Magnetic Field Design for High Efficient and Low EMF Wireless Power Transfer in On-Line Electric Vehicle

Seungyoung Ahn and Joungho Kim

Department of EECS, Korea Advanced Institute of Science and Technology
Daejeon, Republic of Korea
sahn@kaist.ac.kr

Abstract—In this paper, we introduce the On-Line Electric Vehicle (OLEV) system and its non-contact power transfer mechanism. We propose the design methodology to maximize the wireless power transfer capability and power transfer efficiency and to minimize the electromagnetic field (EMF) from the wireless power transfer system in OLEV. By using the series resonant power transfer topology and vertical magnetic flux type of wireless power transfer system for transformer structure, the power transfer capability of 60 kW and efficiency of 80% have been accomplished. Also, by applying passive and active shields, the EMF has been significantly reduced to satisfy the regulation of 62.5 mG.

I. INTRODUCTION

Even though intensive researches have been performed on fully electric vehicles for a long time, still we are facing serious problems to be solved in the battery-powered electric delivery system. These issues are enlarged size, weight, and cost of battery, recharging time, and limited availability of charging service points. Moreover, diminished stocks of lithium could cost increasingly high prices and lead to electric vehicles pricing themselves out of the automotive marketplace.

Recently, KAIST has introduced the novel on-line electric vehicle (OLEV), in which the automotive vehicle constantly receive and recharge their power from the power lines embedded underneath the surface of the road. OLEV has the reduced battery capacity to about 20% compared to that of the conventional battery-powered electric vehicles, while it can consequently minimize the weight and the price of the vehicle and power station.

II. WIRELESS POWER TRANSFER SYSTEM IN OLEV

The concept of the wireless power transfer system applied for electric vehicles, where energy is transferred continuously even while the vehicle is moving, has been introduced even tens of years ago [1]. However, it is reported that the previous system could not be the substitute of fuel engine very efficient to substitute because of noise problem and low efficiency of overall power transfer system. In this paper, we introduce the OLEV system and its non-contact power transfer mechanism. The design methodology for high efficient wireless power transfer system and active and passive shielding techniques for the reduction of electromagnetic field (EMF) from the power line and vehicle are proposed.

The wireless power transfer system in OLEV consists of an inverter, power lines, pickup module, capacitors, battery, and motor as shown in Fig. 2. The 60 Hz of power is converted into 20 kHz at the inverter stage, and the current of 200A flows through the power lines. The magnetic flux generated from the power lines is gathered at the pickup module to recharge the batteries and/or to generate DC power to drive the motor of the vehicle.

As 60 kW of power is wirelessly transferred from power lines to pickup module, the design of power lines and the pickup module are the key technologies for efficient power transfer and also for reduced EMF as all the commercial product should keep the EMF regulations.

Fig. 1 Photograph of on-line electric vehicle system

Fig. 2 The block diagram of overall system for OLEV. The design of power lines and pickup module determines the performance of power transfer system and leakage electromagnetic field.
Fig. 3 shows proposed vertical magnetic flux type power lines and pickup module pair for wireless power transfer from the power lines to the coil in the 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, magnetic flux is induced around each power line and the magnetic fluxes from two power lines are added at the center between the power lines. Pickup coil catches the vertical magnetic flux which passes through coils around the ferrite core.

III. DESIGN CRITERIA AND PROCEDURE

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

The power transfer capability implies the maximum of power 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 Fig. 4, 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 Eq. (1).

$$P_L \equiv \frac{\omega^2 M^2}{(R_L + R_1)^2 + \frac{1}{\omega^2 C_2^2}} I_1^2 R_L \equiv \frac{\omega^2 M^2}{R_L} I_1^2 \quad (1)$$

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. Thanks to the development of power components operating at 20 kHz, which was not available tens of years ago, the efficiency of the inverter in Fig. 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 Eq. (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 shield as shown in Eq. (3). However, as the application of passive and active shield significantly changes the magnitude of EMF, the design of EMF should be performed separately which will be discussed in the next chapter.

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

$$\text{EMF} \propto \frac{1}{d} \quad (3)$$

![Fig. 4 Simplified equivalent circuit model of power transfer system](image)
The design procedure of wireless power transfer system for OLEV is shown in Fig. 5. At the early stage of design, we have to determine the topology and outline of the dimensions for the physical structures such as number of coils, coil size, and dimension and position of ferrite core because the mutual inductance is roughly determined when physical dimension is fixed and it is hard to change the value significantly in the latter stage.

Fig. 6 shows the result of simulated sensitivity analysis of transferred power for the change of main design parameters which is the reference of the optimization of the design. At each design stage, the sensitivity analysis on the effect of each design parameters has been performed using simulation of 3-dimensional field solver.

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Change of Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between 1st and 2nd Coil</td>
<td>±46.3%</td>
</tr>
<tr>
<td>Number of Turns in 2nd Coil</td>
<td>±44.9%</td>
</tr>
<tr>
<td>Dist. between Rail Wires</td>
<td>±40.0%</td>
</tr>
<tr>
<td>Pickup Feinte Width</td>
<td>±24.2%</td>
</tr>
<tr>
<td>Permeability ($\mu$)</td>
<td>±1.0%</td>
</tr>
<tr>
<td>Permittivity ($\varepsilon$)</td>
<td>0%</td>
</tr>
<tr>
<td>Conductance (r)</td>
<td>0%</td>
</tr>
<tr>
<td>Electrical Parameters</td>
<td>Current</td>
</tr>
<tr>
<td>Frequency</td>
<td>±44.1%</td>
</tr>
</tbody>
</table>

Fig. 6 Sensitivity analysis of transferred power for the change of design parameters

IV. ELECTROMAGNETIC FIELD DESIGN

The design of electromagnetic field distribution is also a significant factor in wireless power transfer system especially in the high power transport system. As a magnetic flux more than hundreds of thousands mG from current of thousands of ampere-turn is generated between power lines and pickup coils, even 0.1% of leakage from main flux can be hundreds mG, which is several times larger than the magnetic flux regulation suggested by ICNIRP [2]. Therefore, it is very significant to control the leakage magnetic flux for wireless power transfer system in automotive application because of the high current in the system.

A. Passive Shield Design

The magnetic field shape in the wireless power transfer system first should be designed very carefully. However, OLEV requires some air gap, typically 20cm, between the road surface and the bottom of pickup coil for the movement of vehicle. As most of the leakage magnetic flux comes out through this gap, methods to suppress this magnetic flux should be adopted. There are a number of well-known techniques to reduce radiated emissions from many studies, and one of the most popular methods to reduce radiated emission is shielding [3][4].

Basically vertical metal plate is applied underground as shown in Fig. 8. To improve the shielding effectiveness of the passive shield, we additionally applied the soft contacts between bottom plate and vertical ground plate using metal brushes where each brush is consist of a bundle of metal wires attached beneath the bottom plate of the vehicle. The metal brushes implemented at the bottom of OLEV are shown in Fig. 9. When the number of connections using metal brushes increases, the EMF level has significantly decreased from 144 mG to 35 mG as shown in Fig. 10.
B. Active Shield Design

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 Fig. 11. Active shield can be useful when passive shield with contact of metal brush is not allowed. The active shield is also a metal wire which carries same frequency of current but the phase is the opposite of the current in the pickup for cancellation. In Fig. 12, the direction of magnetic field is shown. To make EMF level less than the regulation at all points, the magnetic field from active shield should be almost the same as that from pickup module at all points. Even though finding optimal point is not easy, we found several solutions in this application. At the position above 20cm from road surface, due to the metallic shield of the vehicle, the magnetic field vector is parallel to the metal plate. The magnetic field vector cancels the leakage magnetic field vector from the pickup module.

In Fig. 13, the magnetic flux density with and without active shield is depicted. When active shield is applied, the leakage magnetic flux is significantly reduced to less than the regulation of 62.5 mG.

![Fig. 11 Concept of active shield for OLEV](image)

![Fig. 12 Magnetic field vector cancellation using active shield.](image)

![Fig. 13 Reduction of EMF by active shield](image)

![Fig. 14 Simulated EMF level with different active shield current. The EMF level is minimized when active shield current is 300 A.](image)

V. CONCLUSION

Design methodologies for 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 pickup coil and optimized the design parameters. The design of series resonant coils and frequency selection were the key design factor for high efficiency of OLEV system. Also, passive metallic plate shield and active shield are proposed to minimize the leakage EMF from the wireless power transfer system in OLEV. By applying these shielding techniques to a commercial product, we achieved EMF level lower than 62.5 mG.

ACKNOWLEDGMENT

This work was supported by the OLEV project of KAIST and the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2010-0029179).

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