DE GRUYTER Energy Harvesting and Systems 2014; 1(3-4): 197–208

Mickaël Lallart*, Claude Richard, Yang Li, Yi-Chieh Wu and Daniel Guyomar

Load-Tolerant, High-Efficiency Self-Powered Energy Harvesting Scheme Using a Nonlinear Approach

Abstract: Small-scale energy harvesting has become a particularly hot topic for replacing batteries in autonomous or nomad systems. In particular, vibration energy harvesting using piezoelectric elements has experienced a significant amount of research over the last decade as vibrations are widely available in many environments and as piezoelectric materials can be easily embedded. However, the energy scavenging abilities of such systems are still limited and are very sensitive to the connected load. The purpose of this paper is to expose a new approach based on synchronous switching on resistive load, which allows both a significant enhancement of the energy harvesting capabilities as well as a high tolerance to a change of the impedance of the connected system, especially in the low value region. It is theoretically and experimentally shown that such an approach permits increasing the energy harvesting abilities by a factor 4 compared to classical DC energy harvesting approach. Furthermore, the self-powering possibility and automatic load adaptation of the proposed method is experimentally discussed, showing the realistic viability of the technique.

Keywords: piezoelectric, energy harvesting, nonlinear

DOI 10.1515/ehs-2014-0015

Introduction

While they initially promoted the development of wireless, autonomous devices, primary batteries have become a break in the spreading of left-behind sensors and sensor networks, as well as a critical limitation in terms of consumer electronics, mainly due to their fixed amount of energy and limited lifetime (typically 1 year – Roundy, Wright, and Rabaey (2003)). In addition, batteries also raise some environmental concerns as their recycling process is particularly complex and costly.

Hence, in order to counteract the limitations introduced by the batteries, a lot of attention has recently been placed on systems able to provide electrical energy using ambient sources (Kahn, Katz, and Pister 1999; Krikke 2005; Yildiz 2009), such as thermal (Sodano et al. 2006; Ujihara, Carman, and Lee 2007; Guyomar et al. 2009; Sebald, Guyomar, and Agbossou 2009), photonics (Hamakawa 2003) or vibrations (Shearwood and Yates 1997; Stephen 2006), giving birth to the “energy harvesting” concept. Among all of the aforementioned sources, vibrations are of particular interest in the scientific community for powering small-scale devices (such as consumer electronics or sensor network nodes), as such a source is commonly available in many environments. In particular, the use of the piezoelectric effect for converting this mechanical energy into useful electrical energy is one of the most studied effects in this field, as piezoelectric systems feature high power density and good integration abilities (Sodano, Inman, and Park 2004; Anton and Sodano 2007).

However, the power delivered by such microgenerators is in the range of a few microwatts to a few milliwatts, which might limits the operations of the connected device. Hence, ways to increase the energy conversion and harvesting abilities is an important issue when designing energy harvesters. In this field, it has been proved that applying a nonlinear treatment to the output voltage of the piezoelectric device might greatly increase the conversion abilities and thus the energy harvesting performance (Taylor et al. 2001; Guyomar et al. 2005; Lefeuvre et al. 2006; Shu and Lien 2006; Shu, Lien, and Wu 2007). This nonlinear treatment, giving rise to the so-called Synchronized Switch Harvesting on Inductor (SSHI) concept, consists in inverting the piezovoltage by connecting the active material to an inductance for a short time period each time the displacement or

***Corresponding author: Mickaël Lallart,** Electrical Engineering, LGEF INSA Lyon, 8, rue de la Physique, VILLEURBANNE 69621, France, E-mail: mickael.lallart@insa-lyon.fr
Claude Richard: E-mail: claude.richard@insa-lyon.fr, **Yang Li:** E-mail: yang.li@insa-lyon.fr, **Yi-Chieh Wu:** E-mail: yi-chieh.wu@insa-lyon.fr, **Daniel Guyomar:** E-mail: daniel.guyomar@insa-lyon.fr, Electrical Engineering, LGEF INSA Lyon, 8, rue de la Physique, VILLEURBANNE 69621, France

equivalently the voltage reaches a maximum or a minimum value, yielding a cumulative process that significantly increase the voltage but also a reduction in the time shift between the voltage and the velocity. Although the harvested energy can be increased by a factor up to 10 compared to standard approach (i.e. without the nonlinear treatment) and can be easily made self-powered using a very small amount of the electrostatic energy available on the piezoelement (Richard, Guyomar, and Lefeuvre 2007; Lallart and Guyomar 2008), the output power is still very dependent on the load and the microgenerator requires additional stages to provide an almost constant output power when the electrical boundaries are varying (Ottman et al. 2002; Ottman, Hofmann, and Lesieutre 2003; Han et al. 2004; Lefeuvre et al. 2007a; Lallart and Inman 2010; Kong et al. 2010). Another approach, still based on a nonlinear process, consists of completely transferring the charge on the piezoelectric element to an inductance (the latter then transferring the energy to the storage stage) when the electrostatic energy is maximum (minimum or maximum piezovoltage). This technique, called Synchronous Electric Charge Extraction (SECE), permits having a harvested energy theoretically totally independent from the load as well as an increase in terms of harvested energy by a factor of 4 (Lefeuvre et al. 2005, 2007b). However, the process is more difficult to implement in a self-powered fashion compared to the SSHI, although some attempts demonstrated the feasibility of similar methods for harvesting energy (Wu et al. 2013).

Hence, the purpose of this paper is to present a simple way for beneficiating both of the harvesting magnification and load tolerance. The proposed concept is based on a nonlinear process similar to the SSHI, but no voltage inversion occurs which allows energy extraction operations close to the SECE and thus a constant harvested energy over a wide range of connected loads in the low load region. With this technique, called AC-SSHR for "Alternative Current Synchronous Switch Harvesting on Resistance," the charges on the piezoelectric element are directly transferred in a pulsed fashion to the load. Furthermore, it will be proved, that, although the basic principles are based on AC voltage (while typical electronic devices require DC voltage), it is possible to use an AC–DC rectifier to obtain a constant output power when the load changes.

The paper is organized as follows. Section "Principles and theoretical development" exposes the basic principles of the proposed technique as well as a simple theoretical modelling for predicting the performance of the method. Then experimental validation for assessing the performance of the technique as well as the theoretical model will be presented in Section "Experimental validation and discussion". Section "Self-powered implementation and voltage conditioning" aims at providing a realistic implementation of the technique to dispose of a truly self-powered, DC output energy harvester that uses the AC-SSHR concept. Finally, Section "Conclusion" summarizes the paper, highlighting the main findings of this study.

Principles and theoretical development

The principles of the proposed technique rely on the so-called Synchronized Switch technique that allows artificially increasing the coupling coefficient of an electroactive structure equipped with piezoelectric materials. While many declinations of this technique exist, for instance parallel SSHI (Guyomar et al. 2005; Lefeuvre et al. 2006), series SSHI (Taylor et al. 2001; Lefeuvre et al. 2006), SSHI-MR (Synchronized Switch Harvesting on Inductor with Magnetic Rectifier – Garbuio et al. (2009)), hybrid SSHI (Lallart et al. 2010), SECE (Lefeuvre et al. (2005, 2006, 2007b)), OSECE (Optimized Synchronous Electric Charge Extraction – Wu et al. (2013)), DSSH (Double Synchronized Switch Harvesting – Lallart et al. (2008)), ESSH (Enhanced Synchronized Switch Harvesting – Shen et al. (2010)) or energy injection (Lallart and Guyomar 2010), they either suffer from load dependency (SSHI and energy injection), requiring an additional load adaptation interface, or are difficult to implement in a self-powered fashion (SECE, DSSH, ESSH and energy injection).

The technique exposed in this paper is still based on the switching process of the previously mentioned techniques, except that the piezoelectric element is directly switched to the load R (Figure 1) without the use of inductance or bridge rectifier. It can be noted that the nonrequirement of the inductance permits higher integrability of the device as well. Each time the displacement (or equivalently the output voltage of the piezoelectric element) reaches an extremum value, the switch is closed, allowing a current flowing from the piezoelectric element

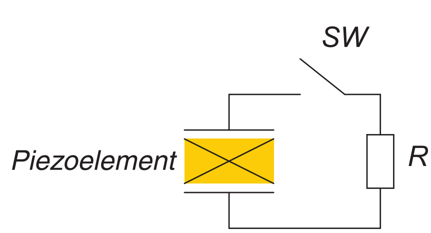

Figure 1 Schematic of the AC-SSHR technique

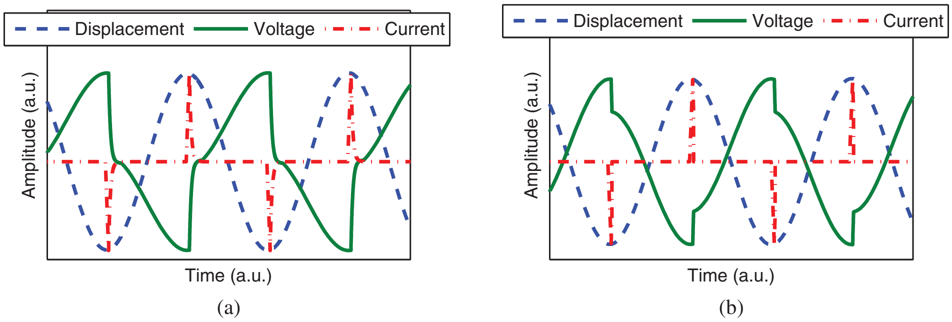

Figure 2 Typical waveforms of AC-SSHR technique. (a) Complete voltage cancellation. (b) Incomplete voltage cancellation

to the load as depicted in Figure 2. According to the closing time period of the switch, the piezoelectric element can completely discharge into the load (Figure 2(a)) or some charges can still remain on the active material (Figure 2(b)). It can be noted here that, although the harvesting operation is done in an AC manner that might not be compatible with the required DC input of typical electronic component, it is possible to use an AC to DC converter as it will be exposed in Section “Self-powered implementation and voltage conditioning”.

Constant vibration magnitude

In a first approach, this section proposes to evaluate the harvesting abilities of the AC-SSHR method when the electromechanical structure features constant deflection. This is typically the case of highly damped and/or weakly coupled systems, where the backward piezoelectric effect that modifies the mechanical behaviour according to the electrical connection can be neglected. Furthermore, it is considered that the deflection is monochromatic.

In this case, only the electrical equation of the electromechanical system is necessary, and given by:

$$I = \alpha \dot{u} - C_0 \dot{V}, \tag{1}$$

where I, V and u refer to the current flowing out of the piezoelectric element, piezoelectric output voltage and displacement of a given point of the structure, and with α and C_0 respectively denoting the force factor and clamped capacitance. When the switch is open, the system is in open circuit, so that the voltage varies with the displacement according to:

$$V = \frac{\alpha}{C_0} u + h(t), \tag{2}$$

with $h(t)$ a piecewise constant function that is a crenel function in the case of monochromatic displacement when considering that the switch closing time is much shorter than half the vibration period. Hence, the voltage expression in eq. [2] can be seen as the combination of the open circuit voltage with the crenel function that is an effect of the switching process and is in phase with the speed:

$$h(t) = H \operatorname{sign}(\dot{u}), \tag{3}$$

where H denotes the magnitude of the crenel function. This magnitude can be found considering the switching process. Assuming that the voltage across the piezoelectric element at the switching instant is equal to V_0, its evolution as a function of the time (with $t = 0$ corresponding here to the switching time instant) during the on state of the switch is given by

$$V(t) = V_0 \exp\left(-\frac{t}{RC_0}\right). \tag{4}$$

Hence, noting τ the switch closing time period (and assuming τ is far less than half the vibration period), the voltage after the switching process is therefore given by

$$V_\tau = V_0 \exp\left(-\frac{\tau}{RC_0}\right) \tag{5}$$

After the switch, the piezoelectric element is left in open circuit until a new extremum is reached. Consequently, from eq. [1], the equation set to find V_0 and H is given by

$$\begin{cases} V_0 \exp\left(-\frac{\tau}{RC_0}\right) = \frac{\alpha}{C_0} u_M - H \\ -V_0 = -\frac{\alpha}{C_0} u_M - H \end{cases} \tag{6}$$

where U_M refers to the displacement magnitude. Resolving eq. [6] therefore yields the value of the voltage V_0:

$$V_0 = 2 \frac{\alpha}{(1 + e^{-\tau/RC_0}) C_0} u_M. \tag{7}$$

Then, from the value of V_0, it is possible to derive the energy W that has been transferred to the load for a single switching event:

$$W = \int_0^\tau RC_0^{\,2}\left(\dot{V}(t)\right)^2 dt = \frac{1}{2}C_0 V_0^{\,2}\left(1 - \exp\left(-2\frac{\tau}{RC_0}\right)\right), \quad [8]$$

which allows getting the harvested power by combination with eq. [7]:

$$P = 2f_0 W = 2\sinh\left(\frac{\tau}{RC_0}\right)\left[\operatorname{sech}\left(\frac{\tau}{2RC_0}\right)\right]^2 \frac{\alpha^2}{C_0} f_0 u_M^{\,2}, \quad [9]$$

with sech(x) the hyperbolic secant function of the variable x and f_0 the vibration frequency.

Figure 3 depicts the harvested power normalized with respect to the maximum AC power that can be harvested without the switching interface (load directly connected to the piezoelectric element – Guyomar et al. (2005)):

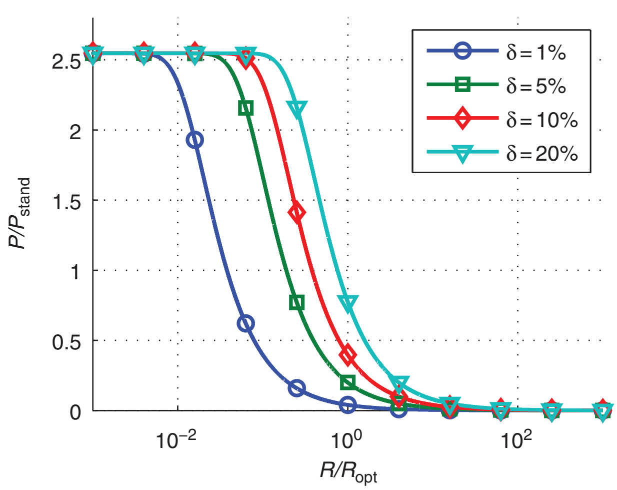

Figure 3 Normalized power as a function of the load for several normalized values of switching time periods considering constant displacement magnitude

$$P_{\text{stand}} = \frac{\pi}{2}\frac{\alpha^2}{C_0} f_0 u_M^{\,2} \quad [10]$$

as a function of the load normalized to the optimal load in the standard AC case without taking into account any damping effect (Guyomar et al. 2005; Renno, Daqaq, and Inman 2009):

$$R_{\text{opt}} = \frac{1}{2\pi C_0 f_0}, \quad [11]$$

for several value of the switch closing time period τ represented by its ratio δ in terms of half vibration period:

$$\delta = 2f_0\tau. \quad [12]$$

This figure clearly shows that the proposed approach permits a significant gain in terms of harvested power ($8/\pi$ compared to the standard AC technique and 4 compared to the DC one – Guyomar et al. (2005)) as well as a constant harvested power when the load is less than the optimal load in the standard case (the value of the normalized switching time period is limited to 20% of half the vibration period to ensure that the switching event can be considered instantaneous). These two advantages are equivalent to the SECE case (Lefeuvre et al. 2005), provided that the load is small enough, but the AC-SSHR features a much easier implementation.

Constant driving force magnitude

When harvesting energy from a vibrating structure, a part of the mechanical energy is converted into electricity and then transferred to the load/storage stage. This therefore leads to a decrease of the mechanical power, yielding a damping effect, and thus the extracted energy becomes limited (Lesieutre, Ottman, and Hofmann 2004; Guyomar et al. 2005). In this part, this damping effect is taken into account to evaluate the performance of the AC-SSHR for harvesting energy. It is therefore considered that the system no longer features constant displacement as a function of the load, but is instead driven by a monochromatic force with a constant magnitude F_M. Starting again from the expression of the voltage:

$$V = \frac{\alpha}{C_0}u + H\operatorname{sign}(\dot{u}) \quad [13]$$

where the magnitude of the crenel function can be obtained from eq. [6]:

$$H = \frac{\alpha}{C_0}\tanh\left(\frac{\tau}{2RC_0}\right)u_M, \quad [14]$$

it is possible to obtain the expression of the displacement magnitude u_M using the Single Degree of Freedom equation of motion of an electromechanical system (Badel et al. 2007):

$$M\ddot{u}(t) + C\dot{u}(t) + K_E u(t) = F(t) - \alpha V(t) \quad [15]$$

with $u(t)$ and $F(t)$ the time-domain displacement at the considered location and applied force, and where M, C

and K_E refer to the dynamic mass, structural damping coefficient and short-circuit stiffness. Assuming a sinusoidal displacement, the voltage V may be approximated to its first harmonic, which yields, in the frequency domain:

$$V(\omega) \approx \frac{\alpha}{C_0}\left[1 + j\frac{4}{\pi}\tanh\left(\frac{\tau}{2RC_0}\right)\right]u(\omega), \quad [16]$$

with ω denoting the angular frequency. Hence, substituting the expression of the voltage in eq. [15] expressed in the frequency domain leads to the expression of the displacement magnitude at the resonance frequency (assuming relatively weakly damped system):

$$u_M = \frac{F_M}{C\omega_0 + \frac{4}{\pi}\frac{\alpha^2}{C_0}\tanh\left(\frac{\tau}{2RC_0}\right)}, \quad [17]$$

giving the expression of the harvested power from eq. [9]:

$$P = 2\frac{\alpha^2}{C_0}\frac{\sinh\left(\frac{\tau}{RC_0}\right)\left[\operatorname{sech}\left(\frac{\tau}{2RC_0}\right)\right]^2}{\left[C\omega_0 + \frac{4}{\pi}\frac{\alpha^2}{C_0}\tanh\left(\frac{\tau}{2RC_0}\right)\right]^2}f_0 {F_M}^2. \quad [18]$$

Figure 4 depicts the harvested power and displacement magnitude as a function of the normalized load and the figure of merit given by the product of the squared coupling coefficient k^2 by the mechanical quality factor Q_m:

$$k^2 Q_m = \frac{\alpha^2\sqrt{M}}{C\sqrt{C_0}\sqrt{C_0 K_E + \alpha^2}}, \quad [19]$$

respectively normalized with the open-circuit displacement and power limit:

$$P_{lim} = \frac{F_M^2}{8C}. \quad [20]$$

Although for low values of $k^2 Q_m$ the obtained power is similar to the one depicted in the previous section because the damping effect is negligible, it can be noted that the power reaches the limit P_{lim} for weakly damped, highly coupled systems, because the vibration magnitude is significantly reduced by the energy extraction process. Furthermore, the load tolerance becomes slightly compromised in such a case, and an optimal load appears, denoting the trade-off between the necessity of letting the mechanical energy to be able to be provided to the system and the extracted energy. It can also be noted that this optimal load for high values of $k^2 Q_m$ is dependent on the switching time period τ. In terms of displacement magnitude, it can be seen that low load values (far less than the discharge time constant) leads to a cancellation of the voltage, yielding a mechanical effect similar to the one obtained in the case of the SSDS damping techniques (Richard et al. 1999; Badel et al. 2006),[1] while for high load values, there is almost no charge flow from the piezoelectric element, and the system behaviour is identical to open-circuit case. In between, the optimal point that maximizes the power appears.

This maximum power as a function of the figure of merit $k^2 Q_m$ is depicted in Figure 5, where the optimal load and/or switching time period is optimized for each point. Thanks to the control of the trade-off between input energy and extracted energy offered by these parameters, it can be seen that the power is never decreasing like in the case of the SECE technique and remains equal to the value of P_{lim} even for high value of $k^2 Q_m$. Furthermore, compared to the standard AC case, it can be seen that the maximum power is reached for lower value of the product of the squared coupling coefficient by the mechanical quality factor. As the latter is not affected by the electronic interface, it can be stated, in a system-level view, that the AC-SSHR approach allows an artificial increase of the global electromechanical coupling coefficient. In a practical point of view, this means that low performance (and thus low cost) piezoelectric materials can be used, or that the size of the latter can be reduced.

Experimental validation and discussion

This section aims at validating the previously exposed concepts and theoretical developments. The experimental structure consists of a cantilever beam attached to a shaker that induces the base vibrations, as depicted in Figure 6. The shaker is driven by a function generator through a power amplifier. The output piezovoltage is monitored by a dSpace® system that controls the switching device (including the switching time period). Piezovoltage, load voltage and base and tip displacements

1 In this case, it can be noted that the output power is not maximized as the input energy available in the mechanical structure is significantly reduced; in other words, as the output power is more or less the input energy times the conversion efficiency, it is mandatory not to totally “kill” the energy source (which is the objective in vibration damping) to have a maximum power output.

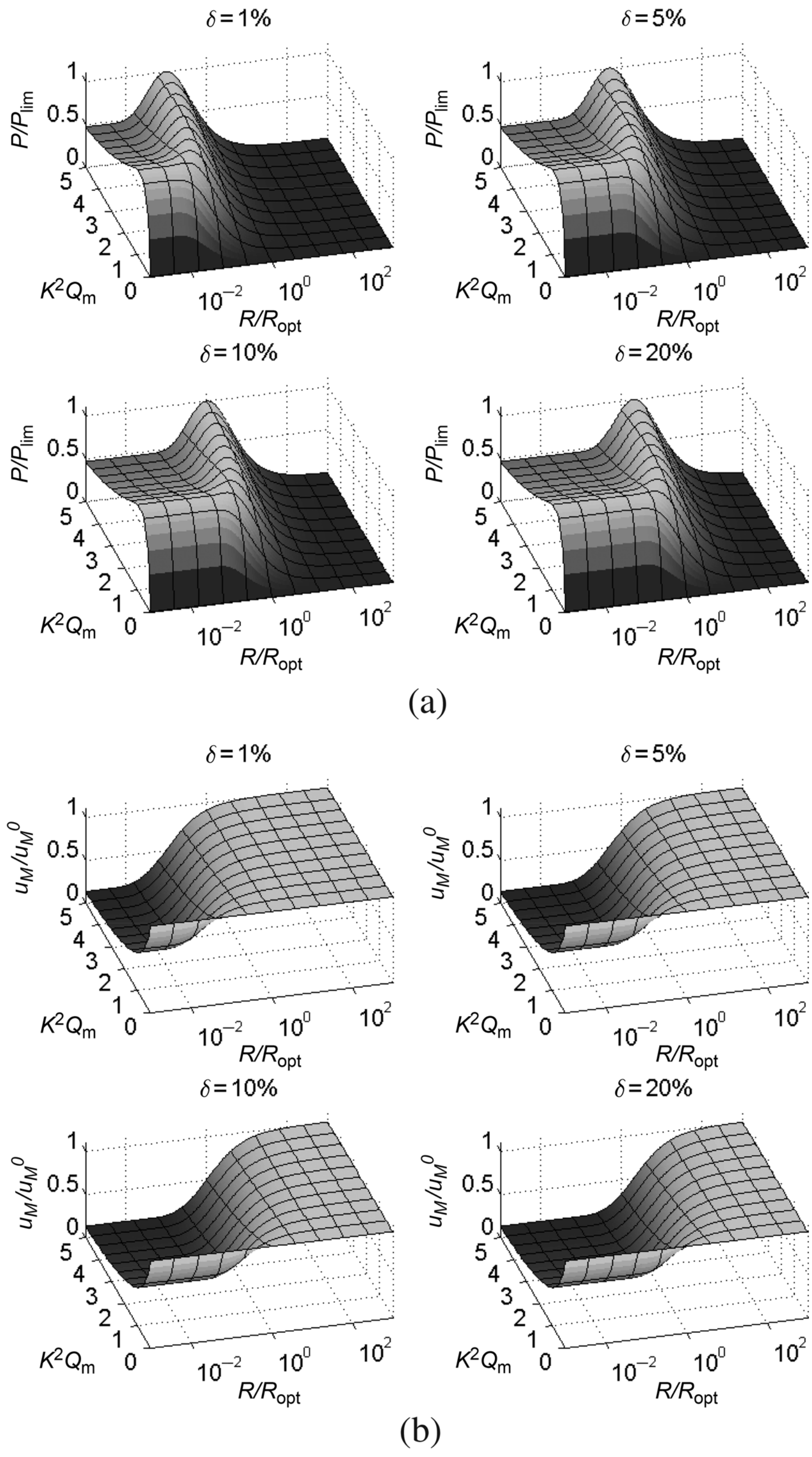

Figure 4 Normalized power and displacement magnitude as a function of the load and figure of merit k^2Q_m for several values of switching time periods considering constant driving force/acceleration magnitude at the resonance frequency. (a) Normalized harvested power. (b) Normalized displacement magnitude

are also monitored by an oscilloscope. Preliminary experimental measurements have been performed in order to identify the structure electromechanical parameters that are listed in Table 1.

The first set of experiments consisted in evaluating the energy harvesting abilities when the cantilever deflection is sinusoidal and features a constant magnitude of 0.6 mm. Three measurements were performed according

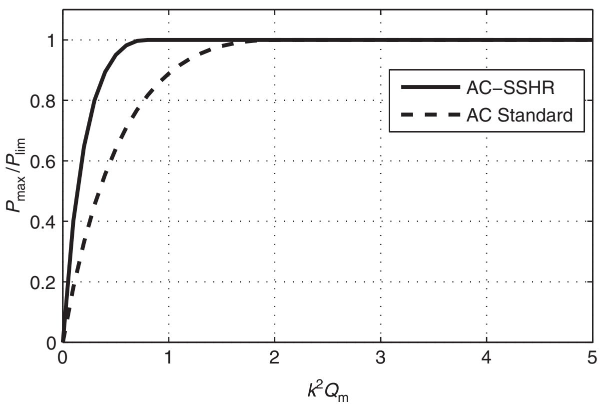

Figure 5 Maximum harvested power for constant driving force/acceleration magnitude and comparison with AC standard technique

to the switching closing time period ($\tau = 0.1$ ms, $\tau = 0.2$ ms and $\tau = 0.1$ ms, corresponding to $\delta = 0.78\%$, 1.56% and 7.80% of half a vibration period). Harvested powers as a function of the load are depicted in Figure 7, both theoretically and experimentally. Both predicted power values and experimentally measured ones show good agreement, although some slight discrepancies occur because of uncertainties in measurement and identification. In particular, while the maximal power magnitude matches quite well, a shift in terms of load can be observed (the experimental curves being shifted to higher load values), which might be explained by uncertainties in the experimental measurements and identification. Therefore, it could also be thought that the experimental standard case would also be slightly shifted. However, this shift is quite small not to compromise the experimental validation. Hence, the trend of the technique in offering an increase of the harvested power compared to the standard technique as well as a relatively good tolerance to load change is experimentally confirmed through the plateau in the power for low load values. Furthermore, the dependency of the constant power load range with the switching closing time period is also demonstrated by the experiments.

Then, a monochromatic force with constant magnitude was considered. In this case, the shaker is driven so that the base acceleration is constant with a value of 0.07 g, which corresponds to an equivalent force of 0.14 mN for the SDOF model. The switching time period is fixed to 0.2 ms (1.56% of half the vibration period). Theoretical predictions and experimental results depicted in Figure 8(a) show good agreement (although a shift, but in this case to lower load values, can still be observed, and can be attributed to measurement uncertainties in the system identification), showing that when the damping effect is considered, the power dramatically drops when the structure is weakly damped and highly coupled and the load tolerance is not exactly ensured,

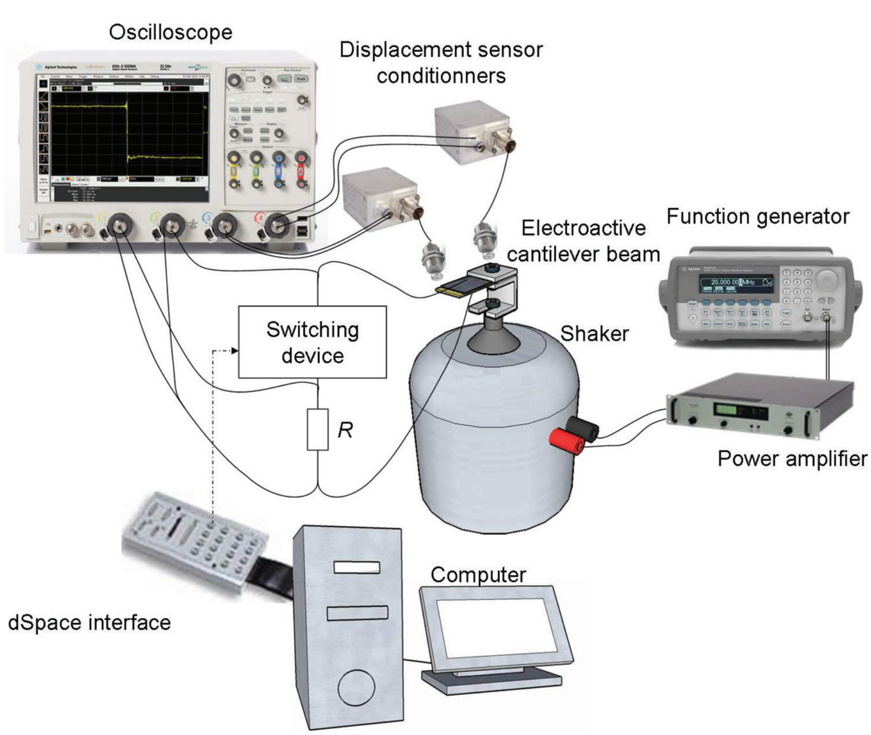

Figure 6 Schematics of the experimental set-up

Table 1 Experimental parameters

Mechanical parameters	
Dynamic mass M	0.2 g
Structural damping coefficient C	1.1 mN s m^{-1}
Short-circuit stiffness K_E	11.6 N m^{-1}
Open-circuit resonance frequency f_0	38.95 Hz
Mechanical quality factor Q_m	45
Electrical parameters	
Clamped capacitance C_0	45 nF
Electromechanical parameters	
Force factor α	0.13 mN V^{-1}
Squared coupling coefficient k^2	3.14%
Product of the squared coupling coefficient by the mechanical quality factor k^2Q_m	1.41

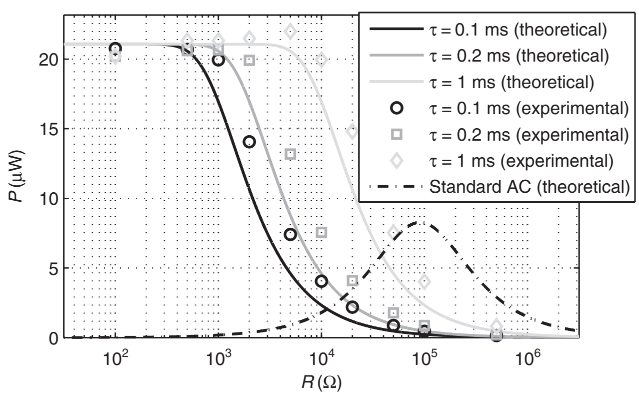

Figure 7 Theoretical and experimental results for constant displacement magnitude

which is reflected by the power increase around a particular load value, yielding an optimal value of the latter (Figure 8(b)). However, the power remains quite constant over a wider load range compared to the case of constant deflection magnitude for the particular configuration of the experimental device, which is actually explained by the fact that the electromechanical damping is more limited for higher load, thus yielding a higher displacement and therefore a higher harvested power.

Self-powered implementation and voltage conditioning

While the previous parts focused on the explanation, modelling and proof of concept of the AC-SSHR technique, realistic applications would require the device to be self-powered in order to have a positive energy balance. Hence, this section aims at exposing a possible implementation of the AC-SSHR technique for realistic use in self-powered, autonomous sensor networks. The basic principles depicted in Figure 9 rely on the use of the self-powered switch described in Richard, Guyomar, and Lefeuvre (2007) as well as a rectifier combined with a buck-boost converter operating in discontinuous mode (DCM) that permits AC/DC conversion while acting as a pure resistive load for the piezoelectric element (Lefeuvre et al. 2007a; Kong et al. 2010).

The principles of the switching device consist in comparing the piezovoltage with its envelope through transistor T_{s11} for positive voltage and T_{s21} for negative voltage. Once the voltage envelope (obtained with a lossy envelope detector formed by diode D_{s11}– resp. D_{s21}–, resistance R_{s11}– resp. R_{s21}– and capacitor C_{s1}– resp. C_{s2}– for positive voltage – resp. negative voltage) is greater than the piezovoltage itself, the comparison transistor

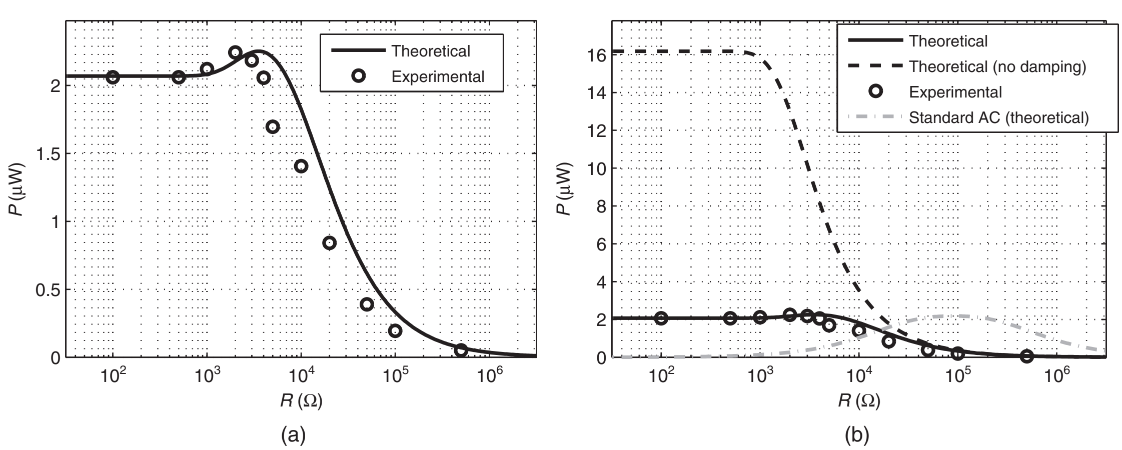

Figure 8 (a) Theoretical and experimental results for constant base acceleration magnitude at the resonance and (b) comparison with constant deflection magnitude case

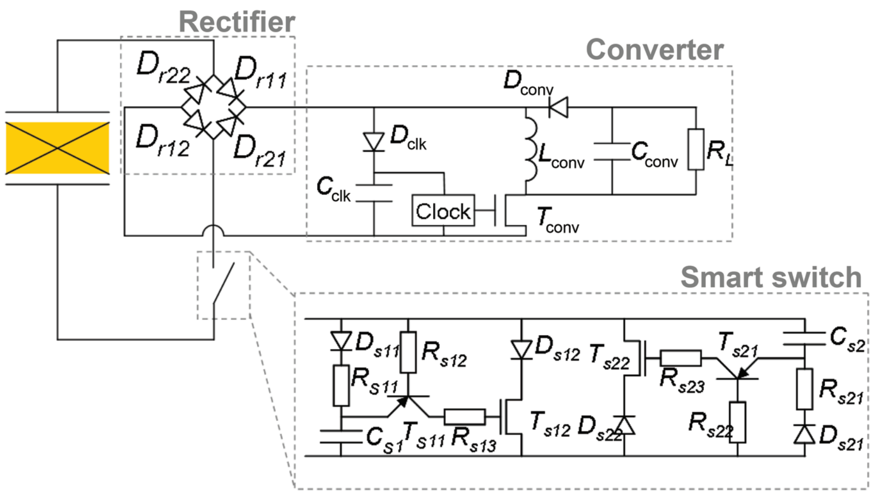

Figure 9 Self-powered AC-SSHR schematics

will turn on and drive the MOSFET transistor (T_{s12} or T_{s22} according to the voltage sign), hence initiating the switching process. The latter then stops when the current cancels thanks to diode D_{s12} or D_{s22}.

The AC/DC rectification consists in switching the piezoelectric element to the inductance L_{conv} through the MOSFET T_{conv} driven by a clock at a much higher frequency than the vibration and time constant τ, yielding a partial discharge of the piezoelement. The clock choice should meet the low-power requirements. Hence, in the following, the ultralow-power clock $OV-7604-C7-STD-020$ from Micro Crystal is selected as it features a maximum current consumption as low as 0.5 μA under a typical voltage range of 1.2–5.5 V. The frequency of the clock is $f_{\text{conv}} = 32$ kHz and the duty cycle $\delta_{\text{conv}} = 50\%$. When the transistor is open, the inductance releases its stored energy into the storage capacitor C_{conv}. R_{L} is the load that represents the circuit connected to the harvester. When operating in DCM, this converter allows presenting a constant impedance R_{in} to the piezoelectric element, independent from R_{L}(Lefeuvre et al. 2007a; Kong et al. 2010):

$$R_{\text{in}} = \frac{2L_{\text{conv}} f_{\text{conv}}}{\delta_{\text{conv}}{}^2} \qquad [21]$$

As previously mentioned, in order to be able to present such a constant load to the piezoelectric element, the converter needs to operate in DCM, i.e. the inductance L_{conv} needs to be totally discharged before the beginning of the next cycle. Assuming that the piezoelectric voltage drop for one converter switching period is negligible and that the current waveforms are piecewise-linear (i.e. the switching frequency is high), it can be shown, by considering the maximum current in the inductor, that the condition for ensuring DCM operation depends on the maximum piezoelectric voltage V_{M} over the rectified voltage V_{DC} ratio as

$$\frac{V_{\text{M}}}{V_{\text{DC}}} \leq \frac{1-\delta_{\text{conv}}}{\delta_{\text{conv}}}. \qquad [22]$$

The successive partial discharges of the piezoelectric element at a much higher frequency than the vibration frequency therefore permits the energy harvesting process to take place in a very similar fashion than in the previously exposed approach. Obviously, such operations can take place only when the switching device is on. Furthermore, it can be stated that, because the switching process stops when the current tends to reverse, the switching time period is automatically adjusted to ensure a voltage cancellation, which actually yields a power that is totally independent from the connected load (assuming negligible losses).

Real implementation of this topology has been investigated with the components listed in Table 2, and qualitative experimental measurements have been performed. With the chosen parameters, the load R_{in} shown to the piezoelectric element is equal to 1,280 Ω, which is 70 times less than the optimal load in standard case, corresponding to a minimal closing time of the switch equals to 3% of the half vibration period, which is consistent with the fast voltage cancellation assumption. Hence, because this input impedance is independent from the connected load at the output of the converter, the harvested power is maximized, as the load seen by the piezoelectric element is constant and equal to this input impedance. Furthermore, the flexibility of the

Table 2 Components of the self-powered AC-SSHR

Denomination	Value/reference
Rectifier	
$D_{r11}/D_{r12}/D_{r21}/D_{r22}$	BAT86
Converter	
D_{clk}	BAT86
C_{clk}	2.2 μ F
Clock	OV-7604-C7-STD-020
D_{conv}	BAT86
L_{conv}	10 mH
T_{conv}	2N7000
C_{conv}	0.47 μ F
Synchronized switch	
D_{s11}/D_{s21}	1DN4148
R_{s11}/R_{s21}	6.8 kΩ
C_{s1}/C_{s2}	2.2 nF
R_{s12}/R_{s22}	1 MΩ
T_{s11}/T_{s21}	MPSA-92
R_{s13}/R_{s23}	150 kΩ
D_{s12}/D_{s22}	BAT86
T_{s12}/T_{s22}	2N7000

system is also ensured, as the device ensures a voltage cancellation because the maximum detection switch stops only when the current tends to reverse. Therefore, when a parameter changes (e.g. piezoelectric capacitance), the switching time is automatically adjusted to ensure the voltage cancellation. The only limitation in terms of application of this circuit lies in the fact that the switching period should be less than half the vibration period. However this constraint is quite weak as the input impedance of the converter may be designed to be low.

Figure 10 depicts the obtained waveforms obtained with such a system, with a load fixed to $R_L = 1$ MΩ and the storage capacitor value chosen to show the ripple in the figure (in order to highlight the energy extraction time instants). It can also be noted that, as the duty cycle of the clock is fixed to 50%, the output voltage should be greater than the maximum piezovoltage to ensure DCM operations (eq. [22]), which is verified here. As seen by Figure 10(a), the obtained piezovoltage waveforms are identical to the one obtained in the previous section, while the load voltage is continuous. However, a slight delay between the occurrence of a voltage extremum and the actual associated switching event appears, because of the principles of the self-powered extremum detection circuit (threshold voltages of discrete components). This would slightly impact the output power (by a factor of $cos^2(\varphi)$, with φ the phase delay, in constant displacement case, but with even lesser impact in constant base acceleration case as the damping effect would be reduced). The inversion process, depicted in Figure 10(b), shows the successive partial discharges of the piezoelectric element that is synchronous with the clock, as well as the energy harvesting process reflected by the rectified voltage increase.

Conclusion

This paper exposed a new approach in the family of switched nonlinear interfaces for energy harvesting enhancement. Based on a synchronous piezovoltage cancellation that allows artificially increasing the electromechanical coupling

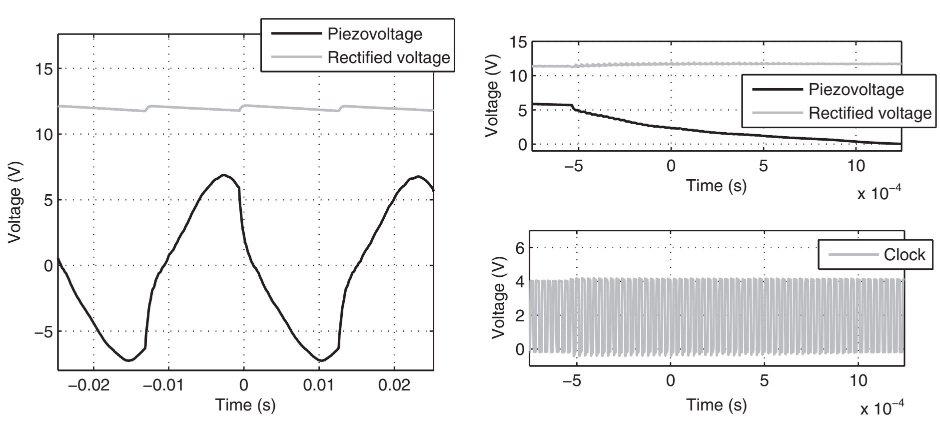

Figure 10 Waveforms of the self-powered AC-SSHR: (a) global piezovoltage and rectified voltage waveforms; (b) enlargement on switching instant

of the piezoelectric device,[2] it is shown that the approach is simple yet effective and integrable (no inductance is needed in the voltage cancellation process) for ensuring high power output on a wide range of loads. Although the constant power is no longer ensured when taking into account the damping effect induced by the energy harvesting process, the ripples are limited and the acceptable load range actually extended. Furthermore, a realistic implementation of the proposed technique is assessed, with an automatic adaptation ability that allows having a total independency on the load, also possibly allowing better performance under broadband excitation.

References

Anton, S. R., and H. A. Sodano. 2007. "A Review of Power Harvesting Using Piezoelectric Materials (2003–2006)." *Smart Materials and Structures* 16:025009.

Badel, A., M. Lagache, D. Guyomar, E. Lefeuvre, and C. Richard. 2007. "Finite Element and Simple Lumped Modeling for Flexural Nonlinear Semi-Passive Damping." *Journal of Intelligent Material Systems and Structures* 18(7):727–42.

Badel, A., G. Sebald, D. Guyomar, M. Lallart, E. Lefeuvre, C. Richard, and J. Qiu. 2006. "Wide Band Semi-Active Piezoelectric Vibration Control by Synchronized Switching on Adaptive Continuous Voltage Sources." *Journal of the Acoustical Society of America* 119(5):2815–25.

Garbuio, L., M. Lallart, D. Guyomar, and C. Richard. 2009. "Mechanical Energy Harvester with Ultra Low Threshold Rectification Based on SSHI Non-linear Technique." *IEEE Transactions on Industrial Electronics* 56(4):1048–56.

Guyomar, D., A. Badel, E. Lefeuvre, and C. Richard. 2005. "Towards Energy Harvesting Using Active Materials and Conversion Improvement by Nonlinear Processing." *IEEE Ultrasonics, Ferroelectrics and Frequency Control Society* 52:584 595.

Guyomar, D., G. Sebald, S. Pruvost, M. Lallart, A. Khodayari, and C. Richard. 2009. "Energy Harvesting from Ambient Vibrations and Heat." *Journal of Intelligent Material Systems and Structures* 20:609–24.

Hamakawa, Y. 2003. "30 Years Trajectory of a Solar Photovoltaic Research." In the 3rd World Conference on Photovoltaic Energy Conversion 2003.

Han, J., A. Von-Jouanne, T. Le, K. Mayaram, and T. S. Fiez. 2004. "Novel Power Conditioning Circuits for Piezoelectric Micro Power Generators." In Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC), 3, 1541–1546.

2 This artificial increase, in a system-level approach, can be explained by the voltage magnification and shift allowed by the nonlinear treatment – therefore allowing the increase of the converted energy given by the integral of the product of the voltage by the velocity from the SDOF model – as well as the maximum power shift to lower values of the figure of merit given by the product of the squared coupling coefficient by the mechanical quality factor compared to the standard case (see Figure 5).

Kahn, J. M., R. H. Katz, and K. S. J. Pister. 1999. "Next Century Challenges: Mobile Networking for Smart Dust." In Proceedings of the Mobicom 1999, 483–492.

Kong, N., D. S. Ha, A. Erturk, and D. J. Inman. 2010. "Resistive Impedance Matching Circuit for Piezoelectric Energy Harvesting." *Journal of Intelligent Material Systems and Structures* 21:1293–302.

Krikke, J. 2005. "Sunrise for Energy Harvesting Products." *IEEE Pervasive Computing* 4:4–35.

Lallart, M., L. Garbuio, L. Petit, C. Richard, and D. Guyomar. 2008. "Double Synchronized Switch Harvesting (DSSH): A New Energy Harvesting Scheme for Efficient Energy Extraction." *IEEE Ultrasonics, Ferroelectrics and Frequency Control Society* 55(10):2019–130.

Lallart, M., and D. Guyomar. 2008. "An Optimized Self-Powered Switching Circuit for Non-linear Energy Harvesting with Low Voltage Output." *Smart Materials and Structures* 17:035030.

Lallart, M., and D. Guyomar. 2010. "Piezoelectric Conversion and Energy Harvesting Enhancement by Initial Energy Injection." *Applied Physics Letters* 97:014104.

Lallart, M., and D. J. Inman. 2010. "Low-Cost Integrable Tuning-Free Converter for Piezoelectric Energy Harvesting Optimization." *IEEE Transactions on Power Electronics* 25(7):1811–19.

Lallart, M., C. Richard, L. Garbuio, L. Petit, and D. Guyomar. 2010. "High Efficiency, Wide Load Bandwidth Piezoelectric Energy Scavenging by a Hybrid Nonlinear Approach." *Sensors and Actuators A: Physical* 165(2):294–302.

Lefeuvre, E., D. Audigier, C. Richard, and D. Guyomar. 2007a. "Buck-Boost Converter for Sensorless Power Optimization of Piezoelectric Energy Harvester." *IEEE Transactions on Power Electronics* 22(5):2018–25.

Lefeuvre, E., A. Badel, C. Richard, and D. Guyomar. 2005. "Piezoelectric Energy Harvesting Device Optimization by Synchronous Electric Charge Extraction." *Journal of Intelligent Material Systems and Structures* 16:865–76.

Lefeuvre, E., A. Badel, C. Richard, and D. Guyomar. 2007b. "Energy Harvesting Using Piezoelectric Materials: Case of Random Vibrations." *Journal of Electroceramics* 19:349–55.

Lefeuvre, E., A. Badel, C. Richard, L. Petit, and D. Guyomar. 2006. "A Comparison Between Several Vibration-Powered Piezoelectric Generators for Standalone Systems." *Sensors and Actuators A: Physical* 126:405–16.

Lesieutre, G. A., G. K. Ottman, and H. F. Hofmann. 2004. "Damping as a Results of Piezoelectric Energy Harvesting." *The Journal of Sound and Vibration* 269:991–1001. doi: 10.1016/S0022-460X(03)00210-4

Ottman, G. K., H. F. Hofmann, A. C. Bhatt, and G. A. Lesieutre. 2002. "Adaptive Piezoelectric Energy Harvesting Circuit for Wireless Remote Power Supply." *IEEE Transactions on Power Electronics* 17(5):669–76.

Ottman, G. K., H. F. Hofmann, and G. A. Lesieutre. 2003. "Optimized Piezoelectric Energy Harvesting Circuit Using Step-Down Converter in Discontinuous Conduction Mode." *IEEE Transactions on Power Electronics* 18(2):696–703.

Renno, J. M., M. F. Daqaq, and D. J. Inman. 2009. "On the Optimal Energy Harvesting from a Vibration Source." *The Journal of Sound and Vibration* 320:386–405. doi: 10.1016/j.jsv.2008.07.029

Richard, C., D. Guyomar, D. Audigier, and G. Ching. 1999. "Semi-Passive Damping using Continuous Switching of a Piezoelectric Device." In Proc. Spie, Smart Structures and Materials 1999: Passive Damping and Isolation, 3672, 104–111.

Richard, C., D. Guyomar, and E. Lefeuvre. 2007. "Self-Powered Electronic Breaker with Automatic Switching by Detecting Maxima or Minima of Potential Difference between Its Power Electrodes." Patent Pct/FR2005/003000, publication number: WO/2007/063194.

Roundy, S., P. K. Wright, and J. Rabaey. 2003. "A Study of Low Level Vibrations as a Power Source for Wireless Sensor Nodes." *Computer Communications* 26:1131.

Sebald, G., D. Guyomar, and A. Agbossou. 2009. "On Thermoelectric and Pyroelectric Energy Harvesting." *Smart Materials and Structures* 18:125006.

Shearwood, C., and R. B. Yates. 1997. "Development of an Electromagnetic Microgenerator." *Electronics Letters* 33:1883–4.

Shen, H., J. Qiu, H. Ji, K. Zhu, and M. Balsi. 2010. "Enhanced Synchronized Switch Harvesting: A New Energy Harvesting Scheme for Efficient Energy Extraction." *Smart Materials and Structures* 19(11):115017.

Shu, Y. C., and I. C. Lien. 2006. "Analysis of Power Output for Piezoelectric Energy Harvesting Systems." *Smart Materials and Structures* 15:1499–512.

Shu, Y., I. Lien, and W. Wu. 2007. "An Improved Analysis of the SSHI Interface in Piezoelectric Energy Harvesting." *Smart Materials and Structures* 16:2253–64.

Sodano, H. A., D. J. Inman, and G. Park. 2004. "A Review of Power Harvesting from Vibration Using Piezoelectric Materials." *The Shock and Vibration Digest* 36:197–205.

Sodano, H. A., G. E. Simmers, R. Dereux, and D. J. Inman. 2006. "Recharging Batteries Using Energy Harvested from Thermal Gradients." *Journal of Intelligent Material Systems and Structures* 18:3–10.

Stephen, N. G. 2006. "On Energy Harvesting from Ambient Vibration." *Journal of Sound and Vibration* 293:409–25.

Taylor, G. W., J. R. Burns, S. M. Kammann, W. B. Powers, and T. R. Welsh. 2001. "The Energy Harvesting Eel: A Small Subsurface Ocean/River Power Generator." *IEEE Journal of Oceanic Engineering* 26:539–47.

Ujihara, M., G. P. Carman, and D. G. Lee. 2007. "Thermal Energy Harvesting Device Using Ferromagnetic Materials." *Applied Physics Letters* 91:093508.

Wu, Y., A. Badel, F. Formosa, W. Liu, and A. E. Agbossou. 2013. "Piezoelectric Vibration Energy Harvesting by Optimized Synchronous Electric Charge Extraction." *Journal of Intelligent Material Systems and Structures* 24(12):1445–58.

Yildiz, F. 2009. "Potential Ambient Energy-Harvesting Sources and Techniques." *The Journal of Technology Studies* 35:40–8.