Finite Element Analysis-Aided Performance Improvement of Circular Coil Assemblies Applied in Electric Vehicle Inductive Chargers

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Summary

Energy efficiency and leakage magnetic field (LMF) are two important issues in inductive chargers. In this work, the maximum achievable coil efficiency and the corresponding LMF strength are formulated as functions of system parameters, and figure of merits (FOM) are proposed for assessing the efficiency and LMF performance of the coil assemblies. The target application is electric vehicle inductive chargers where the LMF is suppressed via passive shielding. The impact of the coil assembly's geometric parameters on both FOMs is examined through a combination of finite element analysis (FEA) simulation and magnetic circuit analysis, and measures to improve the FOMs are studied. Optimization of an exemplary coil assembly within given dimensional limits is conducted and the performance improvement is verified by FEA simulation results.

Keywords: efficiency, inductive charger, optimization, simulation, wireless charging

1 Introduction

Efficiency improvement [1] and leakage magnetic field (LMF) suppression [2] are two important issues in inductive power transfer (IPT) systems. The conversion between electrical energy and magnetic energy is realized via a pair of coil assemblies, one on the transmitter (TX) side and the other on the receiver (RX) side, hence optimization of the coil assemblies is an important concern in system design.

In a typical electric vehicle inductive charger, which is the target application of this work, a coil assembly contains three parts: an aluminum shielding plate, a ferrite core and a copper winding, hence the coil ESR (equivalent series resistance) is a consequence of all three loss terms. The eddy currents in the aluminum plate result in eddy loss, which is related to the conductivity of aluminum, the incident magnetic flux density and the magnetic field frequency. Ferrite core loss can be estimated using the renowned Steinmetz equation, which is a convenient tool for characterizing magnetic core loss under sinusoidal magnetic field excitations. After the core material is determined, the main influencing factors of core loss are the magnetic flux density and the magnetic field frequency. The power loss in the copper winding is influenced by the conductivity of copper and the unevenness of current density distribution on the wire cross section. Under a given excitation current amplitude, all loss terms are affected by the geometric parameters of the coil assembly. The maximum achievable energy conversion efficiency of the coil assemblies (designated as η_c and abbreviated as “coil efficiency” in the rest of this paper) is influenced by not only the coil ESRs but also the mutual inductance, and the difficulty in maximizing η_c lies in the fact that both factors are related to the geometric parameters in complex ways. To objectively assess the efficiency performance of a coil assembly design, figure of merits (FOMs) that reflect the

combined influence of all relevant factors are a useful criterion [3]. Obviously, the η_c -FOM is heavily reliant on the geometric parameters of the coil assemblies. Measures to improve η_c via coil assembly optimization have been widely discussed [3-4].

As for LMF suppression, the measures can be divided into two categories: active suppression [2] and passive shielding [5]. In active suppression schemes, extra coils are usually deployed to generate a magnetic field component that partially counteracts the field generated by the TX and RX coils, thus reducing the overall field strength to an acceptable level. Due to the extra hardware and software cost, such methods are more suitable for high-power applications where passive shielding alone is insufficient. By contrast, passive shielding techniques rely on the design of the coil assembly to reduce the leakage magnetic field strength and are widely adopted due to the simplicity and effectiveness. LMF suppression techniques generally have a negative impact on η_c , and there are many researches on striking a balance between η_c and the LMF strength [4, 6].

In this paper, only passive shielding is adopted. Two FOMs are proposed to assess the efficiency performance and the LMF performance, respectively. This work is focused on the ferrite layer structure and the copper winding parameters and aims to reveal the impact of the geometric parameters on the FOMs. Finite element analysis (FEA) together with magnetic circuit analysis are the main tools. Based on FEA simulations and experimental measurements, a manually optimized design is compared with a reference design to demonstrate the improvement in performance.

2 Performance Evaluation of Coil Assemblies

2.1 Efficiency Analysis

Fig. 1. Simplified schematic of series-series-compensated IPT system.

A simplified schematic of an IPT system with series compensation on both sides is shown in Fig. 1. U_{in} is the inverter output voltage. U_L is the voltage across the load resistance. I_1 and I_2 are the coil currents. C_1 and C_2 are the series compensation capacitors. L_1 and L_2 are the coil inductances. M is the mutual inductance. R_L is the equivalent AC load resistance. R_1 and R_2 are the coil ESRs. Considering that the focus of this work is coil assembly optimization, the power losses in the other components are not considered. Due to the band-pass property of the compensation networks, only the fundamental voltages and currents are utilized in the derivations while the harmonics are neglected. For the sake of simplicity, the coil ESRs are considered in efficiency calculations only.

Methods to maximize η_c have been analyzed in numerous researches [1]. For the simplified IPT system shown in Fig. 1, the output power (P_{out}) is calculated as

$$P_{out} = \frac{1}{2} I_1 \cdot (j\omega M I_2) \leq \frac{1}{2} \omega M |I_1| \cdot |I_2|. \quad (1)$$

The power loss on coil ESRs is calculated as

$$P_{coil} = \frac{1}{2} (|I_1|^2 R_1 + |I_2|^2 R_2) \geq 2P_{out} \frac{\sqrt{R_1 R_2}}{\omega M}. \quad (2)$$

The conditions for minimizing the P_{coil} -to- P_{out} ratio are as follows:

$$\angle I_1 - \angle I_2 = 90^\circ, \quad (3-a)$$

$$|I_1|^2 R_1 = |I_2|^2 R_2. \quad (3-b)$$

The first condition can be satisfied by maintaining the circuits in full resonance, i.e., $L_1C_1 = L_2C_2 = 1/\omega^2$, where ω is the angular operating frequency of the IPT system. In this work, $\omega = 2\pi \times 85000$ rad/s. Equation (2) reveals that the lowest achievable P_{coil} -to- P_{out} ratio is a function of $\frac{M^2}{R_1R_2}$. In this paper, this ratio is selected as the FOM for assessing the efficiency performance of the coil assemblies and designated as FOM_{effi} . A larger FOM_{effi} corresponds to a higher maximum achievable η_c value.

2.2 Leakage Magnetic Field Analysis

LMF is defined as the magnetic field that users might be exposed to under predefined operating conditions, e.g., the magnetic field in the vicinity of an inductively charged electric vehicle. Under the assumption that the flux lines generated by both coil assemblies are overlapped in the LMF region [2], the LMF strength at a selected observation point under conditions (2-a) and (2-b) is obtained as

$$B_{LMF} = \sqrt{k_1^2|I_1|^2 + k_2^2|I_2|^2} = \sqrt{\frac{2P_{out}}{\omega M}} \sqrt{k_1^2 \sqrt{\frac{R_2}{R_1}} + k_2^2 \sqrt{\frac{R_1}{R_2}}}, \quad (4)$$

where $k_{1/2}$ denotes the magnetic flux density generated by 1 Ampere of current in $L_{1/2}$ on the selected observation point. Therefore, the expression $M \cdot \left(k_1^2 \sqrt{\frac{R_2}{R_1}} + k_2^2 \sqrt{\frac{R_1}{R_2}}\right)^{-1}$ is selected as the FOM for assessing the LMF performance and designated as FOM_{LMF} . A larger FOM_{LMF} corresponds to lower LMF strength at the maximum- η_c operating point.

Although the highest B_{LMF} occurs in the case of maximum coil misalignment due to the short distance between the ground-side coil assembly and the boundaries of the vehicle, the FOM_{LMF} calculated based on the k_1 and k_2 data measured at the zero-misalignment position is also a useful indicator of the LMF performance. Overall, the LMF strength in the maximum-misalignment case has a positive correlation with that in the zero-misalignment case.

3 Influence of Geometric Parameters

3.1 Overall Design and Magnetic Circuit Analysis

Fig. 2. Overall design of the coil assemblies and the magnetic flux paths. (a) Front view. (b) Top view. (c) Magnetic flux paths.

As is shown in Fig. 2 (a), a solid ferrite layer is inserted between the planar copper winding and the aluminum shielding plate in the coil assembly. FEA results reveal that under the same ferrite consumption, using an integral ferrite core instead of separate ferrite strips with obvious spaces in between results in the lowest core loss and eddy loss. Protrusions are added along the outer contour of the ferrite layer to improve the mutual inductance and reduce eddy loss in the aluminum plate.

As illustrated in Fig. 2 (c), the magnetic flux lines generated by each turn are decomposed into roughly six components. Self-inductance is related to the sum of all six components. Mutual inductance is related to the sum of d, e and f. Component f is the source of LMF. Copper loss is mainly affected by components a, b and c. The coil assembly's geometric parameters influence all six flux components in complex ways.

At high frequencies, copper loss is increased due to skin effect and proximity effect. With the adoption of Litz wires, skin effect can be significantly diminished. By contrast, the proximity-effect-induced loss in each strand is caused by the magnetic field generated by all other strands, including those in the same turn and the rest that belong to other turns. Therefore, optimization of the coil pitch is required to reduce the coil ESR.

Fig. 3. Geometric parameters of the coil assembly and the electric-circuit analogy. (a) Geometric parameters. (b) Electric-circuit analogy of the magnetic circuit.

Fig. 3 (a) shows the main geometric parameters of the coil assembly. Based on the interactions among copper wire, ferrite core and aluminium plate, an electric-circuit analogy of the coil assembly as presented in Fig. 3 (b) is derived. M_1, M_2, M_4, M_5 and M_6 are positive mutual inductances whereas M_3 is negative. The equivalent inductance of the ferrite core (L_{fer}) is compensated by a series capacitance (C_{fer}) to such an extent that the loop impedance is capacitive. R_{fer} and R_{Al} are small resistances utilized to characterize the core loss and eddy loss, respectively. Copper loss is modelled using an inductance-resistance loop with a high resistance (R_{Cu}). The total coil ESR is affected by the virtual mutual inductances and resistances. It is noteworthy that the $L_{loss1} - R_{Cu}$ loop is used to characterize the loss in L_{turn1} only: the proximity effect caused by L_{turn2} is modelled using M_5 and the other factors are modelled using M_4 . The coil self-inductance, the actual mutual inductance in Fig. 1 and the LMF strength are mainly affected by M_1, M_2, M_3 and M_6 . I_{coil} is the actual coil current. I_{Al} lags I_{coil} by roughly 180 degrees in phase, thus reducing both the actual mutual inductance and the self-inductance. By contrast, I_{fer} has almost the same phase as I_{coil} and improves both the actual mutual inductance and the self-inductance. The reason for the negative value of M_3 is that $|I_{coil}|$ is generally decreased when better magnetic shielding, i.e., a larger $|I_{fer}|$, is available.

3.2 Impact of Geometric Parameters on the FOMs

FEA is conducted using the ANSYS Electronics Desktop 2020 R2 software. A useful feature of this software is that Litz wires can be directly modelled, which is especially helpful for copper loss estimation. The conductivity of copper and aluminium is set to 5.8×10^7 siemens/m and 2.7×10^7 siemens/m, respectively. Based on practical parameters, the Litz wire diameter is set to 2.45mm and the strand number is set to 600. The relative permeability of ferrite (PC40) is set to 2200 and the core loss density is estimated using the following equation:

$$P_{cv} = 18.7176 f^{1.248} \hat{B}^{2.667}. \quad (5)$$

The units of P_{cv} , f and $\hat{B}$ are W/m^3 , Hz and Tesla, respectively. The coefficients are automatically calculated by the software after the loss curves (at 60 degrees Celsius) obtained from the datasheet (provided by TDK corporate) are imported. One can infer from (5) that P_{cv} is roughly proportional to $|I_{coil}|^{2.667}$. By contrast,

copper loss and eddy loss are roughly proportional to $|I_{coil}|^2$. Accordingly, the coil ESR is a monotonically increasing function of $|I_{coil}|$. In the simulations, $|I_{coil}|$ is fixed at 20A.

The geometric parameters shown in Fig. 3 (a) are varied to reveal their impacts on the FOMs. The majority of data are obtained at the zero-misalignment position unless when the impact of coil misalignment is emphasized, so that a quarter model instead of a full model can be used, which significantly reduces the burden on the computer. The mesh is refined until the changes in the simulation results brought by further refinement are insignificant.

The dimensions of the RX- and TX-side aluminium shielding plates are fixed at 600mm×600mm×2mm and 300mm×300mm×5mm, respectively. The ferrite thickness is fixed at 5mm. The vertical distance between the TX coil and the RX coil is fixed at 130mm. For the sake of simplicity, the rounded corners in the copper winding are removed in the FEA model. The parameters of the original design are as follows: $p = 3\text{mm}$, $A = 270\text{mm}$, $B = 270\text{mm}$, $d_{w-f} = 3\text{mm}$, $d_{f-Al} = 2\text{mm}$, $diff_{w-f} = 10\text{mm}$, $diff_{f-Al} = 5\text{mm}$, $h_{ring} = 0\text{mm}$, $w_{ring} = 5\text{mm}$. Unless otherwise specified, only one parameter deviates from the initial value during the simulations.

Fig. 4. Simulated FOMs.

Key observations obtained from the simulation results are listed below. (1) With the increase of inter-layer distances (d_{w-f} and d_{f-Al}), FOM_{LMF} is reduced while FOM_{effi} is enhanced. (2) Increasing the coil assembly size (A or B) or the ferrite-coil size difference ($diff_{w-f}$) has the same effects as increasing d_{w-f} does. (3) Adding a ferrite ring, i.e., protrusions along the outer contour of the ferrite layer, improves both FOMs. By contrast, the impact of w_{ring} is small. (4) Increasing the coil pitch (p) is beneficial for improving both FOMs and the impact is significant. (5) When the outermost turn is fixed, increasing the turn number (N) is beneficial for improving both FOMs. When the innermost turn is fixed, however, N exceeding a threshold reduces both FOMs. (6) When the total ferrite consumption is given, using an integral ferrite layer leads to higher FOMs than using multiple ferrite strips with obvious spaces in between. Part of the simulation results are presented in Fig. 4. Considering that core loss increases faster than copper loss when the excitation current

is increased, core loss is artificially increased tenfold in deriving FOM_{effi2} to simulate higher-power operating conditions. When calculating the FOMs, the unit of M , $R_{1/2}$ and $k_{1/2}$ is μH , Ω and $\mu\text{T/A}$, respectively.

3.3 LMF Suppression via Increasing the Aluminum Plate Size

The largest coil misalignment is set to 70mm in this work. To reduce the model complexity, coil misalignment is confined to the y-axis direction only, so that a half model instead of a full model can be used. Due to the coil misalignment, the LMF distribution is no longer symmetrical with respect to the x-axis, hence the LMF strength is evaluated on two planes located 700mm away from the RX coil centre and the lower FOM_{LMF} (i.e., the worst case) is considered. The normal vectors of the measurement planes are parallel with the y-axis. Simulation results show that FOM_{LMF} can be easily improved by increasing the aluminium plate width (along the y-axis). Meanwhile, the negative impact on FOM_{effi} is insignificant after the Al plate width exceeds 340mm, as is shown in Fig. 5.

Fig. 5. Impact of Al plate width on the FOMs (coil misalignment is fixed at 70mm along the y-axis direction).

4 Optimization of Coil Assemblies

The objectives of coil assembly optimization are to increase both FOMs, particularly FOM_{effi} (even at the expense of slightly lowering FOM_{LMF}), and enhance the coupling coefficient to reduce the reactive power. Due to the large number of geometric parameters and the complex relations among the FOMs and the geometric parameters, the optimal design depends heavily on the specific application. There are some parameters that have opposite impacts on both FOMs, e.g., A , B , $diff_{w-f}$, d_{w-f} and d_{f-Al} . Such parameters should be determined based on whether LMF suppression or efficiency improvement is of higher priority. Some parameters, e.g., p , N (when the outermost turn size is fixed) and h_{ring} , improve both FOMs when they are increased. Such parameters should be increased to a suitable level. The requirements on coil assemblies vary greatly from one system to another, hence the objective of this work is to analyse the possible means of improving the FOMs rather than obtaining an optimal design for a specific system.

Fig. 6. Comparisons between simulated and measured coil ESR. (a) ESR versus N . (b) ESR versus d_{w-f} . (c) ESR versus d_{w-Al} (distance between copper wire and aluminum plate).

Comparisons are made between FEA results and experimental results to verify the accuracy of the former, as is presented in Fig. 6. In the FEA model, the excitation currents in both coils have a constant amplitude of 20A. In the experimental measurements, the excitation current provided by the LCR meter (HIOKI IM3536) is

50mArms (at 85kHz). Although the numbers do not exactly match, the overall trend obtained from FEA is credible.

During the optimization procedure, the vertical distance between the TX coil and the RX coil is fixed at 130mm, the TX- and RX-side Al plate dimensions are fixed at 300mm×350mm×5mm and 600mm×600mm×2mm, respectively. A manually optimized design (quarter model) and the reference design are shown in Fig. 7. Except for the Al plate size, the TX and RX coil assemblies have identical parameters. For the sake of clarity, the RX-side coil assembly is not shown.

With 70mm coil misalignment along the y-axis, the mutual inductance in the reference and optimized designs drops by 28.5% and 22.3%, respectively, which shows the stability of mutual inductance in the optimized design is better. In either the zero-misalignment case or the 70mm-misalignment case, both FOMs are higher in the optimized design.

Fig. 7. FEA models and simulation results (zero misalignment). (a) Reference design. (b) Manually optimized design.

5 Conclusion

Two FOMs are proposed for evaluating the performance of coil assemblies targeted at low-power electric vehicle inductive charging applications. The impacts of the main geometric parameters on both FOMs are revealed using finite element analysis, based on which a manual optimization procedure is conducted. In the optimized design, both FOMs are enhanced and the stability of mutual inductance against coil misalignment is improved, which is validated through FEA simulations. The following three measures can improve both FOMs: (1) maintain a relatively large coil pitch, (2) add a ferrite ring along the outer contour of the ferrite layer and (3) increase the turn number to a suitable value when permitted.

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