Active Autonomous AC-DC Converter for Piezoelectric Energy Scavenging Systems

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Abstract: The paper focuses on an electronic interface which can be used into Piezoelectric Energy Scavenging Systems (PESS). These systems convert the energy of mechanical vibrations into electrical energy using a piezoelectric transducer to realize a power supply for low power electronic systems. To obtain a suitable supply source an AC-DC conversion of the output signal of these transducers is needed and, since the output power level of the energy scavenger can be very low, the conversion should be as efficient as possible. This paper shows an active voltage doubler AC-DC converter for PESS. A novel driving circuitry topology is presented; it has the advantage to be tolerant with respect to the process variations. The converter uses exclusively a fraction of the harvested energy to supply itself and a bias circuit has been designed to make the total current consumption supply independent.

A test chip was diffused in 5V CMOS STMicroelectronics technology. Experimental results show the effectiveness of this solution and efficiencies higher than 90% have been obtained for different load values.

I. INTRODUCTION

In recent years a lot of studies focused on energy scavenging systems which are used to harvest the normally lost environmental energy and to convert it into electrical energy. This solution can be attractive where batteries are a bottleneck for the whole system (i.e. they have a finite life time and their replacement or recharge is not feasible or too expensive). An energy scavenging system, instead, is a theoretically endless energy source. Energy scavenging systems could supersede batteries thanks to two driving forces: 1) reduction of the power consumption of the supplied electronic system, 2) optimization of the harvesting system. This last point can be further subdivided into optimization of the energy transducer and optimization of the electronic interface which has to manage and store the harvested energy.

In literature many papers can be found which describe methodologies to realize the energy-scavenger [1], [6], [8], [10]. A lot of these works are focused on the conversion of the energy associated to mechanical vibrations since they can be easily found in many environments [1], [7].

This paper describes a system based on a piezoelectric transducer since it is one of the more efficient which can be used [1]-[2].

The electrical energy at the output of this transducer is a strong and irregular function of time [1]-[4], [9], hence, to realize a DC supply source, an AC-DC conversion is needed. The paper focuses on the optimization of the electronic interface. In particular an active voltage doubler AC-DC converter, which uses only a fraction of the harvested energy to supply its active devices, is presented. A possible way to realize the driving circuitry of an active voltage doubler is to use comparators [3]-[4], [9] which sense the voltage drop across the switches and drive them. In this paper a different solution is proposed where comparators are replaced with operational amplifiers. A capacitance of 1 μF is used to store the harvested energy which is partially used to supply the active circuitry of the converter so that no external power source is required. Since the voltage across the storage capacitance is variable the converter is also enriched with a circuitry which, differently from [4], makes the bias current supply independent.

A test chip was diffused in 5V CMOS STMicroelectronics technology. Experimental results show the effectiveness of the AC-DC converter in terms of its efficiency, which is higher than 90%.

II. PIEZOELECTRIC ENERGY SCAVENGING SYSTEM

A. Mechanical Aspects

The considered piezoelectric transducer is a cantilever which works in 31-mode when it is excited by the mechanical vibrations. To have a maximally efficient conversion of the mechanical vibrations into electrical energy the cantilever should be excited at its resonant frequency which can be varied adding a mass on its free end [1]. This allows the energy transducer to be tuned with the vibrations which are present in a specific environment. Some experimental measurements [1] showed that the frequency range of mechanical vibrations existing into civil environments is approximately (60-380) Hz.

The piezoelectric transducer can be modeled at resonance by the equivalent circuit [1]-[2] shown in Fig. 1. V_{RO} is a sinusoidal voltage source whose frequency is equal to the transducer resonance frequency and whose amplitude is equal to the open circuit output voltage, while C_P is the electrical capacitance of the piezoelectric cantilever.

The results presented in the paper are based on a piezoelectric cantilever whose geometrical dimensions are 30x15x0.1 mm (LxWxH). The piezoelectric material used is a soft Lead Titanate Zirconate (PZT). In this case C_P is equal to 36 nF, according to experimental measurements.
B. Front End Circuitry

Fig. 1 shows the active topology of the proposed AC-DC converter: switches M_sw1 and M_sw2 are realized with p-channel and n-channel MOSFET respectively while the driving circuitry is composed of operational amplifiers OP1 and OP2, and by the biasing circuitry. The DC sources indicated in Fig. 1 as VОс are the equivalent input offset voltages of the operational amplifiers. The energy stored into capacitance C_{S} is also used to supply this circuitry. Since the voltage across the storage capacitance is variable, a supply independent bias circuitry is used to prevent a non linear power consumption of the driving circuitry. During the start-up the energy stored into C_{S} is not enough to supply the active devices. In this case the operation of the converter is guaranteed by the body-source diode of MOSFETs M_sw1 and M_sw2. Consequently the proposed rectifier can be seen as a parallel of two AC-DC converters: an active one with an higher efficiency and a passive one with a lower efficiency, the latter working only during start-up. The performances of the proposed solution have been simulated with a resistive load R_{L}. Since the effectiveness of the energy transfer from the piezoelectric transducer to the load depends on the value of the load resistance, it was varied between 50 k\Omega to 1 M\Omega seeking the optimum value.

To introduce the working principle let us consider Fig. 2 which shows the case of OP1 (similar considerations apply to OP2). It is possible to apply Kirchhoff Voltage Law to the external mesh:

\[ V_{IN} + V_{SD} - V_{OS} = 0 \]

If the operational amplifier has a DC gain equal to A the voltage on the gate of the M_{sw1} is:

\[ V_{G} = A \cdot V_{IN} \]

Equations (1) and (2) can be solved as a function of V_{G}:

\[ V_{G} = A \cdot (V_{OS} - V_{SD}) \]

In the ideal case the DC gain A of the operational amplifier is infinite; as a consequence the difference in equation (3) has to vanish in order to have a finite value of the gate voltage. In this way, a regulation loop is obtained which modulates the gate voltage V_{G} to keep the source to drain voltage of the MOSFET equal to offset voltage for each value of the drain current.

Fig. 3 gives a graphical representation of this working principle: in the ideal case when drain current is positive the regulation loop sets the working point of the MOSFET at the intersection between its characteristics and the offset voltage. As the current decreases, the loop moves the working point of the MOSFET at lower values of its source to gate voltage, until the current is equal to zero. At this point the regulation loop turns the MOSFET off; since there is no intersection between the MOSFET characteristics and the offset voltage for negative values of the current, they are not allowed and regulation loop holds the transistor off. This principle guarantees that no oscillations of the driving signal will take place.

Furthermore, being a negative current impeded, any unwanted discharge of both C_{r} and C_{S} is prevented. Symmetrical considerations apply to OP2. The value of the offset is not critical because it has simply to be far enough from zero so that the process mismatches will not change its sign. While it is true that an higher offset gives higher losses on the switch, they are still negligible for practical offset values. This makes the circuit quite tolerant to process mismatches.

The real operational amplifier has a finite DC gain; this means that the value of the voltage across the MOSFET is slightly different from the theoretical one. Nevertheless it can be demonstrated that, with the previously described choice of the offset, this will not affect the operation of the circuit.

III. DESIGN OF THE AC-DC CONVERTER

A. Supply Independent Bias Circuitry

Since the driving circuitry should be supplied only by the harvested energy its power dissipation should be as low as possible, in particular the proposed circuit was designed to have an average current consumption of about 500\mu A.

![Fig. 1 Schematic of the proposed ESS. Equivalent circuit of piezoelectric transducer when it is excited at its resonant frequency, front-end circuitry and load can be identified.](image1)

![Fig. 2 Regulation loop composed by the operational amplifier OP1 and MOSFET M_sw1.](image2)

![Fig. 3 Graphical solution of the regulation loop composed by the operational amplifier and MOSFET M_sw1/2.](image3)
A dedicated circuitry was added to keep this current consumption constant as the supply voltage increases, while it would have naturally increased as well: as a consequence the power consumption depends on the supply voltage in a linear way. The proposed scheme, shown in Fig. 4, is modified with respect to [5] by adding diode connected MOSFET (M4). The system, in fact, requires supply currents in the range of tens of nA: in the scheme without M4, resistance R1 would have been in the order of tens of MΩ, which is too area expensive for an integrated solution. The effect of M4 is to reduce the voltage drop across R1 and this lowers its value for a given current I1. Furthermore, a start up function is needed, which was obtained with dummy MOSFETs ML1 and ML2. In particular, the leakage of their body-drain diode was exploited: its effect is to inject a current into node A and B so to have the start-up aid. This solution allows us to avoid additional start-up circuitry, reducing total power consumption.

Simulations shows that the circuitry starts to regulate when the supply voltage is higher than about 680 mV. Above this value the voltages $V_{BiasP}$ and $V_{BiasN}$ can be used to mirror a supply independent current. The total current consumption of the bias circuitry is about 100 nA.

B. Operational Amplifiers

The schematics of the proposed operational amplifiers are shown in Fig. 5a. Because of the level of their input voltage ranges, OP1 and OP2 have to be supply compatible and ground compatible respectively. The bias of the operational amplifiers is given by the supply independent bias circuitry. The operational amplifiers were designed so that they are able to work with the minimum possible value of the supply voltage. In this way the active rectifier takes over the passive one as soon as a very low voltage has been stored into capacitance $C_s$. A 5pF capacitance was introduced to compensate the regulation loop.

The offset voltage was obtained mismatching the aspect ratio of the input MOSFETs $M_A$ and $M_B$: the values of the target offset voltages are equal to 26 mV and 21 mV for OP1 and OP2 respectively. Fig. 7 presents the simulation results of 500 Monte Carlo iterations, showing the possible spread of these voltages. It is possible to see that this spread is sufficiently small to have the correct sign also in case of process mismatches.

The aspect ratio of the MOSFETs $M_{SW1}$ and $M_{SW2}$ has to be chosen so to avoid the loop saturation. The expression of the drain current when the MOSFET is turned on, in a first approximation, is equal to:

$$i_D = k \frac{W}{L} (V_{GS} - V_{th}) V_{DS}$$  \hspace{1cm} (4)

where $V_{th}$ is the threshold voltage of the MOSFET, $W/L$ is its aspect ratio and $k$ is its characteristic constant. The term into the parenthesis is the overdrive voltage: its value is modulated by the regulation loop which, for a each drain current, varies the gate voltage. If the overdrive voltage is enough, the source to drain voltage is equal to $V_{GS}$, that is:

$$i_D = k \frac{W}{L} (V_{GS} - V_{th}) V_{OS}$$  \hspace{1cm} (5)

On the other hand if, for a given current, the overdrive is not enough (which means that the op-amp is saturated), the regulation loop does not work and the source to drain voltage of $M_{SW1}$ or $M_{SW2}$ is not equal to offset voltage. The aspect ratio has to be designed to accommodate the maximum expected current.

Fig. 5b shows a picture of the diffused AC-DC converter. Tab. 1 resumes the characteristics obtained for the amplifiers: in particular the current consumption is about 200 nA for each amplifier. $V_{dd-min}$ is the minimum supply voltage required by the operational amplifiers to work.

![Fig. 4 Schematic of the proposed supply independent bias circuitry.](image)

![Fig. 5a)Schematic of the proposed operational amplifiers; b) picture of the diffused AC-DC converter.](image)

![Fig. 6 MonteCarlo simulation of the offset voltages of the designed operational amplifiers.](image)

| TABLE I. CHARACTERISTICS OF THE DESIGNED OPERATIONAL AMPLIFIERS |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| **Gain-DC [dB]** | **Band-Width [Hz]** | **Vdd-min [V]** | **Voffset [V]** | **Current Consumption [nA]** |
| **OP1**          | 50.37           | 2500            | 0.73            | 26e-5           | 200             |
| **OP2**          | 49.78           | 2610            | 0.675           | 21e-5           | 200             |

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IV. EXPERIMENTAL RESULTS
An experimental characterization of the supply independent bias circuit was performed using a stand alone version of the circuit depicted in Fig. 7b: three MOSFETs Ma, Mb and Mc were added to amplify the bias current by a factor 30: this current is then converted into a voltage drop by means of an external resistance, equal to 2 MΩ. Experimental characterization was done suppling the bias circuit with a triangular waveform in the range 0-4.8 V. Fig. 7a shows that, as soon as the supply voltage is higher than 680 mV, the circuit generates a constant voltage drop across the 2 MΩ resistance which corresponds to a constant bias current, as it was predicted by the simulations.

Fig. 8 shows the efficiency of the AC-DC converter as a function of the value of the load resistance R_L. These results were obtained exciting the piezoelectric transducer with a B&K 8410 shaker at a frequency equal to 200 Hz. The amplitude of the vibrations has been regulated so to have a peak to peak output voltage of the transducer, at no load condition, equal to 3 V. It is possible to see that experimental values are similar to the simulated ones: a measured efficiency higher than 90% has been obtained.

V. CONCLUSIONS
This paper presents a piezoelectric energy scavenging system where the AC-DC conversion is realized with an active voltage doubler which uses exclusively a fraction of the harvested energy to supply itself.

A novel solution was presented where comparators have been replaced with operational amplifiers. They sense the voltage across the switching MOSFETs and drive their gate terminals. A regulation loop fixes the drop voltage across the switch at a value equal to the equivalent input offset voltage of the operational amplifier itself. This solution is tolerant to the process variations since the obtained offset value is not a critical parameter, only its sign is important. Furthermore a supply independent bias circuitry was implemented in order to make the current consumption of the driving circuitry independent on the supply voltage. Average current consumption of the whole active elements is about 500nA.

A test chip has been diffused in CMOS 5V STMicroelectronics technology and experimental results are presented.

An efficiency of about 90% was obtained in a wide range of load values.

VI. References