Theoretical study and Simulation method for optimizing the performance of advanced Energy Harvesting techniques

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Abstract: This paper investigates and compares the efficiencies of four different interfaces for vibration based energy harvesting systems. In some cases, the increase in power was found to be in the order of ten times the output power compared to the standard approach to energy harvested by piezoelectric materials. The authors updated the review of synchronous switching techniques used in the conversion of ambient mechanical energy to useful electrical energy using piezoelectric materials is given. The basic concepts involved in the standard energy harvesting approach and synchronous switch harvesting techniques are presented. A comparative analysis of these techniques, highlighting the strengths and limitations of each approach in terms of power conversion efficiency, load independence, implementation complexity and adaptability for system applications are discussed.

Keyword: Energy harvesting systems, standard approach, piezoelectric materials, synchronous switching techniques.

1. Introduction

Energy harvesting [1, 2] has become important in the last few years due to the amount of methods of harvesting energy and the different fields where they already implemented. The energy harvested as small as it is important to power the sensors [3-5] and make them independent [6]. Converting mechanical energy to electrical energy using smart materials has been the choice for many energy harvesting applications such as autonomous devices [7-10].

The most basic energy harvesting topology to increase the harvested power is the standard technique, which directly connects the piezoelectric element to the load R [1]. A regulated output voltage Vc is obtained in Standard technique DC mode (STD DC) by a full-wave diode bridge. The capacitor Cr is used to filter the output voltage Vc. Power output is related to the load impedance R. Therefore, impedance matching is used to optimize the output power. Gi et al. proposed a DC-DC converter to optimize the power output of a piezoelectric harvesting device [11]. Since a piezoelectric energy system is capacitive in most cases, perfect impedance matching is impossible with a resistive load.

In addition, the inductance required for a perfect match is usually unrealistic. To solve this problem, Guyomar et al. [12] proposed an innovative non-linear circuit named as “Synchronized Switch Harvesting on Inductor” (SSHI). This technique used to control vibration by using a piezoelectric damping element and inducing a phase shift between voltage and strain by a simple vibration-synchronized switching process. It consists of inverting the voltage each time it reaches an extremum. Inversion is achieved by a brief oscillation triggered by an electronic switch. It can also be considered as a periodic change in the stiffness of the system due to a continuous change in boundary conditions. The vibration energy is converted into electrical energy stored on the piezoelectric element and dissipated as heat with each switching operation.
The so-called p-SSHl technique modifies the Standard technique by adding in parallel with the piezoelectric element a branch composing an inductor L in series with a switch SW. The switching operation will only take place when the movement of the harvester or the voltage of the piezoelectric element reaches its extreme. Once the voltage resulting from this switching process is in phase with the deformation speed. Harvested electrical power can be increased by more than 400% under low coupling conditions [13].

A similar topology design is the s-SSHl [14], which places the inductor in series with a piezoelectric element. A switch is also connected with the inductor in series following the same control strategy as previous SSHI. This indicates that most of the time the circuit is open circuit and the piezoelectric voltage is determined by the displacement. Once the reverse action occurs, the charge is driven with the piezoelectric voltage.

Therefore, Lallart et al [15] proposed a Double Synchronized Switch Harvesting (DSSH) and Enhanced Synchronized Switch Harvesting (ESSH). These techniques behave equivalently, the main difference between DSSH and ESSH being in the technological solution to emulate the output load.

In DSSH techniques, energy is transferred to the first storage capacitor Cint as series-SSHl does. Then the second switch SW2 is closed to transfer the energy from the intermediate capacitor Cint to the inductance load. In all this process, the charge is totally independent of the energy extraction by the piezoelectric element [16].

The SECE and DSSH techniques exhibit better harvesting ability with load-independent behavior. The harvesting ability of DSSH is determined by γC, the intermediate inversion factor mainly determined by Cint and L2 [17].

This paper is organized as follows. Section II introduces the goal and the compositions of the proposed energy harvesting topologies. Section III provides the theoretical model and simulation study on the energy harvesting circuits. Then, the simulations are conducted to evaluate the comparison between the topologies performance. The same section investigate the energy harvesting ability of this type of circuits. Finally, conclusions from this study are presented in discussions.

2. Energy harvesting Circuit Topologies

2.1 Mechanical and electrical modeling

In previous parts, we talked about the general functionality of piezoelectric energy harvesters. These types of harvesters are only useful and liable for today’s high demanded industry if only the output power is increased while keeping their lengths and volumes as small as possible. However, to increase the output power, other ways must be sought. The most promising approach is to design an efficient interface charging circuits, storage buffers and hot structure configuration. In this part, we will provide a review on different approaches and see how the output power can be enhanced efficiently by changing electrical components of the interface circuits. As it was mentioned before, cantilever beams are the most used configurations in piezoelectric energy harvesters. Their popularity is because they enable relatively high stress levels on the piezoelectric material while reducing the dimensions of the devices [18]. Therefore, in this part all the optimization methods are based on configuration of cantilever beams. Because the piezoelectric power generator is excited at a sinusoidal force, where the first natural frequency causes the maximum power generator with small displacement and the movements are linear, it can be modeled mechanically with a rigid mass (M), spring (K), damper (C) and piezoelectric material. The following figure shows the spring mass model.
The piezoelectric element is modeled by equations (1), F is the force applied to the piezoelectric element. These equations are derived from the constitutive relations [19-21]. They involve the geometrical dimensions of the piezoelectric element.

\[
\begin{align*}
M \ddot{u} + C \dot{u} + Ku &= F - \alpha V \\
I &= \alpha \dot{u} - C_v \dot{V}
\end{align*}
\]  

(1)

With:
- K stiffness of the piezoelectric element when short-circuited.
- \(\alpha (N/V)\) is the factor of the piezoelectric element and V is the output voltage.
- C (F) is the piezoelectric capacitance.

Multiplying this equation by the speed (\(\dot{u}\)) and then integrating the expression will yield:

\[
\int F \dot{u} \, dt = \frac{1}{2} M \dot{u}^2 + \int \frac{1}{2} C \dot{u}^2 \, dt + \int \alpha \dot{V} \, dt
\]

(2)

The following table 1 represents the type of energy for each term.

| Type of Energy | Equation |
|----------------|----------|
| Provided       | \(\int F \dot{u} \, dt\) |
| Kinetic        | \(\frac{1}{2} M \dot{u}^2\) |
| Potential      | \(\frac{1}{2} K u^2\) |
| Dissipated     | \(\int C \dot{u}^2 \, dt\) |
| Transferred    | \(\int \alpha \dot{V} \, dt\) |

**Table 1. Definition of the piezoelectric energies from equations**

From the constitutive equations of piezoelectricity, the current flowing out of the piezoelectric element, I, can be expressed as:

\[
I = \alpha \dot{u} - C_v \dot{V}
\]

(4)

The energy transferred can then be rewritten as:
Wherein the energy transferred is the sum of the electrostatic energy stored on the piezoelectric element and the energy delivered to the connected load \([22-24]\). The second term of the above equation is the collected energy that needs to be improved for better efficiency and output power.

\[
E = \frac{1}{2} \int Vf \, dt
\]

\[
F = \frac{1}{2} \int Vf \, dt
\]

The following figure shows the electrical representation of the piezoelectric material. There is also a load connected parallel to the capacitance, which shows the loaded piezoelectric output voltage in the frequency domain as a function of \(R\).

\[\text{Fig. 2. Uncoupled equivalent circuit of the piezoelectric harvester without and with the the load resistance}\]

The following formulas show the current and voltage where \(V_p\) and \(u\) show the maximum voltage and the maximum displacement.

\[
V_p = \frac{uR}{s\sqrt{2\pi}\omega C_p} \int u \, dt
\]

The average power delivered to the resistive load of the piezoelectric material \((P_h)\) is:

\[
P_h = \frac{u^2 R^2 \omega^2 C_p^2}{4(s^2 + (\omega R C_p)^2)}
\]

### 2.2 Standard circuit description

The configuration of energy harvesting systems are as following. However, the power generated by the piezoelectric devices cannot be used directly as it is generated. Thus, some other electric interfaces have to be used to make the output power compatible with other devices. To maintain this compatibility a basic charging circuit is connected the piezoelectric to convert the AC voltage to DC or in other word a rectifier is connected and then the generated electrical energy goes to a storage buffer to be stored for the later on uses. The most commonly used circuit is called classic interface. The classic interface consist of a diode rectifier, filter capacitor and load \(P_h\) at the terminal. The following figures show the simple configuration of cantilever beam system.

\[\text{Fig. 3. Standard full bridge rectifier}\]
To calculate the output power, we can assume the mechanical displacement of \( u \) is supposed to be a sinusoidal wave and the open circuit \( V \) on the piezoelectric is also sinusoidal. In this method, the diode rectifier is on the blocked mode thus the piezoelectric element is on an open circuit when the absolute value of \( V \) is lower than \( V_{QR} \) across the capacitor. When the value of \( V \) is more than the \( V_{QR} \) a current flows through the capacitor and then to the load. The generated power is the energy produced in a period \( T \) which can be calculated by integrating the product of the voltage and the current under one period. The power is equivalent to:

\[
P = \frac{4R_R^2u^2}{w_{\text{opt}}^2} \frac{1}{(2R_0 + \omega^2 w_{\text{opt}}^2)}
\]  

(10)

However, the power can also be measured experimentally when the circuit is operating. By simply using the power formula, we have:

\[
P = \frac{V^2}{R_L}
\]  

(11)

The disadvantage of this circuit is that the current flowing to the load is discontinuous and the speed is not in phase with the piezoelectric voltage, so the conventional interface circuit will not work effectively. As mentioned, this circuit is only a standard circuit that will not increase power, so the following circuits and the topology network have been suggested to increase power.

### 2.3 Synchronized Switch Harvesting on Inductor in parallel (parallel-SSHI)

The schematic diagram of Synchronized switching harvesting on inductor in parallel (parallel-SSHI) piezoelectric energy harvesting device with full-bridge rectifier to a simple resistor load. This is called SSHI technique. Assuming the structure is excited at resonant frequency and from the governing equation, the piezoelectric energy harvesting device can be modeled as a current source parallel with a clamped capacitor and the equivalent circuit of entire system is shown as Figure x. In this technique, a bi-directional switch and an inductor \( L \) are added in parallel with the piezoelectric patch. The switch is conducted at each maximum and minimum of the displacement or at the zero crossing of the vibration velocity, in order to reverse the voltage across the piezoelectric element and put it in phase with velocity.

![Fig. 4. Piezoelectric energy harvesting system with parallel SSHI technique](image)

The result is that the energy stored in the structural clamped capacitor \( C_0 \) is extracted by the LC resonance and achieve to a minimum value, and thus the piezoelectric voltage can be increased [17]. The harvested energy of the system with the SSHI technique is similar to that using the standard interface under the strongly coupled condition [18].

\[
P_{\text{SSH}} = \frac{4R_R^2}{(2R_0 + \omega^2 w_{\text{opt}}^2)} \frac{1}{(2R_0 + \omega^2 w_{\text{opt}}^2)}
\]  

(12)
3. Synchronized Switch Harvesting on Inductor in Series (Series-SSHI)

The schematic diagram of synchronized switching harvesting on inductor in series (Series-SSHI) piezoelectric energy harvesting device with full-bridge rectifier to a simple resistor load.

![Fig. 5. Piezoelectric energy harvesting system with series SSHI technique](image)

The piezoelectric energy harvesting device can be modeled as a current source parallel with a clamped capacitor and the equivalent circuit of entire system.

\[
P_{\text{in}} = \frac{V_p^2}{R_{\text{eq}}} = \frac{\tau_1 \tau_2}{\tau_1 + \tau_2} \frac{V_p^2}{2} L^2
\]  

(13)

4. DSSH technique

The DSSH technique optimizes the electromechanical conversion. It also gives a fixed harvested energy regardless of the load. This technique uses a capacitor as an intermediate energy storage stage. The intermediate stage stores energy and transmits the additional energy to the resonant inductor and finally to the load via the smoothing capacitor. This helps the phase alignment of voltage and current. In addition, we get a fixed output and the dead zone present in previous models is removed.

Next, the operation of the DSSH circuit is explained. For the majority of the time, the piezoelectric element is kept in open circuit form. When the voltage on the piezoelectric element reaches the maximum point, the switch S1 is turned on. The time period for which this switch is closed is very small but enough for the capacitor to get charged to its maximum point. At this point, energy is transferred to the capacitor from the piezo element.

When maximum energy transfer is complete, the switch S1 is turned off and simultaneously the switch S2 is turned on. At this point, energy transfers from the capacitor to the inductor. When total energy is transferred to the inductor, the switch S2 opens and directly the diode conducts due to its natural nature.

When the diode conducts, energy is transferred to the smoothing capacitor and finally to the load. As all these processes get completed, the circuit starts operating for the initial operation.
With \( \gamma C \), the overall efficiency of the converter, given by

\[
\eta = e^{-\frac{R}{R_L}}
\]  

With \( \omega_{int} \) and \( \xi_{int} \), the natural angular frequency and the damping coefficient of the system, respectively, defined as

\[
\omega_{int} = \sqrt{\frac{k}{m}} \quad \xi_{int} = \frac{1}{2\omega_{int}}
\]

Finally, it can be seen that the harvested energy does not depend on the rectified voltage VDC, and is therefore independent of the value of the load resistance RL.

5. Modelization and Simulation of energy harvesting techniques

5.1 Energy harvesting techniques modelization

The deformation of a piezoelectric membrane induces a polarization of the piezoelectric material and a charge transfer proportional to the stress:

\[
\mathbf{q} = \alpha \cdot \mathbf{u}
\]

Where \( \mathbf{q} \) is the displaced load (C), \( \alpha \) the coefficient of deformation (C/m) and \( \mathbf{u} \) the deformation (m).

\[i_{PZ} = \alpha \cdot \dot{u}\]

Conventionally, in a first approach, the beam and piezoelectric membrane device is modeled in the near of resonance by a current source \( i_{PZ} \) in parallel with a capacitor C (fig. 7).

5.2 Simulation of energy harvesting techniques

This model is then used in PSIM by adding the recovery device. We only simulate a rectifier delivering on a constant direct current source IS. In order to understand the operation and to calculate the harvested power in steady state, this part is important for the comparison and understanding of the system because the currents are difficult to measure in practice.

With the gain of a circuit \( G_{output} = \frac{\text{output}}{\text{standard}} \) and \( \Delta = \frac{P_{out}}{P_{int}} \),
Fig. 8a. Standard Circuit compositions

Fig. 8b. Piezoelectric Input voltage and current

Fig. 8c. Piezoelectric input power and Standard output power

Fig. 8d. Piezoelectric input power

Fig. 8e. Standard output Power

The Standard technique performance

\[ R_{off} = 71.5 \text{mW} \]  
\[ R_{on} = 22.3 \text{mW} \]
\[
\text{standard} = \frac{P_{\text{IN}}}{P_{\text{OUT}}} = 0.3
\]

(20)

\[
P_{\text{DIFF}} = P_{\text{IN}} - P_{\text{OUT}} = 71.5\text{mW} - 22.2\text{mW} = 49.3\text{mW}
\]

(21)

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**Fig. 9a. SHHL-s Circuit compositions**

**Fig. 10b. Piezoelectric Input voltage and current**

**Fig. 11c. SHHL-s Output voltage and current**
Fig. 12d. Piezoelectric Input power

Fig. 13e. SHHL-s Power output

The SHHL-s performance

\begin{align}
\text{SHHL-s} & = \frac{\text{output power}}{\text{input power}} \\
\text{SHHL-s} & = 6.5 \text{ Standard} \\
\text{SHHL-s} & = 650\% \text{ Standard}
\end{align}

Fig. 14 a. SHHL-p Circuit compositions

Fig. 15 b. Piezoelectric Input voltage and current

Fig. 16 c. SHHL-p Output voltage and current
Fig. 17 d. Piezoelectric Input power

Fig. 18 e. SHHL-\( p \) Power output

The SSHL-\( p \) performance

\[
\begin{align*}
G_{SSHLP} &= \frac{SSHLP}{\text{standard}} \\
\text{SSHLP} &= 74\% \text{ standard} \\
\text{SSHLP} &= 74\% \text{ standard}
\end{align*}
\]  

Fig. 19a. DSSH Circuit compositions

Fig. 11b. Piezoelectric Input voltage and current
The DSSH performance:

\[
Q_{\text{DSSH}} = \frac{Q_{\text{non-linear}}}{Q_{\text{standard}}} 
\]

\[
DSSH = 6 
\]

\[
DSSH = 600\% 
\]

6. Discussions

The Figure 11 illustrates the harvested power as a function of the optimal load and the comparison with non-linear techniques and standard circuit,

All these topologies of non-linear circuits show an improvement in harvesting power compared to the STD technique. The gain is around 800% for p-SSHI, 700% for s-SSHI, 600% for DSSH and 400% for SECE. SSHI parallel and SSHI series depend on the frequency of variation, energy harvesting cannot be optimal over a large frequency band, which contradicts the fact that the system can oscillate over a wide frequency range. The DSSH technique does not present optimal resistance; it allows an efficient recovery whatever the frequency of variation.
7. Comparison of energy harvesting techniques

A comparison between the parameters is needed for the final result. Table 2 gives an overview of the balance between the energy harvesting techniques.

| Technique                                      | Interface Standard | SHHI-s | SHHI-p | DSSH & ESSH |
|------------------------------------------------|--------------------|--------|--------|-------------|
| Normalized power under constant vibration amplitude | Low                | Good   | Good   | Medium      |
| How is the energy harvested under low electromechanical coupling regime? | Poor               | Good   | Good   | Good        |
| How is load independence?                      | Poor               | Poor   | Poor   | Very Good   |
| How is low voltage harvesting?                 | Poor               | Good   | Poor   | Good        |
| Implementation complexity?                     | Any                | Low    | Low    | Medium      |

Table 2. Summarizes the performances of these techniques in terms of harvested power, advantages and drawbacks.

8. Conclusion

This paper investigates and compares the efficiencies of four different interfaces for vibration based energy harvesting systems. This paper illustrates the power versus the load impedance for a given piezoelectric energy harvester excited in forced displacement mode. Both SHI techniques have significant power harvesting ability. To harvest a given level power, p-SSHI and s-SSHI have a wider load range compared with STD technique. The SECE and DSSH techniques exhibit better harvesting ability with a load-independent behavior. The harvesting ability of DSSH is determined by $\gamma C$, the intermediate inversion factor mainly determined by $C_{\text{int}}$ and $L_2$, but with load sensitive SHI performance for high load impedance operation. All of these nonlinear circuit topologies show improvement harvested power compared to STD technique. The gain is around 800% percent for p-SSHI, 700% for s-SSHI, and 600% for DSSH. Many problems arise when deploying these non-linear...
energy harvesting topologies. They rely on signal detection, switch operation, inductors, complex circuitry, and optimal load. Even the load-independent DSSH and ESSH have optimal load region due to the oscillation and losses in circuitry. On one hand, the tradeoff between feasibility and high harvested power should be considered. On the other hand, it is worthy to find an energy harvesting circuit with simple topology and strong power harvesting capability.
References

[1] Ennawaoui, C., Lifi, H., Hajjaji, A., Elballouti, A., Laasri, S., & Azim, A. (2019). Mathematical modeling of mass spring’s system: Hybrid speed bumps application for mechanical energy harvesting. Engineering Solid Mechanics, 7(1), 47-58.

[2] Zhang, Y., Bowen, C. R., Ghosh, S. K., Mandal, D., Khanbareh, H., Arafah, M., & Wan, C. (2019). Ferroelectret materials and devices for energy harvesting applications. Nano Energy, 57, 118-140.

[3] Hajjaji, A., Guyomar, D., Touhtouh, S., Pruvost, S., Boughaleb, Y., Rguiti, M., ... & Benkhouja, K. (2010). Nonlinearity and scaling behavior in a soft lead zirconate titanate piezoceramic. Journal of Applied Physics, 108(6), 064103.

[4] Yang, L., Chi, S., Dong, S., Yuan, F., Wang, Z., Lei, J., ... & Wang, J. (2020). Preparation and characterization of a novel piezoelectric nanogenerator based on soluble and meltable copolyimide for harvesting mechanical energy. Nano Energy, 67, 104220.

[5] Wilson, S. A., Jourdain, R. P., Zhang, Q., Dorey, R. A., Bowen, C. R., Willander, M., ... & Johansson, C. (2007). New materials for micro-scale sensors and actuators: An engineering review. Materials Science and Engineering: R: Reports, 56(1-6), 1-129.

[6] Hajjaji, A., Benayed, A., Sebald, G., Pruvost, S., Guiffard, B., Qiu, J., & Guyomar, D. (2008). Synthesis and characterization of 0.65 Pb (Mg1/3Nb2/3) O3–0.35 PbTiO3 fibers with Pt core. Materials Research Bulletin, 43(3), 493-501.

[7] Zhukov, S., von Seggern, H., Zhang, X., Xue, Y., Ben Dali, O., Pondrom, P., ... & Kupnik, M. (2020). Microenergy Harvesters Based on Fluorinated Ethylene Propylene Piezotubes. Advanced Engineering Materials, 1901399.

[8] Hajjaji, A., Guyomar, D., Pruvost, S., Touhtouh, S., Yuse, K., & Boughaleb, Y. (2010). Temperature/electric field scaling in Ferroelectrics. Physica B: Condensed Matter, 405(13), 2757-2761.

[9] Wegener, M., & Bauer, S. (2005). Microstorms in cellular polymers: A route to soft piezoelectric transducer materials with engineered macroscopic dipoles. ChemPhysChem, 6(6), 1014-1025.

[10] Ennawaoui, C., Lifi, H., Hajjaji, A., Samuel, C., Rguiti, M., Touhtouh, S., ... & Courtois, C. (2019). Dielectric and mechanical optimization properties of porous poly (ethylene-co-vinyl acetate) copolymer films for pseudo-piezoelectric effect. Polymer Engineering & Science, 59(7), 1455-1461.

[11] Gi, H., Park, J., Yoon, Y., Jung, S., Kim, S. J., & Lee, Y. (2020). A Soft-Charging-Based SC DC-DC Boost Converter With Conversion-Ratio-Insensitive High Efficiency for Energy Harvesting in Miniature Sensor Systems. IEEE Transactions on Circuits and Systems I: Regular Papers.

[12] Guyomar, D., & Lallart, M. (2011). Recent progress in piezoelectric conversion and energy harvesting using nonlinear electronic interfaces and issues in small scale implementation. Micromachines, 2(2), 274-294.

[13] Garbuio, L., Lallart, M., Guyomar, D., Richard, C., & Audigier, D. (2009). Mechanical energy harvester with ultralow threshold rectification based on SSHI nonlinear technique. IEEE Transactions on Industrial Electronics, 56(4), 1048-1056.

[14] Nechibvute, A., Chawanda, A., Luhanga, P., & Akande, A. R. (2012). Piezoelectric energy harvesting using synchronized switching techniques. International Journal of Engineering and Technology, 2(6), 936-46.

[15] Lallart, M., Garbuio, L., Petit, L., Richard, C., & Guyomar, D. (2008). Double synchronized switch harvesting (DSSH): A new energy harvesting scheme for efficient energy extraction. IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 55(10), 2119-2130.

[16] Lallart, M., & Guyomar, D. (2008). An optimized self-powered switching circuit for nonlinear energy harvesting with low voltage output. Smart Materials and Structures, 17(3), 035030.
[17] Lallart, M., Anton, S. R., & Inman, D. J. (2010). Frequency self-tuning scheme for broadband vibration energy harvesting. *Journal of Intelligent Material Systems and Structures, 21*(9), 897-906.

[18] Erturk, A., & Inman, D. J. (2008). Issues in mathematical modeling of piezoelectric energy harvesters. *Smart Materials and Structures, 17*(6), 065016.

[19] Ennawaoui, C., Hajjaji, A., Azim, A., & Boughaleb, Y. (2016). Theoretical modeling of power harvested by piezo-cellular polymers. *Molecular Crystals and Liquid Crystals, 628*(1), 49-54.

[20] Meddad, M., Eddiai, A., Cherif, A., Hajjaji, A., & Boughaleb, Y. (2014). Model of piezoelectric self powered supply for wearable devices. *Superlattices and Microstructures, 71*, 105-116.

[21] Belhora, F., Cottinet, P. J., Hajjaji, A., Guyomar, D., Mazroui, M. H., Lebrun, L., & Boughaleb, Y. (2013). Mechano-electrical conversion for harvesting energy with hybridization of electrostrictive polymers and electrets. *Sensors and Actuators A: Physical, 201*, 58-65.

[22] Lefevre, E., Audigier, D., Richard, C., & Guyomar, D. (2007). Buck-boost converter for sensorless power optimization of piezoelectric energy harvester. *IEEE Transactions on Power Electronics, 22*(5), 2018-2025.

[23] Meddad, M., Eddiai, A., Guyomar, D., Belkhtat, S., Cherif, A., Yuse, K., & Hajjaji, A. (2012). An adaptive prototype design to maximize power harvesting using electrostrictive polymers. *Journal of Applied Physics, 112*(5), 054109.

[24] Lifi, H., Ennawaoui, C., Hajjaji, A., Touhtouh, S., Laasri, S., Yessari, M., & Benjelloun, M. (2019). Sensors and energy harvesters based on (1-x) PMN-xPT piezoelectric ceramics. *The European Physical Journal Applied Physics, 88*(1), 10901.