SPICE modelling of a coupled piezoelectric-bimetal heat engine for autonomous Wireless Sensor Nodes (WSN) power supply

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Abstract. This paper deals with an electrical modelling and optimization of a thermal energy harvester dedicated to power autonomous systems. Such devices based on bimetal strips and piezoceramics turn thermal gradients into electricity by a two-step conversion mechanism. This work focuses first on a demonstration of a ST-WSN (GreenNet demonstration platform) supplied by the harvester to validate, for the first time, the harvesters viability. That demonstration focuses attention on the need for an optimized power management circuit for piezoelectric generators able to reach output voltages up to 20V. The work deals then with the proposal of an equivalent lumped element model of the piezoelectric transducer with its SPICE implementation to enable the optimization of a dedicated power management circuit based on the Pulsed Synchronous Charge Extractor (PSCE). Simulations using the SPICE model and the power management circuit lead to an increased extracted power by 144%.

1. Introduction

The field of energy harvesting has become a predominant research area, especially, with the development of wireless sensors and communication node networks. Industrial and health monitoring, smart buildings, internet of things, these are some domains where node networks can be widely used. However, the impractical aspect of wired systems and the problems related to the power supply by short-lifetime batteries are raised for those applications. This brought attention on ambient energy harvesters and explains the great interest in energy scavenging devices over the last years. In this paper, a thermal energy harvester previously presented in [1,2,3] is studied. The harvester is based on coupling a bimetal to a piezoelectric transducer where a two-step conversion mechanism occurs. The heat flowing through the bimetal strip is converted into mechanical oscillations insuring the thermo-mechanical conversion; the second step consists in the conversion of the bimetallic strip impacts into electricity by a piezoelectric transducer. A bimetal strip is characterized by two equilibrium positions as shown in Fig. 1(a). Due to the bimetal thermo-mechanical bi-stability explained in [4], the bimetal snaps up and hits the piezoelectric membrane once its temperature raises and reaches a threshold temperature called the snap-up temperature. At that point, the bimetal is at its upper-position and releases a part of its energy to the piezoelectric. While being in contact with the piezoelectric acting as a cold surface, the temperature of the bimetal decreases until it reaches a certain snapping-back temperature that makes it switch-back to its initial
position and the piezoelectric to be freed from any strain. Thanks to the structure design, a significant thermal gradient is maintained across the harvester [5] allowing the bimetal thermo-mechanical oscillations between a hot source and a piezoelectric membrane acting as a cold surface.

2. Electrical characteristics and demonstration of a ST-WSN (GreenNet)
Prototypes are fabricated out of a Peek substrate to take advantage of its high glass transition temperature around 143°C, as well as its high elastic modulus (3.8GPa) that enhances the piezoceramic clamping and reduces the mechanical energy losses. The heat engine presented here uses a shell-like bimetal made in Invar (Fe-Ni 36%) acting as the low thermal expansion coefficient (CTE) layer and NC4 (Fe-Ni 22%-Cr 3%) acting as the high CTE layer. The bimetal has a three-degree thermal hysteretic behaviour, its dimensions are 1.8cm x 3.6cm x 300µm, and it applies a 1.9N force on the piezoelectric transducer every snap-up.

In this configuration, the quality factor is increased three times in comparison with the previous devices made of Teflon and it reaches 30 with Peek substrate. A usable output power of 2.56µW is measured across a simple diode bridge and a buffer capacitor (C=10µF) for a 5mm-thick prototype on a hot source between 83°C and 105°C and cooled down by ambient air at 25°C without any heat sink.

Thanks to the low power consumption of electronic circuits and the requirements of a single WSN node that can be as low as 1µW in a sleep state [6], a demonstration of a ST-WSN (GreenNet) supplied by this harvester is realized in asynchronous mode (unidirectional data transmission). As the harvester AC output signal is not compatible with standard electronic circuits, a voltage doubler and a 57µF storage capacitor are connected to the device, followed by a level detection circuit. The harvested energy is first stored in the capacitor until a threshold voltage value is reached and detected by a low power comparator. It is then released to supply the WSN. The GreenNet emission circuit transmits 64 bits of data with IEEE 802-15-4 protocol toward the GreenNet reception module every 29s using two devices and every 15s using three cells. Every data reception is illustrated by a switching led as shown in Fig. 1.c. The architecture of this WSN are shown in Fig 1.b and the evolution of the storage capacitor voltage is shown in Fig 1.c. This experiment validates definitively the ability of these harvesters to power WSN and highlights the necessity of a dedicated power management to increase the amount of harvested power in comparison with the standard circuits currently used (rectifier + accumulator), which will be studied in the next part of this paper.

Figure 1. (a) Piezoelectric and bimetal heat engine, (b) Test of a ST-WSN (GreenNet) in an asynchronous mode powered by the thermal energy harvester and state of the reception node

3. SPICE modelling
An equivalent electrical model of the harvester is needed to design and simulate a power management circuit optimized for piezoelectric generators with output voltages as high as 20V. A SPICE of the structure model is established based on the lumped element parameters of a piezoelectric transducer. That model is inspired from Mason’s representation to describe the piezoelectric oscillators [7]. The considered generator, excited near its resonance frequency and undergoing little displacements can be modelled, in the mechanical domain, as a vibrating mass \( m \) taking into account the effective beam mass associated with the deformation mode of the system, a spring \( K_m \) representing the stiffness of the device, a damper \( D_m \) and...
the capacitance of the piezoceramic $C_p$ (Fig. 2.a). In the electrical representation (Fig. 2.b), the piezoelectric transducer is modelled as a transformer whose primary is the mechanical part of the system and whose secondary is its electrical part. The mechanical elements are consequently, replaced by their electrical analogous quantities: an inductance for the inertial term, a capacitance for the stiffness term and a resistance for the mechanical losses. Moreover, the piezoelectric losses are supposed negligible [8], and the coupling factor between the mechanical and the electrical parts is the force factor $\alpha$. This parameter extraction is realized using a vibrometer and the experimental setup is illustrated in Fig. 2.c. Tables 1 and 2 show respectively, the experimental parameters to extract and the calculation of the components of the electro-mechanical model of the piezoelectric transducer.

**Table 1.** Measured parameters of the system

| Parameter | Description |
|-----------|-------------|
| $f_1$     | Short circuit resonance frequency |
| $f_2$     | Open circuit resonance frequency |
| $\gamma$  | Piezoceramic open circuit voltage to the beam displacement ratio |
| $C_0$     | Clamped capacitance of the piezoceramic |
| $Q_m$     | Mechanical quality factor |

**Table 2.** Extracted parameters for the model

$$\alpha = \gamma C_0$$

$$K_m = \frac{1}{C_m} = \alpha \frac{f_1^2}{f_1^2 - f_2^2}$$

$$L_m = \frac{K_m}{4 \pi^2 f_1^2}$$

$$R_m = \frac{2 \pi f_m f_2}{Q_m}$$

Assuming that the mechanical parameters are frequency dependent and that their values change significantly with the boundary conditions of the piezoceramic [9], two motional branches are employed to simulate the piezoelectric response when the bimetal snaps up and vibrates with the piezoceramic or when it snaps down allowing it to vibrate freely (Fig. 3). We show that a succession of electrical pulses models accurately the impact of the bimetal on the piezoelectric membrane. The duration of these pulses as well as their amplitude allows obtaining an electrical representation of these impacts whether it concerns a snap up or a snap down (Fig. 4.c). Finally, voltage controlled switches are used to establish the connection of the voltage sources to one of the two motional branches depending on the bimetal state. The final SPICE model is shown in Fig. 3.

**Figure 3.** Equivalent SPICE model of the piezoelectric transducer taking into account the bimetal impacts
Experimental measurements and simulations using this SPICE implementation are performed and the results of the voltage evolution across the piezoelectric capacitor, showing a good agreement, are exposed on Fig. 4 (a 10MΩ impedance probe is used for simulation and experiments). Thanks to that SPICE model, a standard circuit (voltage doubler + 10µF storage capacitor) is also simulated, and 2.56µW output power are obtained (Fig. 5.b), showing as well, a good agreement with the experimental measurements carried out previously. These steps confirm the validity of this modelling.

**Figure 4.** (a) Experimental piezoelectric signal measured with a 10MΩ probe, (b) SPICE simulation results of the piezoceramic output signal with with a 10MΩ probe, and (c) bimetal impact modelling

### 4. Power management circuit PSCE

To optimize the power transfer from the piezoelectric generator to a storage capacitor, thanks to the SPICE model, the enhanced power performance of the harvester is predicted using PSCE (Pulsed Synchronous Charge Extractor) nonlinear technique studied by T. Hehn [10]. This circuit is shown in Fig. 5.a. It includes a rectifier, an inductance acting as temporary energy storage and three switches S1, S2, S3. Its working principle is explained in Fig. 6, revealing three phases as shown by the timing diagram and the control unit generating the switches controlling signals. During the first state, all the switches are opened and the piezoelectric capacitor charge rises until the voltage reaches a maximum. Once the peak detector detects that maximum voltage across the piezoceramic, phase B starts: the switch S1 is closed and an LC oscillator is then created. This circuit permits the discharging of the capacitor into the inductance and the functioning mode ends when the voltage across the piezo-capacitor reaches the value 0V detected by a zero crossing detector. At this point the energy is completely transferred into the inductor and phase C is initiated to enable the discharge of the inductance into a storage capacitor C\textsubscript{out} during a last phase 3. The switch S1 is opened, S2 and S3 are closed and another LC oscillating circuit is constituted. This phase is terminated when a comparator detects a zero current in the circuit.

The switches control circuit is supplied by the storage capacitor C\textsubscript{out}. At the startup, when this capacitor is discharged, the PSCE circuit is equivalent to a standard circuit constituted of a rectifier and a storage capacitor because only the switch S2 is closed to charge the storage capacitor. The complete circuit is designed and simulated using CADENCE software. The consumption of the controlling circuit is estimated to be lower than 600nW. The simulation of charging a 10µF capacitor leads to an improvement by 144% of harvested power improvement, reaching 6.25µW per cell and up to 19µW with 3 cells (Fig. 5.b). The physical implementation of the simulated PM circuit would allow operating in synchronous mode (bidirectional data) for future Internet of Things applications.
5. Conclusion

This paper presents the improvements and optimizations performed on a thermal energy harvester based on bimetals and piezoelectric materials. A first demonstration of supplying a ST-WSN GreenNet in asynchronous mode with these harvesters is realized confirming their efficiency and viability without any heat sink and cooled down by natural convection only. An electrical model of the harvester is then established based on a lumped element model of a piezoelectric system and a SPICE implementation is proposed for the different working phase of the device: when the bimetal snaps up and when it snaps down. This model is even more necessary to design a dedicated power management inspired from PSCE technique. The circuit’s simulations results reveal a power gain of 144% in comparison with the standard circuits which is promising for the future implementation of autonomous WSN for Internet of Things.

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