General Study on Piezoelectric Transformer

[1]KWOK K.F., [1]DONG P., [1]CHENG K.W.E., [2]KWOK K.W., [1]HO Y.L., [2]WANG X.X. and [2]CHAN H.

[1] Power Electronics Research Center, Department of Electrical Engineering,
[2] Department of Applied Physics
The Hong Kong Polytechnic University
Hung Hom, Hong Kong

Abstract: Piezoelectric Transformer (PZT) is a device which transforms voltage by piezoelectric effect and converse piezoelectric effect of ceramic material. Compared with electromagnetic transformer, it has favorable characteristics of miniaturization, electromagnetic-noise free and the variable voltage gain with frequency and impedance. The modeling of Piezoelectric Transformer is the base of control and optimize. The principle of transforming voltage is presented in this paper. In addition, different modeling methods were brought into comparisons. Merits, shortcomings and the future work in modeling of PZT were given.

Keywords: Piezoelectric Transformer; Equivalent Circuit; Finite Element Methods;

1. Introduction

More and more portable electronic devices are miniaturized and light, which lead Piezoelectric Transformer (PZT) develop widely. PZTs are electrical energy transmission devices in essence, which comes of fifties in twenty century. PZT converses energy via the electro-mechanical coupling between the adjacent piezoelectric actuators and transducers. PZT has favorable characteristics, such as miniaturization, electromagnetic-noise free and the variable voltage gain with frequency and impedance. Due to their special characteristics, in the past few decades, piezoelectric transformers have been developed and used widely in many applications, such as electronic ballasts for fluorescent lamps and DC/DC converters.

Limited by manufacture's techniques of materials, the study and development of PZT are very lowly. Many researchers apply themselves to developing piezo materials, step-up ratio, output power, efficiency to thermal stress and dimension of PZT [1-3]. PZT has been focus on because of the new material applied in piezoelectric transformer.

Piezoelectric transformers [5-7] have been merged to be an alternative for the magnetic transformer because it offers certain advantages over the magnetic counterpart. One of the advantages is no Electromagnetic interference (EMI) because piezoelectric transformers are not based on magnetic energy transfer. It also can provide high voltage stepping ratio. It also does not require copper windings therefore it imposes saving in copper usage especially for large voltage conversion difference.

Modeling is the premise of characteristic analysis and controller design. Precise model of Piezoelectric Transformer is the base of control and optimize. In this paper, the principle of transforming voltage is presented. In addition, different modeling methods were brought into comparisons. Merits, shortcomings and the future work in modeling of PZT were given.

This paper is firstly to review the general modeling method for piezoelectric transformer, it is then to investigate the circuit topology for piezoelectric transformer under multiple operation condition. It should be understood that large power rating of piezoelectric transformers may not be acquired easily, it is necessary to parallel or series some piezoelectric transformers together in order to obtain the required power rating.

However, the parallel connection of the piezoelectric transformers is not easy because the primary and secondary sides of the piezoelectric transformers have a common return path that does not allow them to be paralleled together easily. For transformer without isolation, it is difficult to connect them together. Fig 1 shows the connection diagram of the piezoelectric transformer.

The schematic diagram of the Rosen-type piezoelectric transformers is shown in Figure 1. The transformer is made of lead zirconate titanate. It was prepared by the conventional dry-pressing technique and sintered at 1200°C. The transformer was polarized to the polarization states as shown in Figure 1 at 120°C. The input part is the driver section and the output part is the generator section. Usually, the Rosen-type piezoelectric transformer is used as step-up transformer with a typical voltage gain of 5 to 10. For multiple layer PZTs, the voltage gain could be 100 or more.

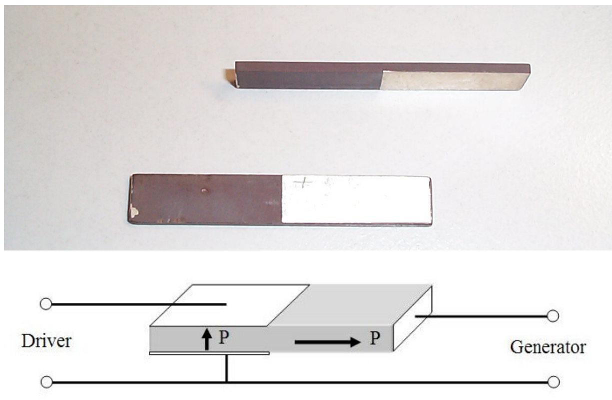

Fig 1: A Rosen-type piezoelectric

The piezoelectric transformer operates at a resonance mode and the power is converted electromechanically through a vibrating piezoelectric structure. The piezoelectric transformer has a number of unique features over a conventional electromagnetic transformer, which includes simple structure, nonflammable, electromagnetic noise free and high operation frequency.

2. Basic Concept

2.1 Operating principle

Some materials, such as bulk ceramics, ceramic thin films, multi-layer ceramics, single crystals, can produce electron charge when suffered stress. The electrical response to the mechanical stimulation is called the direct piezoelectric effect and the mechanical response to the electrical stimulation is the converse or inverse effect. Piezoelectric transformer uses the two effects and the principle of PZT is as follows: (1) The electrical input voltage generates a mechanical vibration, usually at the resonance frequency of the piezoelectric element, which then is reconverted into an electrical voltage, the output voltage of transformer. (2) The unloaded (open circuited) output to input voltage ratio depends on the geometrical dimensions, the electromechanical coupling factor, and the mechanical quality factor. (3) Temperature property; running parameters of PZT vary with temperature and drift is produced.

The detailed equations can be found in the following contents. The equation that defines this relationship is the piezoelectric equation:

$$D_i = d_{ij}\sigma_i \quad (1)$$

Where, Di ≡Electric Displacement (or Charge Density), dij ≡Piezoelectric Modulus, the ratio of strain to applied field or charge density to applied mechanical stress.

Stated differently, d measures charge caused by a given force or deflection caused by a given voltage. We can also use this to define the piezoelectric equation in terms of field and strain:

$$D_i = \frac{\sigma_j \lambda_i}{E_j} \quad (2)$$

Electric displacement is defined as: Di=εijEj
therefore,

$$e_{ij} E_j = d_{ij} \sigma$$

and

$$E_j = \frac{d_{ij}\sigma_j}{\varepsilon_{ij}}$$

which results in a new constant:

$$g_{ij} = \frac{d_{ij}}{\varepsilon_{ij}}$$

This constant is known as the piezoelectric constant and is equal to the open circuit field developed per unit of applied stress or as the strain developed per unit of applied charge density or electric displacement. The constant can then be written as:

$$g = \frac{\text{field}}{\text{stress}} = \frac{\text{volts / meter}}{\text{newtons / meter}^2} = \frac{\Delta L / L}{\varepsilon V / t} \quad (3)$$

Fortunately, many of the constants in the formulas above are equal to zero for PZT piezoelectric ceramics. The non-zero constants are:

$$s_{11} = s_{22},\ s_{33},\ s_{12},\ s_{13} = s_{23},\ s_{44},\ s_{66} = 2\,(s_{11} - s_{12})$$
$$d_{31} = d_{32},\ d_{33},\ d_{15} = d_{24}$$

2.2 Classification and its Characteristics

Instead of the magnetic field coupling that occurs between the primary and secondary windings in a conventional magnetic core transformer, piezoelectric transformers transfer electrical energy via electro-mechanical coupling between the primary and secondary piezoelectric elements for step-up or step-down voltage conversion. At present, there are three main categories: Rosen [8], thickness vibration mode [9] and radial vibration mode [10], shown in Figures respectively.

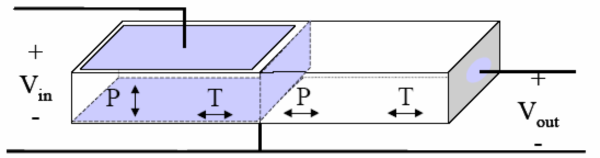

Fig. 2 Rosen Piezoelectric Transformer

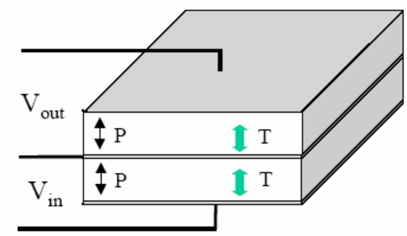

Fig. 3 Thickness Vibration Piezoelectric Transformer

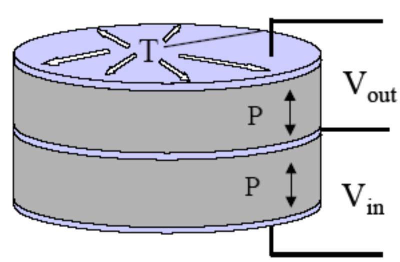

Fig. 4 Radial Vibration Mode Piezoelectric Transformer

Because of the different vibration modes and mechanical structures, these three types of PZTs have different mechanical and electrical characteristics. Rosen PZT shown in Fig. 1 is used widely. Rosen Piezoelectric Transformers are often referred to as high-voltage piezoelectric transformer because of the inherent high voltage gain associated with them. Developed by NEC of Japan in the 1990s, the thickness vibration piezoelectric transformer shown in Fig. 3 is a combination of longitudinal mode piezoelectric actuators and longitudinal mode piezoelectric transducers. The thickness vibration piezoelectric transformer is looked as the low-voltage piezoelectric transformer because of its inherent low voltage gain. The third PZT shown in Fig. 4 is invented in 1998, all the research work of it is under way.

3 Modeling of Piezoelectric Transformer

31 Common Modeling method of PZT

Although different vibration mode and mechanical structure are in piezoelectric transformer, but the relationship between different parts of PZT is the same. According to the piezoelectric equation, wave equation and boundary conditions, the equations described the PZT is given as follows:

Piezoelectric equation:

$$\begin{aligned} S &= sT + dE \\ D &= dT + \varepsilon E \end{aligned} \tag{4}$$

Wave equation:

$$\rho \frac{\partial^2 u}{\partial t^2} = c \frac{\partial^2 u}{\partial x^2} \tag{5}$$

Where, ρ is the thickness of vibration, u is the voltage, c is the capacitor. Correcting the boundary conditions, electric equations to characteristic equations, the model of PZT can given as:

$$\begin{aligned} I &= YV + Av \\ F &= zv - AV \end{aligned} \tag{6}$$

Here, the values in above equations are not given in detail, they can be seen in the references [11,12] according to different PZT. This process can be called modeling by mechanism.

3.2 Equivalent Circuit Model

Development of the equivalent circuit is based on the mathematical relationships that exist between mechanical and electrical phenomena. The three transformers can be characterized by a single-branch equivalent circuit model, shown in Fig. 5. The mechanical dimensions and material parameters of piezoelectric transformers determine the parameters of the equivalent circuit model.

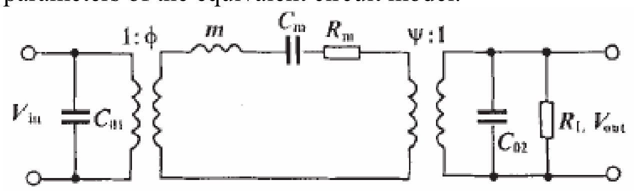

Fig. 5 Equivalent Circuit Model for Piezoelectric Transformer

The equivalent circuit model for their major vibration modes have been studied in prior works [13]. With the good reference provided by equivalent circuit models, PZTs can be actually designed rather than being manufactured by trial and error. Through use of the models, performance can actually be optimized because circuit networks can be analyzed and designed before implementation. But the material properties are not measured directly, which will lead some errors in equivalent circuit model.

3.3 Finite Element Method

In recent years, computer simulations have developed greatly. In addition, the electrode and structure of PZT get complicate; the finite element method is adequate for more accurate analysis. For modeling of PZTs, the first step was to define the coordinates of a number of the key nodes in terms of the transformer dimensions, from which the whole mesh was created. The second step is to impose mechanical and electrical boundary conditions on the transformer model and last is to specify the type of analysis and output control. The flow chart of typical procedures for finite element analysis is given as follows [15], Fig 6:

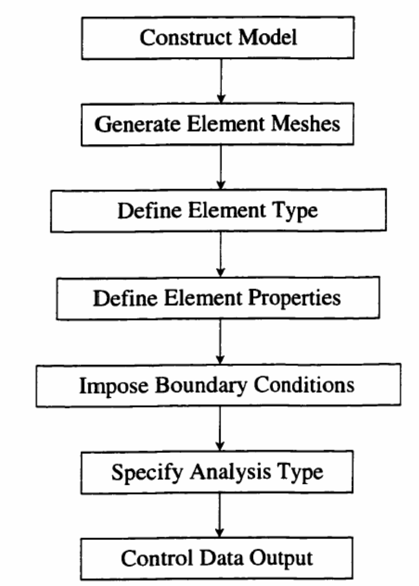

Fig. 6 Flow Chart of Finite Element Method

Contrasting the two methods, finite element method is difficult to consider load effects of a piezoelectric transformer. On the other hand, equivalent circuit model for piezoelectric transformer is simple to consider load effects of a PZT, this model has difficulty in finding equivalent circuit parameters, such as capacitances, inductances, et al. The detailed analysis can be obtained in the article [14].

4. Electrical characteristics

Fig 7 shows a measured characteristic of the voltage conversion for a piezoelectric transformer used in the study. The PZT is a single layer one with rated power of 5W. As the frequency at the input is varied, the voltage conversion ratio changes with frequency. At certain frequency, 66.6 kHz as shown in this transformer, a maximum conversion ratio is obtained. Therefore, by changing the operation frequency, it is able to control the output voltage. Hence a power conversion system can be obtained. The output voltage is fixed at rms 220V. The input is varied and measure to obtain the characteristics.

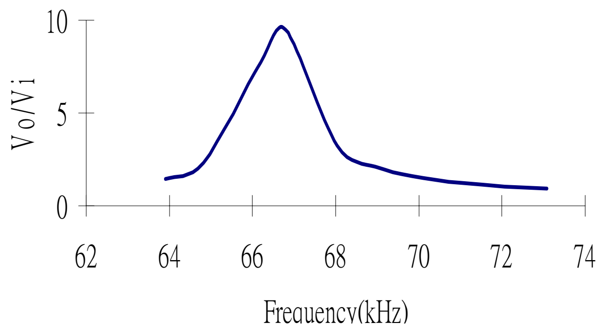

Fig 7: Vo/Vi against frequency With Load 88.5k Ω

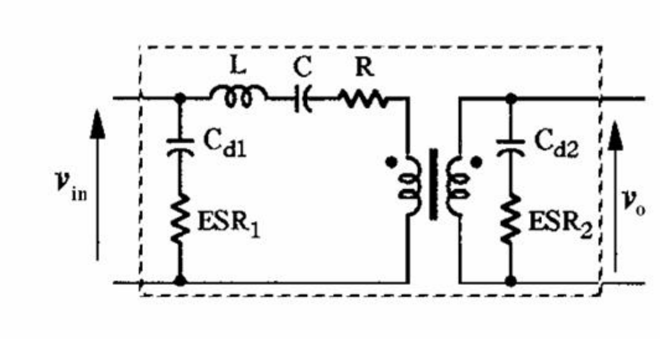

Fig 8 Model of the piezoelectric transformer

Fig 8 shows the model for the piezoelectric transformer. It can be seen that it consists of an LCR network. The L and C for the model are 4mH and 1.42nF. Fig 9 shows the voltage conversion ratio as the load is varied. It can be seen that under the optimal operation frequency, the voltage conversion ratio is varied with load. This is of course sensible because of the loading effect by the converter and the loss in the circuit components. Output voltage is again fixed at rms 200V.

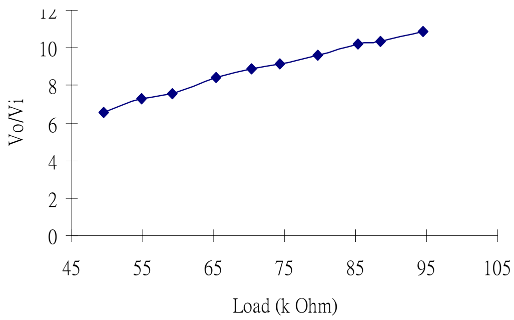

Fig 9: Vo/Vi against Resistance load with 66.6kHz

5. Isolation Solution

It is noted that the piezoelectric transformer has an isolation issue. The primary and secondary sides of the transformer are shorted circuit due to the physical condition. Therefore when a number of transformers are connected in ladder manner to increase the output voltage, the primary size cannot be connected directly using the same driving voltage. The following two circuits are proposed for possible solution.

5.1 Proposed circuit

Fig 10 shows a proposed circuit of the multiple piezoelectric transformers. Two transformers are used. Because of the isolation of the transformer, a magnetic transformer is used for the topology. The measurement of the transformer input and output voltages is shown in Fig 11. The measurement of the output voltage and current is shown in Fig 12. It can be seen that the voltage energized to the transformer is sinusoidal because of the resonant circuit of the inverter bridge. The sinusoidal voltage is therefore imposed on the transformer and the secondary side also receives a sinusoidal voltage and current. Because the secondary is now electric isolated, the output can be connected in series without any floating or isolation problem.

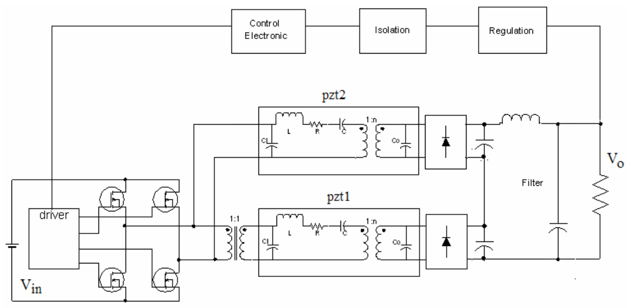

Fig 10: Proposed circuit for the power converters using two piezoelectric transformers

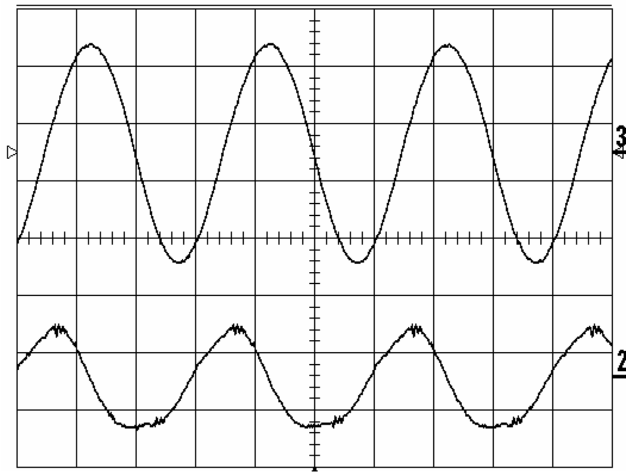

Fig 11: Output voltage (ch3: 200V/div) and input voltage(ch2:50V/div) of the piezoelectric transformer

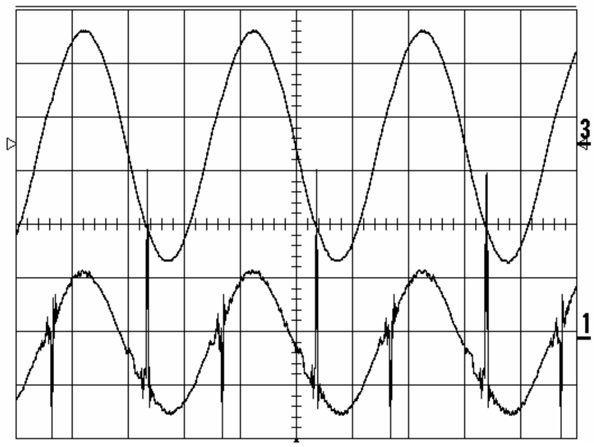

Fig 12: Output voltage (ch3: 200V/div) and output current (ch1:5mA/div) of the piezoelectric transformer

5.2 New circuit for non-isolation

The above method requires the isolation transformer. Therefore it increase the components count does not make sense when two transformer are used for one set of the circuit. The new proposed circuit is based on the boot-strap method and is also similar to the switched-capacitor converter (setup-up, double mode) [4]. Q_2 and Q_1 are switched in a complementary manner. Therefore the voltage developed on V_{o2} can be added to V_{o1}. The voltage V_o is equal to the sum of V_{o1} and V_{o2}. Even the isolation in the PZT2 between the V_{in2} and V_{o2} does not exist; the circuit can still provide the double effect.

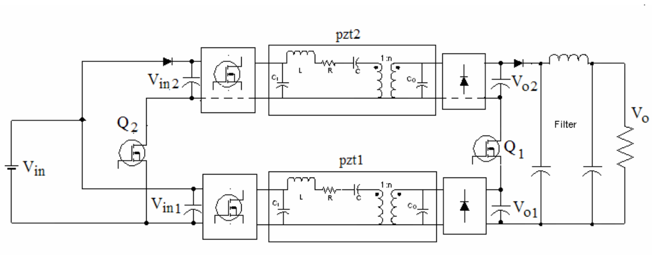

Fig 13: Switched capacitor concept for new PZT circuit.

Form higher voltage stepping, more PZT converters are needed to be connected in ladder. Fig 14 shows the case for 3 times the voltage. In the circuit, the Q_{1a}, Q_{1b} are turned on and off together and Q_{2a} and Q_{2b} are turned on and off together. But Q_{1x} and Q_{2x} are turned on in routine. Other conversion ratios can be deduced similarly.

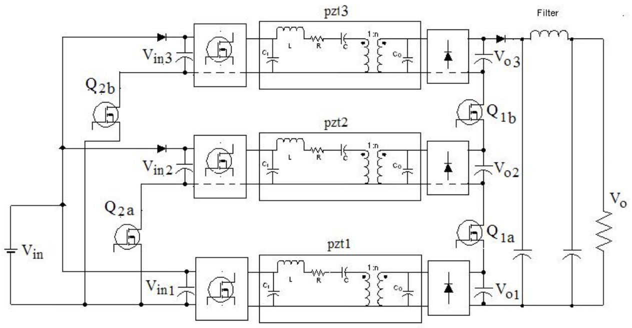

Fig 14: Ladder connection of PZT converters

6. Conclusion

The paper proposed a method to connect a number of piezoelectric transformers together for the use in power conversion. Firstly, the general study of the piezoelectric transformer has also presented. It is followed by comparison of the modeling methods. Finally the power conversion circuits for multiple connection are presented. Because piezoelectric transformers have a common return path, therefore normal method such as circulation limiting may not operate multiple piezoelectric transformers properly. The proposed methods are simple and also sensible.

Acknowledgement

The authors would like to acknowledge the financial support of Research Committee, The Hong Kong Polytechnic University (Project number: G-YD65).

References

[1] Su-Ho Lee; Jae-Il Hong; Ju-Hyun Yoo; Geon Sa-Gong;, "Characteristics of piezoelectric transformer for power supply**"**, Ultrasonics Symposium Proceedings., 1998 IEEE , Volume: 1 , 5-8 Oct. 1998, Page(s): 971 -975.

[2] Yamane, T.; Hamamura, S.; Zaitsu, T.; Minomiya, T.; Shoyama, M.; Fuda, Y., "Efficiency improvement of piezoelectric-transformer DC-DC converter"**,** *;* Power Electronics Specialists Conference, PESC 98 Record. 29th Annual IEEE , Volume: 2 , 17-22 May 1998 , Page(s): 1255 -1261.

[3] Prieto, M.J.; Diaz, J.; Martin, J.A.; Nuno, F., "A very simple DC/DC converter using piezoelectric transformer ", Power Electronics Specialists Conference. PESC. 2001 IEEE 32nd Annual , Volume: 4 , 17-21 June 2001, Page(s): 1755 -1760.

[4] K.W.E.Cheng, "Zero-current-switching switched-capacitor converters", IEE Proceedings-Electr. Power Appl., Vol. 148, No. 5, Sep 2001, pp. 403-409.

[5] Flynn A. M. et al. Fundamental limits on energy transfer and circuit considers for piezoelectric transformers. IEEE PESC, 1998: 1463-1471.

[6] Hamamura S, et al. Noise characteristic of piezoelectric transformer DC/DC converter. IEEE PESC, 1998: 1262-1267.

[7] Syed E M, Dawson F P. Analysis and Modeling of a Rosen type piezoelectric transformer. IEEE PESC, 2001: 1649-1654.

[8] C. A. Rosen. Analysis and Design of Ceramic Transformer and Filter Elements, Ph. D. Dissertation, Electrical Engineering Dept., Syracuse University, Aug. 1956.

[9] Y. Sasaki, K. Uehara and T. Inoue. Piezoelectric Ceramic Transformer Being Driven with Thickness Extensional Vibration. US Patent No. 5241236, Aug. 31, 1993.

[10] R. P. Bishop. Multi-layer Piezoelectric Transformer. US Patent No. 5834882, Nov. 10, 1998.

[11] Huang Yihua, et al. The equivalent circuit model and characteristics of Radial Vibration Mode Piezoelectric Transformer. Acta Electronica Sinica, Vol. 30, No. 11, pp: 85-88. (in Chinese)

[12] Huang Yihua, et al. A Research on Equivalent Circuit Model and characteristics of the strip Bend Vibration Mode Piezoelectric Transformer. Vol. 31, No. 8, pp: 1190-1192. (in Chinese)

[13] S. W. Tehon. Piezoelectric and Magnetostrictive Transducers. Ph. D. Dissertation, University of Illionis, 1958.

[14] Tsuchiya, T, Finite element simulation of piezoelectric transformers. Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on, Vol. 48, Issue: 4, July2001, PP: 872 – 878.

[15] Pitak Laoratanakul. Design and Characterization of Piezoelectric Transformers for High Power Applications. Ph. D. Dissertation, The Pennsylvania State University, Dec. 2002.