A Novel Transformer Structure for High power, High Frequency converter

Chao Yan, Fan Li, Jianhong Zeng, Teng Liu, Jianping Ying
Delta Power Electronics Center
238 Minxia Road, Caolu Industry Zone, Pudong, Shanghai, 201209, China
Tel: 86-021-68723988, Fax: 86-021-68723996, Email: yan.chao@deltaww.com.cn

***Abstract* – Power transformer structure is a key factor for the high power, high frequency converter performance which includes efficiency, thermal performance and power density. This paper proposes a novel transformer structure for the kilo-watt level, high frequency converter which is reinforce insulation needed for the secondary side to primary side. The transformer has spiral–wound primary layers using TIW (triple insulation wire) and PCB-winding secondary layers. All the windings are arranged by full interleaving structure to minimize the leakage inductance and eddy current loss. Further more, the secondary rectifiers and filter capacitors are mounted in PCB-winding secondary layers to further minimize the termination effect. A 1.2KW (O/P: 12V/100A, I/P: 400V) Mega Hz LLC converter prototype employed the proposed transformer structure is constructed, and over 96% efficiency achieved.**

***Keywords:* interleaving structure, PCB-winding, termination effect, LLC converter**

I. INTRODUCTION

Recent years, the front end power supply such as telecom, server and networking power supply has an obvious trend toward high power density, high efficiency. To increase the power density of the power supply, pushing the switching frequency is a good way to reduce the size of passive components which includes the EMI filter, power transformer, output filter inductor and capacitor, etc. The impact of higher switching frequency contains worse switching loss, higher magnetic AC winding loss due to the worse skin effect and proximity effect [1,2,3]. To reduce the switching loss, selecting a suitable soft switching topology for example LLC converter can minimize the switching loss. Then for a high frequency, high efficiency converter, the remained problem is the power transformer design since it takes large part of the total magnetic related loss. Planar transformers have many advantages compared with conventional wired transformer and are widely used in D2D board mounted power (BMP) module [4]. But unfortunately, this multi-layer PCB based winding plus planar core structured transformer is not suitable for front end power supply application since multi-layer PCB can only meet basic insulation between the primary side to secondary side and actually reinforce insulation needed for the front end power supply due to the safety consideration [5].

Thus, the transformer design is a very critical thing for such high power, high efficiency front end power supply application. For the high frequency application, the following factor should be considered: AC winding loss, termination loss, leakage inductance. This paper proposed a novel transformer structure to minimize the AC winding loss, termination loss and leakage inductance and a practical transformer example designs for 1.2KW LLC series resonant converter are detail described in this paper.

II. THE PROPOSED NOVEL HIGH FREQUENCY TRANSFORMER STRUCTURE CONSIDERATION

This section describes the proposed novel high frequency transformer structure considerations in detail. The considerations are interleaving windings, termination configurations and integration technique.

a) Interleaving winding to minimize AC winding Losses

For conventional wired transformer, its primary and secondary windings arrange by sandwiched style for the most of the application. It has the benefit of relative low AC winding loss and easy manufacture of transformer (only two layers reinforce insulation tape needed between the interface of primary and secondary winding). However, for the high frequency and multilayer transformer application, the sandwiched structure still has the large AC winding loss, and the interleaving winding structure is proposed here. The following words explain the details.

Amperes' law governs the relationship between a current in a conductor and the corresponding magnetic field. Assume the flux density is uniform in a direction parallel to the axis of the windings from one end of the windings to the other. Ampere's law becomes

$$F = H \cdot l = N \cdot I \qquad (1)$$

The MMF (Magneto-Motive Force) of x-axis direction of the sandwiched structures is showed in Figure.1 (a). The high MMF means more AC winding losses. The energy density in the field goes up with the square of the field

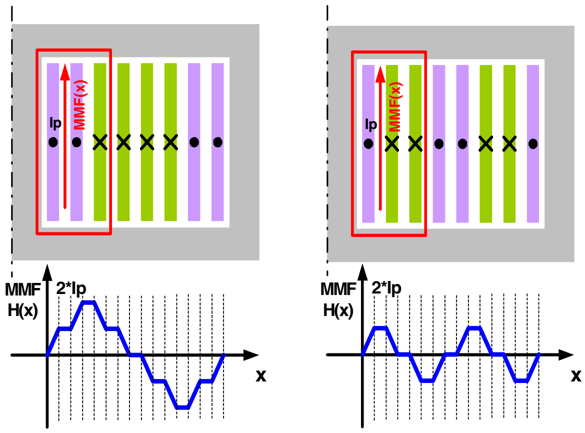


Figure 1: The MMF distributions in two transformers' structure

(a) Sandwiched structure (b) Interleaved structure

strength, as the MMF diagram. At high frequency cases, it will be known that the eddy current losses go up exponentially as the number of the increasing layers. The higher MMF causes higher transformer winding losses.

One solution to reduce the effective number of layers is to break up the winding into smaller sections by interleaving technique, as shown in Figure.3 (b). It obviously reduces the MMF, so has less winding losses.

b) Proper termination configuration to reduce losses

For the high frequency application, the termination loss is not neglectable for the total transformer winding loss. Improper termination configuration brings significant termination loss especially in high frequency, high power application. Fig.2 shows the power transformer center taped secondary winding structure and one termination configuration. The secondary winding of the transformer supposed to be one turn and a two layer PCB to make of this secondary winding. The Fig 2 right graph of the termination configuration, which is side by side configuration of the two wide trace terminations, actually is the worst case from the loss point of view. Because the S1.

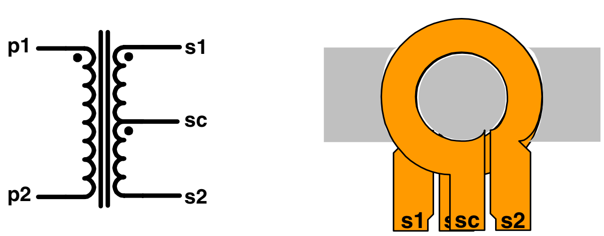


Figure 2: Center taped secondary winding structure and a termination configuration

and SC or S2 and SC terminations has the opposite direction current, considering the high frequency proximity effect, this configuration results in current flow only at the edges facing each other and so the AC winding loss is large.

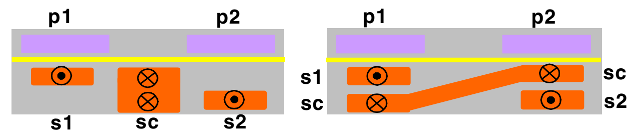


Figure 3: Cross section view of the two termination configuration

Fig. 3 shows the cross section view of the two termination configurations. The right configuration is much better than the left one because the right one have the much even current density distribution and minimize the AC termination loss. This configuration actually is the best way to implement high frequency wirings under the two layer PCB limitation. The two SC terminations can be connected by some via through the top layer and bottom layer on a two layers PCB board.

c) Integration technique to minimize the leakage inductance and termination loss

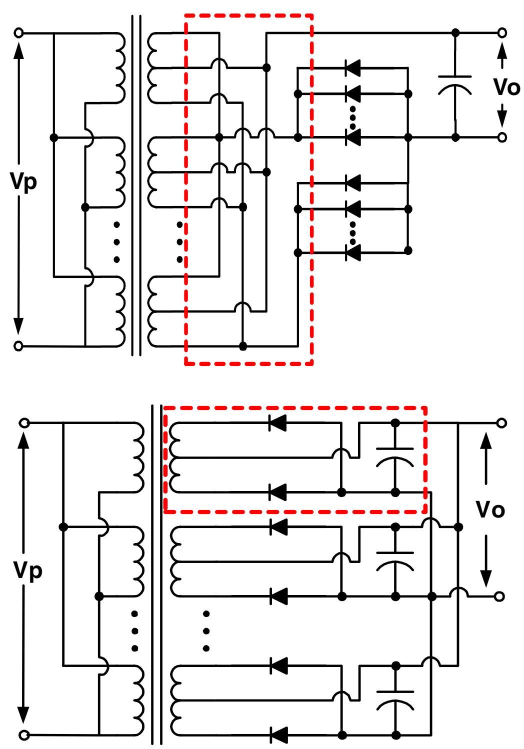


Figure 4: Two power transformer structure model

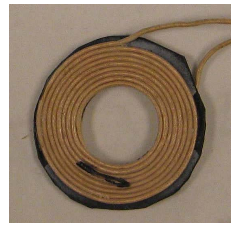
At most of cases, multi-layers of secondary winding in parallel are needed for the specified high power output applications. So the parallel method of secondary winding is a problem. Figure 4 shows the two kind of power transformer structure model which indicated two parallel methods of secondary windings. The first parallel method directly interconnects the secondary windings and the connected terminations then are followed by the rectifiers. This parallel method increases the equivalent terminations length due to the increased interconnection wires and hence increases the effective leakage inductance of the transformer presented at the circuit. Also, the increased terminations length introduces additional AC losses.

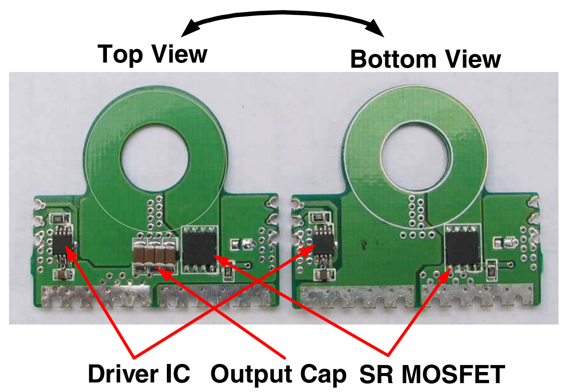
The secondary parallel method parallels the secondary windings at DC output voltage side, this method avoid the suffering of additional AC losses. The rectifiers and the filter capacitors are directly integrated into the secondary winding PCBs. This kind of parallel method obviously minimizes the leakage inductance of transformer actually presented in the circuit. The decreased leakage inductance eliminates much additional voltage stress, which may enable the circuit designer to select the lower voltage rating rectifiers and also optimized the EMC design. Also, the termination loss is minimized.

III. The Proposed Transformer Structure

The figure 5 shows the practical primary windings and secondary windings. The primary winding is a spiral–wound coil with the triple insulation wire which has pass the safety standard to ensure the reinforce insulation between the primary side and secondary side of the transformer. This kind of triple insulation wire has the self-stick characteristics to facilitate the fabrication of the spiral-wound coil. And also this spiral wound coil enables the even current density distribution of the secondary PCB winding at radius direction. The secondary windings make up of the two layers PCB. To minimize the termination loss and leakage inductance of transformer practically presented in the circuit, the rectifiers and filter capacitors are integrated inside the two layers PCB, and the optimized termination configurations are also introduced in the secondary side winding designs. The edge side of the secondary winding shows in Fig. 5(b) is the solder pads for the interconnection of all the paralleling secondary windings. Because the interconnection wires of these PCB secondary windings only carry the DC current, the conduction loss of these interconnection wires could be small.

Figure 6 shows the proposed transformer assembling process, the primary winding and secondary winding are configured at interleaving style. All the transformer windings have eight pieces. Every piece has two primary coils connected in series outside the transformer and a two layers PCB made secondary winding. Inside the every piece, the winding arranges at sandwich style. All these eight pieces are connected in parallel as Figure 6 shown.





(a) Primary winding spiral coil with TIW (b) secondary PCB winding integrate rectifiers and filter capacitor inside

Figure 5: The primary windings and secondary PCB winding

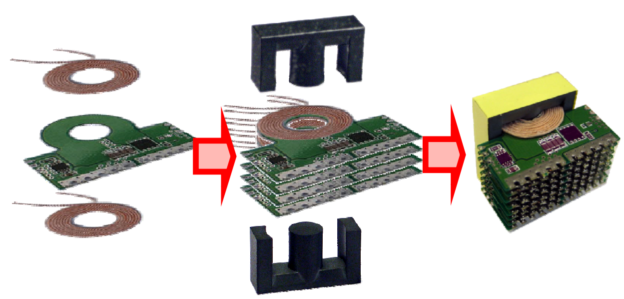


Figure 6: The proposed transformer assembling methods

IV. Experimental Measurements

To validate the above-mentioned consideration and the proposed high frequency, high power transformer with front end power supply application, the experimental prototype is a 1.2kW HB (Half Bridge) LLC-SRC with synchronous rectifier technology shown in Fig. 7. The purpose of the experiment is to measure actual effect using this novel structure in such case. The LLC-SRC main parameters and components are listed in the table 1.

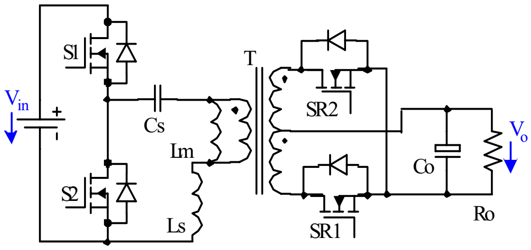


Figure 7: half bridge LLC DC/DC converter

TABLE 1 THE PARAMETERS OF EXPERIMENT

Design parameter /component	Parameter value
Transformer core	ETD29, 3F4 material
Resonant inductance	1.4uH
Resonant capacitance	16.6nF
Magnetizing inductance	12uH
Turns Ratio	18:1:1
Resonant frequency	1MegHz
Primary MOSFET	STW26NM50*2
Secondary Rectifier	TPCA8004*16
Output Capacitor	570uF
Input voltage	390Vdc
Output voltage	12Vdc

TABLE 2 THE 1.2KW LLC CONVERTER LOSS BREAKDOWN

Items	Loss (W)
Primary MOS conduction	7.8
Primary MOS switching	13.04
Secondary MOS conduction	8.13
Secondary MOS switching	4.6
Transformer Core	1.72
Transformer primary winding	0.53
Transformer secondary winding	9.02
Resonant inductor core	1.31
Resonant inductor winding	4.18

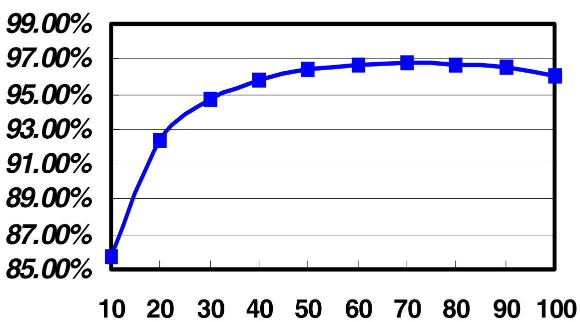


Figure 8: The DC/DC converter efficiency vs. output current

The resonant frequency of Cs and Ls is one Mega Hz and the output voltage 12V and the maximum output current is 100A. The rated output power is 1.2KW. The transformer primary to secondary turns ratio is 18:1:1, and the primary winding are two 9-turn spiral-wound coils in series and secondary winding is a 1-turn PCB windings. Table 2 shows the calculated 1.2KW LLC converter loss breakdown at full load. The total power transformer loss is 11.3W, and which accounts for about 0.9% of the total input power 1250W. The calculated efficiency at 1.2KW full load is around 96.0%.

Figure 8 shows the experimental converter efficiency versus the output current, it can be seen the DC/DC efficiency is over 96% from the 50% to 100% output load. The experimental efficiency result is well agreed with the calculated efficiency. And this efficiency is very high efficiency for the Mega HZ switching frequency converter compared with the industry state of art. The experimental DC/DC converter is actually the D2D stage of a 1.2KW AC/DC Server power supply. Using this mega HZ DC/DC converter, the whole AC/DC power supply achieve the nearly 30W/inch^3 power density with high line AC voltage input (175~264Vac).

V. CONCLUSIONS

In this paper a novel transformer structure for high frequency, high power application is proposed. The two main characteristics of this transformer structure are: the full interleaving structure of the transformer primary and secondary winding and the winding, rectifier integration technique. The advantages of this structure are:

1. Interleaving structure dramatically reduced the transformer's AC winding losses.
2. Secondary side integration technique reduced the termination losses and the parasitic parameters' influence.
3. The structure can be used in high frequency, high power front end case where reinforce insulation needed.

A 1.2KW (O/P: 12V/100A, I/P: 400V) Mega Hz LLC converter prototype employed the proposed transformer structure is constructed, and over 96% efficiency achieved.

REFERENCES

[1] Lloyd H. Dixon, "Eddy current losses in transformer windings and circuit wiring," TI 2001 Magnetic Design Handbook - MAG100A.

[2] N.Dai and F.C.Lee "Edge effects in high frequency transformer windings" Power Electronics Specialist Conference (PESC) 1994

[3] R.Prieto etc, "Taking into account all the parasitic effects in the design of magnetic components", APEC 1998.

[4] Glenn Skutt, Fred C. Lee, Ray Ridley and Dale Nicol, "Leakage inductance and termination effects in a high-power planar magnetic structure," Proc.9th Annual IEEE Applied Power Electronics Conference and Exposition, vol. 1,pp.295-301,1994.
[5] UL60950, "Safety of information technology equipment", Third edition