Optimal Electromagnetic Field Design of Wireless Power Transfer System in On-Line Electric Vehicle

Seungyoung Ahn, Ju Yong Lee, Dong-Ho Cho, and Joungho Kim
Department of Electrical Engineering and Computer Science
Korea Advanced Institute of Science and Technology (KAIST)
Daejeon Korea, sahn@kaist.ac.kr

Abstract

In this paper, we introduce the wireless power transfer mechanism and the electromagnetic field (EMF) reduction techniques for on line electric vehicle (OLEV), and perform design parameter optimization to maximize transfer power efficiency while satisfying power transfer efficiency and EMF regulation.

Keywords : On-line electric vehicle Electromagnetic field Wireless power transfer Optimization

1. Introduction

Recently, intensive research has been performed on fully electric transportation systems in each country due to the shortage of petroleum resources and environmental issues. However, we are still facing serious problems in battery-powered electric delivery systems. The large size, weight, and cost of batteries, long recharging times, and limited availability of charging service points are the limitations of battery-powered electric vehicle.

A novel on-line electric vehicle (OLEV) has been invented, in which the automotive vehicle constantly receives and recharges its power from power lines embedded underneath the surface of the road (Figure 1). OLEV has a minimal battery capacity (about 20% compared to that of the conventional battery-powered electric vehicles) which can consequently minimize the weight and the price of the vehicle and power station.

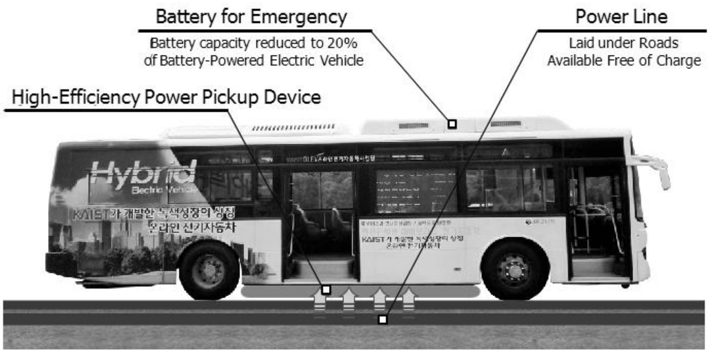
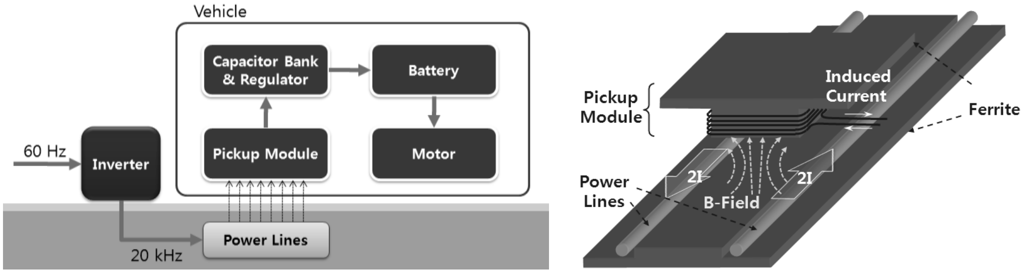


Figure 1: Photograph of on-line electric vehicle system

2. Wireless Power Transfer System in OLEV

The power transfer system for OLEV consists of an inverter, power lines, a pickup module, capacitors, a battery, and a motor, as shown in Figure 2. The non-contact power transfer that occurs between the power lines and the pickup module generates a huge magnetic flux.

One of the key design requirements of the OLEV system is the suppression of the leakage magnetic flux from power lines and the pickup module to maintain the power delivery efficiency and meet the total power needs of the OLEV. In this paper, we propose techniques for the reduction of magnetic flux from the OLEV system. Some passive and active shielding methods are applied to real vehicles based on simulations and measurements, and the application to real vehicles is shown.



(a) (b)

Figure 2: The schematic of power transfer system for OLEV. (a) Block diagram of overall system (b) Wireless power transfer between power lines and pickup module

3. Design Optimization

3.1 **Circuit Design**

From the simplified equivalent circuit model of the wireless power transfer system with two series resonant coils as shown in Figure 3, the power at the load RL is calculated to be proportional to the frequency, mutual inductance, and magnitude of source current assuming that the system is operating at the resonance frequency as shown in (1).

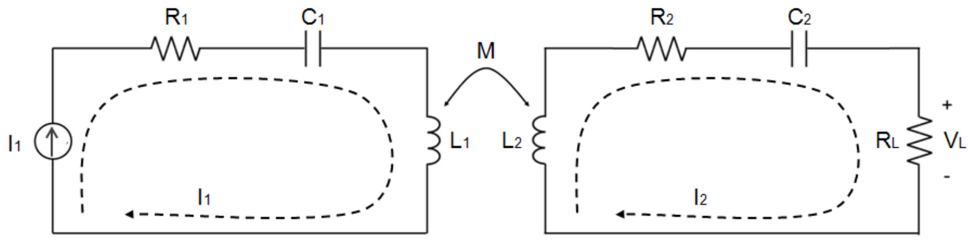


Figure 3: Simplified equivalent circuit model of power transfer system

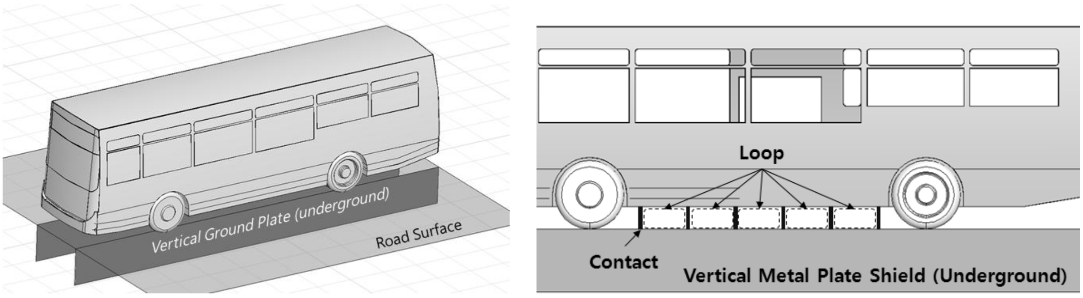
$$P_L \cong \frac{\omega^2 M^2}{(R_2+R_L)^2 + \left(\omega L_2 - \frac{1}{\omega C_2}\right)^2} I_1^2 R_L \cong \frac{\omega^2 M^2}{R_L} I_1^2 \quad (1)$$

$$K \cong \frac{\omega^2 M^2 R_L}{R_1 (R_2+R_L)^2 + \omega^2 M^2 (R_2+R_L)} \cong \frac{1}{1+\frac{R_1 R_L}{\omega^2 M^2}} \quad (2)$$

3.2 **Reduction of EMF**

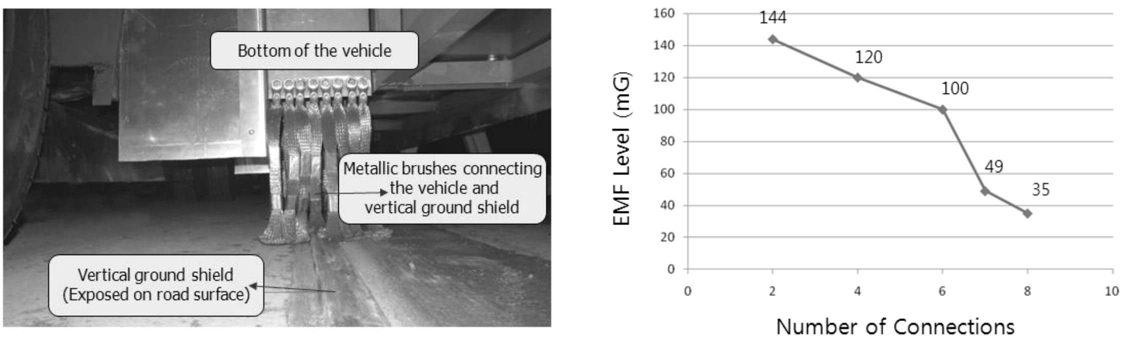
Electromagnetic field (EMF) is basically proportional to the magnitude of the current and inversely proportional to the distance between current position and measurement position without shield. However, as the application of passive and active shield significantly changes the magnitude of EMF, the design of EMF should be performed separately. To improve the shielding effectiveness of the passive shield, we additionally applied the soft contacts between bottom plate and vertical ground plate by metal brushes as shown in Figure 4. The metal brush is a bundle of thin metal wires attached beneath the bottom plate and connects the current path between vehicle body and ground plate underneath of the road surface.

Figure 5 shows the application passive shield which consists of the metal plate shield and metal brush. The number of connections using metal brushes is a significant factor to improve the shielding effectiveness of the passive shielding. The EMF level has been decreased from 144mG to 35 mG when the number of connections using metal brush is increased from 2 to 8.



(a) (b)

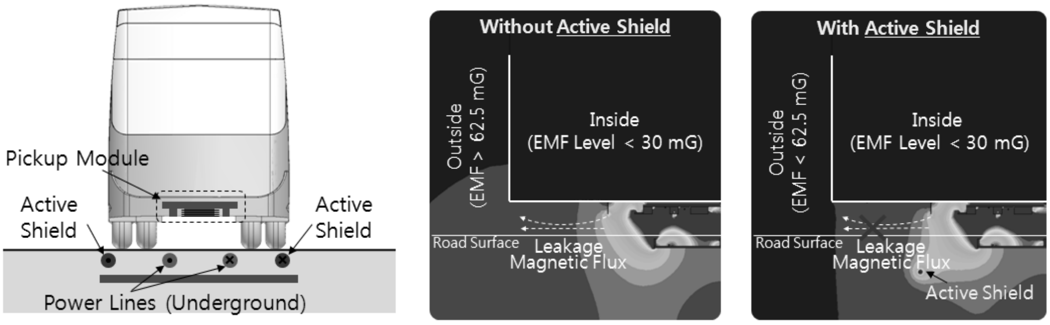
Figure 4: Passive shield for reduction of EMF (a) Vertical metal plate shields buried underground for EMF reduction (b) Soft contact by metal brushes



(a) (b)

Figure 5: Application of suggested passive shield (a) Photograph of implemented metal brush at the bottom of the vehicle (b) Effect of the number of connections on the reduction of EMF

The EMF can be minimized by active shielding method with or without passive shields independently, and the basic concept of active shield is shown in Figure 6 (a). Similar to power lines, the active shield is also a metal wire which carries the same frequency with current but the phase is the opposite of the current in the pickup. In Figure 6 (b) and (c), the magnetic flux density with and without active shield is depicted. When active shield is applied, the leakage magnetic flux is cancelled by the magnetic flux from the active shield and significantly reduced.



(a) (b) (c)

Figure 6: Suggested active shield (a) Concept of active shield for OLEV (b) Simulated magnetic flux density without active shield (b) Simulated magnetic flux density with active shield

3.3 **Optimization of Design Parameters**

Table 1: System Parameters

System Design Parameters	
Width of pickup coil	W_C
Current of power lines	I_S
Number of turns in pickup coil	n

The transferred power, which is the consumed at the load, should be maximized while EMF and power transfer efficiency K satisfy the requirements. We assume that the power transfer efficiency should be greater than or equal to 0.8, and EMF should be less than or equal to 62.5 mG.

variables : W_C, n, I_S

maximize P_L

such that $EMF \le 62.5(mG)$, $K \ge 0.8$, $0 \le W_C \le W_{C,\max}$, $0 \le n \le n_{\max}$, $0 \le I_S \le I_{S,\max}$.

Figure 7 shows the optimal power for different values of the frequency and the load. When load resistance increases, the optimal power decreases and the power transfer efficiency slightly decreases. At the center of the surface, there is an edge across the surface, generated by the power efficiency boundary condition.

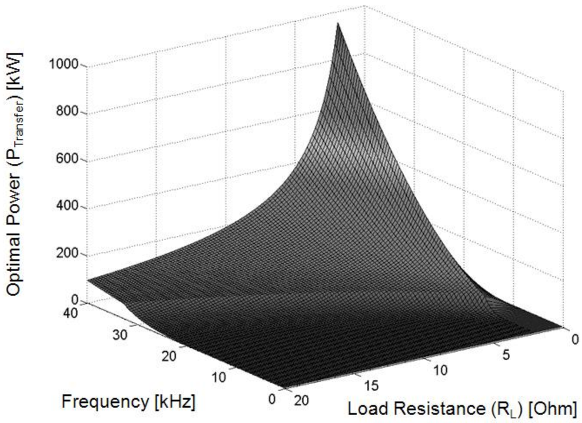


Figure 7: Optimized transferred power for different frequencies and load resistances

4. Conclusion

In the design of the wireless power transfer system in OLEV, the design of electromagnetic field is the most important for optimal electrical performance. To maximize power transfer capacity with high transfer efficiency and without violating EMF regulation, systematic design approach is necessary. For implementation with real vehicle, the power capacity of 60 kW using 5 pickup modules, with 80% power transfer efficiency, and EMF level lower than 62.5 mG have been achieved.

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