Electrical modelling and characterization of a Thermo-Magnetically Activated Piezoelectric Generator (TMAPG)

Adrian A. Rendon-Hernandez¹, Marco Ferrari², Skandar Basrour¹, and Vittorio Ferrari²

¹Univ. Grenoble Alpes, CNRS, Grenoble INP, TIMA, 38000 Grenoble, France
²Institute of Engineering Univ. Grenoble Alpes

E-mail: adrian.rendon@univ-grenoble-alpes.fr

Abstract. This article deals with modeling and characterization of a thermo-magnetically activated piezoelectric generator, we provide breakthrough in addressing the modeling issue of such power generators by reporting equivalent electrical circuit and its characterization. The circuit is based on the standard Butterworth van Dyke model. It includes mechanical, dielectric, and piezoelectric losses by using complex elastic, dielectric and piezoelectric constants that are obtained through fitting measured admittance of piezoelectric transducer. The model is developed of lumped circuits elements and it is valid under both parallel and series wired bimorph connection. Experimental and simulation results show good agreement, within 10.2% (for maximum output voltage), on the generator behavior for both the rectifier circuits implemented.

1. Introduction

Harvesting thermal energy from temperature variations can be done through coupling thermal-dependent magnetization and piezoelectric transduction [1]. When a material exhibiting thermomagnetization is subjected to an external and constant magnetic field as well as to a temporal variation in temperature, a temperature-dependent magnetic force is produced. This force drives the mechanical movement of a bi-stable structure (open and closed positions), which is then converted into electricity. In order to maximize the harvested energy, circuits that aim to increase the power output of a piezoelectric energy harvester need to be tailored. When designing energy harvesters, an equivalent electric model of the system is very helpful in estimating its main features, including the achievable energy output before manufacturing prototypes, assessing the performance of the generator, constructional flaws, and the effects of design changes. Efficient design of energy harvesters should consider the whole energy harvester system (i.e., electromechanical transduction and power electronics management). The generated AC voltage in a piezoelectric energy harvester is typically managed using a rectifier circuit coupled with power management circuits and DC/DC converters [2,3]. Nevertheless, the maximum output voltage level produced by the thermo-magnetically activated piezoelectric generator (TMAPG) has to be optimized to be useful for powering electronic devices. Therefore, we are developing an equivalent electrical model of TMAPG that considers the whole energy harvesting system. Moreover, a comparison of simulated results and experimental testing for TMAPG connected to two types of rectifier circuits, namely, full-wave bridge rectifier (FWB) and Cockcroft-Walton voltage multiplier (CWVM) is discussed. The rest of this paper is organized as follows: section 2 presents the modeling formulation of the equivalent electrical circuit, while simulation of TMAPG and experimental
results are detailed in sections 3 and 4, respectively. Finally, section 5 presents conclusion and future works.

2. Modeling

The thermo-magnetically activated piezoelectric generator system is illustrated in Figure 1(c). The power generator has two stable positions of operation: the closed position (Figure 1(a)) for cold temperatures and the open position (Figure 1(b)) for hot temperatures. The transducer subsystem of TMAPG consists of piezoelectric cantilever bimorph with a permanent magnet at the free end, which has a double role, i.e., providing a constant external magnetic field and acting as a proof mass. The conversion principle of mechanical strain to electrical charge is similar to that of vibration-based energy generators. Therefore, we adapted the theoretical model of a vibration based generator detailed in [4] to model our generator.

![Figure 1. Schematic of TMAPG: (a) closed position, (b) open position, and (c) photograph of test prototype of TMAPG.](image)

2.1. Electromechanical formulation

The model considers the vibration-based generator geometrical, mechanical, electromechanical coupling parameters, and losses elements linked to materials as shown in Figure 2(a). The mechanical elements such as mass, spring and damper are represented by their electrical analogous items, i.e., equivalent inductance $L_m$, resistance $R_b$, and capacitance $C_k$, respectively. The electromechanical coupling block, relating input stress on mechanical side to the voltage on electric domain, is represented through controlled sources (i.e., piezoelectric mechanical-electrical conversion is modeled using Voltage Controlled Voltage Source and electrical-mechanical conversion is modeled using Current Controlled Current Source). Stress and force input are related through the geometrical constant $K_1$ as detailed in [4]. The equivalent inductance $L_m=K_1K_2m$ which relates the second derivative of strain to stress, represents the inertia of the equivalent mass of the transducer. The geometrical constant $K_2$ can be derived from the relation between the displacement of the tip of the cantilever, $z$, and strain [4]. The equivalent resistance $R_b=K_1K_2b$ which relates stress to strain rate, considers the mechanical losses due to damping, and $b$ is the damping coefficient. The equivalent capacitance $C_k$, which represents the compliance, relates stress and strain and it is simply equal to the inverse of the Young’s modulus of the piezoelectric material. The capacitance between electrodes of the bimorph can be written as $C_b=\frac{a^2wl\varepsilon}{2hp}$. Where, $w$, $l$, $\varepsilon$, and $h_p$ are the width, length, absolute piezoelectric dielectric constant, and thickness of piezoelectric layer, respectively, and $a$ is a constant which considers how the bimorph is wired ($a = 1$, if the bimorph is wired in series mode or $a = 2$, if the bimorph is wired in parallel mode). The dielectric losses in piezoelectric materials can be described using a complex dielectric constant [5]. A frequency-dependent element in parallel with the bender capacitance $C_b$ is used to describe the dielectric losses on the electrical domain. Similarly, another frequency-dependent element in parallel with the mechanical compliance capacitance $C_k$ on the mechanical domain block. Whereas mechanical losses can be represented by behavior-controlled sources (i.e., B1 and B2 shown in Figure 2(a)). $V_{in}$ is the input excitation of the circuit, it is described with a voltage pulse with $V_{initial} = 0$ and $V_{on} = -K_1\cdot gap$. To know the value of losses elements on the model, a curve fitting with measurements on electrical admittance is detailed on next section.
3. Simulation of TMAPG

We started by measuring the electrical admittance of a test prototype of TMAPG considering the following conditions: an increase in temperature of the soft magnetic material has been produced until to reach the opening commutation, then, measurements of admittance were performed through HIOKI IM3570 impedance analyser. Afterwards, these data were introduced on admittance curve fitting process implemented on PSpice in order to find the losses elements as listed in Table 1.

![Diagram of TMAPG model](image)

**Figure 2.** (a) Schematic representation of the model of TMAPG showing mechanical domain, electro-mechanical coupling and electrical domain; (b) curve fitting estimation of the admittance of the piezoelectric generator.

| Symbol | Description | Units | Real part | Imaginary part |
|--------|-------------|-------|-----------|----------------|
| $b$    | Damping ratio | -     | $2.48 \times 10^{-3}$ | 0 |
| $\tan(\delta_d)$ | Dielectric loss tangent | -     | $2.9 \times 10^{-3}$ | 0 |
| $\tan(\delta_m)$ | Mechanical loss tangent | -     | $3.7 \times 10^{-3}$ | 0 |
| $d_{31}$ | Piezoelectric constant | CN$^{-1}$ | $-98.8 \times 10^{-12}$ | $3.02 \times 10^{-12}$ |
| $\varepsilon_{33}^T$ | Permittivity constant | Fm$^{-2}$ | $1.35 \times 10^{-9}$ | $-316.98$ |
| $S_{11}^F$ | Elastic compliance | Pa$^{-1}$ | $2.57 \times 10^{-12}$ | $-1.3 \times 10^{-12}$ |

This approach to fit the losses elements implied in the electrical equivalent circuit is based in a simultaneously curve fit of both electrical admittance and its phase rotation. Figure 2(b) illustrates the results of the curve fitting and parameter estimation process of the electrical admittance of the piezoelectric generator. It can be observed a good coherence between the measurements and model behavior of such generators. Once setting the losses elements on the equivalent electric model, a global simulation of the TMAPG can be realized. Following this, simulation of the TMAPG to a FWB (Figure 3(a)) and CWVM (Figure 4(b)) were conducted. Despite the fact that the closing commutation of the generator is not modeled in this work, the opening commutation is the condition producing the major amount of energy, because of the oscillations at opening stage, thus we decided to compare through simulation only this condition. Next section describes the results comparison.

4. Experimental results

Both simulated and experimental voltage outputs from the TMAPG have been presented when using two different rectifier circuits (Figure 3 and Figure 4). With the FWB, the TMAPG produces a maximum output voltage of 1.13V, corresponding to a stored energy of 2.1nJ. With the CWVM, the TMAPG generates a maximum output voltage of 1.18V, corresponding to a stored energy of 2.3nJ. The measured piezoelectric capacitance being 200pF we believe that the voltage drop across $C_{\text{load}}$ for both circuits is affected by the capacitive voltage divider. One advantage of using FWB over CWVM is that for closing commutation, the first is able to extract energy from the generator, while the drawback is the leakage current of using four diodes. CWVM is able to extract 9% more energy during opening.
commutation than using FWB. The obtained simulation results suggest that an energy of 2.8nJ can be stored in a capacitor of 3.3nF during one opening commutation of the generator. Using parametric simulation, optimum load capacitor has been validated for both energy extraction circuits.

**Figure 3.** (a) Full-wave bridge rectifier with load capacitor; (b) output voltage at opening commutation for a $C_{load} = 3.3\text{nF}$; (c) maximal output voltage and energy for both opening and closing commutations as function of $C_{load}$.

**Figure 4.** (a) Cockcroft-Walton voltage multiplier with load capacitor; (b) output voltage at opening commutation for a $C_{load}$; (c) maximal output voltage and energy for both opening and closing commutations as function of $C_{load}$.

5. Conclusion

The equivalent electric model presented shows good agreement, within 10.2% (for maximum output voltage), of the generator behavior for both the rectifier circuits implemented. Future work will involve inclusion of closing commutation condition to the equivalent electrical model.

References

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