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High Frequency High Voltage Generation with Air-core Transformer

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Abstract—A novel high frequency high voltage (HV) generator circuit with air-core transformer is proposed in this paper to achieve high power density packaging structure and compact size advantages. Planar multi-layer printed circuit board(PCB) winding and litz wire wound winding structure are investigated for air-core HV transformer. The electrical design of air-core HV transformer with HV multiplier circuit based on 1.2kV SiC Schottky diode are introduced. A with 450 kHz switching frequency HV generator prototype with 310W output power and 1kV output voltage is built in lab. The litz wire air-core HV transformer prototype is built to compare the efficiency, thermal performance and size with planar air-core HV transformer. The planar PCB air-core transformer based on HV generator can achieve 80.5% efficiency and 1.09kW/L power density. The litz wire wounded transformer based HV generator provide 89.0% efficiency and around 0.53kW/L power density. The design with planar PCB air-core transformer enable high voltage generation circuit system compact planar packaging. The design with litz wire air-core HV transformer behaves higher efficiency and thermal performance with low high frequency AC winding loss.

Keywords—High frequency; high voltage generator; air-core transformer; planar transformer; litz wire wounded transformer

I. Introduction

High frequency high voltage(HV) generators are widely used in applications such as capacitor charging, HV pulse generator, electrostatic precipitation, plasma generator, and other HV pulsed power generators [1-6]. The compact size is attractive in application with limited space. The power density of state-of-the-art HV generators is around 1kW/L due to limited switching frequency. High frequency operation is helpful to reduce the size and weight of high voltage transformers and passive components such as inductors and capacitors in HV generator. Increasing switching frequency can effectively achieve higher power density design for both transformer and voltage multipliers in HV generator. For the conventional HV transformer, complex insulation design between the transformer ferrite core to primary and secondary winding need to be considered. The ferrite core and HV insulation bobbin lead to bulk size. And the overall height of HV generation is quite difficult to be reduced to meet some harsh environment applications with limited space. The planar air-core multi-layer printed circuit board(PCB) winding structure is an enabler to achieve the compact structure by high frequency operation. The HV insulation between the primary and secondary PCB windings can be achieved by thin polypropylene plastic layer. Without ferrite core, the insulation requirement between the core to winding does not exist. The total thickness of HV transformer can be well controlled to make the packaging quite flat together with HV multiplier circuit with surface mounted capacitor and diode. Furthermore, litz wire air-core wounded transformer structure is also investigated to compare the efficiency and power density with planar multi-layer PCB winding design [7-11].

II. Design considerations for HV generation with air-core transformer

The key electrical parameters for the HV generator are listed in Table I.

TABLE I ELECTRICAL PARAMETERS FOR THE HV GENERATOR

Items	Values
Input voltage	48VDC
Output voltage	1kVDC
Output power	310W
Switching frequency	400~500kHz
HV generator power density	>1kW/L

The air-core transformer together with one stage positive and negative voltage multiplier circuits are used to achieve the required high output voltage. With the multiplier circuit, the secondary winding voltage of air-core transformer can be controlled to below 5kVAC for easy HV insulation design and reduced high frequency dielectric loss reduction.

Based on the input voltage and output voltage requirement of the high voltage generator, the transformer turn ratio n can be derived by (1).

$$n = N_S : N_P = \frac{V_O}{V_{IN} * D * H} \tag{1}$$

Where, D is the duty cycle of LCC resonant converter, and H is the gain of LCC resonant converter. n can be chosen as around 6. Based on the input voltage and switching frequency, the primary and secondary winding turns can be determined considering the transformer footprint and required winding

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inductance to reduce the current stress. The high coupling coefficient of the air-core transformer is requested to achieve circuit high efficiency. According to the above considerations, 8 layer 6OZ planar PCB windings are used for planar HV air-core transformer. The turns number for air-core transformer primary and secondary winding is set as 18 and 96 respectively. The secondary winding is placed between 2 primary winding to achieve good coupling coefficient with sandwich winding structure. The detailed layout of the planar air-core transformer PCB primary and secondary windings is illustrated in Fig.1. There are 6 internal layers and 2 top layers for the PCB windings. The 2 top layers provide the electric insulation between the primary and secondary winding without any solid insulation material for good coupling coefficient. The width of PCB windings can be determined to limit the PCB winding current density low than 6 A/mm^2.

The low coupling efficient for the air-core transformer is low compared with the transformer with core. Compared with the equivalent circuit model based on ideal transformer in Fig.2, the coupled inductor equivalent circuit model in Fig.3 provide more accuracy for analysis. The coupling coefficient k of the air-core transformer is defined by (2).

$$k = \frac{M}{L_p * L_s} \tag{2}$$

Where, M is the mutual inductance of the air-core transformer, L_p and L_s are primary winding inductance and primary winding inductance respectively. The parameters for planar PCB air-core transformer is provided in Table I.

TABLE I. PARAMETERS FOR PLANAR PCB AIR-CORE TRANSFORMER

L_p	L_s	M	k	C_p	C_s
10.65uH	233uH	50.39uH	0.85	3.05nF	0.14nF

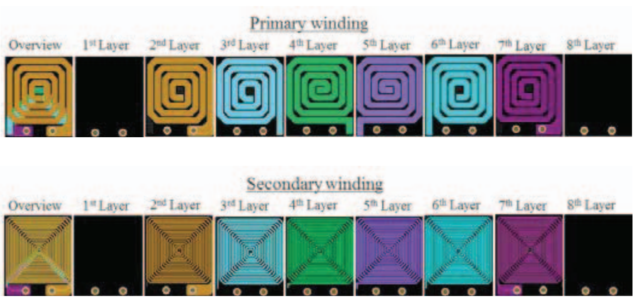


Fig. 1 Layout of the planar air-core transformer PCB primary and secondary windings

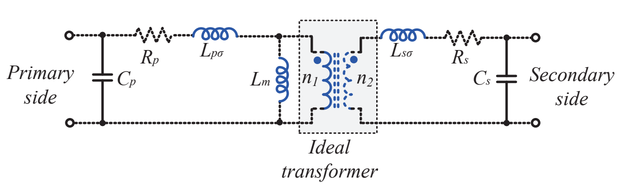


Fig. 2 Equivalent circuit model for air-core transformer based on ideal transformer

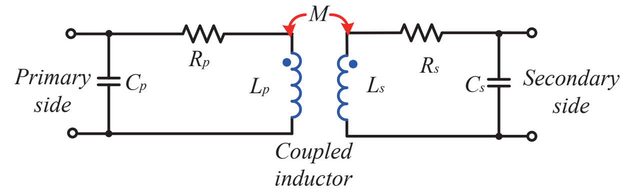


Fig. 3 Equivalent circuit model for air-core transformer based on coupled inductor

Though the planar PCB air-core transformer can achieve compact size with flat structure, the power loss is large and heat dissipation is a challenge. Lite wire wounded air-core transformer is investigated to compare the efficiency, thermal and size performance with planar PCB air-core transformer. The winding layout for the litz wired wounded air-core transformer is illustrated in Fig.4. The primary winding is composed of 3300 string litz wire with 0.03mm diameter, and the primary winding is composed of 300 string litz wire with 0.03mm diameter for the lite wire wounded air-core transformer prototype. The primary turns number is 20, and the secondary number is 125.

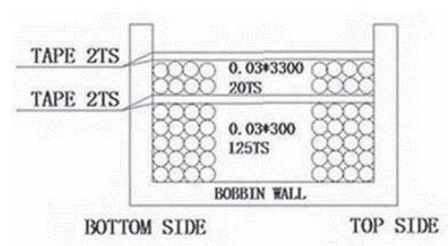


Fig. 4 Winding layout for litz wire wounded air-core transformer

TABLE II. PARAMETERS FOR LITZ WIRE WOUNDED AIR-CORE TRANSFORMER

L_p	L_s	M	k	C_p	C_s
16.24uH	508.31uH	78.03uH	0.86	17.92nF	0.58nF

III. Experimental results HV generator with aire-core transformer

A. *Prototype experimental results of HV generator with planar PCB air-core transformer*

Fig.5 shows the high frequency high voltage generation circuit prototype diagram. The input voltage is 48V DC, output rated output voltage is 1kV DC. The full power rating is around 300W. Fig.6 provides the prototype photos of planar 8 layer 6OZ PCB air-core transformer, HV multiplier circuit board and power inverter with SiC MOSFET. The HV generation circuit hardware prototype operates at 450kHz high switching frequency. The new emerging surface mounted 1.2kV SiC Schottky diodes are used for high frequency voltage multiplier circuit with low power losses. The HV multiplier capacitor is 100nF. The resonant capacitor is 65.6nF with surface mounted ceramic capacitors, and there is no additional resonant inductor by leverage the leakage inductor of the air-core transformer. Fig.7 gives the key waveforms at 1kV/310W output, for HV transformer. The thermal image photos of the PCB air-core transformer is shown in Fig.8. The maximum temperature is around 99°C at 10 minutes continuous operation without fan cooling. The highest temperature point is the interconnection vias of the primary PCB windings.

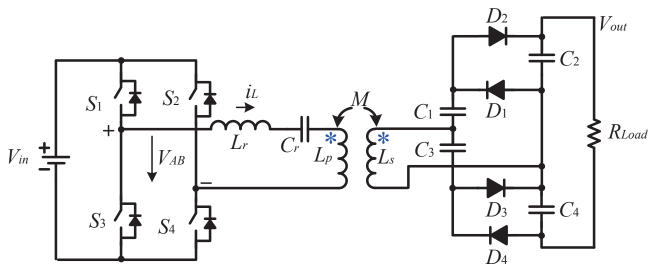


Fig. 5 High frequency high voltage generation circuit diagram

The HV generation circuit prototype can achieve 1.7kW/L power density, and 80.50% efficiency at rated 1kV output voltage and 310W full output power. Fig.9 gives the power loss breakdown chart for planar PCB air-core transformer HV generation circuit. The transformer primary winding loss dominates the total power loss. The ratio between AC and DC resistance is calculated by (3)

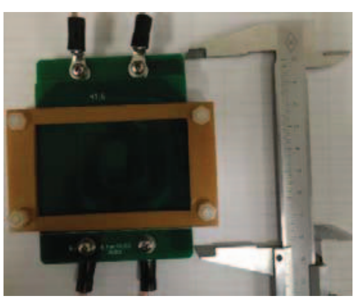
$$\frac{R_{AC}}{R_{DC}} = \Delta\left(\frac{\sinh(2\Delta)+\sin(2\Delta)}{\cosh(2\Delta)-\cos(2\Delta)} + \frac{2(n^2-1)}{3}\frac{\sinh(\Delta)-\sin(\Delta)}{\cosh(\Delta)+\cos(\Delta)}\right) \tag{3}$$

Where,

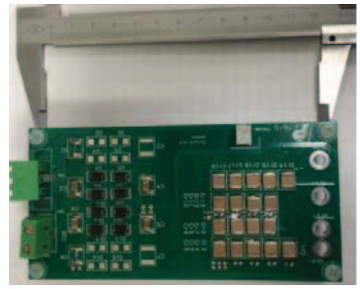
$$\Delta = h\sqrt{\frac{\omega\mu}{2\rho}} \tag{4}$$

ω is angular velocity, μ is magnetic permeability, ρ is electronic conductivity. h is height of conductor. The ratio between AC and DC resistance is calculated by:

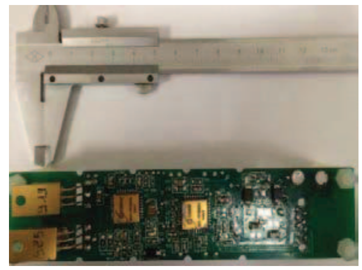
$$\frac{R_{AC}}{R_{DC}} = 18.45 \tag{5}$$



(a) Prototype photos of planar PCB air-core transformer



(b) Prototype photos of voltage multiplier circuit



(C) Prototype photos of high frequency power inverter

Fig. 6 Prototype photos of high frequency high voltage generator with planar PCB air-core transformer

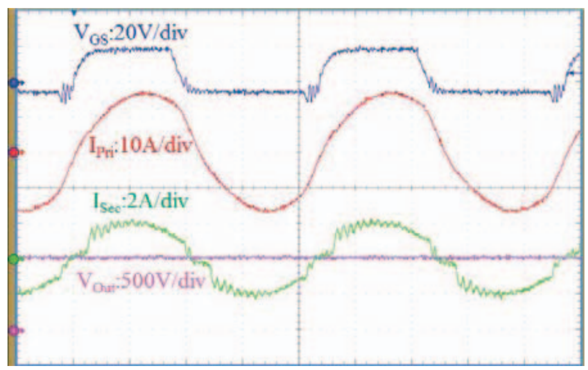


Fig. 7 Key waveforms at 1kV/310W output for planar PCB air-core transformer

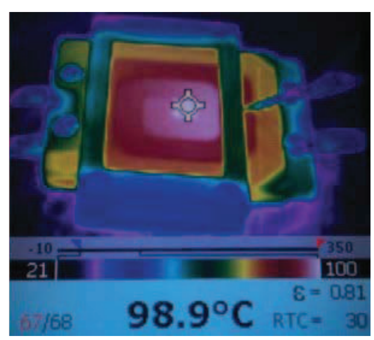


Fig. 8 Thermal image photos for planar PCB air-core HV transformer

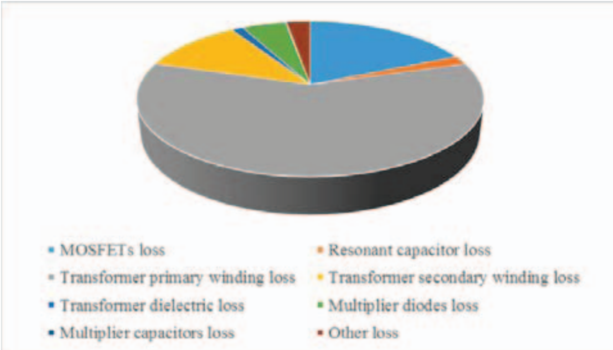


Fig. 9 Power loss analysis for planar PCB air-core transformer based HV generator

B. *Prototype experimental results of HV generator with litz wire wounded air-core transformer*

The hardware prototype of HV generator with litz wire wounded air-core transformer in Fig.10 is built to investigate the efficiency, power density and thermal performance. The measure efficiency for litz wire wounded air-core transformer based HV generator at rated 1kV output voltage and 310W full power is 89.0%, which is 8.5% higher than the design of planar PCB air-core transformer. The experimental waveforms at 1kV/310W output for litz wire wounded air-core transformer based on HV generator are shown in Fig.11. Compared with the experimental waveforms of the design of planar PCB air-core transformer, there are more ringing in the primary winding and secondary winding currents due to the large inter-winding capacitance.

The thermal image photos for litz wire wounded air-core transformer at 1kV/310W output are given in Fig.12. The maximum temperature for litz wire wounded air-core transformer is 96^{o}C at one-hour continuous operation without fan cooling. Smaller wire diameter for the litz wire wounded air-core transformer will help achieve smaller winding resistance at high switching frequency, higher efficiency and lower temperature rise.

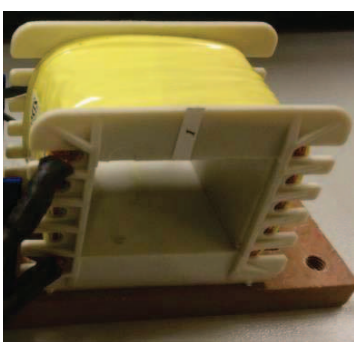


Fig. 10 Prototype photos of litz wire wounded air-core transformer

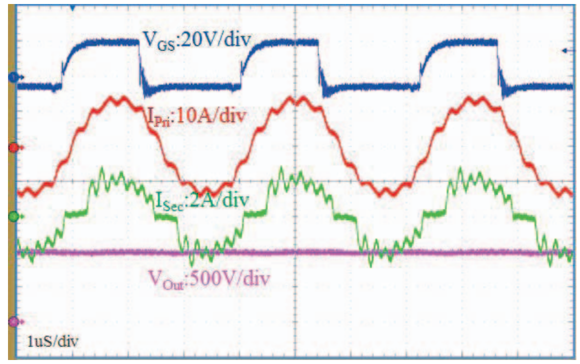


Fig. 11 Experimental waveforms at 1kV/310W output for litz wire wounded air-core transformer based on HV generator

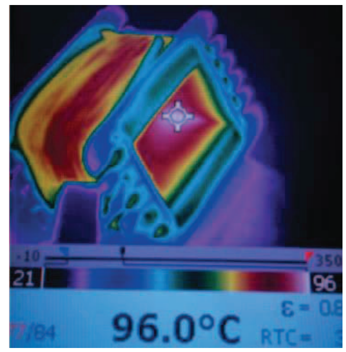


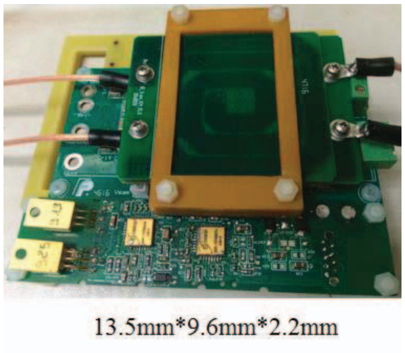
Fig. 12 Thermal image photos for litz wire wounded air-core transformer

IV. Discussions

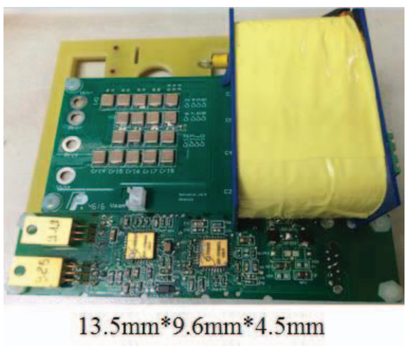
The prototype photos for HV generator with planar PCB air-core transformer and litz wire wounded air-core transformer are shown in Fig13. The power density for planar PCB air-core transformer and litz wire wounded air-core transformer based on HV generator is 1.09kW/L and 0.53 kW/L respectively. From the power density viewpoints, the planar PCB air-core transformer outperform than litz wire wounded air-core transformer due to low height of planar PCB winding structure.

The maximum temperature for litz wire wounded air-core transformer is 96^{o}C at one-hour continuous operation without fan cooling. The maximum temperature for planar PCB air-core transformer is around 99^{o}C at 10 minutes continuous operation without fan cooling. The thermal performance litz wire wounded air-core transformer is much better than planar PCB air-core transformer. Natural cooling without fan is possible for litz wire HV Transformer.

Advanced packaging is required for planar PCB air-core transformer to operate without fan cooling by using high thermal conductivity multilayer PCB materials and thermal management methods to dissipate the PCB winding heat from inner layer to environment. From thickness and size considerations viewpoints, planar PCB air-core transformer outperform than litz wire wounded air-core transformer. The design of planar PCB air-core transformer enable high voltage generation circuit system compact packaging.



(a) HV generator with planar PCB air-core transformer



(b) HV generator with litz wire wounded air-core transformer

Fig. 13 Prototype photos for HV generator with planar PCB air-core transformer and litz wire wounded air-core transformer

V. SUMMARY AND FINAL REMARK

This paper investigates the 450kHz high frequency 300W 1kV output HV generator with planar PCB air-core transformer and litz wire wounded air-core transformer. The design considerations and hardware prototype experimental results are introduced in details. The PCB air-core transformer enable high voltage generation circuit system compact planar packaging with high power density above 1kW/L due to low height of planar PCB winding structure. Advanced packaging technique is required for planar PCB air-core transformer to operate without fan cooling by using high thermal conductivity multilayer PCB materials and thermal management methods to dissipate the PCB winding heat from inner layer to environment. The litz wire air-core HV transformer behaves higher efficiency close to 90% and good thermal performance with low high frequency AC winding loss. Natural cooling without fan is possible for litz wire wounded air-core HV Transformer at continuous power operation.

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