EXPERIMENTAL VALIDATION OF WIDEBAND PIEZOELECTRIC ENERGY HARVESTING BASED ON FREQUENCY-TUNING SYNCHRONIZED CHARGE EXTRACTION
A. Brenes¹, E. Lefeuvre¹ and C.-S. Yoo²

¹Centre for Nanoscience and Nanotechnology (C2N) – Site d’Orsay, Univ. Paris-Sud, Université Paris-Saclay, Bât. 220, Rue Ampère, 91405 Orsay, France
²Electronic Convergence Materials & Device Research Center, KETI, Rep. of Korea
E-mail: alexis.brenes@c2n.universite-paris-saclay.fr

Abstract. This paper reports, for the first time, experimental evidence of the effectiveness of the frequency-tuning synchronized charge extraction technique (FTSECE) for wideband piezoelectric energy harvesting. We also present results proving that, for a single-degree-of-freedom (SDOF) resonator, the theoretical bandwidth of the system is infinite and discuss major practical limitations to that ultimate performance.

1. Introduction

Amongst the topologies based on synchronized switching for piezoelectric energy harvesting, a first technique called “Synchronous Charge Extraction” (SECE) has initially been studied by Lefeuvre et al. [1]. However, this technique is known to yield relatively poor performance for resonators exhibiting a strong electromechanical coupling coefficient. To improve the performance of classical SECE in terms of maximum power and/or bandwidth, recent works have proposed simple modifications to the original circuit [2] [3] [4]. However, to optimize the performances further, one should simultaneously tune the instant and duration of switch closing depending on the oscillation frequency. This last statement has led to the FTSECE technique, shortly described in [5]. No experimental evidence proving its feasibility has been published so far. Moreover, no study has yet determined the analytical solution of the optimal control of FTSECE architectures.

2. System under study

In this paper, we focus on a previously-published architecture [5] where the energy stored in the piezoelectric layer is temporarily transferred to a parallel inductor when a controlled switch S is turned on (see Fig. 1).

Figure 1. Interface circuit used for FTSECE technique [5].

The inductor is chosen so that \( T_{LC} = \frac{2\pi \sqrt{LC}}{} \) is largely inferior to the period of the mechanical oscillations and the charge extraction is supposed to be instantaneous. The generator is a single-
degree-of-freedom linear piezoelectric resonator of stiffness $K$, mass $M$, coupling factor $\alpha$, capacitance $C_p$ and quality factor $Q$, clamped to a base. The displacement of the base is written $y$ and its acceleration $\ddot{y}$. The motion $x$ of the resonator is assumed to be sinusoidal (first-harmonic analysis). The coupled system is described by (1), where $V$ is the piezoelectric voltage and $i$ the current flow at the output of the resonator. The dynamics of the system is given by (1).

$$\begin{align*}
\frac{d^2x}{dt^2} + \frac{\omega_0}{Q} \frac{dx}{dt} + \omega_0^2 x + \frac{\alpha V}{M} &= \frac{d^2y}{dt^2} \\
i &= \alpha \frac{dx}{dt} - C_0 \frac{dV}{dt}
\end{align*}$$

(1)

We also define the electromechanical coupling coefficients $k_m^2 = \alpha^2/KC_p$ and $k^2 = \frac{\alpha^2}{KC_p+\alpha^2}$.

3. Optimal operating conditions of FTSECE

In classical SECE, the charges are extracted from the generator when reaching its maximum voltage until the capacitance of the piezoelectric transducer is fully discharged [3]. Classical SECE has two main drawbacks. First, it does not provide the maximum available power $P_{\text{lim}}$ (see Table I) except for a very specific value of the coupling coefficient ($k^2Q = \pi/4$). Secondly, in the case of strongly coupled generators ($k^2Q > \pi$), the -3dB bandwidth of a classical SECE energy harvester is quite poor compared to other well-known techniques such as linear load adaptation [5]. Two parameters can be controlled in this technique: the voltage drop and the instant of extraction. With the tuning factor $\beta$ and the phase shift $\phi$ defined in Figure 2, the average power extracted from the piezoelectric transducer can be obtained via the method of harmonic balance:

$$P = \frac{16M\gamma^2 1 - \beta}{\pi 8\omega_0 1 + \beta} \left[1 - \Omega^2 + k_m^2 \left(1 + \frac{4}{\pi} 1 - \frac{\beta}{\pi} \sin 2\phi\right)\right]^2 + \left[\frac{\Omega}{Q} + k_m^2 \frac{4}{\pi} 1 + \frac{\beta}{\pi} \cos^2 \phi\right]^2$$

(1)

Figure 2. Typical waveforms in the SECE technique (left) and FTSECE technique (right).

To optimize the harvested power at a given frequency $\Omega$, $\beta$ and $\phi$ must be tuned properly. From (1), the optimal conditions (2) on $\beta_{\text{opt}}$ and $\phi_{\text{opt}}$ leading to the maximal harvested power can be obtained, for instance with a symbolic calculation software (Wolfram Mathematica). Under these conditions, the harvested power is maximum and constant at any frequency, with a theoretically-infinite bandwidth.
\[
\begin{align*}
\phi_{opt} &= -\arctan\left(\frac{Q(1 + k_m^2 - \Omega^2)}{\sqrt{\Omega^2 + Q^2(1 + k_m^2 - \Omega^2)^2}}\right) \\
\beta_{opt} &= \frac{4k_m^2Q\Omega - \pi[\Omega^2 + Q^2(1 + k_m^2 - \Omega^2)^2]}{4k_m^2Q\Omega + \pi[\Omega^2 + Q^2(1 + k_m^2 - \Omega^2)^2]} \\
P(\Omega) &= Q, \quad \forall \Omega
\end{align*}
\]

(2)

4. Experimental measurements and comparison with theoretical predictions

In our setup (see Fig. 6), the piezoelectric energy harvester is composed of a 36x36x0.2 mm³ PZT-5H plate bonded on a 60x37x0.5 mm³ stainless steel plate. This composite plate is clamped to a rigid aluminum base, and a magnetic inertial mass is attached at the free-end of the plate. The control of the switch is operated by a waveform generator delivering voltage pulses two times per period. The mechanical quality factor is \(Q \approx 50\) and the coupling coefficient is \(k^2 \approx 0.042\). The natural frequency is 69.5 Hz. \(L = 150\ \text{mH}\) and \(C_p \approx 100\ \text{nF}\).

Experimental measurements are reported in Fig. 6. They highlight that the -3dB bandwidth of the FTSECE harvester is multiplied by around 3.5 times compared to classical impedance matching.

The FTSECE system bandwidth is theoretically infinite but limited, in practice, by the resistive losses in the circuit (inductor, piezoelectric material, switches, etc.). These losses limit the possibility of voltage inversion through LC-oscillation. Hence, \(\beta\) is bounded by \(\beta_{\text{min}} \leq 0\) which verifies:

\[
\beta_{\text{min}} = -\exp\left(-\frac{\pi}{2} R \frac{C_p}{L}\right)
\]

(3)

where \(R\) is the series resistance of the imperfect inductance (in addition to the usually small resistance of the switch). The evolution of \(\beta_{\text{min}}(L)\) in the case of a piezoelectric resonator with \(C_p = 100\ \text{nF}\) is reported in Figure 4 for commercially-available inductors with volume lower than 1 cm³ (data from [6]). \(\beta_{\text{min}}\) mainly limits the bandwidth of the harvester. In order to optimize the performance of FTSECE, one should use a very small inductance (here lower than 1 mH) to ensure \(\beta_{\text{min}} \leq 0.95\) but this increases the risk of actuating parasitic resonances.
Figure 4. Lower bound of the tuning factor for commercially available inductors (data from [6]). Example for a resonator with $C_p = 100\text{nF}$.

5. Conclusions and future perspectives
The so-called FTSECE technique has been experimentally-validated. For a single-degree-of-freedom (SDOF) resonator, the bandwidth of such a system is theoretically infinite but limited, in practice, by the resistive losses in the circuit (inductor, piezoelectric material, switches, etc.). Diminishing the parasitic resistance by lowering the inductor value would partially solve this problem but increases the risk of actuating high-frequency parasitic modes of the resonator, resulting in additional energy losses. Manufacturing a single-mode resonator to allow the reduction of the inductor losses while avoiding parasitic resonances is the subject of ongoing research.

Acknowledgements
This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20158510060040).

References
[1] E. Lefeuvre, A. Badel, C. Richard, and D. Guyomar, "Piezoelectric energy harvesting device optimization by synchronous electric charge extraction," J. of Intelligent Material Systems and Structures, vol. 16, pp. 865-876, 2005.
[2] E. Lefeuvre, A. Badel, A. Brenes, S. Seok, and C.-S. Yoo, "Power and frequency bandwidth improvement of piezoelectric energy harvesting devices using phase-shifted SECE interface circuit," J. of Intelligent Material Systems and Structures, 2017.
[3] A. Richter et al., "Tunable Interface for Piezoelectric Energy Harvesting," in Systems, Signals & Devices (SSD), 2014 11th International Multi-Conference on, Barcelona, 2014.
[4] P. Gasnier et al., "An Autonomous Piezoelectric Energy Harvesting IC based on a Synchronous Multi-Shots Technique," IEEE Journal of Solid-State Circuits, vol. 49, no. 7, pp. 1561-2014, July 2014.
[5] A. Badel and E. Lefeuvre, "Nonlinear Conditioning Circuits for Piezoelectric Energy Harvesters," in Nonlinearity in Energy Harvesting Systems, E. Blokhina et al., Eds. Cham, Switzerland: Springer, 2016, ch. 10, pp. 353-357.
[6] Farnell. (2017, March) farnell.com. [Online]. http://fr.farnell.com/inductances
[7] A. Badel and E. Lefeuvre, "Wideband piezoelectric energy harvester tuned through its electronic interface circuit," in PowerMEMS, Hyogo, Japan, 2014.
[8] Y. C. Shu and I. C. Lien, "Analysis of power output for piezoelectric energy harvesting systems," Smart Materials and Structures, vol. 15, pp. 1499-1512, 2006.