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Wireless Power Transfer Technology in On-Line Electric Vehicle

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Abstract

The On-line Electric Vehicle (OLEV) is an electric transport system in which the vehicle's power is transferred wirelessly from power lines underneath the surface of the road. Advantages of the OLEV include reducing battery size and cost to about 20 percent of that of conventional battery-powered electric vehicles, thereby minimizing the vehicle's weight and price, as well as the cost of charging the system. In this paper, we introduce a wireless power transfer mechanism to maximize the electrical performance of the power transfer system. Power transfer capacity, power transfer efficiency, and magnitude of leakage in the electromagnetic field (EMF) are analyzed, and the optimization methodology of the design parameters is discussed.

Key words: Wireless Power Transfer, On-Line Electric Vehicle, Electromagnetic Field, Shielding, Optimization.

Ⅰ. Introduction

Since Nikola Tesla's study of wireless power transfer in the beginning of the 20th century [1], there have been challenges in achieving genuine mobility in electronic devices and machines. Research on wireless power transfer technology by Soljačić brought more attention to wireless power transfer systems using magnetic resonances [2]. However, obstacles still remain to the commercialization of wireless power transfer technology, including limitations in power transfer capacity, efficiency, reliability, and safety. In order to deliver wireless power transfer technology to the market, more effort must be made to improve electrical performance, analyze standardization, and develop infrastructures for each application [3].

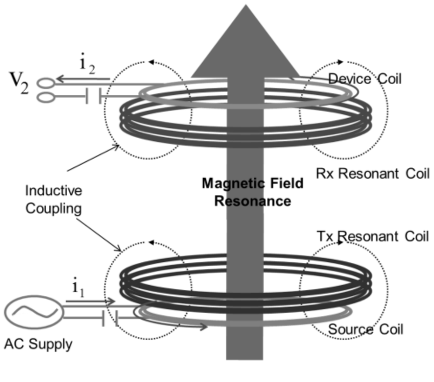

Fig. 1. Schematic of wireless power transfer systems.

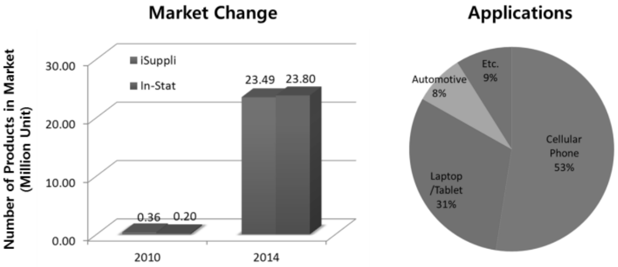

Fig. 2. Market trend of wireless power transfer system.

The application of wireless power transfer systems began with small, portable electronic devices, including mobile phones and laptop computers. However, the technology is now being transferred to the automobile market. In the field of transportation, the use of wireless power transfer systems is particularly meaningful in the realization of electric vehicles [4], [5].

Even though intensive research has been performed on fully electric transportation systems, we are still facing serious problems in battery-powered electric delivery systems. These issues include the large size, weight, and cost of batteries; long recharging times, and limited availability of charging service points. Moreover, diminished stocks of lithium could lead to increasingly high prices and ultimately price electric vehicles out of the automotive market. In light of these difficulties, the use of wireless power transfer systems in electric vehicles is recommended [6].

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Ⅱ. On-Line Electric Vehicle

KAIST has introduced a novel on-line electric vehicle (OLEV), in which the vehicle constantly recharges via power lines beneath the surface of the road (Fig. 3). The OLEV has a minimal battery capacity (about 20 % compared to that of conventional battery-powered electric vehicles), which minimizes the weight and price of both the vehicle and the power station. The design of the power lines and pick-up module determines the performance of the power transfer system and leakage in the electromagnetic field [7].

One of the key design requirements is suppression of the leakage of magnetic flux from power lines and the pick-up module in order to maintain power delivery efficiency and meet the OLEV's total power needs. In this paper, we introduce the wireless power transfer technology applied to OLEVs, and show the techniques for improving electrical performance. Optimization methodology of the design parameters and the shielding of the electromagnetic field are analyzed, and simulation and measurements for the verification are discussed.

The power transfer system for an OLEV consists of an inverter, power lines, a pick-up module, capacitors, a battery and a motor, as shown in Fig. 3. A 60 Hz current for power transfer is converted to 20 kHz at the inverter stage, and a current of about 200 A flows through the power lines. The design of the power lines and pick-up module determines the electrical performance of the power transfer system.

The magnetic flux generated from the power lines is gathered at the pick-up module to generate DC power for the vehicle's motor. The non-contact power transfer that occurs between the power lines and the pick-up module generates a huge magnetic flux. Therefore, the design of the power lines and the pick-up module are the key technologies for effective power transfer and solving the electromagnetic field (EMF) problems.

Fig. 5 shows the vertical magnetic flux of the power lines and pick-up module. There are two power lines with opposite current directions beneath the road surface forming a current loop. Due to the current in the power lines, a magnetic flux is induced around each power line. Between the power lines, the magnetic fluxes from the two power lines are combined. The pick-up module catches the vertical magnetic flux through copper coils around the ferrite core. This type has the advantage of providing efficient power transfer because the direction of the magnetic flux from the power lines is the same as the direction of the flux to the pick-up module.

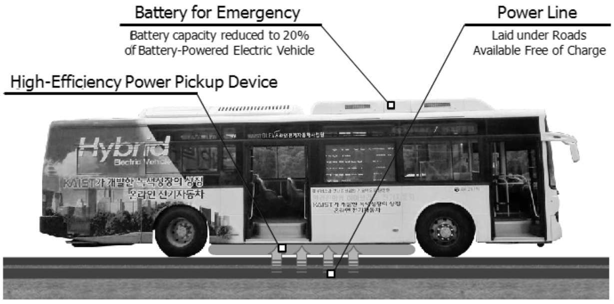


Fig. 3. Photograph of on-line electric vehicle system.

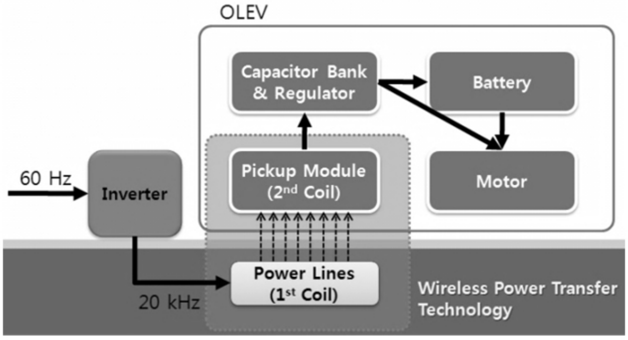
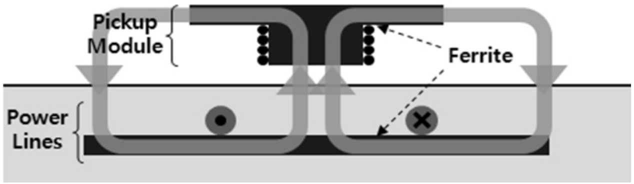
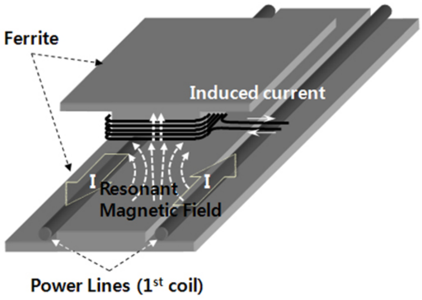


Fig. 4. Block diagram of overall system for OLEV.



(a) Cross-sectional view



(b) Perspective view

Fig. 5. Concept of power lines and pickup coils pair and the generated magnetic flux for vertical magnetic flux type system.

Ⅲ. Procedure of OLEV System Design

In designing the power lines and pick-up module structure for the OLEV system, we considered three criteria for the electrical performance of the wireless power transfer system: power transfer capability, power transfer efficiency, and leakage from the electromagnetic field.

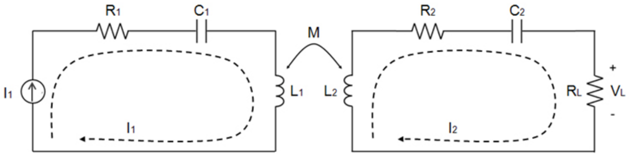


Fig. 6. Equivalent circuit model of power transfer system.

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

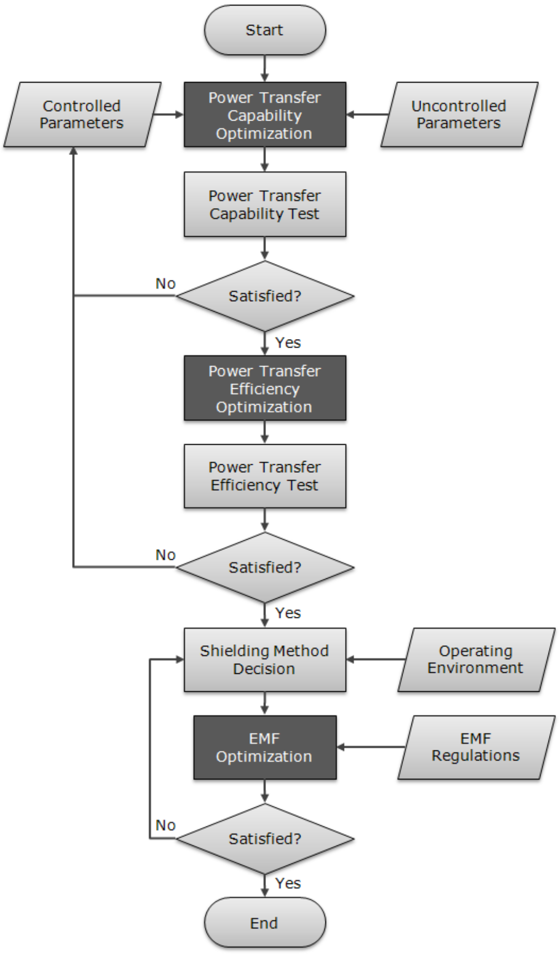
$$K \cong \frac{\omega^2 M^2 R_L}{R_1(R_2+R_L)^2+\omega^2 M^2 (R_2+R_L)} \cong \frac{1}{1+\dfrac{R_1 R_L}{\omega^2 M^2}} \qquad (2)$$

Power transfer capability implies the maximum power that can be transferred from the power lines under the road to the load in the vehicle, which consequently determines the vehicle's maximum speed and battery recharging time. From the simplified equivalent circuit model of the wireless power transfer system with two series resonant coils as shown in Fig. 6, the power at the load R_L 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 Fig. 1.

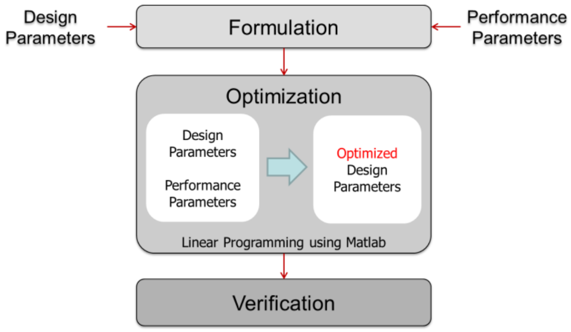
Power transfer efficiency is also an important factor for commercialization and should be reasonably high compared with other types of vehicles. To increase the efficiency, we need to minimize the loss at each stage of the OLEV power system. With the development of power components operating at 20 kHz, which were not available a few decades ago, the efficiency of the inverter has been significantly increased. Also, the mutual inductance should be increased, and the parasitic resistance R_1 and R_2 - the loss from these resistances - should be decreased as shown in Fig. 6 to further increase efficiency.

The third criterion, EMF leakage, is proportional to the magnitude of the current and inversely proportional to the distance between current position and measurement position without a shield. However, as the application of passive and active shields significantly changes the magnitude of EMF, the design of the EMF should be performed separately. This will be discussed in the next section.

The previous design procedure for OLEV wireless power transfer systems is shown in Fig. 7(a). At the early stage of design, we have to determine the topology and outline of the dimensions for the physical structures, such as the number of coils, coil size and dimension, and the position of the ferrite core. This is because the mutual inductance is roughly determined when the physical dimension is fixed and it is hard to change the value significantly at a later stage. Design freedom is therefore limited and the final design parameter is difficult to optimize. For optimal design, several parameters should be considered simultaneously during the design stage. The optimization stage is necessary after the design parameters and performance parameters have been defined, as shown in Fig. 7(b). This will be discussed in section V.



(a) Previous procedure



(b) Suggested procedure

Fig. 7. Design procedures of wireless power transfer system in OLEV.

Table 1. Sensitivity analysis of transferred power for the change of design parameters.

Design parameters		Change of parameters (%)			
		−20	−10	+10	+20
Dimension parameters	Air gap	+46.3	+20.1	−15.9	−33.9
	Number of turns in pickup coil	−44.0	−21.0	+21.0	+44.0
	Dist. between rail wires	−40.0	−18.6	+17.1	+35.1
	Pickup coil width	−24.2	−9.5	+6.9	+12.2
Material parameters	Permeability (μ)	−1.0	−0.4	+0.4	+0.72
	Permittivity (ε)	0	0	0	0
	Conductance (σ)	0	0	0	0
	Frequency	−44.1	−20.7	+21.3	+45.2
Electrical parameters	Current	−44.0	−21.0	+21.0	+44.0
	Frequency	−44.1	−20.7	+21.3	+45.2

Table 1 shows the result of simulated sensitivity analysis of transferred power for the change of main design parameters, which is the reference for the optimization of the design. At each design stage, a sensitivity analysis on the effect of each design parameter has been performed using simulation with 3-dimensional field solver.

Ⅳ. Electromagnetic Field Shielding

Fig. 8 shows the magnetic flux density distribution of OLEV. In the case of the vertical magnetic flux type, there is one magnetic flux path between the power lines and pick-up module where the power is transferred. The return flux comes back to the power lines via the sides of the main flux path. The horizontal magnetic flux type has two magnetic flux paths. The side power lines of this type have return flux paths on the side of the main flux path. The return flux path creates the fringing magnetic flux, and this flux is measured as the EMF level of OLEV. In this work, the target EMF level is 62.5 mG, according to Korea Communications Commission regulations, which follows the ICNIRP design guideline [8].

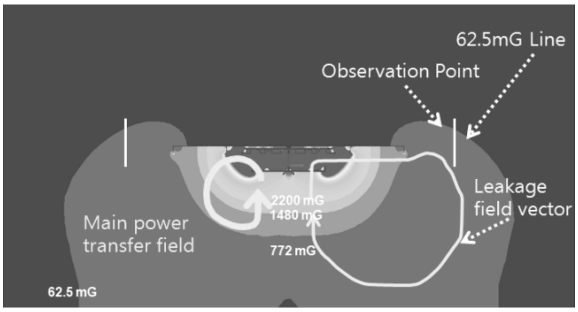


Fig. 8. Distribution of magnetic field for OLEV.

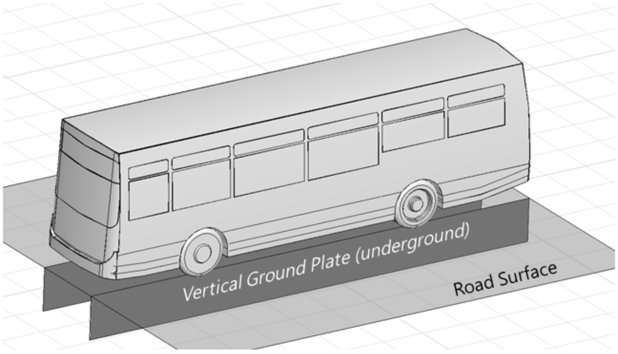


Fig. 9. Construction vertical ground plate for passive shield.

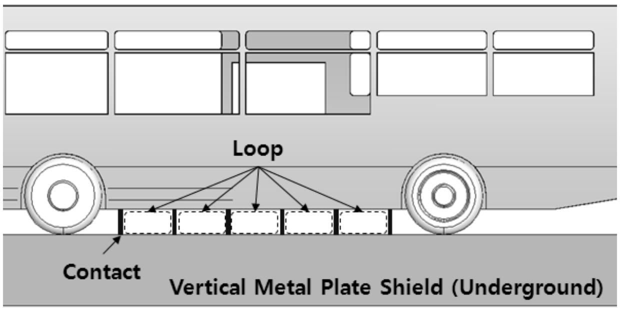


Fig. 10. Connections between vehicle body and underground vertical metal plate for passive shield.

As the OLEV power supply system generates large amounts of magnetic field in order to transfer the 60 kW of power necessary for the vehicle, there are tens of thousands of mG of magnetic flux between the power lines and pick-up module beneath the vehicle while power is being transferred. As a result, if just 0.1 % of magnetic field leakage occurs, the EMF level could exceed the regulation 62.5 mG. The distribution of magnetic field for OLEV is shown in Fig. 8.

Basically, passive shielding using metal plates is applied to OLEV in order to reduce the electromagnetic field. To protect passengers from the magnetic field, a metal plate is applied to the bottom of the vehicle. As the power lines are the source of the magnetic field, vertical plate shields are applied as shown in Fig. 9 [9], [10].

To improve effectiveness of the passive shield, we additionally applied soft contacts between the bottom plate and vertical ground plate by metal brushes, as shown in Fig. 10. The metal brush is a bundle of thin metal wires attached beneath the bottom plate which connect the current path between the vehicle body and the ground plate beneath the road surface. A photograph of the implemented metal brush is shown in Fig. 11. The number

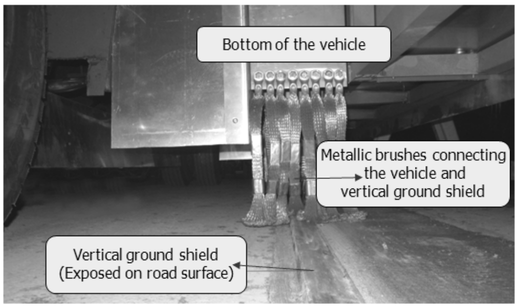


Fig. 11. Photo of implemented metal brush in passive shield.

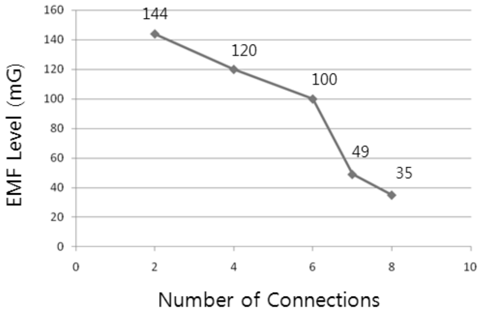


Fig. 12. Effect of the number of connections between the metallic vehicle body and the horizontal ground shield.

of connections using metal brushes is a significant factor in improving the effectiveness of the passive shielding. The EMF level decreases from 144 mG to 35 mG when the number of connections using metal brushes is increased from 2 to 8, as shown in Fig. 12.

The EMF can be minimized by active shielding with or without passive shields independently, and the basic concept of the active shield is shown in Fig. 13. 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 pick-up [11].

In the design of the active shield, the directions of magnetic fields by the source and the active shield should be carefully considered. In Fig. 14, the direction of magnetic field is shown. To make the EMF level less than the regulation at all positions, the magnetic field from the active shield should be almost the same as that from the pick-up module at all positions. More than 20 cm above the road surface, the magnetic field vector is parallel to the metal plate because of the metallic shield at the bottom of the vehicle. Therefore, placing the active shield close to the pick-up coil is more effective. However, if the active shield is closer to the pick-up coil, the current of the active shield should be larger. For this reason, the placement of the active shield is compromised considering the shielding effectiveness and current magnitude. At the optimal value of current, the magnetic flux density is reduced to 1/10 of the density without the active shield, as depicted in Fig. 15.

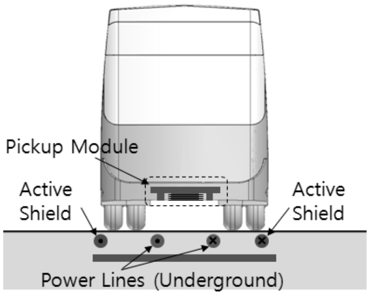


Fig. 13. Concept of active shield for OLEV.

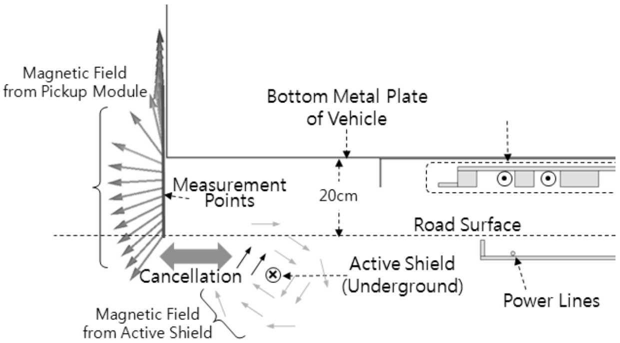


Fig. 14. Direction of magnetic field from pick-up module and active shield.

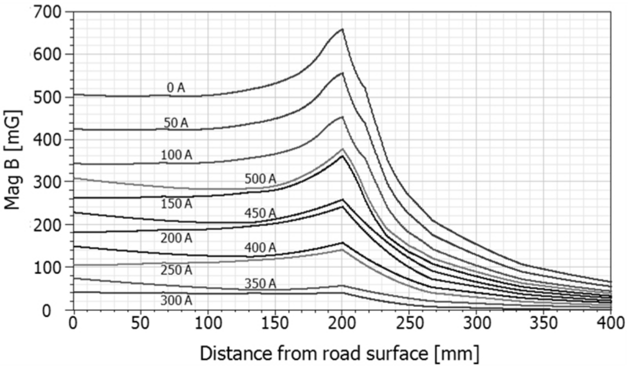


Fig. 15. Change of EMF level according to the current of active shield.

Ⅴ. Optimization of Design Parameters

To optimize the design, we first formulate a parameter optimization problem, such that the transferred power to the pick-up, $P_{Transfer}$ which is consumed at the load R_L of Fig. 6, is maximized while EMF level and power transfer efficiency, K satisfy the requirements. We assume that the power transfer efficiency should be greater

Table 2. System parameters.

Constant system parameters	
Air-gap	g_{Air}(=20 cm)
Resonance frequency	f (= 20 kHz)
Parasitic resistance of power lines	R_1 (=0.1 Ω)
Parasitic resistance of pick-up coil	R_2 (=0.1 Ω)
Load resistance	R_L (= 10 Ω)
System design parameters	
Width of pick-up coil	W_C
Current of power lines	I_S
Number of turns in pick-up coil	N

than or equal to 0.8, and the EMF leakage should be less than or equal to 62.5 mG.

Table 2 shows system parameters, which are divided into two categories: constant system parameters and variable system design parameters. We assume that the air-gap between power lines and pick-up coils, resonance frequency, parasitic resistance of power lines, parasitic resistance of pick-up coil, and load resistance are given as in Table 2. We can change three system design parameters: width of pick-up coil W_C, current of power lines I_S, and number of turns in pick-up coil n.

Accordingly, we formulate our optimization problem as follows:

$$\begin{aligned}
&\text{variables}: W_C,\ n,\ I_S \\
&\text{maximize } P_C \\
&\text{such that} \\
&\qquad EMF \le 62.5(mG), \\
&\qquad K \ge 0.8, \\
&\qquad 0 \le W_C \le W_{C,\max},\ 0 \le n \le n_{\max},\ 0 \le I_S \le I_{S,\max}.
\end{aligned} \tag{3}$$

where $W_{C,max}$, n_{max}, and $I_{S,max}$ are the allowable maximum values of W_C, n, I_S, respectively. To solve our problem, we need to express P_C, K, EMF in terms of W_C, n, I_S. Since $V_C=j(2\pi f)MnIS$, the induced voltage V_C is proportional to f, n, and I_S. Moreover, the EMF is proportional to n and I_S. Fig. 16 shows the effect of W_C on V_C and the EMF. The difference between the simulation result and the mathematical model should be minimized to improve the accuracy of the design parameter optimization procedure.

From Fig. 16, we obtain the approximate expressions for V_C and EMF as follows:

$$|V_C| \approx c_1 f n I_S \sqrt{W_C}\ , \tag{4}$$

$$EMF \approx c_2 n I_S {W_C}^2 \tag{5}$$

where C_1 and C_2 are constants. Then, transfer power $P_{Transfer}$ and total power P_{Total} at resonant frequency can be represented as:

$$P_{Transfer} = \frac{V_C^2}{R_C} \approx \frac{c_1^2}{R_C} f^2 n^2 I_S^2 W_C\ , \tag{6}$$

$$P_{Total} \approx R_1 I_S^2 + \frac{c_1^2}{R_C} f^2 n^2 I_S^2 W_C\ . \tag{7}$$

Therefore, the power transfer efficiency is:

$$K = \frac{P_{Transfer}}{P_{Total}} \approx \left(1 + \frac{R_1 R_L}{c_1^2 f^2 n^2 W_C}\right)^{-1}\ . \tag{8}$$

From (5), (6), (8), we can express the optimization problem in (1) as follows:

$$\begin{aligned}
&\underset{n,\mathrm{I_S},W_C}{\text{maximize}}\ \alpha_1 f^2 n^2 I_S^2 W_C \\
&\text{such that} \\
&\qquad n I_S W_C^2 \le \alpha_2 \\
&\qquad f^2 n^2 W_C \ge \alpha_3 \\
&\qquad 0 \le W_C \le W_{C,\max}, 0 \le n \le n_{\max}, 0 \le I_S \le I_{S,\max}
\end{aligned} \tag{9}$$

where

$$\alpha_1 = \frac{c_1}{R_C},\quad \alpha_2 = \frac{62.5}{c_2},\quad \alpha_3 = \frac{R_1 R_L}{c_1^2 f^2 \left(\dfrac{1}{0.8} - 1\right)}.$$

Let $x = \log(n), y = \log(I_S), z = \log(W_C)$. Then, the optimization problem in (9) can be restated as:

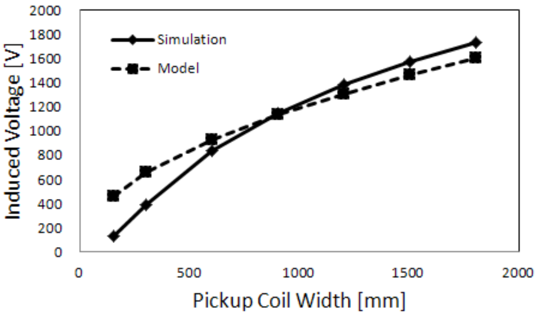
$$\begin{aligned}
&\underset{x,y,z}{\text{maximize}}\ 2x + 2y + z + \beta_1 \\
&\text{such that} \\
&\qquad x + y + 2x \le \beta_2 \\
&\qquad 2x + z \ge \beta_3 \\
&\qquad x \le x_{\max},\ y \le y_{\max},\ z \le z_{\max}
\end{aligned} \tag{10}$$

where

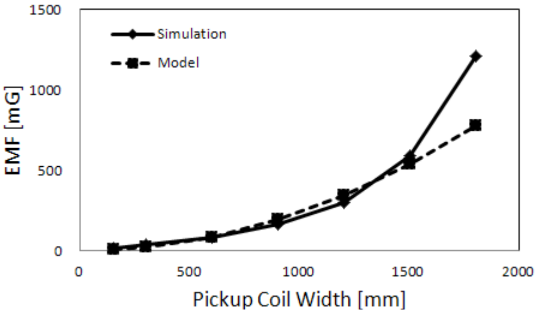
$$\beta_i = \log(\alpha_i), i = 1,2,3,\ \ x_{\max} = \log(n_{\max}),$$
$$y_{\max} = \log(I_{S,\max}),\ \ z_{\max} = \log(W_{C,\max}).$$

Note that the problem (10) is a form of typical linear programming (LP) problem.

In the process of finding optimal design parameters, the parameters which maximize transfer power are determined. The width of pick-up coil should be minimized because it increases EMF more significantly than current and number of turns. Similarly, the current and the number of turns should be increased unless it violates the boundary conditions. The boundary conditions on

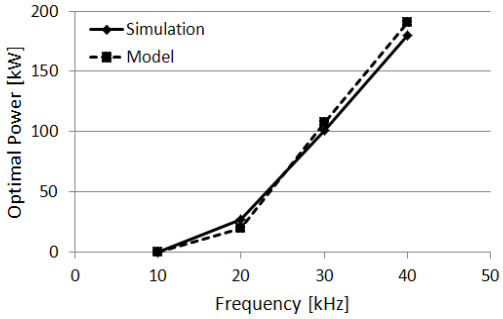


(a) Effect of W_C on induced voltage

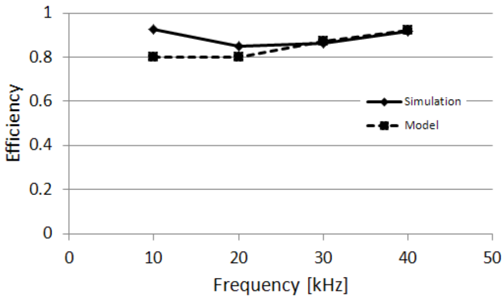


(b) Effect of W_C on EMF

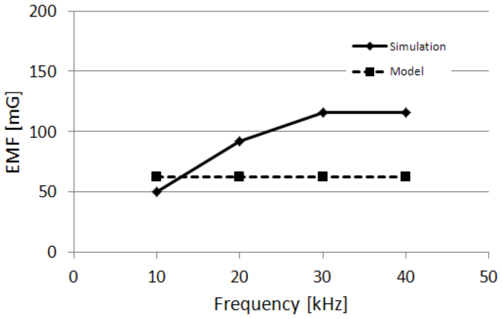
Fig. 16. Simulation data and approximation with equation for the effect of W_C on induced voltage V_C and EMF.



(a) Optimal power



(b) Efficiency, K



(c) EMF

Fig. 17. Optimal transferred power, efficiency, and EMF for different values of frequency.

power transfer efficiency affect the design parameters when the frequency is low or mutual inductance is small. Once the product of frequency and mutual inductance is large enough, the EMF is the only boundary condition, and then the combination of the design parameters is determined to make the EMF 62.5 mG, which is the maximum value allowed in the optimization. In this EMF boundary, the current and number of turns are maximized until they reach the maximum value we set as $W_{C,max}$, n_{max}, $I_{S,max}$ in (9). Finally, two maximum values of n_{max}, $I_{S,max}$ determine the transferred power because the number of turns and current should reach the maximum value for maximum power.

Now, we obtain the optimal solution for the problem (10) and compare it with the simulation results to investigate the validity of the approximation for LP formulation. Fig. 17 shows the optimal transfer power P_C and the variation of constraints such as EMF and K for different values of the frequency f. The optimal power increases as the frequency increases because frequency simply increases the transfer power and has no effect on EMF. The efficiency and EMF should be maintained at the specific level. We can find that the simulation results are similar to the LP solution, which means that the approximation for LP formulation is reasonable. More accurate results can be obtained by applying more complex numerical models in (4) and (5), which describes the voltage and EMF more accurately.

Ⅵ. Conclusions

Design methodologies for the high efficiency of power transfer and the reduction of electromagnetic fields from the system have been proposed. To achieve 80 % of the power transfer efficiency with 60 kW of power transfer capability, we suggested a vertical magnetic flux type pick-up coil and optimized the design parameters. The design of series resonant coils and frequency selection were the key design factor in securing high OLEV system efficiency. Also, a passive metallic plate shield and active shield are proposed to minimize EMF leakage from the OLEV wireless power transfer system. By applying these shielding techniques to a commercial product, we achieved EMF levels lower than 62.5 mG.

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