International Journal of Sciences and Techniques of Automatic control & computer engineering
IJ-STA, Special Issue, CEM, December 2008, pp. 566–579.

Radial Piezoelectric Transformer Study

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Abstract. *Nowadays, piezoelectric transformer (PT) is a good alternative to substitute electromagnetic transformers for its avantages such as low profile, high power density, no windings, no electromagnetic noise and can be miniaturized to a greater degree. In this paper, the model of piezoelectric transformer, functioning in radial mode, is presented. The effects of piezoelectric ceramic sizes (thickness and radius) on the transformer performances have been considered. The simulation results of the voltage gain and the efficiency are studied. The study has been made in low and high frequencies.*

keywords. *piezoelectric transformer, dimensions, radial mode, voltage gain, efficiency, , thickness, radius*..

1. Introduction

Piezoelectric transformer has been studied for many years. Recently, it is actively researched mainly to increase to set-up ratio and the output power [1, 2]. Piezoelectric transformer (PT) has several advantages over the conventional magnetic transformer [3]. First, the piezoelectric transformer can be miniaturized to a greater degree since the energy stored by the elastic vibration is larger than in the magnetic transformers. The idea of smart material interested rather the researchers and engineers as a new category of physical material that has integrated sensor, actuator, power electronics and microprocessor [4]. It can be integer with its electronics on the same substrate.

Second, it has low profile, high power density, no windings and no electromagnetic noise. Pt is interesting in those applications where size, weight or isolation become critical. Their development is due to news piezoelectric materials such as: Single crystals (as Quartz), polymers such as polyvinylidine fluoride (PVDF) and poled ceramics such as PZT, or Pb(Zr,Ti)O3. Within these three categories of piezoelectric materials, according to the different vibration mode and mechanical structures, the piezoelectric transformers could be classified to three main categories: Rosen-Type [5], thickness vibration mode [5, 6 ,7] and radial vibration mode [8, 9]. In a recent work F. Boukezouha et al.[10] have carried out a comparison between a model and

This paper was recommended for publication in revised form by the editor Staff.
Edition: CPU of Tunis, Tunisia, ISSN: 1737-7749

analytical verification. From the original piezoelectric transformer proposed by C.A. Rosen, theoretical and application studies were started by many researchers and other of them introduced a multilayer piezoelectric transformer [11 ,12].

In this article, piezoelectric transformer working in radial vibration mode has been studied. The simulation results of the voltage gain and the efficiency according to the load are given. The paper is organized as follows: The art state is presented in the first section. The second II will point out the functioning principle of piezoelectric transformer. Section III and IV describe respectively the radial vibration mode and the equivalent circuit model of the piezoelectric ceramic used as transformer. Finally, in the last section are presented the simulation results of the voltage gain and the efficiency of the multilayer piezoelectric transformer in accordance with load and intrinsic parameters.

2. Functioning Principle of Piezoelectric Transformer

The operation principle of a piezoelectric transformer (PT) is a combined function of actuators and sensors so that energy can be transformed from electrical form to electrical form via mechanical vibration. This configuration is characterized by transmission of electrical energy through mechanical vibration using both direct and indirect piezoelectric effects (Fig. 1). When an alternative voltage is applied to the primary (indirect piezoelectric effect), mechanical vibrations are created in the material through the electromechanical coupling. The vibration amplitude in the secondary (direct piezoelectric effect) is proportional to the output voltage.

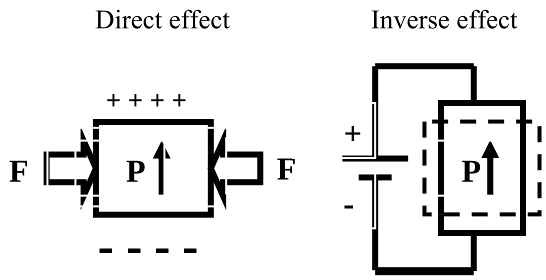

Fig.1. Piezoelectric effect

3. Radial Vibration Mode of PT

PT that we are studying here consists of two disk of piezoelectric ceramic (primary and secondary) parts poled in the thickness direction. They are isolated and rigidly bonded by strong glue. Each part is composed of several thin layers of piezoelectric ceramic (Fig. 2). The same electromechanical mode in the primary and the secondary correspond a vibration of the two piezoelectric ceramic disks in the radius direction. The ratio between the layer number in the secondary and these ones of the primary corresponds to the voltage step-up or step-down ratio. This structure of piezoelectric ceramic type permits to improve notably the electromechanical coupling factor.

This structure is composed with two parts of piezoelectric layers polarized in thickness. The primary is separated from the secondary by a dielectric layer. The stress direction is following the radius [8, 9] (Fig.2). PT is considered as being the association of two piezoelectric transducers corresponding to primary and to secondary of PT bonded mechanically.

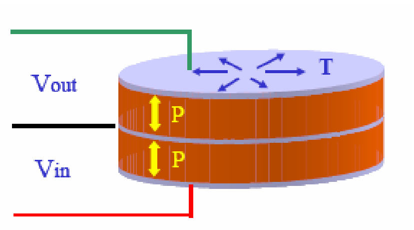

Fig.2. Configuration of Piezoelectric Transformer Vibrating in Radial Mode

4. Electrical Equivalent Circuit of Piezoelectric Transformer

The mathematical model is given in the literature [3, 8, 9, 10]. The theoretical analysis of electromechanical behavior of a piezoelectric transducer takes place on a model which permits to build an equivalent electromechanical circuit. After simplification at the resonance frequency, one obtains the following electrical equivalent circuit (Fig. 3). The details of equivalent circuit model of a multilayer piezoelectric transformer are developed in the reference [11]. We give here only the formulas used to simulate the PT. The following equations show the relationships between each material characteristic and material property, the PT's dimensions and its electrical performances.

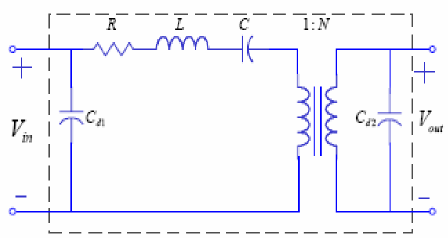

Fig.3. Electrical Equivalent Circuit of Piezoelectric Transformer.

$$C_{d1} = \frac{N_1 \pi r^2 \varepsilon_{33}^T \left(1 - \frac{d_{31}^2}{\varepsilon_{33}^T s_{11}^E}\right)}{t_1} \;;\; C_{d2} = \frac{N_2 \pi r^2 \varepsilon_{33}^T \left(1 - \frac{d_{31}^2}{\varepsilon_{33}^T s_{11}^E}\right)}{t_2} \;;\; R = \frac{\sqrt{2\rho s_{11}^{E\,3}}\,(N_1 t_1 + N_2 t_2)}{16 r Q_m (N_1 d_{31})^2} \;;$$

$$N = \frac{N_1}{N_2} \;;\; L = \frac{\rho s_{11}^{E\,2}\,(N_1 t_1 + N_2 t_2)}{8\pi (N_1 d_{31})^2} \;;\; C = \frac{16 r^2 (N_1 d_{31})^2}{\pi s_{11}^E (N_1 t_1 + N_2 t_2)}$$

The RLC series circuit represents the motional branch; it describes the mechanical oscillations of the material. The input capacitance C_{d1} and output capacitance C_{d2} describe the dielectric behaviour of the piezoelectric layers.

Nomenclature:

We give the nomenclature of used parameters. The details of model are given in the reference [3].
C, L, R: Capacitance, Inductance and Resistance in the mechanical branch of the PT. C_{d1}, C_{d2}: Input and Output capacitance representing the dielectric properties of the PT. R_{load}: load resistance of the PT. t_1: Thickness of the primary layer, t_2: Thickness of the secondary layer, b_p: Width of the PT, Q_m : Mechanical quality constant.

ρ : Density (kg/m^3), ε_{33}^T : permittivity, d_{31}: Piezoelectric constant, N_1, N_2: are the number of layers respectively in the primary and secondary of PT. N is the Transformer-Turn ratio of the PT, P: Polarization, T: Stress, s_{11}^E: Elastic compliance, r: Radius of the layers, G: the voltage gain of the PT, η : the efficiency of the PT, Y_{in} : Input admittance of free space.

Voltage gain and efficiency are expressed by the relations (1) and (2):

$$G(p) = \frac{N C R_{load} p}{C R_{load} p + N^2 \left(1 + C_{d2} R_{load} p\right) \left(1 + C(R + Lp)p\right)} \tag{1}$$

$$\eta = \frac{P_2}{P_1} = |G|^2 \frac{R_{load}}{\mathrm{Re}\left[Y_{in}\right]} \tag{2}$$

$$Y_{in} = j\omega C_{d1} + \frac{1}{R + j\omega L + \frac{1}{j\omega C}} \tag{3}$$

5. Simulation Results

We considered a step-up transformer of millimetre size characterized by a transformer–turn ratio equals to 2. The data used are the following: N_1= 6 ; N_2= 3 ; r = 8 mm ; t_1=150 µm ; t_2= 150µm ; N=2 ; f=150 kHz. The simulation results of the efficiency and voltage gain as a function load are respectively represented in Fig.4 and Fig.5.

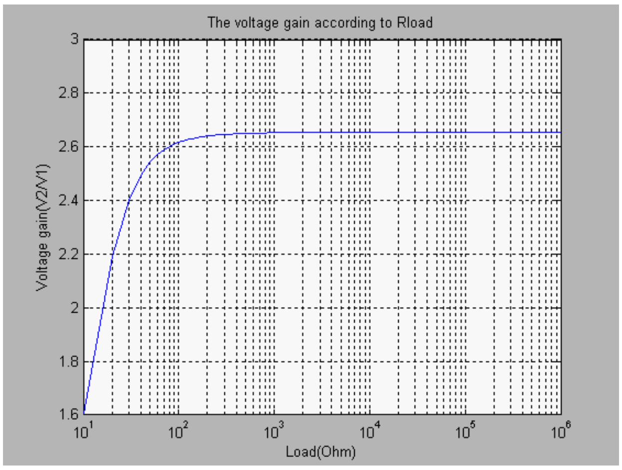

Fig.4. Voltage Gain of Transformer

The voltage gain is of 2,63 for R_{load}=1MΩ (Fig.4). The efficiency is closer to 1 for a load contained between some Ohms and 100 Ω . This begins to decrease from 200Ω and tends towards 0,8 for a load closer to 1000Ω .

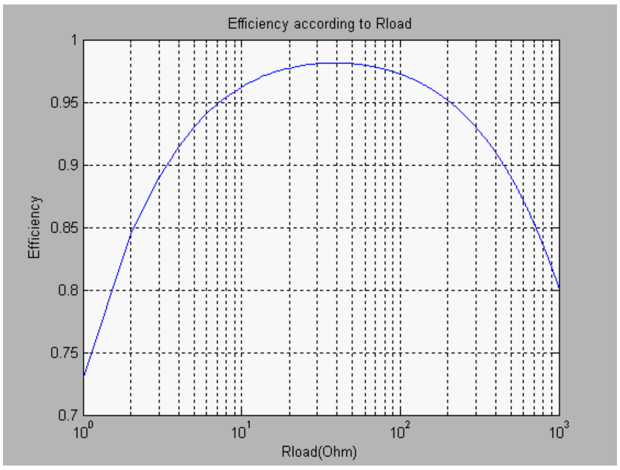

Fig.5. Efficiency of Transformer for $R_{load} \in [0,1000]\Omega$

5.1 Influence of Radius on the Gain and the Efficiency

In the present case, the value of parameters are the same that of precedent case (N_1= 6; N_2= 3 ; t_1=150 µm ; t_2= 150µm ; N=2; f=23 kHz), only r is equal to 50 mm. The curve of voltage gain and efficiency respectively are given in the Fig.6 and Fi.g.7. We remarked that the voltage gain decreases to 0,718 and the efficiency is equal to unity for R_{Load}= some Ωs and tends towards 0,4 for a load R_{Load}= 1000 Ω.

For a radius r=0,25.10^{-6}m and f=4800 Mhz, the voltage gain and efficiency respectively increase (Fig..8 and Fig.9) to 2,5 and 0,45 in accordance with the load (R_{load}) when this one changes from 1 to 1MΩ. These Results show that this transformer can be used in high frequency and loaded with R_{Load}= 10^5 Ω to 1MΩ.

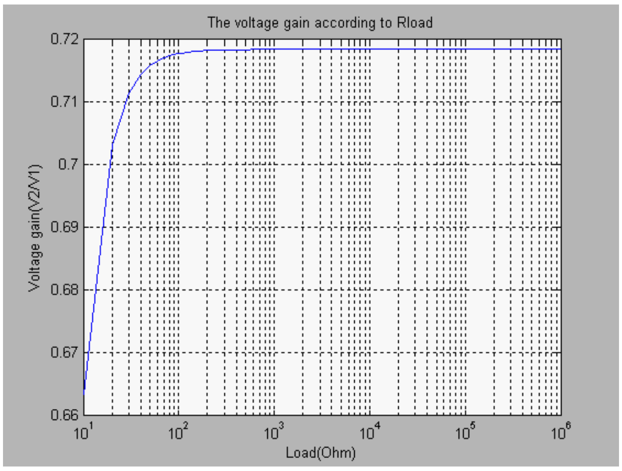

Fig.6. Voltage Gain of Transformer

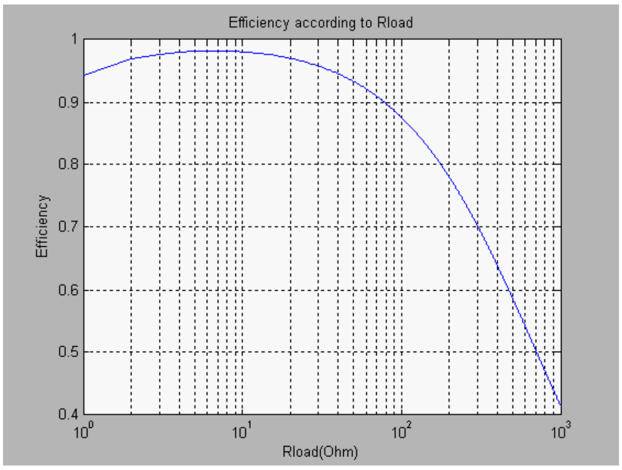

Fig.7. Efficiency of Transformer for $R_{load} \in [0,1000]\Omega$

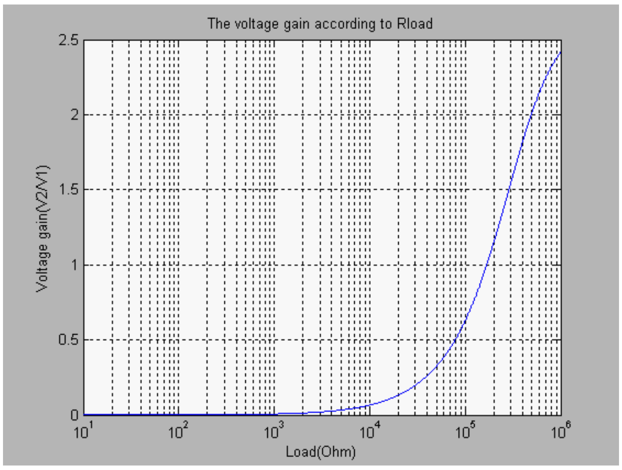

Fig.8. Voltage Gain of Transformer

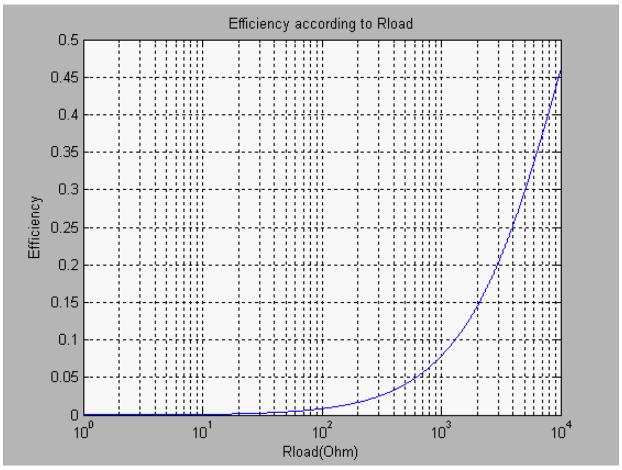

Fig.9. Efficiency of Transformer

5.2 Influence of Thickness on the Gain and the Efficiency

In this case we change the thickness of the piezoelectric ceramic. The parameters are as follows. N_1= 6 ; N_2= 3 ; $r = 8 \times 10^{-3}$; t_1=300 mm ; t_2= 300 mm ; N=2 ; f = 150 kHZ. For t_1=t_2=300mm, the voltage is equal to that one of the first case (Fig.10) but the efficiency (Fig.11) is closer to 1.

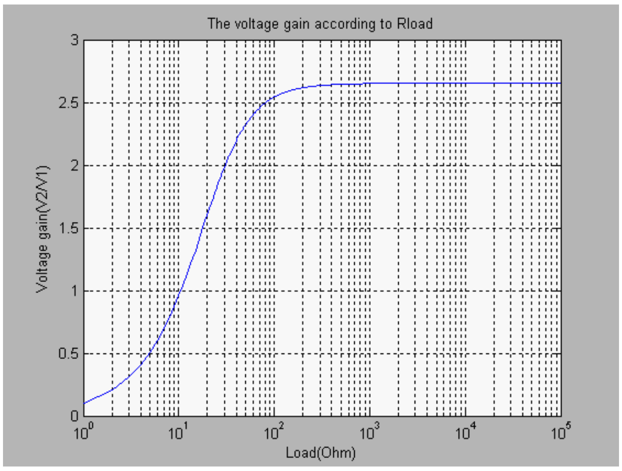

Fig.10. Voltage Gain of Transformer

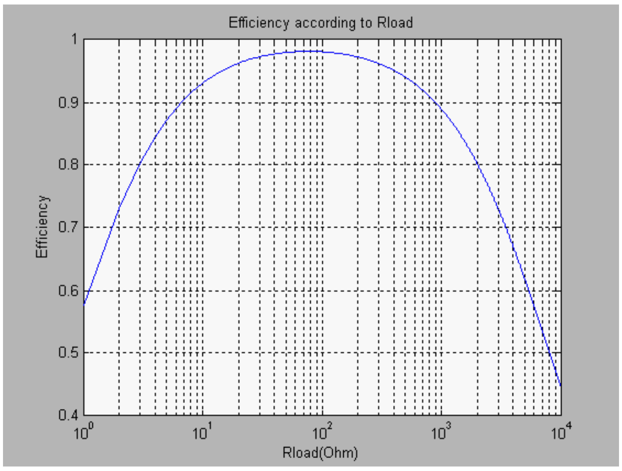

Fig.11. Efficiency of Transformer

For t_1=300mm, t_2=150 mm and f=150kz, the secondary layer is less thick than the primary layer, the voltage gain increases to 3,4 (Fig.12) and efficiency (Fig.13) reaches 0,98 for R_{load} near to 100 Ω and decreases to 0,2 for R_{load}=10 kΩ.

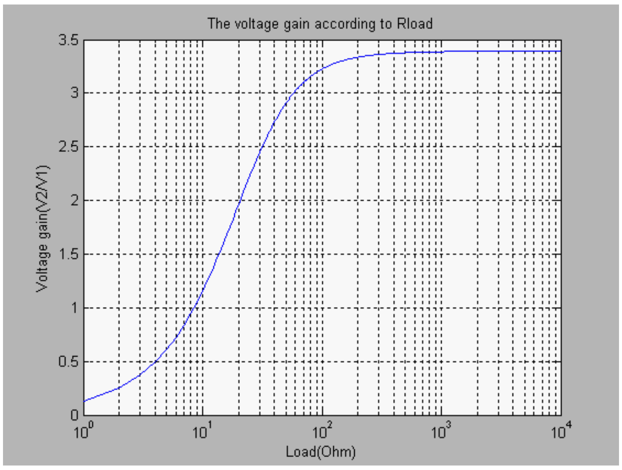

Fig.12 Voltage Gain of Transformer

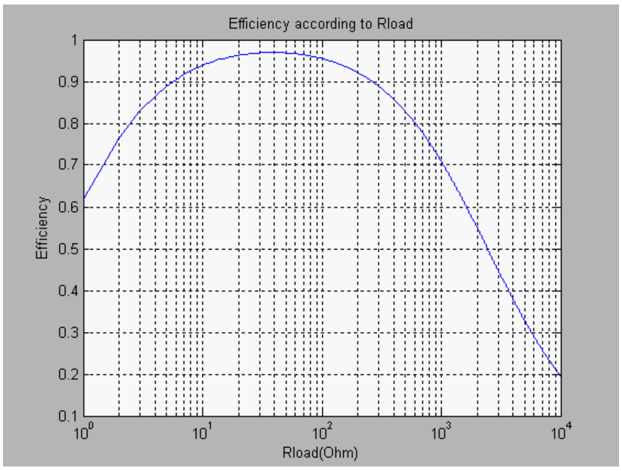

Fig.13 Efficiency of transformer

5.3 Influence of Layer Number on the Gain and the Efficiency

For t1=t2=150µm, N1=N2=6, r=8mm. f=149khz. Fig.14 and Fig.15 represent respectively the voltage gain and the efficiency of the transformer for a transformer ratio equal to 1. The voltage gain is near to one (0,95) for R_{load} more than 100 Ω, and efficiency is equal to one in R_{load} (20-100Ω) range and decreases to 0,24 for R_{load} = 10 kΩ.

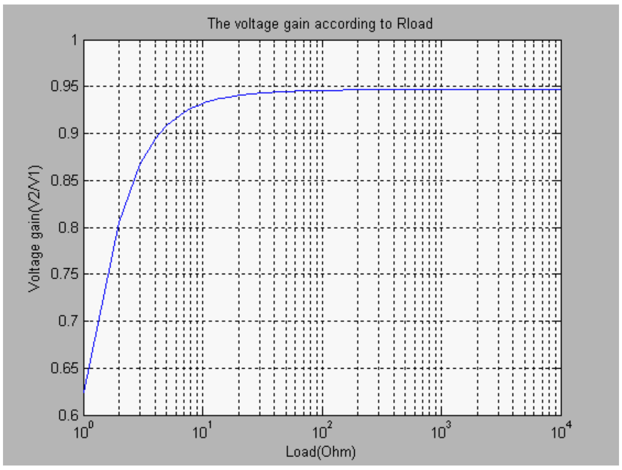

Fig.14 Voltage Gain of Transformer

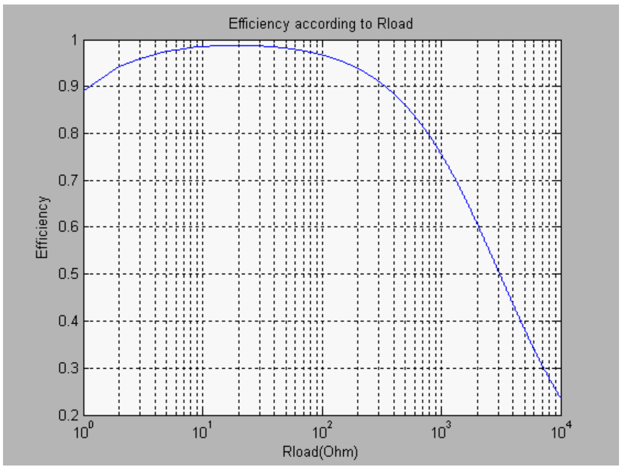

Fig.15 Efficiency of transformer

For t1=t2=150 µm, r=8mm, f=149khz and N1=3, N2=6 correspond to the voltage step-down ratio (Fig. 16 and Fig.17). The voltage decreases to 0,48 and efficiency increases to 0,3 for R_{load} = 10 kΩ.

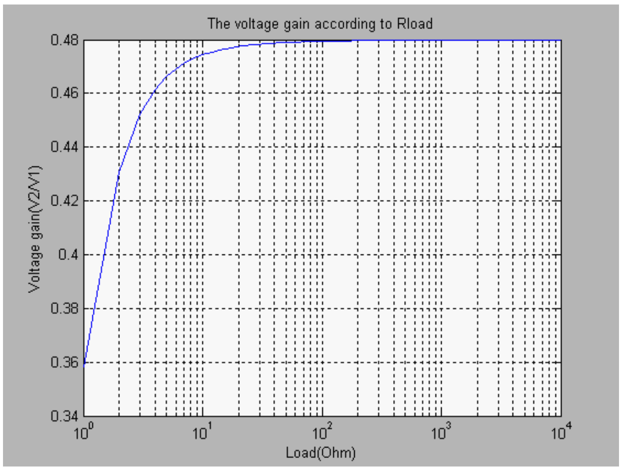

Fig.16 Voltage Gain of Transformer

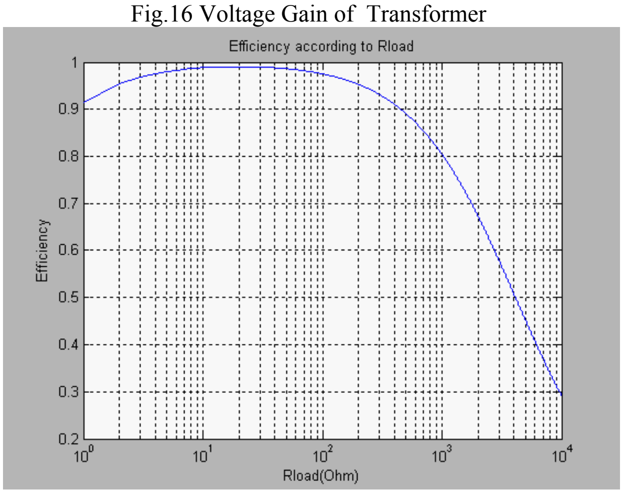

Fig.17 Efficiency of transformer

5.4 Q Effect on the Voltage Gain and the Efficiency

Mechanical quality constant (Q) effect has been tested for three values (1400, 2600 and 6000). The voltage gain is nearly without change. The voltage gain is steadied to 2,6 (Fig. 18).

However, the efficiency of transformer increases jointly with mechanical quality constant (Q). Fig. 19 shows the efficiency evolution. This tends towards one for the greater value of Q and R_{load} between 30 and 100 Ω.

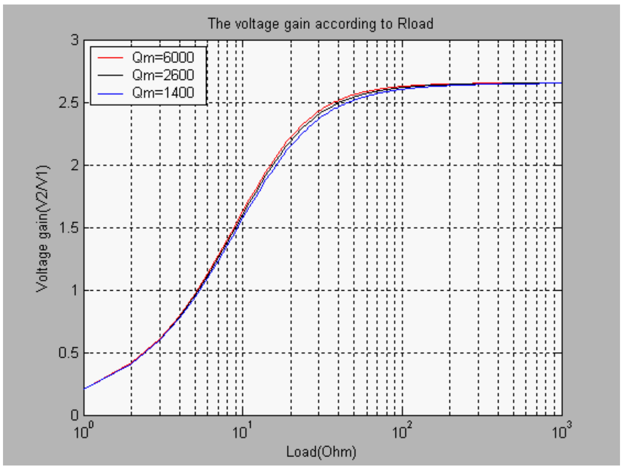

Fig.18 Voltage Gain of Transformer

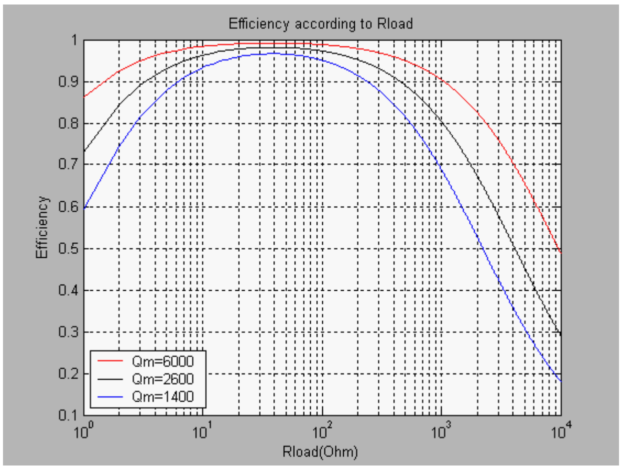

Fig.19 Efficiency of transformer

5.4 d31 Effect on the voltage Gain and the Efficiency

d31 effect on the voltage gain and the efficiency has been simulated for three values ($45x10^{-12}$, $78x10^{-12}$ and $105x10^{-12}$). The simulation results respectively of the voltage gain (Fig. 20) and the efficiency (Fig. 21) show that piezoelectric material is more sensitive to the piezoelectric constant. The results indicate that the piezoelectric material choose depend, between other, particularly of Q, d31 and the desired performances of the transformer.

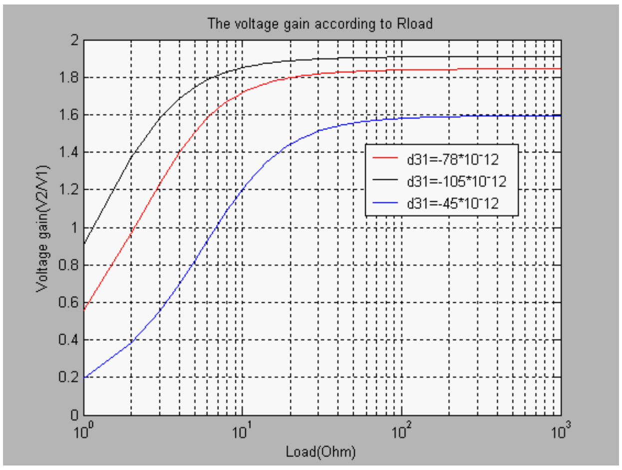

Fig.20 Voltage Gain of Transformer

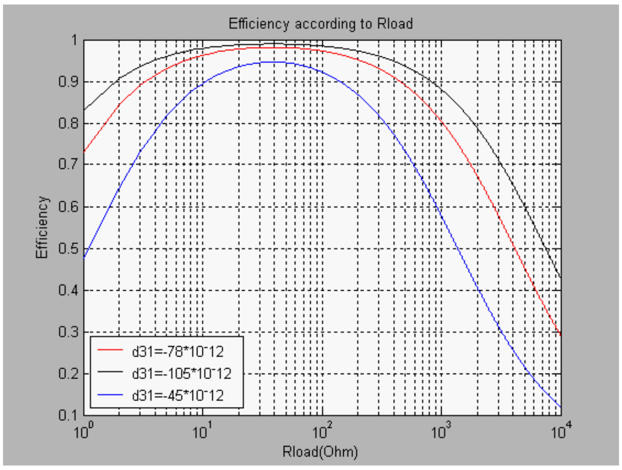

Fig. 21 Effect of d31 parameter on the Efficiency

The simulation results showed that the piezoelectric transformer, functioning in radial mode, can be used as step-up transformer in low as in high frequency. All depends of material characteristic, of geometrical dimensions and of the load applied to the output.

6. Conclusion

The piezoelectric transformer (PT) vibrating in radial mode can be used as step-up transformer and in low frequency (of the order of kHz). The effects of the thickness and the radius have been studied. The simulation show well that the performances of transformer essentially depend on their geometrical dimensions and the intrinsic parameters of piezoelectric material. The piezoelectric transformer, functioning in radial mode, used in high frequency must have a small radius in the order of $0{,}25\text{x}10^{-6}$mm. In the low frequency the PT must to have the same primary and secondary piezoelectric ceramic but these ones are thicker (in order of some hundred millimeters).

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