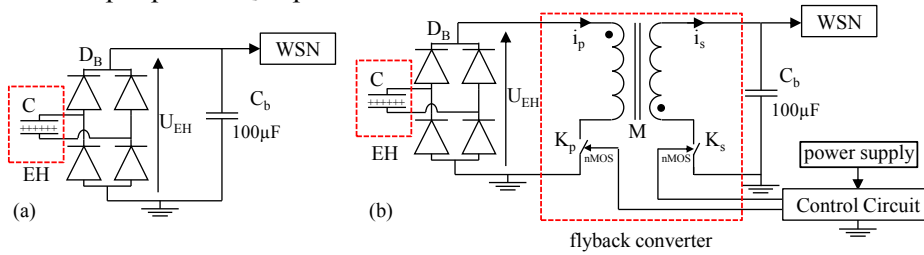

Figure 1. (a) passive PMC and (b) active PMC (flyback converter)

2. Self-starting power management circuit architecture

The whole architecture of the self-starting PMC we propose is depicted in figure 2a. A flyback converter implementing SECE [1] has been chosen as the active PMC: all the energy stored into the EH capacitance is transferred to C_b through the coupled inductors when U_{EH} reaches its maximum. This operation mode has proven its benefits for piezoelectric [3-4] and electrostatic [5] devices.

In our case, two capacitors are used: (i) C_s which powers the control circuit and (ii) C_b which supplies the WSN; they are connected by a diode (D_C). A depletion-mode MOSFET (dMOS) K_{bp} is employed to bypass the flyback converter during the startup, in order to charge C_s. Then, this circuit is able to switch between the passive and the active PMC according to U_{Cs} (the voltage across C_s); this switching is controlled by the 'Startup Control' which is a Schmitt trigger. The operation mode of this circuit can be summarized in 5 steps and the typical voltages on C_b and C_s during startup are presented in figure 2b.

- *State 0 – no-energy state.* At the beginning, there is no energy, K_{bp} is closed, K_{cc} is open, K_{app} is open, U_{Cb}=0 and U_{Cs}=0.
- *State 1 – non-optimized diode-bridge-capacitor conversion.* The energy scavenger starts to harvest energy. As K_{bp} is closed and K_{cc} is open, the flyback converter is bypassed by K_{bp}. The PMC behaves like a diode-bridge-capacitor circuit; the energy goes directly from the EH to C_s and U_{Cs} increases.
- *State 2 – optimized flyback conversion.* When U_{Cs} reaches U_{Cs}^+, 'Startup Control' opens K_{bp} and closes K_{cc}. The Control circuit is supplied by C_s and the flyback conversion starts. U_{Cb} increases. As C_s is not supplied anymore while powering the control circuit, its voltage decreases until falling below U_{Cs}^-. The Startup control switches to state 1 to recharge C_s. This commutation between state 1 and state 2 continues until U_{Cb} reaches $U_{Cs}^-+V_{thDc}$ (threshold voltage of D_C).
- *State 3 – end of startup.* The PMC remains in the flyback conversion configuration, optimizing power extraction from the energy harvester. K_{cc} stays closed, K_{bp} open.
- *WSN measurement.* When U_{Cb} reaches U_{Cb}^+, 'WSN Control' (also a Schmitt trigger) closes K_{app} and makes the WSN perform its measurement and transmission cycle.
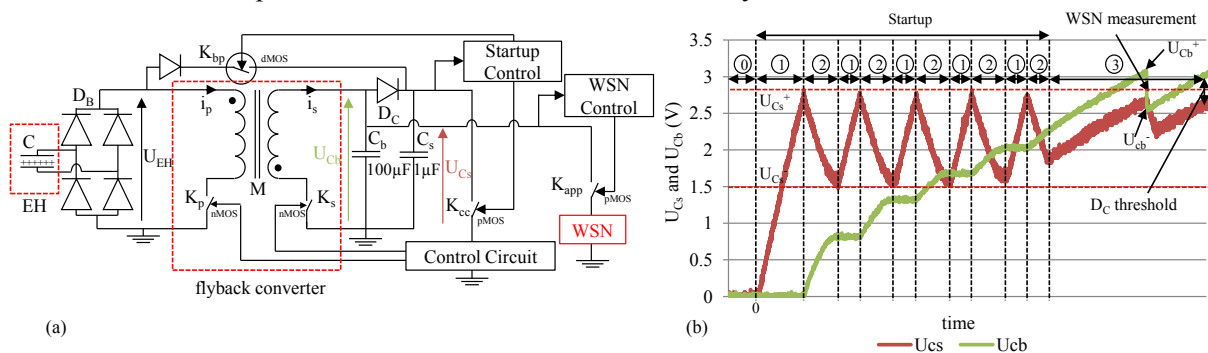

Figure 2. (a) self-starting PMC architecture and (b) mode of operation (extracted from experimental results)

3. Electronic circuit made with Discrete Commercial Off-The-Shelf components

The challenge of this circuit lies in the design of the 'startup control' and of the 'control circuit' that must be low power, autonomous and able to work from a zero-energy state.

3.1. Self-powered Schmitt trigger - 'Startup Control' and 'WSN Control'

As previously explained, *'Startup Control'* and *'WSN Control'* are Schmitt triggers. It is quite easy to make Schmitt triggers with low-consumption comparators with internal reference (e.g. MAX917) and by adding resistors to induce a hysteretic behavior. Yet, the power consumptions of these components are in the 700-800nA range, which is quite elevated for a startup circuit whose interest is limited to the startup phase.

Our Schmitt triggers have been made from discrete commercial off-the-shelf components. Their core concept is a dMOS-based self-powered voltage comparator (figure 3a). The dMOS is here used as a voltage limiter: its gate is connected to the ground and a high-impedance load ($R_0>100M\Omega$) is placed at its source. In this configuration, U_{dmos} will be limited by the dMOS threshold voltage (V_{thdmos}): $U_{dmos}=\min(U_{in}, V_{thdmos})$. Two CMOS inverters, powered by U_{in} and connected to the dMOS source, act as a buffer switching at $U_{sw}=U_{in}/2$.

When $U_{in}<V_{thdmos}$, $U_{out}=U_{dmos}=U_{in}$. Then, for $U_{in}>V_{thdmos}$, U_{dmos} saturates at V_{thdmos}; U_{out} remains equal to U_{in}. When U_{in} reaches $2V_{thdmos}$, U_{dmos} is still equal to V_{thdmos} and U_{out} switches to 0. A hysteretic behavior is achieved by adding resistors in this circuit; diodes can also be added to shift the switching levels. The complete self-powered Schmitt trigger is presented in figure 3c. Its power consumption is in the 50-100nA range depending on the switching levels (10 times lower than Schmitt triggers made from comparators).
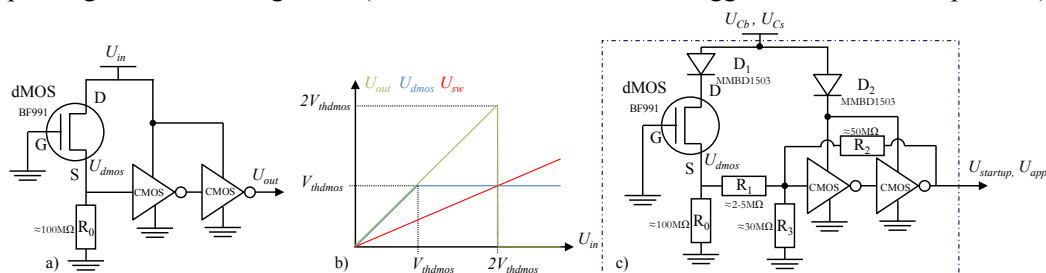

Figure 3. (a) Self-powered voltage comparator and (b) mode of operation. (c) Schmitt trigger

3.2. Control Circuit

The Control Circuit is the other key element of this architecture. In SECE, the control circuit is aimed at detecting the output voltage's maximums and to control at the right time K_p and K_s. The control circuit is made of a RC differentiator (R_D-C_D) and a comparator (figure 4a) to detect the zero crossings of U_{EH}'s derivative, i.e. its maximums. Three delay cells (figure 4b) generate the control times T_1 and T_3 for K_p and K_s (figure 4c). The circuit has been made from standard electronic components and its power consumption is comprised between 500nA@3V and 1µA@3V.
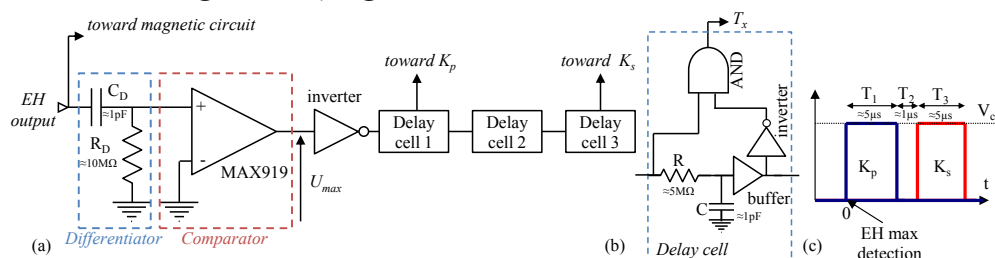

Figure 4. (a) Control circuit architecture, (b) delay cell and (c) transistors control as a function of the time

4. Experimentations on simple electret-based and piezoelectric mechanical energy harvesters

4.1. Electret-based vibration energy harvester

A simple electret-based vibration EH [6] (figure 5a) has been connected to the self-starting PMC. It oscillates at 35Hz and harvests 23µW of raw output power on a 50MΩ-load (figure 5b). $U_{Cs}(t)$ and $U_{Cb}(t)$ are presented

in figure 5c validating the good operation of the self-starting PMC. And then, it proves that even with this simple device, it is possible to power a Wireless Sensor consuming 112µJ after 200s (figure 5c), and every 5s after the startup phase.

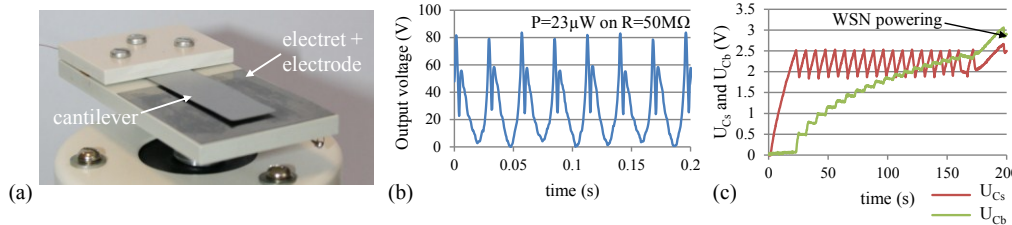**Figure 5.** (a) Simple electret-based vibration energy harvester, (b) output voltage on a 50MΩ-load after the diode bridge and (c) U_{Cs} and U_{Cb} as a function of the time and WSN measurement

4.2. Piezoelectric strain energy harvester
The same experiment has been performed on a simple piezoelectric energy harvester (figure 6a) deformed by hand at 7Hz and harvesting about 100µW. Our self-starting PMC is again validated (figure 6c), and logically, as the output power is much higher than in the previous case, the startup duration is highly reduced (about 12s) and a measure can be performed about every second after the startup phase.
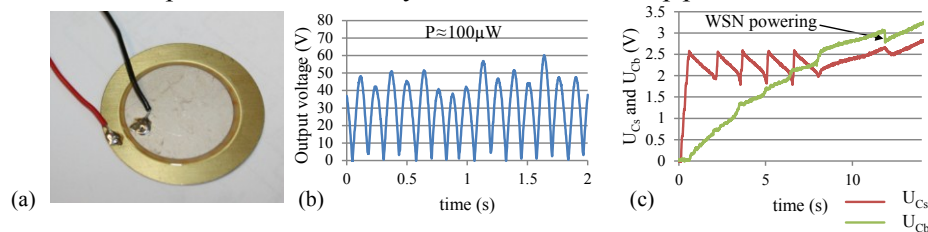

Figure 6. (a) Simple piezoelectric energy harvester (buzzer from Murata), (b) output voltage on a 10MΩ-load after the diode bridge and (c) U_{Cs} and U_{Cb} as a function of the time and WSN measurement

5. ASIC implementing the self-starting PMC

5.1. Architecture
An integrated PMC [7] has been fabricated in AMS 0.35µm CMOS process (figure 7a). The autonomous integrated circuit, whose architecture is depicted in figure 7b, is mainly composed of the control circuit, the Startup control and the WSN control functions. All its blocks are powered by C_s, except the WSN control which is dependent on the voltage across the WSN storage capacitor (C_b). The Flyback circuit and its diode bridge, the two buffer capacitors, the derivation capacitor C_D and the dMOS K_{bp} are off-chip, and K_{cc} is removed. Thanks to these external components, the architecture is not limited in terms of tolerated harvester voltages, enabling the use of a low cost and easily available CMOS technology.
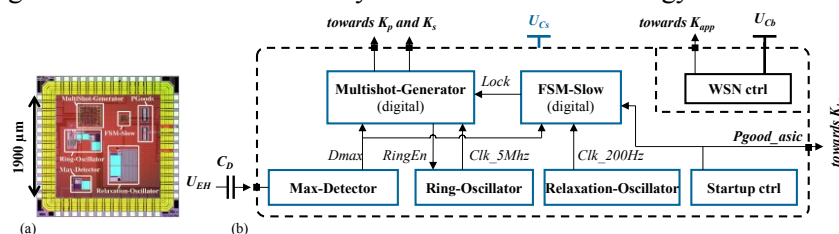

Figure 7. (a) Die of the ASIC implementing the self-starting PMC and (b) its internal architecture

5.2. Flyback control
The chip detects when the harvester has reached a maximum voltage thanks to the block "*Max-Detector*". This block, described in [8], shows a power consumption of 150nW @ 3V with a low detection delay (50 µs). It uses a transconductance amplifier biased by a 20nA current source. Instead of using delay cells (as in 3.2), the Flyback control is performed by a digital state machine clocked by a 5 MHz ring-oscillator. The ring is powered at a low stabilized voltage (≈ 1.2V) enabling a low power operation (200 µW) and a clock frequency

independent of U_{Cs} level. Two input vectors of 8-bits set the number of clock cycles corresponding to the closing duration of K_p and K_s. This block has the particularity to switch the ring oscillator only during the Flyback control. It enables a very low power operation of the Flyback control since the harvester is discharged at a very low duty cycle (2% max) compared with the EH mechanical period.

5.3. Start-up control and WSN control

The Startup and WSN control functions are performed with two very low power POR (Power On Reset) which consume 50 nA@3V, and detect when U_{Cs} and U_{Cb} exceed 3V and fall below 2V to control K_{bp} and K_{app}. A power cut separates U_{Cs} and U_{Cb} in two power supply domains avoiding the pads' ESD diodes to conduct if a voltage (U_{Cs} or U_{Cb}) becomes greater than the other one. This enables to use a low threshold voltage diode (D_C) between C_b and C_s.

5.4. Harvesting energy from very low frequency deformations

Figure 8 shows an example of a complete operation of the proposed system harvesting energy from a piezoelectric harvester (figure 6a) excited with a mechanical frequency of 1.6 Hz and providing an input power of 30 µW. It validates the good operation and the compatibility of the PMC we propose with ASICs.
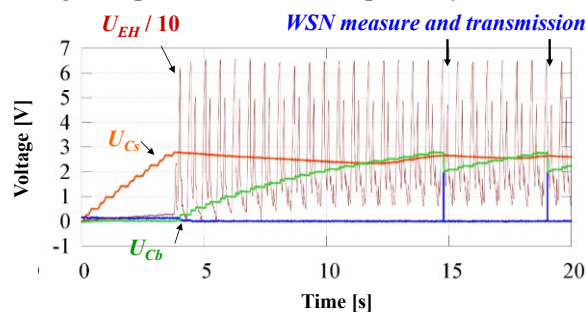

Figure 8. Experimental time-domain waveforms for a piezoelectric buzzer excited at 1.6 Hz

6. Conclusions

We have proposed an autonomous and self-starting PMC architecture employing a dMOS as a bypass of its power converter. A Schmitt trigger using a dMOS as a voltage limiter has been developed to control the startup with an ultra-low power consumption not exceeding 100nA. A PMC implementing a SECE on a flyback converter has also been designed; its power consumption is in the 500nA-1µA range. The operation has been validated with an electret-based vibration EH at 35Hz and a piezoelectric EH at 7Hz. This architecture has finally been implemented in an ASIC and validated on a low-frequency piezoelectric energy harvester. This new PMC is completely autonomous and can be made from standard off-the-shelf components or in ASICs. The proposed architecture is able to turn most of piezoelectric and electret-based mechanical EH into viable supply sources for battery-free WSN.

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