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# Hybrid synchronized switch harvesting using piezoelectric and electromagnetic conversion

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**Abstract**—In the present work, a preliminary investigation of a hybrid nonlinear energy harvesting scheme based on the coupling of two energy conversion mechanisms is exposed. The proposed approach is derived from the Synchronized Switch technique and consists in combining piezoelectric and electromagnetic transduction. The working principle and preliminary simulations results obtained with the proposed scheme are presented, showing the enhancement of the voltage inversion compared to the sole use of piezoelectric effect.

## I. INTRODUCTION

A strong research effort in recent years has been done to harvest the energy available in the environment and to use it as a power source for wireless sensor nodes. Among ambient energy sources, mechanical vibrations are one of the most prevalent ones. Energy harvesting from vibrations has therefore become a focus of interest, motivated by the increasing use of autonomous sensors and sensor networks. Three main technologies are employed to convert mechanical energy into electrical energy: electromagnetic, piezoelectric and electrostatic energy scavengers thus leading to the concept of vibrational energy harvester. Due to their integration potential and power density, piezoelectric energy harvesters, based on the direct piezoelectric effect, have been widely studied and nonlinear treatments applied to the piezovoltage have been developed in order to enhance the energy conversion [1]. Energy extraction strategies have also been extended to electromagnetic vibration energy harvesters (based on the Faradays's law of induction), such as the nonlinear SMFE (Synchronous Magnetic Flux Extraction) technique, which provides a considerable optimization of the energy transfer irrespective of the load impedance [2]. This paper proposes a new hybrid energy harvesting principle based on the coupling of these two energy conversion mechanisms, with a particular attention to the resulting enhancement of the piezoelectric element output voltage due to the synchronized switching interface.

## II. PRINCIPLES AND THEORETICAL ANALYSIS

### A. Principles

The objective of this section is to expose a theoretical model of the proposed energy harvesting system. The proposed model is derived from the Synchronized Switch nonlinear interface [3] which consists of adding a switching device in series with an inductor to the piezoelectric element. The idea is therefore to convert the inductor from a passive electrical component

to an active electrical system. The general resulting circuit is illustrated in Figure 1 and can be divided into two sub-sections, one corresponding to the piezoelectric (PZT) generator and the second one corresponding to the electromagnetic (EM) generator. The state of the switches S1 and S2 (respectively normally off and on) leads to open and short circuit configurations for the piezoelectric and electromagnetic generators respectively, as it will be explained in section B.

### B. Theoretical Model

Assuming linear elasticity and near resonance conditions, the typical configuration of a vibration energy harvester can be modeled as a second-order system consisting of a modal mass  $M$ , a spring  $K$  and a damper  $D$ .

From an electrical point of view, a piezoelectric generator is equivalent to a current source proportional to the relative vibration velocity  $\dot{u}$  connected in parallel with a capacitor while an ideal electromagnetic generator can be modeled as a velocity depended voltage source in series with an inductor. The constitutive equations of this model are therefore given by:

$$\begin{cases} M\ddot{u} + D\dot{u} + K_e u = F - \alpha V_p - \beta I_m \\ I_p = \alpha \dot{u} - C_0 \dot{V}_p \\ V_m = \beta \dot{u} - L_0 I_m \end{cases} \quad (1)$$

where  $u$  is the displacement of the structure (assumed to be sinusoidal),  $V_p$  and  $V_m$  the piezoelectric and electromagnetic voltages respectively and  $I_p$  and  $I_m$  the piezoelectric and electromagnetic currents respectively;  $\alpha$  and  $\beta$  are the force factors of the piezoelectric and electromagnetic elements respectively;  $C_0$  represents the piezoelectric clamped capacitance and  $L_0$  the inductance of the electromagnetic transducer at rest. The operations of the proposed configuration are described as follows. First, the switch S1 is open and S2 is closed, leading to open circuit condition for the piezoelectric element and

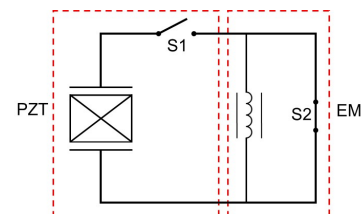


Fig. 1: Circuit schematic

short circuit condition for the electromagnetic element. Under these conditions, the mechanical speed is related to the voltage derivative for the piezoelectric element, following equation (2), and to the current derivative for the electromagnetic element, following equation (3):

$$I_p = 0 \Rightarrow \dot{V}_p = \frac{\alpha}{C_0} \dot{u} \quad (2)$$

$$V_m = 0 \Rightarrow \dot{I}_m = \frac{\beta}{L_0} \dot{u} \quad (3)$$

When the mechanical displacement reaches a maximum or a minimum value, the electronic switches S1 and S2 are briefly turned on and off respectively, so that the piezoelectric element is connected with the electromagnetic element establishing an oscillating electrical L-C circuit. Consequently, a current flow from the piezoelectric element appears as:

$$L\ddot{q} + R\dot{q} + \frac{q}{C_0} = 0 \quad (4)$$

where  $q$  is the charge of the piezoelectric element. Unlike the standard synchronized switch interface (null initial current flow), equation (4) is solved considering  $I_p = I_m$  and  $V_m = V_p$ , leading to the voltage and current oscillation as defined in equations (5) and (6) respectively:

$$V(t) = e^{-\frac{R}{2L_0}t} [V_0 \cos(\omega_0 t) + \frac{I_0}{C_0 \omega_0} \sin(\omega_0 t)] \quad (5)$$

$$I(t) = e^{-\frac{R}{2L_0}t} [-C_0 V_0 \omega_0 \sin(\omega_0 t) + I_0 \cos(\omega_0 t)] \quad (6)$$

where  $I_0$  is equal to  $2\frac{\beta}{L_0}u_m$  and corresponds to the current provided by the electromagnetic element and  $V_0$  corresponds to the maximum output voltage provided by the piezoelectric component ( $V_M$ ). Focusing on the voltage inversion only, in order to achieve a quasi-instantaneous inversion, the switch S1 must be again turned off when the current is null. In the steady-state case, the relation between the output voltage magnitudes before and after the inversion process are given by:

$$\begin{cases} V_M - V_m = 2\frac{\alpha}{C_0}u_M \\ V_m = \gamma V_M \end{cases} \quad (7)$$

where  $\gamma$  is the equivalent inversion coefficient, defined as:

$$\gamma = e^{-\frac{R\pi}{2L_0}} e^{-\frac{R}{2L_0\omega_0} \arctan(\frac{I_0}{C_0 V_M \omega_0})} \sqrt{1 + \left(\frac{I_0}{C_0 V_M \omega_0}\right)^2} \quad (8)$$

therefore possibly higher than the inversion coefficient in the non-hybrid case (that is equal to  $e^{-\frac{R\pi}{2L_0}}$ ) thanks to the contribution of the electromagnetic generator (yielding non-zero initial current condition).

### III. NUMERICAL VALIDATION

As a preliminary validation process, the proposed scheme was analyzed with *Matlab* using Euler's integration method, where the parameter values used for the simulation are 50 nF for  $C_0$ , 30 mH for  $L_0$  and 1 mN·V<sup>-1</sup> for  $\alpha$ . The results obtained are illustrated in Figure 2 depicting the enhancement of the voltage inversion when comparing the piezoelectric element alone and the hybrid configuration (considering  $\beta$  equals to 1

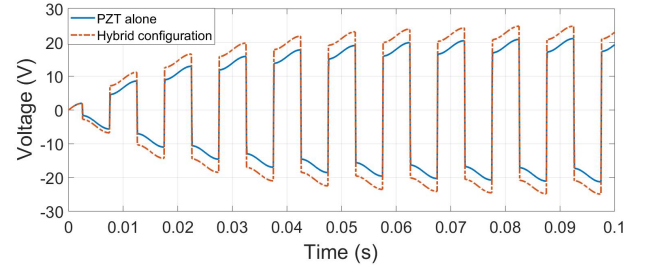


Fig. 2: Voltage waveforms

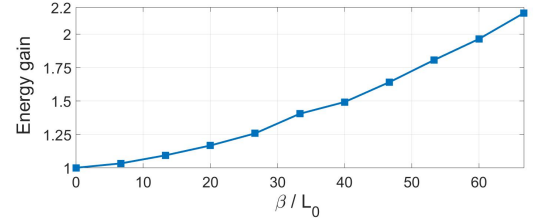


Fig. 3: Converted energy gain

NA<sup>-1</sup>). The corresponding converted energy in these conditions are 11.8  $\mu$ J and 17.5  $\mu$ J for the piezoelectric element alone and the hybrid configuration respectively, allowing a global energy gain of 40%. Increasing the value of the electromagnetic force factor, leads to an increase of the energy gain that can be obtained with the hybrid model, as depicted in Figure 3.

### IV. CONCLUSION

The proposed work, derived from the synchronized switch nonlinear interface, focused on the coupling of two energy conversion mechanisms, combining piezoelectric and electromagnetic transductions. The study has shown an enhancement of the voltage inversion due to the contribution of the electromagnetic generator, thus leading to a gain of 40% in terms of converted energy in the considered example. Further works aim at investigating the enhancement of the current inversion, taking into account the losses of the electromagnetic element, the actual evaluation of the harvested energy and an experimental validation of the proposed model.

### V. ACKNOWLEDGMENTS

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