Abstract
In the mechanism of wireless power transfer in on-line electric vehicle (OLEV), the design of magnetic field is the key technology to determine its electrical performance of power transfer capacity, transfer efficiency, and electromagnetic field (EMF) level. To satisfy all the requirements, systematic approach for optimization of design parameters is required. Even though shielding for reduction of EMF can be applied independently, the shielding effectiveness of the applicable shielding method should be considered in optimization of design parameters. In this paper, we introduce the wireless power transfer mechanism and the EMF reduction techniques, 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, Efficiency, Optimization, Linear Programming

1 INTRODUCTION
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 cause electric vehicles to price themselves out of the automotive marketplace.

KAIST has introduced a novel on-line electric vehicle (OLEV), 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
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.

2 POWER TRANSFER MECHANISM
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 3. 60 Hz for power transfer is converted to 20 kHz at the inverter stage and a current of about 200A flows through the power lines. The magnetic flux generated from the power lines is gathered at the pickup module to generate DC power for the vehicle motor. The non-contact power transfer that occurs between the power lines and the pickup module generates a huge magnetic flux. So, the design of the power lines and the pickup module are the key technologies for effective power transfer and the solution of the electromagnetic field (EMF) problems.

Figure 3 shows the vertical magnetic flux of the power lines and pickup module. There are two power lines with opposite current directions underneath 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 added. The pickup module catches the vertical magnetic flux through copper coils around the ferrite core. This type has the advantage of 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 pickup module.
3 DESIGN METHODOLOGY

3.1 Definition and Formulation of Design Criteria

In the design of the power lines and the pickup module structure for OLEV system, we consider three criteria for the electrical performance of the wireless power transfer system: power transfer capability, power transfer efficiency, and leakage from the electromagnetic field.

The 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 maximum speed and recharging time of the vehicle. From the simplified equivalent circuit model of the wireless power transfer system with two series resonant coils as shown in Figure 4, the power at the load \( P_L \) 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 (1).

The power transfer efficiency is also an important factor for commercialization and it should be reasonably high compared with the efficiency of other types of vehicles. To increase the efficiency, we need to minimize the loss at each stage of the power system of OLEV. With the development of power components operating at 20 kHz, which was not available tens of years ago, the efficiency of the inverter in Figure 2 is significantly increased. Also, the mutual inductance should be increased, and the parasitic resistance \( R_1 \) and \( R_2 \) which are the loss from these resistances should be decreased as derived in (2) to increase the efficiency even more.

The third criterion of leakage EMF is simply proportional to the magnitude of the current and inversely proportional to the distance between current position and measurement position without a shield as shown in Eq. (3). However, as the application of passive and active shields significantly changes the magnitude of EMF, the design of the EMF should be performed separately which will be discussed in the next section.

\[
\begin{align*}
    P_L & \equiv \frac{\omega^2 M^2}{(R_2 + R_L)^2 + \frac{\omega^2 L_2}{\omega^2 C_2}} t_i^2 R_1 \equiv \frac{\omega^2 M^2}{R_1} t_i^2 \\
    K & \equiv \frac{\omega^2 M^2 R_L}{R_i (R_2 + R_L)^2 + \omega^2 M^2 (R_2 + R_L)} \cong \frac{1}{1 + \frac{R_1 R_L}{\omega^2 M^2}}
\end{align*}
\]

3.2 Previous Procedure of Wireless Power Transfer System Design

The previous design procedure for the wireless power transfer system for OLEV is shown in Figure 5. 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 because the mutual inductance is roughly determined when the physical dimension is fixed and it is hard to change the value significantly in the latter stage.

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 parameters has been performed using simulation with 3-dimensional field solver.

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Change of Parameters</th>
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<tbody>
<tr>
<td>Air Gap</td>
<td>-20%</td>
</tr>
<tr>
<td>Number of Turns in Pickup Coils</td>
<td>-10%</td>
</tr>
<tr>
<td>Dist. between Rail Wires</td>
<td>0%</td>
</tr>
<tr>
<td>Pickup Coil Width</td>
<td>+10%</td>
</tr>
<tr>
<td>-20%</td>
<td></td>
</tr>
<tr>
<td>-10%</td>
<td></td>
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<tr>
<td>0%</td>
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<td>+10%</td>
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<td>+20%</td>
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</tbody>
</table>

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

4 SHIELDING FOR REDUCTION OF EMF

4.1 Passive Shielding

Figure 6 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 pickup 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 of OLEV is 62.5 mG according to the regulation of Korea Communications Commission which follows the ICNIRP design guideline [4-5].

As the power supply system of OLEV generates large amounts of magnetic field to transfer 60 kW of power which is necessary for the vehicle, there are tens of thousands mG of magnetic flux between the power lines and pickup module beneath the vehicle while power is transferred. So, if even 0.1% of leakage magnetic field comes out from OLEV system, the EMF level could exceed the regulation of 62.5 mG. The distribution of magnetic field for OLEV is shown in Figure 6.

To improve the shielding effectiveness of the passive shield, we additionally applied soft contacts between bottom plate and vertical ground plate by metal brushes as shown in Figure 8. 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. The photograph of implemented metal brush is shown in Figure 9.

The number of connections using metal brushes is a significant factor to improve the shielding effectiveness of the passive shield. The EMF level has been decreased from 144 mG to 35 mG when the number of connections using metal brushes is increased from 2 to 8 as shown in Figure 10.
4.2 Active Shielding

The EMF can be minimized by active shielding with or without passive shields independently, and the basic concept of active shield is shown in Figure 11. 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 the design of active shield, the directions of magnetic fields by the source and active shield should be carefully considered. In Figure 12, 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 pickup module at all positions. At the position above 20cm from road surface, the magnetic field vector is parallel to the metal plate because of the metallic shield at the bottom of the vehicle. So, to place the active shield close to the pickup coil is more effective. However if the active shield goes closer to the pickup 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.

In Figure 13 (a) and (b), the magnetic flux density with and without active shielding is depicted. When the active shield is applied, the leakage magnetic flux is cancelled by the magnetic flux from the active shield and significantly reduced to less than the regulation of 62.5 mG. Figure 12 shows the optimization procedure of the active shield design where the position and current magnitude should be determined. 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 Figure 14.


5 DESIGN PARAMETER OPTIMIZATION

5.1 Formulation of Design Parameters

In this section, we formulate a parameter optimization problem such that the transferred power to pickup, $P_{\text{transfer}}$, which is consumed at the load $R_L$ of Figure 2, is maximized while EMF level 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 the leakage EMF 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 pickup coils, resonance frequency, parasitic resistance of power lines, parasitic resistance of pickup coil, and load resistance are given as in Table 2. We can change three system design parameters: width of pickup coil $W_C$, current of power lines $I_S$, and number of turns in pickup coil $N$.

Accordingly, we formulate our optimization problem as follows:

$$EMF \leq 62.5(mG),$$

such that

$$K \geq 0.8,$$

$$0 \leq W_C \leq W_{\text{C,max}}, 0 \leq n \leq n_{\text{max}}, 0 \leq I_S \leq I_{S,max}.$$  (1)

From Figure 15, we obtain the approximate expressions for $V_C$ and EMF as follows:

$$V_C \approx c_1 f n I_S W_C,$$  (2)

$$EMF \approx c_2 n I_S W_C^2.$$  (3)

Figure 15: Simulation data and approximation with equation for the effect of $W_C$ on (a) induced voltage $V_C$ (b) and EMF level
where $C_1$ and $C_2$ are constants. Then, transfer power $P_{\text{transfer}}$ and total power $P_{\text{total}}$ at resonant frequency can be represented as

$$P_{\text{transfer}} = \frac{V_C^2}{R_C} \approx \frac{C_1^2}{R_C} f^2 n^2 \sqrt{\gamma} W_C,$$

(4)

$$P_{\text{total}} \approx R_C I_S^2 + \frac{C_2}{R_C} f^2 n^2 I_S W_C.$$

(5)

Therefore, the transfer power efficiency is

$$K = \frac{P_{\text{transfer}}}{P_{\text{total}}} = \left(1 + \frac{R_C R_L}{C_1^2 f^2 n^2 W_C}\right)^{-1}.$$  

(6)

From (3), (4), (6), we can express the optimization problem in (1) as follows:

$$\text{maximize } \alpha_1 f^2 n^2 \gamma W_C$$

such that

$$nl_3 W_C^2 \leq \alpha_2$$

$$f^2 n^2 W_C \geq \alpha_3$$

$$0 \leq W_C \leq W_{C,\text{max}}, 0 \leq n \leq n_{\text{max}}, 0 \leq l_3 \leq l_{S,\text{max}}$$

(7)

where

$$\alpha_1 = \frac{C_1}{R_C}, \quad \alpha_2 = \frac{62.5}{C_2}, \quad \alpha_3 = \frac{R_C R_L}{C_1^2 f^2 \left(\frac{1}{0.8} - 1\right)}.$$  

Let $x = \log(n)$, $y = \log(l_3)$, $z = \log(W_C)$. Then, the optimization problem in (7) can be restated as:

$$\text{maximize } 2x + 2y + 2z + \beta_1 y^2$$

such that

$$x + y + 2x \leq \beta_2$$

$$2x + z \geq \beta_3$$

$$x \leq x_{\text{max}}, \quad y \leq y_{\text{max}}, \quad z \leq z_{\text{max}}$$

(8)

where

$$\beta_1 = \log(\alpha_1), \quad \beta_2 = 1, \quad \beta_3 = 3, \quad x_{\text{max}} = \log(n_{\text{max}}),$$

$$y_{\text{max}} = \log(l_{S,\text{max}}), \quad z_{\text{max}} = \log(W_{C,\text{max}}).$$

Note that the problem (8) is a form of typical linear programming (LP) problem.

5.2 Numerical Results of Design Parameters

In the process of finding optimal design parameters, the parameters which maximize the transfer power are determined. The width of pickup 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 the 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 $W_{C,\text{max}}, n_{\text{max}}, l_{S,\text{max}}$ in (7). Finally, two maximum values of $n_{\text{max}}, l_{S,\text{max}}$ 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 problem (8) and compare it with the simulation results to investigate the validity of the approximation for LP formulation. Figure 16 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 (2) and (3) which describes the voltage and EMF more accurately.
Figure 17 plots the optimal power for different values of the frequency $f$ and the load $R_L$. When the load resistance increases, the optimal power decreases and the power transfer efficiency slightly decreases. At the center of the surface in Figure 17, there is an edge across the surface, which is generated due to the power efficiency boundary condition. The power transfer efficiency boundary is critical when the frequency and load resistance are in this range.

![Optimized transferred power for different values of frequency and load resistance](image)

6 CONCLUSIONS

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. The two procedures of reducing EMF and optimizing the wireless power transfer system design parameters are performed. For a more accurate design, more complex modelling of design parameters is required. 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.

7 ACKNOWLEDGMENTS

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8 REFERENCES