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Research paper

Loss Analysis of High Frequency Transformers on a 3kW-Class DC-DC Converter using the Co-Simulation of Circuit and electromagnetic field analysis

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Abstract

Background/Objectives: This study examined the loss analysis of a high frequency transformer using the thermal-electromagnetic coupled 3D-FEA considering practical converter circuit to improve the more accurate temperature analysis.
Methods/Statistical analysis: The circuit used is a 3kW-class DC-DC converter. The circuit used was a 3kW-class DC-DC converter. FEA was used to analyze the electromagnetic field. The FEA modeling is based on the practical converter circuit and the measured current waveform.
Findings: Thermal-electromagnetic coupled analysis was carried out to compare the results of the experiment and FEA models. The transformer flux density and thermal analysis of the stationary state was less than 0.38[T] and 35 [℃].
Improvements/Applications: Most thermal studies for high frequency transformers are analytical and thermal equivalent circuit models. Therefore, thermal-electromagnetic coupled 3D-finite element analysis (FEA) considering the practical frequency excitations is required.

Keywords: *converter, co-simulation, FEA, High frequency transformer, loss analysis.*

1. Introduction

Since the invention of the transformer, thermal problems have always been a problem in their design and use at increasingly high frequencies [1].Accordingly, many studies have assessed methods of reducing the temperature through a cooling system or through a design method considering the temperature increase [2]. The design and maintenance of the transformer will change the life of the transformer [3]. In addition, several large power transformers built during the 60s and 70s are considered to be close to the end of their design life [4]. Therefore, it is necessary to develop an accurate and reliable method to predict the failure of transformer [5]. These studies are based on thermal networks considering only the steady state, uniform power losses and constant thermal properties. The most accurate and widely used finite element method for analyzing the characteristics of transformers must predict the input source through a mathematical function or sequence table. Therefore, thermal-electromagnetic-coupled 3D-finite element analysis (FEA) considering the practical frequency excitations is required.

Also, a key for the design of magnetic components in power electronics is low volume, high efficiency and low price. Magnetic components, such as transformers and inductors, should be operated within the thermal limitation of the circuit. A loss of the transformer is an important design parameter. In many high frequency design cases, the high frequency transformer is limited by its loss. Therefore, the transformer should estimate the losses under a range of frequency excitations in a power electronics circuit. Two major losses occur in the transformer: the core and winding losses. The heat sources are based on the analysis results of the core and copper loss.

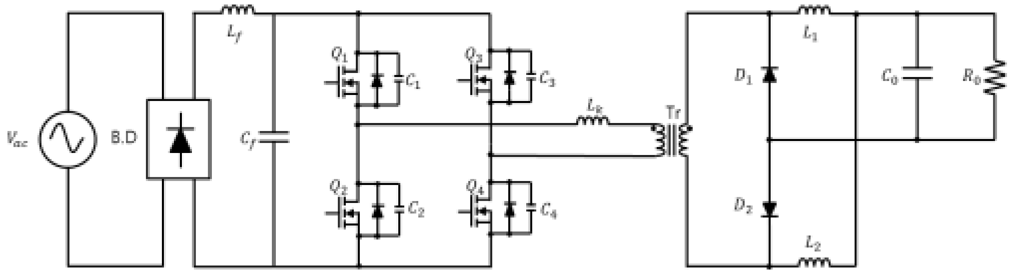
Most thermal studies for high frequency transformers are analytical and thermal equivalent circuit models. These studies are based on thermal networks considering only the steady- state, uniform power losses and constant thermal properties. Therefore, thermal-electromagnetic coupled 3D-finite element analysis (FEA) considering the practical frequency excitations is required.

In this study, thermal behavior analysis of high frequency transformer was performed using thermal-electromagnetic coupled 3D-FEA considering practical converter circuit to improve the accuracy of temperature analysis. The circuit used was a 3kW-class phase-shift full-bridge DC-DC converter. FEA modeling is based on a practical converter circuit and the measured current waveform. Thermal-electromagnetic coupled analysis was carried out to compare the results of the FEA models.

2. Co-Simulation for 3kW-Class converter circuit configuration and specification

The converter circuit used a DC-DC full-bridge converter circuit with double current rectification. The input AC power was rectified to DC through a bridge diode, and the high frequency signal was filtered through an LC filter. The transformer primary circuit consisted of four MOSFETs connected in the form of a full bridge and was controlled by the phase shift method. The secondary circuit of the transformer consisted of a diode current and a rectifier circuit that is suitable for large power output using two inductors. This study examined the transformer that is a part of the converter.

Fig. 1 shows the circuit configuration and results of circuit simulation for a 3kW-class full-bridge DC-DC converter considering the practical converter behavior. Table 1 lists the specifications of the converter and interior transformer.



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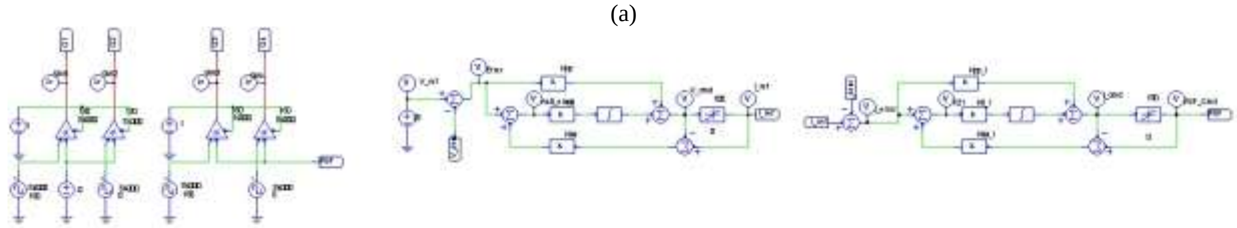

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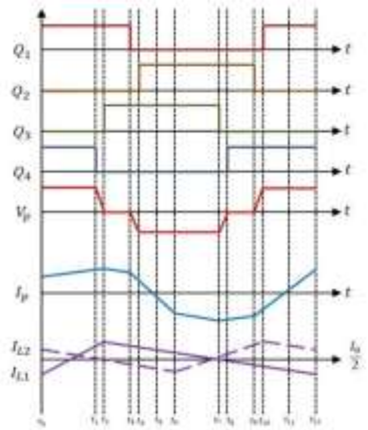

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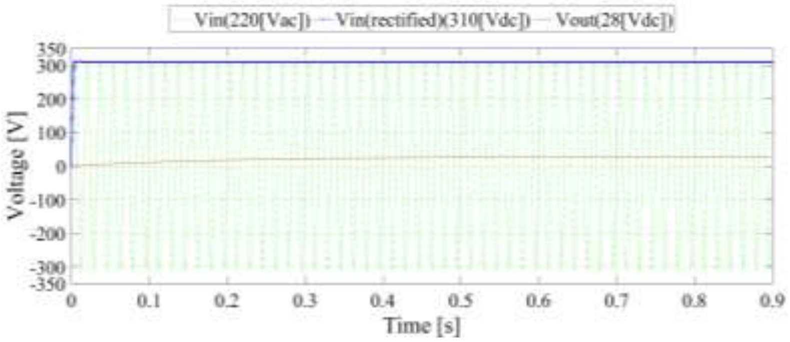

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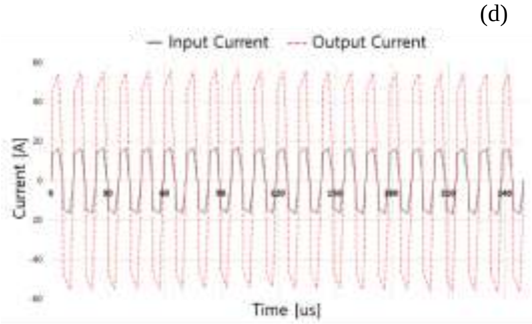


(e)

Figure 1: Circuit structure and results of 3kW converter

(a) Circuit configuration (b) Control part (c) Time chart for switching (d) Results of simulation (e) Current waveform for transformer

Table 1: Specifications of the converter and transformer

DC-DC Converter			**Transformer**		
Parameter	**Value**	**Unit**	**Parameter**		**Value**
			Core type		
Input voltage	310	V_{dc}	Core Material		EE
Output voltage	28	V_{dc}	Core Size		PL-15
Output current	111	A	Turns Ratio		7066
Leakage inductance	3.6	μH	saturation magnetization		10:3
Output inductor	25	μH		Primary	0.55[T]
Output capacitor	22,000	μF	Winding		
Switching frequency	84	kHz		Secondary	USTC-Φ0.12*150(2line)
					USTC-Φ0.12*150(3line 2paraller)

3. Design of High Frequency Transformer

The turn ratio of a transformer should be designed so that the output voltage is maintained, even at the lowest voltage and at full load. To design the transformer, first, the material of the core that can operate at high frequency is selected, and the required core size is calculated according to equations (1) to (6), and the EE- The 7066 core is selected.

$$P_{in} = \frac{P_{out}}{\eta} \quad (1)$$

$$I_{dc} = \frac{P_{in}}{V_{in(\mathrm{min})}} \quad (2)$$

$$I_{pm} = \frac{P_{in}}{V_{in(\mathrm{min})} \times K_t} \quad (3)$$

$$N_p = \frac{A_W \times J}{\eta} = \frac{A_W \times K_p \times K_u \times J \times V_{in(min)} \times K_t}{P_{in}} \quad (4)$$

$$A_e = \frac{V_{in} \cdot t_{on(max)}}{N_p \cdot \Delta B} \quad (5)$$

$$A_P = \left(\frac{11.1 \times P_{in}}{K_t \times K_p \times K_u \times \Delta B \times f_s}\right)^{1.143} = A_e\, A_W = \left(\frac{11.1 \cdot P_{in}}{\Delta B \cdot f_s \cdot K'}\right)^{1.143} \quad (6)$$

WhereP_{in} is input power, P_{out} is output power,η is efficiency, I_{dc} is input current, $V_{in(\mathrm{min})}$ is the minimum value of input voltage, I_{pm} is current of primary section for transformer, K_t is topology factor, N_P is number of transformer's primary turns, A_W is core window area, K_p is core window utilization factor for primary, K_u is total core window utilization factor,A_e is core cross section area, and A_P is area product.

The winding ratio was calculated using Eqs. (7) to (9), considering the currents on the primary side and the current on the secondary side. In addition, the winding was wound using a Litz wire, which has a reduced volume of the winding and is excellent for high frequency characteristics.

$$\frac{V_o}{V_{in}} = \left(\frac{N_s}{N_p} \times ph\right) - \left(I_o \times \left(\frac{N_s}{N_p}\right)^2 \times \frac{L_k}{V_{in}} \times f_s\right) \quad (7)$$

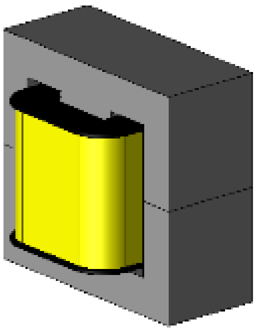
$$N_P = \frac{V_{in(\mathrm{max})} \times ph_{eff}}{2 \times B_{max} \times A_e \times f_s} \quad (8)$$

$$N_s = N_P \times \frac{V_s}{V_p} \quad (9)$$

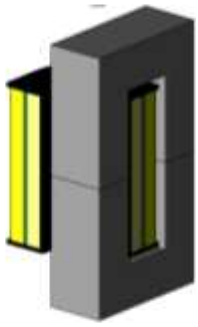
Where V_o is output voltage, N_s is number of transformer's secondary turns, L_k is leakage inductance, f_s is switching frequency, and ph_{eff} is effective phase shift.

The minimum input voltage of the converter, 260 [V_{dc}], applied to the primary side, ph_{eff}, which is the overlapping ratio of the on-duty of each switch, was0.95. The maximum magnetic flux density B_{max} of core is limited to 0.3[T] and when calculated by referring to the data sheet of the transformer core EE-7066, A_e = 679.2[mm^2] and the value of leakage inductanceL_k is determined as 3.6[uH] after winding is wound. The values of the windings and the primary and secondary windings were determined by substituting these values.

The primary and secondary winding of the transformer was 11.53[A]and 33.34[A], respectively. The primary and secondary winding of USTC-∅0.12 * 150 and USTC-∅0.12 * 150, respectively, were used in parallel. Figure 2 shows the designed transformer for electromagnetic field analysis applied 3-D FEA.



(a)



(b)

Figure 2:. Design of the High Frequency Transformer (a) Full model (b) 1/4 model (applied FEA)

3. Comparison of characteristics analysis for the FEA applied practical waveform

A co-simulation of circuit and electromagnetic was performed to obtain more accurate analysis results of the transient analysis section and steady-state section. To verify the improved results, the calculated results were compared with the electromagnetic analysis results. Figure 3 shows the input current waveform. Figure 4 shows the magnetic flux density results, and Figure 5 shows the temperature distribution of the core with loss. The results of electromagnetic analysis through FEA could not be confirmed by considering the calculated constant current waveform, and the error can be expected to increase if the input current modeling is incorrect. The temperature of the thermal-electromagnetic coupled 3D-FEA for high frequency transformer. The transformer thermal analysis of stationary state is less than 35 [℃]. On the other hand, in the case of a co-simulation, all sections from the transient to the steady state can be confirmed more accurately.

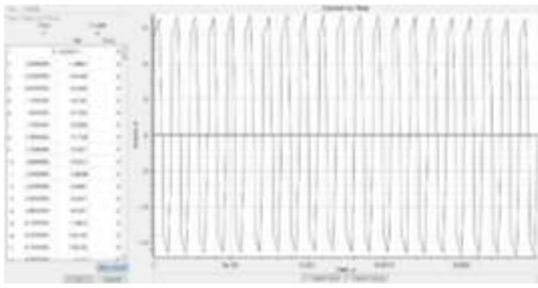
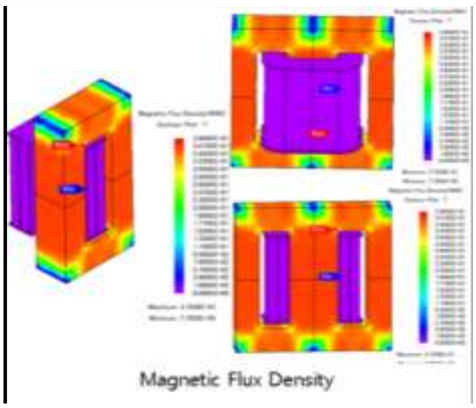


Figure 3: Input current of the co-simulation and electromagnetic analysis applied to FEA



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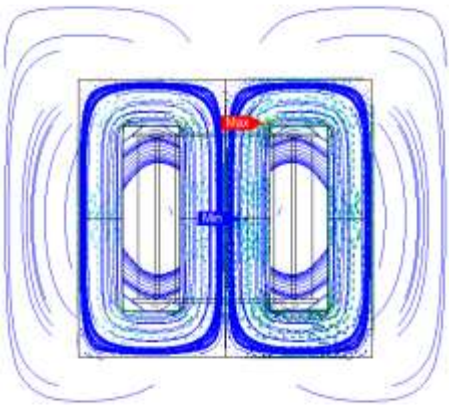

(b)

Figure 4: Results of the flux density for high frequency transformer (a) Flux density (b) Flux line and vector

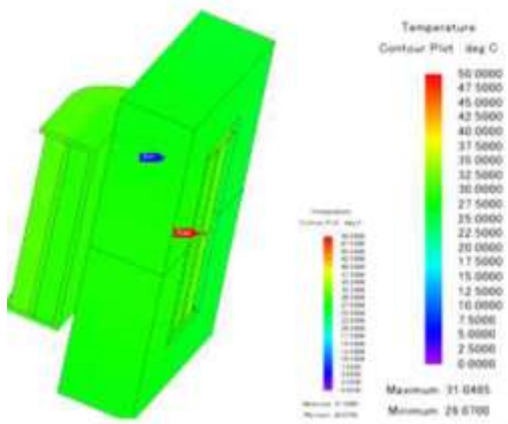

Figure 5: Results of the temperature distribution for a high frequency transformer core

4. Conclusion

The thermal behavior of high frequency transformer was examined using thermal-electromagnetic coupled 3D-FEA considering practical converter circuit to improve accuracy of temperature analysis. FEA modeling was based on a practical converter circuit and the measured current waveform. Thermal-electromagnetic coupled analysis was carried out to compare the results of the experiment and FEA models. The transformer flux density and thermal analysis of the stationary state was less than 0.38[T] and 35 [℃].

Acknowledgment

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