

# Numerical Analysis and Design of Moving Contactless High Power Transformer

Dongsu Lee<sup>1</sup>, Dong-Uk Jang<sup>2</sup>, Hyung-Chul Kim<sup>2</sup>, and Sang-Yong Jung<sup>1\*</sup>

<sup>1</sup>*School of Information and Communication Engineering, Sungkyunkwan University, Suwon 440-746, Korea*

<sup>2</sup>*Electrical Power Supply Division, Korea Railroad Research Institute 360-1, Uiwang 437-050, Korea*

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**This paper presents numerical analysis and design of high power contactless transformer with a large air-gap for moving on a guided linear track which is appropriate for high-speed train or MAGLEV. The system has the typical characteristics of large leakage inductance, small magnetizing inductance, and low coupling coefficients giving rise to lower power transfer efficiency, which have been compensated by the purposely-designed contactless transformer coupled with the resonant converter modulating with high switching frequency. In particular, the best model selected from the generated six design candidates has been applied for 3D Finite Element Analysis (FEA) investigating on iron loss to evaluate the overall system efficiency.**

**Keywords :** contactless transformer, 3D Finite Element Analysis (FEA), coupling coefficients, resonant converter, high switching frequency

## 1. Introduction

Recently, contactless power transmission system is widely used in many industry applications such as automated guided-vehicles, medical applications, semiconductor facilities, and etc. Contactless power transmission system delivers electrical energy to a load with assistance of contactless power transformer that has no mechanical contact. Due to the distinctive superiority of reliability, safety, and flexibility, it finds increasing applications to supply high power to electric facilities. In particular, moving contactless high power transformer is most attractive solution for high-speed train or MAGLEV mainly due to mechanical clearance at high speed running on a guided rail.

Moving contactless high power transformer is composed of a long primary wire on a linear motional track, a large air-gap for mechanical clearance, and secondary pick-up coils wound around transformer core. On account of a large air-gap, it has the significant low coupling coefficients, and is hard to maintain the higher power transfer efficiency [1, 2]. In detail, the primary leakage inductance of the contactless transformer is usually larger than the magnetizing inductance, hence it is inevitable to

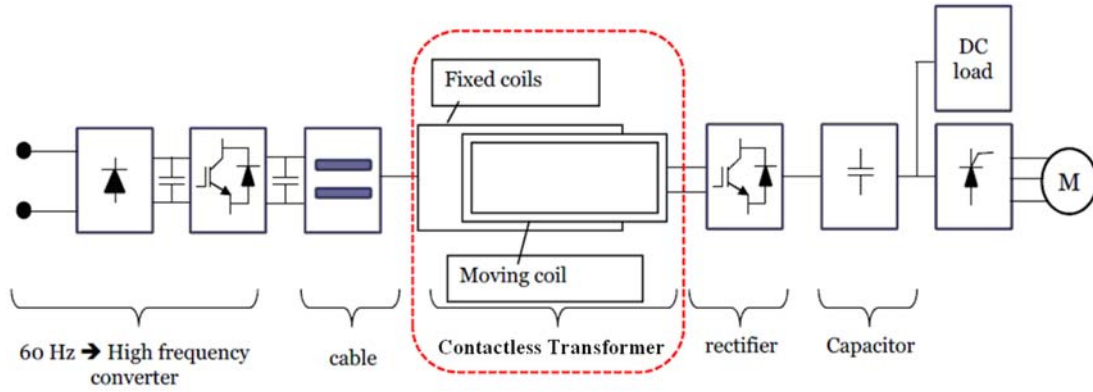
have huge magnetizing current flow [3]. However, such a lower inductance can be compensated by high frequency excitation in terms of reactance, thus power transfer efficiency can be improved by coupling to the resonant converter modulating with high switching frequency (10-100 kHz) [4-6]. Operating performance and parameter identification of power transformer excited with high switching frequency should be thoroughly investigated with the numerical results obtained by 3D FEA [7].

In this paper, structural design of contactless high power transformer (5 kW) for the purpose of improving size effectiveness, coupling coefficients, and efficiency has been performed. Totally six design candidates with different topology have been considered and evaluated for moving contactless power transformer. Furthermore, the selected prototype is forwarded to optimal design in terms of smaller size and lighter weight by getting rid of useless parts in secondary core, while maintaining the regulated magnetic flux density in core. The finally designed one is applied for 3D FEA investigating on iron loss to evaluate the overall power transfer efficiency.

## 2. Moving Contactless Power Transformer

The conceptual diagram of moving contactless power transmission system taken into consideration is shown in Fig. 1. The input is equipped with a line voltage with 60

\*Corresponding author: Tel: +82-31-299-4952  
Fax: +82-31-290-5828, e-mail: syjung@ece.skku.ac.kr



**Fig. 1.** (Color online) Conceptual diagram of contactless power transmission system.

Hz, which goes through a full-bridge rectifier to become a DC power. It passes through the standardized half-bridge DC/AC switching circuit with high frequency, which is fed to the matching transformer and contactless induction coil. As it were, it is said to be isolated input and output stages. At the output stage, full-bridge rectification circuit is also applied to generate a rated DC power through the rectifier and filtering device, which is finally utilized to the various types of electrical loads.

### 3. Design Characteristics of Contactless Power Transformer

#### 3.1. Coupling coefficient and iron loss

Good criterion to judge the magnetic flux coupling between the primary and the secondary is coupling coefficient, which is known as more critical in a contactless power transformer, full of leakage flux. Coupling coefficient of power transformer is defined as follows.

$$K = \frac{L_M}{\sqrt{L_{11}L_{22}}} \quad (1)$$

$$\begin{cases} K = \text{coupling coefficient} & L_{11} = \text{primary inductance} \\ L_M = \text{mutual inductance} & L_{22} = \text{secondary inductance} \end{cases}$$

where parameters should be obtained from numerical analysis for the better accuracy. Numerical approaches using 3D FEA has been used for characteristic analysis of contactless power transformer, of which mandatory governing equation is as follows.

$$\nabla \times \frac{1}{\mu} (\nabla \times \vec{A}) = \vec{J}_s \quad (2)$$

Low coupling coefficient, distinctive to contactless power transformer with a large air-gap, means that little portion of magnetic flux excited at the primary interlinks

the secondary, which gives rise to the larger input power to provide the rated power to loads. Thus, structural design to improve the coupling coefficient by modifying the magnetic reluctance across air-gap is requisite for the enhanced power transformer efficiency [8]. Definitely, it can be realized by reducing air-gap or enlarging cross-sectional area, face-to-face at the primary and secondary core.

For the purpose of compensating the lower inductance of contactless power transformer in terms of reactance, resonant converter modulating with high switching frequency is generally equipped, which gives rises to significant iron loss. In this paper, iron loss has been analyzed and evaluated numerically, where eddy current loss and hysteresis loss are identified separately [9].

$$P_{fe} = K_e \cdot f^2 \cdot B_{\max}^2 + K_h \cdot f \cdot B_{\max}^{1.6} \quad (3)$$

where  $K_e$  and  $K_h$  denote the coefficient of eddy current loss and hysteresis loss, respectively. Iron loss should be minimized to avoid the high temperature rise in core and maintain the system efficiency.

#### 3.2. Design of transformer core

Large air-gap is a major obstacle for maintaining the required Electro-Motive Force (EMF) in the secondary, which should be compensated with enlarged cross-sectional area of core under the given values of number of secondary turns ( $N_s$ ), flux density ( $B_m$ ), and switching frequency ( $f$ ), as formulated in (6)

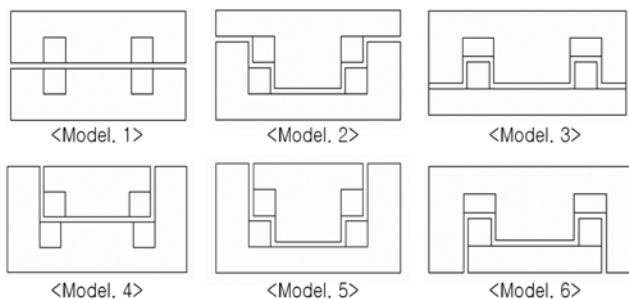
$$A_c = \frac{V_s}{N_s B_m f K_f} \quad (4)$$

$$\begin{cases} A_c = \text{cross section of core} & K_f = \text{waveform coefficient} \\ V_s = \text{secondary voltage} & N_s = \text{number of secondary turns} \end{cases}$$

In practical, since the primary coil is build-up on the long linear motional track, it is inevitable to have small

**Table 1.** Performance specifications of the contactless transformer.

| Specifications     | Design specification | Specifications       | Design specification |
|--------------------|----------------------|----------------------|----------------------|
| Primary Coil turns | 2 [turn]             | secondary coil turns | 2 [turn]             |
| voltage            | 70.7 [V]             | current              | 70.7 [A]             |
| air-gap            | 2 [mm]               | frequency            | 20 [kHz]             |

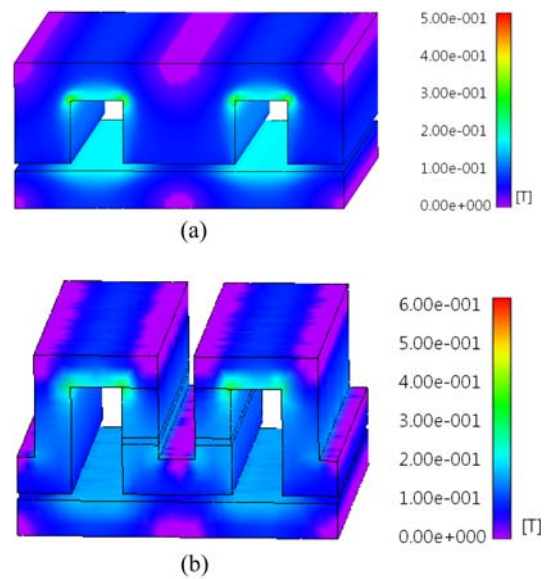
**Fig. 2.** Six design candidates with different topology.

number of turns, which is regarded as another reason for lower primary inductance. In addition, there have been the strict constraints of magnetic flux density fluctuation for avoiding large iron loss and current density for large copper loss, which are closely correlated with cooling methods.

In this paper, magnetic design of high power transformer (5 kW), available for providing auxiliary power to high speed train, has been carried-out, which is coupled to the resonant converter modulating with the switching frequency of 20 kHz. The primary and the secondary voltage is identical as 70.7 V, likewise identical number of coils turns (2-turns). Air-gap length is set to be 2 mm for mechanical clearance from running at 2 m/sec. Magnetic flux density is preferred not to exceed 0.2 [T] (peak-to-peak scale) in overall transformer core, which is empirically determined for 20 kHz, and current density is limited by  $4A_{rms}/mm^2$  in order to be installed with the nature cooling method. In particular, Table 1 shows

**Table 2.** Comparison results of six design candidates.

| Model | Size [mm] |        |       | Coupling Coefficient | Efficiency [%] |
|-------|-----------|--------|-------|----------------------|----------------|
|       | Width     | Height | Depth |                      |                |
| 1     | 80        | 42     | 194   | 0.907                | 90             |
| 2     | 84        | 42     | 182   | 0.923                | 89             |
| 3     | 88        | 39     | 174   | 0.945                | 90             |
| 4     | 84        | 40     | 216   | 0.920                | 90.5           |
| 5     | 84        | 42     | 212   | 0.915                | 90.7           |
| 6     | 88        | 39     | 202   | 0.937                | 91.5           |

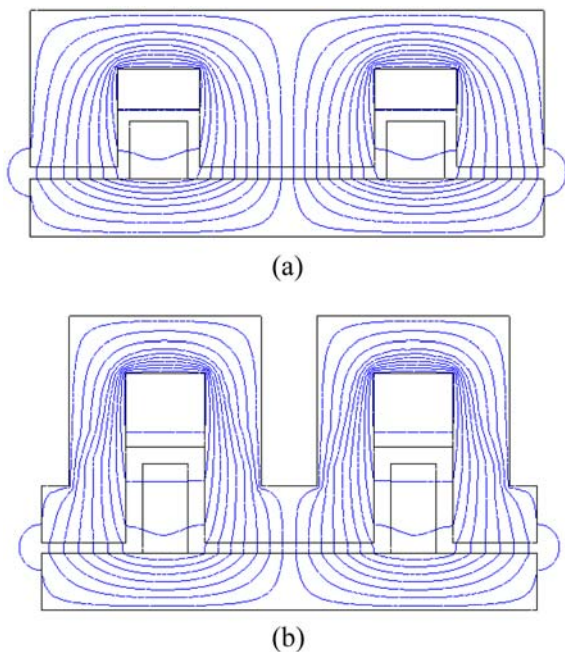
**Fig. 3.** (Color online) Magnetic flux density (a) Model 3 (b) Optimized Model 3.

design specifications of the contactless transformer. six design candidates with different topology have been generated for contactless power transformer satisfying the design specifications shown in Fig. 2.

#### 4. Performance Evaluation on Purposely Designed High Power Transformer

Proposed six design candidates have been evaluated in terms of size effectiveness, coupling coefficients, and efficiency, of which results are shown in Table 2. It is preferably concluded that Model 3 has the superiority to the other ones particularly in the total volume and coupling coefficients, maintain agreeable high efficiency. Furthermore, the selected Model 3 has been forwarded to optimal design for the smaller size and lighter weight by getting rid of useless local parts in secondary core. It can be easily found with the lower magnetic flux density resulted from 3D FEA and made to be higher up to 0.2T, which should sacrifice the iron loss and efficiency. The distribution of magnetic flux density and flux lines for Model 3 and the optimized Model 3 are shown in Fig. 3 and 4, respectively, which shows more effective results at the optimized one. In addition, iron loss resulted from 3D FEA using (3) is shown in Fig. 5 for Model 3 and the optimized Model 3, which shows increase of iron loss and decrease of efficiency from 90% to 84.1% after all.

Accordingly, it is noted that trade-off relation of size effectiveness and efficiency will ask for thorough investigation on the installing environment and the operating

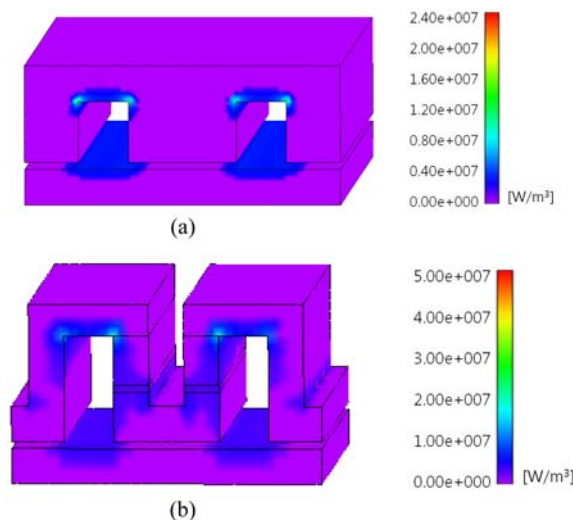


**Fig. 4.** (Color online) The flux line (a) Model 3 (b) Optimized Model 3.

performance of contactless power transformer compatible for the applied system. Moreover, optimal design of contactless power transformer coupled with the resonant converter modulating with high switching frequency should be followed aiming at the enhanced overall system efficiency, coupling coefficient, and size effectiveness, while maintaining the required output power providing to the various types of electrical loads.

### 5. Conclusion

This paper presents numerical analysis and design characteristics of contactless high power transformer (5 kW) coupled to the resonant converter modulating with 20kHz switching frequency. In particular, coupling coefficient to judge the effective magnetic flux, excited from the primary interlinking to the secondary, has been numerically identified with 3D FEA. In addition, iron loss, significant at the high frequency excitation, has been computed using 3D FEA to evaluate the system efficiency. Totally six design candidates have been considered and investigated in terms of size effectiveness, coupling coefficient, and efficiency, and then the selected one is additionally optimized in the smaller size and lighter weight by getting rid of useless part in core. Moreover, iron loss and system efficiency is numerically evaluated



**Fig. 5.** (Color online) The iron loss density [W/m<sup>3</sup>] (a) Model 3 (b) Optimized Model 3.

empathizing on trade-off design characteristics of size effectiveness and efficiency of contactless power transformer.

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