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Resistive short-circuit (RSC) strategy for wideband piezoelectric energy harvesting

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Abstract—This paper introduces a new energy harvesting technique dedicated to highly coupled piezoelectric energy harvesters (PEH). This harvesting technique is useful to compensate for the mismatch between the input frequency and the resonant frequency of the PEH, enabling impedance matching. The proposed extraction technique, called “Resistive Short-Circuit” technique (RSC) is similar to the “Resistive Capacitive” technique (RC) in terms of bandwidth and power performances when applied to highly coupled PEHs. In this paper, we validate the implementation of the RSC technique. The power output of the RSC technique matches the RC one. However, the space requirement is greatly reduced, as only two NMOS are needed versus a full capacitor bank. Optimal parameters of the RSC model match the experimental ones in term of short circuit duration and optimal load.

Keywords—Piezoelectric Energy Harvesting, Interface Circuit, Short-circuit control

I. INTRODUCTION

Vibrational energy harvesting has emerged as a promising technology for powering small electronic devices. However, the unpredictable nature of ambient vibrations and conditions presents a significant challenge in efficiently converting this energy into usable electrical power. One of the main remaining locks is to guarantee the operation of the harvester at the Maximum Power Point (MPP) over a wide frequency band [1].

Several solutions to enlarge the power bandwidth have been investigated in the state of the art. Mechanical systems with several resonant frequencies have been used but their power density are often very low. Resonant frequency tuning is also used. It can change the stiffness of the harvester by several possible ways: mechanical, piezoelectric or electrical. In this article, we focus on the electrical resonant frequency tuning techniques. Indeed, it has been proven [2] that when used with very low power electronics and efficient extraction techniques, they enable an increase of the power density of the overall system (no need for bulky actuators). It is based on highly coupled piezoelectric structures, i.e. structures for which a modification of the electrical load will have a significant impact on the mechanical dynamics of the system.

SECE based techniques like FTSECE [3] or SCSECE [4] are among the techniques with the highest power envelope [2]. These techniques rely on the resonant transfer of all the energy of the piezoelectric capacitance to an inductor. The quality factor of this inductance should be high to mitigate the resistive losses but it lowers the response time of the associated electronics, which then increases the power consumption [5]. Techniques with a smaller power envelope like SC-SEH [6] do not suffer from this problem as it often relies on load emulation thank to a DC/DC converter. In this case, the constraint on the inductor’s quality factor is less

important but the electrical transients increase due to the charging of a large storage capacitor. RC techniques are a bit better in term of power and convergence time but they need many discrete capacitors [1]. In this paper, we propose a piezoelectric harvesting technique that has a power envelope similar to the RC technique, that does not need a fast response time (like SECE based interfaces), is more space efficient than the RC technique and faster than the SC-SEH technique. This extraction technique is associated to a Microcontroller Unit (MCU)-based MPPT algorithm for highly coupled PEH that has previously been published [7].

II. RESISTIVE SHORT-CIRCUIT TECHNIQUE

Contrary to the RC technique which connects a bank of capacitors and resistors, the proposed RSC technique performs a variable duration short-circuit (emulating the capacitive effect) and drive a DC-DC converter (emulating the variable resistive load) at the same time. It has already been shown in the state of the art that applying short-circuits can emulate a capacitive load [6]. However, our work is based on the resistive technique (R) only and not the SEH technique (with a rectifier capacitor), hence, we do not have to wait for long electrical transients. It is useful to analytically describe the equivalent loads applied by the technique to the PEH, like it is done in [2]. This way we can estimate the power output versus frequency or calculate the optimal loads. We have come with such a model but the description of the analytical model is not in the scope of this paper.

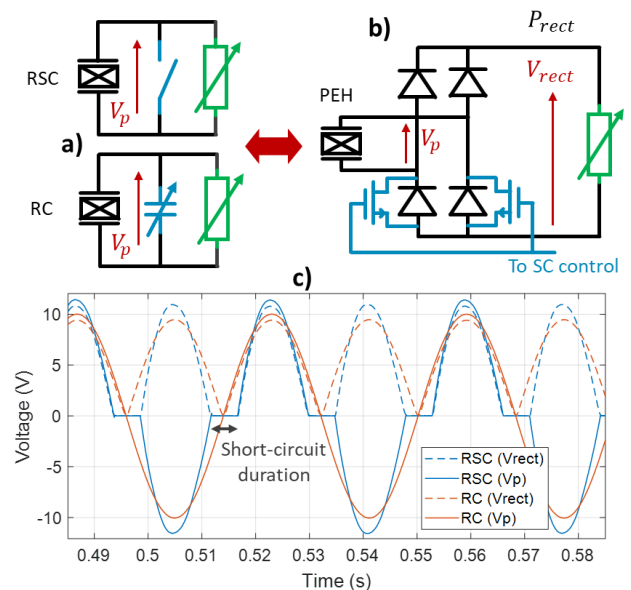


Fig. 1. a) RC and RSC techniques concept and b) possible implementation for the short-circuit with two NMOS and c) theoretical waveforms (RSC vs RC) for the same RMS voltage

Fig. 1 shows the concept of the RSC technique and the proposed implementation. Two NMOS at the bottom of the full bridge rectifier enables the short circuit. This short-circuit implementation is an interesting way to perform the short circuit of the PEH with discrete electronics since the two MOS sources are grounded, simplifying their control. In our work, a Flyback converter in discontinuous conduction mode replaces the variable resistive load, allowing the energy transfer on a storage capacitor as in [7].

III. MEASUREMENTS AND RESULTS

The operation of the RSC technique has been tested thanks to a dSPACE platform (DS1103) coupled with Matlab. A variable resistor box was used to emulate different resistive loads. The short circuit was controlled by a microcontroller and other discrete electronics not shown on Fig. 1. A power amplifier is connected to a shaker to control the ambient vibration amplitude and frequency connected to the PEH. The dSPACE platform was used to send information to the different instruments (decade box, MCU and amplifier) to test several conditions of frequency [25.5 – 30 Hz], short circuit duration [0 – π rad] and resistive loads [2k Ω – 10M Ω] at the same acceleration amplitude (0.5 m/s²). The test bench is the same as in [7]. The PEH used in this paper is a PMN-PT-based device presented in [8] and whose characteristic parameters are given in TABLE I.

TABLE I. LINEAR MODEL OF USED PEH

Piezoelectric capacitance (C_p)	41.9 nF
Effective mass (M)	15.2 g
Short-circuit resonant frequency (f_{sc})	26.9 Hz
Spring constant (K)	434.2 N/m
Damping coefficient (D)	33.8 mN/m/s
Electromechanical coupling coeff. (k_m^2)	13 %
Acceleration amplitude for tests (a)	0.5 m/s ²

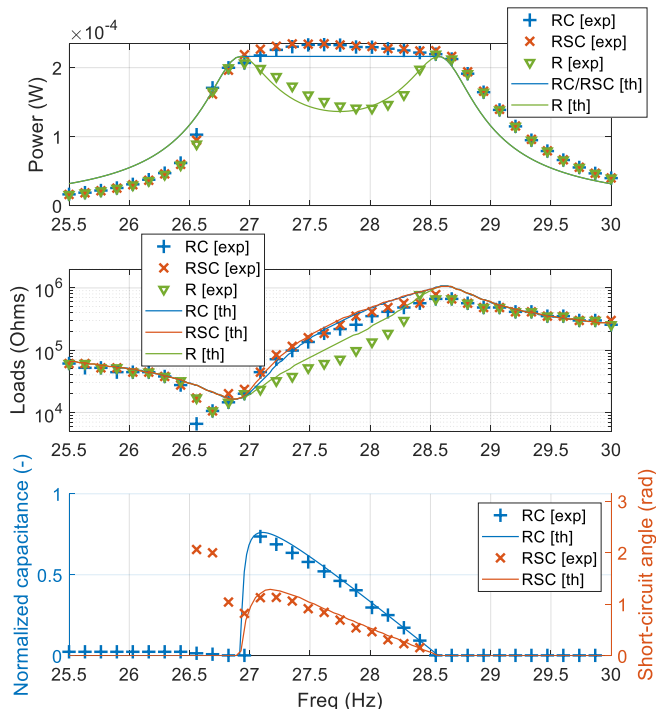


Fig. 2. Comparison between RC and RSC technique at 0.5 m/s²

The performance of the RSC technique is illustrated in Fig. 2. It is compared with the results for the R and RC technique. The power response shows non-linear characteristics due to the piezoelectric material (PMN-PT).

We can see here that in term of power, the RSC technique is close to the RC technique. The experimental optimal resistive load parameters do not perfectly match the theoretical ones, but we are fitting here a linear model on a non-linear PEH, which explains the differences. The experimental optimal resistive loads for RC and RSC are close both experimentally and theoretically. Concerning the experimental short-circuit angle, it is close to the theoretical one. Some values of the short circuit angle are experimentally far from the theoretical ones before the short circuit resonant frequency (around 27 Hz) but it was verified that the power measurements without short circuit are close which is consistent with the model.

IV. CONCLUSION

In this paper, we proposed and validated a new energy harvesting technique, the RSC technique, which is similar in term of power and bandwidth to the RC technique but with less space requirements. Indeed, this technique only needs two MOS at the bottom of the full bridge rectifier versus a full bank of discrete capacitors for the RC technique. The power output matches the power output of the RC technique.

A next step will be to integrate this energy harvesting technique into a complete architecture with a DC/DC converter and an MPPT algorithm.

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