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Applicated on a loss of hybrid transformer winding for multi-output high frequency (300W) LLC resonance converters

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Abstract: With a growing concern over environmental issues, smaller and more energy efficient electronic devices continue to draw attention. Usually, high frequency has more advantages in making switching power smaller. A number of suppliers have already launched single-output power (single or double-digit W) which can be operated in high frequency (higher than 500kHz.) Despite increasing demand for multi-output high-capacity power, it is not easy to operate this power in high frequency. Reducing the loss of both switching components and transformer winding holds great significance in high frequency operation. This abstract is written to suggest a new transformer structure for multi-output (300W) high-frequency (500kHz) operation as well as present mathematical analysis and test results on the loss of transformer winding operated in high frequency. This suggestion can lead to approximately 40% of transformer size reduction compared to the existing one operated in 100kHz

Keywords: High frequency; Hybrid transformer; Multi-output; LLC resonance converter

I. INTRODUCTION

LLC resonance converters which have high efficiency and low noise are being widely used in telecommunications power sources, game consoles, FPD panel and etc. Consequently, a growing number of people show interests in this field of research. It is a known fact that magnetic components can be made smaller by increasing switching frequency. This increase, however, may damage switching components, switching, magnetic component core, winding and eventually the entire power system.

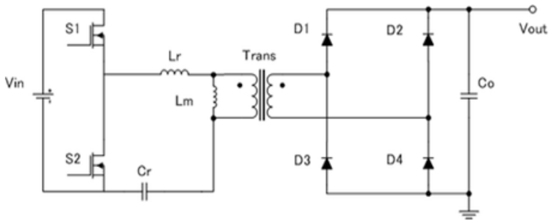
Figure 1 shows the most common circuit structure of LLC resonance converter. LLC resonance converters have half-bridge switching circuit on the primary side and synchronous rectifier circuit on the secondary one, which can be better applied to high-capacitance and multi-output power.

II. CIRCUIT AND TRANSFORMER STRUCTURE

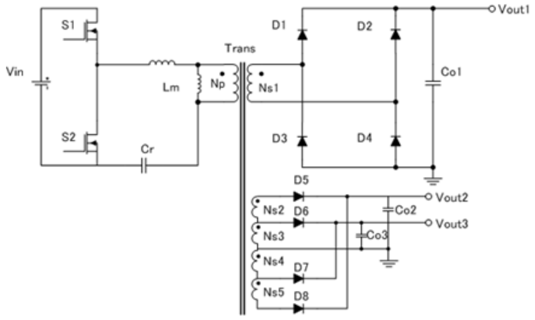
Following two factors need to be taken into account for the purpose of making smaller power and achieving higher power density. First, we need to choose a circuit which can better achieve high efficiency. Second, power flow continuation is critical to increasing conversion efficiency. In theory, input power can be continuously supplied and power conversion efficiency is the highest when main switch duty is close to 100%. PWM control, however, can not reach 100% of switch duty.

On the other hand, bridge resonant converters can have mutual switching operation when the duty of both high and low side switch is 50%. Out of bridge resonant converters, parallel resonant converter can better realize power flow continuation. Main part of the circuit is operated by sine waves depending on the effect of resonant circuit, which can minimize the impact of high frequency going into switching components and transformer Figure 2 shows a block diagram of the AC adapter power supply. It is separated by an isolation power transformer.

Specifications:
Intput voltage: 380V
Total output power: 315W
Output power1: 147W(70V/2.1A)
Output power2: 12.8W(25.6V/0.5A)
Output power3: 153.6W(12.8V/12A)
Max temperature: 75℃



(a)Single-output type



(b) Multi-output type.

Figure.1. LLC resonance converter circuit.

In desigining LLC resonance converter, the turns ratio of a transformer is defined based on the equation (1).

$$\frac{Np}{Ns} = \frac{Vin}{2*k*(V_O+V_f)} \qquad (1)$$

K: The coupling coefficient of transformer
Vf: Voltage drop in secondary synchronous rectifier diode
Np, Ns: Transformer winding

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The common value of K (which refers to the transformer's coupling coefficient) is 0.95 to 0.98. With K at 0.95 and Vr at 0.7V, the turn ratio of transformer is as follows(2).

$$Np:Ns1=3:1, Np:Ns2,5=15:1, Np:Ns3,4=8:1 \quad (2)$$

The magnetic flux density and the size of transformer core are defined based on equation (3) and (4).

$$I_{pmax} = \frac{V_o * n}{4 * k * L_p * F_s} \quad (3)$$

$$B_m = \frac{L_p * I_{pmax}}{N_p * A_e} \quad (4)$$

Bm: The magnetic flux density of transformer
Lp: Primary inductance
Fs: Converter switching frequency
Ipmax: Primary's resonance current peak point
Ae: Transformer core's cross section

As seen in equation (3) and (4), transformer's Bm goes into reverse with converter's switching frequency. Therefore, there are two following ways to reduce transformer's size.

Hold transformer core's Bm primary turn ratio. With higher switching frequency, transformer's Bm value will fall, which can lead to smaller transformer core.

Hold the Bm value and cross section of transformer core. Lowering the primary's turn ratio can reduce the entire size of transformer.
Meanwhile, Steinmetz equation in equation (5) shows that core loss is proportional to the power of x in operating frequency[6-9]. Therefore, the Bm value needs to set lower for high frequency transformer, than for low frequency transformer.

$$\begin{aligned} P_v &= P_h + P_c + P_e \\ &= C_{dc} K_h f B_{\max}^2 + K_c f^2 B_{\max}^2 + K_e \left(f B_{\max} \right)^{1.5} \end{aligned}$$

$$P_v = C_m f^x B_{\max}^y \quad (5)$$

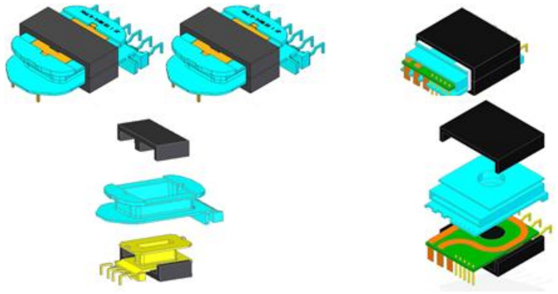
Ph: Hysteresis loss
Pc: Eddy Current loss
Pe: Residual magnetism loss
Kh: Hysteresis loss factor
Kc: Eddy Current loss factor
Ke: Residual magnetism loss factor
Cm,x,y: Characterization factors

Figure 2 describes the structure of transformer for resonant converter[1-5]. In Figure 2, (a) shows a transformer whose operating frequency is 100kHz. Because of its large power capacity, using one transformer should increase core size, which makes it difficult to form cores. In addition, secondary current (12A) reduces the winding loss, which makes Litz type winding (φ0.1 x 240) a proper winding type. Two transformers are connected together in parallel. In Figure 2, (a) is a transformer consisting of two bobbins with one bobbin coiled with primary winding (Np) and the other one with secondary winding (Ns1-5.)
In Figure 2, (b) is a proposal type transformer[10-12]. The switching frequency of a proposal type transformer is five times larger than the transformer (a). Hence, we can reduce the entire transformer size by lowering primary winding counts. Meanwhile, for a transformer that is operated in high frequency, we need to lower the turn ratio in order to curb the winding loss. Set output 2 (12A) as the benchmark for the turn ratio and calculate other turn ratios based on equation (1).

Copper has a high level of heat radiation. Therefore, we used copper plates for large current capacity winding. Meanwhile, for low current capacity winding, we used MLB. Moreover, primary and secondary windings need to be sandwiched each other in order to contain the impact of leaked magnetic flux. Two holes are made in both sides of bobbins to make insulated sections at the centre, in which primary winding, secondary copper plate and MLB are seated. This structure allows for loss reduction of both transformer leakage inductance and winding. Table 1 shows the parameters of two transformers that are operated in 100kHz and 500kHz.

Table 1. Data for transformer design

The number of transformers used	Two transformers in parallel	One transformer
Switching frequency	100kHz	500kHz
Core cross section	60mm^2	120mm^2
Core dimension	34:10:2:1	17:5:1:1
Turn ratio	400uH	65uH
Primary inductance	80uH	3uH
Leakage inductance	100kHz	500kHz



(a) Operating frequency:100kHz
(b) Operating frequency:500kHz

Figure 2. Structure of transformer for resonant converter

III. ANALYSIS OF THE TRANSFORMER WITH HYBRID INSULATED STRUCTURE

In the previous section, we have discussed the parameters and transformer structure for operation in high frequency. There are two factors that affect the winding loss of transformers. First, the increase in switching frequency affects transformer's winding loss. Second, the current density distribution in copper wires is related to transformer's winding loss. Most transformers are wound with multiple copper wires, not a single wire. The current distribution inside of copper wire is largely affected by the arrangement of copper wires and the direction of electric current flowing through metal. Thus, designing the current distribution of copper wires is of great importance. When

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it comes to high frequency transformer, the winding loss is largely caused by skin and proximity effects, rather than DC loss that is associated with winding. Figure 3 shows the copper wire's skin depth variation with frequency. With switching frequency of 100kHz, δskin is 206um. With switching frequency of 500kHz, δskin is 3.5um.

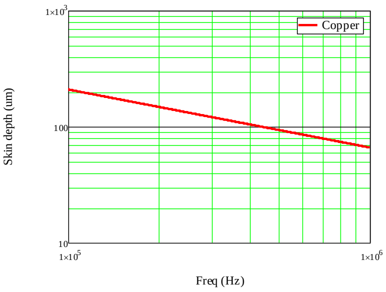

Figure 3. Copper wire's skin depth variation with frequency

We have used Dewell's equation in (6) to calculate winding's Rac/Rdc and AC loss. However, the winding structure of other output transformers are much more complicated, so that it was hard to reach the answer, using that equation. Therefore, the new approaches that we came up with was to use three-dimensional magnetic field analysis simulation in order to analyze winding loss.

$$\frac{Rac}{Rdc} = AA(\varphi) + \frac{p_e^2 - 1}{3} BB(\varphi)$$

$$\mathrm{AA}(\varphi) = \varphi \frac{\sinh(2\varphi) + \sin(2\varphi)}{\cosh(2\varphi) - \cos(2\varphi)}$$

$$BB(\varphi) = 2\varphi \frac{\sinh(\varphi) - \sin(\varphi)}{\cosh(\varphi) + \cos(\varphi)}$$

$$\varphi: \mathrm{h}/\delta_{\mathrm{skin}}$$

$$p_e = \sqrt{k} * p \qquad (6)$$

p:Number of layer in a portion; δ:Skin depth

For better design of transformer winding structures, MMF diagram has been used to analyze the current density (J) and magnetic field intensity (H) of interleaved and non-interleaved types. The result is shown in Figure 4. A conventional type in (a) of Figure 4 is about two layers of primary winding and secondary winding to the right. As a result, as increasing amount of eddy current flows along with P and S sides, increasing the current density of P and S windings and eventually causing the winding loss. On the other hand, the interleaved type (b) demonstrates primary winding situated outside and secondary winding between P and P. Accordingly, different current direction of S and P causes reverse magnetic flux, which, in turn, offsets the growth of current density that was seen in the conventional type. Based on this observation, we have used three-dimensional magnetic field analysis simulation to analyze the current density of winding. As a result, we found that the current density was reduced in the interleaved type, compared to the conventional type.

Figure 6 is our new transformer winding structure, in which the whole three bobbins are coiled with primary winding (Np), the middle bobbin with PCB winding (Ns1-3) and copper winding (Ns4-5). Table 2 shows the result of leakage inductance for this transformer type. As seen, the leakage inductance level can be kept to minimum in the interleaved type.

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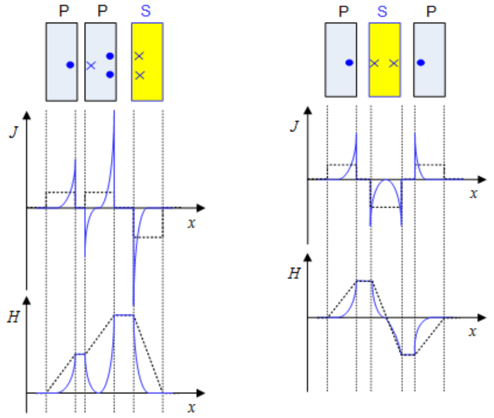
Figure 7 shows the transformer samples used in real experiments, resonance current wave form and temperature. Transformer's maximum temperature was 72°C under the following conditions - operating frequency at 500kHz, output power at 300W and natural cooling of 25°C.



(a) Conventional type (b) Interleaved type

Figure 4. MMF diagram analysis

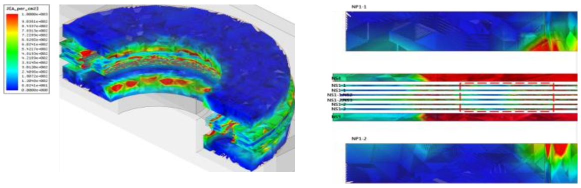


Figure 5. Analysis of current density in transformer winding cross section

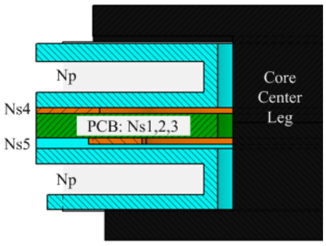


Figure 6. Transformer winding structure

Table 2. Transformer leakage inductance matrix

All shourt Leakage [uH}						
	NP1	NS1	NS2	NS3	NS4	NS5
NP1	**2.41034**					
NS1		0.070897				
NS2			0.038983			
NS3				0.039966		
NS4					0.004027	
NS5						0.004077

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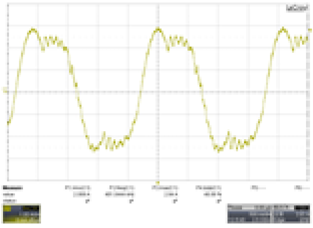
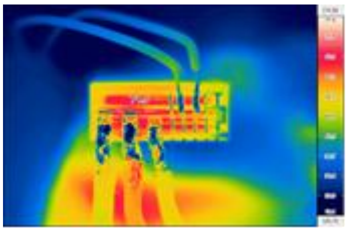
(a)Transformer sample



(b)Resonance current wave forme



(c) Temperature test

Figure 7. Test result (input voltage: 380Vdc, output power: 300W and frequency: 500kHz)

IV. CONCLUSION

This abstract is to make a suggestion on a new transformer for LLC resonant converter operated in high-frequency. A maximum 30% of size reduction, in comparison with the ordinary transformer (100kHz), was realized with switch frequency set in 500kHz. This tranformer with a new structure for multi-output was proven to minimize the winding loss, which in turn managed to reduce the loss of transformer and curb the temperature rise. Magnetic field analysis and tests have been conducted as a final step to finally confirm the design method of transformer in high frequency.

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BIOGRAPHIES

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Ge Li received the B.S. degree in electronics in 1994 from Shenyang Technical University, Shenyang, China, and the M.E. and Dr. Eng. Degrees form Kyushu University, Fukuoka, Japan in 2001 and 2004 respectively.

He was engaged in the development of switching power supplies and their noise analysis from 2004 to 2009 at the power system business Grp, TDK Corporation, Chiba, Japan. He then worked on development for magnetic component for switching power supplies in the Digital module Division of Samsung Electro-Mechanics Co., Suwon, Korea.