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# A Tunable Hybrid SSHI Strategy for Piezoelectric Energy Harvesting with Enhanced Off-resonance Performances

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## Abstract.

In this paper, we propose a new electrical strategy for piezoelectric energy harvesting: the Tunable Hybrid SSHI. This strategy, inspired from the hybrid SSHI of Lallart et al., combines features of the parallel SSHI with a modified series SSHI. We prove analytically and numerically that with a fine combination of those two strategies, the harvesting bandwidth can be sensibly increased. Associated with a high coupling harvester, it is shown that the harvesting bandwidth is 3 times larger compared to the series and parallel SSHI.

## 1. Introduction

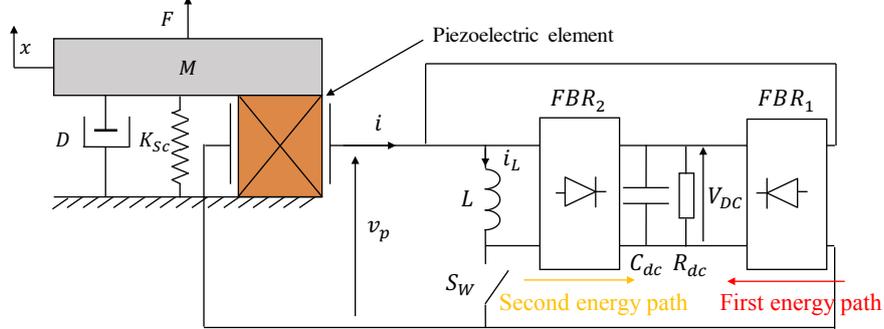
Piezoelectric energy harvesters (PEH) have been widely investigated in the last two decades in order to replace or complement batteries for powering wireless sensor nodes. In order to maximize the extracted energy from such scavengers, the electrical interface is a key point to consider.

The first electrical interfaces that have been proposed consisted in a diode bridge rectifier, followed by a storage capacitance. This interface, called Standard Energy Harvesting (SEH) interface, was easy to implement and did not require any active components. Nevertheless, its efficiency was relatively limited, leading to poor harvesting performances. In 2005, Guyomar et al. established the Synchronous Switch Harvesting on Inductance (SSHI) techniques [1]. Thanks to a nonlinear treatment of the piezoelectric voltage, those techniques exhibited outstanding performances compared to the SEH interface. Thereafter, various improvements of these techniques have been developed: for instance, Junrui et al. proposed to optimize the inversion process thanks to the Synchronized Bias-Flip technique [2]. Lallart et al. proposed the Hybrid SSHI scheme, combining the Magnetic Rectifier SSHI (MR-SSHI) with the parallel SSHI, which greatly improved the robustness of the harvesting interface to load variations [3].

Recently, new electrical interfaces have been proposed to tune the electromechanical resonant frequency of harvesters, and hence to enhance the harvesting bandwidth of the harvesters [4, 5]. In this paper, we propose to model and analyze an extension of the Hybrid SSHI, originally presented in [3]. In order to tune both the electrically induced damping and the electromechanical resonant frequency, we introduce two tuning parameters,  $\beta$  and  $R_{dc}$ , which correspond to the ratio of the voltage after the inversion process divided by the voltage right after the inversion process, and the load connected to the storage capacitance, respectively. The proposed strategy is analytically modelled, simulated, and its performances are finally compared to other SSHI strategies.

## 2. Analytical modelling of the Hybrid SSHI

A linear piezoelectric harvester can be modelled as a single-degree-of-freedom (SDOF) system with an equivalent mass  $M$ , stiffness  $K_{sc}$ , and damper  $D$ , as shown in Figure 1.



**Figure 1.** SDOF electromechanical model connected to the proposed Tunable Hybrid SSHI

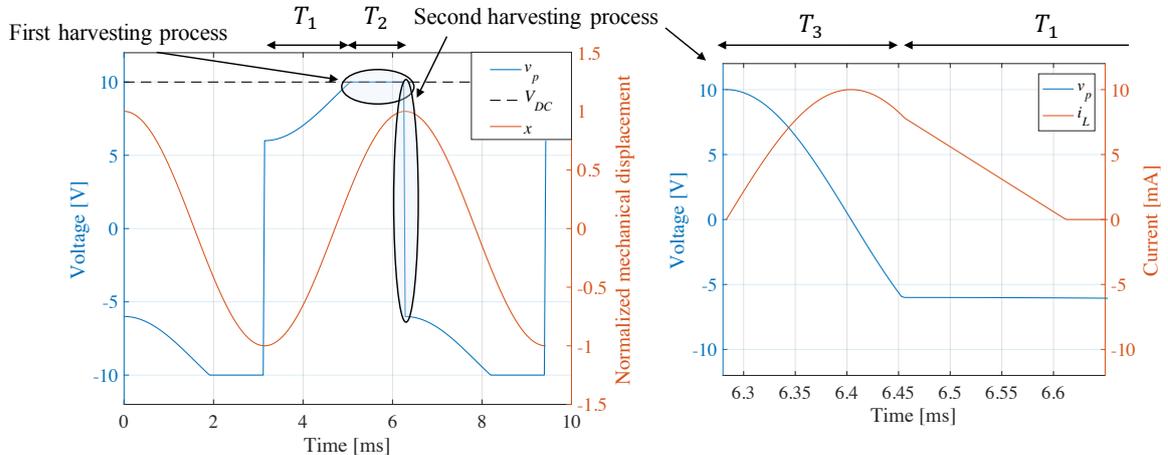
The governing equations of such linear electromechanical system are given by (1).

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

Where  $F$ ,  $i$  and  $v_p$  are the driving force, the current drawn from the piezoelectric material to the electrical interface, and the voltage across the piezoelectric material.  $\alpha$  and  $C_p$  are the force factor and the piezoelectric material capacitance, respectively.  $x$  is the mechanical displacement, and is assumed to be at steady state  $x = X_m \cos(\omega t)$ . In the proposed Tunable Hybrid SSHI, the energy may be harvested in two steps during a single semi-period of vibration. The harvesting process goes as follow:

- In  $T_1$ , the piezoelectric voltage grows as the charges are stored into  $C_p$ , until  $|v_p| = V_{DC}$
- When  $|v_p| = V_{DC}$ ,  $T_2$  starts, and the energy is transferred from the piezoelectric material to  $C_{dc}$  through the Full Bridge Rectifier  $FBR_1$ . This constitutes the first harvesting process.
- As soon as a displacement extremum is reached,  $T_3$  begins.  $S_w$  is closed, forming a LC loop between the piezoelectric material capacitance  $C_p$  and the inductance  $L$ .
- After a parametrizable time, we are back in  $T_1$ .  $S_w$  is opened, and the remaining current in the inductance is then transferred in  $C_{dc}$  through the Full Bridge Rectifier  $FBR_2$ . This constitutes the second harvesting process.

The piezoelectric voltage  $v_p$ , mechanical displacement  $x$  and inductance current  $i_L$  waveforms can be observed in Figure 2.



**Figure 2.** Tunable Hybrid SSHI typical waveforms, with  $V_{DC} = 10V$  and  $\beta = -0.6$

Considering that the harvested energy is equal to the energy dissipated in the resistance  $R_{dc}$  (modelling the power consumption of a sensor node for instance), the relation between the displacement magnitude  $X_m$  and  $V_{DC}$  can be given by:

$$\frac{V_{DC}^2 \pi}{R_{dc} \omega} = - \int_{t_1}^{\frac{\pi}{\omega}} \alpha \dot{x} V_{DC} dt + \frac{1}{2} C_p V_{DC}^2 (1 - \beta)(\gamma + \beta) \quad (2)$$

With  $t_1$  being the instant  $|v_p|$  reaches  $V_{DC}$ . (2) can be rearranged in:

$$V_{DC} = \frac{2 R_{dc} \alpha \omega}{(1 + \beta) C_p R_{dc} \omega + \pi - \frac{\omega}{2} C_p R_{dc} (1 - \beta)(\gamma + \beta)} X_m \quad (3)$$

With  $\omega$  being the vibration's angular frequency.  $\beta \in [-\gamma, 1]$  is the ratio of the voltage right after the inversion process divided by the voltage before after the inversion process.  $\gamma$  is the minimum value of the inversion ratio considering the losses during the inversion process, and is usually approximated by  $\gamma \approx e^{-\frac{\pi}{2Q_I}}$  with  $Q_I$  being the quality factor of the  $L$ - $C_p$  loop [6]. Integrating (1), and applying the energy balance method, extensively detailed in [6] on the parallel SSHI, we eventually find the expression of the displacement magnitude  $X_m$ , as a function of the dimensionless DC voltage  $\overline{V}_{DC} = \frac{C_p V_{DC}}{\alpha X_m}$  and the dimensionless load  $r = R_{dc} C_p \omega$ :

$$X_m = \frac{F}{\sqrt{\left( K_{sc} - M\omega^2 + \frac{\alpha^2}{C_p} \left( 1 - \frac{\pi \overline{V}_{DC}}{2r} \right) \right)^2 + \left( D\omega + \alpha^2 \left( \frac{2}{r} + \frac{(1 - \beta)(1 - \gamma)}{\pi} \right) \overline{V}_{DC}^{-2} \right)^2}} \quad (4)$$

The harvested power can be calculated from (3) and (4) with  $P = V_{DC}^2 / R_{dc}$ . The power expression given by the association of (3) and (4) is only valid when the condition (5) is satisfied.

$$R_{dc} < \frac{2\pi}{\omega C_p (1 - \beta)(\gamma + \beta)} \quad (5)$$

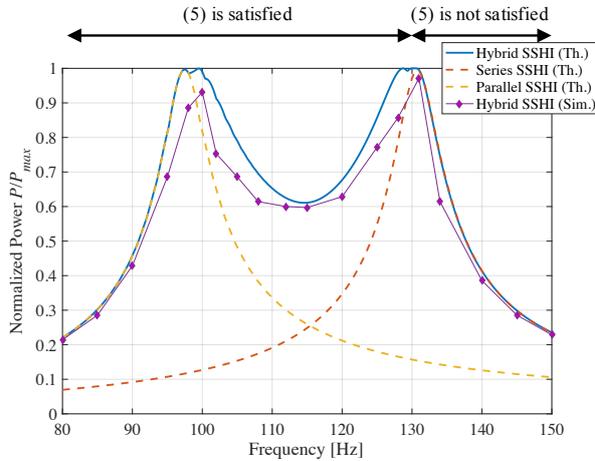
For some values of  $(\beta, R_{DC})$  which do not satisfy the condition given by (5), the piezoelectric voltage  $v_p$  may never reach  $V_{dc}$ . Therefore, the energy is only transmitted through the  $FBR_2$  and the Tunable Hybrid SSHI works similarly as the SECPE presented in [7]. In this case, the harvested power can be expressed as follow:

$$P = \frac{2\alpha^2 F^2 C_p^{-1} (1 - \beta)(\gamma + \beta)}{\left( D\omega + \frac{4\alpha^2 (1 + \beta)}{C_p (2C_p R\omega (1 + \beta) + \pi (1 - \beta))} \right)^2 + (K - M\omega^2 + \alpha^2 / C_p)^2} \quad (6)$$

In the first case, depicted by the combination of (3) and (4), the resonant frequency of the harvester depends on both  $\beta$  and  $R_{dc}$ . In the second case, depicted by (6), the resonant frequency of the harvester is fixed to the open circuit resonant frequency of the harvester.

### 3. Analytical and numerical results

The theoretical equations derived in the previous section have been computed on a highly coupled piezoelectric harvester, whose characteristics are given in [4]. In Figure 3, the theoretical power frequency response of the proposed Tunable Hybrid SSHI is compared with the series SSHI, parallel SSHI, and numerical results obtained from electrical simulations on Cadence (Spectre circuit simulator). Figure 4 shows the optimal couples  $(R_{dc}, \beta)$  as a function of the vibration's frequency.



**Figure 3.** Tunable Hybrid SSHI analytical and numerical power frequency responses for the PEH used in [4].

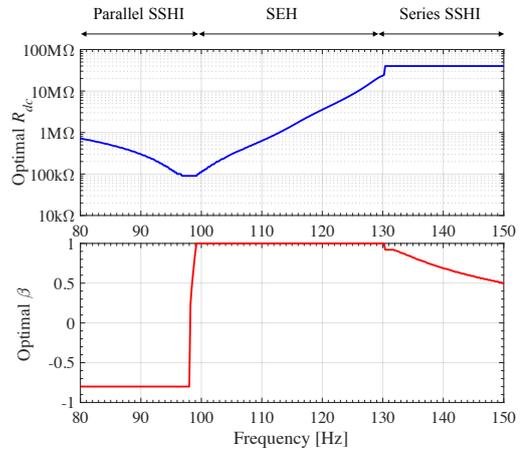
From Figure 4, it can be observed that, depending on the vibration's frequency, the hybrid SSHI behaves differently. When the vibration's frequency is smaller than the short-circuit resonant frequency of the harvester, it behaves similarly as a parallel SSHI, with  $\beta = -\gamma$ . When the vibration's frequency is higher than the open-circuit resonant frequency of the harvester, the hybrid SSHI behaves as a Series SSHI. When the vibration's frequency lies between the short-circuit and open-circuit resonant frequencies, the hybrid SSHI behaves similarly as a SEH interface, with  $\beta = 1$ . As shown in Figure 3, the harvesting bandwidth of the hybrid SSHI is approximately 3 times larger than the harvesting bandwidth of SSHI interfaces.

#### 4. Conclusion

In this paper, we introduce a new electrical strategy, the Tunable Hybrid SSHI, inspired from the hybrid SSHI [3]. We prove through analytical and numerical analysis that this technique allows to drastically enhance the harvesting bandwidth compared to the Series and Parallel SSHI. A thorough comparison of this strategy with other recently proposed tunable techniques is currently being studied.

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**Figure 4.** Optimal  $(R_{dc}, \beta)$  maximizing the harvested power as a function of the vibration's frequency