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Synchronized Switch Harvesting for hybrid energy harvesting systems

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Abstract—In the present work, a hybrid nonlinear interface based on the coupling of piezoelectric and electromagnetic transducers for energy harvesting purposes is exposed. Based on the Synchronized Switch Harvesting on Inductor (SSHI) technique, the proposed scheme aims at including as much as electroactive parts as possible, replacing the passive inductance by an electromagnetic transducer. The working principle and experimental validations are presented, showing the enhancement of the harvested power provided by the active electromagnetic system, when compared to the SSHI and the standard approach.

I. INTRODUCTION

Over the past decades, the development of wireless sensor networks has received a great interest. To supply such sensor nodes, harvesting ambient energy appears to be a key technology for replacing the conventional batteries, going towards the development of autonomous self-powered devices. When dealing with energy harvesting from the nearby environment, radiations, thermal gradients and vibrations are just few examples of potential energy sources. The strong ubiquity and the high power density of mechanical vibrations make these an interesting potential power source for electromechanical systems [1]. Electromagnetic and piezoelectric transductions have been widely exploited to convert ambient vibrations into electrical energy, as they can both reach relatively high power levels with no external electrical source requirement [2]. Due to their integration potential and power density, piezoelectric energy harvesters have been widely studied and nonlinear treatments applied to the piezovoltage have been developed in order to enhance the energy conversion [3]. For instance, Guyomar *et al.* proposed the so-called SSHI technique (Synchronized Switch Harvesting on Inductor), for greatly improving the energy conversion abilities of piezoelectric materials. In such an interface, one can note that the inductor can play an active role if coupled with a permanent magnet that is moving relatively to a coil. Hence, the idea behind the proposed hybrid model is to convert the inductor from a passive electrical component to an active electromagnetic system, leading to the concept of Synchronized Switch Harvesting on ElectroMagnetic system (SSH-EM). The combination of the two energy conversion effects on the same harvesting system induces an enhancement of the output voltage of the piezoelectric element, resulting in a higher harvested energy.

II. PRINCIPLES AND THEORETICAL ANALYSIS

A. Principles

The proposed concept of SSH-EM is derived from the Synchronized Switch nonlinear interface 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 electromechanical system. The general resulting circuit is illustrated in Figure 1. The state of the switches S1 and S2 (respectively normally off and on) leads to normally open and short circuit configurations for the piezoelectric and electromagnetic generators respectively, as it will be explained in the following section.

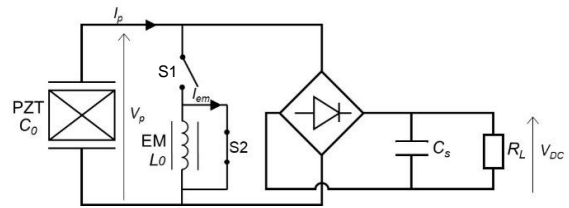


FIGURE 1. CIRCUIT SCHEMATIC

B. Theoretical Model

Assuming linear elasticity, vibrating mechanical structures excited near one of their resonance frequencies can be modeled as a second-order mass (M)-spring (K)-damper (C) system. From an electrical point of view, a piezoelectric generator is equivalent to a current (I_p) source proportional to the relative vibration velocity \dot{u} connected in parallel with a capacitor C_0 while an ideal electromagnetic generator can be modeled as a velocity depended voltage (V_{em}) source in series with an inductor L_0 . The constitutive equations of this model are therefore given by:

$$\begin{cases} M\ddot{u} + C\dot{u} + K^{E,H}u = F - \alpha V_p - \beta I_{em} \\ I_p = \alpha \dot{u} - C_0 \dot{V}_p \\ V_{em} = \beta \dot{u} - L_0 \dot{I}_{em} \end{cases} \quad (1)$$

where u is the displacement of the structure (assumed to be sinusoidal), V_p and I_{em} the piezoelectric voltage and electromagnetic current respectively and α and β are the force factors of the piezoelectric and electromagnetic transducers respectively. 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 short circuit condition for the electromagnetic element. When the mechanical displacement reaches an extremum 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. The switch SI must be again turned off when the current is null. In the steady-state case, the relation between the output voltage magnitudes before (V_M) and after (V_m) the inversion process are given by:

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

where γ_P is the equivalent inversion coefficient, defined as:

$$\gamma_P = \gamma_0 e^{-\frac{r_s}{2L_0\omega_s} \arctan\left(\frac{I_M}{C_0 V_M \omega_s}\right)} \sqrt{1 + \left(\frac{I_M}{C_0 V_M \omega_s}\right)^2} \quad (3)$$

noting that the parameter $\gamma_0 = e^{-\frac{r_s \pi}{2L_0\omega_s}}$ corresponds to the inversion coefficient of the non-hybrid synchronized switching case.

When analyzing the estimated harvested power, constant displacement magnitude of the structure is firstly considered (*i.e.* without considering the electromechanical damping effect in terms of mechanical vibrations). Secondly, the performance of the SSH-EM interface is quantified taking into account this damping effect induced by the energy harvesting process (which is the case of highly coupled and/or weakly damped microgenerators excited by constant acceleration very close to one of their resonance frequencies). Eq. (4) evaluates the harvested power as a function of the displacement magnitude (possibly taking into account the damping effect).

$$P = \frac{V_{DC}^2}{R_L} = \frac{4R_L \alpha^2}{\left[R_L C_0 (1 - \gamma_P (V_{DC})) \omega_0 + \pi\right]^2} \omega^2 u_M^2 \quad (4)$$

III. EXPERIMENTAL VALIDATIONS

When considering constant displacement magnitude, the structure was excited using a shaker yielding a relative displacement of $110 \mu\text{m}$. Fig. 2 shows the harvested power for the SSH-EM, SSHI and standard techniques together with the theoretical predictions. The experimental results show good agreement with the theoretical analysis, demonstrating a power gain to of 10 compared to the maximum harvested power in the standard interface (20% more compared to SSHI).

Experimental results when considering the damping effect, along with the theoretical predictions, are depicted Fig. 3, where the structure is driven at resonance frequency under a constant sinusoidal acceleration of 3.8 ms^{-2} (0.39g). As expected, the SSH-EM technique leads to higher harvested power levels for low-coupled systems, while leading to a power drop for higher couplings because of the combined damping effect between the piezoelectric and electromagnetic transducers.

IV. CONCLUSION

The proposed technique demonstrated how replacing the passive inductance with an active electromagnetic generator leads to a power enhancement, boosting the power gain to a factor of 10 when compared to a standard electrical interface,

with the possibility of increasing this gain by optimizing the energy conversion capabilities of the electromagnetic transducer.

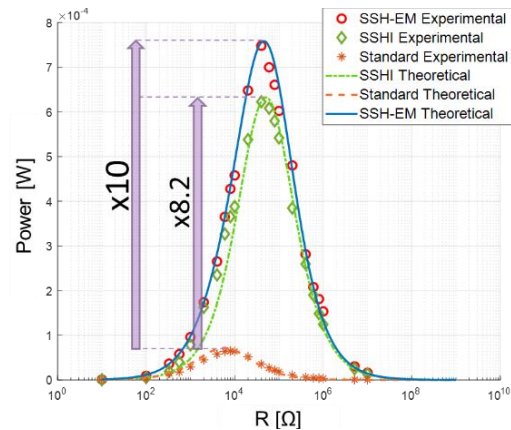


FIGURE 2. EXPERIMENTAL AND THEORETICAL HARVESTED POWER (CONSIDERING AN ADDITIONAL CAPACITOR OF $0.22 \mu\text{F}$ IN PARALLEL WITH THE PIEZOELECTRIC ELEMENT) IN THE CONSTANT DISPLACEMENT MAGNITUDE CASE

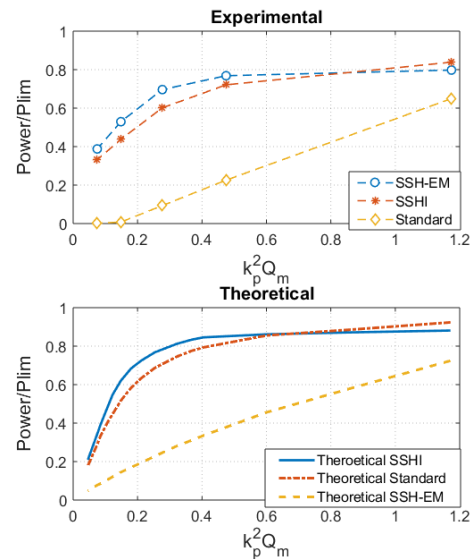


FIGURE 3. EXPERIMENTAL AND THEORETICAL NORMALIZED MAXIMUM HARVESTED POWER (W.R.T. THE POWER LIMIT) FOR EACH TECHNIQUE VERSUS THE SQUARED COUPLING COEFFICIENT AND THE MECHANICAL QUALITY FACTOR

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