Multilevel Modeling of Integrated Power Harvesting System using VHDL-AMS and SPICE

Hela Boussetta
MNS GROUP,
TIMA Laboratory,
Grenoble, France
hela.boussetta@imag.fr

Marcin Marzencki
MNS GROUP,
TIMA Laboratory,
Grenoble, France
marcin.marzencki@imag.fr

Yasser Ammar
MNS GROUP,
TIMA Laboratory,
Grenoble, France
yasser.ammar@imag.fr

Skandar Basrour
MNS GROUP,
TIMA Laboratory,
Grenoble, France
skandar.basrour@imag.fr

Abstract

In this paper, we describe a novel top/down methodology for behavioral and structural modeling of multi domain microsystems. The study case is an integrated power harvesting circuit used for supplying power to nodes in wireless sensor networks. The system includes an analog circuit, a piezoelectric MEMS generator and a storage capacitor. The classical validation of such systems by separate simulation of each element: FEM analysis for mechanical part and traditional circuit-simulators for electrical part does not offer the possibility to predict the behavior of the complete system. To overcome such limitations, we propose to use a simulation environment based on VHDL-AMS and SPICE languages.

Keywords

Multi-domain modeling, VHDL-AMS, SPICE, co-simulation, Piezoelectric MEMS, Power management circuit.

1. INTRODUCTION AND MOTIVATION

In order to support the modeling of non electrical systems, several modeling methods using energy equivalences between electrical and mechanical domains were proposed [2]. Nevertheless, such way can lead to neglect interaction effects or cross coupling between parts from different energy domains. This issue may affect the final design in terms of decreasing performances or increasing design time. Signal flow approaches using tools like MATLAB™/Simulink™ from Mathworks, allows only unidirectional quantities, whereas there are bidirectional ones in Kirchoff networks [6]. Another approach consists in using high accuracy models based on partial equations solved with finite elements tools. Such approaches present two limitations in the case of muti-domain simulations. The first one is the cost in terms of time because of very slow simulations. The second limitation is its incompatibly with circuit based modeling.

Analog languages like VHDL-AMS or VERILOG-AMS provide powerful capabilities for modeling components and their interactions in multiple energy domains. In this work, we privileged the use of VHDL-AMS because it can operate at various levels of abstraction. Besides, the language provides more degrees of freedom when writing complex Differential Algebraic Equations needed for MEMS modeling. In the other hand, VERILOG-AMS is recommended for circuit level modeling [2].

We decided to use SMASH™ from Dolphin Integration [8] as a tool of simulation for the complete system. Two main reasons encouraged us to take this decision. The first one is the possibility to «directly» connect components described in different languages. The second one is the way in which the VHDL-AMS tolerances are considered. Usually circuit simulators do not take diverse tolerances into account but provide a basic set of tolerances and settings. VHDL-AMS offers the possibility of using tolerance groups. Indeed, the tolerance group of a subset is used by a simulator to determine how accurately to compute values of analog quantities of the subtype [7] The correct handling of this formalism offered by the language is essential in multi-domain simulations needed for MEMS. There is a great variation of values, for example the displacement is in the order of nanometers while the internal stress in materials are often greater than GPa. The correct implementation of tolerance groups offers control simulation possibilities in order to avoid convergence problems.

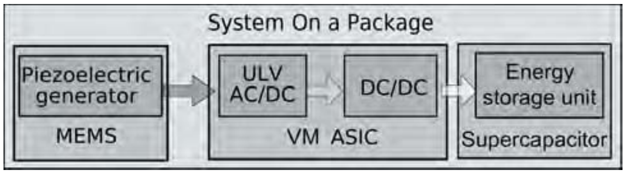

Figure.1. Schematic of the energy harvesting circuit.

The study case taken to validate this methodology is an integrated power harvesting circuit presented in the Figure.1. These devices are commonly used as nodes in Wireless Sensor Networks [2].We propose in this paper a novel methodology consisting in modeling in the same environment an integrated Power Harvesting System composed of a MEMS structure (in our case a micropower generator) and an electrical circuit which boosts and rectifies the low amplitudes AC signals delivered by such generators. This electrical circuit is based on a voltage multiplier composed with ultra low threshold voltage diodes. This paper is organized as follows: section 2 presents the top/down modeling methodology validated by a case study of a piezoelectric MEMS generator. Section 3 describes a power management circuit in structural way (assembly of basic SPICE elements). Section 4 gives relevant co-simulation results obtained with VHDL-AMS and SPICE cohabitation under SMASH^{TM}/Dolphin^{TM}. Finally section 5 concludes the article.

2.MODELING OF THE MEMS GENERATOR

In the following part, we describe the VHDL-AMS modeling approach of a MEMS generator. We start from one dimensional system where only the general behavior of such transducer is presented. Then, an enhanced model of the piezoelectric generator is introduced in order to better predict the real behavior of such system.

2.1. 1D model for a piezoelectric microgenerator

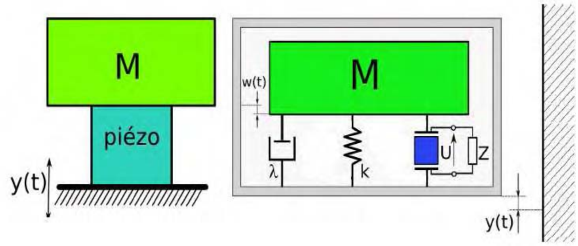

Figure.2. Piezoelectric transducer submodel.

2.1.1 Transducer submodel

The purpose of this simple model is to validate our approach for transduction modeling. The system is considered as a simple structure represented in the Figure.2. The mechanical deformation of the device leads to an electrical signal using the piezoelectric effect. The entire system is subjected to vertical mechanical vibrations *y(t)*. The displacement of the seismic mass *w(t)* is relative to the mobile cage. The rigidity *k* is calculated from the material stiffness c_{33} and device dimensions, as detailed in the Equation (1) where A is the surface of the element and L is its length.

$$k=\frac{c_{33}^{E}A}{L} \qquad (1)$$

The viscous damping coefficient λ , is taken into account. The transducer is excited by a sinusoidal acceleration of amplitude A_i. This coupled electromechanical structure can be modeled as a damped harmonic oscillator, described by the Equation (2). F_p represents the force introduced by the piezoelectric element, linked both with the stiffness and with the piezoelectric coupling.

$$M\,\ddot{w}+\lambda\,\dot{w}+F_P+M\,A_i=0 \qquad (2)$$

The piezoelectric coupling of the structure has been derived directly from the constitutive equations of piezoelectricity according to (3)

$$\begin{aligned} T_3&=C_C S_3-e_{33}E_3\\ D_{33}&=e_{33}S_3+\epsilon_c E_3 \end{aligned} \qquad (3)$$

The vertical stress T_3, the electric field E_3 and deformation S_3 are replaced respectively by the force F_P, the voltage across the piezoelectric element U and the displacement of seismic mass *w(t)* according to (4).

$$\begin{aligned} F_p&=T_3 A\\ U&=-E_3 L\\ w&=S_3 L \end{aligned} \qquad (4)$$

By combining the equations (1) to (4) , we can deduce the behavior of the system represented by two coupled equations (5),

$$\begin{aligned} F_p&=K_c w+\alpha U\\ I&=\alpha\dot{w}-C\dot{U} \end{aligned} \qquad (5)$$

where α is a geometric coefficient linked with the piezoelectric coefficient of the material e_{33}, as described in (6).

$$\alpha=e_{33}\frac{A}{L} \qquad (6)$$

The deduced differential equations (5) are then correctly incorporated into an architecture by implementing the set of the differential equations described in (5) into a VHDL-AMS architecture. The port interface defines conservative-law mechanical and electrical terminals. The synoptic view of the global system is shown in Figure.3. The "*Force_sine*" is a pure mechanical subsystem whose input terminal t_p is connected to the anchor and output terminal t_m to the piezoelectric generator. The "*PIEZO GENERATOR*" module has mechanical interface input connected to the "*Force_sine*" and electrical output interface to an electrical module; in our case the "*Voltage Multiplier*". The energy is then stored in the capacitor *C_LOAD*.

This kind of modeling connection permits to conserve laws energy in the system. and preserve interaction effects and cross coupling between mechanical and electrical part.

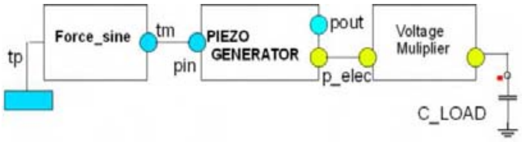

Figure.3. Synoptic view of modeled harvesting system

To validate the modeled generator, we used 1g acceleration as a stimulus to excite a seismic mass of 10g at its resonance frequency that equals to 100 kHz. Damping is considered equal to 1%. The transient analysis is done on open circuit.

A sinusoidal voltage output of 150mV amplitude is generated as shown in the plot of the Figure.4.

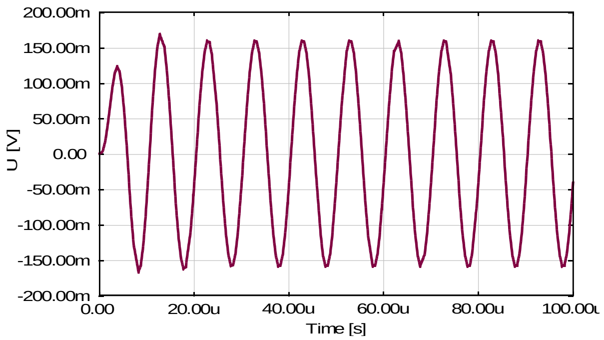

Figure.4. Open-circuit output voltage of the 1D micropower generator excited at its resonant frequency for an acceleration input of 1g.

2.1.2 Enhanced model for resonant piezoelectric microgenerator

The model considered in the previous section was kept intentionally simple to focus on the functionality of the piezoelectric transduction. Therefore, the structure was considered in one dimension and did not take into account neither the physical parameters of the used materials nor the impact of the geometric dimensions

The design of the enhanced structure is based on the microfabrication techniques of SOI substrates.

As described in Figure.5, the micropower generator is based on a cantilever beam of length L_P, width B_P and thickness H_P on which a thin piezoelectric layer is deposited. At the end of the beam, is attached a big seismic mass of length L_M, width B_M and thickness H_M. This seismic mass is used to decrease the resonance frequency and increase the harvested energy. An applied acceleration induce the displacement of the mass and the deformation of the beam. Therefore, the beam apply constraints on the piezoelectric layer whose generate electric charges. Thanks to the proposed dimensions of this mass, we can tune the resonant frequency of the generator.

Several important considerations are taken into account especially the important size of the mass compared to the one of the beam, the rigidity of the mass and its rotational inertia. It is also important to consider that the acceleration is applied to the mass and not to the end of the beam.

The impact of the electrical and mechanical properties of materials were introduced in the expression of the effective parameters deduced from boundary conditions. Additional informations about the description of the model can be found in reference [1].

Because of the complexity of the model, we supposed that all harvested mechanical energy is converted into electrical energy. That means that the three types of structural, viscous and electrical losses in the material are intentionally omitted. Similarly to the modeling approach proposed in the first general model, the piezoelectric coupling is directly deduced from the piezoelectric consecutive equations. Different parameters used in the model are illustrated in the Figure.5 and the Figure.6.

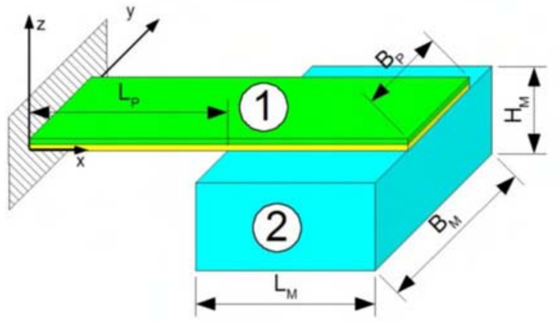

Figure.5. Schematic of the structure modeled for the enhanced model.

Because of the lack of a formalism in VHDL-AMS to directly solve partial differential equations, some geometrical variables, as the the displacement of the beam, were computed according to Maple^{TM} software. Then, the necessary time parameter was introduced to obtain the expression of $w_2(t)$ that defines vertical displacement of the barycenter of the mass.

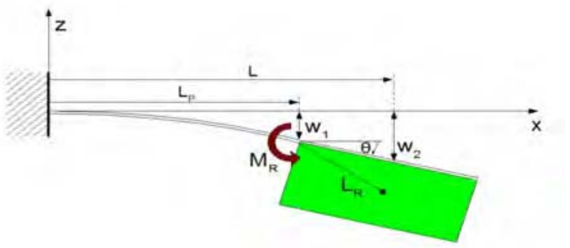

Figure.6. Different parameters used to define the dynamic behavior of the model.

Described models are parameterized using generic interface lists in entity declarations. This way of coding makes our models good candidates for reuse just by changing constants that define physical and geometric parameters. Then, those number of degrees of freedom (geometric and physical) multiply analysis possibilities and so greatly cut down the simulation time compared to the FEM computation. Thus, the proposed model can be used to obtain several valuable results. First, we will study the impact of the piezoelectric properties of the material used on the model by keeping the same dimensions of both devices and just changing the piezoelectric material layer.

The used piezoelectric materials can be either Aluminum Nitrite (AlN) or Lead Zirconium Titanate (PZT) thin layers.

To study the microgenerator with AlN layer, we just have to substitute the generic parameters responsible of physical properties of the used material (PZT) in the entity declaration of the previous model by AlN ones. A sinusoidal acceleration of 1g was used to simulate the submodel of the microgenerator. A seismic mass of 400 µm by 400 µm and a beam of 400 µm length in an SOI wafer (410 µm thick) were used. An AC analysis was first carried out to study the behavior of the system versus frequency. For the PZT layer, we note a first peak at 1169Hz (against 1200Hz in FEM analysis) as shown in Figure.7. The second pick observed at higher frequencies corresponds to the resonance introduced by the rotational mass inertia considered in this work. Then, we studied the transient response of the system to the same excitation at its resonant frequency. Once the system stabilized, the evolution of the output voltage versus time in the case of PZT layer is reported in Figure.8.

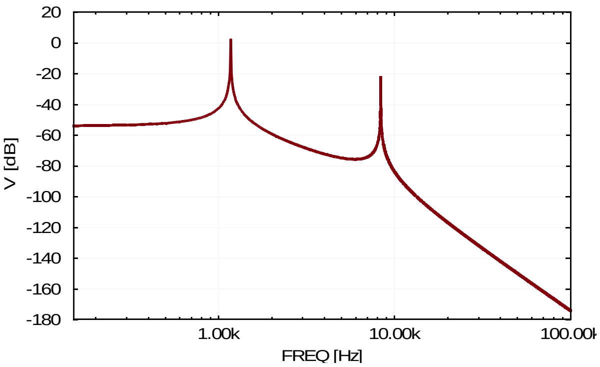

Figure.7. Output voltage at resonance at micropower generator (with PZT-4 as piezoelectric layer) versus frequency for acceleration input of 1g.

For the AlN material, we note a lower amplitude of about 0.1V and a resonant frequency of 1260 Hz. It is clearly demonstrated that for a given structure, the PZT solution permitted us to harvest a greater voltage. This result was expected because of the poor coupling coefficient of AlN material compared to PZT one.

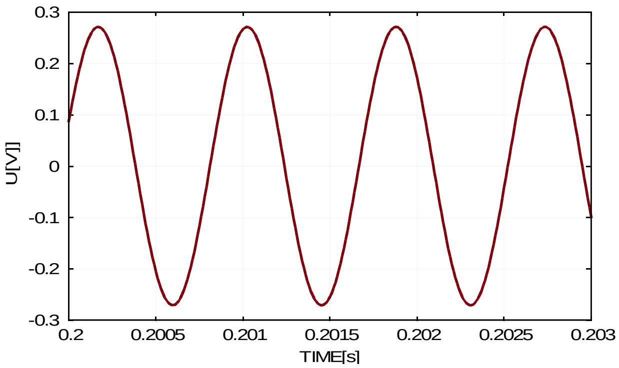

Figure.8. Output voltage at resonance on micropower generator (PZT-4 layer) versus time for acceleration input of 1g.

However, microfabrication process in case of AlN by sputtering techniques is easier than for PZT ones. The deposition of AlN is relatively simple, compatible with CMOS process and does not require post process polarization. For that reasons, we decided to continue investigate structures based on this material. For example, we have changed the dimensions of the structure and analyzed the output voltage produced. We used twice the dimensions for the mass (800µm by 800µm) with a SOI wafer (525 µm thick). We obtained the output voltage versus time reported in Figure.9.

The AC analysis demonstrates that the system resonates at 1363 Hz which is very close to 1300 Hz obtained with FEM analysis. We can successfully harvest 1.8V across the electrodes in open circuit.

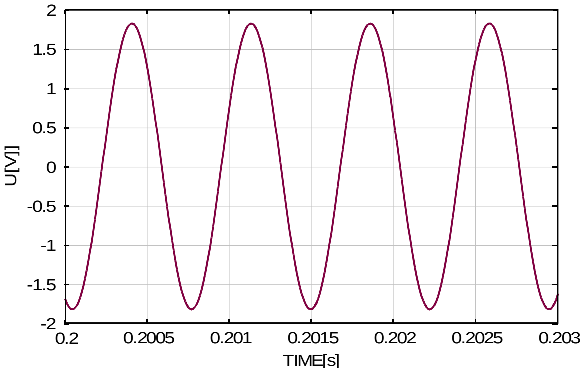

Figure.9. Output voltage at resonance of micropower generator (AlN layer) versus time for acceleration input of 1g.

3. POWER MANAGEMENT CIRCUIT

The power management circuit is a voltage multiplier structured as shown in Figure.10. This circuit is used to multiply and rectify the input voltage. The conventional structure of a voltage multiplier is based on diodes and capacitors.

The output voltage of the micropower generator is often smaller than the threshold voltage of the standard diode. To overcome this problem, we proposed a novel low threshold diodes based on DTMOS transistor. The idea is to connect the gate, the drain and the bulk together in order to obtain a diode with a low threshold voltage.

More details concerning the operation of the proposed diode are given in [4]. For very low currents, the result of characterized device based on PMOS transistors (W=5µm and L=300nm) is a diode with threshold voltage inferior to 200mV.

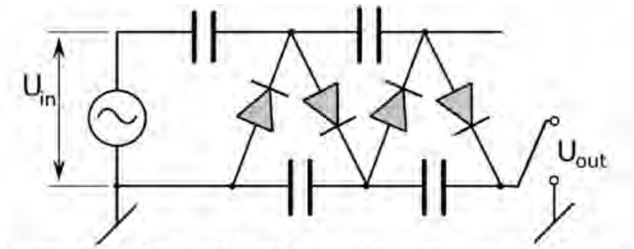

Figure.10. Conventional four stage voltage multiplier.

To model this circuit, we chose SPICE language. In fact, instead of trying to equal SPICE compact models as performed in the literature [5], we decided to use parameterized SPICE models given by the tool. Thus, we had to select the appropriate model of transistor. The Level1 MOS was selected in order to decrease simulation time. In fact, this model is a basic MOSFET model generally used for discrete components especially in power electronics but it is a good compromise between accuracy and time in system level simulations. To improve the accuracy of the model, BSIM4-V4 (level 54 in Smash^{TM} 8.0) can be then used. This model takes into account the effects of device geometry and process parameters. It enables us to better predict the real behavior of such system but it notably slows down simulation time. In the following section, we will present the global simulation of the complete system composed by the piezoelectric microgenerator linked to the voltage multiplier .

4. GLOBAL SIMULATIONS

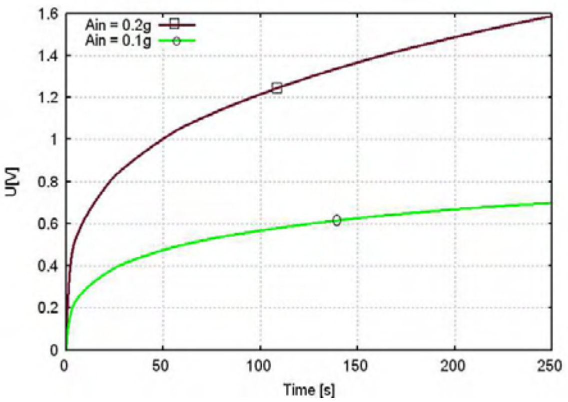

Figure.11. Simulation results curves of 1µF capacitor charge for two different values of input acceleration amplitude.

The simulated model consists on a structural connection between the parametric micropower generator with AlN layer modeled in section 2 connected with a structural model of a six stages voltage multiplier. In annex A, is presented the testbench code used to verify the functionality of the entire system. The reported code show how SPICE and VHDL-AMS models are efficiently connected in the same testbench

In fact, in each stage of the voltage multiplier, we have used the proposed diode by correctly connecting the PMOS transistors. The internal capacitors of the voltage multiplier are about 40pF. This value is imposed by the HCMOS9 technology restrictions used for the fabrication of the power management circuit. In Figure.11, we show the simulations results obtained from the process of charging of 1µF capacitor connected to the output of the full system. We demonstrate that we can harvest more than 1.5V for a very low acceleration of about 0.2g. We mention that the validation of each system separately can be done in a short simulation time but the complete validation of the system is quite slow especially for lower input acceleration amplitudes or higher capacitor loads. This can be explained by the use of different quantities in different energy domains involved in the equations to be solved

5. CONCLUSION AND FUTURE WORK

The reusable aspect of our models offers to the designers the possibility to select and use their suitable configurations without having to understand the details of blocks, just by changing some parameters. Indeed, the piezoelectric generator model remains valid for other materials and the voltage multiplier circuit is extensible to other technologies. Furthermore, we demonstrate that using VHDL-AMS, we can not only model a system in a descriptive behavior, but also in physical level that can predict the experimental results. However, we noticed that VHDL-AMS low level models can lead to slow simulations. The use of Verilog-A for circuit level approach in multi-domain simulations will be proven in future work. In fact, on going simulations consist on validating the complete system under the same AMS Cadence environment with the voltage multiplier designed in HCMOS9 technology cascaded with the low level VERILOG-A description of a piezoelectric MEMS microgenerator that takes into account the three types of damping mentioned above.

ACKNOWLEDGMENTS

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ANNEX A

Listing1. Global Simulations testbench

```
>>> SPICE

*Subcircuit call for the Voltage multiplier circuit VM*
*described in separated file*
XA      n1      n13  VM
Cload  n13      0     1u
*Instansation of vhdl-ams piezoelectric generator*
X1       n1    TEST(TOP)

>>> VHDL

LIBRARY IEEE,PIEZO_LIB;
USE IEEE.ELECTRICAL_SYSTEMS.ALL;
USE IEEE.MECHANICAL_SYSTEMS.ALL;
USE PIEZO_LIB.ALL;

ENTITY testbench is
        port(TERMINAL n1: electrical);
END ENTITY testbench;

ARCHITECTURE top of testbench is
           TERMINAL pout,pin:TRANSLATIONAL ;
BEGIN
--Piezoelectric generator instantiation
  PZT_G:entity PIEZO_LIB.piezo_enhanced_model (arch)
  Generic map (--geometric parameters
                Lp=>400.0e-6,--Beam length
                Bp=> 800.0e-6,-- Beam Width
                Hm=> 525.0e-6,--Mass Hight
                Lm=> 800.0e-6,--Mass length
                Bm=> 800.0e-6,-- Mass Width
                hs=> 10.0e-6, --Silicon Support thickness
                si_rho=> 2330.0, -- Silicon density
                rho_m=> 2330.0--Mass material density
-- Physical parameters
--Compliance Matrix
                C11s=> 166.0e9;
                C13s=> 64.0e9;
                C33s=> 166.0e9;
                C11p=> 354.0e9;
                C33p=> 395.0e9;
                C13p=>  120.0e9;
--Piezoelectric layer thickness
               Hp=> 1.0e-6,
--Piezoelectric coefficients
                e31=> -0.58,
                e33=> 1.55,
                eps=> 9.5 * PHYS_EPS0)
      port map (p_mec_out => pout,
                p_mec_in=> pin,
                p_elec=> n1,
                p_elec2=> GROUND);

-- Force sine source instantiation
FSRC: entity PIEZO_LIB.force_sine(bce)
  Generic map (acc_ampl => 1.0,--Applied acceleration
                Hm=> 525.0e-6,--Mass Hight
                Lm=> 800.0e-6,--Mass length
                Bm=> 800.0e-6,-- Mass Width
                Freq=> 1363.0
                )
  port map     (tp => pin,
                tm  => ANCHOR
                );
END ARCHITECTURE top;
```
