Self-Biased Inductor-less Interface Circuit for Electret-Free Electrostatic Energy Harvesters

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Abstract. This paper presents a simple and efficient interface circuit for electrostatic energy harvesting devices, which uses neither controlled electronic switch nor inductor. A built-in voltage multiplier enables to get bias voltages higher than the circuit output voltage, resulting in an increased power output. This interface circuit was implemented using off-the-shelf components. Its operation was validated from 1V to 14V output voltages. Measured output power ranged from 10nW to 650nW using a capacitor varying between 45pF and 155pF at 15Hz. Measurements showed that it was possible to initiate the energy conversion cycles with start-up voltages as low as 100mV.

1. Introduction

Energy harvesting from mechanical vibration using electrostatic devices have focused significant research efforts over the last decade. This energy conversion principle is particularly interesting because the transducer is a simple mechanically-actuated variable capacitor, which can be easily manufactured and miniaturized using MEMS technologies. At micro-scale, tolerated electric fields are quite high, and theoretical power densities of electrostatic devices compete piezoelectric and electromagnetic devices ones.

Generating electrical energy using a variable capacitor without internal polarization (electret) requires to charge and discharge the capacitor in a synchronous way with the mechanical motion of its moving electrode. For this purpose, various power management electronic circuits have been proposed. However, practical implementation of such active interfaces remains difficult at microwatt scale, making a real obstacle for the development of electret-free electrostatic energy harvesting systems [1]. Indeed, at microwatt scale, the power losses of the electronic switches used in actives interfaces and the power consumption of their control circuit generally turn out to be more important than the electrical power generated by the variable capacitor itself. Yen et al proposed a simplified circuit using only one active switch without synchronization constraint [2], but energy-efficient implementation is also difficult to achieve at microwatt scale in this case [3].

Another drawback which is common to most of these interface circuits is the use of bulky magnetic components (inductors, transformers), that limits miniaturization. Moreover, in some specific applications such as medical implants, the use of magnetic parts is not possible because of compatibility requirements with Magnetic Resonance Imaging.

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We are focusing here on interface circuits working without inductor and without active switches. In this domain, de Querioz et al have proposed a circuit based on Bennet’s “doubler of electricity” [4]. Contrary to interface circuits using active switches, this circuit showed to be remarkably easy to implement and viable from the energy point of view down to the nanowatt scale. Dragunov et al proposed circuits with increased output current derived from this concept [5]. Based on the same principle, de Querioz recently presented a solution to increase the bias voltage and the output power [6], but this solution required using at least two variable capacitors.

The approach which led to the new circuit presented in this paper started from the analysis of another very simple circuit frequently used to assess the functionality of electrostatic energy harvesting devices [7]. Our objective beyond this work is to develop strongly integrated and highly reliable energy harvesting systems for active medical implant applications [8].

2. Approach and theoretical analysis of the proposed interface circuit

2.1. Interface circuits with pre-charged biasing capacitor

One of the simplest circuits which can be used to harvest energy with an electret-free variable capacitor is depicted in Fig. 1 (a). It is composed of a pre-charged capacitor $C_{bias}$ connected in series with a load resistor $R_{load}$ and the variable capacitor $C_{var}$ [7]. Apart for testing electrostatic energy harvesting devices, this circuit has no real interest because of the alternating nature of the load voltage. From this remark comes the idea that the principle of the biasing capacitor could be useful if combined with a rectifier. This is for instance the case of the circuit depicted in Fig. 2 (b), in which the load resistor is replaced by a diode rectifier ($D1$, $D2$). The electrical energy generated by the variable capacitor is stored in the capacitor $C_{store}$.

![Schematic diagrams of (a) interface circuit with biasing capacitor and resistive load, (b) interface circuit with biasing capacitor, diode rectifier and energy storage capacitor.](image)

Before presenting a solution to pre-charge the capacitor $C_{bias}$ and keep it charged, operation of this circuit is first analysed with the help of the simulation waveforms shown in Fig. 2. In this simulation, $C_{var}$ is varied at 100Hz between its maximum value $C_{max}=300pF$ and its minimum value $C_{min}=100pF$. $C_{bias}$ is pre-charged at 15V and $C_{store}$ is pre-charged at 10V. The ON-state voltage drop across the diodes is noted $V_D$. Leakage currents are neglected in the following analysis.

According to Fig. 2, four time sequences can be identified over an energy conversion cycle:

- From $t_0$ to $t_1$, the diodes $D1$ and $D2$ are blocking, $C_{var}$ is decreased at constant charge $Q_0=C_{max}(V_{Chias-V_D})$ and its voltage is increased from $V_{Chias-V_D}$ to $V_{Chias-V_Cstore-V_D}$.

- From $t_1$ to $t_2$, the diode $D1$ is conducting, $C_{var}$ voltage is equal to $V_{Chias-V_Cstore-V_D}$ and the charge $Q_1=C_{max}(V_{Chias-V_D})-C_{min}(V_{Chias-V_Cstore-V_D})$ flows through $C_{var}$, $C_{bias}$ and $C_{store}$.

- From $t_2$ to $t_3$, the diodes $D1$ and $D2$ are blocking, $C_{var}$ is increased at constant charge $Q_2=C_{min}(V_{Chias-V_Cstore-V_D})$ and its voltage is decreased from $V_{Chias-V_Cstore-V_D}$ to $V_{Chias-V_D}$.

- From $t_3$ to $t_4$, the diode $D2$ is conducting, $C_{var}$ voltage is equal to $V_{Chias-V_D}$ and the charge $Q_3=C_{min}(V_{Chias-V_Cstore-V_D})-C_{max}(V_{Chias-V_D})$ flows through $C_{var}$ and $C_{bias}$.

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Figure 2. Simulation waveforms of the circuit with biasing capacitor, diode rectifier and energy storage capacitor ($C_{bias} = 10\text{nF}$, $C_{store} = 10\text{µF}$).

$C_{bias}$ was chosen much larger than $C_{var}$, so the variations of $V_{bias}$ are negligible over an energy conversion cycle. Similarly, $C_{store}$ was chosen much larger than $C_{bias}$ and the voltage $V_{Cstore}$ can be considered as constant over several energy conversion cycles. By neglecting the voltage drop across the diodes, the energy harvested per cycle can be approximated by (1).

$$W_{Cycle} = (C_{max} \cdot V_{bias} - C_{min}(V_{bias} + V_{Cstore})) \cdot V_{Cstore} \quad (1)$$

2.2. Interface including a charging circuit for the biasing capacitor

The previous the energy conversion cycle analysis showed the total charge flowing through $C_{var}$ and $C_{bias}$ over a period of operation ($Q_1 + Q_2$) is null. Therefore, the average voltage across $C_{bias}$ remains stable if one neglects the leakage current of the components. In practice, only a small fraction of the harvested energy should be sufficient to keep $C_{bias}$ charged and compensate the effect of leakage currents.

A first observation of the circuit waveforms of Fig. 2 shows that it would be possible to recharge $C_{bias}$ by connecting a diode $D3$ between top electrodes of $C_{store}$ and $C_{var}$; each time $D2$ is conducting, $C_{bias}$ would be recharged by $C_{store}$ at the voltage $V_{Cstore}$.

Equation (1) indicates that the harvested energy increases with $C_{bias}$ voltage, so it would be interesting to get higher voltages than $V_{Cstore}$ across the biasing capacitor. A simple solution to increase voltages consists in using voltage multiplier circuits, but these circuits require variable input voltage. The circuit waveforms show that the voltages across $D1$ and $D2$ vary periodically between 0 and $V_{Cstore}$. Consequently, it should be possible to connect the input of a voltage multiplier circuit across $D1$ or $D2$ in order to recharge $C_{bias}$ at a voltage which would be a multiple of $V_{Cstore}$. Starting from these remarks and observations, several implementations can be envisaged [9].

One of the simplest solutions is depicted in Fig. 3. In this new interface, the biasing capacitor is charged by a built-in voltage multiplier circuit, which may include from 1 to $n$ cells. By neglecting the voltage drop across the diodes and the voltage ripple across $C_{bias}$ and $C_{store}$, the voltage across $C_{bias}$ can be expressed as (2).

$$V_{Cbias} = n \cdot V_{Cstore} \quad (2)$$
According to (1) and (2), the energy harvested per cycle using \(n\)-cells of the voltage multiplier can be expressed as (3). This equation is valid only if \(\frac{C_{\text{max}}}{C_{\text{min}}}>\frac{(n+1)}{n}\). Otherwise, the voltage variation across \(C_{\text{var}}\) is smaller than \(V_{\text{Cstore}}\) and \(D1\) and \(D2\) are always blocking so there is no energy conversion. It is interesting to note that this threshold becomes lower when the number of cells is increased, making possible the energy conversion at lower mechanical displacement magnitude of the variable capacitor electrodes.

\[
W_{\text{cycle}} = n \cdot V_{\text{Cstore}}^2 \cdot C_{\text{min}} \left( \frac{C_{\text{max}}}{C_{\text{min}}} \cdot \frac{n+1}{n} \right)
\]

(3)

**Figure 3.** Schematic diagram of the self-biased interface circuit.

Fig. 4 (a) shows plots of theoretical energies harvested per cycle versus the capacitance variation ratio \(C_{\text{max}}/C_{\text{min}}\) for \(n\) between 1 and 4. As comparison, the maximum theoretical energy harvested per cycle using Yen’s circuit [2] was also plotted in this figure. These results indicate for instance that for \(C_{\text{max}}/C_{\text{min}}=2\), the self-biased circuits with 2, 3 and 4 cells theoretically harvest respectively 4, 12 and 16 times more energy than Yen’s circuit for a given voltage \(V_{\text{Cstore}}\). Fig. 4 (b) shows plots of the theoretical charge-voltage cycles for a number of cells \(n\) between 1 and 4.

**Figure 4.** (a) Normalized energy converted per cycle vs capacitance ratio \(C_{\text{max}}/C_{\text{min}}\), (b) charge-voltage diagrams of the variable capacitor
3. Experimental results

The circuit of Fig. 3 was implemented using a macro-scale rotating variable capacitor \( (C_{\text{max}}=45 \text{pF}, C_{\text{min}}=155 \text{pF}) \), low leakage PAD5 diodes, 560pF capacitors for the voltage multiplier, and \( C_{\text{bias}}=2.4 \text{nF} \). The frequency of operation was set to 15Hz. The voltages were measured using AD549JHZ high input impedance op-amp. Experimental and theoretical harvested powers plotted in Fig. 5 (a) exhibit similar shape as a function of \( V_{\text{Cstore}} \). The differences which can be observed between theory and measurements indicate that the losses of the system increases with the number of cells. The analysis of the circuit practical limitations and efficiency will be deepened in further work. Fig. 5 (b) shows the start-up of the system, with \( C_{\text{store}} \) pre-charged at 1 volt, showing the ability of the circuit to self-start from very low voltages and self-adapt to variations of the output voltage. Our experiments showed that the circuit start-up was possible with initial output voltages as low as 100 mV.

![Figure 5. (a) Experimental and theoretical harvested powers (resp. plain and dashed lines) vs voltage \( V_{\text{Cstore}} \), (b) experimental start-up of the self-biased circuit \( (C_{\text{store}}=4.7\text{nF}) \).](image)

4. Conclusion

This paper presents a new interface circuit for electrostatic energy harvesting devices, only composed of diodes and capacitors. As there is neither active switch nor control circuit, practical implementation is very simple and robust. Expected characteristics in terms of power output were confirmed by experimental results. Our future work will focus on the analysis of the effect of the components imperfections on the system performances.

5. References

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