Two self-powered energy harvesting interfaces based on the optimized synchronous electric charge extraction technique

Yipeng Wu¹, Adrien Badel¹, Fabien Formosa¹, Weiquan Liu¹, Amen Agbossou²

¹ Laboratoire SYMME, Université de Savoie, 74944 Annecy-le-Vieux, France
² Laboratoire LOCIE, Université de Savoie, 73376 Le Bourget du Lac, France

E-mail: yipeng.wu@univ-savoie.fr

Abstract. Optimized synchronous electric charge extraction (OSECE) interface is a load weakly-dependant circuit, which is a favorable characteristic for piezoelectric wideband vibration energy harvesting. However, it introduces synchronous switches that need to be self-powered in a stand-alone system. This paper presents the design and experimental testing of two self-powered approaches for the OSECE technique. One is made of electronic switches driven by analog peak detector circuits; the other uses mechanical switches directly controlled by the ambient vibrations. Finally, advantages and drawbacks of the two approaches will be compared and discussed.

1. Introduction
During the last decade, piezoelectric vibration energy harvesting devices (VEHD) have attracted more and more research attention [1]. They are based on a piezoelectric electrical generator (PEG) that transforms mechanical energy into electrical energy, and an energy extraction circuit (EEC) that extracts and stores the generated energy. Because environmental vibrations have wide frequency spectrums usually with a strong random component, how to broaden the operating bandwidth of the VEHDs is one of the most challenging issues before their practical deployment. Many works aim at developing wide band mechanical oscillator to enlarge PEGs bandwidth [2], while the optimization of the EECs which makes them appropriate to wideband vibrations is still behind.

PEG has its output impedance, to maximize the extracted power, the impedance matching strategy is usually used. However, the piezoelectric output impedance is a function of the vibration frequency due to its capacitive behavior, while most EECs cannot tune their input impedance sensitively. So this strategy is inappropriate to wideband vibrations. The synchronous electric charge extraction (SECE) EEC successfully addresses this impedance matching issue [3], but the switching closing time in this approach needs to be accurately controlled, which makes it hard to operate autonomously in stand-alone VEHDs. For this reason, Wu et al proposed an optimized synchronous electric charge extraction (OSECE) technique that simplifies the switch control strategy [4]. The interface circuit is then easily self-powered. Moreover, the energy conversion of the PEG is also enhanced compared to the SECE technique.

This paper presents two self-powered approaches to drive the synchronous switches in the OSECE circuit. If the switches are realized using metal-oxide-semiconductor field-effect transistors (MOSFETs), two identical peak detector (PKD) circuits are designed to detect the vibration displacement extreme and drive the switches synchronously. The approach does not require any additional piezoelectric elements to generate the switch control signal. However, it introduces a phase...
lag in the control signal and an extra energy consumption to power the PKDs, which reduces the harvested power compared to the ideal case. These effects are particularly studied in the next section. Due to the simple switch control strategy, mechanical switches can also be used to replace the electronic switches in the OSECE EEC. The switches take advantage of the two stoppers and the moving part of the oscillator, so they can be passively controlled by the vibration itself. As a result, the added stoppers in the structure introduce a piecewise stiffness in the oscillating system. This nonlinear stiffness significantly increases the operating bandwidth of the PEG [5]. Finally, both of the approaches are experimentally realized.

2. Self-powered OSECE circuits

2.1. Ideal OSECE circuit

The OSECE EEC is shown in figure 1. A flyback transformer with two primary and one secondary windings splits this interface into two parts: a left part which is used to extracted electric charges; a right part which is a load circuit (a storage capacitor \( C_s \) and an equivalent resistance \( R_s \) represents the input impedance of the following electronic modules).

![OSECE circuit schematic](image)

Figure 1. Schematic of the OSECE circuit

When the piezoelectric voltage reaches a maximum (minimum), the switch \( S_1 \) (\( S_3 \)) is triggered to open, the charges accumulated on the piezoelectric element are then transferred to the primary inductor \( L_1 \) \( (L_2) \). At the moment that all the electric charges have been extracted, as the switch has not been triggered to open, a fraction of the energy stored in the inductor flows back to the piezoelectric element similar to the initial energy injection technique [6]. The injection phase will be finished as soon as the primary diode in series with the closed switch is reverse-biased, the piezoelectric element is open-circuited again. So in the OSECE approach, an accurate switch closing time is not required, it just has to be shorter than half of the vibration period. From reference [4], the harvested power can finally be expressed by equation (1) in the case of a constant vibration amplitude \( u_m \), where \( \omega_I \) and \( Q_I \) are the natural pulsation and the quality factor of the primary \( \{L_1, C_0\} \) oscillating circuit, \( m \) is the turns ratio of the transformer and \( t_m \) is the duration of the energy extraction phase. Although the equation still shows that the harvested power depends on the load resistance, increasing the parameter \( m \) reduces the dependence. For values of \( m \) between 1 and 10, it was shown in [4] that the dependence to the load is strongly reduced compared to the classical standard approach.

\[
P_{\text{ideal}} = \frac{2\alpha^2 \omega}{\pi C_0} \left[ \frac{\sin^3(\omega_I t_m) e^{\frac{\nu_m}{\omega_I}}}{\left(1 + \cos(\omega_I t_m) e^{\frac{\nu_m}{\omega_I}}\right)} \right] u_m^2 \\
\omega_I t_m = \arctan\left(-m \sqrt{\frac{2\pi}{R_s C_0 \omega}} + \pi S\right)
\]

2.2. Electronic self-powered OSECE circuit

If the synchronous switches \( S_1 \) and \( S_3 \) in the OSECE circuit are made up of the electronic switches, due to the simple switch control strategy, two identical analog PKDs whose inputs share the common piezoelectric element are designed to drive them. The EEC is then self-powered, as shown in figure 2.
Two N-channel MOSFETs are selected for $S_1$ and $S_2$. Their low on-state voltage drops do not drastically hinder the quality factor $Q_I$ of the circuit. In addition, MOSFETs are voltage controlled that requires a smaller storage capacitor $C_p$ in the PKD. This characteristic reduces the energy consumption.

Figure 2. Electronic self-powered OSECE circuit (1) Comparator (2) Envelope detector

Figure 3. self-powered OSECE waveforms of the structure displacement $(u)$, piezoelectric voltage $(V)$, voltage across the capacitor $C_p$ $(V_c)$, and switch control signal $(S)$

$$
\varphi = \cos^{-1} \left( 1 - \frac{(V_{\text{max}} - V_u)C_p}{\alpha u_{\text{st}}} \right)
$$

(2)

$$
E_p = \left\{ \begin{array}{ll}
2 + \frac{C_p}{C_o} & \frac{1}{2} C_p V_{\text{max}}^2 \\
\end{array} \right.
$$

(3)

$$
P_{\text{eff}} = \frac{\alpha^2 \omega^4}{2\pi C_o} \frac{\sin^2(\omega t_m) e^{\frac{\alpha \omega}{C_o}}}{1 + \frac{C_p}{C_o} + \cos(\omega t_m) e^{\frac{\alpha \omega}{3C_o}}} u_{\text{st}}^2 \left[ 2 \cos \varphi + \frac{C_p}{C_o} (\cos \varphi - 1) \right]^2
$$

(4)

Figure 3 presents the typical waveforms in the self-powered circuit. The switch control signal $S_1$ ($S_2$) is the output of the positive (negative) PKD. The MOSFET switches will be driven to close as soon as their control signal value is larger than the gate-source threshold voltage $V_{GS(th)}$. Because there exist the threshold voltages of the diode $D_p$ and the BJT $T_p$ in the PKD circuit, the voltage $V_{M}$ just before the energy extraction phase is always lower than the maximal piezoelectric voltage $V_{\text{max}}$, which introduces a switching phase lag compared with the ideal case. Assuming this value is $\phi$, and the difference between $V_{\text{max}}$ and $V_M$ is roughly equal to 1.4V according to the datasheets, $\phi$ can be then expressed by equation (2).

In addition, during the stage 1 shown in figure 3, the small capacitor $C_p$ is charged by the piezoelectric element, the stored energy in $C_p$ will finally dissipated in the PKD circuit. The piezoelectric element in this stage is not in open-circuit condition, the outgoing charge can be
expressed by the approximated value \( C_p V_{\text{max}} \). Considering the difference between the energy stored in \( C_0 \) if the piezoelectric element was in a true open-circuit condition and in the case where the PKDs are connected, the energy consumption in the PKD circuit can be finally evaluated by equation (3).

In the self-powered circuit, the theoretical expression of the energy extraction phase is the same as that in the ideal approach. However, taking into account the phase lag and the additional energy lost, the harvested power is finally given by equation (4). According to the above equations, figure 4 shows the theoretical harvested powers as well as the experimental values. Compared with the harvested power using standard EEC, the load dependency using OSECE techniques is much lower. The discrepancy between the self-powered and the ideal OSECE approaches is due to the above two effects. However, experimental results still confirm the potential of the self-powered OSECE approach.

![Figure 4. Harvested power as a function of the load resistance (plain lines: theoretical results; lines with dots: experimental results. \( m = 0.95, \mu_{sd} = 1.2 \text{mm}, Q_I = 5.5, C_p/C_0 = 0.03 \))](image)

2.3. Mechanical self-powered OSECE circuit

The mechanical self-powered OSECE circuit is shown in figure 5. Most of the time, the piezoelectric element in the structure is in open-circuit condition, when the displacement reaches the bounded stroke, the electric charges accumulated on the PEG reach a maximum. As the tip of the beam hits one of the stoppers, the corresponding mechanical switch is closed. The OSECE EEC begins to extract the energy. After this extraction phase, even if the stopper and the beam are still engaged, the reversed diode will cut off the primary loop circuit. The operation principle is just the same as the ideal OSECE approach. As the mechanical stoppers limit the vibration displacement of the oscillator, the harvested power in this VEHD can also be expressed by equation (1), where \( \mu_{sd} \) roughly equals half of the distance between the two stoppers.

![Figure 5. Mechanical self-powered OSECE circuit](image)

Moreover, from reference [5], the mechanical stopper in the PEG introduce a piecewise stiffness in the oscillating system, which increases the operating bandwidth of the PEG, especially when considering a forward sweep acceleration, as shown in figure 6, where the excited acceleration amplitude is 1g, mechanical damping factors of the beam and the stoppers are both 0.01, their resonance frequencies are 87Hz and 200Hz respectively. First, the beam vibration follows a linear cantilever beam behavior (without stoppers) and increases monotonically from A to B. Then the vibration amplitude reaches the maximal distance and starts to deform the stoppers. The operating bandwidth is significantly extended beyond the original frequency bandwidth. When the excitation

![Figure 6. The frequency response of the oscillating structure](image)
frequency reaches to point D, the motion drops down to point E. Subsequently, the free end of the beam cannot reach the stoppers and follows the frequency response of the linear beam again. Because the mechanical stoppers are the synchronous switches of the OSECE EEC, the theoretical widest energy harvesting bandwidth is from point B to D. When the excitation frequency is not in this bandwidth, the circuit is unable to harvest any energy.

3. Experimentation and discussion
Both of the self-powered circuits are tested on the classical PEG represented in figure 5. The base of the PEG is fixed on a shaker, and the mechanical stoppers can be tuned to adjust the maximal stroke or can be removed. The external acceleration is a forward sweep signal whose frequency interval is [80, 100]Hz and amplitude is 1.2g. Three kinds of the VEHDs are compared in the experiment: linear PEG plus standard EEC, linear PEG plus electronic self-powered OSECE EEC, and nonlinear PEG plus mechanical self-powered OSECE EEC.

Figure 7 gives the experimental results of the three VEHDs. It is clearly shown that using electronic self-powered EEC, the harvested power is always higher than when using the standard EEC. Using the nonlinear PEG, due to the mechanical stoppers, the vibration amplitude around the resonance frequency is limited at the benefit of a wider bandwidth. Moreover, due to the advanced OSECE approach, even if the vibration amplitude is limited, high power can be obtained, especially when the load is larger than 50kΩ.

4. Conclusion
Two self-powered OSECE approaches are proposed in this paper: An electronic self-powered approach as well as a mechanical one. The difference between these self-powered approaches and the ideal case are theoretically analyzed and compared. Finally, advantages and drawbacks of the two self-powered approaches are also given: compared to the electronic self-powered approach, the mechanical switches allow to increase the bandwidth at the detriment of the maximal harvested power.

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