

AC Resistance Modeling of Edgewise Coils for Wireless Power Transfer in the 85kHz Band

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Abstract— In recent years, research on dynamic wireless power transfer during driving (DWPT) for electric vehicles has been actively pursued. For the transmitting and receiving coils used in DWPT systems, it is crucial to accurately evaluate their AC resistance characteristics. Litz wire is widely used for high-frequency coils, and its AC resistance has already been formulated considering the skin effect and proximity effect. Compared to Litz wire coils, edgewise coils offer advantages such as reduced manufacturing difficulty and cost, along with superior heat dissipation. However, a universally applicable model for evaluating the AC resistance of edgewise coils is not yet sufficiently established. This paper proposes an AC resistance model for edgewise coils used in the 85kHz band. This model enables AC resistance calculation without electromagnetic field analysis and offers the advantage of easily capturing AC resistance variations due to parameter changes. Compared to conventional methods, it provides greater freedom in setting parameters related to conductor dimensions, allowing flexible reflection of shape characteristics and simplifying AC resistance design. Furthermore, the proposed model demonstrated validity with an error of less than 3% compared to FEM analysis and less than 10% compared to actual device experiments.

Keywords— *Wireless Power Transfer, Edgewise Coil, AC resistance*

I. INTRODUCTION

The adoption of electric vehicles is advancing from the perspective of countering global warming and improving energy utilization efficiency. To further enhance the convenience of electric vehicles, challenges related to charging time and charging infrastructure have been pointed out, and wireless power transfer is gaining attention as one solution. Dynamic wireless power transfer, which supplies power while the vehicle is in motion, is being researched as a technology contributing to improving the range and operability of electric

vehicles [1]-[3]. Magnetic resonance coupling is employed for dynamic wireless power transfer during vehicle operation, where the transmitting and receiving coils are critical components forming the resonant circuit. The electrical characteristics of these coils significantly impact system efficiency and design. Among these, the coil's AC resistance is particularly affected by the skin effect and proximity effect, necessitating appropriate evaluation. Litz wire is widely used for high-frequency coils, and formalized evaluation methods for its AC resistance have already been proposed [4]-[6]. On the other hand, edgewise coils, which are formed by shaping rectangular copper plate conductors into a spiral configuration, face the challenge that models capable of universally evaluating their AC resistance are not sufficiently established, making quantitative evaluation during the design stage difficult. However, compared to Litz wire coils, they offer the potential for reduced manufacturing difficulty and cost, and further possess the characteristic of excellent heat dissipation due to their larger conductor surface area [7]. These characteristics make them promising candidates for application in coils for dynamic wireless power transfer during vehicle operation. Therefore, this paper proposes a model capable of quantitatively evaluating the AC resistance for edgewise coils used at 85 kHz in dynamic wireless power transfer systems during vehicle operation. During modeling, an AC resistance model is derived that independently considers resistance losses due to the skin effect and proximity effect. Skin effect resistance arises from the magnetic field generated by the conductor itself and can be theoretically derived using a simplified model. In contrast, proximity effect resistance results from interactions with surrounding conductors and is highly dependent on conductor arrangement and dimensional conditions. This makes theoretical derivation difficult, necessitating evaluation through numerical analysis. Since no direct conventional model exists for edgewise coils, this paper

uses prior research [8] on the AC resistance model of the structurally similar Printed Spiral Coil (PSC) as a comparison. The prior research fixed the PSC's pitch, coil size, and coil aspect during AC resistance modeling. The proposed model allows for a wide range of freedom in parameters that were fixed in the prior research. Furthermore, the proposed model formula enables the calculation of AC resistance without requiring electromagnetic field analysis. This also facilitates the observation of AC resistance variations in response to parameter changes. Consequently, the process of calculating AC resistance can be significantly shortened, promising easier AC resistance design for edgewise coils. The validity of the proposed model is verified through electromagnetic field analysis (FEM) and physical experiments using prototype coils.

II. SKIN EFFECT RESISTANCE IN EDGEWISE COILS

A. Skin effect

When high-frequency alternating current flows through a conductor, the phenomenon where current flow becomes difficult near the conductor's center due to eddy currents generated within the conductor itself is called the skin effect. The distance over which the current decreases to $1/e$ times its value from the conductor surface toward the center is called the skin depth. Fig. 1 illustrates the skin effect in an edgewise coil.

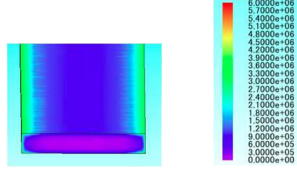


Fig. 1 Skin effect in edgewise coils

B. Theoretical derivation of skin effect resistance

Fig. 2 shows the overall schematic diagram and coil parameters of the edgewise coil addressed in this paper.

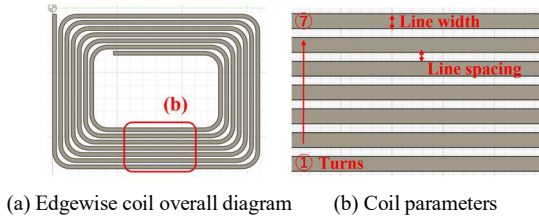


Fig. 2 Edgewise coil schematic diagram

The parameters for edgewise coils include thickness, coil size, and coil aspect ratio in addition to those shown in Fig. 2, and the parameters follow the notation in Table. 1.

Table. 1 Notation for each parameter

Line width	w [m]
Line spacing	s [m]
Turns	N
Thickness	t [m]
Coil size (area)	S [m ²]
Coil aspect	A

The skin effect resistance of an edgewise coil is derived by applying the AC resistance formula for rectangular copper foil conductors [9]-[10] (per unit length straight conductor). As a result, the skin effect resistance formula for an edgewise coil (per unit length) is shown in Equation (1). For equation (1), it is necessary to multiply by the trace length of the edgewise coil. The functional expression for the trace length of the edgewise coil in the design of this paper is given by equation (2). The parts corresponding to a , b , and c in the edgewise coil are shown in Fig. 3.

$$R_{skin} = \frac{1}{\pi^2 \sigma \delta w'} K \left(\frac{h}{w'} \right) [1 - e^{-2t'/\delta}] \quad (1)$$

$$w' = w/\sqrt{\pi}, \quad t' = t/\sqrt{\pi}$$

$$h = \sqrt{w'^2 - t'^2}$$

$$l(w, s, N) =$$

$$4 \sum_N [\{a - (N - 1)(w + s)\} + \{b - (N - 1)(w + s)\} + cN] \quad (2)$$

a : Coil short side / 2 — Outer radius (edge portion)

b : Coil long side / 2 — Outer radius (edge portion)

c : Center arc radius (edge portion)

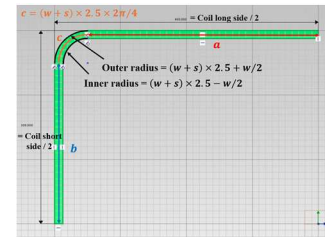


Fig. 3 Trace length parameter

The proposed model is thus obtained by multiplying equation (1) by equation (2). Next, we verify the validity of the proposed model. The coil used to calculate the skin effect resistance is a single-turn edgewise coil (line width 15 mm, thickness 2 mm, coil outer dimensions 600 mm × 800 mm, no proximity effect),

and comparisons are made with simulation results. The verification results are shown in Table 2. In this paper, the finite element method (FEM) electromagnetic field analysis software JMAG is used as the simulation tool to calculate the AC resistance of the edgewise coil. The edgewise coil in JMAG, as shown in Fig. 4, differs in shape from the actual coil in Fig. 2 and has a discontinuous turn configuration. However, adjacent turns are electrically connected, and the model can be considered a simulation with minimal geometric error. Table 2 shows that the error rate is extremely low. Compared to models in previous studies, we conclude that the error rate remains within an acceptable range even when considering copper plate and turn shape factors. Therefore, the proposed model can accurately model the skin effect resistance of edgewise coils.

Table. 2 Accuracy verification of the proposed model

Skin effect resistance R_{skin} [mΩ]		Error rate [%]
Proposed Model	Simulation	
8.919	9.086	1.838

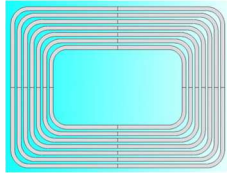


Fig. 4 Edgewise coil in JMAG.

III. PROXIMITY EFFECT RESISTANCE IN EDGEWISE COILS

A. Proximity effect

When high-frequency current flows through a conductor, the magnetic field generated by this current affects nearby conductors, inducing currents in them and causing the current distribution in the conductors to become non-uniform. This phenomenon is called the proximity effect. Furthermore, Figure 5 illustrates the proximity effect in an edgewise coil.

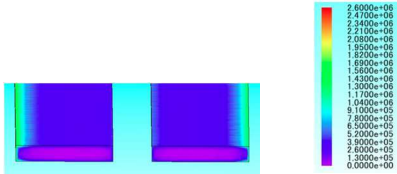


Fig. 5 Proximity effect in edgewise coils

B. Analytical derivation of proximity effect resistance

First, we describe the derivation method for the proximity effect resistance of edgewise coils. Previous studies derived the proximity effect resistance by analytically deriving the shape

function within the proximity effect theoretical equation for spiral coils. In this paper, we model the proximity effect resistance of edgewise coils using the simplest method without employing theoretical equations, thereby reducing the amount of analytical data while achieving a more accurate model. The detailed derivation procedure is shown below.

- ① Analyze an edgewise coil with a specified number of turns in JMAG. → Determine the AC resistance.
- ② Calculate the skin resistance of the coil analyzed in ① using the proposed skin resistance model equation.
- ③ Subtract the resistance from ② from the resistance in ① to obtain the resistance excluding the skin effect. → Define the resistance obtained in ③ as the proximity effect resistance.
- ④ Based on the proximity effect resistance data obtained in ③, derive a proposed model for proximity effect resistance using polynomial regression with the numerical analysis software Mathematica.

Numerous studies [11]-[13] have analytically derived the proximity effect resistance and inductance for spiral coils, suggesting this is an effective method. The proposed model formula ultimately incorporates coil parameters as variables. Before performing Step ①, verify whether each parameter of the edgewise coil affects proximity effects and select the parameters to be variables. Here, verification is performed for three parameters: line width, line spacing, and turns. The results of verifying the proximity effect characteristics for each parameter using JMAG are shown in Fig. 6. Note that all parameters not being varied in the verification are fixed to the values in Table 3. Fig. 6 shows that line width has little effect on the proximity effect. On the other hand, the effects of line spacing and number of turns are significant. Based on these results, the parameters to be varied are line spacing and number of turns. The analysis model for the edgewise coil analyzed in Step ① is as shown in Table 4.

Table. 3 Reference coil

Line width	15mm
Line spacing	15mm
Turns	5
Thickness	2mm
Coil External Dimensions	600mm × 800mm

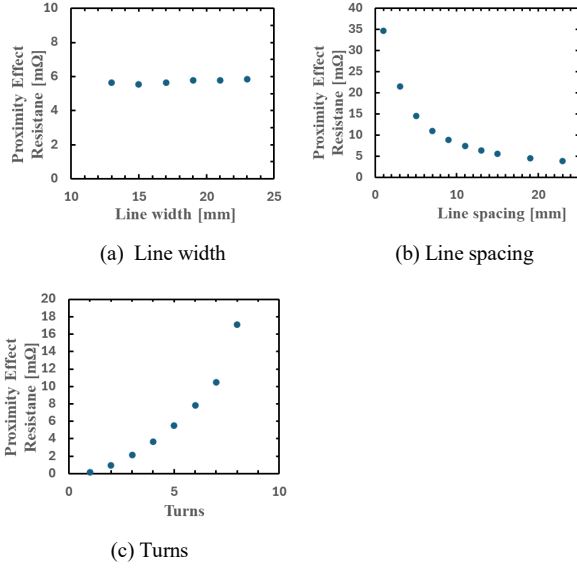


Fig. 6 Proximity effect characteristics (Line width, Line spacing, Turns)

Table. 4 analysis model details

Line width	12.5mm
Line spacing	5~15mm (1mm intervals)
Turns	2~8 (Volume 1 interval)
Thickness	2mm
Coil External Dimensions	600mm × 800mm
Frequency	85kHz

The number of analytical models is the product of variations in line spacing and turns, resulting in a total of 77 models. Next, steps ② and ③ are performed to calculate the proximity effect resistance for all 77 models, after which step ④ is executed. In regression analysis, for simple polynomial regression, the number of terms increases with higher degrees. Since modeling equations with many terms are not suitable for device design, this paper adds terms to the model starting with those showing the greatest improvement in the Bayesian Information Criterion (BIC). Ultimately, a six-term polynomial regression including non-constant terms is performed. The results from Mathematica are shown in Table 5 and Fig. 7. Table 5 shows that the RMSE is very low. Figure 7 also indicates that the 77 data points and model values exhibit a similar distribution. Table 6 and Equation (3) present the model equation obtained from polynomial regression.

Table. 5 Results of polynomial regression

Degree	Terms	AIC	BIC	R ²	RMSE [mΩ]
5	6	-70.2111	-53.8045	0.999673	0.139825

Added term	BIC	R ²	RMSE [mΩ]
None	542.184	0	7.73134
N^2	447.681	0.723068	4.06856
sN^2	267.581	0.974772	1.22800
s^2N^2	109.866	0.996927	0.428591
s^3N^2	60.6718	0.998468	0.302611
N	-53.8045	0.999673	0.139825

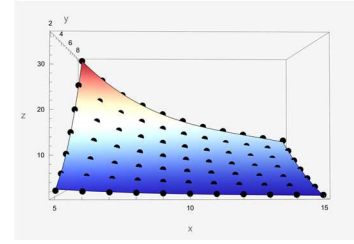


Fig. 7 Polynomial regression plot results

(x = Line spacing : y = Turns : z = R_{prox})

Table. 6 Polynomial regression model

α_0	α_1	α_2	α_3	α_4	α_5
$-1.0647 \cdot 10^{-3}$	$-3.61810 \cdot 10^2$	$1.45353 \cdot 10^1$	$-2.10375 \cdot 10^{-1}$	$1.222277 \cdot 10^{-3}$	$7.86253 \cdot 10^{-4}$

$$R_{prox}(s, N) = \alpha_0 + \alpha_1 \cdot s^3 N^2 + \alpha_2 \cdot s^2 N^2 + \alpha_3 \cdot s N^2 + \alpha_4 \cdot N^2 + \alpha_5 \cdot N \quad (3)$$

Equation (3) is a model expression with degrees of freedom for line spacing, line width, and number of turns. Other parameters—thickness, coil size, and coil aspect—are expressed as coefficient components reflected within Equation (3). Since thickness, coil size, and coil aspect were expected to have less influence on proximity effects compared to line spacing and turns, they were not included as variables in the proposed model equation. However, the other parameters are expressed as coefficient components as shown in Equation (4), enabling modeling of proximity effect resistance based on these six parameters. To derive the coefficient function in Equation (4), the proximity effect characteristics of thickness, coil size,

and coil aspect were verified using JMAG. The verification results are shown in Fig. 8. The parameters of the reference coil were modified from the values in Table 3 to a line width of 12.5 mm and a line spacing of 10 mm. Furthermore, the coil size and coil aspect, considered fixed parameters of the reference coil, were set to 0.48 m² and 0.75, respectively, when they themselves did not change.

$$R_{prox.all} = R_{prox}(s, N) \times f(t) \times f(S) \times f(A) \quad (4)$$

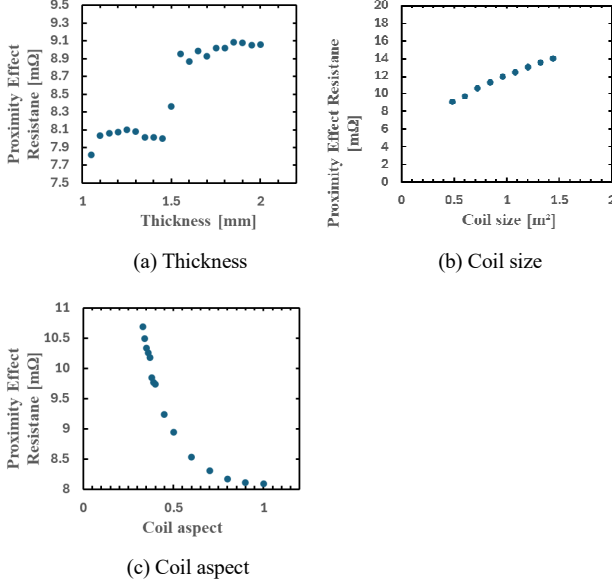


Fig. 8 Proximity effect characteristics (Thickness, Coil size, Coil aspect)

Based on Fig. 8 results, the three parameters are coefficient-fitted using Mathematica's polynomial regression, as was done when deriving Equation (3). The polynomial regression method employs a universal approach, with the degree determined by selecting the one yielding the most appropriate evaluation index value. Table 7 and Equation (5) show the results of the coefficient fitting. The final AC resistance model equation, including equation (5), is given by equation (6) below.

Table. 7 Coefficient fitting results

Parameter	β_0	β_1	β_2	β_3	β_4	β_5
t	-7.409 $\cdot 10^1$	2.58765 $\cdot 10^5$	-3.52053 $\cdot 10^8$	2.35889 $\cdot 10^{11}$	-7.78213 $\cdot 10^{13}$	1.01192 $\cdot 10^{16}$
S	5.8707 $\cdot 10^{-1}$	9.49167 $\cdot 10^{-1}$	-1.96716 $\cdot 10^{-1}$	-	-	-
A	2.9844	-9.42427	1.74576 $\cdot 10^1$	-1.47675 $\cdot 10^1$	4.73727	-

$$\begin{cases} f(t) = \beta_0 + \beta_1 t + \beta_2 t^2 + \beta_3 t^3 + \beta_4 t^4 + \beta_5 t^5 \\ f(S) = \beta_0 + \beta_1 S + \beta_2 S^2 \\ f(A) = \beta_0 + \beta_1 A + \beta_2 A^2 + \beta_3 A^3 + \beta_4 A^4 \end{cases} \quad (5)$$

$$R_{ac} = R_{skin} \cdot l(w, s, N) + R_{prox}(s, N) \times f(t) \times f(S) \times f(A) \quad (6)$$

IV. SIMULATION AND EXPERIMENTAL COILS

A. Simulation

A comparison is made between the proposed model (6) and the simulation. JMAG is used for the simulation of all nine models. The models and results compared are shown in Table 8 and Table 9. Table 9 shows that the AC resistance error for all nine models is extremely low. Therefore, it is considered that the AC resistance of the edgewise coil can be accurately represented within the parameter ranges specified in Table 10 using the proposed model.

Table. 8 Comparative model

Index	Line width [mm]	Line spacing [mm]	Turns	Thickness [mm]	Coil size [m²]	Coil aspect
1	12	10	8	1.1	1.44	3.0
2	16	5	5	1.5	0.96	2.0
3	20	15	2	2.0	0.72	1.5
4	16	10	2	1.1	1.44	3.0
5	20	5	8	1.5	0.96	2.0
6	12	15	5	2.0	0.72	1.5
7	20	10	5	1.1	1.44	3.0
8	12	5	2	1.5	0.96	2.0
9	16	15	8	2.0	0.72	1.5

Table. 9 Comparison results

Index	AC resistance R_{ac} [mΩ]		Error rate [%]
	Simulation	Proposed Model	
1	210.6	213.0	1.1
2	93.36	94.88	1.6
3	20.95	21.12	0.82
4	39.72	39.97	0.63
5	137.9	134.5	2.5
6	71.65	71.55	0.14
7	74.73	75.86	1.5
8	35.06	35.37	0.88
9	76.61	75.44	1.5

Table. 10 Applicable parameter range

Line width	12~20mm
Line spacing	5~15mm
Turns	1~8
Thickness	1~2mm
Coil size (area)	0.48m ² ~1.44m ²
Coil aspect	0.33~1.00

B. Actual machine experiment

A comparison is made between the proposed model (6) and the actual machine experiment. The coil used in the experiment is the coil with the parameters shown in Table 11 below. The experimental coil is measured by sequentially cutting the coil from 8 turns down to 1 turn. The experimental measurement scenes and comparison results are shown in Fig. 9 and Fig. 10. From Fig. 10, it can be seen that the proposed model shows little discrepancy with the experimental results. The maximum AC resistance error was 8.2%, achieving less than 10%. However, factors contributing to the error are considered to include manufacturing errors in the edgewise coil and model errors with JMAG.

Table. 11 Experimental edgewise coil	
Line width	13mm
Line spacing	15mm
Turns	8
Thickness	2mm
Coil External Dimensions	600mm × 800mm



(a) Measurement system (b) When the number of turns decreases

Fig. 9 Measurement scene

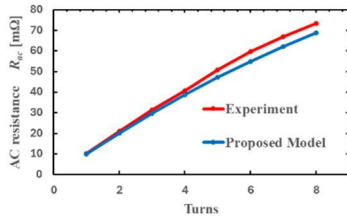


Fig. 10 Comparison results

V. CONCLUSION

This paper modeled the AC resistance of edgewise coils by considering six parameters. Previously, AC resistance through electromagnetic field analysis by simulating coil geometry. However, the proposed model enables AC resistance calculation without such analysis. This significantly reduces

calculation time and, being a functional equation, facilitates easy capture of AC resistance variations due to parameter changes. This facilitates the design of AC resistance for edgewise coils. Experimental measurements on actual equipment achieved an error rate of less than 10%, proving the effectiveness of the proposed model and demonstrating the feasibility of coil design using JMAG.

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