A Coil Design and Control Method of Independent Active Shielding System for Leakage Magnetic Field Reduction of Wireless UAV Charger

Jedok Kim†, Jangyong Ahn†, Sungryul Huh†, Kibeom Kim† and Seungyoung Ahn††

SUMMARY This paper proposes a single coil active shielding method of wireless unmanned aerial vehicle charger for leakage magnetic field reduction. A proposed shielding system eliminates the leakage magnetic field generated from the transmitting and receiving coils by generating the cancelling magnetic field. In order to enhance shielding effectiveness and preserve power transfer efficiency, shielding coil design parameters including radius and turns will analyze. Based on the analysis of coil design, shielding effectiveness and power transfer efficiency will estimate. In addition, shielding current control method corresponding to leakage magnetic field strength and phase will describe. A proposed shielding system has verified by simulations and experiments in terms of the total shielding effectiveness and power transfer efficiency measurements. The simulation and experimental results show that a proposed active shielding system has achieved 68.85% of average leakage magnetic field reduction with 1.92% of power transfer efficiency degradation. The shielding effectiveness and power transfer efficiency variation by coil design has been experimentally verified.

Key words: Active shielding, Wireless power transfer, Inductive power transfer, Electromagnetic field, Unmanned aerial vehicle (UAV)

1. Introduction

Currently, the utilizations of the unmanned aerial vehicle (UAV) are increasing, in the area of surveillance, geometric information, intelligent transportation system, and package delivery [1-4]. However, the UAV has the onboard power limitation that is caused by the limited battery capacity. The utilization of additional battery makes the increase of UAV weight, so UAV operation will not be efficient. For this UAV limitation, the applications of wireless power transfer (WPT) technologies to the UAV are drawing attention [5-7]. The advantages of the WPT application to the UAV are that WPT can provide convenient UAV charging, and it can contribute to the automated UAV operation. The inductive power transfer (IPT) is used for charging UAV because of their high power capacity and efficiency [8].

However, the IPT systems for UAV charging require high electric power compared to the portable device. This means that the high-density magnetic field will generate around the IPT system. In addition, this strong magnetic field could be a leakage magnetic field. This leakage magnetic field influences the adverse effect to human. The electromagnetic field (EMF) generating from UAV charger could be the severe safety issues compared to the portable device. This is because that the IPT system of the UAV generates high-density magnetic fields, but humans can adjacent to the charger like a portable device. Regarding this EMF for human exposure, most countries are strongly recommending compliance with the guidelines of the EMF for human exposure [9-10]. These guidelines are the minimum requirements for commercialization of the IPT system. However, EMF safety could not be assured even though the IPT system complies with the EMF limitations specified in the guidelines. This is because that no adverse health effects have been confirmed the current international EMF safety guidelines or exposure standards. Therefore, the EMF of IPT system should be minimized for ensuring safety of human health.

In order to reduce the leakage magnetic field, EMF shielding methods such as passive shielding, reactive shielding, and active shielding can be applied [11]. The passive shielding methods are classified into the conductive shielding and the magnetic shielding. The conductive shielding method provides high shielding effectiveness (SE), but high heat and power transfer efficiency (PTE) degradation will generate because of the eddy effect. The magnetic shielding method is to regulate an alternate magnetic flux path by using paramagnetic materials such as ferrite. The magnetic shielding method does not make PTE degradation, but SE of the magnetic shielding method is rapidly reduced when the air gap is in the magnetic flux path [12]. The reactive shielding method is another way to reduce EMF; and this shielding method can effectively reduce the EMF of the high power IPT system [13-14]. The reactive shielding method provides the high SE and less PTE degradation. The reactive shielding application in [14], about 53% of EMF had reduced, and this SE is enough to reduce the EMF of mobile phones. However, this could not be enough SE of the IPT system for UAV chargers.

The active shielding system can be considered as the alternative to reduce the EMF of the IPT system. A principle of the active shielding system is to eliminate the leakage magnetic field by generating the cancelling magnetic field. The cancelling magnetic field has the opposite vector direction with the leakage magnetic field so two magnetic

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fields are eliminated each other in terms of the phasor. The power supply methods of the active shielding systems can be classified into two types as 1) dependent power source, and 2) independent power source [15-16]. The dependent active shielding is to use partial turns of transmitting (TX) and receiving (RX) coils for shielding by designing reversed coil turns [15]. Each shielding coil for the TX and RX coil has 180° of phase differences for the powering TX and RX coil. However, this active shielding method requires an identical number of coils with the IPT system. This is because that the shielding coil of the dependent active shielding system dominantly operates for their parent coils.

The independent active shielding system is to supply shielding power from the independent power source [16]. This method can control appropriate shielding current in terms of the current strength and phase. The independent active shielding method proposed in [16] was the method to reduce electromagnetic field in specific area for protecting electronic device. This method provides the SE for the electronic device that is situated far from the IPT system. However, this method provides selective SE for a specific target area so the SE will be reduced except for the specific target shielding area. Accordingly, the independent active shielding method proposed in [16] cannot be used for EMF reduction for human exposure because EMF reduction for human exposure requires all around the IPT system. For this reason, design and control method of independent active shielding system specialized in EMF human exposure is necessary.

When applying the independent active shielding system, the coil design parameters such as radius and turns should be considered. This is because that the design parameters make the variations of magnetic field generation characteristics. In addition the design parameters of the shielding coil influence to impedance of the IPT system. This means that the SE and PTE could be decreased when the shielding coil is designed as not appropriate. Therefore, the coil design should be considered when applying the independent active shielding.

This paper proposes an independent active shielding method for the wireless UAV charger. The composition of this paper is as follows. In Section II, the analysis of the coil design and the shielding current determination method are presented. In Section III, the verifications of the proposed active shielding system by EM simulation and experiments are presented.

### 2. Coil design and control of active shielding system

Fig. 1 shows the conceptual structure of the UAV charging system with a proposed active shielding system. A direct current (DC) is converted to AC power that has a specific operating frequency through the inverter. This AC power is supplied to the TX coil, and the TX coil generates the magnetic field for transmitting power. The magnetic field generated by the TX coil is excited to the RX coil, and the excited TX magnetic field makes induced voltage at the RX coil. As a result, the RX coil generates a magnetic field so electric power can be transferred without any conductive connection.

When the IPT system is in operation, TX and RX coil generate high intensity magnetic field. The magnetic fields are generated from two coils, and two magnetic fields have different magnetic vector so the leakage magnetic field will generate as the synthesized magnetic field. The canceling magnetic field strength should be identical and the phase should be 180° for the synthesized leakage magnetic field. In order to achieve this condition, position, radius, turns, and control of the shielding system should be analyzed.

#### 2.1 Magnetic field calculation

\begin{align}
B_{spiral} & \approx \sum_{i=1}^{n} B_{i} \cdot dl \\
B_{p-spiral} & \approx \sum_{i=1}^{n} B_{i} \cdot N_{si} \\
& \approx \sum_{i=1}^{n} \mu_{0} \left( \frac{k_{ri}}{r_{si}} \right)^{2} I_{0} \sin \theta_{p-N_{si}} e^{-jk_{ri}d_{p-N_{si}} \cdot \theta_{si}}
\end{align}

where, \( \theta_{si} = \sin \left( \theta_{p-N_{i}} \cos \varphi_{p-N_{i}} \cos \varphi_{p-N_{i}} \right) \)
Fig. 2(a) shows the geometrical model of the distance to point \( p \) from the center of coil. The magnetic field strength at point \( p \) is the variable of coil radius, current and distance from coil center to point \( p \). If the coil is designed as multiple turns, the calculation of magnetic field strength should be considered in terms of the changes of the radius. Fig. 2(b) shows the flat spiral circular coil and all coil turns are coplanar. The total magnetic field \( B_{p-spiral} \) generated from flat spiral coil can be calculated as (1). However, the coil radius is gradually changed turn by turn so the magnetic field strength at point \( p \) \( B_{p-spiral} \) should consider these changes, and these can be calculated as (2) by considering gradually changing coil radius. Note that \( \mu_0 \) is the permeability of free space, \( k \) is the wave number \( (2\pi/\lambda) \), \( \lambda \) is the wavelength \( (c/f) \), \( c \) is the velocity of light \( (3 \times 10^8 \text{ m/s}) \), \( f \) is the frequency, \( r_{N_{St}} \) is the coil radius, and \( N_{St} \) \( (i=1,2,\ldots,n) \) is the coil turn.

2.2 Determination of the shielding coil position

![Image](51x395 to 161x458)

(a) Charging on the ground  (b) Charging on the vehicle roof

Fig. 3 EMF to human exposure in accordance with charger position

The more distance is increased, the more magnetic field strength is will gradually decrease. This means that the required shielding current will increase when the shielding coil is installed far from the target shielding region. Fig. 3(a) shows the example of the UAV charger position that is installed on the ground. When the UAV charger is installed on the ground, the target shielding region will be the upper side of the charger. In this case, the shielding coil position is recommended to install near the RX coil because this position is close to the target shielding area. In other words, less power consumption for shielding is required. On the contrary, the case that the UAV charger is installed on the roof of the vehicle as shown in Fig. 3(b), the target shielding region will be the lower side from the UAV charger. In this case, it is better to install the shielding coil near the TX coil in terms of the power consumption reduction for shielding. In this paper, we assume that the UAV charger is installed on the ground so a position of shielding coil has determined near the RX coil.

Fig. 4 shows the geometric coil array of the TX, RX, and shielding coil. The shielding coil is coaxial with the TX and RX coil of the IPT system. This means that all coils have an identical distance for the \( x \)-axis and \( y \)-axis to point \( p \) so the distance of the \( x \)-\( y \) axis from the point \( p \) can calculate as \( \sqrt{d_{xp}^2 + d_{yp}^2} \) in the Cartesian coordinate system. However, the distance of \( z \)-axis is different, so the distance to point \( p \) will differ with regard to the \( z \)-axis. When the RX and shielding coil are coplanar, distance from the TX coil to point \( p \) \( d_{TXp} \) can calculate as (3), and distance from the RX and shielding coil \( d_{RXp}, d_{SHP} \) can calculate as (4).

\[
d_{TXp} = \sqrt{(d_{xp}^2 + d_{yp}^2) + (d_{z1} + d_{z2})^2} \quad (3)
\]

\[
d_{RXp} = d_{SHP} = \sqrt{(d_{xp}^2 + d_{yp}^2) + d_{z2}^2} \quad (4)
\]

\( B_{p-Total} \) is the total magnetic field at point \( p \) and it is determined by the summation of the magnetic field generated from the TX, RX, and shielding coil at point \( p \) as (5), and the SE is defined as (6). \( B_{p-TX}, B_{p-RX}, \) and \( B_{p-SH} \) are the magnetic flux of the TX, RX and shielding coil respectively, and these are calculated corresponding to the coil design through (2). Obviously, the SE may enhance when the total magnetic field is minimized. This means that the SE is determined by generating a canceling magnetic field corresponding to the leakage magnetic field. TX and RX magnetic field could have different strength and phase, so a current of shielding coil should determine to generate an identical canceling magnetic field with a leakage magnetic field in terms of the strength and phase.

\[
B_{p-Total} = B_{p-TX} + B_{p-RX} + B_{p-SH} \quad (5)
\]

\[
SE = 100 \times \left( 1 - \frac{B_{p-Total}}{B_{p-TX} + B_{p-RX}} \right) \quad (6)
\]

![Image](51x395 to 161x458)

SH coil  RX coil  TX coil

Fig. 4 Geometric array and distance of the TX, RX, and shielding coil

2.3 Coil position determination

In order to achieve high SE, the shielding coil should be designed that is able to generate the identical magnetic field with the leakage magnetic field. This means that the high SE at point \( p \) can be achieved by determining appropriate coil design and controlling a current of the shielding coil. However, the difference of the magnetic field generation characteristics will be increased by the difference of the coil radius. In other words, identical magnetic field
strength can be achieved in a specific area, but it cannot achieve at the other area because of the difference of magnetic field generation characteristics. Therefore, the radius difference between the TX, RX, and a shielding coil will hinder uniform SE.

Fig. 5(a) shows the magnetic field strength variations by the coil radius. The coil that has a small radius generates a strong magnetic field near to coil center, but it is sharply decreased compared to a large radius coil. On the contrary, the large radius coil generates a weak magnetic field near to coil center, but it is slowly decreased comparing a small radius coil. These differences of the magnetic field generation characteristics caused by the radius will influence the SE. More specifically, the more shielding coil radius is increased compared to the TX or RX coil, the more discrepancy of the magnetic field will increase. This means that the SE in the center of the coil will decrease because the shielding coil that has a large radius generates a weak magnetic field at the center of the coil. On the contrary, the canceling magnetic field will stronger than the leakage magnetic field as far as increasing the distance from the coil center.

Similarly, the number of turns makes the changes of magnetic field characteristics because each coil turn has a different radius because of coil pitch. Fig. 5(b) shows the magnetic field strength variation by coil turns. The inside turns generate magnetic field as small radius coil, but outside turns generate magnetic field as large radius. This means that if the number of shielding coil turns have increased, a discrepancy of magnetic field generated from inside and outside coil will increase. Therefore, the SE will be changed when the shielding coil is designed as multiple coil turns. In addition, the shielding coil design that has large radius compared to TX and RX coil can make the increase of the total magnetic field in specific regions.

Fig. 6 shows the relationship of magnetic field vector in accordance with the position. The canceling magnetic field is harmonized with the leakage magnetic field in the area between IPT coil and shielding coil. This phenomenon is caused by the reversal of the magnetic field vector. The canceling magnetic field has the opposite vector of the leakage magnetic field, so it cancels the leakage magnetic field in the outside area of shielding coil. However, the vector direction is changed as $180^\circ$ in the area between IPT coil and shielding coil. As a result, the canceling magnetic field will harmonize with the leakage magnetic field, so the magnetic field strength will increase in this region. The changes of the harmonized magnetic field strength are similar to the characteristics of the magnetic field strength variations by the difference of the coil radius. If the distance between the IPT coil and shielding coil is increased, the harmonized magnetic field will slowly decrease. Therefore, this characteristics should consider when determining shielding coil radius for achieving uniform SE.

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Fig. 6 Effect of the canceling magnetic field in accordance with the region

2.4 Shielding current control

The IPT system generates at least two magnetic fields that are generated by the TX and RX coil, and these have different strengths and phases. Thus, the magnetic field of the IPT system will estimated in terms of the phasor. The canceling magnetic field should identical to the leakage magnetic field in terms of the strength and phase. The canceling magnetic field strength $B_{p-Sh}$ can calculate as (7) with regard to the strength and phase of TX and RX magnetic field. $\varphi_{RX}$ is the phase of RX coil current and phase reference is the TX coil current. When the IPT system is operating in resonant condition, the phase difference
between TX and RX current will 90°. If the current strength of TX and RX coil is identical and it operates in resonant condition, \( B_{p-SH} \) can calculate as the RMS value of the two magnetic fields as (8).

\[
B_{p-SH} = \left( B_{p-TX} + B_{p-RX} \right) \cos \left( \frac{\phi_{RX}}{2} \right),
\]

where \( 0^\circ \leq \phi_{RX} \leq 90^\circ \)

\[
B_{p-SH} = \sqrt{B_{p-TX}^2 + B_{p-RX}^2},
\]

where \( \phi_{RX} = 90^\circ \), \( B_{p-TX} = B_{p-RX} \)

In order to achieve high SE, a phase of the cancelling magnetic field should tune as 180° of the phase difference for the leakage magnetic field. The phase of the cancelling magnetic field can determine by considering the magnetic field strength and phase of the TX and RX coil as (9). Fig. 7 shows the phasor diagram of the variation of cancelling magnetic field determined by dominant magnetic field. If the TX magnetic field strength is dominant, phase of the canceling magnetic field will determine close to -180°. On the contrary, phase of the canceling magnetic field will determine close to -90° when the RX magnetic field is dominant. Based on this relationship, phase of the canceling magnetic can be controlled when the current strength and phase of the TX and RX coil is changed.

![Fig. 7 Phasor diagram in accordance with the dominant magnetic field](image)

\[
\phi_{SH} = -180 + \left\{ \tan^{-1} \left( \frac{B_{RX}}{B_{TX}} \right) - \frac{90 - \phi_{RX}}{2} \right\}
\]

where \( 0^\circ \leq \phi_{RX} \leq 90^\circ \)

2.5 PTE variation by shielding coil design

Fig. 8 shows the equivalent circuit model of the IPT system with an active shielding system. The shielding system has an independent power source and all coils have mutual inductance between each other. This means that the IPT system operation can influence to the shielding system, and the shielding system can also influence to the IPT system. In this relationship, voltage and current of the circuit can be expressed as (10) and (11) respectively. \( V_{TX}, V_{SH} \) are the input voltage of TX and shielding coil and \( I_{TX}, I_{RX}, I_{SH} \) are the current of TX, RX, and shielding coil respectively. \( R_{TX}, R_{RX}, R_{SH} \) and \( C_{TX}, C_{RX}, C_{SH} \) are the internal resistance and capacitance of TX, RX, and shielding system. \( M_{TR}, M_{TS}, M_{RS} \) are the mutual inductances between coil and subscript 'T', 'R', 'S' indicates the TX, RX, and shielding coil respectively. \( \omega \) is the angular operating frequency and \( R_L \) is the load resistance.

![Fig. 8 Equivalent circuit model](image)

\[
\begin{bmatrix}
V_{TX} \\
0 \\
V_{SH}
\end{bmatrix} =
\begin{bmatrix}
Z_{TX} & j\omega M_{TR} & j\omega M_{TS} \\
-j\omega M_{TR} & Z_{RX} & j\omega M_{RS} \\
-j\omega M_{TS} & -j\omega M_{RS} & Z_{SH}
\end{bmatrix}
\begin{bmatrix}
I_{TX} \\
I_{RX} \\
I_{SH}
\end{bmatrix} =
\begin{bmatrix}
V_{TX} \\
0 \\
V_{SH}
\end{bmatrix}
\tag{10}
\]

where, \( Z_i = R_i + j\omega L_i + \frac{1}{j\omega C_i} \) \( i \in \{TX,RX,SH\} \)

Based on Kirchhoff’s voltage laws (KVL) equation, efficiency influence by a shielding system can be estimated in terms of the power consumption of shielding coil by impedance. When radius or turns of shielding coil is increased, the impedance of shielding system will increase because of the increases of inductance. This means that the more impedance is increased, circuit will be a high voltage-low current system. This characteristic makes to reduce ohmic loss defined as \( I^2Z \). Therefore, the increase of inductance in accordance with the increasing radius and turns may contribute to preserve PTE of shielding system.

On the one hand, the PTE degradation caused by the active shielding system can be regarded as the influence of the mutual inductance between the IPT system and shielding system. The mutual inductance is the additional inductive reactance in terms of the resonant condition of the IPT system. This means that the resonant condition could be changed by mutual inductance with shielding coil, so it could make the degradation of the PTE. In addition, the power of the IPT system is transferred to shielding system through magnetic coupling because the mutual inductance makes the additional impedance of the IPT system.

However, the active shielding system does not apply additional capacitor so it does not operate in a resonant condition for the IPT system because natural capacitance \( C_{SH} \) of the shielding system does not achieve a resonant condition. This means that the transferred power from the IPT system to the shielding system will be the reactive power so electrical energy is hardly transferred based on the low power factor. If the shielding coil inductance is
increased by applying multiple turns, reactance of the shielding system for the operating frequency will increase. This increasing reactance contributes to prevent the power transfer to the shielding system, so PTE degradation of the IPT system can be reduced.

Based on these characteristics, PTE $\eta$ including the power consumption of the active shielding system calculates as (12). $P_{TX}$ and $P_{SH}$ are the supply power of the TX and the shielding system, and $P_L$ is the transferred power to load. Obviously, the reduction of the shielding system power consumption will contribute preserving PTE. In addition, influences from shielding system to IPT system in accordance with the mutual inductance are considered. As a result, PTE of the total system is defined as the ratio of total power supply and transferred power to the load.

$$\eta = \frac{P_L}{P_{TX} + P_{SH}}$$

(12)

3. Simulations and experimental verifications

3.1 Simulation and experimental setup

Fig. 9 shows the simulation model designed through ANSYS Maxwell software. The design of TX and RX coil has identical radius and turns and inductance of two coils are 53.5 $\mu$H. Ferrite core and aluminum plate have applied to TX and RX coil. Two coils have 95 mm of outer radius and 35 mm of inner radius and coil diameter is 4 mm. The size of ferrite is 200 mm × 200 mm × 4 mm and the aluminum plate is 200 mm × 200 mm × 2 mm. Total Shielding coil designs that are used for simulations have 150 mm, 200 mm, and 250 mm of radius. The radius reference of all shielding coils are the inner radius so radius will increase by each turn. The measurement points for SE analysis have determined at the coil center (M.P1), Ferrite edge (M.P2), 20 cm of distance from coil center (M.P3), and 30 cm of distance from coil center (M.P4). The initial measurement point has started at the 10 cm of axial distance from the RX coil, and the SE have measured at 10 cm, 20 cm, and 30 cm of vertical distance.

<table>
<thead>
<tr>
<th>Coil parameters</th>
<th>$L$ [mH]</th>
<th>$f_{L}$ [A]</th>
<th>$\phi_{L}$ [deg]</th>
<th>$P_{L}$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius [mm]</td>
<td># of turns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TX coil</td>
<td>150</td>
<td>1</td>
<td>0.78</td>
<td>17.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.98</td>
<td>11.2</td>
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<td></td>
<td>5</td>
<td>15.15</td>
<td>3.9</td>
<td>145</td>
</tr>
<tr>
<td>RX coil</td>
<td>200</td>
<td>1</td>
<td>1.14</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>4.10</td>
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<td>22.85</td>
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<td></td>
<td>5</td>
<td>30.17</td>
<td>3.8</td>
<td>144</td>
</tr>
</tbody>
</table>

Fig. 10 shows the experimental setup of the proposed active shielding system. All configurations of the experimental setup are identically designed with simulation setup as Table 1. In order to supply power to the TX and shielding coil, two inverters are utilized. The signals of two
inverters are generated by one field programmable gate array (FPGA), and signal to the shielding system inverter is controlled for tuning shielding current phase. The target shielding point that is maximizing SE is selected at 50 mm of axial distance from the RX coil center. Accordingly, current strength and phase of the active shielding system has tuned as Table 2.

The total magnetic fields of all measurement points have measured by the magnetic field probe, Narda Safety Test Solutions ELT-400, GmbH. Specification of the magnetic field probe is that probe diameter is 125 mm and measurement uncertainty is ±4% in 50 Hz to 120 kHz frequency range. All measurement points have been measured in peak value detection mode. The electronic load has used for load of the IPT system and load resistance has set as 10.2 Ω. For all experiments, the input voltage of the IPT system has fixed at 30 V, and operating frequency has selected as 85 kHz. Note that the shielding current for all shielding coil cases have tuned in 0.5 V steps, so the shielding current is not exactly identical with the desired current strength calculated by (8).

3.2 Simulation and experimental results

Fig. 11 shows the simulation results of the magnetic field distribution for 150 mm, 200 mm, and 250 mm shielding coil design that has shown the highest SE. Fig. 11(a) is the magnetic field distribution of the IPT system without shielding, and above 10 μT of the magnetic fields have measured in M.P1, M.P2, and M.P3 with 10 cm distance, and 5.6 μT of EMF has shown in M.P4 with 10 cm distance. The EMF of each M.P has dropped under 10 μT in 20 cm distance, and these have continually decreased in accordance with the increase of distance. The active shielding systems that have 150 mm of shielding coil radius with 4 turns have shown the most SE among the tested shielding coil, and average SE of 150 mm shielding coil was 68.85%. The average SE is the average shielding effectiveness of all measurement points.

The shielding coil that has 200 mm of radius with 4 turns has shown the 56.7% of average SE, and it is less about 12% than 150 mm case. The decrease of the SE is due to the difference of the magnetic field generation characteristics caused by the radius differences with TX and RX coil radius. The active shielding system with 250 mm coil radius has the lowest SE among the three coils. Especially, the EMF level of the 250 mm shielding coil radius has increased in M.P3 and M.P4 compared to that of measurement points compared with the IPT system without shielding system. Fig. 11(c) shows the magnetic field distribution for the case to apply 200mm-3turn shielding coil. The leakage magnetic field has decreased compared to the case of no shielding, but the SE was less than 150mm-4turn case. Fig. 11(d) is the simulation result for the case to apply 250mm-3turn shielding coil. This simulation result shows that leakage magnetic field in the area between the RX and shielding coil is increased. In addition, the leakage magnetic field generated at the left and right side of the IPT system has increased compared to the case of no shielding system.

Fig. 11 Simulation results of magnetic field distribution

(a) No shielding          (b) Shielding: 150mm-4turn
(c) Shielding: 200mm-3turn  (d) Shielding: 250mm-3turn

(e) Color map of magnetic field strength (unit: μT)

Fig. 12 EMF simulation and experimental results – 4 turn shielding coil

Fig. 12 shows the simulation and experimental results of the EMF level with and without an active shielding system. Simulations and experimental results are well matched for all measurement points. The EMF results without shielding system have shown above 10 μT of EMF in M.P1, M.P2, and M.P3 with 10 cm distance, and 5.6 μT of EMF has shown in M.P4 with 10 cm distance. The EMF of each M.P has dropped under 10 μT in 20 cm distance, and these have continually decreased in accordance with the increase of distance. The active shielding systems that have 150 mm of shielding coil radius with 4 turns have shown the most SE among the tested shielding coil, and average SE of 150 mm shielding coil was 68.85%. The average SE is the average shielding effectiveness of all measurement points.

The shielding coil that has 200 mm of radius with 4 turns have shown the 56.7% of average SE, and it is less about 12% than 150 mm case. The decrease of the SE is due to the difference of the magnetic field generation characteristics caused by the radius differences with TX and RX coil radius. The active shielding system with 250 mm coil radius has the lowest SE among the three coils. Especially, the EMF level of the 250 mm shielding coil radius has increased in M.P3 and M.P4 compared to that of

3.2 Simulation and experimental results

Fig. 11 shows the simulation results of the magnetic field distribution for 150 mm, 200 mm, and 250 mm shielding coil design that has shown the highest SE. Fig. 11(a) is the magnetic field distribution of the IPT system without shielding, and above 10 μT of the magnetic fields have measured in M.P1, M.P2, and M.P3 with 10 cm distance, and 5.6 μT of EMF has shown in M.P4 with 10 cm distance. The EMF of each M.P has dropped under 10 μT in 20 cm distance, and these have continually decreased in accordance with the increase of distance. The active shielding systems that have 150 mm of shielding coil radius with 4 turns have shown the most SE among the tested shielding coil, and average SE of 150 mm shielding coil was 68.85%. The average SE is the average shielding effectiveness of all measurement points.

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without the shielding system. These regions are the area between RX and shielding coil, so leakage and canceling magnetic field have harmonized in accordance with the magnetic vector as Fig. 6. As a result, the large shielding coil radius does not contribute to reduce leakage magnetic field in this area, and average SE will decrease in accordance with the increase of EMF.

Fig. 13 shows the SE variations by the number of coil turns for 200 mm shielding coil radius. All shielding coils have set the target shielding point to 50 mm of axial distance from the RX coil center, so the SE in M.P1 have shown the similar SE except for a single turn as shown in Fig.13(a). However, the SE at the outside of the IPT system is changed by the number of coil turns. The differences of SE between the numbers of turns are due to the radius differences of each coil turn. The shielding coil that has large radius compared to the TX and RX coil generates a weak canceling magnetic field at the center of the IPT system. If the canceling magnetic field strength is adjusted to maximize SE at the center of the IPT system, the canceling magnetic field strength will be dominant than the leakage magnetic field at the outside of the IPT system. In addition, this magnetic field variation is cumulated because each coil turn has a different radius so the discrepancy of the magnetic field generation characteristics is cumulated. As a result, the SE at inside and outside of the IPT system will change, so the number of shielding coil turns can be considered in terms of the magnetic field generation characteristics. In this experiment, 200 mm radius shielding coil with three turns has shown the highest SE, and the highest SE was 68.85% when shielding coil has 4 turns. The reason why the 150 mm shielding coil radius has shown the uniform SE for all turns is that 150 mm of shielding coil radius has the radius close to the TX and RX coil. This means that the canceling magnetic field can reduce the leakage magnetic field effectively both inside and outside of the IPT system even though the number of coil turns are increased.

The total SE of the 200 mm radius shielding coil has shown the variations of the SE by the changes of coil turns. The results show that the unconditional increase or decrease of the number of coil turns does not contribute to enhance SE. This means that the number of turns can relieve the discrepancy of the magnetic field generation characteristics caused by the initial radius difference with the TX and RX coil. In other words, the SE at the inside of the IPT system can be adjusted by the combination of the inner and outer coil turns that have different magnetic field generation characteristics.

The SE of the 250 mm radius shielding coil has shown the low SE compared to 150 mm and 200 mm radius shielding coils, and this is due to the harmonization of the magnetic field in the area between RX and shielding coil. In addition, 250 mm radius shielding coil has more magnetic field generation discrepancy than 200 mm shielding coil radius. This means that the determination of the initial shielding coil radius has the boundary condition. As a result, the determination of the large shielding coil radius does not recommend when high SE is required in close distance with the IPT system.

Fig. 14 shows the PTE variation by the shielding coil radius and the number of coil turns. The shielding coil that has 150 mm radius with 4 turns has shown 85% of PTE. PTE without shielding system was 86.92% so 1.92% of PTE has decreased. The more radius and coil turns are increased, the PTE degradation has reduced. This is based on the decrease
of power factor for the IPT system caused by the increase of shielding coil impedance, described in 2.5. However, shielding coil design makes the variation of SE, so the coil design cannot be determined only in terms of the PTE. As a result, the determination of the radius and the number of turns will be a tradeoff between the SE and PTE.

4. Conclusion

In this paper, a single coil active shielding method of wireless UAV charger for leakage magnetic field reduction has proposed. The coil design parameters such as radius and the number of turns has influenced to the SE and PTE degradation. Current strength and phase of the active shielding system has controlled for SE enhancement. The proposed active shielding system is experimentally verified, and 150mm-4turn shielding coil has shown about 68.85% of total SE in 1.92% of the PTE degradation. In addition, the SE and the PTE variations caused by the variations of the shielding coil design parameters have verified. Based on this result, a proposed shielding method can be regarded as an alternative to reduce EMF when the high SE is required in short-range.

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