Design and Analysis of High-Voltage Transformer for HID Lamp Igniter

W. S. Kim[1], B. H. Cho[1] and K. C. Lee[2]

Seoul National University[1]
Dept. of E.E. #43, San 56-1,
Shillim-dong, Gwanak-gu,
Seoul, Korea.
wskim77@snu.ac.kr

Interpower Co., Ltd.[2]
1578-51, Shillim-dong,
Gwanak-gu, Seoul, Korea.

kyuchan6@empal.com

Abstract -- In this paper, requirements for the HID lamp igniter transformer capable of hot strike are described. A small size high voltage (HV) transformer composed of a ferrite core and an outer `wall is designed. The characteristics such as flux linkage, current density and inductance are simulated with Finite Element Methodology. The design guideline of the HV transformer that produces an output voltage with a peak value of 25kV and a pulse width of larger than 100nS for a 35W automotive HID ballast prototype is discussed as an illustrative example.

I. INTRODUCTION

The High Intensity Discharge (HID) lamp is widely known for high lumens, high efficiency and long life-time. The HID lamp exhibits negative-resistance characteristics in the operating regions, and the lamp resistance varies over time. An electronic ballast system commonly used is shown in Fig. 1 [1][2]. It is composed of a dc-dc converter, which can boost the battery voltage up to the hid lamp voltage, a dc-ac inverter, which alternates the voltage for the long-lifetime, and a controller.

A High Voltage (HV) igniter is also an essential component in the HID ballast. For systems such as the automotive head-light application requiring hot strike, the ballast should provide enough breakdown voltage (25 kV) during ignition [3][4]. An external igniter is normally implemented in the ballast system.

If the bulky size of the automotive HID lamp ballast can be reduced with low cost, the scope of the HID lamp will widen to other applications such as the electric torch and lighting apparatus. Especially, in the D1 type of the HID lamp in the automotive application, the size of the HV transformer is a dominant size factor of the HID lamp ballast. Moreover, several considerations, such as voltage gain, secondary self inductance, energy transfer and parasitic components, should be attended to in designing the igniter transformer.

To satisfy these considerations, the essential factors of designing the HV transformer are described in this paper. An innovative cylindrical HV transformer model which has an additional outer core is proposed and simulated. A design guideline is established and analyzed with the Finite Element Methodology (FEM) tool. From the experimental results obtained with the igniter for the 35W automotive HID ballast prototype, the design guideline is verified.

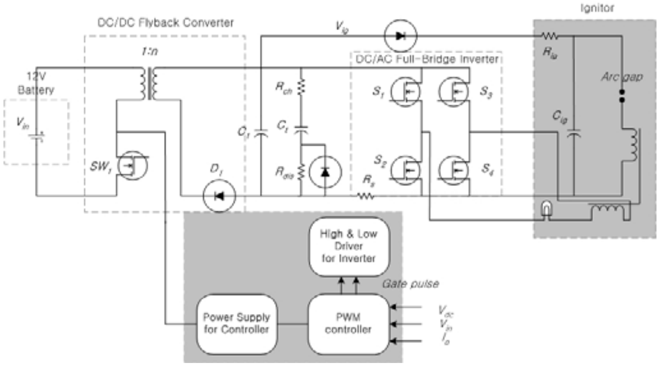


Fig. 1. Conventional automotive HID lamp ballast

II. DESIGN CONSIDERATION

There are several points to be considered in designing the HV transformer for the HID lamp.

A. *Secondary self inductance*

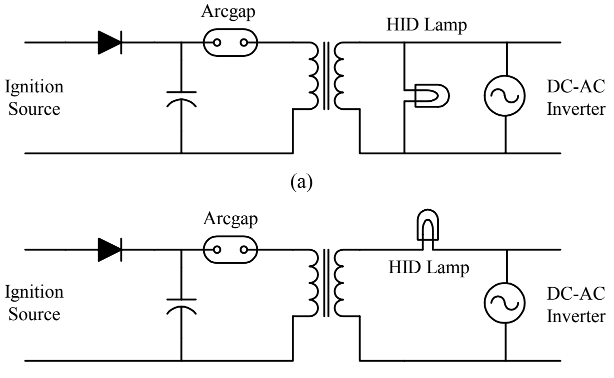
The igniter is divided into two main circuit configurations: series and parallel connections, as shown in Fig. 2. Due to the voltage problem in the parallel connection, the series connection is widely used. After the ignition, the secondary side of the igniter transformer is appears in series with the lamp. When the secondary self inductance (L_2) is too large, the rising or falling slope of the square wave voltage of the inverter reduces. In the worst case, with the dead time, the lamp may not be able to hold the arc and may turn off. Thus, the secondary self inductance should be limited.

B. *High secondary voltage generation*

Normally, an ignition voltage of 4~10kV is required in cold strike. In hot strike, the lamp needs around 25kV with more than 100nS of pulse width because of the pressure in the bulb. A HV pulse transformer is required with a minimum turns ratio.

This work is supported by Ministry of Commerce, Industry and Economy (MOCIE) in Korea

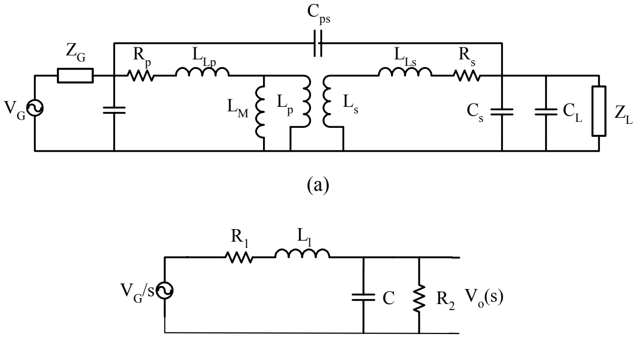
0-7803-8975-1/05/$20.00 ©2005 IEEE.



(a)

(b)

Fig. 2. Two main HV igniter configuration; (a) parallel connection, (b) series connection



(a)

(b)

Fig. 3. Equivalent circuit of HV transformer; (a) equivalent circuit , (b) simplified circuit

C. Low Parasitic Components

Fig. 3 shows the equivalent circuit of the igniter transformer. After Arcgap turns on, the source voltage V_G is the capacitor voltage. For numerical analysis, the high pulse type input voltage is considered in three main timing sequences: rise time, flap top and fall time. The lamp should be turned on during the rise time for a reasonable operating margin. The equivalent circuit is simplified, as shown in Fig. 3(b) and the output voltage equation is as below.

$$V_o(s) = \frac{V_g}{s} \frac{R_2 \parallel \frac{1}{sC}}{R_2 \parallel \frac{1}{sC} + R_1 + sL_1} = \frac{V_g}{sL_l C} \frac{1}{(s+\alpha_1)(s+\alpha_2)} \qquad (1)$$

where

$$C \approx n^2 (C_s + C_l) + C_p, \quad L_l \approx L_{lp} + \frac{L_{ls}}{n^2}$$

$$R_1 = R_p + Z_g, \quad R_2 = \frac{Z_l + R_s}{n^2}$$

$$\alpha_1, \alpha_2 = \left[\left(\frac{R_1}{2L_l} + \frac{1}{2R_2 C} \pm \sqrt{\left(\frac{R_1}{2L_l} + \frac{1}{2R_2 C}\right)^2 - \left(\frac{R_1 + R_2}{R_2 C L_l}\right)} \right]$$

Rise time, $T = 2\pi\sqrt{L_l C a}$, $a = R_2 / (R_1 + R_2)$

The rise time is affected by the leakage inductance, L_l, the parasitic capacitance, C, and the resistance ratio, a as shown in Eq. (1). Clearly, for large values of the turns ratio, the capacitance of the transformer secondary windings needs to be minimized for a fast rising time and a minimum oscillation.

D. Coupling

Coupling of the high voltage transformer is the main factor in determining the capability of energy transfer. In the case of HV transformer applications, coupling coefficients (*k*) need to be maximized due to the higher turns ratio. Good coupling can minimize the lamp breakdown voltage and the turns ratio. The coupling coefficients are affected by the following reasons and have no relationship with the no. of turns.

- Winding
- Relative distribution between two windings
- Core material

E. Flux Saturation and Insulation

In HV or Pulse transformer applications, the key issue is to prevent the core saturation. There are two main types for saturation: volt-sec saturation and NI value limitation. Because the ballast tries to ignite the lamp more than once for reliability, the HV transformer should be designed not to saturate in this repetitive reaction. In high power applications, an air core is normally used.

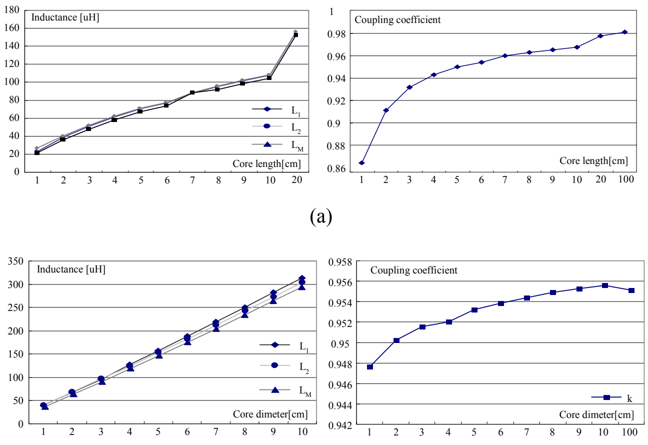
The insulation can result in serious problems. In the igniter requiring hot strike ability, a high voltage around 25kV is generated and hundreds of turns are adapted on the secondary side. Reasonable insulation plan is required, such as bobbin design, material or wire type.

F. Size and Cost

The igniter only needs to start a lamp. A tiny, compact, and inexpensive igniter is required for portable lighting and automotive headlights.

III. ANALYSIS OF THE DESIGN FACTORS

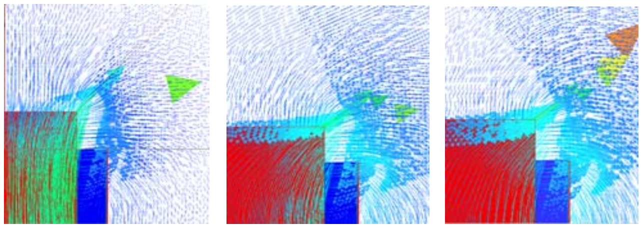
In designing the HV transformer, there are several designing factors such as core shape and winding technique. Unlike high power applications, introduction of a magnetic core can increase the magnetizing inductance and reduce the leakage inductance. For a HV igniter transformer, a rod-type ferrite core is commonly used due to the required high voltage gain with a minimum size. Maxwell 2D is used to analyze the optimal core shape. The simulation is achieved under two assumptions: First, the proximity effect can be ignored. Second, the simplified model, which has a 3:20 turns ratio, can explain the tendency of the inductance and the coupling coefficients. The results are described in Fig. 4. A longer core shape has larger inductance. Coupling coefficients also increased directly proportional to the length. Similar results are observed with cross section variations. From these results, due to the increase of leakage flux with a wider cross section area, as shown in Fig. 5, the long rod-type core is seen to be



(a)

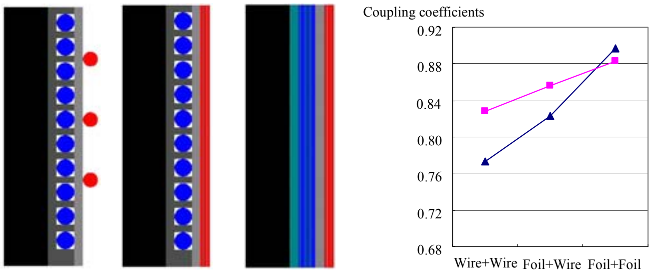
(b)

Fig. 4. Simulation results with changing the core parameters; (a) under core length variation , (b) under core diameter variation



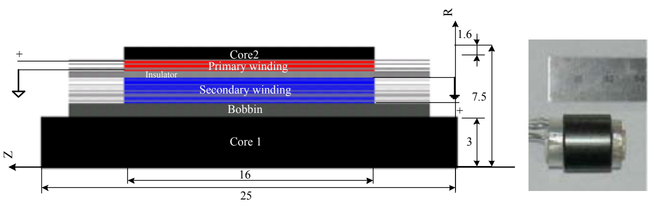
(a) (b) (c)

Fig. 5. Simulation result of the Flux vector distribution under the diameter variation: (a) d=1cm, (b) d=10cm, (c) d=100cm



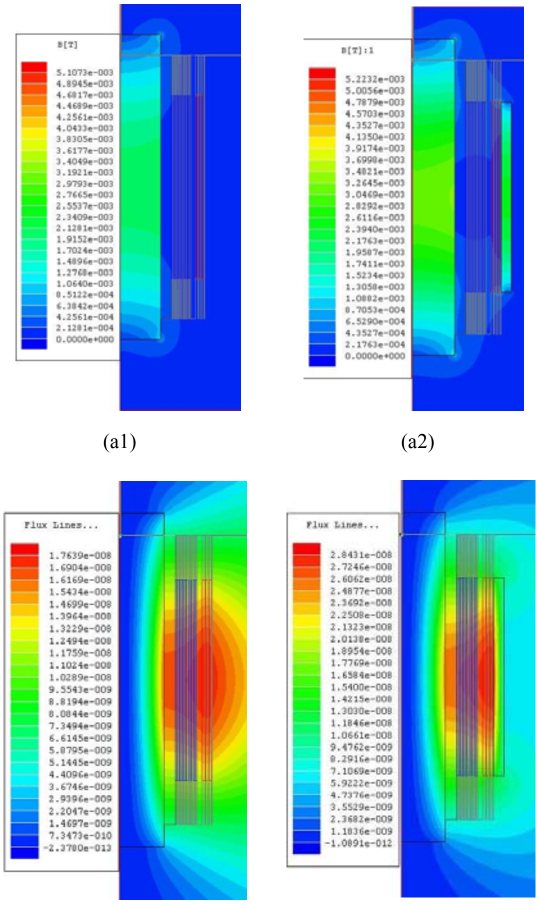
(a) (b)

Fig. 6. Several design of HV Transformer(a) and comparison results of the coupling coefficient(b); (a) : Red : primary side, Blue : Secondary side, Black : Ferrite core, Dark gray : Insulator; (b) Rectangular-line : simulation result (Maxwell 2D, Ansoft Co.), Triangle-line : experimental results



(a) (b)

Fig. 7. Cross section view (a) and prototype (b) of the Proposed HV Transformer for HID Lamp (R-Z model) [mm]



(a1) (a2)

(b1) (b2)

Fig. 8. Simulation result of the flux density and flux line distribution map for the conventional rod-type model and proposed one (R-Z model): Flux density of the conventional (a1) and proposed models (a2), Flux line of the conventional (b1) and proposed models (b2)

more effective than the disc-type core under the particular size limitations.

Several winding strategies are attempted to maximize the coupling coefficients under the high voltage insulation constraints. Fig. 6(a) shows three different winding techniques. The use of foil for both the primary and secondary windings provides the maximum coupling coefficients (Fig. 6(b)).

As far as the insulation is concerned, it is easier to design the insulation layer in the foil winding technique by placing the high voltage winding of the secondary in the inner layer. It also does not require a special bobbin.

III. PROPOSED IGNITION TRANSFORMER

In order to optimize the size of the transformer by reducing the leakage flux in the rod-type transformer, a new core configuration is proposed in Fig. 7. It includes a cylinder type outer core covering the winding. The flux density distribution of the core is simulated in Fig. 8. An additional core (core 2) forms the outer wall and the flux pass, which increases the self inductance and decreases EMI at the ignition phase. Due to corona discharge at high voltage, aluminum is chosen as the conductor. Adding core 2, the coupling coefficient is enhanced with the foil winding.

In choosing the desirable values, the key design parameters, such as physical dimensions, limitation of L_2, winding type, turn ratio and core type are used. By literature survey and experimental results, 1mH of secondary self inductance is chosen as the maximum value which confirm the proper operation. In the rod-type core, the portion of flux lines that pass through air is large enough to be ignored. The effective mean pass length of flux lines in the air is calculated with FEM tools. L2 is calculated using Eq.2 and compared with experimental results in Fig. 9.

$$L_2 \cong \frac{\mu_o n^2 A_c}{l_{c1} + l_{c2}} \frac{2}{\pi} (1 + \frac{2 \cdot l_g}{D_{cp}})^2 \times 10^{-4} [uH] \tag{2}$$

where

$\mu = \mu_0 = 4\pi \cdot 10^{-7}\, H - m$, A_c : core cross section area[cm^2],

n : No. of secondary turns, D_{cp} : diameter of the core[cm],

l_{c1} : core1 length[cm], l_{c2} : core2 length [cm],

l_g : mean pass length of the flux [cm]

The conductor and the insulator thickness is selected with its skin depth and insulation ability. The penetration depth of aluminum and the Effective cross section dimension of the conductor are described in Eq.(3) and Eq.(4). Relative resistibility based on the copper is 0.625. Using fourier analysis, the frequency is calculated as a mean of the first five frequency components of the output voltage.

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}} = \frac{7.5}{\sqrt{f}} \times \sqrt{0.625} = \frac{5.7}{\sqrt{f}} [cm] \tag{3}$$

$$A = \frac{I_{\max}}{I'_{\max} \cdot k \cdot 0.625} = 0.27 \sim 0.44 [mm^2] \tag{4}$$

where

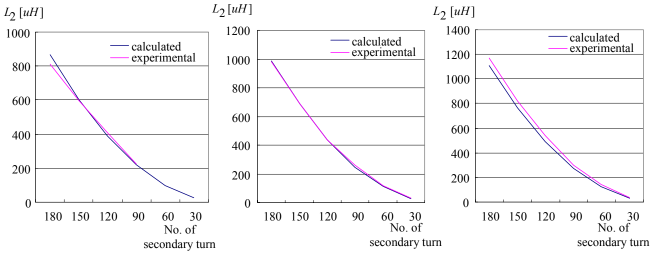
$\delta = 2.3 \cdot 10^{-6}\, \Omega - cm$, $k : temperature\ coefficients$

$I_{\max} : Maximum\ rated\ current,\quad I'_{\max} : Maximum\ current\ rate$

From L_2 and turns ratio after considering the coupling coefficients, L_1 is calculated and the primary voltage (V_1) can be calculated with respect to L_1, charging capacitance and the arcgap operation time. By repeating this process, the desired parameter can be calculated. A design algorithm is drawn in Fig. 10. The dimensions are $25 \times 17 \times 17 mm$, and the diameters of the inner and outer cores are 6mm and 16mm respectively.

IV. SIMULATION AND EXPERIMENTAL RESULTS

To test the transformer, the circuit shown in Fig. 1 is built to provide an input voltage of 800V. A 100uF charging capacitor is used to hold the breakdown voltage of the arcgap. A Spice arcgap model is used in the simulation result as shown in Fig. 11. From the simulation result, it is seen that more than 1uH of primary self inductance is required. Trade off design is needed to find the optimal point between the charging capacitor and the primary self inductance of the HV transformer.



(a) (b) (c)

Fig. 9. Comparison of the L_2 in the variation of core diameter; (a) 6 Φ, (b) 8 Φ, (c) 10Φ

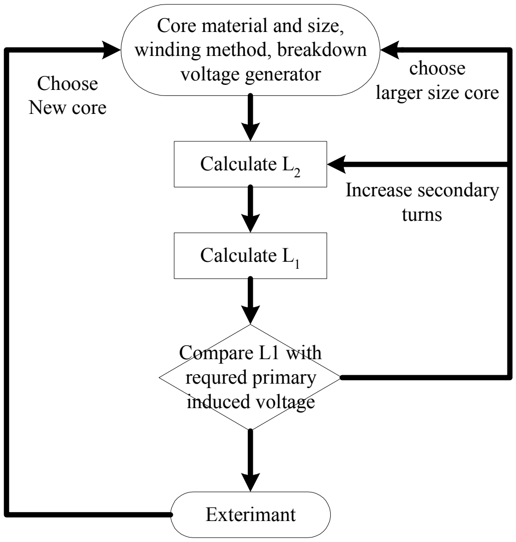
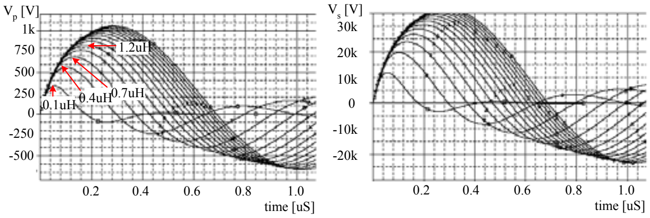


Fig. 10. Design algorithm of igniter transformer

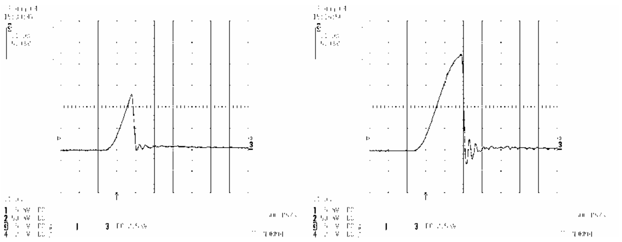
TABLE I
DESIGN PARAMETERS

Ferrite Core	Core 1 : Rod type (diameter(D) : 8mm, length(L) : 25mm) Core 2 : Tube type(D : inner[mm] : 13.8, outter[mm] : 17, length[mm] : 16), μ_i: 400. B_m [mT]: 50(25℃), 800(100℃), B_r[mT] : 132, H_c[A/m] : 64
Primary winding (n_1)	5 turns (Al, width[mm]: 16, thickness[um] : 12)
Secondary winding (n_2)	150 turns (Al, width[mm] : 16, thickness[um] : 12)
Insulator	Polyethylene (35[kV/mm], width[mm] : 20, thickness[um] : 16)
Primary self inductance (L_1)	1.2 [uH]
Secondary self inductance (L_2)	910 [uH]



(a) (b)

Fig. 11. Simulation results; (a) primary voltage of the proposed TF, (b) secondary voltage of the TF



(a) (b)

Fig. 12. Experimental waveform of the Lamp voltage with 5kV/div, 0.1uS/div; (a): cold strike; (b): hot strike

Fig. 12 shows the experimental waveforms of the proposed transformer. The output voltage of 25kV is generated and is applied to the lamp in the hot state.

IV. CONCLUSION

Different winding techniques are investigated in terms of coupling coefficients. A new core configuration is introduced to optimize the overall size of the transformer. It show 36% reduction in size compared to the conventional rod-type transformer. The designed transformer is tested with a hardware ballast system satisfying its performance including the hot strike.

REFERENCES

[1] Kyu-chan Lee, B.H. Cho, *"Design and Analysis of Automotive High Intensity Discharge Lamp Ballast using Microcontroller Unit,"* Power Electronics IEEE Transaction on Power Electronics, Vol. 18, No 6, pp. 1356-1364 ,2003, November.

[2] T.F. Lin, C.S. Moo, and Moo Hsieh, *"An electronic gear for short-arc xenon lamps,"* PCC Osaka 2002, Vol. 3, PP 1468-1472, 2002, April.

[3] Moo, C.S. Moo, T.F. Lin and Y.C. Chuang, *"Designing an igniter for short-arc xenon lamps,"* 34thIAS Annual Meeting. Conference Vol. 1, PP 612-617, 1999, October.

[4] Y.-Q. Hu, J. Zhang, W. Chen and C.-C Wen, *"Analysis and design of metal halide lamp igniter,"* PESC. 2001, Vol. 1, PP 132-137 2001, Jun.

[5] *"Requirements for Igniter for Xenon lamps,"* OSRAM Munich Germany, 1978

[6] P. W. Smith, *"Transient Electronics,"* JOHN WILEY & SONS, LTD, PP 137-168, 2002.

[7] L.M. Redondo, E. Margato and J.F. Silva, *"Rise time reduction in high-voltage pulse transformers using auxiliary windings"*, IEEE Transactions on Power Electronics, Vol. 17 Issue: 2 , PP 196-206, 2002, March

[8] J.P. O'Loughlin, J.D. Sidler and G.J. Rohwein, *"Air core pulse transformer design,"* Power Modulator Symposium, 1988, PP 325-330, 1988, Jun.

[9] J. C. Martin and I.D. Smith *"High Voltage Pulse Generating Transformer,"* US Patent No. 3456221(1969)

[10] R.W. Erickson, D. Maksimovic, "Fundamentals of Power Electronics" 2000

[11] *"Getting Started: A 2D Magnetic Force Problem, 2D Eddy current Problem,"* Ansoft, 2003, November.