Optimization and AMS modeling of capacitive vibration energy harvester

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Abstract This paper presents optimization, design and modeling of a conditionning circuit of a vibrational energy harvester with capacitive electromechanical transducer. The conditionning circuit is inspired from the Buck DC-DC converter architecture, and composed from a charge pump and a flyback circuit. We found that the switching should be ordered by the internal state of the circuit, an not by some fixed timing scenario. The paper presents how to find the optimal operation mode of the harvester. To validate the study, the system was modeled using a mixed VHDL-AMS - ELDO model.

Keywords: energy harvesting, vibration energy, capacitive transducer, flyback, charge pump

1 INTRODUCTION

Capacitive harvesters require complex conditionning circuits having a great impact on their energetic performances, and whose optimization has been a subject of numerous studies [1].

This paper presents the results of study, optimization and modeling of a vibrational energy harvester system, whose conditionning circuit architecture was proposed in [1] (fig. 1). The most challenging element of this architecture is the switch commuting between the charge pump and the flyback phases. We studied the factors influencing the energy performance of the harvester, and found that there is an optimal timing for switching between theses two phases. We proposed the switch to be ordered by the internal state of the circuit, rather than be programmed with some periodic fixed-frequency and duty ratio time sequence.

To validate our results, we built a complete model of the harvester. The resonator and transducer were modeled at VHDL-AMS language, which allowed to model the electromechanical coupling. The switch was modeled at VHDL-AMS using its functional description. The electrical elements were modeled using ELDO model. The parameters of the resonator model correspond to the device presented in [2].

2 CHARGE PUMP OPERATION

The charge pump achieves the electromechanical energy conversion and defines the the harvested power.

The role of the charge pump is to make use of C_{var} variation so to transfert the electrical charges from C_{res} to C_{store} capacitor [1]. During the pumping, the voltage of C_{res} decreases and the voltage of C_{store} increases, and the harvested energy is represented by the C_{store} and C_{res} voltage difference. Since C_{res} is usually chosen to be much higher than C_{store} and C_{var}, V_{res} is nearly constant during the harvester operation. In absence of the load resistor, the harvested energy is given by:

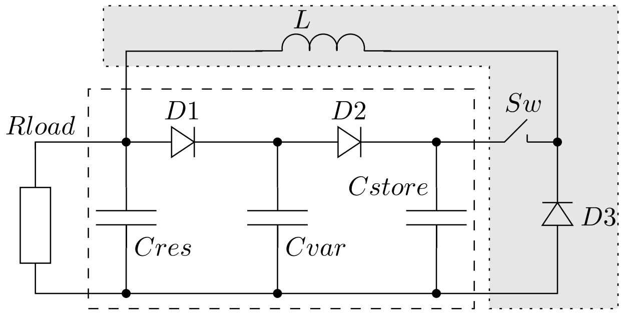

Figure 1: Conditionning circuit of energy harvester inspired from the BUCK DC-DC converter. In dashed frame, the charge pump, in gray, the flyback circuit.

$$W = \frac{C_{\mathrm{store}}C_{\mathrm{res}}}{C_{\mathrm{store}} + C_{\mathrm{res}}}(V_{\mathrm{store}} - V_{\mathrm{res}})^2. \quad (1)$$

The fig. 2 gives a typical plot for the time evolution of V_{res}, V_{store} and of the accumulated harvested energy. These curves report the saturation phenomenon: V_{store} can't increase above some V_{sat}, which depends on the V_{res} voltage and max-to-min ratio of the variable capacitor [1]. To continue the energy harvesting, it is necessary to put some charges back from C_{store} to C_{res}, which is done by a flyback circuit.

Let us suppose that the flyback circuit starts from some value V_2 of the C_{store} voltage, and reduces it to V_1. We also can say that the flyback circuit takes from the charge pump a part of the harvested energy (in order to use it for the load supply), and the harvested energy stored in the pump is reduced from W_2 to W_1 (fig. 2).

Note that V_2 and V_1 are between V_0 and V_{sat}, and they should be considered as design parameters to be

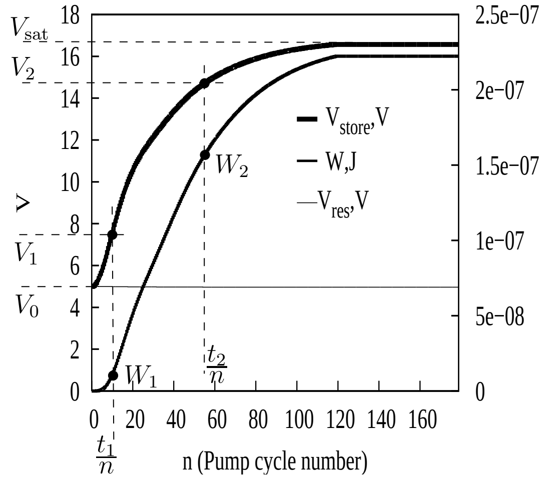

Figure 2: Pump charge operation : V_{store}, V_{res} and gained energy curves. V_0 is the starting voltage, $V_0 \approx V_{\text{res}}$.

optimized so to maximize the harvested power.

3 CHARGE PUMP OPTIMIZATION

3.1 Choice of V_1 and V_2

Neglecting the flyback operation time, the mean harvested power is given by :

$$P = \frac{W_2 - W_1 - W_{\text{fly}}}{(n_2 - n_1)T}, \quad (2)$$

where n_1 and n_2 are the pump cycle numbers, and are related with V_1 and V_2 as shown in the plot fig. 2, T is the duration of one charg pump cycle, W_{fly} is the energy loss due to the flyback. W_1 and W_2 are related with V_1 and V_2 by (1).

$V_{\text{store}}(n)$ is given by the following formula [1] :

$$V_{\text{store}}(n) = V_0((1 - \tfrac{C_{\max}}{C_{\min}})(\tfrac{C_{\text{store}}}{C_{\min}+C_{\text{store}}})^n + \tfrac{C_{\max}}{C_{\min}}). \quad (3)$$

To found the optimal values of V_1 and V_2, one have to maximize the function (2), which can only be done numerically, given the complexity of the relation. This maximization will give an interval [n_1, n_2] corresponding to the optimal interval [V_1, V_2].

The formula for P doesn't include the losses associated with the charge pumping, since they are essentially due to the charge leakage and are proportional to the pumping time, hence, don't affect the optimal t_1 and t_2 values.

3.2 Capacitance value optimization

A pump charge is composed from three capacitors : C_{res}, C_{store} and C_{var}. C_{res} should be as high as possible to maintain fixed the harvester output voltage; ideally, it should be infinite.

The value of C_{store} defines the number of cycles needed to saturate the charge pump. The value of this capacitance doesn't impact directly on the harvested power level. However, the C_{store} value has a direct impact on the absolute maximal level of energy accumulated by the charge pump (roughly equal to $C_{\text{store}}(V_{\text{store sat}} - V_{\text{res}})^2/2$, and on the absolute value of the maximal C_{store} charge ($C_{\text{store}}V_{\text{store sat}}$). So, since the charge of C_{store} is envolved by discrete portions roughly defined by $C_{\max}$ and V_{res}, when C_{store} is small, the number of the quantized levels of V_{store} and W becomes small limiting the choice of the optimal operation region. Thus, when C_{store} is comparable with $C_{\max}$, the maximal harvested power will decrease. When $C_{\text{store}} >> C_{\max}$, the value of C_{store} doesn't have a great importance for the maximal harvested power.

The value of $C_{\max}$ should be as high as possible, since it defines the energy and charge amount which is taken by C_{var} from C_{res} at one pump cycle. Hence, the maximal harvested power is roughly proportional to its value.

$C_{\min}$ is usually thought to be minimized, since $V_{\text{store sat}}$ is proportional to $C_{\max}/C_{\min}$. However, a minimization of $C_{\min}$ is very costly in practice (because of parasitic capacitances). Thus it is very important to know exactly which is a real impact of this parameter on the maximal harvested power.

Firstly, let us suppose that C_{var} varies with a fixed magnitude, between $C_{\min}$ and $C_{\max}$. If $C_{\min}$ is zero (extreme case), each charge pump cycle brings to C_{store} a charge equal to $C_{\max}V_{\text{res}}$. Thus, the voltage on C_{store} increases by $C_{\max}V_{\text{res}}/C_{\text{store}}$ at each charge pump cycle, and such a linear voltage increase is not limited : the saturation voltage is infinite. On the other hand, whereas C_{store} voltage increases linearly with time, the C_{store} energy increases quadratically. Thus, at each following pump charge cycle C_{store} gets more energy than at the preceding cycle, and the optimal V_1 and V_2 are infinite.

However, two factors limit V_1 and V_2. The first one is the technological limitation of the voltage allowed on the chip. The second one is the fact that the energy brought at each cycle on C_{store} comes from the mechanical domain, and is limited by the energy of the mechanical vibrations. In fact, once C_{var} is charged (when $C_{\text{var}} = C_{\max}$), it potential is V_{res}, and should be elevated up to V_{store}, the C_{var} charge being constant. The energy needed for such a potential elevation, equal $Q_{\text{var}}(V_{\text{store}} - V_{\text{res}})$, is took from the resonator vibrations. So, when V_{store} is so high that its energy is comparable to the mechanical energy of the vibrations, the hypothesis about fixed magnitude of C_{var} variations is not valid anymore: the mechanics hasn't enough energy to reduce C_{var} above some minimal value. This phenomenon is an example of electromechanical coupling in the harvester system.

So, in practice, the minimal useful value of C_{min} is limited by the maximal C_{store} voltage, which is limited in turn by the technology and available mechanical energy.

4 FLYBACK CIRCUIT AND OPTIMAL SWITCH OPERATION

The role of the flyback circuit is two-fold. Firstly, it puts back the charges from C_{store} to C_{res} reducing the voltage difference. Secondly, it employs the energy got from this potential reduction for the load supply.

In our analysis we considered that the flyback circuit is ideal and lossless.

Given the considerations of the section 3.1, switching should happen so to at right values ot should garantee the optimal operating conditions for the charge pump, i.e., the level of voltages V_1 and V_2. This can not be achieved with a fixed periodic switch timing because of, for example, a possible variation in the vibration frequecy. Switching should be driven by the internal state of the circuit, for example, by the voltage level on C_{store}. Another possibility is to measure the current through the switch and turn the switch off when it crosses some threshold level, I_{th}. This value can be derived from V_1 and V_2, since this current represents the energy harvested by the pump between V_1 and V_2 which is stored in the inductor during the energy flyback :

$$\frac{C_{\mathrm{store}}C_{\mathrm{res}}}{2(C_{\mathrm{store}}+C_{\mathrm{res}})}(V_2-V_1)^2=\frac{LI_{\mathrm{th}}^2}{2} \qquad (4)$$

In our model, the switch is turned on when C_{store} voltage becomes superior to V_2, and turned off when the current become superior to I_{th}. Thus, a switch is a three-terminal device : two switching terminals and one control terminal allowing a measure of the C_{store}voltage.

5 MODELING ISSUES

5.1 Modeling of the resonator and transducer

The electromechanical parts of the system were modeled using VHDL-AMS behavoural description.

The mechanical part was modeled as lumped-parameter second-order damped resonator and as a capacitive transducer associated with its mobile mass. The mobile mass is mechanically coupled with the global (external) system by the spring which allows a transmission of the external vibrations toward the mass.

The resonator is modeled by the Newton equation:

$$F_{\mathrm{transd}}+ma_{\mathrm{ext}}+kx+\mu\dot{x}=m\ddot{x}, \qquad (5)$$

where k, μ and m are the stiffness, damping coefficient and mass of the resonator, x is the displacement of the mobile mass, a_{ext} is acceleration of the external system characterizing the external vibrations.

F_{transd} is the force generated by the capacitive transducer. It represents the coupling between the mechanical (resonator) domain and the electrical (conditionning circuit) domain. It is given by the following equation :

$$F_{\mathrm{transd}}=\frac{V_{\mathrm{var}}^2}{2}\frac{\mathrm{d}C_{\mathrm{var}}}{\mathrm{d}x}. \qquad (6)$$

where V_{var} is the voltage applied on the transducer, C_{var} is the transducer capacitance. The function $C_{\mathrm{var}}(x)$ depends on the geometry of the transducer. In our case it was provided by the characterization of the device presented in [3]. The fitted curve $C_{\mathrm{var}}(x)$ was directly implemented in the VHDL-AMS model.

The electrical behaviour of the transducer is described by the usual capacitance equation :

$$i_{var}=\frac{\mathrm{d}(C_{\mathrm{var}}V_{\mathrm{var}})}{\mathrm{d}t}. \qquad (7)$$

The equations (5-7) are directly written in the VHDL-AMS model. The modeled device has one non-conservative input terminal (external acceleration quantity) and two conservative electrical terminals. There is no "output" quantity : the model provides a dipole which behaves like a variable capacitor, whose instantaneous capacitance is influenced by the external acceleration, the dynamics of the mechanical system and the applied electrical voltage.

5.2 SWITCH MODELING

To explore the technique of state-driven switching describe above and to validate our approach to the harvester optimization, we modeled the switch by a behavioral (functional) model written in VHDL-AMS. The modeled electrical device has three terminals. The swithing is achieved between *em* and *ep* terminals, the *gate* terminal is used for the switch control (fig. 3). The switch model contains a one-bit memory register, since it store its state ("on" or "off").

The operation of the device is described by the following equations, which are directly implemented at VHDL-AMS language :

$$\begin{cases} U = R_{on} I, & \text{if ON="1" and } I < I_{th} \\ ON = \text{"0"}, & \text{if ON="1" and } I > I_{th} \\ U = R_{off} I, & \text{if ON="0" and } V_{contrl} < V_{th} \\ ON = \text{"1"}, & \text{if ON="0" and } V_{contrl} > V_{th} \end{cases}, \quad (8)$$

where I and U are the switch current and voltage, R_{on} and R_{off} are the resistances in on and off states.

6 SIMULATION RESULTS

The circuit was simulated in Analog Artist Environnemnt of CADENCE. We designed symbols for the "resonator+transducer" block and for the switch block, and the schematic was captured in Schematic environnement of Cadence (fig. 3). The electrical elements were modeled using AdvanceMS simulator allowing to use together Eldo and VHDL-AMS models.

The codes of the VHDL-AMS models, with numeric parameter values, can be found in [2].

The plots of fig. 4 present the simulation results for fig. 3 system submitted to sinusoidal vibrations. One can note that the mobile mass vibration magnitude (x) varies, although the amplitude of the input acceleration magnitude is constant. This is a manifestation of the electromechanical coupling mentionned in section 3.2 : the x magnitude decreases when V_{store} increases. The left and right lower plot family gives a zoom respectivly on the flyback circuit operaton and on the charge pump operation.

7 CONCLUSION

The use of VHDL-AMS language simplified greatly the modeling of the harvester, since a set of simple physical equations allowed do highlight higly-nonlinear coupling behaviour. The use of functional model of the switch is very useful to explore the optimal modes of operation of the conditionning circuit, priorly to electrical implementation of the switch. Given the complexity of the switch operation, the latter have to be implemented using active electronic elements (MOS transistors...), and it have to be supplyed by the harvested energy. Design of such an "intelligent" switch is the subject of the ongoing work.

8 ACKNOWLEDGMENTS

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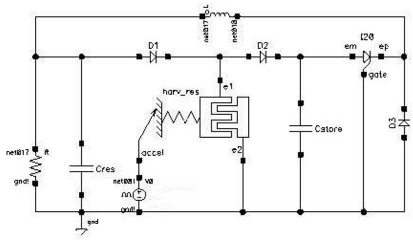

Figure 3: Schematic of the complete harvester model. The devices *harv_res* and $I20$ are modeled in VHDL-AMS. $L = 2.5$ mH, $C_{\text{res}} = 1$ μF, $C_{\text{store}} = 3.3$ nF.

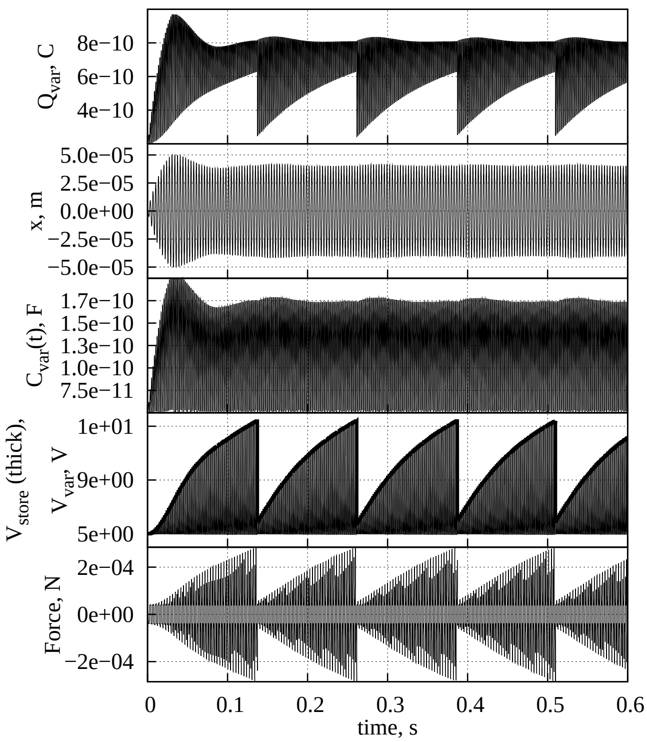

Figure 4: Simulation results of the harvester mixed model (fig. 3)