Inductorless impedance matching strategy using multiple capacitance configurations

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***Abstract*—This paper presents a way to realize impedance matching for piezoelectric harvesters. This strategy is based on a capacitive network that can tune the output voltage of a diode bridge rectifier. The interface and its control have been validated in simulation using Cadence, and they allow to implement an impedance matching strategy without using an inductor.**

I. Introduction

Small-scale Piezoelectric Energy Harvesters (PEHs) has received a particular attention during the last decade, due to their potential to replace batteries to power sensor nodes and electronic devices [1, 2]. The main goal of the harvesting circuit is to extract the maximum power from the piezoelectric element. Impedance matching between the generator and the load is a classical approach to optimize the energy transfer [3]. This is usually done by using a DC/DC converter whose duty cycle is dynamically adjusted [4]. This solution however requires a bulky inductance. In this paper, we propose an impedance matching strategy based on a fully capacitive network, leading to a miniaturized solution with less complexity and switching losses.

II. Impedance Matching Theory Applied to PEHs

A. Piezoelectric energy harvester modeling

A constant amplitude sinusoidal deformation of the piezoelectric element implemented in a piezoelectric generator is considered. In this case, the piezoelectric generator can be modeled as a perfect current source in parallel with a capacitance C_p representing the ability of the piezoelectric material to store charges [3] (Fig.1). The current i_p is sinusoidal and can be expressed as $i_p = I_p \cdot \sin(\omega t)$, with ω being the pulsation of the harvested vibrations, and I_p the current amplitude, which is a function of the mass displacement amplitude, of the vibration frequency, and of the coupling between the mechanical and electrical parts of the system.

B. Standard harvesting circuit

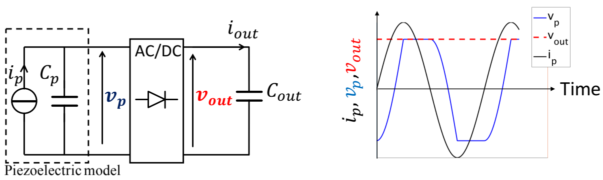

Fig. 1. Standard interface circuit for vibrations harvesting

Neglecting the diode threshold voltages, the diode bridge starts conducting when the absolute piezoelectric voltage $|v_p|$ becomes equals to v_{out}, and stops conducting when the current polarity changes. Hence, the energy transfer is highly dependent on the value of v_{out}. If v_{out} is too low, the diode bridge conducts almost all the time. However, because of the small value of v_{out}, the amount of energy transferred during a period is quite low. In another hand, if v_{out} is too large, the conduction time of the diode bridge is very small, also leading to low harvested energy. Hence, there is a trade-off between the time of conduction of the diode bridge and the voltage v_{out} under which the energy transfer is done.

C. Maximum power point (MPP)

In order to find the MPP, meaning the voltage v_{out} maximizing the energy transfer, we have to analyze the circuit shown in Fig.1. The harvested power using the classical diode bridge is given by (1).

$$P_{harvested} = \frac{2v_{out}}{\pi}(I_p - v_{out}C_p\omega) \quad (1)$$

$P_{harvested}$ is maximized when v_{out} is equal to half of the peak open circuit voltage of the piezoelectric element as shown on Fig. 2 and expressed by (2).

$$(v_{out})_{opt} = \frac{(v_p)_{open}}{2} = \frac{I_P}{2C_p\omega} \quad (2)$$

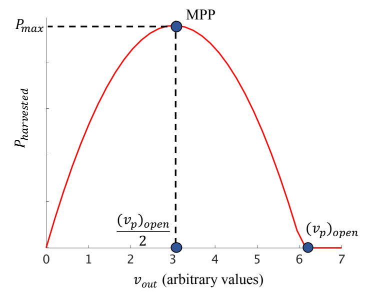

Fig. 2. Harvested power $P_{harvested}$ as a function of v_{out}

The standard way to force v_{out} to its optimal value is to connect a DC/DC converter to the capacitor C_{out} and to control its duty cycle in order to tune its input impedance and hence its input voltage v_{out} [3,4]. However, it requires a bulky inductor, and adds high frequency switching losses and conduction losses that can considerably reduce the harvested energy.

III. Proposed Strategy – Inductorless Impedance Matching

A. *Description of the strategy*

Instead of using a DC/DC converter, we propose to periodically modify v_{out} by adapting the output capacitance C_{out}. The electrostatic energy E_c stored in C_{out} can be expressed as (3).

$$E_c = \frac{1}{2} C_{out} v_{out}^2 \tag{3}$$

We can conclude, as shown by (4), that for a certain amount of energy stored in C_{out}, there exists an optimal output capacitor value that fixes v_{out} to its optimum value, leading to an optimal energy transfer from the piezoelectric harvester to the storage capacitor.

$$(v_{out})_{opt} = \frac{(v_p)_{open}}{2} = \sqrt{\frac{2E_c}{(C_{out})_{opt}}} \tag{4}$$

Hence, if we want to adjust the output capacitor value, we should increase it as the energy is stored in order to maintain the system to its MPP. Fig.3 and Fig.4 introduce the example of an "output voltage path" using 6 capacitances C_{unit} of $600nF$.

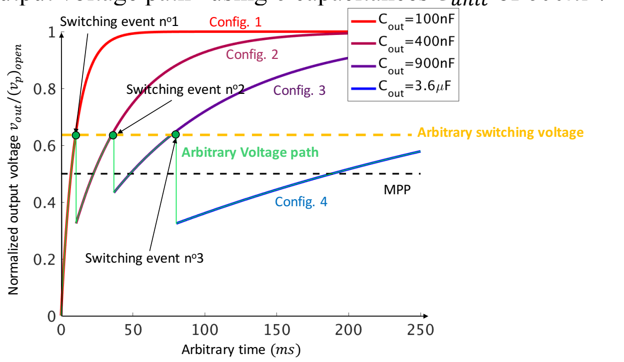

Fig. 3. Arbitrary voltage path with four arbitraries capacitances values

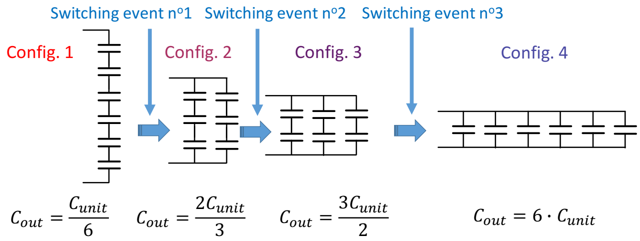

Fig. 4. Possible configurations of the capacitive network with 6 capacitances

As shown on Fig.3 and Fig.4, the voltage rises quickly with the smaller capacitance configuration. When the voltage reaches $0.65 * (v_p)_{open}$ (arbitrary value taken as an example), the capacitive network configuration is changed (from Config. 1 to Config. 2), leading to an increase of the equivalent capacitance C_{out} and a decrease of the voltage v_{out}. Then, the voltage starts rising again (more slowly due to the increased capacitance) until the next switching event. The losses induced by the switching events are negligible as long as the 6 capacitances C_{unit} are the same.

B. *Simulation of the strategy*

We simulated the proposed strategy on Cadence, with $C_p = 10nF$, $I_p = 100\mu A$, $\omega = 1665\ rad.s^{-1}$ and 6 identical $600nF$ capacitances. The control is done using voltage comparators with a pre-programmed switching value of approximately 65% of $(v_p)_{open}$. The energy accumulated E_c in the output capacitances can be shown on Fig. 5. We can notice that the energy accumulated during $250ms$ is 131% more important than with the 6 capacitances connected in parallel without switching ($3.6\mu F$), and way more important than with any other fixed connection pattern of the 6 capacitors. The performances of this strategy can be maximized by increasing the number of capacitances used in the network, and by choosing optimal switching voltages.

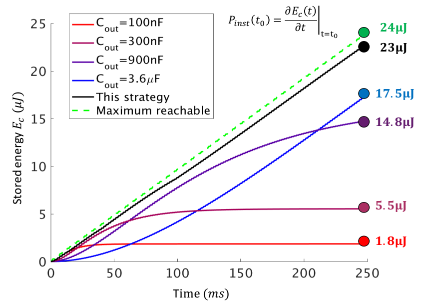

Fig. 5. Accumulated energy comparison between standard interfaces and our proposed strategy

IV. Conclusion

In this paper, we presented a MPP strategy for piezoelectric harvesters. This strategy allows, through a discrete tuning, to work most of the time around the optimal voltage v_{out} without any inductance nor high frequency switching transistors. This strategy could be extended to other harvesters such as solar panels, thermoelectric generators or biofuel cells, since they also require a MPP tracking to deliver their maximum power.

In the future, we would like to adapt this kind of impedance matching strategy to other vibrations-based energy harvesting strategies such as SSHI (Synchronized Switch Harvesting on Inductance) interfaces.

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