# Energy Harvesting Circuit Using Variable Capacitor with Higher Performance

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**ABSTRACT**

The search for compact autonomous devices has been increasing in the microelectronics industry. These devices have the capacity to generate their own energy in order to be charged. One of the ways of harvesting environmental energy for charging such devices is by using mechanical vibrations through the use of variable capacitor. Taking this principle into account, this work presents a behavioral analysis of a system model of harvesting vibratory energy for low power, made up of a circuit which includes a variable capacitor. An architecture of a circuit which improves the relation concerning the amount of harvested energy/circuit area in relation to conventional architectures is also presented as well as a comparison between the circuit with the proposed architecture and the conventional circuit. In this way, it was verified that, under the same functioning conditions, the conventional circuit harvested a maximum power of 4,5 μW whereas the circuit with the new architecture harvested a 6,25 μW power.

**Index Terms:** Vibratory energy harvesting, variable capacitor, energy conversion, DC/DC power conversion

## 1. INTRODUCTION

With the development of the micro and the nanotechnology, the electronic devices have been in rapid advancement. In this process, the size reduction is followed by the energy consumption reduction. Along with these advancements, new sources of energy are also researched, in particular, the so-called autonomous sources. These sources are integrated to these devices in order to make them independent from the external energy sources [1]-[3]. Autonomous sources are able to capture energy in different ways, such as light, vibration, heat and electromagnetic waves from the environment where they are inserted.

Among the autonomous devices, the autonomous sensors are pointed out once they are devices able to act without the need of other components. They generate the necessary energy to feed their circuits; they read the sensors, process the signals and send them via wireless by means of frequency radio. The tendency of these technologies is that only one chip will be able to contain the autonomous source, the sensor of the magnitude to be measured, the transmitter circuit and the control circuit to manage the whole functioning process.

The autonomous sensors have great advantages in relation to the conventional ones. First of all, there is a reduction of the wire quantity used for the electrical connections between the source and the several sensors. A second advantage is the fact that there is no need for replacing the chemical batteries used for feeding the sensors.

Many devices can have the mechanical vibrations as a single way of harvesting energy because such devices can be inside machines, automobiles or spacecrafts in which there is no other way of harvesting. In these situations, the energy from the vibrations can be converted into electrical energy through the use of piezoelectric materials, electromagnetic systems, or by means of electrostatic charges using variable capacitors [1], [4]. This research focuses on the energy conversion of mechanical vibrations into electrical energy with the use of an electrostatic transducer, represented by a variable capacitor of MEMS technology.

The harvesting of electrical energy through a variable capacitor is an alternative for attaining a great quantity of energy in a reduced space. The energy harvesting in this system is proportional to the square voltage over the variable capacitor and the new technologies provide the use of higher and higher voltages. Integration becomes simpler as well because the variable capacitors can be built in its circuit substrate [4]-[7].

The architecture of energy harvesting circuit is object of several studies with the intention to obtain a higher energy amount [4]-[8]. In general, this architecture is built from a charge pump and a flyback circuit. Some critical points are verified in this architecture. One of them is the physical construction of the flyback circuit switch that consumes much energy due to the high work voltage and its high commutation frequency. As to the second point, the control circuit construction is complex and it consumes much energy.

In this research, a new architecture of a circuit for vibratory energy harvesting of low power by using variable capacitor is shown. The proposed architecture reduces the flyback circuit use by diminishing the switch losses and simplifying the control circuit. Moreover, it attains a noteworthy increase in the energy harvesting. The proposed architecture was compared to a conventional architecture and it harvested a higher amount of energy. A model VHDL-AMS for the transducer and a model for the ELDO for simulating the electrical circuit were used.

## 2. ENERGY HARVESTING THROUGH CIRCUITS WITH VARIABLE CAPACITOR

An option for producing electrical energy through electrostatic charges is the use of two electrodes in parallel in order to form a capacitor. One of the electrodes is connected to a proof mass and it displaces itself during the vibration in relation to the second electrode which is fixed in the substrate [6]. In this kind of transducer, the capacitance varies from a maximum value to a minimum one. It is represented in figure 1, the structure of the variable capacitor [9].

According to expression (1), the charge stored in a capacitor is function of its capacitance and its voltage. By charging a variable capacitor with an initial charge, and then, leaving its terminals open so that the value of this charge does not change, while a capacitance variation is taking place, there will also be a change in voltage over the capacitor. The voltage increase, which occurred in the variable capacitor when the capacitance value decreases, is used to boost electrons in the circuit, working therefore as charge pump. The energy taken by each variation cycle of the capacitor is given by the expression (2) in which $V_{in}$ is the initial voltage of the capacitor, $C_{max}$ and $C_{min}$ are the maximum and minimum values of the variable capacitor, respectively.

$$Q = (C * V) \tag{1}$$

$$E = \frac{1}{2} V_{in}^2 (C_{max} - C_{min}) \tag{2}$$

It is represented in Figure 2 the conventional resonant circuit used for electrical energy harvesting through electrostatic charges. The circuit can be divided into three parts: the first part is the charge pump which boosts the electrons to go round the circuit, composed of $C_{res}$, $C_{var}$, $C_{store}$, $D_1$ and $D_2$; the second part is the flyback circuit which is responsible for the return from $C_{store}$ charges to $C_{res}$ made up of L, $D_3$ and the $S_w$ switch; and the third part is the mechanical system composed of a spring and a proof mass connected to the variable capacitor [10].

The mechanical part was modeled by using a resonating dampened equation of second order associated to a capacitive transducer coupled to a proof mass. The proof mass is mechanically coupled to the external system by means of a bar which allows the transmission of the external vibrations for the mass. The mechanical system is described by (3).

$$(F_{transd} + a_{ext}m - kx - \mu\dot{x}) = m\ddot{x} \tag{3}$$

In this system, the following values were used for simulation: m = 46 µg, $k$=152,6 fo = 298 Hz, µ = 2,185*10$^{-3}$, $X_{max}$ = 50 um, $C_{min}$ = 150 pF, $C_{max}$ = 450 pF. Where k is the stiffness coefficient of the spring, µ is the damping coefficient, $a_{ext}$ is the external acceleration, $F_{transd}$ is the force generated by the transducer, x is the displacement, m is the proof mass and $f_o$ is the resonance frequency of the mechanical system.

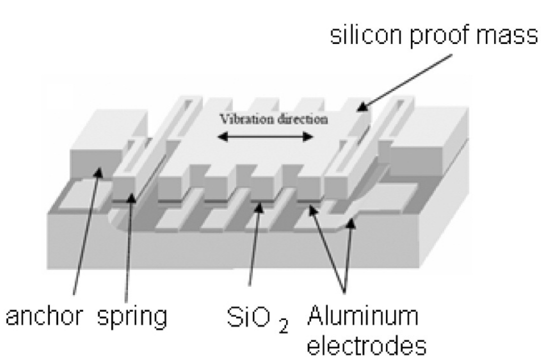


**Figure 1.** Structure of variable capacitor [9]

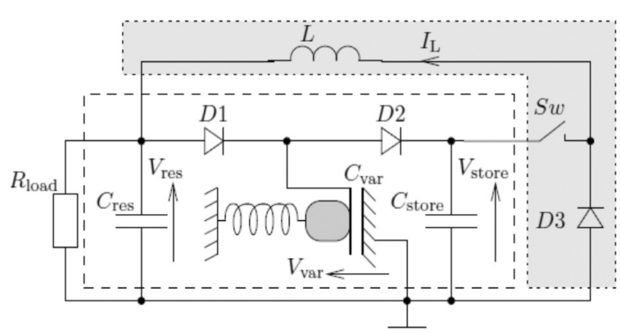


**Figure 2.** Circuit for energy harvesting [10]

In circuit of Figure 2, the $C_{var}$ capacitor is the variable capacitor which has its value modified according to a mechanical vibration. The $C_{store}$ capacitor has the function to store temporarily the charge supplied by $C_{var}$ and then send it to $C_{res}$. The $C_{res}$ capacitor has the function to supply energy for the load resistance, maintaining its voltage constant and then supply charge to $C_{var}$. [5].

In circuit of Figure 2, it can be initially adopted the condition that $V_{res} = V_{var} = V_{store}$ and that $C_{var}$ is the maximum. When the $S_w$ switch is opened and a capacitance decrease occurs, caused by vibration, there will be the increase in $C_{var}$ voltage. Consequently, the $D_2$ diode will be directly polarized and the charge of this capacitor will be transferred to the $C_{store}$, increasing the voltage over it. When the capacitance increases, the voltage over the $C_{var}$ decreases, so it gets smaller than $V_{res}$. In this way, $D_1$ remains directly polarized taking $C_{res}$ charges to $C_{var}$. This process repeats itself during the vibration.

When $C_{store}$ reaches the maximum value determined by the logic of circuit control, the switch is closed. The $C_{store}$ energy is transferred to $C_{res}$ recharging it. When the switch is opened, the inductor discharges its energy into $C_{res}$ making up a serial circuit among inductor, $C_{res}$ and $D_3$. From this point, the circuit starts effectively to gain energy because $V_{res}$ starts increasing and its voltage will be higher than the voltage it initially had.

Figure 3 represents the waveforms over the circuit in which the $V_{store}$ voltage increases each time a $C_{var}$ variation occurs. The bottom part of the Figure represents the current over the inductance due to $C_{store}$ discharge, when the switch is opened.

When starting a cycle of the variable capacitor, $C_{var}$ starts decreasing its maximum value. Cvar voltage starts to increase and the maximum value that $V_{var}$ can reach is given by the expression (4). Nevertheless, this value is limited to a value a little higher than the $V_{store}$ due to D2 conduction.

The transference of $C_{var}$ charges to $C_{store}$ takes place when $V_{var}>V_{store}$. As in each cycle $V_{store}$ increases, it is necessary that $V_{var}$ reaches values higher and higher so that the charge transference starts. In this way, the first cycles of $C_{var}$ variation transfer more charges to $C_{store}$ than the last ones, when $V_{store}$ is near to the maximum value, that is, at each cycle fewer charges are transferred from $C_{var}$ to $C_{store}$.

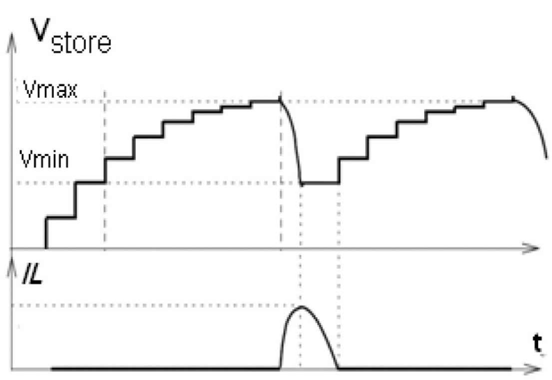


**Figure 3.** Voltage waveform over $C_{store}$

$$V_{Cmax} = V_{in}(C_{max}/C_{min}) \tag{4}$$

The voltage that $V_{store}$ reaches for each vibration cycle is given by the expressions (5) and (6), where n is the number of times that the capacitor varies.

$$V_{store_n} = V_{store_{n-1}} + \Delta V_{store} \tag{5}$$

$$V_{store_n} = V_{store_{n-1}} + (C_{max} - C_{min}) * \left[\left(\frac{C_{max}}{C_{min}}\right) * V_{res} - V_{store_{n-1}}\right] / C_{store} \tag{6}$$

The energy amount that the system gained in a specific interval of time can be found by subtracting the final energy over $C_{res}$ and $C_{store}$ from the initial energy over these capacitors. The expressions (7) and (8) show the calculus of the total gain of energy.

$$EG = \left(E_{res_f} + E_{store_f}\right) - \left(E_{res_{ini}} + E_{store_{ini}}\right) \tag{7}$$

$$EG = \frac{1}{2}\left[\left(C_{res} * V_{res_f}^2 + C_{store} * V_{store_f}^2\right) - \left(C_{res} * V_{res_{ini}}^2 + C_{store} * V_{store_{ini}}^2\right)\right] \tag{8}$$

Where the *f* and *ini* rates indicate the end and initial values, respectively, of each variable.

In the conventional resonant circuit, shown in Figure 2, the increase of voltage over $C_{store}$, due to the vibration, serves as potential energy for the flyback circuit functioning, once the real energy gain of the resonant depends on this circuit.

The disadvantage of this circuit is that parts of the energy that $C_{store}$ gained with the vibration are wasted in the process of sending back the $C_{store}$ charges to $C_{res}$. Thus, only the energy accumulated in the inductor which is transferred to $C_{res}$, when the switch is opened, is used by the load resistance. Besides this factor, the higher frequency of switch commutation impels the increase of the losses as well as it makes the control circuit of switch more complex.

### *A. New resonant circuit for energy harvesting*

In this circuit, the load resistance is put between $C_{store}$ and $C_{res}$, according to Figure 4. As occurs in the circuit of Figure 2, voltage over the $C_{store}$ capacitor increases due to the $C_{var}$ vibration which takes charges from $C_{res}$ and puts them in $C_{store}$. The higher voltage of Cstore enables it to supply energy to the load resistance and the same current which will feed such resistance sends back the charges to $C_{res}$. In this way, it is the $C_{store}$ itself that supplies the charge current, therefore it does not need the flyback circuit to supply energy to

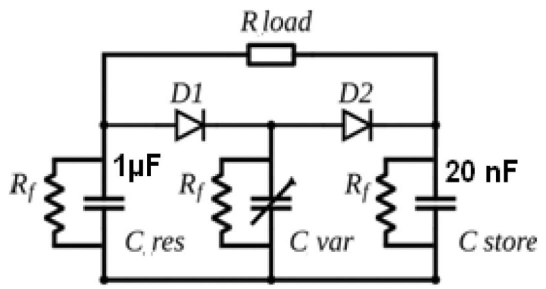


**Figure 4.** Representation of the capacitor leakage

the resistor. This circuit can have an energy efficiency higher than the original resonator.

The current which is produced by the $C_{var}$ variation divides itself between the load resistance and the $C_{store}$ capacitor. When the current produced by $C_{var}$ is higher than the current consumed by the load resistance, the difference between these currents goes to the $C_{store}$ capacitor, causing an increase in voltage.

Supposing that the variation value of the variable capacitance and the frequency are constant, after a determined time interval, voltage over $C_{store}$ and over the load resistance stabilizes.

Disregarding the losses due to leakage current and taking over that the $V_{store}$ value is constant, consequently the current generated by $C_{var}$ is completely transmitted to the load resistance.

The charge supplied by the $C_{var}$ capacitor for a vibration cycle is given by the expression (9):

$$Q = (C_{max} - C_{min}) * \left[\left(\frac{C_{max}}{C_{min}}\right) * V_{res} - V_{store}\right] \quad (9)$$

The current supplied by $C_{var}$ is given by the expression (10):

$$i_{var} = \frac{dQ}{dt} = \frac{d(C_{max} * C_{min})}{dt} \quad (10)$$

The current supplied by Cva, $i_{var}$ current, can be expressed by equation (11).

$$i_{var} = f(C_{max} - C_{min})\left[\left(\frac{Cmax}{Cmin}\right)V_{res} - V_{store}\right] \quad (11)$$

Where $f$ is the vibration frequency of the variable capacitor. The charge current $i_{RL}$ is given by the expressions (12) and (13). The $i_{RL}$ charge can be equaled to $i_{var}$ current, when Vstore is constant, resulting in the expression (10) which shows the $R_{Load}$ value.

$$i_{Rload} = \frac{V_{res} - V_{store}}{R_{load}} \quad (12)$$

$$R_{Load} = \frac{V_{res} - V_{store}}{(C_{max} - C_{min}) * [\left(\frac{C_{max}}{C_{min}}\right) * V_{res} - V_{store}] * f} \quad (13)$$

The power over $R_{Load}$ is calculated by the expression (14).

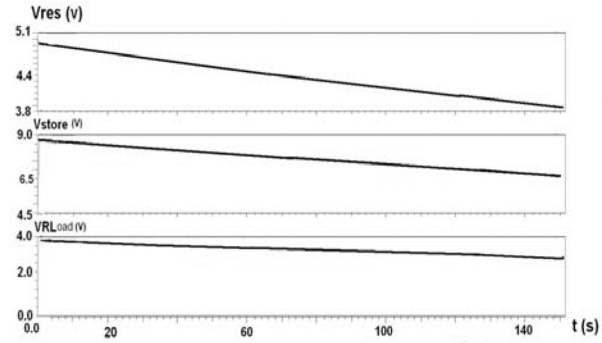


**Figure 5.** $V_{res}$, $V_{store}$ and load resistance voltages

$$P_{RLoad} = (V_{res} - V_{store}) * (C_{max} - C_{min}) * \left[\left(\frac{C_{max}}{C_{min}}\right) * V_{res} - V_{store}\right] * f \quad (14)$$

As the circuit is presented in Figure 4, its energy will disappear due to the capacitor losses represented by the resistors in parallel with each capacitor. The energy of this circuit will decrease because the capacitor charge is slowly drained to the ground. It is represented in Figure 5 the behavior of the circuit voltages in which the $R_{load}$ voltage, $V_{res}$ and $V_{store}$ decrease slowly.

### *B. New circuit proposed with flybqck*

In order to make up for the leakage current losses of the capacitors, we coupled to the circuit of Figure 4 a flyback circuit. In this way, the equations from the previous section are still valid because the circuit losses are disregarded by the energy gain of the flyback circuit. The load resistance is now attached between the new point, over $C_3$ and the $C_{res}$ capacitor. Such change is shown in Figure 6. Again, it is $C_{store}$ that supplies energy for the flyback circuit. Equation (15) describes the functioning of the flyback

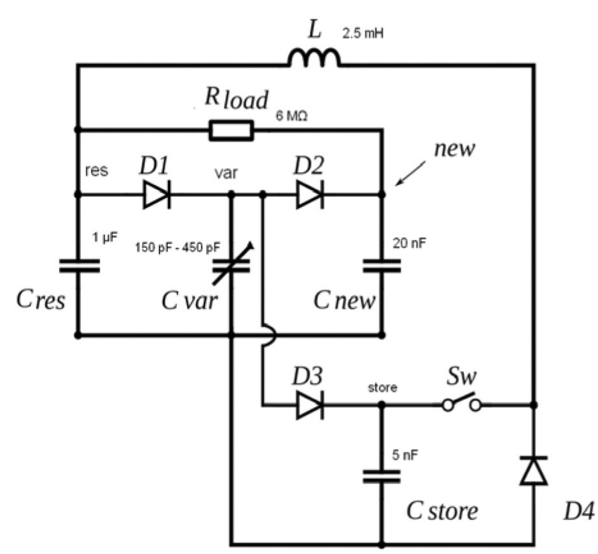


**Figure 6.** New Circuit proposed with Flyback

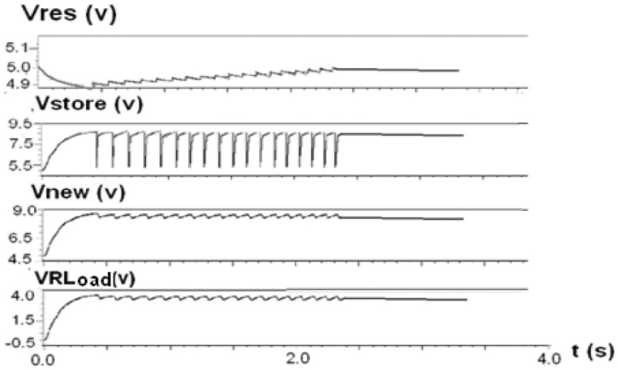


**Figure 7.** Waveform over Vnew, Vstore, Vres and $VR_{Load}$

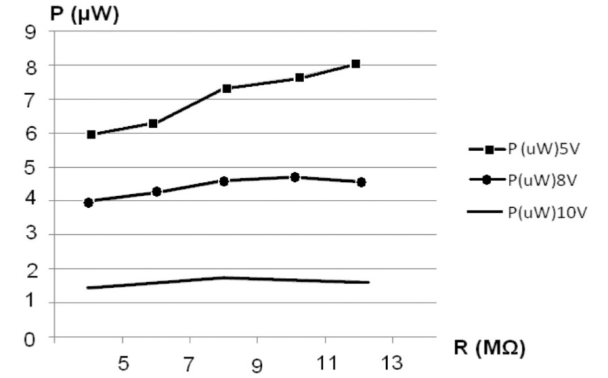


**Figure 8.** Graph of harvested power for the 5, 8 and 10 V voltages

circuit. The advantage of using the flyback, in this way, is that it is only activated to make up for losses due to leakage current, resulting in a low frequency of switch commutation, which reduces the losses by the switching and makes the control circuit easy. The $S_w$ switch is activated every time $V_{res}$ voltage decreases 2% of its nominal value resulting in the flyback circuit functioning until $C_{res}$ voltage returns to its reference value. This circuit represents a new version of the resonant circuit. It is able to harvest a higher amount of energy than the circuit presented in Figure 2.

$$\frac{C_{store}C_{res}}{2(C_{store}+C_{res})}\left((V_{store_{max}} - V_{res})^2\right)=\frac{LI_L^2}{2} \tag{15}$$

Figure 7 represents the waveform over $V_{novo}$,$V_{store}$, $V_{res}$ and $VR_{Load}$ for the circuit of Figure 6. In this circuit, the voltage over the load resistance sets up due to the increase of $V_{novo}$ and the decrease of $C_{res}$ voltage which occurs naturally in function of the value of the load resistance. The higher the load resistance is, the higher the voltage over it will be. Notice that contrary to the waveform, presented in Figure 5, the voltages over $R_{Load}$ and $C_{res}$ remain stable.

## 3. MODEL FOR HARVESTING ENERGY AND RESULTS

The conventional system presented in Figure 2 was modeled by using VHDL_AMS for the electromechanical transducer, the resonant and the switch. An ELDO model for the electrical part was used. The models were presented in literature [5], [7].

For the circuit of Figure 6, it was used the same model making the changes in the electrical ELDO model and in the VHDL-AMS model of the switch so that the new circuit works properly.

The result of a simulation, for the circuit in Figure 6, is represented in Figure 8, in which we have the following initial conditions: $V_{res} = V_{store}$ =5 V, $R_{load}$ voltage of $VR_{Load}$ = 0 V and load resistances of 6 MΩ. A model of an exponential diode with inverse saturation current of 10 pA was used. After the simulation beginning, $V_{store}$ increases and it stabilizes near 8,5 V. The $V_{res}$, however, decreases a little due to the charges which are taken initially from $C_{res}$. The $R_{load}$ voltage gets near to 3,2 V.

### *A. Power harvested by the proposed circuit*

For the resonant circuit proposed in Figure 6, it was noted that the output voltage varies in function of the load resistance and so does the harvested power. The amount of harvested power also depends on the initial $C_{res}$ voltage, once the higher the $V_{res}$ is, the higher the maximum voltage in the variable capacitor and the energy harvesting will be.

Three simulations in VHDL – AMS for this circuit were accomplished. It had the purpose to verify the amount of harvested energy for the different initial voltages of $V_{res}$ taking several values of the load resistance. For each simulation, it was previously supplied an initial voltage for the $C_{res}$ capacitor. It is represented in Figure 8 the graph of harvested power for the $V_{res}$ of 5, 8, and 10 V in function of the load resistance. It is represented in Table 1 the maximum value of the harvested power for each $V_{res}$ of the two circuits.

### *B. Comparison between the proposed resonant circuit and the conventional one*

While taking the conventional resonant circuit and comparing it with the new resonant circuit proposed and by using the same parameters for the two circuits with maximum and minimum values of the variable capacitor, vibration frequency and $C_{res}$ voltage, it can be observed a meaningful power gain of the resonant circuit proposed in relation to the conventional resonant circuit.

**Table 1.** Harvested power

| The first res(V) | RLoad power (μW) |
|---|---|
| 5 | 1,74 |
| 8 | 4,69 |
| 10 | 8,04 |

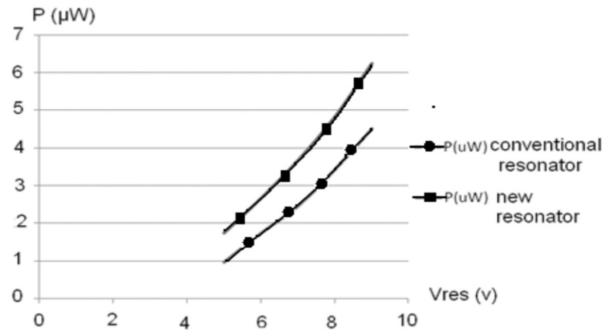


**Figure 9.** Harvested power for the two circuits in Vres function

**Table 2.** Maximum harvest value for each circuit.

| $V_{res}$ (v) | Conventional resonator power (μW) | New resonator power (μW) |
|---|---|---|
| 5 | 0,96 | 1,74 |
| 6 | 1,72 | 2,66 |
| 7 | 2,45 | 3,67 |
| 8 | 3,42 | 4,83 |
| 9 | 4,5 | 6,25 |

It is represented in Figure 9 the harvested power for both circuits in function of $C_{res}$ voltage. Table 2 illustrates the maximum harvested value for the initial voltage of $V_{res}$ for the two circuits.

## C. *Experimental Part*

Aiming to accomplish the experiments, a variable capacitor using two copper plates measuring 20X20 cm, in parallel, was built. A thin layer of mica as dielectric was used. The bottom plate was fixed in a wooden structure whereas the upper one was mobile and it moved by means of a DC motor. The movement velocity of the upper board was determined by the value of DC voltage applied over the motor.

An experiment was carried out in order to verify the increase of voltage over the capacitor when the capacitance decreases. For fulfilling this experiment the TLC27L2 amplifier of input impedance around $10^{12}\ \Omega$ was used to make up the voltage measure over the capacitor, according to the diagram illustrated in Figure 10.

Initially the variable capacitor was adjusted for its maximum capacitance. The SW switch was closed so that the capacitor could be charged with 5 V. After that, the switch was opened and the capacitor changed to the minimum capacitance. The voltage measurement of the capacitor which had its value varying from 5V to 13,82 V was accomplished.

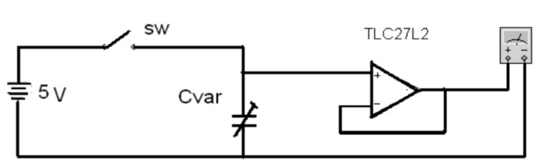


**Figure 10.** Diagram for variation measurement of the capacitor voltage

## D. *Power harvesting proof*

To verify the amount of harvested power, the circuit presented in Figure 11 was built. The $C_{res}$ capacitor of 1μF, the $C_{new}$ capacitor f 27 nF, both of polyester, were used, as well as a $R_{loud}$ of 14 MΩ. The diodes were of the 1N4148 type which presents a reverse current lower than 10 nA at a temperature of 25°C. Voltage over $C_{res}$ was measured with a digital voltmeter and the $C_{new}$ voltage with a digital oscilloscope. For these voltage measurements, the buffer use by means of an operational TLC 27L2. amplifier was necessary.

For the experiment fulfillment, the switch was initially closed and charging $C_{res}$ with 6V and afterwards it was opened. The variable capacitor had vibration in 100 Hz frequency produced by the DC motor. The upper plate of the capacitor was pushed downwards, decreasing the distance between the two plates, resulting in the increase of the capacitance. The capacitance value varied between 650 pF and 1,85 nF. These values were found by using an RC series circuit.

During the measurements, voltage over $C_{res}$ remained practically constant in 6V and voltage of the "new" point attained a value approximately of 11V, as shown in Figure 12. The $R_{load}$ had a 5V voltage and the harvested power was approximately 1.8 μW.

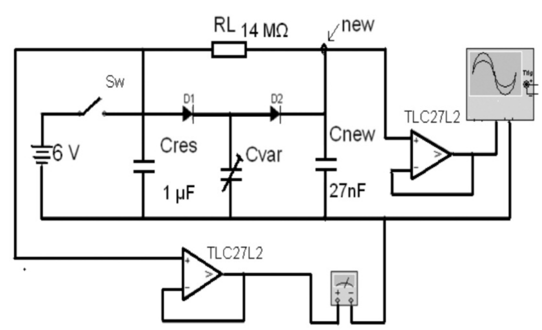


**Figure 11.** Diagram of the harvesting power circuit using variable capacitor

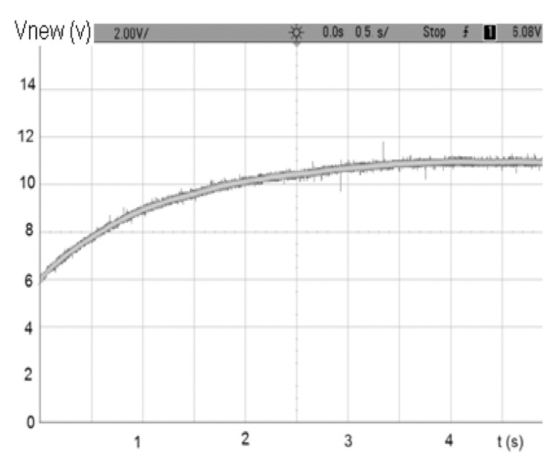


**Figure 12.** Graph of voltage of the new point obtained by a digital oscilloscope

## 4. CONCLUSION

As a result of the comparison between the two architectures, we can conclude that the amount of harvested energy by the resonant circuit with the proposed architecture (maximum power 6,25 μW) is superior in relation to the architecture of the conventional resonant circuit (maximum power 4,5 μW). This occurs for the entire $V_{res}$ variation band having as result a better use of vibration energy by the proposed circuit than by the harvesting circuit of conventional energy.

We could corroborate, through the experiments, the power harvesting with the use of variable capacitor. As concerns the charge resistance, it was obtained a harvested power of 1,8 μW, for a capacitance variation from 650 pF to 1.85 nF, in a 100 Hz frequency, what proves the model efficacy.

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