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Study and design the circuit for piezoelectric vibration energy harvester to charge a datalogger

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ABSTRACT

The studies presented in this paper focus on the recovery of vibrational energy using a piezoelectric beam. The device implemented in this work is quite far from industrial realities, but it has the advantage of being easily reproducible and inexpensive. In a first step we will design a circuit for mechanical Energy Harvesting. In practice these systems recover the little energy from ambient vibrations in order to power low consumption electrical systems (typically from a few µW to mW). After comparison with a basic recovery system (diode bridge) examined both experimentally and by simulation, the model is used on a more efficient recovery system. This study focuses on non-linear circuit topologies, and the improvement of the recovered power compared to the standard technique (STD) To charge a datalogger. The simulation results of this system evaluate an improvement of 325% compared to the standard system.

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1. INTRODUCTION

In recent years, applications using piezoelectric materials have developed considerably. The advantage of these materials is that they strongly couple mechanical and electrical quantities. The main interest of piezoelectric materials is that they allow to act on the mechanical state of a structure by modifying the electric field applied to the material. This has led to the applications of vibration control and positioning actuator. By promoting the flow of charges in a piezoelectric material bonded to a structure, it is possible to extract small powers (ranging from micro or milliwatt). Finally, piezoelectric materials have found a particularly interesting field of application in the conversion of electrical energy: piezoelectric transformers are an advantageous replacement for electromagnetic transformers, especially for applications subject to miniaturization. In general, their use tends to develop in mobile or embedded electronic devices [1].

Low-energy communicating devices are increasingly used for home automation or personal health monitoring [1], [2]. The recovery of energy from ambient vibrations [3] is an alternative to avoid the use of batteries or to increase the lifetime of systems. We present here the possibilities offered by a piezoelectric membrane recuperator attached to a vibrating beam to power a low-power wireless communication module. This module is the basic building block of a wireless sensor network [4-7]. The piezoelectric device is presented in a first part with its excitation and measurement system. The second part shows the experiments necessary for the modeling and explains the resulting model [8]. The energy harvesting is then implemented in the third part with a comparison between the experimental results and those from simulations for the simplest device. The last part analyzes the amount of energy needed to power the communication module and compares it with the energy actually recovered [9,10]. The converters to be possibly inserted between the storage and the load are also discussed in this part.

2. THEORETICAL MODELING AND DISCUSSION

2.1. Fundamental equations of piezoelectricity

Piezoelectricity is a physical phenomenon present in certain materials with a crystalline structure. A piezoelectric material is, by definition, capable of coupling elastic and electrical energies. The piezoelectric effect exists in two forms detailed below: the direct effect and the inverse effect [11].

The linear equations constituting piezoelectricity, linking mechanical quantities to electrical quantities, can be expressed in four different ways. For each pair of equations (1) to (2), a mechanical quantity (S or T) and an electrical quantity (D or E) are determined as a function of the remaining quantities. Each pair of equations involves three different coefficients [12-14]:

$$\begin{cases} \boldsymbol{S = s^{E}T + d^{t}E} \\ \boldsymbol{D = dT + \varepsilon^{T}E} \end{cases} \tag{1}$$

$$\begin{cases} \boldsymbol{T = c^{E}T - e^{t}E} \\ \boldsymbol{S = eS + \varepsilon^{S}E} \end{cases} \tag{2}$$

For reasons of cost and availability, the recuperator consists of a vibrating beam on which a piezoelectric membrane is glued. The electromagnet driven by an LM12 audio amplifier is used to set the beam in vibration (figure 1). The frequency and the excitation level are regulated by a function generator. An accelerometer and its conditioner delivers an image voltage of the acceleration. The accelerometer also serves as a seismic mass.

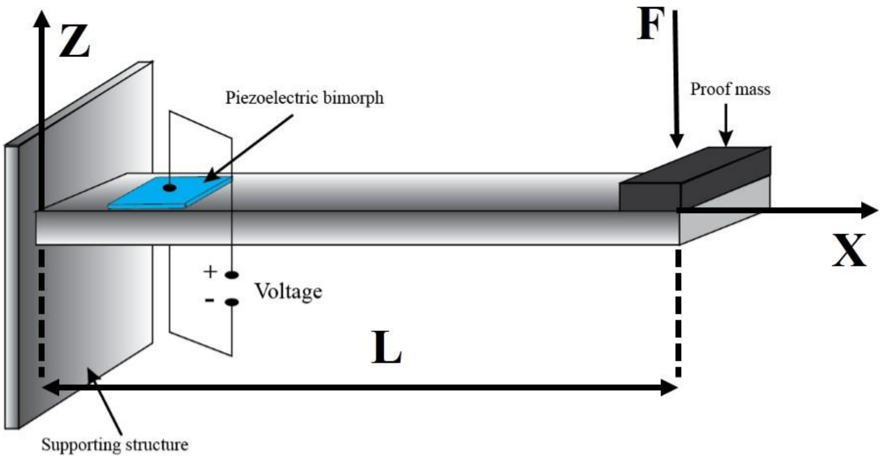

Figure 1. Cantilever beam piezoelectric system

$$\begin{cases} \boldsymbol{M\ddot{u} + C\dot{u} + Ku = F - \alpha V} \\ \boldsymbol{I = \alpha\dot{u} - C_{p}\dot{V}} \end{cases} \tag{3}$$

Where :

- K stiffness of the piezoelectric element when short-circuited,
- α (N/V) is the factor of the piezoelectric element and V is the output voltage
- Cp is the piezoelectric capacitance

2.2. Basic structure

The objective of this part is to design a system to recover and store the charges moved during the movements of the beam and the piezoelectric membrane in order to feed the datalogger. Given the alternating

nature of the voltage produced by the transducer, the simplest solution is the single-phase rectifier with capacitive filtering.
use the simulation tool with I_{PZ} = 2 mA and C_L = 10µF. By modifying the current consumed by the load (Is), they record P and V_{DC}.Compared to the analytical expression, the simulation allows to understand intuitively that the power supplied is directly related to the level of the rectified voltage.

The problem of impedance matching is addressed here by the simulation, but it can also be studied in practice by varying the P_C load resistance and calculating the R_C power supplied in steady state from the V_{DC} measurement.

$$P_C = \frac{V^2}{R_C} \quad (4)$$

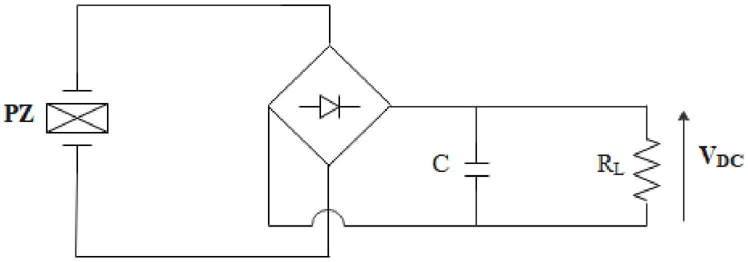

Figure 2. Standard full bridge rectifier

The assembly shown in figure 2, replacing the datalogger load. The V_{PZ} voltage is measured using a high impedance isolation sensor and sent to the oscilloscope.

2.3. Feeding of a datalogger

Here we are trying to model the consumption of the datalogger which presents a continuous consumption in standby mode I_S = 5µA under 5V, and a momentary consumption in active mode when it performs a measurement and sends a data. This consumption is 16mA at 5V during T_{MES} = 1s, i.e., an P_{MES} power of 1.2 mW. Measurements and transmissions are made every T_{CYCLE} = 10 min.
The piezoelectric recuperator must therefore provide an average power over a measurement cycle of:

$$\langle P \rangle = V_{DC}.I_S + \frac{E_{MES}}{T_{CYCLE}} \quad (5)$$

In order to guarantee an almost constant V_{DC} bus voltage, we dimension the capacitance C_L assuming that C_L absorbs consumption peaks without any noticeable voltage drop so that the V_{DC} voltage drop does not exceed 0.5V during the short measurement and transmission phases.

$$E_{MES} = \frac{1}{2} C_L.\left(V_{max}^2 - V_{min}^2\right) \quad (6)$$

Which gives a C_L value close to 10 µF. As these simulations are relatively heavy, a total duration of 2 minutes is simulated taking into account the signals rectified at 100.5 Hz. It is important to set as precisely as possible the number of points per period during the test phases.
The device is properly sized for the application, but it does not operate at the operating point or maximum recoverable power. Indeed, as we have seen previously, the recoverable power depends very strongly on the V_{DC} voltage. The recovery is really not optimal, because the I_D current at the output of the rectifier is zero for a large part of the period. Indeed, at each half-wave, the voltage across the piezoelectric terminals must be inverted, and the dynamics of this inversion is proportional to the excitation frequency of the piezoelectric. To improve energy recovery, many techniques exist. It is also possible on the one hand to add to this device a mini converter in order to adapt the load impedance seen from the recovery device and on the other hand to use another control structure as discussed in the following paragraph with a LT1764 structure.

3. PRINCIPLE OF OPERATION

Energy management systems Several energy recovery systems have been realized during the last ten years but a majority of them use a secondary source. Examples of realizations of autonomous systems in this part that seem relevant to me. The autonomous system proposed by Amirtharajah [4], is a DSP (Digital Processor Signal) powered by an electromagnetic generator. The circuit for the passage of energy between the generator and the DSP consists of a transformer that acts as a voltage booster followed by a rectifier and a DC/DC converter. The circuit diagram is presented on the below.

Ottman [5] introduced an energy recovery structure in 2002. This structure optimizes the energy that passes between the piezoelectric generator and the battery. It contains a rectifier and a DC-DC converter. It also uses a voltage step-down chopper whose switching duty cycle is automatically adjusted to maximize the output power. It was necessary to add a duty-cycle control circuit because the duty-cycle has a great influence on the current in the battery. The results showed that the recovered energy could be increased by 400% compared to a direct load without a converter.

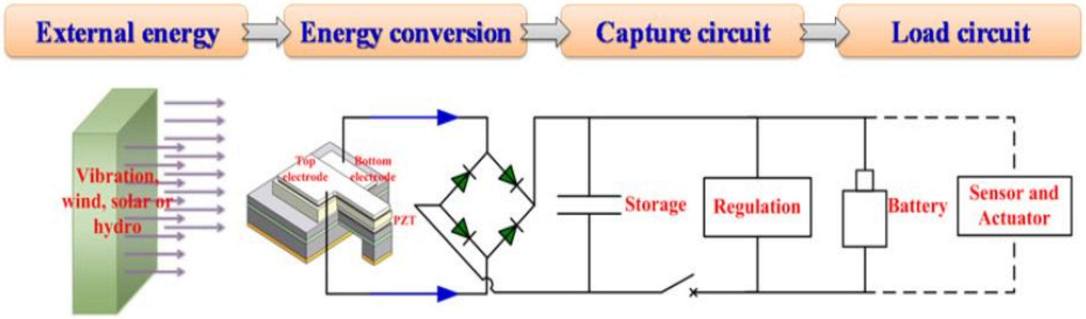

Figure 3.Block diagram of proposed system

3.1. Power conditioning circuit

This model is then used in LtSpice by adding the recovery device. In a first step. We only simulate a rectifier delivering on a constant direct current I_S source (by changing IS, we modify the consumption of the load). In order to understand the operation and to calculate the recoverable power in steady state, we observe the input and output currents and voltages of the rectifier with capacitive filtering (figure 4). This part is important for the understanding of the system because the currents are difficult to measure in practice.

This technique uses a circuit consisting of a diode bridge and a flyback converter. A control circuit is necessary to control the switching sequence of the switch (the MOSFET transistor acts as a switch). The converter is controlled by the gate voltage V_G of the PMOS and NMOS transistor. This voltage is determined by a control circuit which checks the maximum voltage of V_R and when V_R is zero.

When the VR voltage reaches a maximum voltage, a voltage of 10V is applied to the transistor gate. The transistor is then on (switch closed) and allows the transfer of energy from the piezoelectric element to the inductance L. When all the loads are transferred, the transistor becomes off (switch open) and the inductance is discharged into the storage capacitor that feeds a load R.

The general model of a piezoelectric element can be represented by a current generator, in parallel with a capacitance. The value of the capacitance (3.3 nF). The value of the resistance not being specified, I chose a rather high value (150 kΩ) knowing that an MFC has a high impedance. Finally, the value delivered by the current generator (2 mA) was chosen so as to have a current lower than 200 µA at the terminals of the capacitance. We are therefore in the same conditions as before (R=220 Ω, C=10µF, diode bridge). It can be seen that the resistor charges in about 180 seconds to reach a voltage of 9.5 Volts. This is rather consistent with the results obtained.

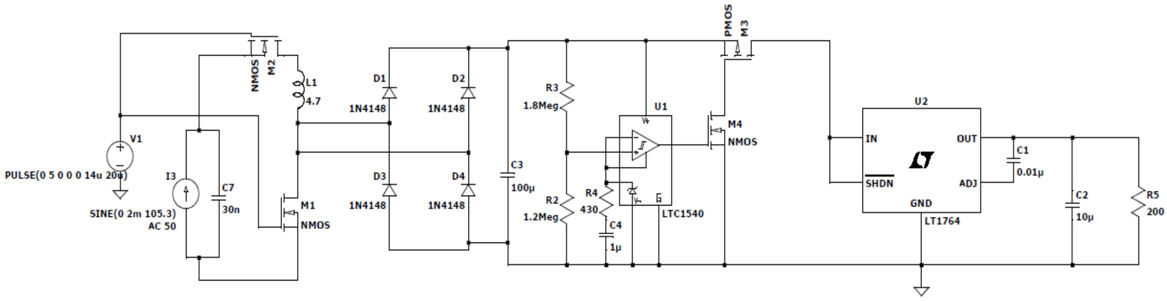

Figure 4. Block of a SECE circuit in LtSpice

The circuit for triggering the control signal of transistor T1 and T2. T1 is of PMOS type while T2 and T3 are of NMOS type. T1 and T2 form a PUT (Programmable Unijunction Transistor) and is used as a trigger allowing the transistor T3 to be turned on or off at the required time. When the voltage V at the output of the diode bridge reaches a maximum, the value of the voltage Ve1 at the emitter of T1 minus the voltage V_{C2} at the collector of T2 and the base of T3 is maximized. Therefore, switch T3 is immediately switched on, and the electrical energy is then transferred to the inductance L.

3.2. LT1764 Vibration Energy Harvesting Systems

The LT1764 energy harvesting systems were proposed by Linear Technology.

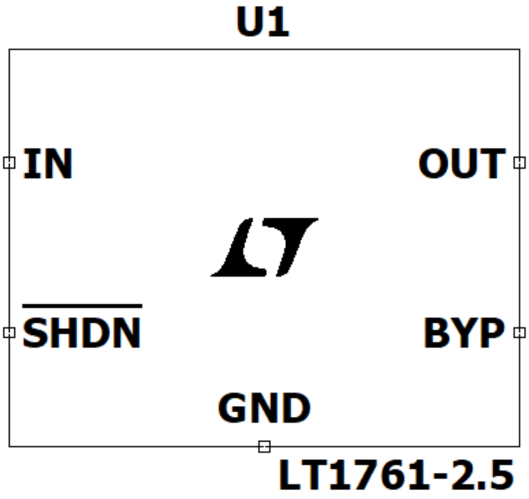

Figure 5. The circuit LT1764-2.5

The LT1764 is a low dropout regulator optimized for fast transient response. The device is capable of supplying 3A of output current with a dropout voltage of 340mV. Operating quiescent current is 1mA, dropping to <1µA in shutdown. Quiescent current is well controlled; it does not rise in dropout as it does with many other regulators. In addition to fast transient response, the LT1764 has very low output voltage noise which makes the device ideal for sensitive RF supply applications. Output voltage range is from 1.21V to 20V. The LT1764 regulators are stable with output capacitors as low as 10µF. Internal protection circuitry includes reverse battery protection, current limiting, thermal limiting and reverse current protection. The device is available in fixed output voltages of 1.5V, 1.8V, 2.5V, 3.3V and as an adjustable device with a 1.21V reference voltage. The LT1764 regulators are available in 5-lead TO-220, DD and Exposed Pad 16-lead TSSOP packages

3.3. simulation test setup

The electrical characteristics of piezoelectric generators are generally not very favorable: high voltage and AC voltage, low current, high output impedance. Thus, the energy produced by these piezoelectric generators is generally not directly usable for powering conventional electronic devices. As a rule, an energy recovery module is used in which the piezoelectric generator is coupled to a diode bridge to convert the AC voltage into DC voltage. The diode bridge is followed by a battery or filter capacitor.

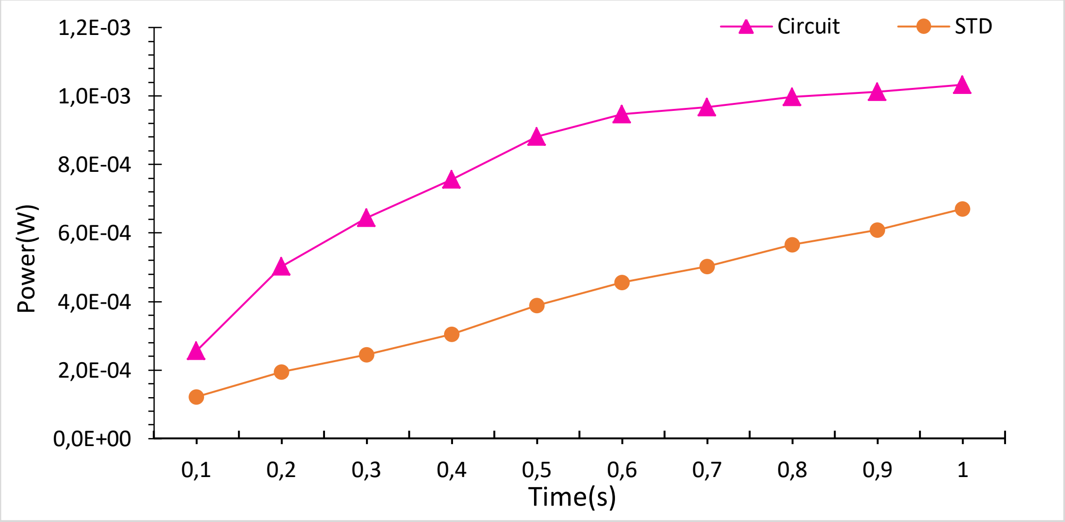

Figure 6. Power variations as a function of the time in 105.3 Hz

Figure 6 show Power supplied by the P_{PZ} recuperator If we place ourselves in the same conditions and with the optimum values of the previous section (f=100.5Hz, R=220Ohms) and add the diode bridge followed by a resistor as shown in the diagram below, we obtain an RMS voltage Ueff=5.7 Volts. Thus we have a power which is P=1.1 mW and therefore higher than before because the voltage is rectified.

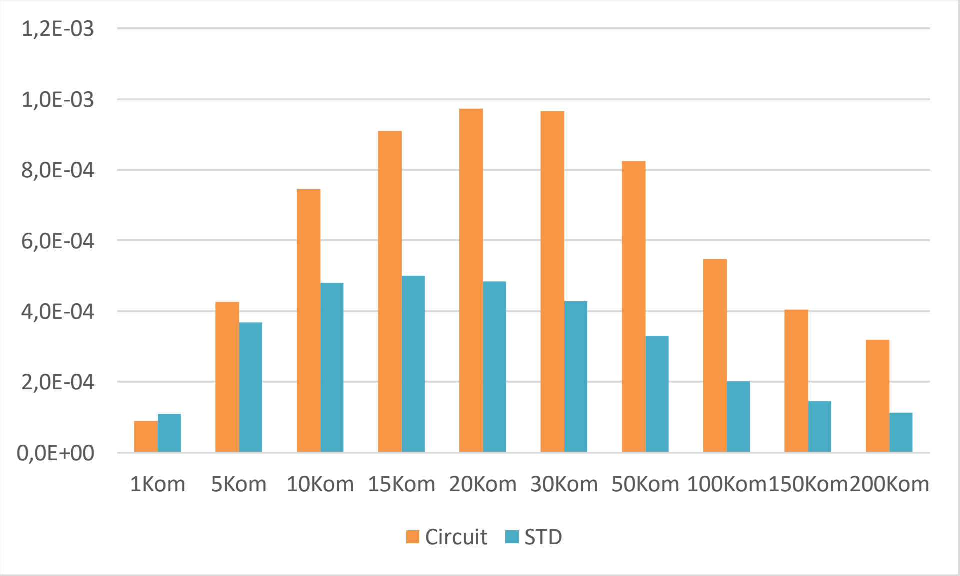

Figure 7. Power variations as a function of the load

In this study, we find that the power recovered from a voltage rectified with a diode bridge can be of the order of 1.2 mW. The current is of the order of 100 µA. I did not carry out the tests for lower resistance values because I did not manage to obtain other time slots to carry out experiments since researchers are working on the same vibratory system. Now let's add a capacitor to store energy instead of the resistor. I proceeded in 2 steps. I visualized the charge of the capacitor without the resistor in the circuit.

Then I discharged the capacitor on a 100 kΩ resistor. We can see that the resistor consumes 90% of the energy stored by the capacitor in about 2 min. The resistor actually plays the role of a battery that charges itself. The equivalent diagram below is the simulation on the LtSpice software of the circuit tested previously.

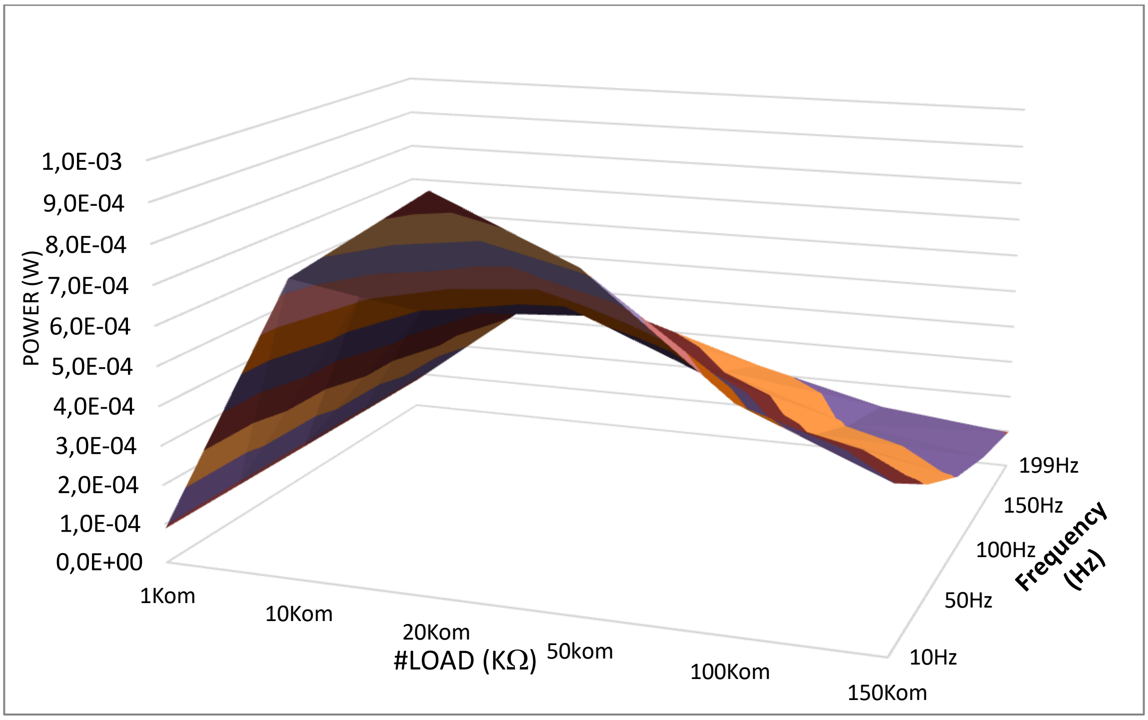

Figure 8.Power variation as a function of load and frequency

Figure 8 shows the percentage of each component in the performance points (f, R), the performance of the circuit is good at (f = 10Hz, R = 1kΩ), with the diode ratio close to the maximum power at the same coordinates (f = 10Hz, R = 10k), the peak power for the circuit (f = 100Hz, R = 50kΩ).

Noting that for sufficiently high load levels the optimal value of the duty cycle is approximately constant. The results for charging a battery using this system indicate an improvement of 325% compared to direct charging. In additions, the energy collected is then 3 times greater. The flyback converter then delivers a useful power of 1.3mW for a load resistance between 200Ω and 55kΩ, which corresponds to an output voltage between 2.5V and 25V.

4. CONCLUSION

The energy harvesting of vibration is a rather delicate research subject because the main objective is to realize autonomous energy harvesting circuits with components that consume very little energy.

However, this subject is a promising field. The realization of autonomous micro-generators corresponds to a real need, either for the power supply of portable electronic devices of common use, or within the framework of wireless sensor networks. Following the results obtained and the comparison of the powers supplied by each system according to the current consumed by the load.

The results are presented. As for the diode bridge, it is observed that the recoverable power (as well as the DC bus voltage) evolves as a function of the current consumed. The circuit device allows to recover much more power. If we consider that between the circuit and the datalogger we have a lossless system allowing to adapt the impedance.

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