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Study and Modeling of a Traveling Wave Piezoelectric Transformer

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Abstract. This paper reports the study and the modelling of a new topology of traveling wave piezoelectric transformer (TWPT). Unlike conventional piezoelectric transformers, the proposed transformer uses progressive waves to carry out the electromechanical conversion. Moreover, associated with an appropriate converter, it enables any kind of AC-DC or AC-AC power conversion. An analytical modelling of the system is carried allowing defining numerically the voltages, currents, displacements and stresses in the piezoelectric transformer over time as a function of the geometrical and physical parameters of the materials.

1. Introduction

In conventional piezoelectric transformers (PT), the coupling between primary and secondary sides is realized by mechanical coupling through a standing wave. In general, these transformers will only provide one or two output voltages with fixed phase shift compared to the input thus limiting their use to simple power converter topology. The generation of a traveling wave inside the PT instead of a stationary wave allows obtaining at the secondary side numerous output voltages with the same amplitude and different phase-shifts between them. The traveling wave piezoelectric transformer could thus be used in a universal power electronic converter able to realize different complex electrical conversion like DC/DC, DC/AC or DC/AC multi-phases. To the author's knowledge, only one paper [1] proposes the use of a traveling wave for electric to electric conversion but for a bulk wave and without considering the generation of a multiphase system at the output. In this paper, we will present a piezoelectric transformer converting energy by generating a flexural traveling wave leading to an octophase system at the outputs.

2. Structure and working principle of the TWPT

2.1. Geometry of the TWPT

The common geometry used to generate a traveling wave is a ring [2]. This architecture presents the assets of working at a resonant frequency of the element and allows to obtain the highest energy transfer between

the primary and secondary sides of the transformer. As stated above, two modes of propagation of the wave are possible: a flexural wave and a bulk wave. For a flexural wave; the TWPT must consist in two piezoelectric ceramics polarized in opposite directions and gathered together (figure 1). For a bulk wave, only one piezoelectric ceramic is necessary. In the following, we will focus on the flexural wave generation. The objective of this device is to generate a flexural wave in the thickness direction that will propagate along the circumference of the ring. This flexural wave appears near the resonance.

2.2. Generation of the traveling wave

The excitation of a resonance with only one signal will lead to a standing wave. The generation of a traveling wave can be realized by the generation of two standing waves with a phase shift of $\frac{\pi}{2}$ and a $\frac{\lambda}{4}$ displacement between them. The combination of these two standing waves leads to a progressive wave that will propagate alongside the circumference of the ring. The position of electrodes on the surface of the piezoelectric ceramic depends on the mode of resonance we want to excite. On figure 2 is represented the typical scheme used for the mode 3 of flexural mode. In this mode of resonance, the ring will present six antinodes and six nodes that will propagate along the circumference of the TWPT (figure 3). In order to generate the standing waves two main sets of electrode are used. The ones in light gray are driven by a sinusoidal voltage and on the ones in dark gray is applied a voltage with a phase shift of $\frac{\pi}{2}$ compared to the first one. These two sets of electrodes are responsible for each standing wave. The electrodes in white represent the output electrodes. In this scheme, we can see 8 output electrodes with a size twice smaller than the input electrodes. It means that we will obtain an octophase system at the output of the TWPT.

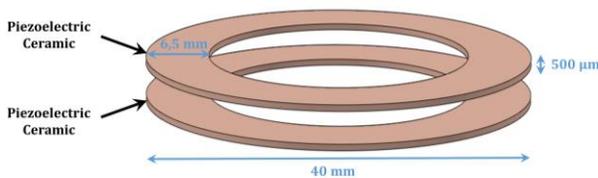


Figure 1. Ring Architecture of our TWPT

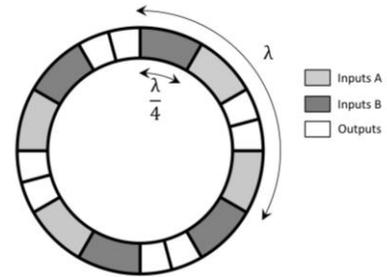


Figure 2. Electrode scheme on the surface of the TWPT

3. Analytical modelling

It is only useful to know the displacement of the flexural wave, in transformer applications, it is necessary to have a complete analysis of the electrical performances of the TWPT. In order to do that, we propose to obtain a model linking all the current and voltage values for the different electrodes.

The analysis is based on the Euler-Bernoulli beam theory. For this analysis, we separate the transformer into different sections corresponding each to one electrode. We make the hypothesis that these sections are treated as beams as represented in figure 4. Furthermore, we consider that the TWPT vibrates at a specific frequency and we thus realize a harmonic analysis at pulsation ω . The flexural wave appears in direction x_3 and propagates alongside direction x_1 . We considered thus the flexural stresses and moments (resp. F1 and F2) and the linear and angular speeds (resp. U1 and U2).

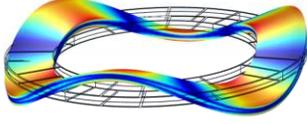


Figure 3. Flexural deformation of the ring

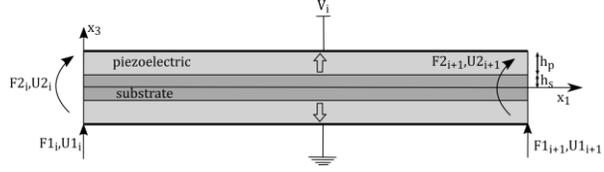


Figure 4 : Beam element representing a ring section under flexural stress.

From the Euler Bernoulli beam theory and piezoelectric equations, we find that the propagation of a flexural wave in the direction 3 alongside direction 1 is governed by equation (1)

$$K_b \frac{\partial^4 u_3}{\partial x_1^4} + \rho_b \frac{\partial^2 u_3}{\partial t^2} = 0 \quad (1)$$

with K_b the flexural rigidity and ρ_b the linear density of the TWPT depending on the material characteristics and geometry of the transformer. From this equation, we can determine the form of the deformation u_3 .

$$u_3(x_1) = \alpha_1 \cos(\lambda x_1) + \alpha_2 \sin(\lambda x_1) + \alpha_3 \cosh(\lambda x_1) + \alpha_4 \sinh(\lambda x_1) \quad (2)$$

with α_i coefficients that depend on the boundary conditions and λ the wavelength of the wave. Furthermore, by writing these conditions, we can determine transfer matrixes G_L and T_L depending on the geometric parameters and linking the mechanical variables (stresses and speeds) at one side to the ones at the other sides and the voltage on the electrode considered.

$$B_i = \begin{pmatrix} F1_i \\ F2_i \\ U1_i \\ U2_i \end{pmatrix} = G_L \begin{pmatrix} F1_{i+1} \\ F2_{i+1} \\ U1_{i+1} \\ U2_{i+1} \end{pmatrix} + T_L V_i = G_L B_{i+1} + T_L V_i \quad (3)$$

As contrary to previous work [3] where are only considered fixed or free boundary conditions, here, the matrixes are associated one with each other's along the TWPT. This allows obtaining a matrix P_i linking the mechanical variables at one point as a function of all the voltages on the electrodes (V is the matrix column of all the voltages on the electrodes).

$$B_i = \begin{pmatrix} F1_i \\ F2_i \\ U1_i \\ U2_i \end{pmatrix} = P_i V \quad (4)$$

Thereafter, from the equations of piezoelectricity we have $I_i = j\omega C V_i - N_b (U2_i - U2_{i+1})$. The current flowing through an electrode is a function of the voltage V_i and the angular velocities $U2$ at the extremities of the section (C is the clamped capacitance and N_b is an electromechanical coupling coefficient). Thus from this equation and (4) we determine an admittance matrix Y_{tot} linking all the currents and voltages on the electrodes:

$$I = Y_{tot} V \quad (5)$$

This admittance matrix is valid without considering if an electrode is an input or an output.

4. Simulation results

To simulate the device, we considered a TWPT whose dimensions are presented in figure 1. The material considered for the simulation is a PZT with the following characteristics: a density $\rho = 7500 \text{ kg/m}^3$, a

piezoelectric coefficient $d_{31} = -123 \times 10^{-12}$ C/N, an elastic compliance $s_{11} = 12.3 \times 10^{-12}$ m²/N and a permittivity $\epsilon_{33} = 1475 \epsilon_0$. The system was driven by sinusoidal voltages of amplitude 15V and charged with load resistance of 10 k Ω . Losses were also taken into account by using complex properties of the material.

The first analysis realized is a frequency sweep to observe the resonant frequencies of the piezoelectric transformer. For example, the voltage gain of the converter as a function of frequency is represented in figure 4. We see on the graph two resonances ($f_1 = 3980$ Hz and $f_2 = 11040$ Hz) corresponding to the 3rd and 5th modes of resonance. Due to the scheme of electrodes the third resonance presents the highest voltage gain.

Furthermore, the admittance matrix is composed of nonlinear functions of the resonance frequency and thus it is difficult to replace the matrix by a simple equivalent circuit. Nonetheless, at a specific frequency we can completely determine the type of admittance linking two electrodes (capacitance or inductance). This process was realized in Simulink where the admittance matrix was represented by a set of inductances or capacitances depending on the admittance matrix value. The input electrodes were driven by two sinusoidal voltages of amplitude 15V, at frequency f_1 with a phase shift of $\frac{\pi}{2}$ and a load resistor of 10 k Ω was plugged at each output electrode. Figure 5 shows the voltages at the output of the TWPT, depicting the octophase system. The amplitude of the output voltage corresponds to the value found with the frequency sweep.

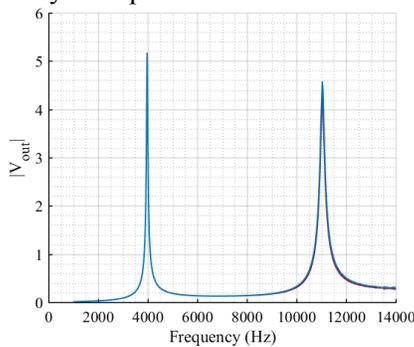


Figure 4. Voltage gain of the TWPT as a function of the excitation frequency

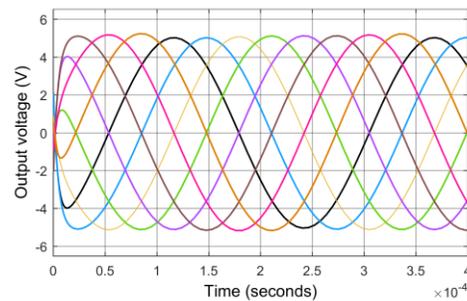


Figure 5. Output voltages at the output of the TWPT ($f_1 = 3980$ Hz)

5. Conclusion

This paper presents the architecture of a new traveling wave piezoelectric transformer. The analytical analysis of the transformer is presented and simulated. The results of the simulation of the model fit quite well with the finite element analysis. This new architecture of piezoelectric transformer allows obtaining a multi-phase system at the output thus opening the possibility of a universal power converter able to realize different kind of conversions.

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