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Comparison of Energy Extraction Circuits for Bistable Piezoelectric Energy Harvesters

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Abstract—The present work focuses on ambient vibrations energy harvesting. Specifically, this article deals with bistable piezoelectric energy harvester. In order to rectify the piezoelectric voltage and to supply power to autonomous sensors, these systems require an energy extraction circuit. As an interesting feature, energy extraction circuits allow to increase the harvested power and bandwidth of piezoelectric energy harvester. However, depending on the energy extraction circuit, the performance gain and the useful voltage and frequency range can be limited. The present work compares the performances of various energy extraction circuits, depending on the supply voltage and the operation frequency. Such analysis reveals that a hybrid energy extraction circuit combining features of existing circuits could be particularly relevant for bistable piezoelectric energy harvesters.

Keywords—Piezoelectric energy harvester, nonlinear systems, vibrations, harvesting circuit, power management.

I. INTRODUCTION

For the past decades, there has been a growing interest for energy harvesters that could replace or complement batteries, for powering low-power electronic systems. In order to convert ambient vibrations into electrical energy, bistable piezoelectric energy harvesters (PEH) have been widely investigated [1]. Bistable PEH, as long as they operate on their high-energy orbits, combine high harvested power with large harvesting bandwidth [2][3]. Moreover, bistable PEH need an energy extraction circuit (EEC) to extract electrical energy and rectify the piezoelectric voltage. Different EECs have been proposed in the literature [4]. Among the different EECs that have been proposed, synchronized switch circuit have been widely investigated [5]. These EECs are an important part of any energy harvesting system and need to be carefully optimized in order to maximize the harvested power and the bandwidth of bistable PEH. However, these studies do not consider the existence of the high-energy orbit since they focused on linear PEH. In this work, we propose an analytical study of the harvested power as a function of the supplied voltage and the frequency in order to evaluate the interest of a hybrid EEC for bistable PEH.

II. MODELLING

In order to extract the electrical energy from the piezoelectric transducer, the PEH needs an energy extraction circuit. Various well-known EEC are described in the literature [4]. This study focuses on four of them: the standard energy harvesting (SEH), the parallel synchronous switch harvesting on inductor (P-SSHI), the serial synchronous switch harvesting on inductor (S-SSHI) and the synchronous electric charge extraction (SECE). Depending on the EEC, a specific processing is applied on the piezoelectric voltage v_p leading to different expressions of the rectified voltage V_{dc} . As presented in [6], the

electrical charge extracted from the piezoelectric transducer on a half period of the piezoelectric voltage corresponds to the electrical charge flowing through the load R and the switching device and can be expressed as:

$$\int_0^{\frac{T}{2}} i_p dt = \frac{V_{dc} T}{R} + \int_0^{\frac{T}{2}} i_{switch} dt \quad (1)$$

Note that the SEH does not have any switching device ($i_{switch} = 0$). Therefore, the electrical charge extracted from the piezoelectric transducer on a half period of the piezoelectric voltage corresponds to the electrical charge flowing through the load. The rectified voltage V_{dc} can be expressed as a function of the load R , the piezoelectric capacitance C_p , the piezoelectric force factor α and the displacement amplitude x_m :

$$\begin{cases} V_{dc_{SEH}} = \frac{4R\alpha\omega x_m^2}{L\left(2RC_p\omega + \frac{\pi}{2}\right)} \\ V_{dc_{P-SSHI}} = \frac{8R\alpha\omega x_m^2}{L\left(2RC_p\omega(1-\chi) + \pi\right)} \\ V_{dc_{S-SSHI}} = \frac{8R\alpha\omega x_m^2(1+\chi)}{L\left(4RC_p\omega(1+\chi) + \pi(1-\chi)\right)} \end{cases} \quad (2)$$

In (2), χ is the voltage inversion ratio induced by the inductor L of the switching device. The harvested power is simply expressed as:

$$P_h = \frac{V_{dc}^2}{R} \quad (3)$$

III. RESULTS AND DISCUSSION

Fig. 1 illustrates the harvested power as a function of the supplied voltage for the SEH, the SECE, the P-SSHI and the S-SSHI circuits with a vibration frequency $f_{vib} = 32$ Hz.

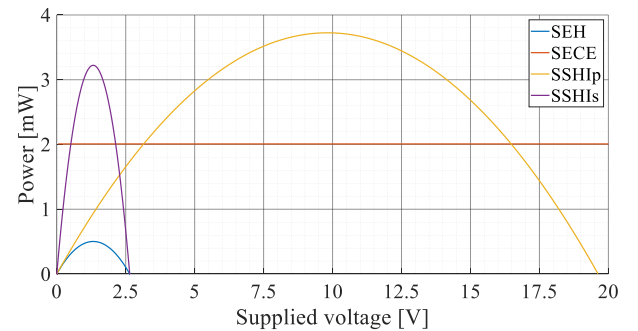


Fig. 1. Harvested power as a function of the supplied voltage for the SEH (blue line), the SECE (red line), the P-SSHI (yellow line) and the S-SSHI (purple line), with $f_{vib} = 32$ Hz.

The supplied voltage range for the SEH and the S-SSHI circuits is around 2.6 V. However, the maximum harvested power is higher with S-SSHI circuit (3.2 mW) than with the SEH circuit (0.5 mW). Note that for both circuits, the maximum harvested power is reached with a supplied voltage of 1.3 V. As illustrated in Fig. 1, both the P-SSHI and the SECE circuits considerably increase the supplied voltage range. However, even if the voltage range is increased, the SECE circuit exhibits a lower harvested power. Moreover, the latter is constant regardless of the supplied voltage. As a matter of example, the harvested power with the SECE circuit is 2 mW for the whole voltage range whereas it reaches a maximum of 3.7 mW with a supplied voltage of 9.7 V with the P-SSHI circuit. Fig. 1 has been obtained considering that the bistable PEH remains on the high-energy orbit. However, bistable PEH exhibit a specific frequency for which the high-energy orbit suddenly disappears, which needs to be considered for assessing the performance of a given EEC [1].

Fig. 2 illustrates the harvested power as a function of the supplied voltage for the SEH, the SECE, the P-SSHI and the S-SSHI circuits with $f_{vib} = 32$ Hz, when considering the existence of the high-energy orbit of the bistable PEH. Plain lines represent the supplied voltages for which the high-energy orbit exists. Unlike plain lines, dash lines represent voltages for which the high-energy orbit no longer exists. It is shown that the useful supplied voltage range is considerably reduced compared to Fig. 1 which does not consider the high-energy orbit. As a matter of example, the voltage range of the S-SSHI circuit is 0.9 V instead of 2.6 V when not considering the existence of the high-energy orbit. Like the S-SSHI, the voltage range of the P-SSHI is from 0V to 9.4 V instead of 0V to 19.6 V when not considering the existence of the high-energy orbit. Note that the voltage range of the SEH and the SECE circuits are not affected since the high-energy orbit always exists under a vibration frequency $f_{vib} = 32$ Hz and an acceleration amplitude $\gamma_m = 10$ m.s⁻².

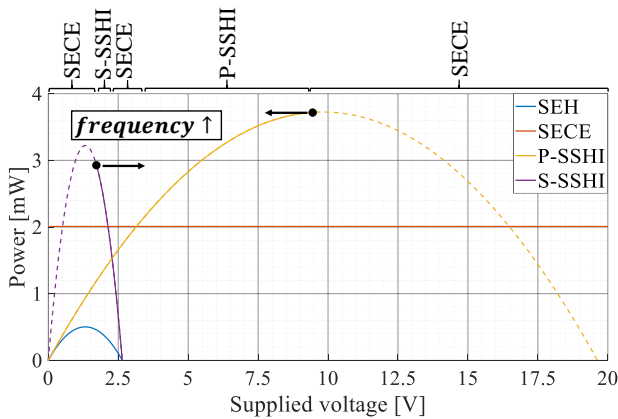


Fig. 2. Harvested power as a function of the supplied voltage for the SEH (blue line), the SECE (red line), the P-SSHI (yellow line) and the S-SSHI (purple line), with $f_{vib} = 32$ Hz, $\gamma_m = 10$ m.s⁻² and the existence of the high-energy orbit.

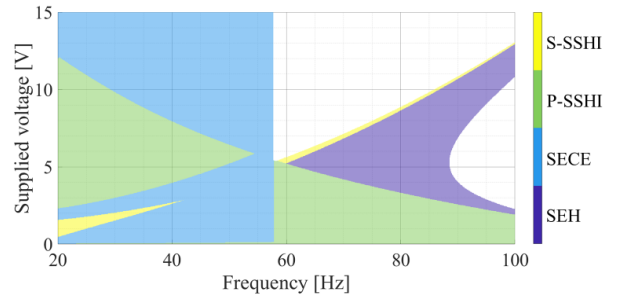


Fig. 3. EEC Range of Interest (RoI) as a function of the frequency and the supplied voltage with $\gamma_m = 10$ m.s⁻².

Fig. 3 illustrates the Range of Interest (RoI) of each circuit. The RoI is defined as the frequency and voltage range for which the harvested power of an EEC is greater than the harvested power with any other presented EEC. The RoI thus allows to select the right operating mode of a hybrid EEC in order to maximize the harvested power with any vibration frequency and voltage in the storage element. As a matter of example, with $f_{vib} = 32$ Hz and $\gamma_m = 10$ m.s⁻², the operating mode sequence should be the following: *SECE* > *S-SSHI* > *SECE* > *P-SSHI* > *SECE*, as the voltage in the storage capacitor increases.

IV. CONCLUSION

In the present work, the harvested power has been studied as a function of the supplied voltage and the frequency. Analytical results demonstrate the interest of a hybrid EEC in order to increase the harvested power. Moreover, the RoI allows to select the right operating mode of a hybrid EEC depending on the supplied voltage and the vibration frequency. These preliminary results will be used for the development of maximum power point tracking algorithm and hybrid EEC for bistable PEH.

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