A Parameters Optimization Method of High Frequency Transformers Used in The On-Board Charging System of Electric Vehicle

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***Abstract*— A level 2 charging standard has been proposed by cooperated Electric Vehicle (EV) manufacturers with a power rating from 2.5 to 19.2 kW. The time to fully charge the EV battery can be reduced to between 0.7 and 2.9 hours under home or public charging conditions. Hence, the EV's on-board charging system requires high power density and a high frequency transformer to fulfill the design requirements of a light weight, compact, and high power charging system. This paper introduces a High Frequency Coaxial Transformer (HFCT) with >99% power efficiency accompanied by an optimization method for its leakage inductance (L_{eq}) and coupling capacitance (C_{ps}). An investigation of the shielding effect of the HFCT has been conducted by using the FEM based numerical technique and optimized results have been achieved.**

I. Introduction

The on-board charging system of the EV has became popular in recent research works. While the EV only runs in a specific range regarding its energy storage capacity, drive train efficiency and power conversion efficiency, the on-board charging system definitely occupies an important role among EV components. Transformers currently on the market are usually bulky because of their low operating frequency. This also increases the volume and weight of the on-board charging system. The newly developed HFCT is suitable for use on the EV which operates in a frequency range of 100~150 kHz with >99% power efficiency, and with a possible power range above 20 kW. For example, an 8 kW HFCT of the existing design weights only 900 grams and it is ready to be mass-produced.

On the other hand, an increase in the operating frequency of transformers might cause serious Electromagnetic Compatibility (EMC) problems. Compared to planar transformers, the HFCT performs better with EMC issues. These issues are often caused by the C_{ps} of transformers. Hence, a Faraday shield has been inserted between the primary and secondary windings of the HFCT to reduce the C_{ps}. Moreover, to solve further EMC issues on the transformer, this paper will also introduce an optimization method to determine the best distance between primary and secondary windings. The coupling capacitance can be reduced according to increased distance while the L_{eq} is also increased. Greater L_{eq} will consume more energy, which decreases the efficiency of the HFCT. Hence, a trade-off will be found to address the issues of the values of C_{ps} and L_{eq} by the use of the introduced optimization method.

II. Numerical Modeling of HFCT

A. Computation Model

Figure 1 shows the structure of the HFCT where the transformer dimensions are varied according to its power rating and voltage requirements.

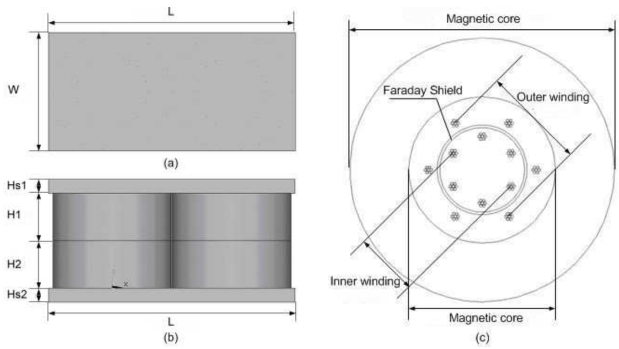


Fig. 1. HF coaxial transformer: (a) top view; (b) side view; and (c) half cross-section.

B. Magnetic Field Computation

The transformer's magnetic filed can be determined by the following vector potential equation:

$$\nabla \times (\nu \nabla \times A) + \sigma(\partial A / \partial t) = J. \tag{1}$$

where A and J are magnetic vector potential and current density respectively, v is the magnetic reluctivity, and σ is the conductivity. The energy function is generalised from linear techniques. Galerkin's method is used to discretize the governing equation to solve the problem. The system matrix equation can be obtained as shown in equation (2):

$$G = [S]\{A\} + [M]\{A\} - \{K\} \tag{2}$$

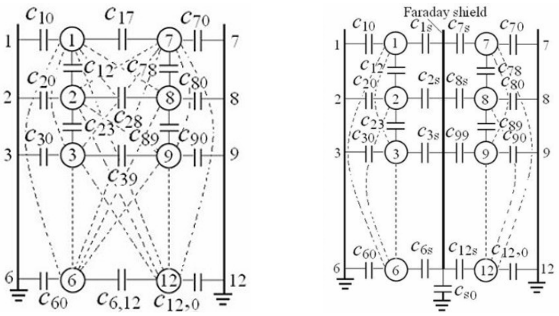
C. Electric Field Computation

Based on Maxwell's theory, the relationship between potential and charge in a multi-conductor system can be described by the electric scalar potential V, which satisfies Poisson's equation:

$$-\nabla \cdot (\varepsilon \nabla V) = \rho \tag{3}$$

where ε is the permittivity, and ρ is the space charge density. The shield or each turn of the winding can be taken as an independent conductor. Based on the theory of capacitances in multi-conductor systems [3], we can obtain N equations relating the potentials $V_1, V_2, \ldots, V_N$ of the N conductors to the charges $Q_1, Q_2, \ldots, Q_N$; and the capacitance coefficients $C_{11}, C_{i1}, C_{21}, \ldots, C_{ij}$. Figure 2 shows a detailed parasitic capacitance network model of the HFCT with and without a Faraday shield. The parasitic capacitance can be obtained by using the FEM matrix equation as in (4) for the relationship between charge and potential where [S] is the global coefficient matrix and {Q} is the charge matrix.

$$[S]\{V\} = \{Q\} \tag{4}$$

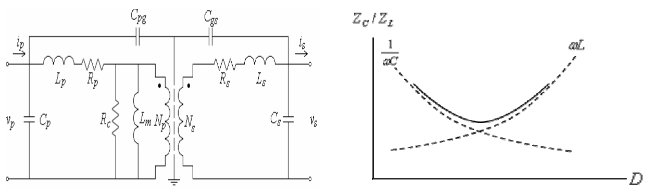


(a) Without shield (b) With shield

Fig. 2. The capacitance network model of the HFCT for HF noise analysis.

D. Optimal Design of Transformer Equivalent Impedance

To meet the requirements of switching mode power systems and EMC standards, the trade-off of C_{ps} and L_{eq} can be determined by using a multi-objective optimization method. The insertion of the Faraday shield, which has some impact on the impedance will also be considered. The approximated optimization value of leakage inductance is calculated using a magnetic energy technique [4]. The FEM simulation technique can then be used to obtain a more accurate result. Figure 5 shows the HFCT equivalent circuit and the variation of L_{eq} and C_{ps} against the distance (D) between the primary and secondary windings.

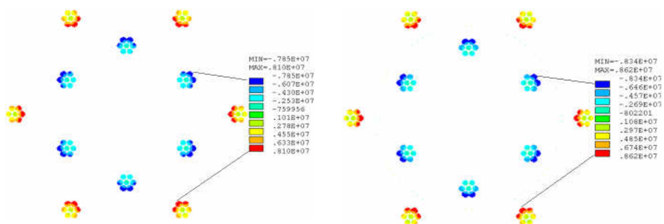


(a) (b)

Fig. 3. The HFCT with faraday shield (a) HF transformer equivalent circuit; and (b) L_{eq} and C_{ps} versus D.

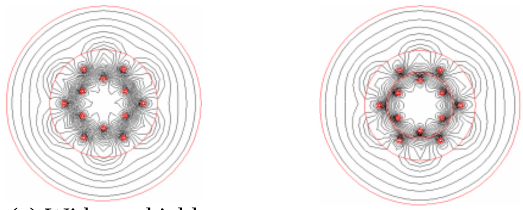
III. Simulation Results and Analysis

A. Eddy Current and Flux Distribution



(a) Without shield (b) With shield

Fig. 4. Eddy current distribution - short circuit condition.



(a) Without shield (b) With shield

Fig. 5. Flux distribution under short circuit condition.

Figures 4 and 5 show the HFCT simulation results with and without the Faraday shield. As observed, the insertion of the Faraday shield does not affect the magnetic performance because the magnetic field is almost perpendicular to the shield conductor surface.

B. The Validation of Shielding Effect

The calculation results for the non-shielded and well-grounded shield cases are shown in Table I. The calculated results show that C_{ps} is significantly reduced from 19.96 pF to 0.08 pF due to the insertion of the Faraday shield in the HFCT. The measured value of C_{ps} at the working frequency (0.2MHz) is 20.7pF, which is consistent with the calculated value of 19.96pF.

TABLE I
HFCT CAPACITANCE CALCULATION RESULTS

		C_p (pF)	C_s (pF)	C_{ps} (pF)
No Shield	Coaxial part	6.99	3.12	7.82
	End region	0.68	0.43	12.14
	Total	7.67	3.55	19.96
Shield Grounded	Coaxial part	11.75	9.62	0.00
	End region	12.92	12.88	0.08
	Total	24.67	22.50	0.08

IV. Conclusion

This paper introduces a HFCT with high power density characteristics, which is well-suited to the requirements of an on-board EV charging system. The HFCT has good power efficiency of >99%. An analysis of the shielding effect of the HFCT has also been conducted. Moreover, an optimization method has been proposed to find the trade-off between C_{ps} and L_{eq}. Optimization results will be presented in the full paper.

V. References

[1] J. Lu and F. Dawson, “Analysis of Eddy Current Distribution in High Frequency Coaxial Transformer with Faraday Shield,” *IEEE Trans. On Magnetics*, Vol. 42, No. 10, pp3171-3173. Oct. 2006

[2] J. Lu, F. P. Dawson and S. Yamada, “Application and Analysis of Adjustable Profile High Frequency Switchmode Transformer Having a U-Shaped Winding Structure,” *IEEE Trans. on Magnetics*, Vol. 34, No. 4, pp1345-1347, Jul. 1998.

[3] L. Dalessandro, F. D. S. Cavalcante, and J. W. Kolar, “Self-Capacitance of High-Voltage Transformers”, *IEEE Trans. on Power Electronics*, Vol. 22, No. 5, pp. 2081-2092, Sept. 2007.

[4] W. G. Hurley and D. J. Wilcox, “Calculation of Leakage Inductance in Transformer Windings”, *IEEE Trans. on Power Electronics*, Vol. 9, No. 1, pp. 121-126, Jan. 2005.

[5] Junwei Lu, “High Frequency and High Power Density Magnetic Devices and Future Trends”, *International conference on Power Electronics and Motion(PCIM2009)*, invited paper, April 2009.