VHDL-AMS based Modeling of Electrostatic Vibration Powered Energy Harvester using an In-Plane Overlap Plate (IPOP) Mechanism

Ayyaz Mahmood Paracha*, Gilles Amendola, Philippe Basset, Tarik Bourouina

ESIEE-ESYCOM, 2 bd. Blaise Pascal, 93162, Noisy-le-Grand, France

Abstract

CMOS compatible vibration powered MEMS energy harvesters, with a high power generation at low vibration frequencies are a big challenge. We proposed two different designs of variable capacitors with an available power density of 59 µW/cm^3 at 290 Hz [1]. Complete system consists of a MEMS based variable capacitor followed by a power processing electronics. For an implementation of an electronic unit, we have chosen to optimize a topology proposed in [2]. It is composed of two main blocks i.e. charge pump and flyback circuitry. The aim of current work is to present a concept of global modeling of a system based on VHDL-AMS. We are focusing on simulating the charge pump which also includes the variable capacitor. This global simulation allows us to observe stored energy in storage capacitance and to calculate net losses in charge pump.

Keywords: Vibration-to-electricity converters, Electrostatic transduction, Charge pump, VHDL-AMS modeling

1 - INTRODUCTION

In recent times, various works have been reported about powering of sensors from an ambient environment, and to make them independent of externally attached power sources. This concept can be helpful in many ways: it reduces the bunch of wires used for the electrical connections in between the power source and different sensors, device's lifetime increases, cost maintenance decreases as there is no need to replace the external batteries. In addition, environmental polluting chemical materials can be eliminated. In order to provide autonomous nodes in a sensor network (cf. Fig. 1) and to power smart-dusts, ambient vibration is a power source that is largely considered, as there is a presence of broadband vibration spectrum in applications like automotives, air planes, etc…

The three existing mechanisms to harvest energy from environmental ambient vibrations are electrostatic, piezoelectric and electromagnetic. Among these, electrostatic-based energy harvesters are preferred as they have good compatibility with CMOS process and are considered the best for miniaturization. The heart of the electrostatic converter is a variable capacitor which has two sets of electrodes. First one is attached to a moving mass called as proof mass and second one is fixed to the substrate. A huge proof mass is normally used to target low resonance frequency applications. External vibrations force the mobile part to move relatively to the substrate, leading to mechanical-to-electrical energy transduction, if a constant charge is maintained on the electrodes while the capacitance decreases.

CMOS compatible vibration powered MEMS energy harvesters are a big challenge, with a high power generation at low vibration frequencies. The aim of this work is to present a

*Contact author: Tel. + (33) 1 45 92 67 55, email: mahmoodp@esiee.fr

concept of global modeling of a system i.e. MEMS based variable capacitor (electromechanical transducer) with associated electronics and to simulate the system using VHDL-AMS, a platform of mixed signals simulations [3].

2 - HARVESTER DESIGN AND WORKING

Recently we have proposed two architectures based on an IPOP topology [1], shown in Fig. 2. IPOP resembles to a concept of traditional parallel plate capacitor. As a result of the lateral movement of the movable plate, there is a capacitive variation due to a change in the electrode's overlap area. The devices are based on a silicon–glass technology [4]. Based on the mechanical and electrical characterization of the two designs, the theoretically available power density [5] for Comb Configuration (CC) and Proof mass Configuration (PC), with lossless electronics are 59 µW/cm^3 at 290 Hz and 12.95 µW/cm^3 at 255 Hz respectively. So CC was found to be better because of the reduced parasitic capacitance. Now in order to have complete system we need a power processing circuit, which is optimized with our application.
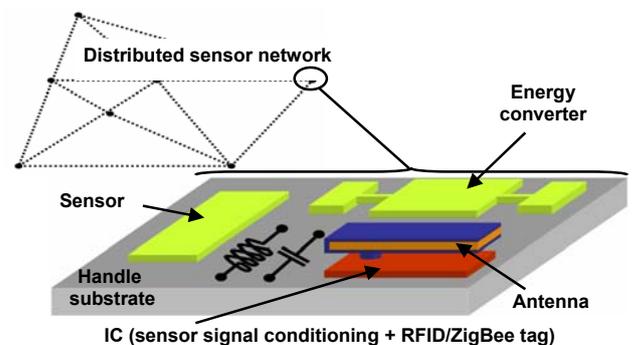

Figure 1 – Project Overview: the vibration-to-electricity converter is the power source for nodes in a distributed network. Each node includes a sensor, a chip-size antenna and an IC.
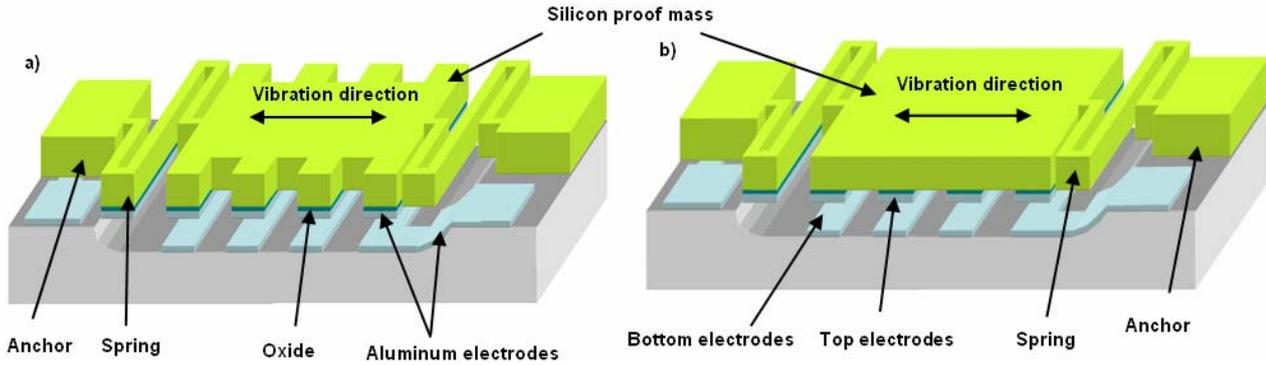
Figure 2 - Proposed energy harvester design: a) comb configuration (CC), b) proof mass configuration (PC), [1]

The power processing electronics, for an electrostatic-based energy harvester, has to charge and discharge the variable capacitor in each mechanical cycle with the net charge kept as constant, as we are focusing on constant charge phenomena. In our case, we have chosen to optimize the electronic circuit configuration described in [2]. It consists of two parts: charge pump and flyback circuitry, as shown in Fig. 3. The charge pump allows an accumulation of the electric charges. It is made up of two diodes D_1 and D_2, and the variable capacitor C_{VAR}. D_1 and D_2 function like switches, whereas C_{VAR} is an energy harvesting source. Initially the reservoir capacitance C_{RES} is charged, as a result of which electric potential across it increases as compared to C_{VAR}. As a consequence, there is a flow of charge towards C_{VAR}, until the time there is a same potential across both capacitances. Then as a result of external mechanical vibrations, C_{MAX} becomes C_{MIN} and the voltage across C_{VAR} becomes higher as compared to C_{STORE}. Thus C_{VAR} discharges into C_{STORE}, until both capacitances acquire same potential. This cycle continues, and with every mechanical cycle electric charge and hence potential across C_{STORE} steps up. When the sufficient quantity of charge is accumulated in the temporary storage C_{STORE}, it is then transferred periodically to the reservoir C_{RES}, using the flyback circuitry, triggered by a switch. The main advantage of the used topology is the use of a single switch in place of two as used conventionally [5]. Hence the simplicity increases. The configuration of the flyback circuit is same as of a buck chopper. It includes a switch which can be represented by a transistor, a free wheeling diode D_{FLY} and an inductance L_{FLY}. One condition to

be respected is $C_{RES} >> C_{STORE}$ in order to maintain a constant voltage across load. An interface of the charge pump with the flyback circuitry has two drawbacks: firstly there is a need of an additional circuit to control the switch trigger during the flyback operation and secondly it works well only at high resonance frequencies i.e. in the kHz's range. In the presented work we are focusing on the modeling of the variable capacitor and its interface with the charge pump only (as highlighted in Fig. 3). This modeling allows us to simulate the mechanical part in charge pump circuit, to observe stored energy in C_{STORE} and to evaluate electrical losses at this level. Hence the VHDL-AMS model helps us to predict exact energy which is being converted and cannot be calculated by the theoretical study in [5].

3 - SYSTEM MODELING

Heart of the charge pump is the variable capacitance. It can be represented by 1 DOF mass-spring system as shown in Fig. 4. Its electromechanical behavior can be represented as:

$$m \frac{d^2 x}{dt^2} + b_m \frac{dx}{dt} + kx + F_e = -m \frac{d^2 y}{dt^2}, \qquad (1)$$

where m, b_m, k, x, y and F_e are mass, fluidic damping, mechanical stiffness, internal displacement of the proof mass, external excitation and lateral electrostatic force respectively. The mechanical-to-electric energy conversion corresponds to a loss of the mechanical energy of the system. This loss is being caused by an electrical damping which is produced by F_e between movable and fixed electrodes. This force acts in a direction opposite to that of the vibration and hence it opposes the displacement of proof mass. It depends on a rate of change of the capacitance with respect to the proof mass displacement and given as:
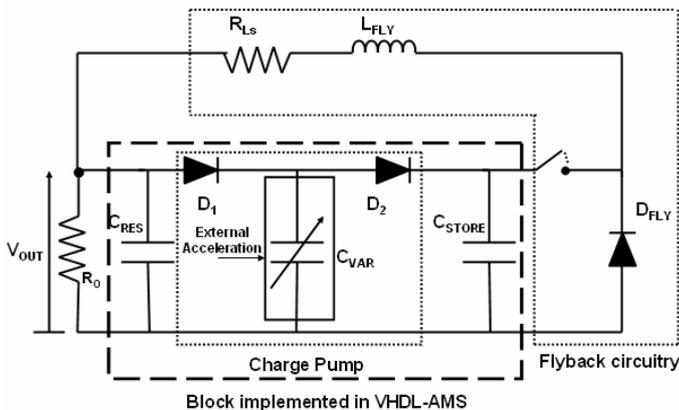

Fig. 3 – Simulated electronic power processing circuit (Block implemented in VHDL-AMS is being highlighted)
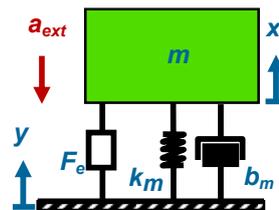

Fig. 4 – Mass spring system

$$F_e = -\frac{Q^2}{(C_{var}(x))^2}\frac{\partial C_{var}(x)}{\partial x}, \qquad (2)$$

Variable capacitance can be written as a sum of three parameters i.e.:

$$C_{var}(x) = C_{lin}(x) + C_{fringe}(x) + C_o, \qquad (3)$$

where C_{lin} is a linear capacitance, C_{fringe} is a fringe capacitance (consisting an effect of a neighbor electrode and edge effects) and C_o is a constant capacitance (which includes a parasitic connection capacitance and a substrate capacitance and is assumed to be constant with displacement). C_{lin} is determined by a formula of linear capacitance whereas an expression of C_{fringe} is a fitting of FEM simulations based on *Designer* from *Coventor^{tm}*. Fig. 5 shows a curve of C_{lin} and C_{fringe} and Fig. 6 shows sum of two capacitances implemented in VHDL-AMS. The mathematical expressions used in this model are given as:

$$C_{lin} = \frac{N\varepsilon l(w-|x|)}{h}, \qquad (4)$$
$$C_{fringe} = 660|x|^3 - 0.051x^2 + (1.4e-6)x + 2.8e-11$$

where N, ε, l, w and h are the number of electrodes, permittivity of dielectric, length and width of an electrode and an air-gap between the top and bottom electrodes respectively.
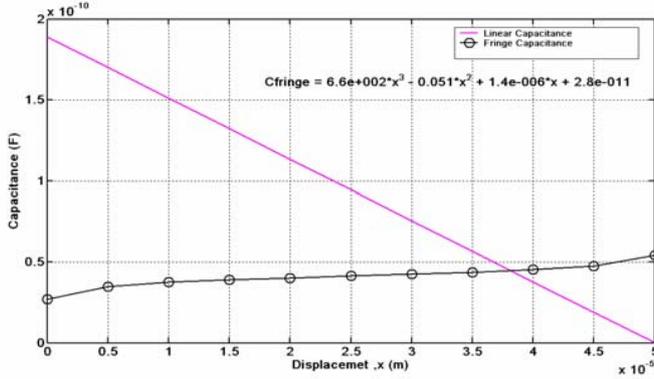

Fig. 5 – Linear and fringe field capacitance variation with respect to proof mass displacement and the equation of fringe capacitance
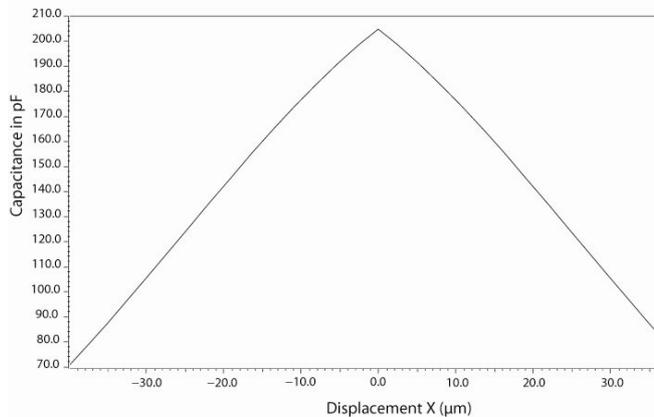

Fig. 6 – Sum of linear and fringe field capacitance variation with respect to proof mass displacement, implemented in VHDL-AMS

The input of the VHDL-AMS model is an external acceleration, a_{ext} and all the physical dimensions of variable capacitor i.e. m, b_m, k, N, ε, l, w and h are generic parameters. Capacitors C_{RES} and C_{STORE} are also written using VHDL-AMS. So by the help of simulations we can access the energy stored in each capacitor given as:

$$E_{STORE} = \frac{1}{2}C_{STORE}\,V_{STORE}{}^2$$
$$E_{RES} = \frac{1}{2}C_{RES}V_{RES}{}^2 \qquad , \qquad (5)$$
$$E_{int} = \frac{1}{2}C_{RES}V_{RES\,0}{}^2$$

where E_{STORE}, E_{RES} and E_{int} are energy stored in C_{STORE}, C_{RES} and initial energy stored in C_{RES} respectively. An increase in energy across C_{STORE} is given by:

$$\Delta E = (E_{STORE} - E_{STORE\,int}) - (E_{RES} - E_{int}), \qquad (6)$$

where $E_{STOREint}$ is an initial energy of C_{STORE}. Diodes D_1 and D_2 in the charge pump are also being modeled using VHDL-AMS. The mathematical model used for diode current is given as:

$$I_d = I_s(\exp(\frac{V_d - r_s I_d}{n\times\left(\frac{kT}{q}\right)})-1), \qquad (8)$$

where I_s is reverse current, V_d is voltage across the diode, n is ideality factor, k is Boltzmann constant, T is temperature and q is charge of a single electron. Modification of n between 0.5 and 1 allows us to simulate different types of diode. So we can simulate charge pump with conventional PN junction and schottky diode hence an effect of the threshold voltage on the energy stored in C_{STORE} can be observed.

Table 1 shows the part of VHDL-AMS code used to implement the model of variable capacitor and associated F_e. In the code, an implementation of the equations of C_{var} and F_e is being done using the mathematical property:

Table 1 – VHDL code for C_{var} and Fe

```
BEGIN
  Force == m*gamma; --Input force
  vitesse == x'dot; --Excitation Velocity
  accel == vitesse'dot; --Excitation acceleration
  Cvar == C0+((epsilon*N*(W-
(x*tanh(x*1.0E6)))*L)/(h))+A1*(x**3)*(tanh(x*1.0E6))
+ B1*x**2 +C1*x*(tanh(x*1.0E6)) + D1; --Variable
capacitance
  Fe == - 0.5*(vC**2)*(A1*x**2 +
B1*x*(tanh(x*1.0E6)) +
((epsilon*N*L)/(h))+C1)*(tanh(x*1.0E6));
--Electrostatic force
  k*x+(m*accel)+(kv*vitesse) - Felec == Force;
-- 1DOF mechanical system
  cap_charge == (Cvar)*vC; --Charge
  Fvisc == kv*vitesse; --Force applied by fluid damping
  Frap == k*x; --Force applied by spring opposite to
excitation
  iC == cap_charge'dot; --Current
END;
```

$$Lim_{a \to \infty}[x \times \tanh(ax)] = |x|, \qquad (7)$$

It is being done in order to eliminate the removable discontinuity produced by the derivative of C_{var}. The inputs to the model used for the simulation is given in Table - 2. As a result of a_{ext}, fig. 7 shows the varying voltage, the capacitance variation across the variable capacitance and the proof mass displacement. Fig. 8 shows the energy step up across C_{STORE} with conventional PN diode and schottky diode. We can see that with the low threshold diodes the net energy generated increases as the energy loss in diodes decreases, but this increase in not enormous, as the threshold voltage of diodes is negligible as compared to the voltage across the variable capacitor.

4 – CONCLUSION AND PERSPECTIVES

A VHDL-AMS based model of an energy harvester with a charge pump is being presented. It allows us to simulate the complete system and gives us a platform to optimize our harvester, evaluate power losses, choose suitable electronic components and adapt associated circuit according to the required application. Our simulation results demonstrate that the model of the variable capacitor is working well in the charge pump. As the capacitance varies as a result to the external mechanical vibrations, the value of the stored energy

Table 2 – Input to VHDL-AMS model

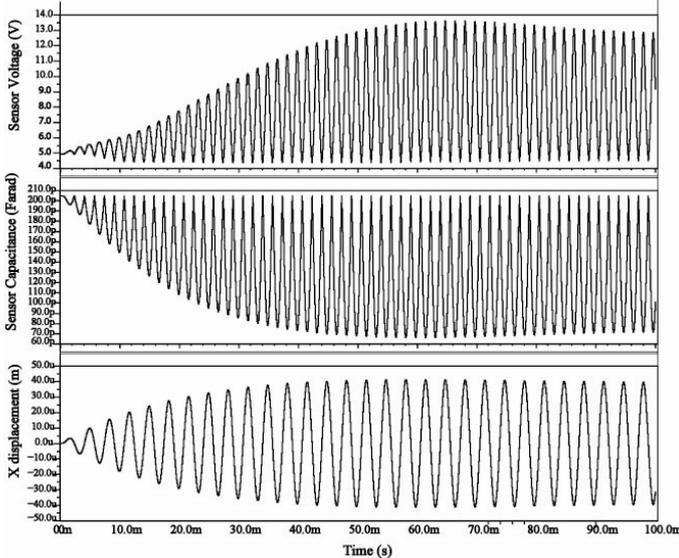|	
a_{ext} = 1g m/sec²	m = 50 mg
k = 180 N/m	N = 100
l = 6.4 mm	w = 50 μm
h = 1.5μm	bm = 1e-3 Ns/m
C_{res} = 100μF	C_{STORE} = 200pF
L_{FLY} = 4mH	R_{LS} = 10 Ω

Fig. 7 – Voltage across the transducer, with capacitance variation and proof mass displacement when an input acceleration of 1g is applied
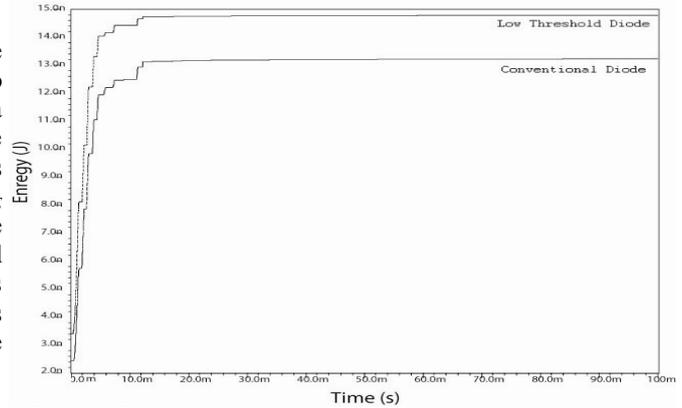
Fig. 8 – Energy step-up in the storage capacitance for two different types of diodes, i.e. simple PN junction and schottky diode.

in the storage capacitor also starts increasing and after some cycles the energy becomes constant indicating a saturation zone. For the comparison, we simulated the charge pump with the conventional PN diode and the schottky diode. It is observed that using the low threshold voltage diode does not affect enormously the energy level. Future work includes, simulating the full system i.e. the fly back circuit along with the charge pump. This will include the selection of suitable low loss component to implement the switch and to synchronize it with the available vibration spectrum as well as the resonance frequency of the harvester.

References:

[1] A. M. Paracha et al., "A bulk silicon-based vibration-to-electric energy converter using an In-Plane Overlap Plate (IPOP) Mechanism", *Proc. of PowerMEMS 2006*, 2006, *pp. 169-172*

[2] B. C. Yen, H. L. Jeffery, "A variable capacitance vibration-to-electric energy harvester", *IEEE trans. on circuits and systems*, vol. 53, no. 2, Feb. 2006, *pp. 288-295*.

[3] François Pêcheux, et al., "VHDL-AMS and Verilog-AMS as Alternative Hardware Description Languages for Efficient Modeling of Multidiscipline Systems", *IEEE Trans. on Computer-Aided Design of Integrated Circuits and Systems,* vol. 24, no. 2, pp. 204-225.

[4] C. M. Tassetti *et al.*, "New tunable RF MEMS Microinductor design", *J. of Micromechanics and Microengineering*, vol. 14, no. 9, pp. 17-22, 2004

[5] S. Meninger *et al.*, "Vibration-to-electric energy conversion", *IEEE Trans. on VLSI*, vol. 9, no. 1, pp. 64-76, 2001.