Journal of Engineering and Development, Vol. 10, No. 4, December (2006) ISSN 1813-7822

Design of Round Radial Mode Piezoelectric Transformer for Lamp Ballast Applications

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Abstract

In conventional electronic ballast for a fluorescent lamp, inductor-capacitor-transformer tank circuit is used. A Piezoelectric Transformer (PT) can potentially be used to replace such a tank circuit to save space and cost. In the past, ballast design using a PT requires selecting a PT from available samples which are normally not matched to specific application and therefore resulting in poor performance, also piezoelectric transformer design has been difficult due to the complex interaction between the physical and electrical circuit characteristics.

In this research, a design procedure has been developed for designing a PT tailored for 220-V 40-W electronic ballast with high efficiency (90%) and Zero-Voltage-Switching (ZVS) for the semiconductors without the use of any external inductance. In this design a round radial-mode piezoelectric transformer (Transoner) was used and to achieve optimum solution, 3-D graphic to circuit requirement is used which allows the engineer to design according to the circuit criteria, the design is programmed by using the MATLAB package.

الخلاصـــــة

تحتاج الدائرة التقليدية لتشغيل مصباح الفلورسنت إلى ملف ومتسعة ومحولة، يمكن الاستغناء عن هذه العناصر الثلاثة واستبدالها بعنصر واحد ألا وهو المحولة البيزوكهربائية ذات الحجم والكلفة الأقل. في البحوث السابقة تم الاعتماد على المحولات البيزوكهربائية المتوفرة في الأسواق التي لا تتوافق تماما مع متطلبات دائرة ما مما يعطي كفاءة قليلة، بالإضافة إلى ذلك فأن تصميم محولة بيزوكهربائية لمثل هذه التطبيقات صعبا وذلك بسبب العلاقات المتداخلة مابين الخواص الفيزيائية والكهربائية.

يهتم هذا البحث في تطوير العملية التصميمية لتصميم محولة بيزوكهربائية دائرية بحيث تتناغم كليا مع دائرة تشغيل مصباح الفلورسنت ٤٠ واط، ٢٢٠ فولت، ٥٠ هرتز بكفاءة عالية ٩٠% وكذلك الحصول على حالة انعدام الفولتية(ZVS) للدائرة الالكترونية بدون الحاجة إلى أي ملف خارجي، في هذا التصميم تم اعتماد النموذج القطري ذو الشكل الدائري للمحولة البيزوكهربائية (ترانسونر). وللحصول على الحالة المثلى تم استخدام الرسومات ثلاثية الأبعاد لمتطلبات الدائرة ليتيح للمهندس التصميم وفق المعايير المطلوبة للدائرة و قد تمت برمجة التصميم باستخدام برنامج MATLAB .

1. Introduction

Piezoelectric Transformers (PT) have important advantages over low power electromagnetic (ferrite) transformers. In particular, they have high power density, small size and weight while maintaining high throughput efficiency. They could be designed to have very high voltage isolation between primary and secondary, can operate at high frequencies and they do not generate electromagnetic noise [1,2]. Piezoelectric ceramics are characterized as smart materials and have been widely used in the area of actuators and sensors. The operation principle of a piezoelectric transformer (PT) is a combined function of actuators and sensors so that energy can be transformed from electrical form to another electrical form via mechanical vibration [3-5].

Due to their special characteristics, in the past few decades, piezoelectric transformers have been developed and used widely in many applications, such as electronic ballast for fluorescent lamps and inverter for backlighting the LCDs in a notebook computer, AC adapter for mobile computer, battery charger for mobile phones, gate drivers of MOSFET and IGBTs and signal isolation, DC/DC converter, photomultiplier high voltage power supply, electronic ignition system, clock pulse shaping circuit, and driving circuit for piezoelectric actuators such as ultrasonic motors. It was even used as a discharge exciter for light emission [5,6].

In a conventional magnetic transformer, the electrical input is converted to magnetic energy and then reconverted the magnetic energy back to an electrical output. The piezoelectric transformer has an analogous operating mechanism. It converts an electrical input into mechanical energy and subsequently reconverts the mechanical energy back to an electrical output. Generally speaking, the two piezoelectric elements, piezoelectric actuator and the piezoelectric transducer, can work in either longitudinal mode or transverse mode with a corresponding resonant frequency. According to the different vibration mode and mechanical structures, the piezoelectric transformers could be classified to three main categories**:** Rosen-Type, thickness vibration mode and radial vibration mode [4-5].

The radial vibration mode piezoelectric transformer, developed by FACE Electronics, USA in 1998, is a combination of piezoelectric actuators and transducers that both operate in the transverse mode. The round radial vibration mode piezoelectric transformer (Transoner) shown in **Fig.(1)**, has been studied and detailed characteristics and physics-based equivalent circuit models have been given [4-8]. This piezoelectric transformer can be utilized in such applications as DC/DC converters, adapters, and electronic ballasts for linear/compact fluorescent Lamps [9,10].

In order to increase the step-up or step-down ratio, either the electric actuator or electrical transducer can be made up of more than one layer of piezocermic materials. This kind of piezoelectric transformer was called multiplayer piezoelectric transformer, as report in many papers [11,12].

The objective of this research is to presents the design method for radial mode piezoelectric transformer for a given performance specifications, by establishing clear relationships between the ballast circuit performance parameters and the PT device parameters. A step-by-step design procedure for the PT proposed for a 40-W 220-V electronic ballast application with high efficiency, and Zero-Voltage-Switching (ZVS) is taken as an example to illustrate such design procedure. Radial mode PT is considered because up to this point, only radial mode PT capable of such power handling capability has been reported. Complicated relationships between the circuit performance parameters and the PT parameters were developed and used to reach a workable solution.

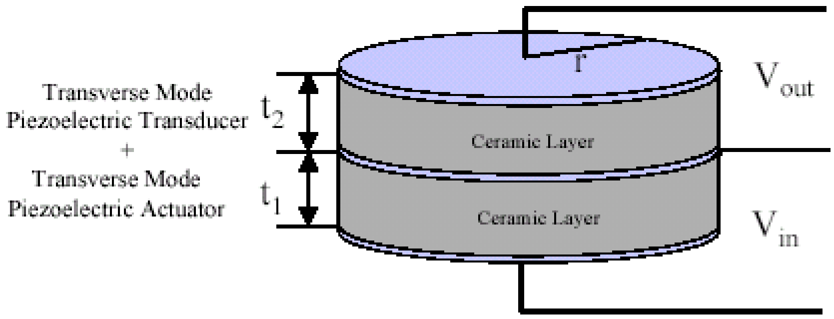


Figure (1) Radial vibration mode piezoelectric transformer

2. Overview of the Radial Mode Piezoelectric Transformers

The round radial vibration mode piezoelectric transformer (Transoner), as shown in **Fig.(3)**, is the combination of a transverse mode piezoelectric actuator and a transverse mode piezoelectric transducer. With the applied voltage, V_{in}, on the primary side, i.e., the piezoelectric actuator, the material becomes polarized in the direction parallel to that of the material thickness. In this case, the greatest vibration strain occurs in the planar direction perpendicular to the polarization direction. The planar vibration of the piezoelectric actuator transmits to the piezoelectric transducer. The vibration transmits from the primary side, inducing an electric charge on the electrode plates of the piezoelectric transducer in order to generate the output voltage, V_{out}. The vibration direction of the transverse mode piezoelectric transducer is perpendicular to the direction of the induced polarization. The round radial vibration mode piezoelectric transformer has the same distance, r, from its center to the edges of the electrode plates. Therefore, the fundamental vibration wavelength, λ, of the round radial vibration mode piezoelectric transformer is:

$$\lambda = 2r \quad \text{.......... (1)}$$

where:

r: is the radius of the round-shaped radial vibration mode piezoelectric transformer.

This radial vibration mode piezoelectric transformer can be utilized in ballasts, Adapters and converters [9].

For the Transoner, the fundamental vibration frequency f_r is inversely proportional to the radius and directly proportional to the wave propagation speed N_R of the material. [11] as shown in eq.(2)

$$f_r \approx \frac{N_R}{D} \quad \text{.......... (2)}$$

where:

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

The equivalent circuit Models and characteristic equations of the Transoner have been carefully derived in [6] and are summarized here. The conventional simplified equivalent circuit for the Transoner is shown in **Fig.(2)**.

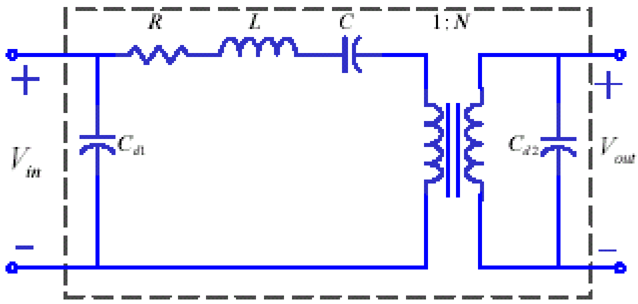


Figure (2) Simplified conventional equivalent circuit of Transoner

The component value of the equivalent circuit in **Fig.(2)** are related to physical parameters of the PT. Equations (3-8) show such relationships [7,11]:

$$C_{d1} = \frac{N_1.\pi.r^2.\varepsilon^T{}_{33}.\left(1 - \frac{d_{31}{}^2}{\varepsilon^T{}_{33}.S^E{}_{11}}\right)}{t_1} \quad \text{.......... (3)}$$

$$R = \frac{\sqrt{2.\rho.S^{E^3}{}_{11}}.(N_1.t_1 + N_2.t_2)}{16.r.Q_m.(N_1.d_{31})^2} \quad \text{.......... (4)}$$

$$L = \frac{\rho.S^{E^2}{}_{11}.(N_1.t1 + N_2.t_2)}{8.\pi.(N_1.d_{31})^2} \quad \text{.......... (5)}$$

$$C = \frac{16.r^2.(d_{31}.N_1)^2}{\pi.S^E{}_{11}.(N_1.t_1 + N_2.t_2)} \quad \text{..........} \quad (6)$$

$$C_{d2} = \frac{N_2.\pi.r^2.\varepsilon^T{}_{33}.\left(1 - \frac{d_{31}{}^2}{\varepsilon^T{}_{33}.S^E{}_{11}}\right)}{t_2} \quad \text{..........} \quad (7)$$

$$N = \frac{N_1}{N2} \quad \text{..........} \quad (8)$$

Definitions of the material symbols in the above equation are summarized in **Table (1)**.

Table (1) Material symbols and definitions

ρ	Density
$\varepsilon^T{}_{33}$	Permittivity
Q_m	Mechanical Quality Factor
d_{31}	Piezoelectric Coefficient
$S^E{}_{11}$	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

In **Fig.(2)**, the internal resistance R stands for the mechanical loss of the piezoelectric device. To consider the dielectric loss of the material for better efficiency predication, two frequency dependent resistors, R_{cd1} and R_{cd2} can be added in parallel with the input and output capacitances, C_{d1} and C_{d2} respectively, as shown **Fig.(3)**. R_{cd1} and R_{cd2} could be estimated by [6].

$$R_{cd1} = \frac{1}{\omega_s.C_{d1}.\tan\delta} \quad \text{..........} \quad (9)$$

$$R_{cd2} = \frac{1}{\omega_s.C_{d2}.\tan\delta} \quad \text{..........} \quad (10)$$

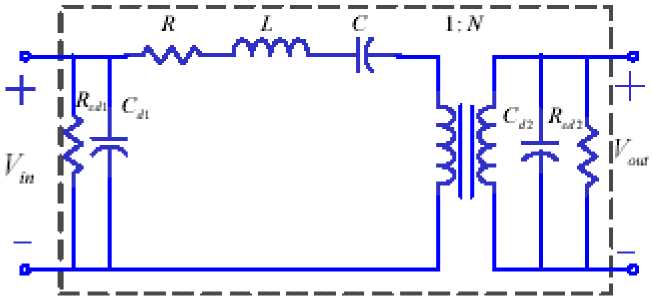


Figure (3) Conventional equivalent circuit of Transoner

3. Radial Mode Piezoelectric Transformer Design for Electronic Ballast

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 as shown in **Fig.(4)**. It shows one typical electronic ballast circuit that uses an L-C resonant tank to generate high voltage for igniting and sustaining a linear fluorescent lamp. This L-C resonant tank is composed of resonant inductor L, DC-blocking capacitor C, a voltage step-up transformer, and high-voltage resonant capacitor C_{d2}. Input capacitor C_{d1} works as an additional turn-off snubber capacitor for half-bridge switches S_1 and S_2. The cost of these five passive components constitutes the major cost of the conventional electronic ballast. However, the L-C resonant tank of the conventional electronic ballast shown in **Fig.(4)** is almost identical to the equivalent circuit of the piezoelectric transformer shown in **Fig.(2)**, except for the addition of the resistor, R, in the latter. Generally speaking, this resistance R is negligible as compared with the equivalent turn-on resistance of fluorescent lamps. In the ballast, a radial mode piezoelectric transformer can be utilized to replace the conventional L-C resonant tank to both save cost and weight [6-8].

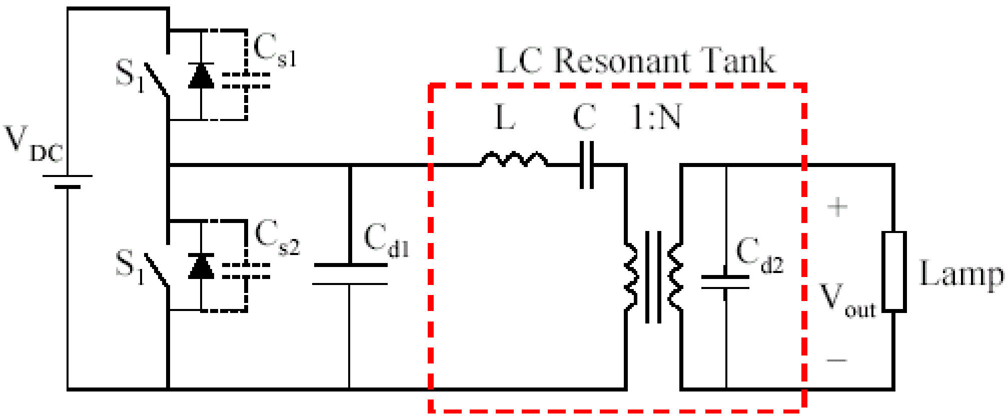


Figure (4) Typical conventional electronic ballast circuit

In the past, PTs used in such applications have been selected from available samples, which may not match the application. It's a well-known fact that for an unmatched load condition, the efficiency of a PT can be very poor. Rarely has one seen a situation in which the piezoelectric transformer could be custom designed to fit each application [5,8,11]. In this section, the focus is on the design of a PT ballast circuit for a 220-V, 40-watt fluorescent lamp. Besides providing proper lamp starting voltage and steady-state voltage gain, the ballast circuit also has to be such that the main inverter circuit must have zero-voltage-switching (ZVS) operation. And all of these requirements can be accomplished by properly designing a proper PT to replace the tank circuit conventionally consisting of inductor and capacitors. In the end, minimum components are used and the efficiency power is excellent. Design equations will be provided with an outline of the step-by step procedure used in the design process using MATLAB. The basic circuit, shown as **Fig.(5)**, that is assumed in the design process has a simple half-bridge topology. An added benefit is the ability to achieve zero voltage switching for the main switches, S_1 and S_2, thus greatly aiding the efficiency of the circuit.

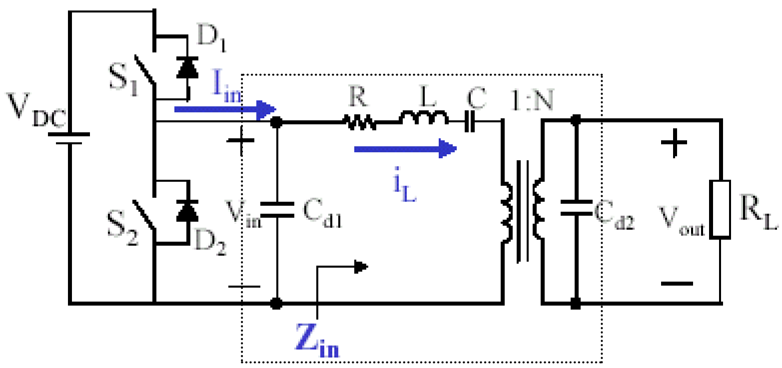


Figure (5) Half-bridge ballast circuit topology using a transoner

3-1 PT Design Requirements and Design Procedure

3-1-1 Design Requirement

Table (2) summarizes the design specification for the ballast circuit. The additional requirement in the design is the zero-voltage-switching of the inverter transistor devices. Matching network can sometimes be added between the PT and the lamp to increase the PT efficiency. However, this will not be considered in this design because by this procedure we get efficiency more than 90% then no need to matching network which adds additional components to the circuit.

Table (2) Ballast circuit design specifications

Circuit Input Voltage (Vin)	220Vrms 50Hz AC
Rectified DC Bus Voltage (Vbus)	280V
Lamp Resistance (RL)	600 Ω
Lamp Power (Po)	40 W
Efficiency	90 %

From **Table (1)**, it can be seen that a PT has two kinds of parameters: (1) material parameters: ρ, ε^T_{33}, Q_m, d_{31}, S^E_{11}, $\tan\delta$ and (2) dimensional parameters: N_1, N_2, t_1, t_2, r. Its equivalent circuit parameter values are highly related to the material and dimensional parameters of the PT.

3-1-2 Design Procedure [7,11]

1. Select the Piezocermic Material

Selection of material is mostly based on availability. Once chosen, the materials parameters (ρ, ε^T_{33}, Q_m, d_{31}, S^E_{11}, $\tan\delta$) are given. In this example, PKI-802 piezocermic [9,10] was chosen for the PT with properties shown in **Table (3)**.

Table (3) Properties of Pki-802

ρ	7.6 g/cm^3
ε^T_{33}	1000 ε_o
Q_m	900
$-d_{31}$	$100*10^{-12}$ m/V
S^E_{11}	$10.4*10^{-12}$ m^2/N
N_R	2360 m/s
$\tan\delta$	0.35%

2. Select the Radius (r)

The approximate first radial resonant frequency of the PT can be calculated as equation (2) accordingly **[7,11,12]**. In this example, the diameter of the prototype piezoelectric transformer is selected to be 825-mil or 2.096-cm or 0.825-inch based on available materials and reasonable size. Ultimately the diameter should be selected through thermal analysis considering the power level and efficiency of the circuit. Using Equation (2), it is found that the approximate resonant frequency, f_r, will be 98 kHz.

3. Select Number of Layers (N2) of the Secondary Side

From equation (8) the voltage gain of the PT is affected by the ratio of N_1, the number of primary layer and N_2, the number of the secondary layer. This flexibility is available to the designers, just like the turns ratio of a conventional transformer.

4. Decide Secondary Layer Thickness t_2

The maximum efficiency could be achieved if the load matches the output impedance of PT, i.e., equation (11) is met [4]**:**

$$R_L = \frac{1}{\omega_s . C_{d2}} \quad \ldots\ldots (11)$$

Each linear fluorescent lamp has fixed impedance during sustained operation that is considered resistive, as the lamp voltage and current are in phase. By utilizing (11) and a given frequency, one can solve for the necessary capacitance, Cd2, the PT should exhibit for maximum efficiency.

$$C_{d2} = \frac{1}{\omega_S . R_{LAMP}} = \frac{1}{2\pi . 98.10^3 . 600} = 2.75\text{nF} \quad \ldots\ldots (12)$$

From equation (8), (12) and **Table (3)**.

$$t_2 = \frac{N_2 . \pi . r^2 . \varepsilon^T{}_{33} . \left(1 - \frac{d_{31}{}^2}{\varepsilon^T{}_{33} . S^E{}_{11}}\right)}{C_{d2}} = 0.06\ \text{in} = 60\text{mils} \quad \ldots\ldots (13)$$

5. Select Number of Layers (N1) of the Primary Side

From the previous steps, the output layer is designed. The primary layer number N1 and thickness t1 are the two parameters need to be decided in this step. Here t1 was selected as the design variable, N1 was iterated until we can meet the following three requirements at the same time: (1) voltage gain requirement, (2) ZVS requirement, and (3) efficiency requirement. That is, N1 is set to be 1, and check if a proper t1 can be found to satisfy all three requirements as indicated. If not, then N1 is set to 2 and repeat. The details of the three requirements are described as follow:

i. Voltage Gain Requirement:

According to the design specification, the required voltage gain is $Av > Av_{min}$. Av_{min} could be calculated as follows:

- The RMS value of the line voltage is V_{ac}= 220 V
- The peak value of the line input voltage is Vac_peak= $\sqrt{2} . V_{ac}$
- The Rectified DC Bus Voltage is around: Vbus= 280V

- The Power of the Lamp is 40W Pout=40W
- Since the input voltage of the piezoelectric transformer is a trapezoidal waveform, considering the fundamental driving frequency, the peak value of the PT input voltage is:

$$V_{IN-PEAK} = \frac{2.\sin(\pi.0.25)}{\pi^2.0.25}.V_{bus} \quad \text{...} (14)$$

- Then the required voltage (minimum voltage gain Av_{min}) should be:

$$A_{V_{MIN}} = \frac{\sqrt{P_{out}.R_L}}{V_{in-rms}} = 1.3652 \quad \text{...} (15)$$

- According to the equivalent circuit of PT, the voltage gain of the PT could be calculated as eq.(16).

$$A_V = A_V(f_s, t_1) = \left| N.\frac{\left(N^2/R_{LAMP} + j2\pi f_s N^2 C_{d2}\right)^{-1}}{R + j2\pi f_s L + 1/j2\pi f_s C + \left(N^2/R_{LAMP} + j2\pi f_s N^2 C_{d2}\right)^{-1}} \right| \quad \text{..........} (16)$$

- To meet the voltage gain requirement, Av > Av_{min}.
  So N1 needs to be increased to meet the voltage gain requirement.

ii. ZVS Requirement:

In order to achieve Zero Voltage Switching (ZVS), enough energy is needed to charge/discharge the input capacitor, *Cd1*, sufficient dead time is also needed for the resonance, as shown in equation (17,18) [11].

$$\Delta i_{Lpeak}(t_1, f_s) \geq \sqrt{\frac{C_{d1}(t_1).(C(t_1) + C_{d1}(t_1))}{L(t_1).C(t_1)}}.V_{bus} \quad \text{..............................} (17)$$

where:

$$\Delta i_{Lpeak}(t_1, f_s) = \frac{2.V_{bus}}{\pi.|Z_{in}(t_1.f_s)|}.\frac{\sin(\pi.d)}{\pi.d}\sin(\angle Z_{in}(t_1.f_s)) \quad \text{........................} (18)$$

In eq.(18), *Zin* is input impedance excluding the input capacitor *Cd1*, and *fs* is the switching frequency of the half-bridge. Using Vbus=280V and Equation (3-8), the left-hand side of eq.(17), Δi_L *peak* (t_1, f_s) can be expressed in terms of t1 and fs. The parameters Cd1, C, and L on the right-hand side of eq.(17) can also be found by using (3-8).

iii. Efficiency Requirement:

One other consideration should be for efficiency, efficiency of the PT can be represented by (19), η_{spec} is a user specified number. In this example, η_{spec} is chosen to be 90%, and N is an integer. As indicated earlier, N1 is iterated from one upward until a common solution that satisfies voltage gain requirement, ZVS condition and efficiency requirement. In this example, N1=3.

$$\eta(f_s, t_1) = \frac{1}{1 + \left[1 + (2\pi f_s R_L)^2\right] \frac{N^2 R(t1)}{R_L}} \geq \eta_{spec} \quad \text{.. (19)}$$

iv. Solution:

The thickness t1 was selected as the design variable; N1 was iterated until we can meet the following three requirements at the same time: (1) voltage gain requirement, (2) ZVS requirement and (3) efficiency requirement. That is, N1 is set to be 1, and check if a proper t1 can be found to satisfy all three requirements as indicated. If not, then N1 is set to 2 and repeat. In the design process, if no solution can be found, then increase N1 by one and check again until a solution is found. In this design, when the primary layers were increased to three, solution can be found (N1=3).

From (3-19) one can see that once PT material is chosen, and the secondary side parameters N2, t2 are fixed then the voltage gain Av, the peak value of inductor current Δi_L *peak* and efficiency η are purely a function of t1 and fs. A 3-D plot of Av, Δi_L *peak* and efficiency vs. the two variables t1 and fs are shown in **Figus.(6, 7) and (8)** respectively.

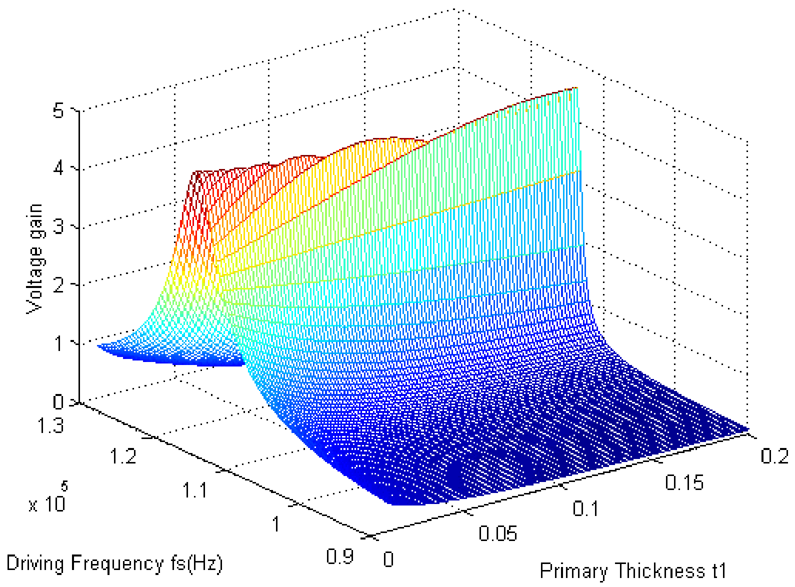


Figure (6) Voltage gain of Transoner versus primary layer thickness and frequency with three primary layers

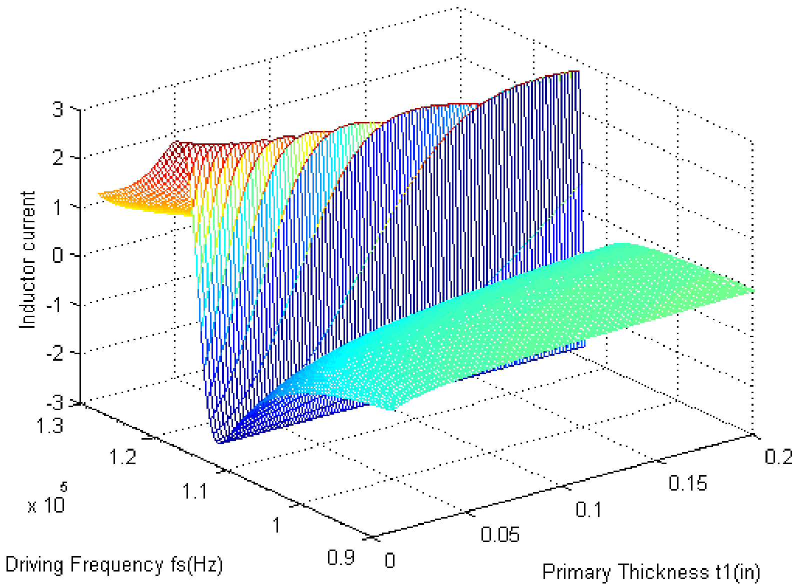


Figure (7) Inductor current versus primary layer thickness and frequency with three primary layers

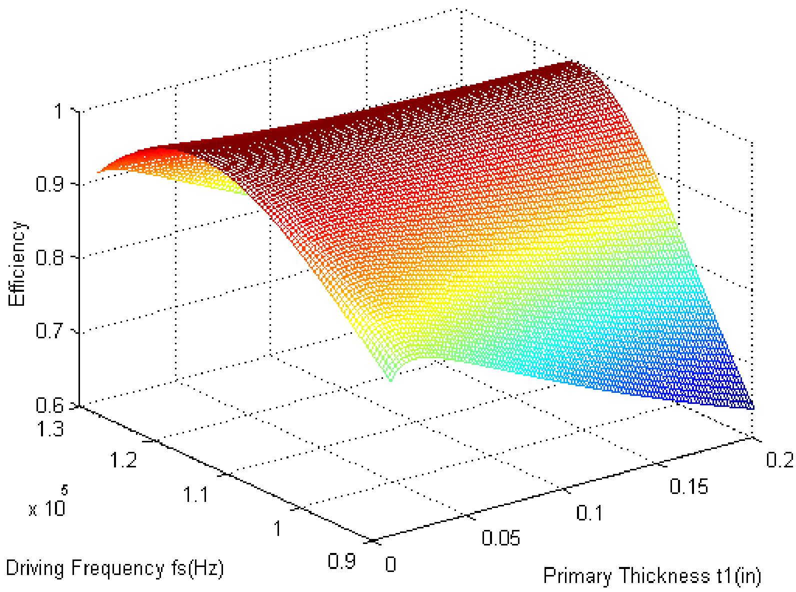


Figure (8) Efficiency current of Transoner versus primary layer thickness and frequency with three primary layers

By taking a slice of these plots at the minimum voltage gain, two-dimensional surface projections can be generated which allows one to easily see where in the (t1 x fs) plane a solution exists as shown in **Fig.(9)**, where inside the curve meets the requirement.

Similarly, two other two-dimensional surface projections can be generated to check whether the efficiency requirement and the ZVS requirement are met. In order to create the smallest range of choices for primary layer thickness are shown in **Figs.(10)**, and **(11)** respectively.

The three plots are then overlapped to find the common choices of both t1 and fs, which are elements of all three two-dimensional projections. Any choice within this overlapped region will provide a useful PT that satisfies all the three requirements.

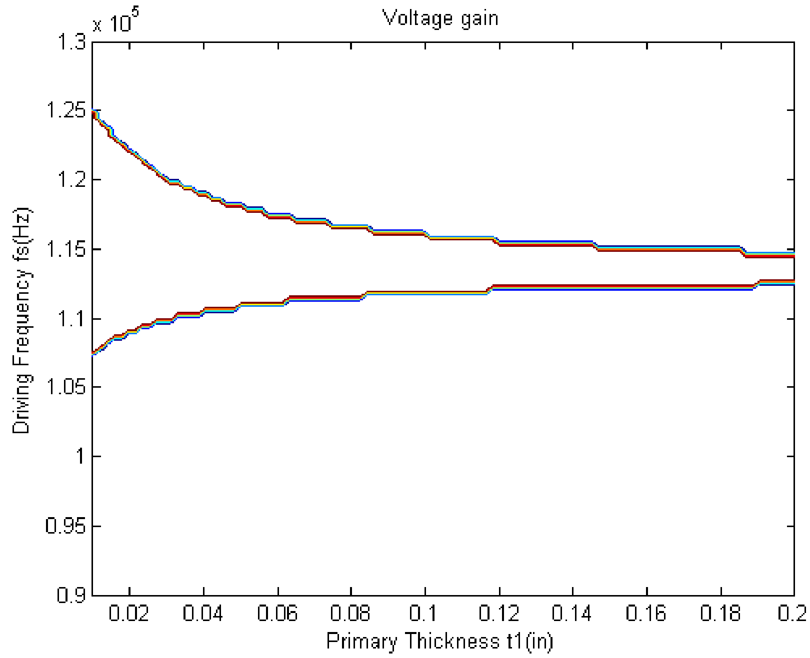


Figure (9) Region where voltage gain is greater than the required minimum voltage gain

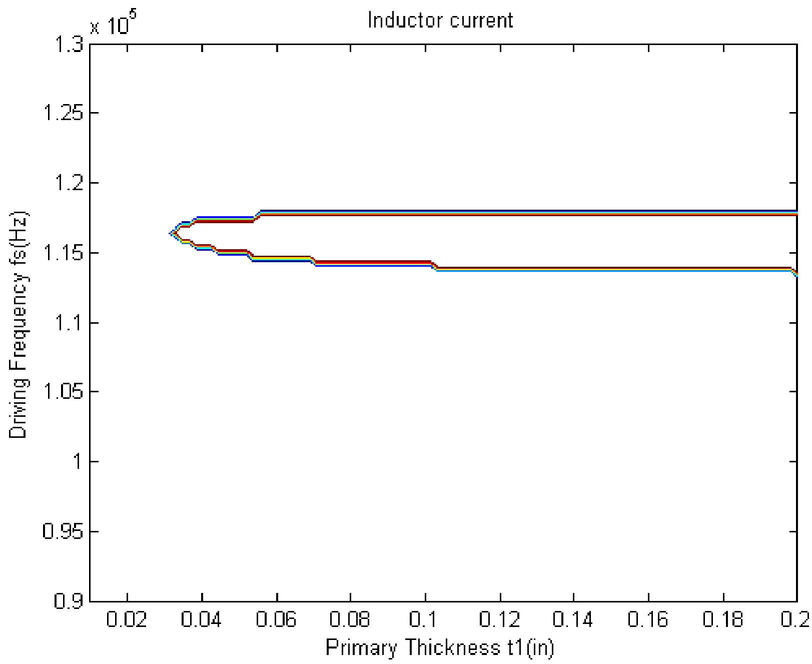


Figure (10) Region where inductor current is great enough to achieve ZVS

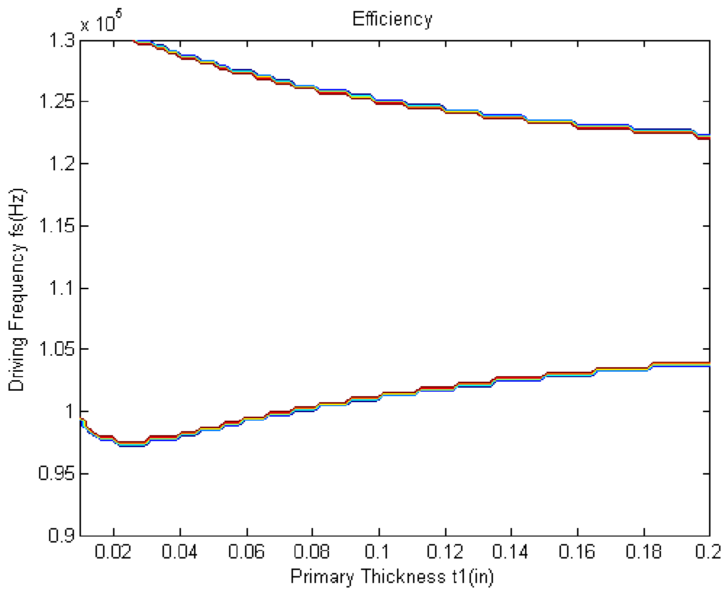


Figure (11) Region where efficiency is greater than the preset minimum

By overlapping the inside the curves regions in **Fig.(9)-Fig.(11)**, a solution region can be found. In other words, this region satisfies all the design requirements. The completed solution region in the (t1 x fs) space was shown in **Fig.(12)**. Selecting a point within the solution region gives a workable design.

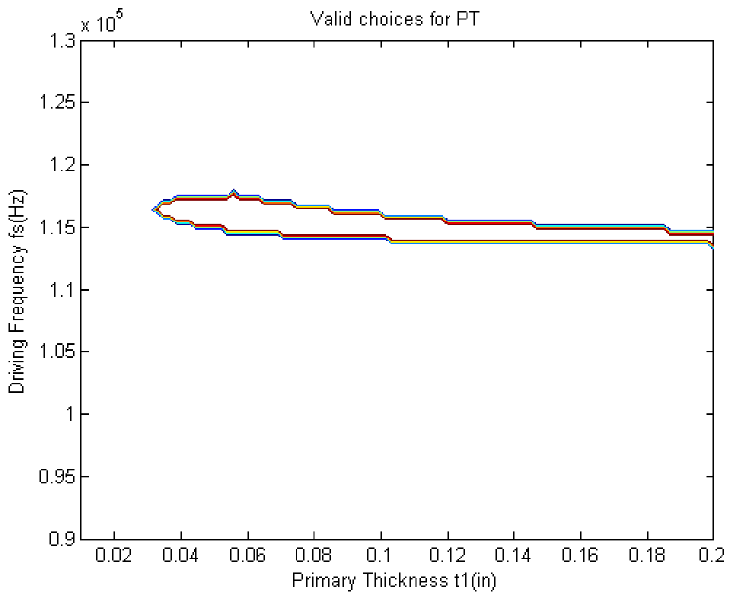


Figure (12) Valid choices for the prototype (PT) transoner

6. Design of the Primary Layer Thickness t_1

From **Fig.(12)**, we can get many possible available designs from the region and evaluate the characteristic of the designed PT. A comparison of different design is possible but is not done in this approach because the sample material available was 60mils, so t1 is selected according the availability of the materials and the related frequency is f_s=116 kHz. Dimensional parameters are t_1=0.06 in, t_2=0.06 in, r=0.4125 in, D= 0.825 in, N1=3 and N2=1.

The complete PT has three primary layers of 60-mil each and a secondary layer of 60-mil. The overall diameter is 825-mil. A theoretical equivalent circuit model parameters using the characteristic equations (3-8) to get the equivalent circuit parameters shown within **Table (4)**. For better understanding of the design process, a flowchart was shown in **Fig.(13)** to summarize the whole design process.

Table (4) Theoretical equivalent circuit parameters of the Pt

C_{d1}	R	L	C	C_{d2}	R_{cd1}	R_{cd2}	N
8.1147 nF	1.2533Ω	2.5mH	0.801nF	2.287nF	48.308k Ω	171.43k Ω	3

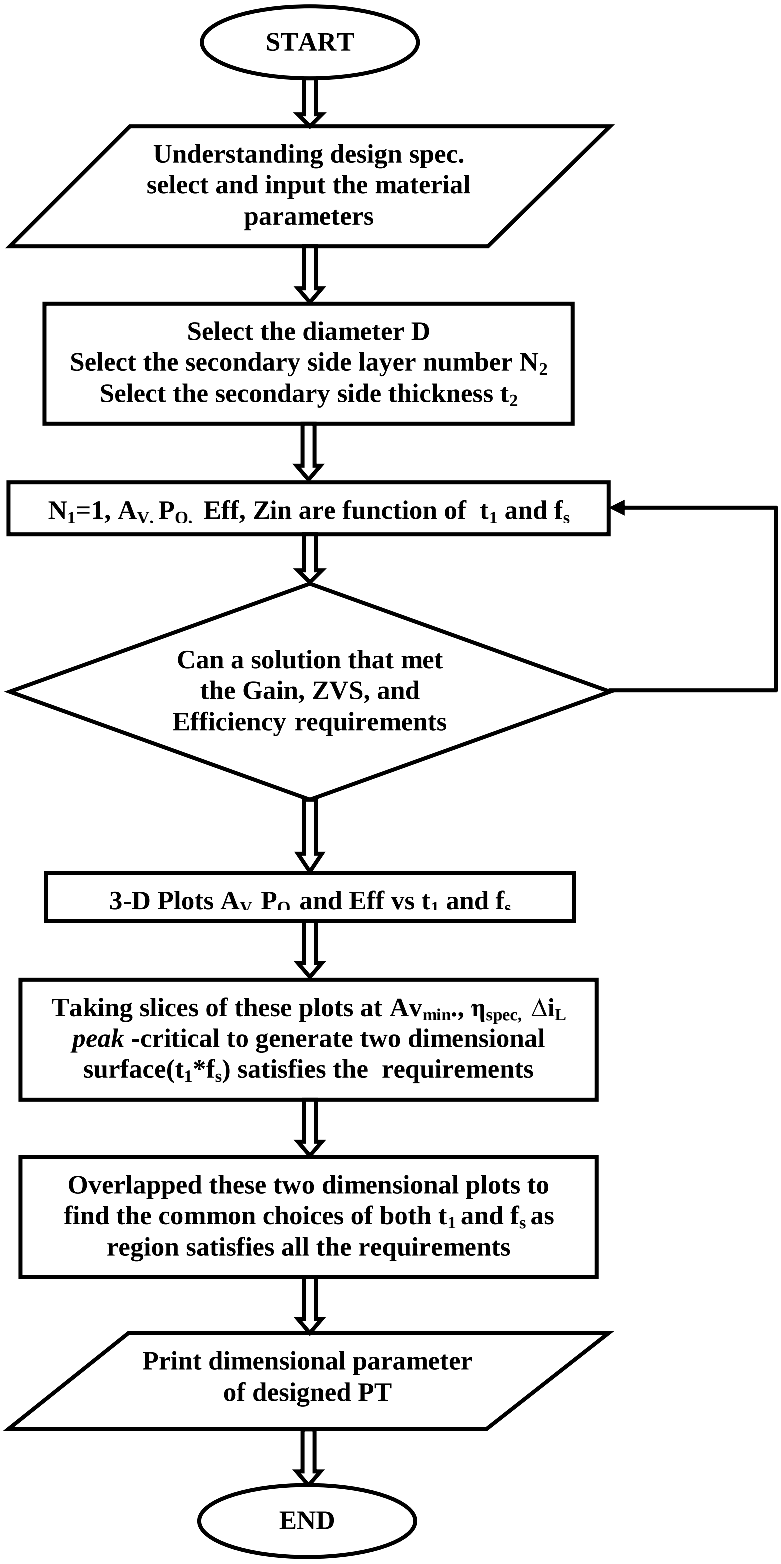
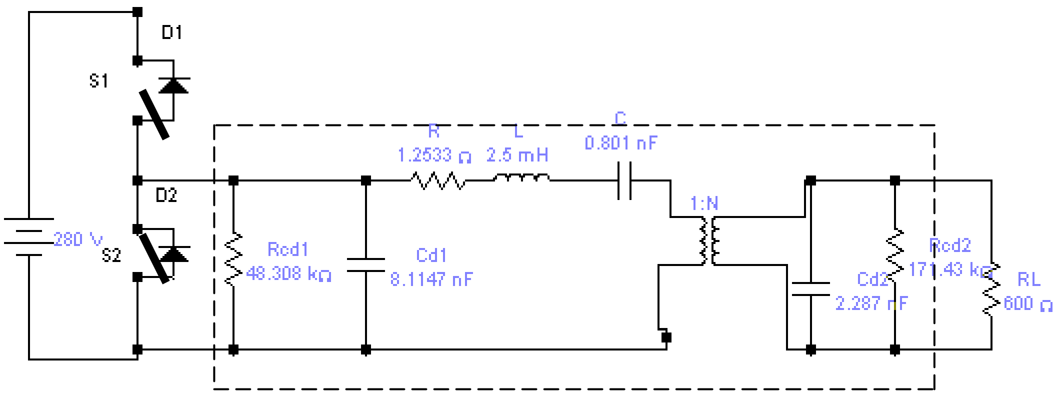


Figure (13) Flowchart of designing the piezoelectric transformer for electronic ballast

3-2 Inductor-less Electronic Ballast

According to the evaluation of voltage gain, ZVS condition and efficiency discussed in Section 3-1, the radial vibration mode piezoelectric transformer can be used for the electronic ballast to drive a 4-foot 40-watt linear fluorescent lamp at V_{DC}=280. At steady state, the equivalent on-resistance of this lamp is equal to 600 Ω. The radial vibration mode piezoelectric transformer serves as a piezoelectric transformer resonant tank that replaces the conventional passive L-C resonant tank. With its inherent piezoelectric resonant characteristics, the radial vibration mode piezoelectric transformer is able to both ignite and provide sustaining voltage to a linear fluorescent lamp. Without requiring any magnetic device, **Figure (14)** shows the circuit for the proposed inductor-less piezoelectric transformer electronic ballast.

The efficiency of the whole prototype circuit was around 90%, including control circuit, half-bridge, and the radial vibration mode piezoelectric transformer.



Piezoelectric Transformer

Figure (14) Electronic ballast with piezoelectric transformer

4. Conclusion

Replacing conventional L-C resonant tanks with piezoelectric transformers reduces the component count and cost of electronic ballasts for fluorescent lamps. Furthermore, the low-profile design of piezoelectric transformers minimizes the total packaging size for the application circuit, possibly translating into additional cost reduction as well.

Several conclusions were drawn from this research:

1. The proposed design procedure proves to be very effective in designing a piezoelectric transformer for given ballast circuit requirements. Because of the numbers of parameters involved and the intertwine relationships; it is very difficult for a designer to come up with a PT design that can meet the entire requirement. The proposed procedure provides an efficient and practical way of accomplishing such.

2. A PT prototype based on the proposed design procedure work very well with the ballast circuit. Power factor of near unity, efficiency of 90% and zero-voltage-switching are all achieved.

3. It is observed that radial mode PT characteristics match lamp resistance so that high efficiency can be achieved. Other types of PT do not match as well.

Within this research, the accepted simplified equivalent circuit model has been shown to exhibit similar characteristics to a parallel-series resonant circuit. The one thing setting the PT apart, from a circuit made up of discrete inductance and capacitance, is the internal resistance and input capacitance. It has been shown that the dielectric losses in the material, does not significantly affect the potential efficiency of the devices throughout the entire resonant frequency range.

The physical-to-electrical design equations have been revealed, as developed by Ray-Lee Lin, for the radial mode piezoelectric transformer. Using these equations, the physical dimensions and material properties can be used to directly calculate the equivalent circuit model parameters. A sample was designed to meet the required voltage gain, ZVS operation, and high efficiency for a 220-volt 50Hz AC input application. A circuit was constructed using the piezoelectric transformer that was designed, in order to prove the viability of the design process. Test results demonstrated the ability of the PT to not only ignite and sustain a 40 lamp, but also provide ZVS for the half bridge switches, at an efficiency of around 90%.

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