Radial Mode Piezoelectric Transformer Design for Fluorescent Lamp Ballast Applications

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Abstract—In a ballast circuit, the piezoelectric transformer (PT) is used to replace the conventional inductor-capacitor resonant tank saving valuable space and cost. During circuit operation, a very high voltage is required to initially ignite the lamp while during sustained operation the voltage requirements are significantly reduced. With ballast in mind, a design process has been developed to optimize a radial mode piezoelectric transformer or Transoner® to fit a specific application while simultaneously providing highly efficient performance and the capability to provide ZVS to the switches. The design procedure was verified by a custom-designed PT operating in a 32-W ballast.

Index Terms—Ballast circuit, inductor-capacitor resonant tank, piezoelectric transformer (PT), Transoner.

I. INTRODUCTION

IN ORDER to power an incandescent lamp, one must only provide a voltage source, which can yield the power level prescribed by the on-state filament resistance. In contrast, fluorescent lamps require a certain voltage to ignite the lamp and a quite different voltage to sustain a given power level. This is the function of a lamp ballast circuit.

A conventional electronic ballast circuit usually consists of a parallel or series resonant converter, which contains a magnetic inductor and a high-voltage capacitor connected in series. Piezoelectric transformers (PT) can potentially be used to replace the conventional L - C resonant tank to save cost, weight and packaging height [1]–[4]. Previous ballast design using the piezoelectric transformer required selecting from readily available models not always mated to a specific application [2], [3]. Rarely has one seen a situation in which the piezoelectric transformer could be custom designed to fit each application. In this paper, results of such an endeavor will be given for a 32-W 120-V standard line ballast. A radial mode piezoelectric transformer or Transoner (a trade name by Face Electronics, USA) will be designed to fit the aforementioned ballast. To the authors' knowledge, a radial-mode PT is the only type of PT that has been reported to be capable of providing output power in the 32-W range as required by the application. In the paper, design equations will be provided with an outline of the step-by-step

Fig. 1. Half-bridge ballast circuit topology using a Transoner.

Fig. 2. Physical construction of Transoner.

procedure used to design a Transoner. A prototype Transoner based on the design process was fabricated by Face Electronics and then tested experimentally in the ballast circuit. The specific goals of the design process require that the Transoner meets proper voltage gain, efficiency, and the ability to provide a zero-voltage switching condition for the circuit shown as Fig. 1.

II. PT EQUIVALENT CIRCUIT MODEL AND CONSIDERATIONS IN POWER CONVERSION EFFICIENCY

The accepted equivalent circuit model for a piezoelectric transformer or PT has been well developed in [3] and [5]–[7]. This model is an electrical circuit, representative of the properties exhibited by two or more layers of piezoceramic physically coupled together. Electrical connections are made through metallic physical connections on the surface of each layer. Fig. 2 shows a two-layer Transoner and the physical electrical connections. Transoner can be constructed to have multiple primary and secondary layers of different thickness [8], as the application requires. Fig. 3 captures the simplified equivalent circuit model common to all piezoelectric transformers.

Given the above equivalent circuit model, a resistive load can be connected in parallel with the output capacitance, $Cd2$. It has been reported that when the load match (1), the PT efficiency is the highest [2], [5]

$$RL = \frac{1}{\omega_s \cdot Cd2}. \quad (1)$$

It should be noted that a matching network can sometimes be added between the PT and the load to increase the PT efficiency.

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Fig. 3. Piezoelectric transformer equivalent circuit model.

TABLE I
EQUIVALENT CIRCUIT MODEL PARAMETERS

CZ-3 Equivalent Circuit Model Parameters	
Cd1	10.2nF
R	901mΩ
L	1.67mH
C	2.89nF
Cd2	2.79nF
N	4.73

However, this technique is not considered in this paper as it adds additional components to the design. In this design process it is mandated that no additional elements should be added and thus (1) will be used as one of the constraints used in this design process for Transoner.

In order to visualize the result in (1), a three-dimensional (3-D) plot can be constructed using the applied frequency, f_s , and load resistance, R_L , as the independent axes and the resulting efficiency as the dependant axis. As an example, the Face Electronics CZ-3 Transoner was chosen, and its equivalent circuit model parameters are shown in Table I.

In Fig. 4 the efficiency of the CZ-3 Transoner is plotted against the load resistance, R_L , and the driving frequency, f_s . By carefully following lines of constant frequency, the highest efficiency for a given frequency is achieved when the load resistance follows the formulation of (1).

There are two defining resonant points of a piezoelectric transformer. The first is the result of when there is a short circuit applied to the output. The second occurs when there is an open circuit load. The equations defining these frequencies appear as (2) and (3), respectively. Operating the piezoelectric transformer with any load resistance assures that the respective resonant frequency will appear between these two limits

$$\omega_{SC} = \frac{1}{\sqrt{L \cdot C}} \quad (2)$$

$$\omega_{OC} = \frac{1}{\sqrt{L \cdot (C^{-1} + (N^2 \cdot Cd2)^{-1})}} \quad (3)$$

III. EFFICIENCY WITH CONSIDERATION OF DIELECTRIC LOSS

In order to better predict the efficiency of a piezoelectric transformer, the dielectric loss of the material can also be considered. This can be modeled as in [5] where the loss is seen as a frequency dependant resistance, R_{Cdx} , in parallel with both the input and output capacitances, $Cd1$ and $Cd2$. In order to calculate this loss, $\tan \delta$, the dissipation factor of the

Fig. 4. Theoretical efficiency of the Prototype CZ-3 PT.

Fig. 5. Theoretical efficiency of the CZ-3 PT including dielectric losses.

piezoceramic is used as specified by the material manufacturer, as in

$$R_{Cdx} = \frac{1}{\omega_S \cdot Cd_x \cdot \tan \delta} \quad (4)$$

The result of this added loss, creates both an overall lower predicted efficiency and a change in the shape of the plot. Fig. 5 shows the efficiency plot including the dielectric losses of the materials. At frequencies both above and below resonant frequency range, the shape is dramatically different. Fig. 6 is the result of calculating the difference between the two efficiency curves. As can be seen, the difference is negligible near the resonant frequency range. This result is also true for any PT when the dissipation factor or $\tan \delta$ of the material is relatively small, which is observed in most all piezoceramics.

If it is assumed that the piezoelectric transformer is operated at or near the resonant frequency for a particular load, the relationship described by (1) holds true even when the dielectric losses of the material are taken into account. A piezoelectric transformer is essentially a high-Q resonant tank circuit. The efficiency is the best when it's operated near its resonant frequency. dc input power cannot pass through and input harmonic frequency components are suppressed.

Fig. 6. Efficiency difference is negligible between f_{SC} and f_{OC} .

IV. TRANSONER DESIGN EQUATIONS

The equivalent circuit model described above evolves from the physical construction of the piezoelectric transformer and the material characteristics. Equations (5)–(10) show the intimate relationship between each material characteristic and physical dimension as it pertains to Transoner as developed in [6] and [7]. Table II contains the definitions of the various material coefficients

$$Cd1 = \frac{N_1 \cdot \pi \cdot r^2 \cdot \epsilon_{33}^T \cdot \left(1 - \frac{d_{31}^2}{\epsilon_{33}^T \cdot S_{11}^E}\right)}{t_1} \quad (5)$$

$$R = \frac{\sqrt{2 \cdot \rho \cdot S_{11}^E} \cdot (N_1 \cdot t_1 + N_2 \cdot t_2)}{16 \cdot r \cdot Q_m \cdot (N_1 \cdot d_{31})^2} \quad (6)$$

$$L = \frac{\rho \cdot S_{11}^E \cdot (N_1 \cdot t_1 + N_2 \cdot t_2)}{8 \cdot \pi \cdot (N_1 \cdot d_{31})^2} \quad (7)$$

$$C = \frac{16 \cdot r^2 \cdot (d_{31} \cdot N_1)^2}{\pi \cdot S_{11}^E \cdot (N_1 \cdot t_1 + N_2 \cdot t_2)} \quad (8)$$

$$Cd2 = \frac{N_2 \cdot \pi \cdot r^2 \cdot \epsilon_{33}^T \cdot \left(1 - \frac{d_{31}^2}{\epsilon_{33}^T \cdot S_{11}^E}\right)}{t_2} \quad (9)$$

$$N = \frac{N_1}{N_2} \quad (10)$$

V. TRANSONER DESIGN PROCESS

The relationship described in (1) is very important, as it initiates the Transoner design process. In order to best illustrate the design process, a specific example will be completely worked out in the body of this paper.

Each linear fluorescent lamp has a fixed impedance during sustained operation that is considered resistive, as the lamp voltage and current are in phase. By utilizing (1) and a given frequency, one can solve for the necessary capacitance, $Cd2$, the Transoner should exhibit for maximum efficiency.

Table III contains a summary of relevant circuit characteristics for a hypothetical ballast design.

The full-wave rectified source voltage will exhibit an average of 155 V with the addition of a bulk dc bus capacitor. The circuit topology will be a simple half-bridge, which will directly drive

TABLE II
MATERIAL COEFFICIENTS

Material Symbols and Definitions	
ρ	Density
ϵ_{33}^T	Permittivity
Q_m	Mechanical Quality Factor
d_{31}	Piezoelectric Coefficient
S_{11}^E	Elastic Compliance
$\tan \delta$	Dissipation Factor
N_R	Radial Mode Frequency Constant
t_1	Primary Layer Thickness
t_2	Secondary Layer Thickness
N_1	Number of Primary Layers
N_2	Number of Secondary Layers
r	Radius of the Layers

TABLE III
RELEVANT CIRCUIT CHARACTERISTICS FOR A HYPOTHETICAL BALLAST DESIGN

Design Example: Ballast Circuit Specifications	
Circuit Input Voltage	120Vrms 60Hz AC
Lamp Resistance	500 Ω
Lamp Power	32 W

the Transoner as in Fig. 1. Hence, the voltage gain requirement for the Transoner can be calculated from the power level and the lamp resistance as in (11). In this case, the required gain Av_{PT} is approximately 2.0 V/V. With this in mind, the design process can begin

$$Av_{PT} = \frac{\sqrt{P_{LAMP} \cdot R_{LAMP}}}{0.4 \cdot V_{BUS}} \quad (11)$$

A. Step One—Build the First Layer

The approximate resonant frequency of a radial-mode piezoelectric transformer can be calculated through the use of its diameter or radius as in [2] and [6]. Equation (12) below utilizes the radial frequency constant, N_R , as specified by the manufacturer, to calculate the fundamental operating frequency equating one full wavelength of the resonant frequency to the material diameter. Table IV shows the material characteristics for APC-841 piezoceramic [9], which will be used in this design example

$$f_r \cong \frac{N_R}{D} \quad (12)$$

In this example, the diameter of the prototype Transoner is selected to be 825-mil or 2.096 cm based on available materials and reasonable size. Ultimately the diameter of Transoner should be selected through thermal analysis considering the

TABLE IV
MATERIAL CHARACTERISTICS FOR APC-841 PIEZOCERAMIC

APC-841 Properties	
ρ	7.6 g/cm ³
ϵ_{33}^T	1350 ϵ_0
Q_m	1400
d_{31}	109 10^{-12} m/V
S_{11}^E	11.7 10^{-12} m ² /N
N_R	2055 m/s
$\tan\delta$	0.35 %

power level and efficiency of the circuit. Solving (12), it is found that the approximate resonant frequency, f_r , will be 100 kHz. Given f_r , (1) can be solved yielding the output capacitance as in (13). Equation (9) can then be utilized to yield the thickness of the secondary layer(s). For this example N_2 is chosen to be unity for simplicity. The result can be seen in

$$Cd2 = \frac{1}{\omega_r \cdot R_{LAMP}} = 3.2 \text{ nF} \quad (13)$$

$$t_2 = \frac{N_2 \cdot \pi \cdot r^2 \cdot \epsilon_{33}^T \cdot \left(1 - \frac{d_{31}^2}{\epsilon_{33}^T \cdot S_{11}^E}\right)}{Cd2} \cong 0.050 \text{ in.} \quad (14)$$

B. Step Two—Add Input Layer and Calculate Voltage Gain

By adding an input layer, the equivalent circuit model is complete. The voltage gain of the Transoner can be plotted as a function of both driving frequency, f_s , and primary layer thickness, t_1 , by calculating the complete equivalent circuit model as a function of t_1 using (5)–(10). A practical range of material thickness is from 10-mil to 200-mil. Fig. 7 shows the resulting plot in three-dimensions. The minimum voltage gain required for this design was calculated to be 2.0 V/V from (11). As can be seen, there is no primary layer thickness within the range that can be selected to provide this magnitude of gain.

In order to increase the voltage gain, one method is to increase the internal turn ratio within the equivalent circuit model by adding primary layers. This process can be repeated until the voltage gain is as desired. In this case, only two primary layers were needed. The resulting voltage gain plot can be seen in Fig. 8.

By taking a slice of the plot of Fig. 8 at the minimum voltage gain, a two-dimensional (2-D) surface projection can be generated which allows one to easily see where in the $(t_1 \times f_s)$ plane a solution exists. Using this technique Fig. 9 was generated.

C. Step Three—Find an Acceptable Primary Layer Thickness

Analyzing Fig. 9, it can be seen that the entire range of primary layer thickness can meet the voltage gain requirement. In order to narrow down a smaller range of thickness, more constraints must be included.

With the choice of a half-bridge topology [1]–[5], zero voltage switching can be achieved as in [1] and [2] if enough dead-time is provided and the relationship seen as (15) is met.

Fig. 7. Voltage gain of the prototype versus primary layer thickness and frequency, (with only one primary layer).

Fig. 8. Voltage gain of prototype versus primary layer thickness and frequency (with two primary layers).

Fig. 9. Region where the voltage gain is greater than the minimum.

In short, the energy within the internal inductance, L , should be great enough to charge/discharge the internal capacitance, C , and the input capacitance, $Cd1$, during the dead-time period. By solving (15) for the internal inductor current, a critical value (16) evolves which must be surpassed in order for ZVS to take place. The peak inductor current can be approximated

Fig. 10. Region where inductor current is great enough to achieve ZVS.

through the use of (17) as in [1] and [2] where Z_{in} is the input impedance of the piezoelectric transformer excluding $Cd1$, but including the lamp load, and A is the ratio of the rise/fall time to the period. Using the same technique as Fig. 9, a 3-D plot of the peak inductor current has been sliced where it exceeds the minimum or critical value and is shown as Fig. 10

$$\frac{1}{2} \cdot L \cdot \Delta i_{L_{peak}}^2 \geq \frac{1}{2} \cdot Cd1 \cdot V_{bus}^2 \cdot \left(1 + \frac{Cd1}{C}\right) \quad (15)$$

$$\Delta i_{L_{peak}} \geq \sqrt{\frac{Cd1 \cdot (C + Cd1)}{L \cdot C}} \cdot V_{bus} \quad (16)$$

$$\Delta i_{L_{peak}}(f_s) = \frac{2 \cdot V_{bus}}{\pi \cdot |Z_{in}(f_s)|} \cdot \frac{\sin(\pi \cdot A)}{\pi \cdot A} \sin(\angle Z_{in}(f_s)). \quad (17)$$

One final consideration should be for efficiency. To better enhance the appeal of using a piezoelectric transformer in place of the conventional L - C resonant tank, the efficiency of the circuit should not be sacrificed. The efficiency of the prototype Transoner can be plotted in three dimensions with both the primary layer thickness and frequency as the dependent axes. A limit can be set for the minimum allowable efficiency based on the Transoner size and power level. Here, a limit was set at 90% or better and the efficiency plot is sliced at this level allowing a 2-D projection as before. This plot is shown as Fig. 11.

In order to create the smallest range of choices for primary layer thickness, the three plots are then overlapped to find the common choices of both t_1 and f_s , which are elements of all three 2-D projections. Any choice within this overlapped region will provide a useful Transoner for the application. Primary thickness, t_1 , should be made as small as possible within the region of solution such that the finished Transoner has minimal interference between vibration modes [2]. Fig. 12 shows the complete solution region in the $(t_1 \times f_s)$ space.

D. Step Four—Choose a Primary Layer Thickness and Calculate the Complete Circuit Model

From Fig. 12, the range of primary layer thickness, which will work with our circuit, varies over quite a large range. This range may be further narrowed by increasing the level of the efficiency minimum or by placing other constraints on the design. For this example, the primary thickness was chosen to be 60-mil. Thus, the complete Transoner has two primary layers of 60-mil each

Fig. 11. Region where efficiency is greater than the preset minimum.

Fig. 12. Solution region that meets all requirements.

Fig. 13. Physical construction of the prototype transoner.

and a secondary layer of 50-mil. The overall diameter is 825-mil. A simple diagram of the prototype is shown as Fig. 13.

It should be pointed out that lamp ignition voltage gain was not placed as a design constraint in the proposed design process. Using this type of PT for this type of lamp, the lamp starting voltage requirement is easy to meet. Therefore, to avoid unnecessary complication in an already complicated procedure, it's not included in the design constraint and the sample designs have never had problems starting the lamps.

VI. EXPERIMENTAL RESULTS

In order to verify the design procedure, Face Electronics manufactured the sample described in this design procedure designating it as Transoner VTB-1. The measured equivalent circuit parameters appear in Table V. As can be seen, most of the parameters match very well except for the equivalent

TABLE V
MEASURED EQUIVALENT CIRCUIT PARAMETERS

VTB-1 Equivalent Circuit Parameters	Theoretical	Measured	Error (%)
Cd1 (nF)	4.9	4.61	-5.9%
R (Ω)	1.91	2.21	+15.7%
L (mH)	3.78	2.36	-37.6%
C (pF)	527	930	+76.5%
Cd2 (nF)	2.97	2.90	-2.4%
N	2	2.08	+4%
fr (kHz)	112.8	107.4	-4.8%

Fig. 14. Comparison of theoretical and measured steady-state voltage gains.

internal inductance and capacitance. However, the resonance frequency matches rather well. One possible reason for this difference is that the Transoner design equations assume perfect coupling between the primary and secondary layers. In addition, the manufacture of Transoner requires the addition of copper layers and adhesive, which may alter the performance of the complete piezoelectric transformer.

Further analysis reveals that the performance of the theoretical model and the measured model is very close. Figs. 14–16 show both the theoretical and actual performance, based on the equivalent circuit models, predicting voltage gain during steady state operation, efficiency, and inductor current, respectively, when a load of 500- Ω is attached to the outputs. As can be seen from these plots, the actual performance agrees very well with the model prediction.

The custom-designed PT sample was used in the evaluation ballast circuit; Fig. 17 shows the prototype ballast circuit and the schematic diagram of the power circuit. The detailed description of the controller section can be found in [1]. Fig. 18 shows the waveform. By viewing the voltage that drives the piezoelectric transformer, one can determine whether or not the switches are operating in a zero voltage switching condition. The duty cycle for each switch is set to approximately 25%. During the dead-time period, the current in the inductor charges/discharges the piezoelectric transformer input capacitor, Cd1 and the MOSFET drain-source capacitances. Here, one can see that the voltage transitions in a sinusoidal manner from the bus to ground during one portion of the dead-time period and from ground back to the bus during the other period. At the time when the transition tries to exceed the bus voltage or go below the ground reference, the body diode of the respective MOSFET conducts. During the

Fig. 15. Comparison of theoretical and measured efficiency.

Fig. 16. Comparison of theoretical and measured inductor current. Where each inductor current exceeds its critical line, indicates a region of possible ZVS operation given the appropriate switch dead time.

Fig. 17. (a) Simplified schematic of the prototype electronic ballast. (b) Prototype electronic ballast using piezoelectric transformer.

body diode conduction, the voltage across the switch is virtually zero. If the switch is turned on during this condition the turn-on switching losses are minimized. In the experiment that led to this waveform, the approximate efficiency of the inverter during the operation was 90%. The efficiency of the PT was approximately 95%. This leads to a combined efficiency of approximately 86% for the ballast at room temperature. The total losses were approximately 5 W, with 1.7 W in the PT and 3.3 W

Fig. 18. (a) Bottom switch S2 drain-to-source voltage displaying ZVS operation. (b) Lamp voltage and current.

in the driving/control circuitry based on the efficiency calculations of the PT device.

VII. CONCLUSION

The use of Transoner in fluorescent ballast applications has the potential to not only decrease size, weight, and cost, but also reduce electromagnetic emissions by eliminating the resonant inductor while simultaneously providing soft-switching. The Transoner design process described here can enable engineers to easily compare different geometries using a graphical method such that optimization and tuning of Transoner becomes a visual process. As can be seen from the results, the performance of the actual Transoner designed in this hypothetical application matches the performance of the theoretical model very well. The custom designed Transoner was also tested in the ballast circuit initially igniting then providing full power to an MEW FHF-32 fluorescent lamp, while concurrently enabling ZVS.

While the Transoner look promising for fluorescent lamp applications, it should be pointed out that there are disadvantages

associated with this approach. These include relative low efficiency due to large internal resistance, inconvenience of adding filament preheating power in cases where this is necessary, and sensitivity to mechanical mounting methods. Further research is needed.

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