Ring-dot Piezo-electric Ballasts for 36-W Fluorescent Lamps

Monthakarn Peerasaksophol, Sutham Srilomsak, Pitak Laoratanakul and Thanatchai Kulworawanichpong

Abstract—This paper presents the design and experimental of ring-dot piezoelectric ballasts for a 36-W, T-8 fluorescent lamp. The piezoelectric transformer used in this paper is a radial contour-vibration mode device with a diameter of 30 mm, a thickness of 2.7-mm and a desired resonant frequency of 80 kHz. The design process can be conducted step-by-step with a set of empirical formulae. Therefore, designed test samples can be implemented for performance evaluation. In this paper, three different pieces of the ring-dot piezoelectric transformer were formed. The tests were carried out by using the implemented piezoelectric transformers as a part of electronic ballasts to drive a 36-W fluorescent lamp. The results show that overall efficiency of the implemented piezoelectric transformers was as high as 96.1% at a resonant frequency of 81.4 kHz.

Keywords—Piezoelectric transformer, electronic ballast, ring-dot type, radial contour vibration mode.

I. INTRODUCTION

Invention of piezoelectric transformers (PZT) was first published in 1954 by Rosen, Fish and Rothenberg [1] and granted later the US patent no. 2830274 in 1958. Recently, almost sixty years after the first invention, the piezoelectric transformer has become a potential device to replace a wound-type, magnetic-core transformer in various applications. The piezoelectric transformer is an energy conversion device that can convert electric energy into mechanical vibration energy or vice versa. It must be made from appropriate materials in order to give satisfactorily desired performances. Piezoelectric ceramic materials have special characteristics in which the voltage gain of the piezoelectric transformer is changed significantly due to the applied force at the resonant frequency. Therefore, they are suitable and widely accepted for use as piezoelectric transformers in association with various electrical devices. With special design, the piezoelectric transformer can perform as a step-up or a step-down transformer without any magnetic core to cause magnetic field interference. At the beginning of the invention of the piezoelectric transformers, it had not been accepted or used in commercial sectors. Until the 1990s, the piezoelectric transformers have been attracted by several Japanese companies to be used as a coreless transformer of portable electronic devices, e.g. notebook, PDA, mobile, etc. The combination with the piezoelectric transformer has led to the considerable reduction in weight and size of the electronic devices. In addition, there is no or less magnetic field interference produced by the piezoelectric transformers. In this paper, the only application to be considered is the replacement of the piezoelectric transformer over heavy and sizable magnetic-core inductors in electronic ballast circuits for 36-W, T-8 fluorescent lamps [2-6].

In this paper, the design and implementation of the ring-dot piezoelectric transformer operating in contour vibration-mode for 36-W, T-8 fluorescent lamp ballasts was proposed. In Section 2, empirical formulae used to calculate the desired structure dimension of the piezoelectric transformers were given. The proposed design procedure was illustrated step-by-step in Section 3. The driving circuit for fluorescent lamps was also briefed in this section. In Section 4, simulation and experimental results were discussed. Section 5 gave the conclusion remark and future works.

II. RING-DOT PIEZOELECTRIC TRANSFORMER

A. Structure and Mode of Operation

The piezoelectric transformer is an application of piezoelectric materials that act in both transverse (actuator) and longitudinal (transducer) modes. Although piezoelectric transformers can be formed in many configurations, only radial vibration mode of operation can enable high electric power applications such as electronic ballasts, notebook adapter, etc [7-17]. The piezoelectric transformer in radial vibration mode transfers electrical power from its input port into mechanical power and thereafter converts mechanical power into electrical power at its output port, all in radial direction. The ring-dot type has simple configuration giving the radial vibration mode [18]. Several electronic ballast applications of this type can be found from recent literatures [19-22]. The structure of ring-dot configuration is shown in Fig. 1.
B. Equivalent Circuit and Parameter Calculation

Baker, Huang, Chen and Lee [4] summarized an equivalent circuit for piezoelectric transformers as shown in Fig. 2. This model consisted of series components that are resistance (\(R\)), inductance (\(L\)), capacitance (\(C\)) and an ideal transformer of a turn ratio \(1:N\). Additional shunt capacitances (\(C_{d1}\) and \(C_{d2}\)), at input and output ports were added due to high frequency operation. Briefly, circuit parameters of radial vibration mode piezoelectric transformers can be obtained from the following equations.

\[
R = \sqrt{\frac{2\rho S_{31}^E}{16\pi d_{31}^2(1+N)t}}
\]

\[
L = \frac{\rho S_{31}^E}{8\pi d_{31}^2(1+N)t}
\]

\[
C = \frac{16\pi^2 d_{31}^2}{\pi S_{31}^E(1+N)t}
\]

\[
C_{d1} = \frac{\pi^2 e_{33}^E(1 - d_{31}^2)}{t}
\]

\[
C_{d2} = \frac{N\pi^2 e_{33}^E(1 - d_{31}^2)}{t}
\]

III. PIEZOELECTRIC TRANSFORMER FOR ELECTRONIC BALLASTS

A. Electronic Ballasts for Fluorescent Lamps

The main function of electronic ballasts is to energize an electric lamp with stabilized lamp current. The electronic ballast with a half-bridge resonant inverter is simple and efficient. This structure as shown in Fig. 3 has been widely accepted and used for fluorescent ballast applications [2-4,14-21]. The piezoelectric transformer in the ballast circuit appears to replace the passive resonant circuit of electronic ballasts. With delegated design of the piezoelectric transformer, the resonant frequency to light the lamp can be specified.
frequency, the maximum peak voltage output across the lamp can be expected. In this paper, a simple electronic ballast circuit as shown in Fig. 3 is exploited. The circuit configuration is divided into three main parts. The first part is the variable-frequency signal generator. TL494 is used as the signal generator whose frequency can be adjusted in a range of 3 – 200 kHz. The second part is the MOSFET driver. It has the main function to maintain voltage across the MOSFETs. IR2110 and opto-couplers HPCL3130 are employed. The last part is the power circuit. It consists of the diode-bridge rectifier and the half-bridge inverter. The output of this part is connected to the input port of the piezoelectric transformer to light a 36-W FL lamp.

B. Parameter Design of Piezoelectric Transformers

In this paper, 36-W, T8 fluorescent lamps are considered. The ring-dot piezoelectric transformers operating in radial vibration mode are designed. The formulae given in the previous section, (1) – (5), are very useful. To demonstrate the design procedure, it is better to follow a specific design example as

Step 1: Lamp resistance calculation

It assumes that the resistance of a fluorescent lamp under study is constant. Since 36-W, T8 fluorescent lamps have the rated values: 36 W 220 V and 50 Hz, thus

\[ R_{\text{Lamp}} = \frac{V_{\text{Lamp}}^2}{P_{\text{Lamp}}} = \frac{(220 V)^2}{36 W} = 1.345 k\Omega \]

Step 2: Diameter calculation

The diameter of piezoelectric transformer can be expressed as a function of the resonant frequency \[ f_r \]. In this paper, the desired resonant frequency is set at 80 kHz. Thus,

\[ f_r \approx \frac{N_r}{D} \rightarrow D = 0.027 m \]

\[ N_r \] is the radial frequency constant specified by manufacturers. It notes that APC-840 is the piezoelectric ceramic used in this paper. See Appendix B for details.

Step 3: Thickness calculation

Since \( C_{d2} \) is simply obtained, this capacitance can be used in (4) to calculate the thickness of the piezoelectric transformer. Therefore,

\[ C_{d2} = \frac{1}{2\pi f_r R_{\text{Lamp}}} = 1.498 nF \]

\[ t = \frac{\pi (13.48 \times 10^{-3})^2}{1.498 \times 10^{-3}} \left[ \frac{(-125 \times 10^{-12})}{(10.62 \times 10^{-3})(1250\varepsilon_0)} \right] \]

\[ = 2.72 \, mm \]

Due to the limitation of powder extrusion and sintering for piezoelectric transformers, a diameter of the prototypes is shifted to 30 mm. This results in a small change in its resonant frequency and also other properties.

C. Prototype Implementation

The parameter calculation described in the previous section gives only the outer diameter and thickness of the PZT disc. After sintering ring-dot type piezoelectric transformers, coating with a thin copper layer is the last process to specify which portions of a whole are input, output and ground ports of the piezoelectric transformers. In addition, the size of input and output electrodes influences output characteristics of piezoelectric transformers such as maximum voltage gain, resonant frequency, impedance spectra, etc. By varying three diameters: \( D \) (outer diameter of the outer electrode), \( \Delta \) (inner diameter of the outer electrode) and \( d \) (diameter of the inner electrode), relationships of these parameters resulting in the piezoelectric transformer characteristics can be determined.

In this paper, three pieces of piezoelectric transformers were implemented for test. Detail of dimension parameters for the three pieces of the piezoelectric transformers implemented in this paper is summarized in Table I.

<table>
<thead>
<tr>
<th>ID</th>
<th>Thickness (mm)</th>
<th>( d ) (mm)</th>
<th>( \Delta ) (mm)</th>
<th>( D ) (mm)</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>2.00</td>
<td>10.00</td>
<td>12.00</td>
<td>29.70</td>
<td>7.38</td>
</tr>
<tr>
<td>R2</td>
<td>2.10</td>
<td>16.74</td>
<td>18.74</td>
<td>29.82</td>
<td>1.92</td>
</tr>
<tr>
<td>R3</td>
<td>2.00</td>
<td>20.00</td>
<td>22.00</td>
<td>29.80</td>
<td>1.01</td>
</tr>
</tbody>
</table>

\( \alpha \) is a ratio of input and output electrode areas.
transformers. The test procedures conducted here were to determine the resonant frequency of the implemented piezoelectric transformers.

### TABLE II
PARAMETERS OF THE IMPLEMENTED PIEZOELECTRIC TRANSFORMERS

<table>
<thead>
<tr>
<th>PZT Parameters</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R ) (( \Omega ))</td>
<td>Calculated value</td>
<td>3.45</td>
<td>3.61</td>
</tr>
<tr>
<td></td>
<td>Measured value</td>
<td>4.72</td>
<td>5.68</td>
</tr>
<tr>
<td></td>
<td>Error(%)</td>
<td>26.9</td>
<td>36.4</td>
</tr>
<tr>
<td>( L ) (mH)</td>
<td>Calculated value</td>
<td>3.30</td>
<td>3.40</td>
</tr>
<tr>
<td></td>
<td>Measured value</td>
<td>3.22</td>
<td>5.64</td>
</tr>
<tr>
<td></td>
<td>Error(%)</td>
<td>2.5</td>
<td>39.7</td>
</tr>
<tr>
<td>( C ) (nF)</td>
<td>Calculated value</td>
<td>1.10</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>Measured value</td>
<td>1.22</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>Error(%)</td>
<td>9.8</td>
<td>38.4</td>
</tr>
<tr>
<td>( C_{d1} ) (nF)</td>
<td>Calculated value</td>
<td>6.65</td>
<td>6.38</td>
</tr>
<tr>
<td></td>
<td>Measured value</td>
<td>6.79</td>
<td>5.17</td>
</tr>
<tr>
<td></td>
<td>Error(%)</td>
<td>2.1</td>
<td>23.5</td>
</tr>
<tr>
<td>( C_{d2} ) (nF)</td>
<td>Calculated value</td>
<td>3.32</td>
<td>3.19</td>
</tr>
<tr>
<td></td>
<td>Measured value</td>
<td>3.22</td>
<td>4.16</td>
</tr>
<tr>
<td></td>
<td>Error(%)</td>
<td>3.1</td>
<td>23.3</td>
</tr>
</tbody>
</table>

The experimental circuit in Fig. 3 was used for performing the frequency response test of the implemented PZTs. The experiment was conducted by varying the frequency of the input signal generated by the half-bridge inverter as those of the simulation. The voltage gain at each particular frequency was observed to identify the resonant peak. Fig. 7 showed an example of the measured input and output signals from one implemented PZT. The resonant frequency of each PZT was presented in Table III.

### TABLE III
COMPARISON OF RESONANT FREQUENCIES

<table>
<thead>
<tr>
<th>PZT ID</th>
<th>Resonant frequency (kHz)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured value</td>
<td>Calculated value</td>
</tr>
<tr>
<td>R1</td>
<td>76.10</td>
<td>83.80</td>
</tr>
<tr>
<td>R2</td>
<td>81.56</td>
<td>83.46</td>
</tr>
<tr>
<td>R3</td>
<td>84.30</td>
<td>83.52</td>
</tr>
</tbody>
</table>

Fig. 8 illustrated the experimental frequency responses of the voltage gain for R1 – R3. As a result, The PZT having the largest value of \( \alpha \) gave the lowest resonant frequency among them.

### V. CONCLUSION
This paper illustrates design and implementation of ring-dot piezoelectric transformers for use in an electronic ballast circuit of fluorescent lamps. The design process started with empirical formulae and, therefore, obtained dimension of piezoelectric transformers was slightly refined to fit the experiment. In this research, the voltage gain and efficiency of the ring-dot piezoelectric transformers which have 2-3 mm of thickness were investigated. The results showed that the voltage increased with the electrode area ratio and the load resistance. The voltage gain was not significantly increased when the thickness varied in a range of 2 – 3 mm.

### APPENDICES

#### A. List of Symbols and Definitions
- \( d_{31} \) is the piezoelectric coefficient
- \( r \) is the radius of piezoelectric transformer
- \( S_{E} \) is the elastic compliance
- \( \tan \delta \) is the dissipation factor
- \( \rho \) is the material density
- \( \varepsilon_{33}^{T} \) is the material permittivity
- \( Q_{m} \) is the mechanical quality factor
B. Material Constants for APC-840 [24]

\[ d_{31} = 125 \times 10^{-12} \text{ m/V} \]
\[ S_{44}^0 = 1.25 \times 10^{-11} \text{ m}^2/\text{N} \]
\[ \tan \delta = 0.4\% \]
\[ \rho = 7.9 \times 10^{-11} \text{ kg/m}^3 \]
\[ \varepsilon_{33}^0 = 1250\varepsilon_0 \]
\[ Q_m = 500 \]
\[ N_f = 2130 \text{ m/s} \]

REFERENCES