Design and Construction of a Multifunction Piezoelectric Transformer

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Abstract
In recent years, piezoelectric materials have particularly found advantageous field of application in electrical energy's conversion. Especially, the piezoelectric transformers are becoming more and more usable in electrical devices owing to several advantages such as small size, high efficiency, no electromagnetic noise, and non-flammability. The purpose of this study was to investigate a transformer design that allows having multi-functionality with different efficiency and wider range of voltage gain at resonance frequency. The piezoelectric transformer construction utilizes radial mode both at the input and output port and has the unidirectional polarization in the ceramics. An electromechanical equivalent circuit model based on Mason's equivalent circuit was developed so as to describe the characteristics of the piezoelectric transformer. Excellent matching was found between the simulation data and experimental results. Finally, the results of this study will allow to deterministically designing multifunction piezoelectric transformers with specified performance.

Keywords Piezoelectric transformer · Multifunction · Radial mode · Voltage gain · Efficiency

Introduction

One of the general objectives in the development of technological devices is to minimize the total volume and weight without compromising performance. This gave birth to the need of new components with enhanced functionality and production technologies [1–3]. Recently, the demand for miniaturized and highly efficient transformer has increased with the rapid rise of portable equipment such as notebook-type computers and digital video cameras. The miniaturization of electromagnetic transformer raises certain problems to pertain manufacturing both the coils and the magnetic core, increase of magnetic leak, degradation of performances, and electromagnetic pollution of the environment. One interesting solution consists of using a piezoelectric transformer, in which the transformation of voltage is achieved through the elastic resonance of piezoelectric vibration [4–7]. The piezoelectric transformer offers several advantages compared to the electromagnetic ones such as higher electromechanical power density, no electromechanical noise, higher efficiency at resonance, easier miniaturization, non-flammability, and simpler fabrication process [1].

In addition to the conventional applications such as ballast for back light inverter in notebook computers, camera flash, and fuel ignition, several new applications have emerged such as AC/DC converter, power supply for displays, image intensifiers, and automobile lighting. Several transformer designs have been proposed to meet the specifications in multifunctional applications [8–11].

As a general rule, a piezoelectric transformer (PT) has two parts: primary and secondary. The input is an actuator which is excited by an alternative voltage which creates a vibration. And the output part is a sensor that converts the vibration into an alternative voltage. There are lots of transformer structures that are used for different applications. The most classical ones are the Rosen-type PT [12–14]; it is known for its high voltage gain and matching load impedance. The thickness vibration mode of PT [15–17] and the radial vibration mode of PT [18, 19] present low voltage gains and matching load impedances.

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The first section of this paper proposes the development of electromechanical model of the piezoelectric transformer established according to a single-dimension description based on Mason's equivalent circuit model. The second part presents a realization method of the piezoelectric transformer radial mode by using piezoelectric multilayer, with a presentation of the process of fabrication. The obtained measurements of the voltage gain and efficiency for two types of piezoelectric transformer and their discussion are given in the third section in order to demonstrate the multi-functionality of this structure in radial mode. Finally, a good agreement is observed between the two sets of data, which consequently validates the proposed modeling to justify the choice of design.

Radial vibration mode of PT

Characterization

The piezoelectric transformer in radial mode is established on a simple principle operation based on a stack of disk-shaped ceramics. Primary and secondary PT, separated by a rigid insulation (rigid insulation ensures better coupling between primary and secondary in order to minimize losses), may consist of one or more layers alternately polarized along the thickness (Fig. 1). These transformers have a range of resonant frequencies ranging between 50 and 250 kHz for power densities often exceeding 40 W/cm^3.

For the Transoner, the fundamental vibration frequency is inversely proportional to the radius and directly proportional to the wave propagation speed of the material [18] as shown in Eq. (1),

$$f_r = \frac{N_R}{D} \tag{1}$$

where D is the diameter and N_R is the material wave speed.

The material used in this study is a lead zirconate titanate (PZT) polarized according to the thickness provided by the company "Ferroperm" with Pz26 reference, which has the advantage of having a great quality factor Q_m. The principal characteristics of this material, as well as the geometrical data of the transformer, are indicated in Table 1.

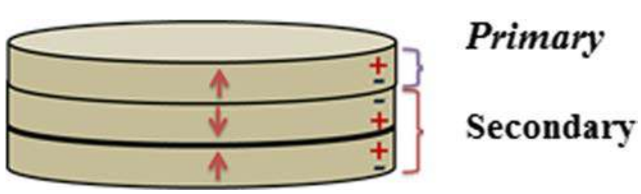

Fig. 1 Round-shaped radial vibration mode of piezoelectric transformer

Table 1 Material parameters of the piezoelectric transformer

Parameters	Symbol	Value
Density	ρ	7.7 10^3 kg/m^3
Compliances short circuit	S_{11}^E	13 10^{-12} m^2/N
	S_{33}^E	20 10^{-12} m^2/N
Permittivity	ε_{33}^T	9.5568 10^{-9}F/m
Piezoelectric coefficient	d_{31}	–130 10^{-12} C/N
	d_{33}	330 10^{-12} C/N
Mechanical factor of quality	Q_m	400
Surface of sample	A	200 mm^2
Diameter of sample	D	16 mm

Modeling of the radial vibration mode of PT

The analysis of piezoelectric transformers has been carried out by employing one dimensional wave equation. Accordingly, the mechanical and electrical properties can be derived in a straightforward manner. In order to study its interaction, it is preferable to use the equivalent circuit approach. Meanwhile, mechanical parameters can be replaced by their electric counterparts. Around the 1950s, the piezoelectric transformers had emerged, and its equivalent circuits had been derived [9–11] in the forms of different basic model cells.

Figure 2 shows the simplified equivalent circuit model common to all piezoelectric transformers. In this scheme, the series circuit RLC represents the motional branch and describes the mechanical oscillations of the material (current I in this branch is proportional to the piezoelectric transformer structures). The input capacitance C_{d1} and output capacitance C_{d2} describe the dielectric behavior of the piezoelectric layers of the transformer. The coupling between electrical and mechanical branches is represented by the equivalent transformer (ratio 1:N).

The parameters of the transformer are given by the following expressions:

$$C_{d1} = \frac{N_1 \pi r^2 \varepsilon_{33}^T \left(1-\frac{d_{31}^2}{S_{33}^T S_{11}^E}\right)}{t_1}$$

$$R = \frac{(N_1 t_1 + N_2 t_2)\sqrt{2\rho S_{11}^E}}{16 r Q_m (N_1 d_{31})^2}$$

$$L = \frac{\rho \left(S_{11}^E\right)^2 (N_1 t_1 + N_2 t_2)}{8\pi (N_1 d_{31})^2}$$

$$C = \frac{16 r^2 (d_{33} N_1)^2}{\pi S_{11}^E (N_1 t_1 + N_2 t_2)}$$

$$C_{d2} = \frac{N_2 \pi r^2 \varepsilon_{33}^T \left(1-\frac{d_{31}^2}{S_{33}^T S_{11}^E}\right)}{t_2},$$

$$N = \frac{N_1}{N_2}$$

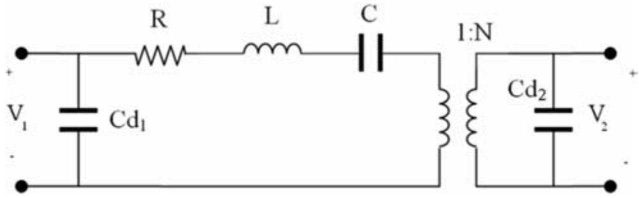

Fig. 2 Equivalent circuit simplifies of piezoelectric transformer [5]

C_{d1} is the capacity of the primary's transformer, C_{d2} the capacity of the secondary's transformer, R the resistance, L the inductance, C the capacity, N the transformation ratio, V_2 the output voltage of the transformer, N_1 the numbers of primary layer, N_2 the numbers of secondary layer, r the radius of the layers, t_1 the thickness of primary, and t_2 the thickness of the secondary.

Evolution of the transformer characteristics

In this part, one is interested in the characteristics of the piezoelectric transformer according to the value of load resistance R_{Load} connected to the secondary.

The voltage gain of the piezoelectric transformer is given by:

$$G = \frac{1}{\sqrt[N]{\left(\frac{1}{N^2} + \frac{C_{d2}}{C} - \omega^2 L C_{d2} + \frac{R}{R_{\text{Load}}}\right)^2 + \left(\omega\left(RC_{d2} + \frac{L}{R_{\text{Load}}} - \frac{1}{\omega C R_{\text{Load}}}\right)\right)^2}} \quad (2)$$

And the transmitted power is expressed according to the load by:

$$P_2 = \frac{V_1^2 N^2 R_{\text{Load}}\left(1 + (\omega C_{d2} R_{\text{Load}})^2\right)}{\left(N^2 R\left(1 + (\omega C_{d2} R_{\text{Load}})^2\right) + R_{\text{Load}}\right)^2} \quad (3)$$

From the absorbed and transmitted powers, one deduces the expression of the efficiency:

$$\eta = \frac{P_2}{P_1} = \frac{1}{1 + \frac{N^2 R}{R_{\text{Load}}}\left(1 + (\omega C_{d2} R_{\text{Load}})^2\right)} \quad (4)$$

Experimental setup

Preparation of PT

With the use of more and more onboard electronics and autonomous systems in different areas, such as transport or the medical community, piezoelectric materials are becoming more used as a sensor and actuator. For this reason, we have chosen lead zirconate titanate (PZT) for their best piezoelectric properties [20, 21].

We have relied on these ceramic materials in order to achieve multilayer piezoelectric transformer [22]. The Pz26 powder from MEGGIT-Ferroperm is isostatic pressed at 3000 bar. The sintering was carried out at 1200 °C during 4 h. This preparation step is based on a heat treatment which can switch from a system of individual particles to a solid state of more or less successful compact. Converting the powder into a dense solid takes place by changing the shape of the powder grains and replacing the gas-solid interfaces by solid-solid interfaces and also by the disappearance of the porosity. Thus, before the electrical characterization, both surfaces of the sample were covered with silver electrode by screen printing. The silver paste was dried at 150 °C during 15 min and fired at 650 °C during 5 min. The electric bias field applied for polarization is 3.6 kV/mm in a silicone oil bath under 80 °C. This step is finished by the realization of piezoelectric transformer in radial mode with a diameter of 16 mm. Two configurations of transformer are studied in this work varying the number of layers in both primary and secondary. The assemblies of layers are achieved with epoxy glue provided by the company "Epotecny.".Figure 3 presents the prototype of a piezoelectric transformer realized in radial mode.

This study focuses on two types of structures piezoelectric transformers; the first structure will be used as a voltage step-up with two primary layers with a thickness that is equal to 840 μm for each and a secondary layer which have a thickness of 870 μm; the second structure is used as a voltage step-down with a primary layer with a thickness which is equal to 1020 μm and two secondary layers having a thickness of 850 μm for each.

Principle of measurement

This section describes the setup developed to characterize the efficiency and voltage gain.

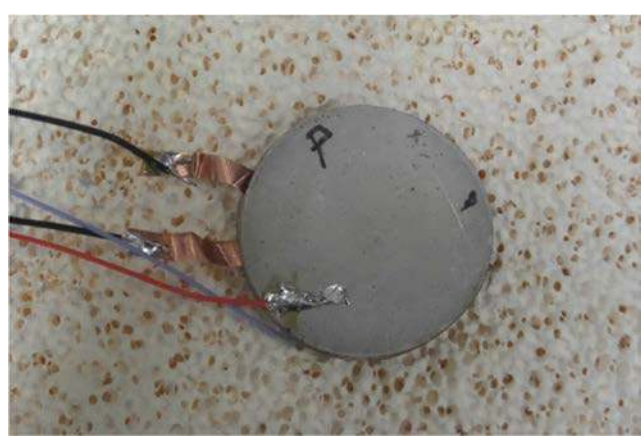

Fig. 3 Prototype of piezoelectric transformer in radial mode

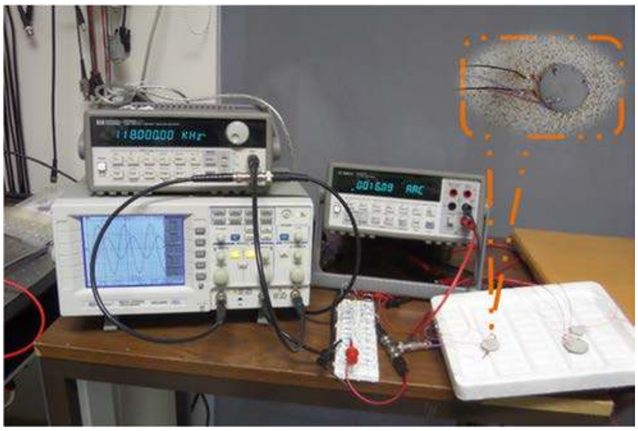

Fig. 4 Photograph of measurements setup for gain and efficiency evaluation of PZT based PT

The measurement setup is presented in Fig. 4. PT was driven by sinusoidal voltage with different amplitude generated by the function generator Hewlett-Packard HP33120A. The transformer is connected with the output part to an electrical load R, which varies from 1 to 40 kΩ. The current output circuit is monitored by Digit Multimeter (Agilent 34,401 A) connected to oscilloscope as a voltage drop across the small resistor (5.62 Ω). In this setup, the current is chosen as it is known to be less sensitive to the noise from the electrical network (50 Hz) in order to avoid problems of impedance adaptation. The RMS power harvested on the load is subsequently derived using $P = R \times I^2_{RMS}$, where I_{RMS} is the current measured by the current amplifier. All the data are monitored by an oscilloscope (GW Instek GDS-8405).

Results and discussion

The behavioral analysis of the piezoelectric transformer is realized from the equivalent electrical circuit established in the preceding paragraph. The characterization of the transformer is made by the measurement of voltage gain and efficiency at resonance frequency and as a function of the load resistance placed in the transformer output. In order to verify the experimental measurement, MATLAB/Simulink TM environment is used for the simulation of the theoretical model, which a good agreement is observed between the two sets of data. Our study is focused on two piezoelectric transformer structures with a diameter of 16 mm by varying the layers of the primary and secondary. Table 2 recapitulates the dimensioning of the transformers 1 and 2 at the resonance frequency.

Transformer 1

In order to characterize in electric viewpoint, the two prototypes realized the measurements of gain and efficiency as a function of load which carried out to compare the experimental results with those obtained by the theoretical model. The structure of transformer 1 is constituted of two layers in primary and one in secondary with a total thickness of 2.55 mm; thus, the primary voltage applied to the transformer is 1.94 V with a fundamental resonance frequency range of the order of 116.86 kHz.

Table 2 Dimensioning of the piezoelectric transformers

Structures	Thickness of secondary	Thickness of primary	d_{33}
Transformer 1	$e_1 = e_2 = 840$ μm	$e_3 = 870$ μm	$[150; 190] pC/N$
Transformer 2	$e_1 = 1020$ μm	$e_2 = e_3 = 850$ μm	$[210; 240] pC/N$

Figure 5 shows the measurements of evolution of the voltage gain as a function of load. One notices that starting from the optimum load impedance, which is equal to 0.5×10^5 Ω the voltage gain increases up to value 4.5. Experimental points are almost superimposed on simulation results. It is well seen that our radial mode piezoelectric transformer is an elevator of voltage.

Figure 6 represents the efficiency of the transformer 1, as functions of the load resistance. For this measurement, the frequencies were adjusted so that the efficiency attained maximums for the given load resistance. The transformer 1, which function as voltage step, operate with low load so as to determine the optimal operating point of the PT; the efficiency of this one has achieved the value of 65% for $R_{Load} = 0.85$ kΩ. Experimental results are in good agreement with the theoretical results.

Transformer 2

The configuration of transformer 2 is constituted of one layer in primary and two in secondary with a total

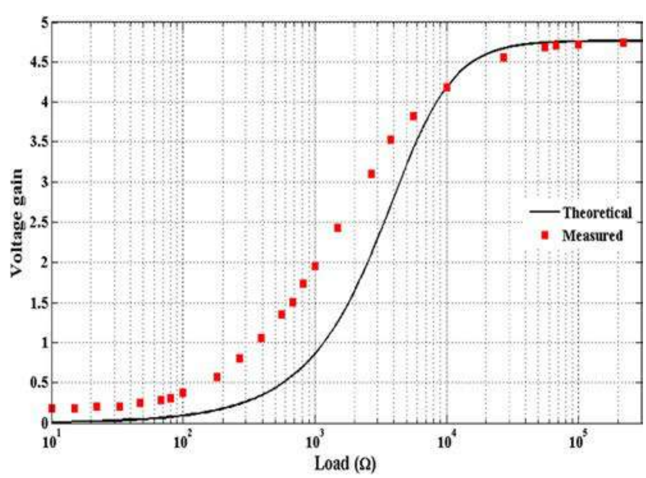

Fig. 5 Voltage gain of the transformer 1 according to the load

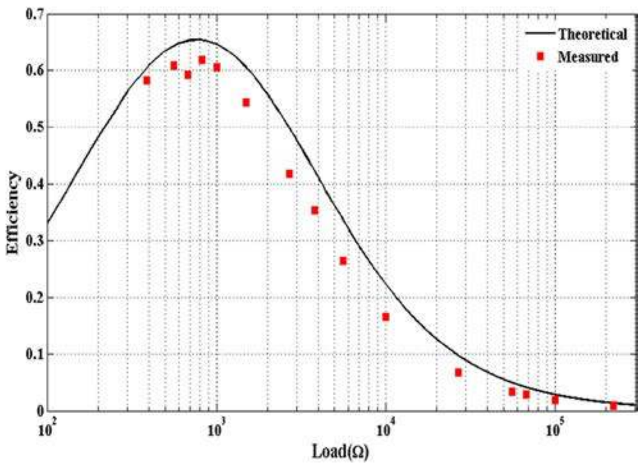

Fig. 6 Efficiency of the transformer 1 according to the load

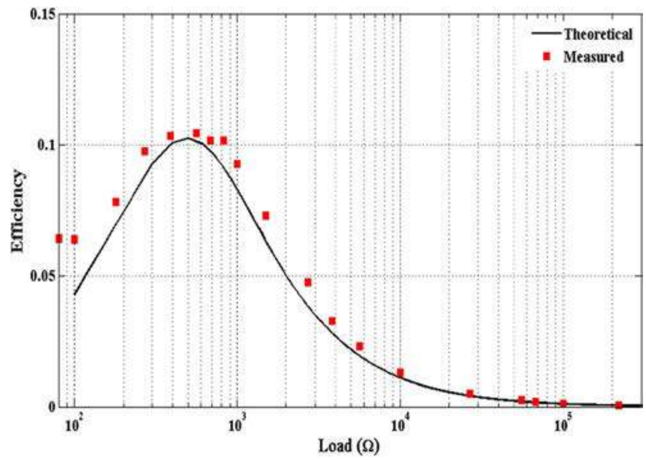

Fig. 8 Experimental and simulation results for efficiency of the transformer 2 as functions of the load resistance

thickness of 2.72 mm; therefore, the primary voltage applied to the transformer is 2.68 V. The operating resonance frequency of the transformer is 87 kHz. Figure 7 shows the evolution of experimental results of the voltage gain as functions of the load resistance. One notices that starting from the optimum load impedance, the voltage gain increases to value 0.31. It is well seen that our radial mode piezoelectric transformer is a step-down which the theoretical and practical results have superposed.

Figure 8 shows the effect of load resistance (R_{Load})on the efficiency of the transformer 2, measured at 2.68 V. For this measurement, the frequencies are adjusted so that the efficiency attains maximum for the given load resistance. It can be seen that the maximum efficiency increases with load resistance with a maximum value of 11%, for$R_{\text{Load}} = 0.56$ kΩ; this is the optimal operating point of the PT. Finally, the results practiced and those obtained by the theoretical model are almost in good coherent.

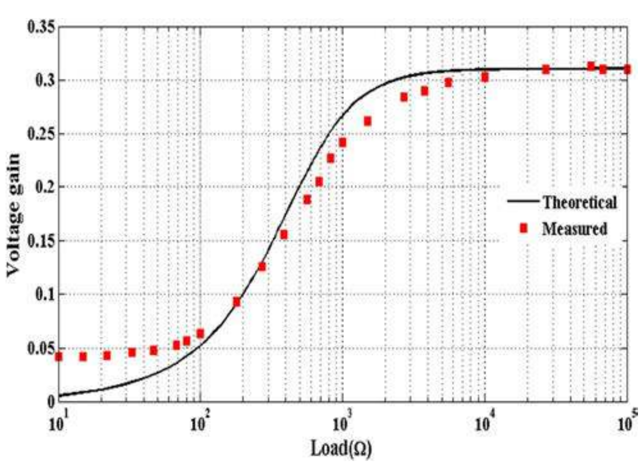

Fig. 7 Experimental and simulation results for voltage gain of the transformer 2 according to the load resistance

Conclusion

This work is driven by new needs particularly in the areas of micro-systems (micro-actuators, micro-motors, micro-pumps, etc.); consequently, it is a solution for passive components integration of galvanic isolation based on piezoelectricity. The piezoelectric transformers behave mainly as a selective filter; it can transmit power if it operates around its resonance. Consequently, the efficiency and gain (transformation ratio) fluctuate widely with its load. This is a very important difference compared to a magnetic transformer where these two parameters are almost constant over a large load dynamics and operating frequencies. Optimization of performance's piezoelectric transformers as well as efficiency can be improved with the application of non-linear methods. These techniques are based on synchronized switching also on the temporal evolution of the mechanical system quantities.

In this paper, we have studied and realized a piezoelectric transformer in radial mode, which transformer works as step-up and step-down. The simulation results were calculated by MATLAB, using an equivalent circuit. We performed two configurations; the first transformer functions as a step-up; it consists of two layers in primary and one in secondary. The electrical characteristics depends on the load showing that the voltage gain and efficiency vary depending on the load such as the gain reaches its maximum value 4.5 for a load of 50 kΩ and the efficiency of this transformer is 65% for $R_{\text{Load}} =$ 0.85 kΩ. The second working step-down transformer consists of a single layer in primary and two secondary layers. The voltage gain has a value equal to 0.31 for a load 10 kΩ. The experimental results show a maximum efficiency of 11% at a load resistance of $R_{\text{Load}} = 0.56$ kΩ; the experiment results are in good agreement with the simulation results. Simulation with MATLAB allows a prediction of the efficiency and the voltage gain of the PT. Finally, piezoelectric transformers multilayer offer outstanding performance in terms of gain voltage and useful efficiency for applications requiring voltage adjustment or galvanic isolation, perfectly dedicated to high performance applications with low power.

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