High Power Density, High Frequency, and High Voltage Pulse Transformer

S. C. Kim, S. H. Jeong and S. H. Nam

Abstract - The high operation frequency mainly reduces transformer volume in the power supply. A high frequency and high voltage pulse transformer is designed, fabricated, and tested. Switching frequency of the transformer is 100 kHz. Input and output voltages of the transformer are 250 V and 4 kV, respectively. Normal operation power of the transformer is 3 kW. Maximum volume of the transformer is 400 cm^3. The power density is thus 7.5 W/cm^3. The transformer will be installed in a metal box that has nominal operation temperature of 85 degree centigrade. The transformer and other high voltage components in the box will be molded with Silicon RTV(Room Temperature Vulcanize) that has a very low thermal conductivity. Procedures of design and test results are discussed. Analytical as well as experimental results of various parameters such as transformer loss, leakage inductance, distributed capacitance are also discussed. In addition, thermal analysis results from ANSYS code for three different operation conditions are discussed.

Keywords - high power density, high frequency, high voltage pulse transformer.

1. Introduction

The high frequency switching operation is essential item for small-size and light weight power supplies. In high-density power supplies, transformer is important factor for their volume and weight decision. Power density of the transformer increases proportional to an operation switching frequency of the power supply[1][2]. In this paper, we will describe design and development procedures as well as test results of a high voltage, high density, and high frequency pulse transformer. The transformer is designed for a power supply that drives a TWT microwave amplifier. Specifications of the transformer are 100 kHz switching frequency, 3 kW power, maximum 400 cm^3 volume, and minimum power density of 7.5 W/cm^3.

2. High frequency, high density, high voltage pulse transformer

Fundamental specifications of the required transformer are 100 kHz switching frequency, 250 Vdc input voltage, two outputs of 2 kV and 4 kV voltages, normal operation power of 3 kW, and maximum allowable volume of 400 cm^3. The minimum power density is thus 7.5 W/cm^3.

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2.1 Electrical parameters

From the fundamental parameters, turns ratios of the transformer is calculated as 16.67 and 8.43 for the 4 kV and 2 kV outputs, respectively. With typical winding techniques, the required transformer performance can not be fulfilled because of several reasons such as transformer volume limit, total loss limit, self-resonance frequency and current limit, stray capacitance and leakage inductance limit, response time limit, etc. Especially, we can not easily control the stray capacitance and the leakage inductance, which in turn can produce large peak values of self-resonant current, and thus unacceptably increase the operating temperature of the transformer.[2][3][5] Therefore, the secondary winding is separated by four windings to reduce such values of stray capacitance and leakage inductance. This configuration is also beneficial when we arrange the winding layers to reduce proximity effects between windings and thus reduce the transformer loss. Fig. 1 shows the winding diagram of the high frequency, high voltage, and high density pulse transformer. This transformer is using for military aircraft and its flying altitude is about 55,000 ft. Environmental specifications of the transformer are -55 ~ 85 ℃ operating temperature, 6 kV minimum insulation, and maximum operating height of 16.5 km. Based on the fundamental parameters, input and output requirements of the transformer are calculated and shown in Table 1. For the calculation, a pulse duty of 0.9 and a transformer efficiency of 90 % are used. Fig. 2 shows the pulse transformer connection scheme with the load. As shown in Fig. 2, all secondary windings are connected in series to finally produce the required high voltage of 4 kV.

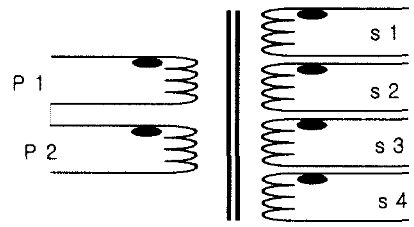


Fig. 1 Winding diagram of the high frequency, high density, and high voltage pulse transformer

Table 1 Calculated parameters of the transformer

Input	Output
Vp = 240.02 Vrms	Vs1, Vs2, Vs3, Vs4 = 520 Vrms
Pin(total) = 3.057 kW	Pout(total) = 2.75 kW
Iin(total) = 13.4 Arms	Iout(total) = 4.8 Arms
turn ratio = 1	turn ratio s1, s2, s3, s4 = 2.167

2.2 Core and flux density

Core of the pulse transformer should be as small as possible while fulfilling the required operating frequency and temperature. The maximum allowable transformer volume is 400 cm^3. Various core materials are reviewed, and Magnetic ferrite EC type core 47228-EC with R material is selected. In Fig. 3, dimensions of the core are shown. The core has 50.5 cm^3 volume(Ve). Using the R47228-EC core, losses are calculated. Fig. 4 shows calculated plots of winding, core, and total transformer losses as a function of flux density.

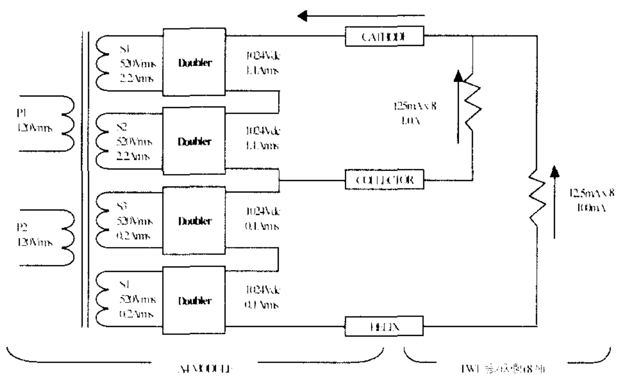


Fig. 2 Pulse Transformer connection (with TWT). Trans-former primary: 100 kHz, full bridge switching

Fig. 5 shows calculated plots of total winding thickness and available window thickness of the transformer. From the figures 4 and 5, one can recognize that the selectable range of operating flux density is 1500 G 2000 G. The total usable power of the core is 8.29 kW for 1500 G, and 16.58 kW for 2000 G.[2] Therefore, the core is enough to handle the required transformer power of 3 kW and transformer is to be proper temperature rise at actual transformer install structure. The maximum transformer size with the core is about 139.926 cm^3 that is much smaller than the allowable volume of 400 cm^3. The power density of the transformer is then about 21.44 W/cm^3, which is about three times larger than the requirement.

2.3 Insulation and wire

To have the required dielectric strength of 6 kV in the transformer, Skyrol SR50 (Dielectric strength: 7 kV/mil, Thickness: 0.25 mil) is used as an insulation film. Layer-to-layer insulation thickness between primary and secondary winding is chosen 2 mil that gives more then 2.3 insulation safety margin between windings. At wire design, the wire current density of transformer is assumed as 500 Dcma (circular mil/A). Skin depth of copper at 100 kHz is 0.225 mm.[3][5] To fully occupy the copper area, cross sectional wire dimension should be smaller than the skin depth. Therefore, copper foil with 0.2 mm thickness is used as the primary wire, and Litz wire (35 AWG x 50) is used for the secondary winding. Table 2 summarizes design values of each transformer winding. Table 3 shows the list of number of turns and layers for each winding in two different operating flux densities of 1500 G and 2000 G.

Fig. 3 R-47228EC core(mm): A=72.4, B=27.9, C=19, D=17.8, E=9.53, F=19, G=16.9

2.4 Winding arrangement

Several different winding arrangements are fabricated to find an optimum arrangement. Fig. 6 shows the final arrangement. It only shows half of the winding arrangement. As shown in Fig. 6, the windings are arranged so that the magneto-motive forces between primary and secondary are balanced. The two primary (p1 and p2) are positioned in the middle, and high current

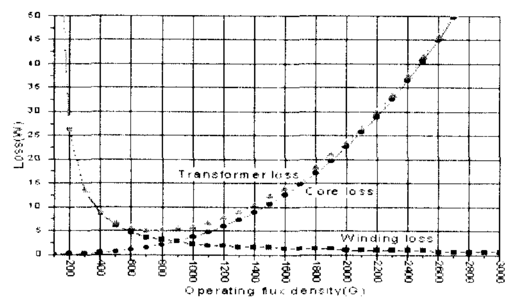


Fig. 4 Various transformer losses (calculated values).

secondary windings (s1 and s2) are arranged near the primary to cancel out as much flux as possible from which the proximity effect can be minimized. The other two low current secondary windings (s3 and s4) are positions after the high current secondary windings since the current is lower than others, and thus they have less proximity effects to others.

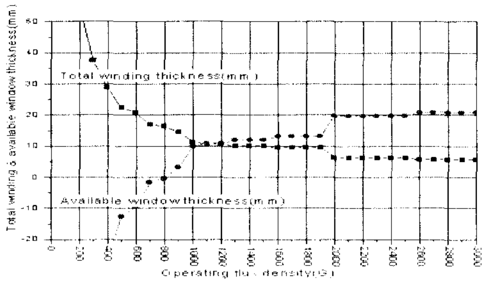


Fig. 5 Total winding and available window thickness of the pulse transformer (calculated values).

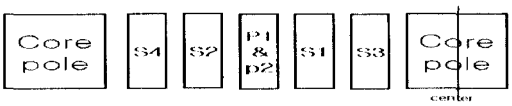


Fig. 6 Pulse transformer winding layout

2.5 Parameter measurement

Two transformers with different operation flux densities of 1500G and 2000G are fabricated and their electrical parameters are measured. The measurement results are listed in Table 4. As listed in the table, the resonance frequencies for two cases are both extremely higher than the operating frequency of 100 kHz. From Table 4, peak resonance current can be calculated by using the following equations.

$$I_{pk}=\frac{V_s}{\omega_0 L_L}\times e^{-(\frac{R_w}{2L_L})\frac{1}{4f_0}} \text{ (A) },\quad \omega_0=\frac{1}{\sqrt{L_L C_d}} \qquad (1)$$

where Vs and Rw are the primary voltage and the winding resistance (5.24 and 5.67), respectively. The calculated peak resonance currents are 0.274 A for 1500 G and 0.269 A for 2000 G. These values are sufficiently lower than the nominal operation currents and do not affect the operating condition of the transformer.

Table 2 Wire design of each transformer windings

	Wire current density: 500 Dcma
Primary(p) Foil	Required copper area: 4.24 mm^2
	Foil width: 23.46 mm
	Foil thickness: 0.2 mm
Secondary (s1, s2) Litz (35AWGx50)	Required copper area: 0.7 mm^2
	Litz wire copper area: 0.7697 mm^2
	Litz total area (with insulation): 1.1319 mm^2
Secondary (s3, s4) Litz (35AWGx10)	Required copper area: 0.06 mm^2
	Litz wire copper area: 0.1539 mm^2
	Litz total area (with insulation) : 0.2264 mm^2

Table 3 Transformer winding design

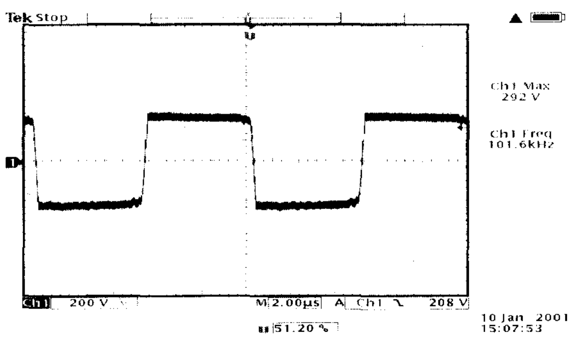
	1500Gauss	2000Gauss
P	12 turn 12 layer	8turn 8 layer
s1, s2	26 turn, 2 layer	18 turn 1 layer
s3, s4	26 turn 1 layer	18 turn 1 layer

Table 4 Measured parameters

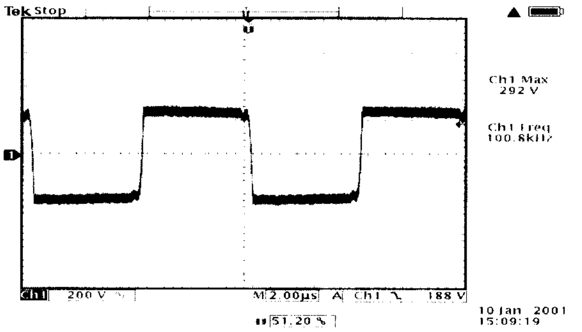
operation flux density (1500Gauss)	Quality factor(Q) = > 115
	leakage inductance(L_l) = 2.04 μH
	winding capacitance(C_w)=0.277 nF
	resonant frequency(f_o)=4.0 MHz
	distributed capacitance(C_d)=3.12 pF
operation flux density (2000Gauss)	Quality factor(Q) = > 99
	leakage inductance(L_l) = 1.29 μH
	winding capacitance(C_w) = 0.224 nF
	resonant frequency(f_o) = 6.0 MHz
	distributed capacitance(C_d) = 1.96 pF

2.6 Output waveform

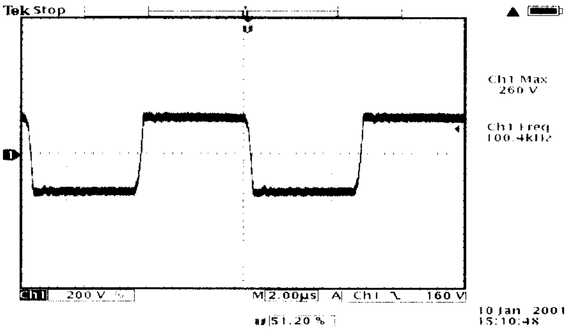
The transformers are connected as shown in Fig. 2. Output waveforms for each secondary windings are measured. The primary winding is excited from a full bridge FET switching circuit. Typical waveforms are given in Fig. 7. The waveforms in Fig. 7 are results of the 2000 G transformer. As can be seen in the figure, outputs are perfectly reproducing the 100 kHz switching waveforms without any resonance on the turn-on and turn-off timing. On the flat-top of the pulse, there are no signs of oscillation on outputs except the s2 output winding. At the end of s2 output flat-top, there can be seen small amount of oscillation. However, the amplitude is small and this will not affect the performance of the power supply system.



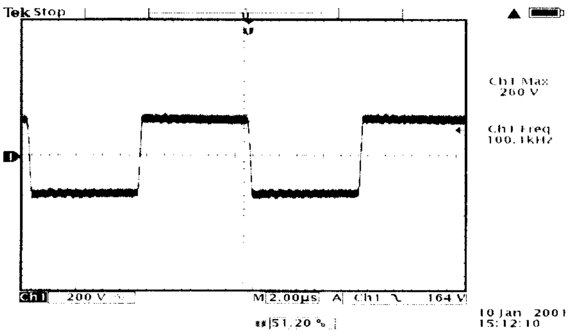
(a) Output waveform of s1.



(b) Output waveform of s2



(c) Output waveform of s3.



(d) Output waveform of s4.

Fig. 7 Output waveforms of a pulse transformer with 2000 G flux density

2.7 Thermal analysis

Thermal analysis of the pulse transformer is performed by using a finite element method of ANSYS software [4]. From the analysis, thermal distribution, hot point, and reaching time to thermal steady state of the transformer can be obtained. For three different operation conditions are simulated. Condition I is for without molding the transformer, and the transformer is operating in 85 ℃ air. Condition II is for entirely molding the transformer with silicon RTV(Room Temperature Vulcanize), and the molded transformer is in 85 ℃ air. Condition III is also molded with silicon, but base core surface of the transformer is adhered to an Aluminum plate that has a constant temperature of 85 ℃. The condition III is the most proximate condition in a typical application. The transformer case with 2000 G flux density is applied for the analysis. For the conditions I and II, the analysis results indicate that the hot point temperatures of the transformer may rise above 200 ℃. For the condition III, hot point temperatures of the transformer are maintained below 94 ℃ since the thermal energy can transfer to the constant temperature Aluminum plate. Table 5 summarizes the simulation results of the condition III. Fig. 8 shows the three dimensional thermal distribution for the case of the condition III. The curie temperature of the transformer core is 230 ℃, and temperature characteristics of all other materials are good well above 100 ℃. Moreover, the core loss is minimum at 100 ℃. Therefore, the simulated temperature of 94 ℃ can be regarded as the optimum operating temperature of the transformer.

Table 5 Thermal analysis result for condition III

Maximum heating	94	℃
Thermal steady state	0.55	hour
Hottest point	transformer pole	
Thermal emission	conduction to AL	

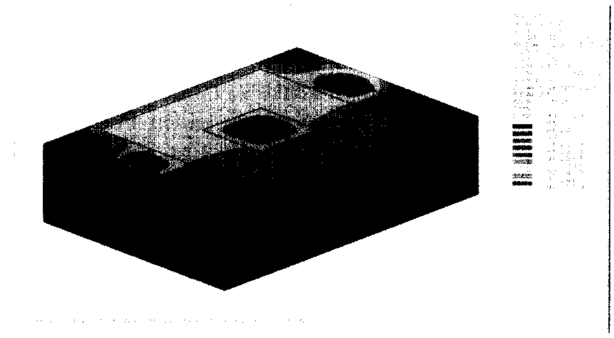


Fig. 8 Thermal analysis result for condition III

3. Summary

A high power density, high frequency, and high voltage pulse transformer is designed, fabricated, and tested. Transformer specifications are 100 kHz switching frequency, 250 Vdc input voltage, two outputs of 2 kV and 4 kV voltages, normal operation power of 3 kW, and maximum allowable volume of 400 cm^3. The minimum power density is thus 7.5 W/cm^3. The tested results show that the transformer has excellent capability. The design especially overcomes the self-resonant effects by reducing and distributing stray capacitance and leakage inductance. The design also effectively minimizes total transformer losses while increasing the power density to 21.44 W/cm^3 that is about three times higher than the required density. This transformer is designed and fabricated efficiency of 90%. This transformer is applied at high voltage power supply and total power efficiency is measured above 90%. Therefore transformer is operated design efficiency. Thermal analysis result suggests that the transformer will give best performance in operating temperature of 85 ℃, which will be the operating condition for typical applications.

Acknowledgement

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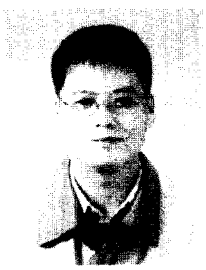

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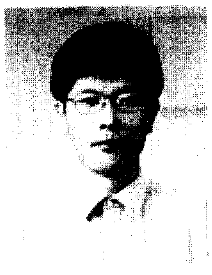

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