Capacitive Energy Harvester with Active Charge Leakage Compensation and Piezoelectric Generator

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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 circuit. The conventional circuit harvested a maximum power of 4.5µW whereas the circuit with the new architecture harvested a 6.25 µW power. A piezoelectric generator to provide initial power and to supply the circuit losses is still used.**

I. Introduction

The development of micro and nanotechnology has made possible the miniaturization of electronic systems. This size reduction was followed by the reduction of energy consumption, enhancing the functionality and autonomy of these systems. Aiming to achieve autonomous systems, new energy sources have been researched, so-called autonomous sources. These sources are able to capture energy in different ways, such as: light, vibration, heat and electromagnetic waves from the environment to which they are inserted. These sources are integrated to these devices in order to make them independent [1]-[3].

Autonomous systems 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 circuit. A second advantage is the fact that there is no need for replacing the chemical batteries used for feeding the circuits.

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.

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.

The architecture of energy harvesting circuit is object of several studies. The aim is to obtain a higher energy amount [2]-[6]. In general, this architecture is built from a charge pump and a flyback circuit. Some aspects are studied to obtain a better efficiency of the system, such as: the improvement of the control logic of the flyback circuit key [3] and a construction of new architecture of the variable capacitor MEMS which presents a better performance [5].

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 harvesting energy circuit to variable capacitor was attached to a piezoelectric generator in order to provide the initial energy for the capacitors and to supply the losses by circuit leakage current.

II. 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 [3]. In this kind of transducer, the capacitance varies from a maximum value, C_{max}, to a minimum one, C_{min}.

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 across 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, thus, as charge pump. The energy taken by each variation cycle of the capacitor is given by the expression (1) in which V_{in} is the initial voltage of the capacitor and ΔC is the difference between C_{max} and C_{min} values of the variable capacitor.

$$E = \frac{1}{2} V_{in}^2 \Delta C \tag{1}$$

Figure 1 shows the conventional resonant circuit used for electrical energy harvesting through electrostatic charges. The circuit can be divided into two 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 Sw switch; [2].

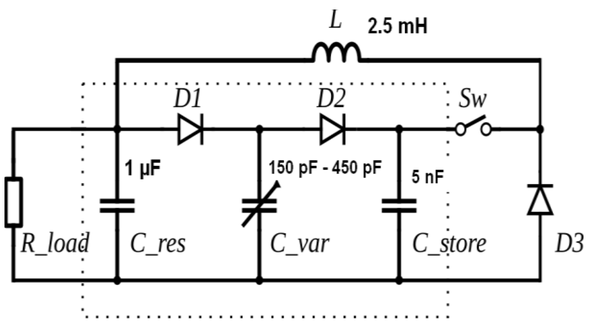

Figure 1. Circuit for energy harvesting.

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 R_{Load} resistor, maintaining its voltage constant and then supply charge to C_{var}. [3].

For circuit analysis, it can be initially adopted the condition that $V_{Cres} = V_{Cvar} = V_{Cstore}$ and that C_{var} is the maximum. When the Sw switch is opened and a capacitance decrease occurs, caused by vibration, there will be the increase in V_{Cvar}. Consequently, the D_2 diode will be directly polarized and part of the charge of this capacitor will be transferred to the C_{store}, thus, increasing the voltage over it. When the capacitance increases, the voltage over the C_{var} decreases, thus, it gets smaller than V_{Cres}. 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}, thus, 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_{Cres} starts increasing and its voltage will be higher than the voltage it initially had.

When starting a cycle of the variable capacitor, C_{var} starts decreasing its maximum value. V_{Cvar} starts to increase and the maximum value that V_{Cvar} can reach is V_{in}ΔC. Nevertheless, this value is limited to a value a little higher than the V_{Cstore} due to D_2 conduction. The transference of C_{var} charges to C_{store} takes place when $V_{Cvar} > V_{Cstore}$. As in each cycle V_{Cstore} increases, it is necessary that V_{Cvar} 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_{Cstore} is near to the maximum value, that is, at each cycle fewer charges are transferred from C_{var} to C_{store}.

The voltage that V_{Cstore} reaches for each vibration cycle is given by the expression (2), where *n* is the number of times that the capacitor varies, $Vstore_n$ is the value of V_{store} after the nth vibration of C_{var} and $\beta = C_{max}/C_{min}$.

$$V_{Cstore}[n] = V_{Cstore}[n-1] + \Delta C \times \left(\beta V_{Cres} - V_{Cstore}[n-1]\right)/C_{store} \tag{2}$$

In the conventional resonant circuit, shown in figure 1, 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}. So, 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.

II. NEW ARCHITECTURE OF RESONANT CIRCUIT FOR ENERGY HARVESTING

In this circuit, the load resistance is put between C_{store} and C_{res}, according to Figure 2. As occurs in the circuit of Figure 1, 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 C_{store} 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 load current, therefore it does not need the flyback circuit to supply energy to the resistor. This circuit 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.

As the circuit is presented in Figure 2, 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.

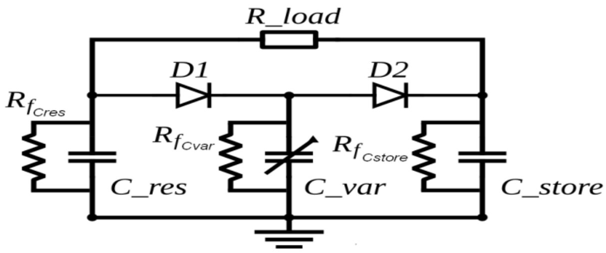

Figure 2. New architecture with the representation Representation of the leakage resistances.

III. ARCHITECTURE PROPOSED WITH FLYBACK

In order to make up for the leakage current losses of the capacitors, we coupled to circuit of figure 2 a flyback circuit. The load resistance is now attached between the new point, over C_{new} and the C_{res} capacitor. Such change is shown in Figure 3. Again, it is C_{store} that supplies energy for the flyback circuit. Equation (4) describes the functioning of the flyback 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 Sw switch is activated every time V_{Cres} 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 1.

$$\frac{C_{store} \cdot C_{res}}{2(C_{store} + C_{res})}\left(V_{Cstore}^{\max} - V_{Cres}\right)^2 = \frac{L \cdot i_L^{\;2}}{2} \qquad (4)$$

It is represented in Figure 4 the waveform over V_{Cnew}, V_{Cstore}, V_{Cres} and V_{RLoad} for the Figure 3 circuit. In this circuit, the voltage over the load resistance sets up due to the increase of V_{Cnew} voltage and the decrease of V_{Cres} 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.

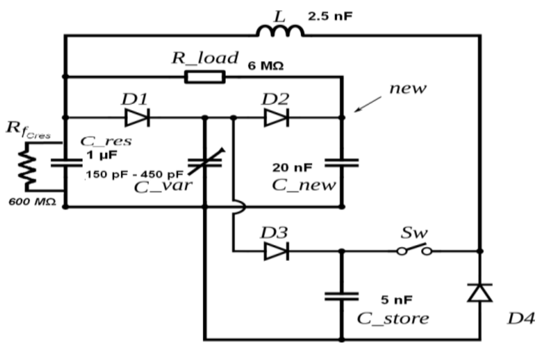

Figure 3. New architecture with flyback.

IV. RESULTS AND MODEL FOR HARVESTING ENERGY

The conventional system presented in Figure 1 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 [3], [5].

For the Figure 3 circuit, 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.

Simulations result, for the circuit in Figure 3, is represented in Figure 4, in which we have the following initial conditions: V_{Cres} = V_{Cstore} = 5V; V_{RLoad} = 0V and R_{Load} = 6MΩ. It was considered only the leakage resistance Rf_{Cres} because the other resistances are very high.

After the simulation beginning, the The V_{Cres} voltage decreases a little due to the charges which are taken initially from C_{res}. The load voltage gets near to 3.2 V.

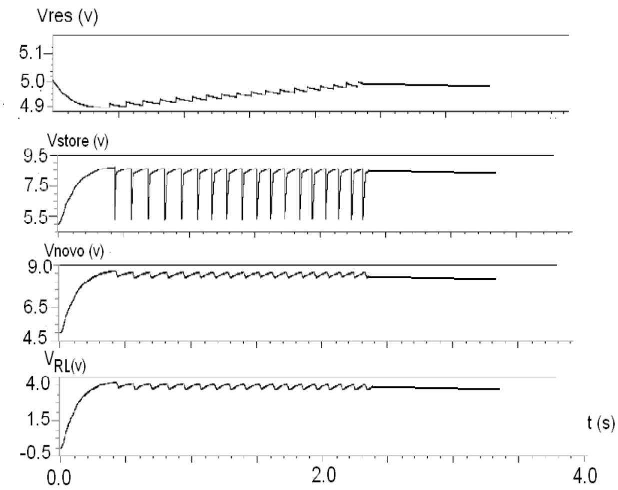

Figure 4. Waveform over V_{Cnew}, V_{Cstore}, V_{Cres} and V_{RLoad}.

Comparing the conventional resonant circuit with the new resonant circuit proposed, using the same parameters for the two circuits with maximum and minimum values of the variable capacitor, vibration frequency and V_{res} voltages, it can be observed a meaningful power gain of the resonant circuit proposed in relation to the conventional resonant circuit. It has been made several simulations for the two circuits with different values of the load resistance for each value of V_{res}. It is illustrated in Figure 5 the power supplied for several values of the load resistance for the proposed architecture. Table 1 illustrates the maximum harvested value for the initial voltages of V_{res} for the two circuits.

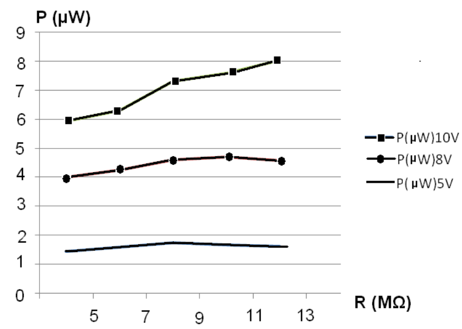

Figure 5: Graph of harvested power for the 5, 8 and 10 V to the proposed architecture.

TABLE I. MAXIMUM HARVEST VALUE FOR EACH CIRCUIT.

V_{res} (V)	P. conventional cir. (µW)	P. New cir.(µW)
5	0.96	1.74
6	1.72	2.66
7	2.45	3.67
8	3.42	4.83
9	4.50	6.25

V. PIEZOELECTRIC

The circuit of energy harvesting, by using electrostatic charges requires its capacitors to be charged previously so that it can work. It is only from an initial charge that the circuit can harvest energy. If the capacitors were completely discharged, there would be no charge movement.

Thus, it is necessary to create a way to supply the initial energy for the capacitors. Such energy should be originated from some source which is integrated to the system. There would be no sense in having to attach a source to an external voltage because the circuit would lose the characteristic of being autonomous and independent from other devices.

Aiming to solve this problem, we propose an introduction of a small piezoelectric generator to supply only the initial energy which the circuit of energy harvesting with electrostatic charges needs.

In order to accomplish the simulations, we use the characteristics of a PZT membrane of 1.45 millimeters. For this membrane, the resonance frequency is approximately 300Hz, with a maximum amplitude of, approximately, 1.2V [1]. It was a vibration frequency equal to the vibration frequency of the circuit of energy harvesting with variable capacitor. This occurred since both of them are in the same casing and they should vibrate in the same frequency.

For supplying the initial voltage to the capacitors of the circuit of energy harvesting with variable capacitor, we attached an output of the multiplier circuit to the C_{res} capacitor, as shows the mixed system of energy harvesting in figure 6. With such attachment, we can provide the initial energy that the circuit needs for functioning and supply the losses due to the leakage currents of the capacitors.

As the losses, due to the leakage current of the capacitors, are supplied by the piezoelectric generator, we can take out the flyback circuit once it had the function to provide such losses. In this way, this configuration presents the advantage of having no need of the flyback, leaving out the switch and its control circuit, making the configuration simpler, however, much more effective.

The piezoelectric generator along with the multiplier circuit of voltage is able to provide a 5V voltage which is set up, as initial voltage, to the circuit capacitors to variable capacitor. The maximum power supplied by the piezoelectric generator and multiplier circuit set is of 0.163µW, whereas the power given to the charge after the energy harvesting circuit to variable capacitor is approximately 2µW, as we can see in the Figure 7 graph.

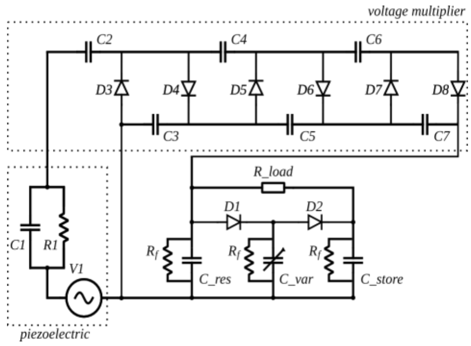

Figure 6: Attachment of the piezoelectric generator to the circuit with variable capacitor.

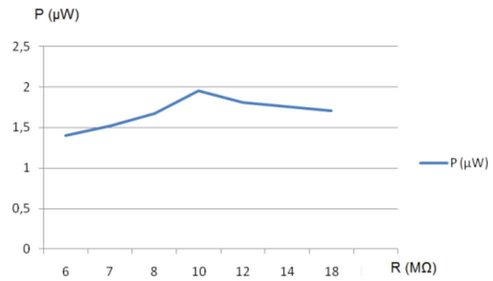

Figure 7: Graph of power in function of load resistance.

VI. CONCLUSION

The energy harvesting using variable capacitor is a way for feeding autonomous chips. We can have several circuit configurations for harvesting energy. The conventional configuration using variable capacitor produced a maximum Power of 4,5uW, while the new configuration presented a maximum Power of 6,25uW, obtaining a better performance.

We verified that the attachment of the piezoelectric generator with the energy harvesting circuit to variable capacitor makes up a very interesting architecture. The piezoelectric generator, by itself, is able to supply a voltage of 5V and a power of 0.163µW, whereas the set can provide approximately 2µW presenting a better result.

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