FIELD ANALYSIS OF TWT HVPS TRANSFORMER AND HV MODULE

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Abstract

The role of a high power density DC power supply is very important in designing a compact and high efficiency TWT microwave amplifier. In order to fabricate a compact power supply, it is necessary to reduce transformer volume by increasing switching frequency of the power supply. However, a step-up ratio of the transformer in the high voltage DC power supply could not be indefinitely increased due mainly to self-resonant by stray capacitance and leakage inductance. Therefore, the pulse transformer should be carefully designed to fulfill its function 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 allowed volume of the transformer is 400 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 that has a very low thermal conductivity. Calculated and measured results of various parameters such as transformer loss, temperature rise, leakage inductance, distributed capacitance, and hysterisis characteristics are presented. In addition, field analysis results obtained with ANSYS code for the transformer and the HV module are also presented.

I. INTRODUCTION

In high-density power supplies, transformer size 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. In this paper, we describe deign 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 average power, maximum 400 cm^3 volume, and minimum power density of 7.5 W/cm^3 [1].

II. TRANSFORMER DESIGN

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

A. 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 secondary 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. 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. Environmental specifications of the transformer are -55 ~ 85 °C 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. 1 shows the winding diagram of the pulse transformer. 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.

Table 1. Calculated parameters of the transformer

Input	Output
Vp = 253 Vdc (240.02 Vrms)	Vs1, Vs2, Vs3, Vs4 = 520Vrms (548 Vdc)
Pin (total) = 3.057kW	Pout (total) = 2.75kW
Iin (total) = 13.4Arms	Iout (total) = 4.8Arms
Turns ratio = 1	Turns ratio s1, s2, s3, s4 = 2.167

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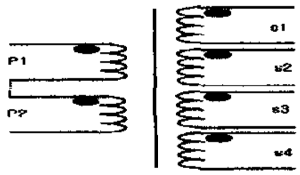

Fig. 1. Winding diagram of the high frequency, high density, and high voltage pulse transformer

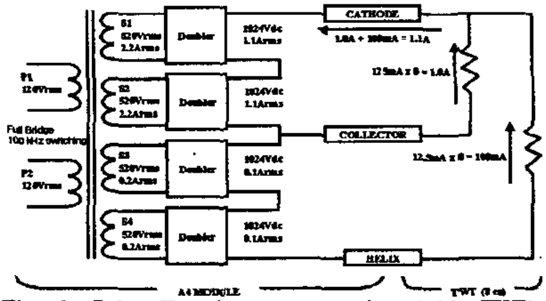

Fig. 2. Pulse Transformer connection (with TWT). Transformer primary: 100kHz, full bridge switching.

B. CORE, INSULATION, AND WIRE

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 (V_e). To have the required dielectric strength of 6 kV in the transformer, kapton film H type (breakdown strength: 275 kV/mm) 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). After considering skin depth, copper foil with 0.2 mm thickness is selected as the primary wire, and Litz wires (35 AWG x 50 and x 10) are selected for the secondary winding [1].

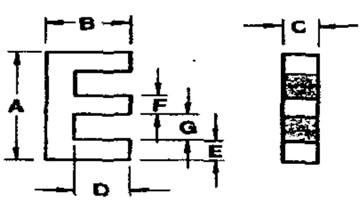

Fig. 3. R-47228EC core (mm) : A=72.4, B=27.9, C=19, D=17, E=9.53, F=19, G=16.9, transformer size = A x 2B x (C + 2G) = 213.3 cm^3_{max}.

C. WINDING ARRANGEMENT

Several different winding arrangements are fabricated to find an optimum arrangement. Fig. 4 shows the final arrangement. It only shows half of the winding arrangement. As shown in Fig. 4, 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 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. 4. Pulse transformer winding layout

D. WINDING DESIGN

With the selected core, insulation film, and wire, the transformer losses are calculated at different flux densities [2]. For the calculation, total voltage drop due to switching device is assumed as 1 V. Also considering available window area of the core, the usable flux density is obtained as higher than 1500 G. At 1500 G, the total transformer loss is about 12.4 W that includes core and winding losses [1].

Transformer temperature rise [2] without forced cooling can be calculate from

$$\Delta T = 80 \bullet A^{-0.7} \bullet P_{loss}^{0.85} \quad [°C] \qquad (1)$$

where, A : thermal radiation surface of transformer

P_{loss} : transformer loss.

Table 2 summarizes the winding design of the transformer at 1500 G flux density. Leakage inductance and stray capacitance are also calculated as shown in the table [3].

Table 2. Transformer winding design at 1500 G

Operation flux density (G)	1500	S3	26 turn, 1 layer
Total winding thickness (mm)	9.55	S1	26 turn 2 layer
Total window thickness (mm)	13.2	p	12 turn, 12 layer
Total DC resistance (Ω)	0.82	S2	26 turn, 2 layer
Core/winding loss (W)	10.6/ 1.8	S4	26 turn, 1 layer
Transformer loss (W)	12.4	ΔT	42.3 °C
Leakage inductance (μH)		0.33	
Stray capacitance (pF)		500	
Resonance frequency (MHz)		> 10	

III. MEASUREMENT

The transformer with 1500 G operation flux density is fabricated and their electrical parameters are measured. The measurement results are listed in Table 3. As listed in the table, the resonance frequency is extremely higher than the operating frequency of 100 kHz. However, the measured resonant frequency is much lower than the calculated frequency of 10 MHz as shown in Table 2. The result is due to the fabrication process where the compact packing of the transformer winding is very important. Therefore, the measured leakage inductance is increased from the calculated value, while the stray capacitance is reduced.

Table 3. Measured parameters

Operation Flux Density (1500Gauss)	Quality factor (Q) > 115
	Leakage inductance (L_L) = 2.04 μH
	Winding capacitance (C_w) = 0.277 nF
	Resonance frequency (f_o) = 4.0 MHz
	Distributed capacitance (C_d) = 3.12 pF

From Table 3, peak resonance current can be calculated by using the following equations.

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

where , $\omega_0 = \frac{1}{\sqrt{L_L C_d}}$, and L_L and C_d are the leakage inductance and stray capacitance, respectively. V_s and R_w are respectively the primary voltage and the winding resistance (5.24 Ω). The calculated peak resonance currents are 0.274 A for 1500 G. This value is sufficiently lower than the nominal operation currents and therefore do not affect the operating condition of the transformer. Temperature rise of the transformer is measured with a transformer that uses 2000 G flux density. Without forced cooling in room temperature, the core temperature rises to 85 °C, which corresponds to ΔT of 60 °C. The calculated ΔT for the 2000 G transformer is 77 °C and it agrees quite well with the measured value. The bobbin temperature rises to 90 °C. The maximum hot point temperature in the winding rises to 135 °C. By considering real normal operation condition of 85 °C, the temperature rise is also measured, and the ΔT is measured as 9 °C. We obtained same result from the ANSYS simulation [1].

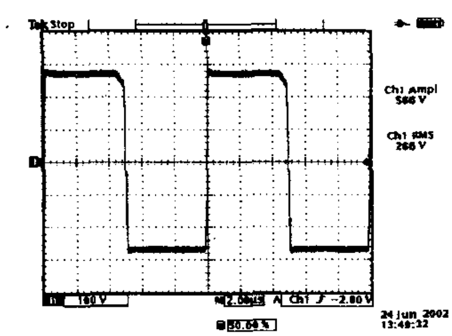

Fig. 5. Output waveform of the pulse transformer measure at S1 output (2 μs/div.).

Fig. 5 shows a typical output waveform of the pulse transformer. The waveform in Fig. 5 is measured at the S1 output. The output waveform reproduces input waveform without any significant deformation and resonance in the flat-top.

IV. FIELD ANALYSIS

Magnetic field analysis of the transformer is performed with the ANSYS software [4]. Fig. 6 shows magnetic field simulation result of the transformer. Maximum flux occurs at the center pole of the core and is about 1500 G, which is in good agreement with the calculated value. Moreover, the flux is quite uniformly distributed on the overall core volume.

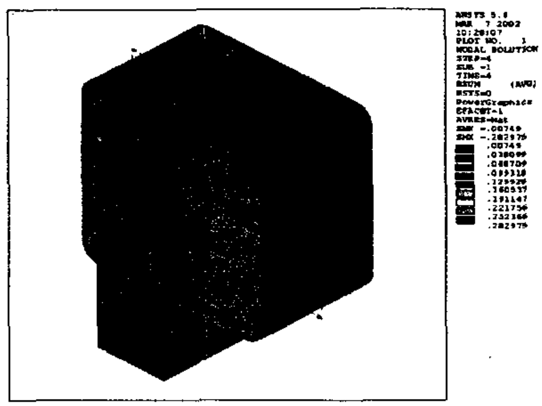

Fig. 6. Magnetic field analysis of pulse transformer

Electric field of the high voltage (HV) module is also analyzed to find any harmful field enhancement in the module. Fig. 7 shows the HV module of TWT HVPS. The HV module includes the pulse transformer, filter capacitors and rectifier diodes. Size of the module is 68 (H) x 100 (L) x 192(W) mm.

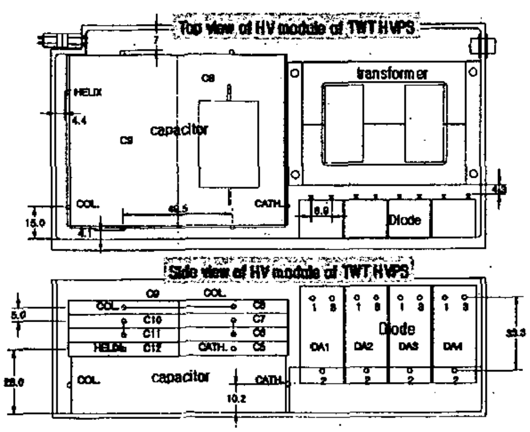

Fig. 7. HV module of TWT HVPS

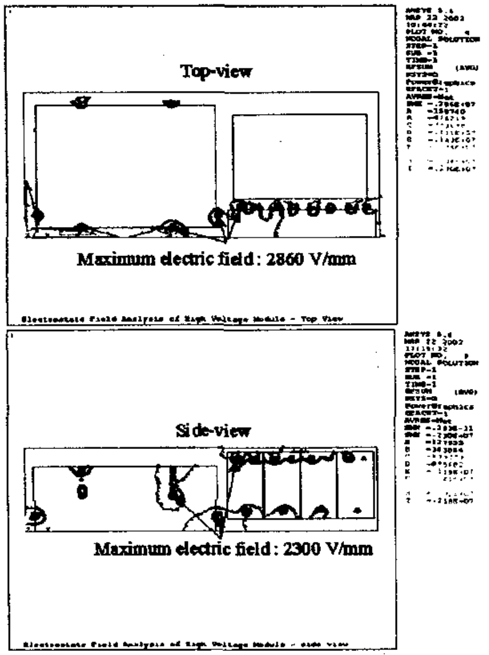

Fig. 8. Plots of electric field analysis of the HV module

Fig. 8 shows results of the electric field analysis. As indicated in the figure, maximum electric field in the module is 2.86 kV/mm. Since the HV module is molded with silicon RTV, the breakdown strength of the module is much higher than air that has 3.0 kV/mm strength. Therefore, the module could be considered safe from the analysis.

V. 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 primary input voltage, two secondary 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. Therefore, the transformer almost perfectly reproduces input waveform at the output. The design also effectively minimizes total transformer losses while increasing the power density to 14.1 W/cm^3 that is two times higher than the required density. According to the result of field analysis, simulated flux density of the transformer agrees very well with the design value. Electric field analysis of the HV module shows that the maximum field in the module is lower than breakdown strength of air that is 3 kV/mm.

VI. REFERENCS

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