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Abstract. This paper proposes a simple interface circuit enabling resonant frequency tuning of highly coupled piezoelectric harvesters. This work relies on an active AC/DC architecture that introduces a tunable short-circuit sequence in order to control the phase between the piezoelectric current and voltage, allowing the emulation of a capacitive load. It is notably shown that this short-circuit time increases the harvested power when the piezoelectric operates outside of resonance. Measurements on a piezoelectric harvester exhibiting a large global coupling coefficient (k^2=15.3%) have been realized and have proven the efficiency and potential of this technique.

1. Introduction

The last decade has seen a growing interest in new sustainable energy sources that could replace batteries. Mechanical energy harvesting is a good alternative to solar or thermal generators, since vibrations can be found in closed confined environments. Piezoelectric elements are of particular interest because of their high energy densities and integration potential [1,2].

Piezoelectric Energy Harvesters (PEHs) are relatively efficient when the vibration frequency matches the harvester's resonance frequency. However, environmental excitations are subject to variations that can lead the vibration frequency to shift away from the generator resonance frequency, reducing considerably the efficiency of the PEH and thus the extracted energy [3].

In order to extend the frequency range where a large amount of energy can be harvested, it is possible to dynamically adjust the interface circuit, which has an influence on the harvester due to the electromechanical coupling [4]. In addition to the well-known resistive tuning, it has been recently shown that adding capacitances in parallel of a highly coupled piezoelectric material allows the tuning of the stiffness of the harvester, leading to an adaptation of its resonance frequency. However, this strategy requires the use of a large off-chip capacitive bank that needs to be tuned step by step [5,6].

In this paper, we propose a new solution to emulate a capacitive behavior by short-circuiting the PEH during a tunable time, as shown in figure 1. This enables the control of the phase between the piezoelectric voltage and current, allowing the emulation of a complex load that has a direct influence on the resonance frequency of the harvester. Using this strategy, a continuous tuning of the resistive (R_{in}) and capacitive (φ_2) load is achievable with components that can easily be integrated in a small chip.
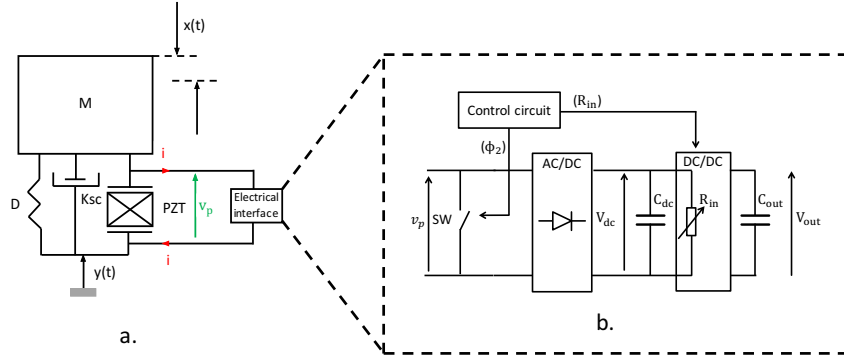
Figure 1. (a) Generic mechanical to electrical conversion model and (b) proposed interface circuit

2. Theoretical analysis

The study of this strategy is derived through a theoretical demonstration that is introduced in the following. The standard mass-spring-damper type PEH model with a single degree of freedom is shown in figure 1. Assuming that the strain of the piezoelectric material is purely sinusoidal, with a constant amplitude ($x(\theta) = X_m \cdot \cos(\theta) = X_m \cdot \cos(\omega t)$), its governing equations are given by (1).

$$\begin{cases} F = M \cdot \gamma = M \cdot \ddot{x}(\theta) + D \cdot \dot{x}(\theta) + K_{sc} \cdot x(\theta) + \alpha \cdot v_p(\theta) \\ i(\theta) = \alpha \cdot \dot{x}(\theta) - C_p \cdot \dot{v}_p(\theta) \end{cases} \quad (1)$$

where F, M, D, K_{sc}, α refer to the driving force, the dynamic mass of the system, the mechanical damping, the global equivalent stiffness and the piezoelectric coupling coefficient respectively. C_p is the dielectric capacitance of the harvester, v_p and i are the piezoelectric voltage and the load current respectively. The expression of the piezoelectric voltage during a half-period is given by (2).
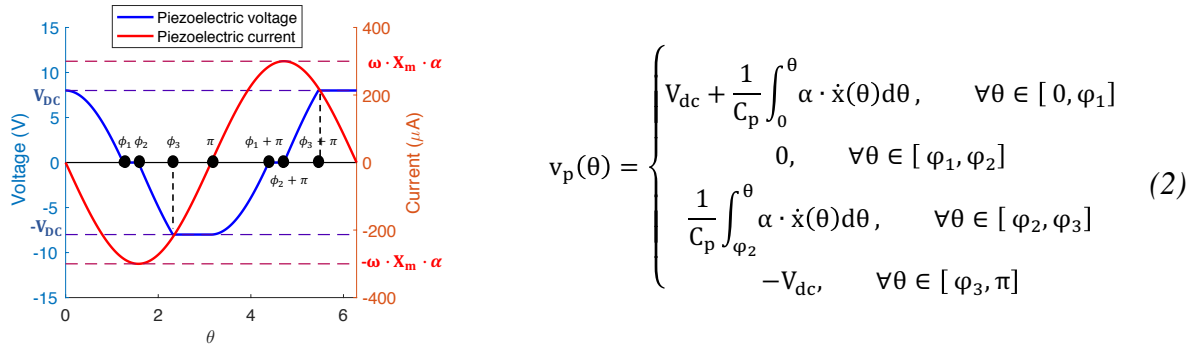

Figure 2. Typical waveforms using the active AC/DC strategy

$$v_p(\theta) = \begin{cases} V_{dc} + \dfrac{1}{C_p} \displaystyle\int_0^\theta \alpha \cdot \dot{x}(\theta)d\theta, & \forall \theta \in [\,0, \varphi_1] \\[2mm] 0, & \forall \theta \in [\,\varphi_1, \varphi_2] \\[2mm] \dfrac{1}{C_p} \displaystyle\int_{\varphi_2}^\theta \alpha \cdot \dot{x}(\theta)d\theta, & \forall \theta \in [\,\varphi_2, \varphi_3] \\[2mm] -V_{dc}, & \forall \theta \in [\,\varphi_3, \pi] \end{cases} \quad (2)$$

Where φ_1 is the angle when the piezoelectric voltage reaches 0 and when the generator should be short-circuited, φ_2 the angle when the short-circuit is opened, φ_3 the angle when the piezoelectric voltage reaches $-V_{dc}$, and V_{dc} the output voltage of the AC/DC rectifier, directly controlled by the input impedance R_{in} of the DC/DC converter. We can express the parameters φ_1, φ_3 and V_{dc} as in (3).

$$\begin{cases} \varphi_1 = \arccos(1 - \dfrac{V_{dc} \cdot C_p}{X_m \cdot \alpha}) \\[3mm] \varphi_3 = \arccos(\cos(\varphi_2) - \dfrac{V_{dc} \cdot C_p}{X_m \cdot \alpha}) \\[3mm] V_{dc} = \dfrac{X_m \cdot \alpha \cdot R_{in} \cdot \omega}{\pi + R_{in} \cdot C_p \cdot \omega} \cdot (1 + \cos(\varphi_2)) \end{cases} \quad (3)$$

From (1), (2) and (3), we can express the Fourier series representation of v_p as a function of φ_2 and R_{in}. The fundamental of this series is given by (4).

$$\begin{cases} \widehat{v_p}(\theta, \varphi_2, R_{in}) = \dfrac{2 \cdot X_m}{\pi}(a(\varphi_2, R_{in}) \cdot \cos(\theta) + b(\varphi_2, R_{in}) \cdot \sin(\theta)) \\ a(\varphi_2, R_{in}) = \dfrac{\alpha \cdot R_{in} \cdot \omega}{\pi + R_{in} \cdot C_p \cdot \omega} \cdot [1 + \cos(\varphi_2)] \cdot [\sin(\varphi_1) + \sin(\varphi_3)] + \dfrac{\alpha}{C_p} \cdot [\dfrac{\varphi_3 + \varphi_1 - \varphi_2}{2} + \\ \qquad \dfrac{\sin(2\varphi_3) + \sin(2\varphi_1) - \sin(2\varphi_2)}{4} - \sin(\varphi_1) + \cos(\varphi_2) \cdot \sin(\varphi_2) - \cos(\varphi_2) \cdot \sin(\varphi_3)] \\ b(\varphi_2, R_{in}) = \dfrac{\alpha \cdot R_{in} \cdot \omega}{\pi + R_{in} \cdot C_p \cdot \omega} \cdot [1 + \cos(\varphi_2)] \cdot [-\cos(\varphi_1) - \cos(\varphi_3)] + \dfrac{\alpha}{C_p} \cdot [\cos(\varphi_1) - 1 + \\ \qquad \dfrac{\sin^2(\varphi_3) + \sin^2(\varphi_1) - \sin^2(\varphi_2)}{2} + \cos(\varphi_2)\cos(\varphi_3) - \cos^2(\varphi_2)] \end{cases} \quad (4)$$

$a(\varphi_2, R_{in})$ and $b(\varphi_2, R_{in})$ are the Fourier coefficients of the piezoelectric voltage's first harmonic. Assuming that only the fundamental of the voltage affects the dynamic mass motion, the differential equation of the piezoelectric system given by (1) can be rewritten in the Fourier domain as shown by (5).

$$F = M \cdot \underline{\ddot{x}}(\theta) + D \cdot \underline{\dot{x}}(\theta) + K_{sc} \cdot \underline{x}(\theta) + \alpha \cdot \widehat{v_p}(\theta, \varphi_2, R_{in}) \qquad (5)$$

Applying the Laplace transform on (5), isolating $\underline{x}(\theta)$, and getting its amplitude X_m, we obtain the expression of the strain amplitude given by (6).

$$X_m = F \cdot [(K_{sc} - M \cdot \omega^2 + \alpha \cdot 2\pi^{-1} \cdot a(\varphi_2, R_{in}))^2 + (\omega \cdot D - \alpha \cdot 2\pi^{-1} \cdot b(\varphi_2, R_{in}))^2]^{-\frac{1}{2}} \qquad (6)$$

The expression of the harvested power transmitted in the DC/DC's input resistance is given by equation (7).

$$P = V_{dc}^2 \cdot R_{in}^{-1} \qquad (7)$$

Combining (3), (6) and (7), we can determine for any parameter couple $(\boldsymbol{\varphi_2, R_{in}})$ the harvested power with this strategy.

3. Experimental results
A PEH having a high electromechanical coupling has been used for the experimental validation of the proposed strategy (figure 3). The characteristics of the PEH are given in Table 1. The experimental setup consists in an electromagnetic shaker that can simulate an input vibration. The cantilever displacement and acceleration are sensed by a laser placed a few decimeters upon the shaker. The piezoelectric device is placed on the shaker and is directly connected to the electrical interface.

Figure 3. Highly coupled piezoelectric harvester

Table 1. PEH parameters

Parameters names	Parameters values	Units
D	0.18	$N.s.m^{-1}$
α	0.0053	$m.s^{-2}$
k^2	15.3%	-
M	5.6	g
K_{sc}	14151	$N.m^{-1}$
R_p	420000	Ω
C_p	11	nF
V_{diode}	0.25	Volts

The experimental results have been compared with the theoretical results, obtained thanks to the computation of the equations (6) and (7), as shown on figure 4. The piezoelectric voltage, the short-circuit control and the piezoelectric system acceleration, respectively in yellow, pink, and blue, can be observed on figure 5.
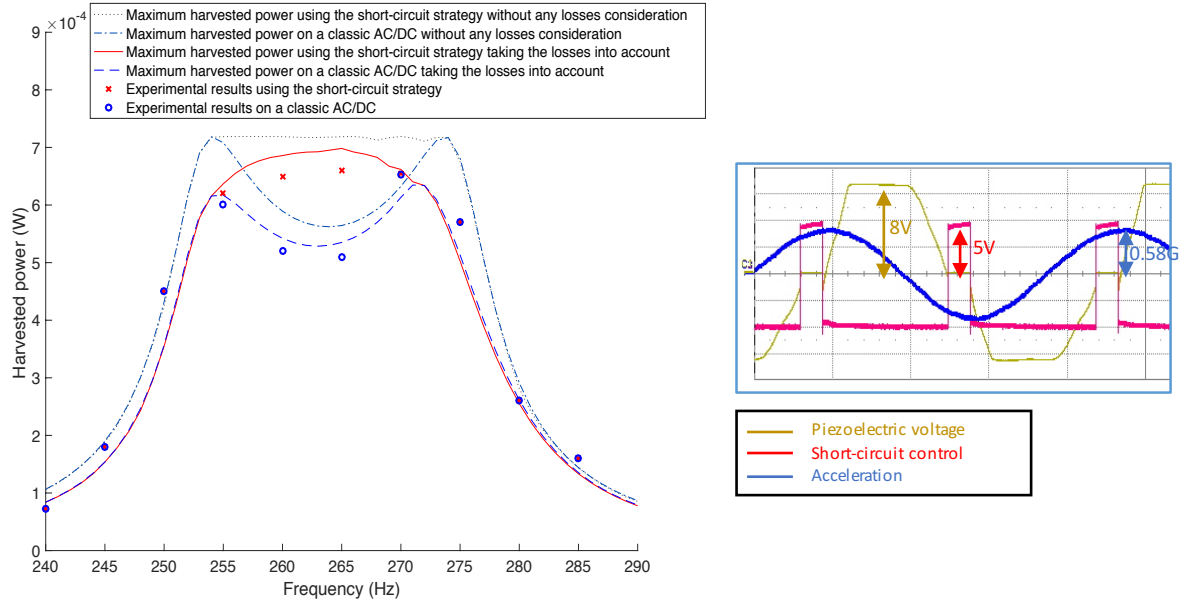
Figure 4. Comparison between theoretical and experimental harvested power

Figure 5. Experimental acceleration and voltage waveforms

4. Discussions

We can observe that the short-circuit technique improves the performances of the PEH between its resonance (253Hz) and anti-resonance (275Hz) frequencies, due to its capacitive effect. Experimentally, under a sinusoidal ambient acceleration γ of 0.58G, we have been able to harvest more than 600μW over a 20Hz bandwidth. In order to take into account the losses in the piezoelectric material ($R_p = 420k\Omega$) and the voltage drops across the diodes ($V_{diode} = 0.25V$), we added these parameters in our theoretical models, as shown on figure 3 and figure 4. In order to reduce these losses, an interface circuit implementing this strategy based on an active AC/DC that includes a short-circuit sequence control should be designed.

5. Conclusion

This paper presents a new interface circuit that can dynamically tune the resonance frequency of a highly coupled PEH. Using an active AC/DC that introduces a short-circuit sequence, this interface is able to synthesize a capacitive load. Through a theoretical analysis and an experimental validation, we proved that this strategy enhances up to 35% the off-resonance performances of the PEH.

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