AC resistance prediction of litz wire planer spiral coil based on litz wire loss model

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Abstract**-- The Litz wire is utilized to wireless power transfer system and induction heating according to has small AC resistance in high frequency. Prediction of AC resistance of the Litz wire is important for design optimization of the Litz wire, hence the recent study has proposed analytical AC resistance prediction model of the Litz wire. However, verification in practical coils using the Litz wire is still insufficient. The purpose of this paper is to verify the prediction accuracy of AC resistance using a full analytical model in a practical coil. For practical coil, planer spiral coils are selected, and AC resistance of the planer spiral coil is calculated by combining with the loss model and the FEM analysis. As a result, the Litz wire loss model is found to well predict the measured AC resistance of the Litz wire planer spiral coil, supporting the appropriateness of the Litz wire loss model.**

Index Terms**— Copper loss, Finite-element method (FEM), Litz wire, Proximity effect**

I. Introduction

The wireless power transfer system (WPT) [1] and induction heating (IH) [2][3] are technologies that utilize high-frequency magnetic field and are widely used in industrial and residential applications. In these applications, high frequency AC current flows through a coil to generate the magnetic field. However, a winding resistance and copper loss of the magnetic devices is increased by skin and proximity effects in the high-frequency operation. Therefore, reducing the AC resistance of the magnetic devices is an important technical issue for practical design of the magnetic devices.

A promising solution for this issue is to use of the Litz wire. The Litz wire is made of large number of thin strands, the surface of which is coated by insulator material for isolation. These strands are twisted in multiple levels so that each strand can ideally experience all the positions inside the Litz wire cross-section. As pointed out in [4], twisting the strands can prevent concentration of the ac current in particular strands. Therefore, the AC current distribution in the Litz wire is ideally equal to the DC current distribution, because of the uniform current flow in each strand. As a result, the Litz wire is expected to exhibit the small AC resistance similar to the DC resistance.

However, the too thin strands and many levels of twisting may result in an increase in manufacturing cost and decrease the packing factor of the Litz wire. Hence, the actual Litz wire is made of the appropriate thin strands and simple twisting structure. Consequently, the AC resistance of the Litz wire increases because the AC current is biased to particular strands due to imperfect twisting structure. In addition, a proximity effect loss which is a part of the AC resistance is generated by the AC magnetic field from the outside of the Litz wire. The external AC magnetic field is highly dependent on the winding structure of the magnetic device. Therefore, the practical design of the Litz wire needs optimization of the strand thickness and the twisting structure according to the frequency and the winding structure. In this sense, efficient design of the Litz wire may need a prediction of the copper loss from the geometrical specifications of the Litz wire, such as the twisting structure, the diameter, and the number of the strands.

The predictions method of the Litz wire copper loss are classified into numerical and analytical methods. The numerical methods are generally structure modeling and electromagnetic analysis of the Litz wire using the finite-element-method (FEM) analysis [5]-[7]. However, the FEM analysis requires enormous calculation resource and time, modelling technology. Therefore, the practical design of the Litz wire by the numerical methods is difficult. By contrast, the analytical method is to formulate the AC resistance contributed by the skin and proximity effect in the Litz wire [8]-[15]. A number of studies have been accumulated and proposed formulations of skin and proximity loss associated with structures such as strands, bundles, twisting pattern and twisting pitch in the Litz wire. However, these loss models require complex calculations to accurately model the skin and proximity effects associated with the complex structure of the Litz wire. Recently, [15] has complied these analytical insights of the preceding studies and constructed the full analytical loss model of the Litz wire, in which the strands are twisted in multiple levels. This loss model predicts copper loss only with physical constants and geometric parameters for ease of use in the design of the Litz wire. In this loss model, the prediction accuracy of AC resistance has been verified in single Litz wires, and toroidal coils with a simple coil structure. However, verification in practical coils using the Litz wire is still insufficient.

The purpose of this paper is to verify the prediction accuracy of AC resistance using a full analytical model in a practical coil. For practical coil, planer spiral coils used in induction heating and wireless power transmission systems are selected. For practical coil, planer spiral coils used in IH and WPT are selected. Hence, the magnetic field of each winding in a spiral coil is calculated utilized the FEM analysis, and AC resistance of the planer spiral coil is calculated by combining with the loss model. In this case, the 2-dimensional static magnetic field is used in the FEM analysis, and the Litz wire is simplified to a round wire, because this paper is attempting to simplify the FEM analysis more than the prediction methods proposed in other studies[16]-[18].

The following discussion consists of 5 sections. Section II briefly describes the full analysis loss model of the Litz wire [15]. Section III describes how external magnetic fields are calculated utilized the FEM analysis. Section IV presents experiments performed to verify the AC resistance prediction of the planer spiral coil used the full analysis loss model. Finally, section V gives conclusions.

II. Review of Litz Wire Loss Model

In this section, the loss model of a Litz wire (wire twisted in 3 levels) as shown in Fig. 1, is described. The Litz wire is formed of bundles (2nd and 3rd level bundles) obtained by twisting bundles (1st level bundle) formed by twisting insulated strands and twisting the bundle no more 5 a plurality of times. Because, twisted uniformly the bundles no less than 6 is difficult and the copper loss increase [18].

In the loss model, the copper loss of the Litz wire is classified into eddy current loss due to the skin and proximity effect in the strand and bundle as shown in Fig. 2. This model assumes that the Litz wire is much longer than the twist pitch. Thus, since the proximity effect in the bundle can be neglected, an equation of the copper loss is simplified.

Therefore, the copper loss P_L of the Litz wire can be formulated as the sum of the skin effect loss P_{skin}, the proximity effect losses $P_{prox\perp}$. The skin effect loss P_{skin} is the loss caused by the AC current flow in the Litz wire. The proximity effect losses $P_{prox\perp}$ is the loss caused by the eddy current generated by the external AC magnetic field in perpendicular to the Litz wire, respectively. In this case, in the normal magnetic devices, the magnetic field is applied in perpendicular to the Litz wire. Therefore, $P_{prox//}$ of the Litz wire is not discussed. $P_{prox//}$ is the loss caused by the eddy current generated by the external AC magnetic field in parallel to the Litz wire.

Besides, P_{skin} is proportional to the square of the root-mean-square value of the AC current I_L. On the other hand, $P_{prox\perp}$ is proportional to the external AC magnetic field $H_{L\perp}$. Therefore, P_L can be characterized by two factors R_L and $G_{\perp}$. Hence,

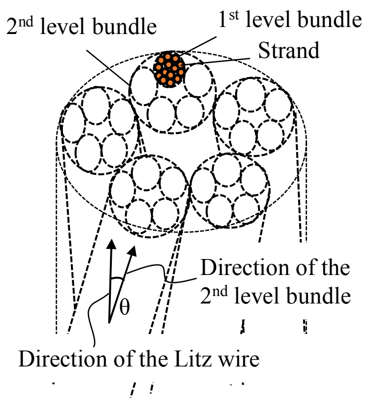


Fig. 1. Litz wire structure under consideration with 3 twisting levels.

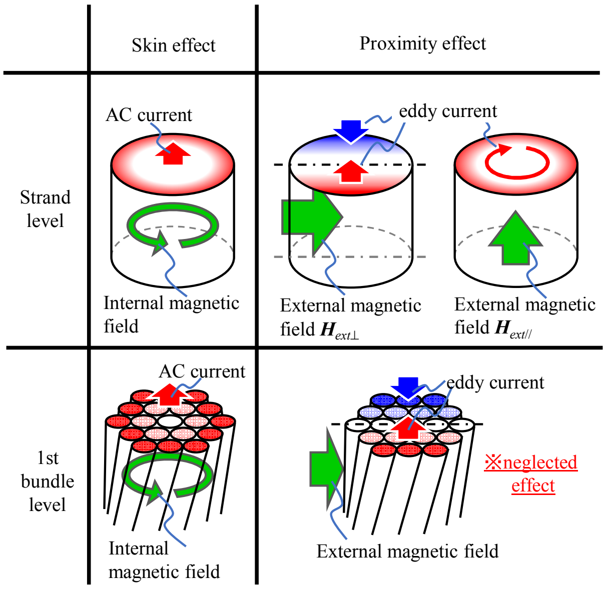


Fig. 2. Classification of the skin and proximity effect of the Litz wire.

$$
\begin{aligned}
P_L &= P_{skin} + P_{prox\perp} \\
&= R_L I_L^2 + G_{L\perp} H_{L\perp}^2,
\end{aligned}
\tag{1}
$$

where R_L is the loss coefficient of the skin effect, $G_{L\perp}$ is the loss coefficient of the proximity effect.

In common magnetic devices, the external magnetic fields $H_{L\perp}$ applied to the wire belonging to a winding turn are generated by the AC current flow in the other winding turns of the same winding. In this case, $H_{L\perp}$ are proportional to I_L. Therefore, the AC resistance R_{ac} of the Litz wire is obtained from

$$
P_L = R_L I_L^2 + G_{L\perp} H_{L\perp}^2 = R_{ac} I_L^2. \tag{2}
$$

The loss model [15] gives the analytical formulae of R_L and $G_{L\perp}$ of the Litz wire based on the geometrical and structural parameters, such as the numbers and radius of strands, 1st bundles and the Litz wire:

$$
\begin{aligned}
R_L &= \frac{\rho \ell m}{\pi \alpha_s^2 n_s n_b} F(\gamma_s) F(\gamma_b) \\
&+ \frac{4\pi\rho \ell n_s n_b K(\gamma_s)}{8\pi^2 a_L^2}\left(\frac{4m^3}{3} - \frac{13m}{6} + \frac{11}{6m}\right),
\end{aligned}
\tag{3}
$$

$$G_{L\perp} = 4\pi\rho\ell n_s n_b K(\gamma_s)\left(\frac{3m}{4} + \frac{1}{4m}\right), \tag{4}$$

where ρ is the resistivity of the copper, ℓ is the Litz wire length, m is the length ratio of the strand to the Litz wire, α_s is the strand radius, n_s is the number of the strand in a 1st level bundle, n_b is the number of the 1st level bundle in the Litz wire, a_L is the Litz wire radius, γ_s and γ_b are the parameter defined as (5) and (6), and F and K are functions defined as (7) and (8), respectively.

$$\gamma_s \equiv \alpha_s \sqrt{\frac{\omega\mu}{\rho}}, \tag{5}$$

$$\gamma_b \equiv \alpha_b \sqrt{\frac{\omega\mu}{\rho_{eff}}}, \tag{6}$$

$$F(x) \equiv \frac{x}{2} \frac{\mathrm{ber}\, x\, \mathrm{bei}' x - \mathrm{ber}' x\, \mathrm{bei}\, x}{(\mathrm{ber}' x)^2 + (\mathrm{bei}' x)^2}, \tag{7}$$

$$K(x) \equiv -x \frac{\mathrm{ber}_2\, x\, \mathrm{ber}' x - \mathrm{bei}_2\, x\, \mathrm{bei}' x}{(\mathrm{ber}\, x)^2 + (\mathrm{bei}\, x)^2}, \tag{8}$$

where ω is the angular frequency, μ is the permeability of the copper, α_b is the 1st level bundle radius, ρ_{eff} is the effective resistivity characterizing the bundle-level skin effect [14][15]. In the analysis method, the effective resistivity ρ_{eff} has been defined as

$$\rho_{eff} = \frac{A_s R_s}{\eta}, \tag{9}$$

where A_s is the cross-section area of the strand and η is the packing factor. This definition of ρ_{eff} is slightly different from that proposed in [14]. However, the previous method modified the definition based on the electromagnetic theory.

Finally, a length of the strand can be calculated from the measured DC resistance R_{DC} of the Litz wire, a cross-sectional area of the strand, and a total number of the strands. Therefore, the length ratio m of the strand to the Litz wire can be estimated as

$$m = \frac{R_{DC}\pi a_s^2 n_s n_b}{\rho\ell} = \frac{1}{\cos\theta}. \tag{10}$$

III. Calculation of External Magnetic Field due to FEM Analysis

As we have seen above, the full analysis method calculated the loss coefficient of the skin effect R_L and proximity effect $G_{L\perp}$ based on (3)-(10) from the specifications of Litz wire. Next, the copper loss (AC resistance) is calculated based on (2) from the loss coefficients R_L, $G_{L\perp}$ and the external magnetic field $H_{L\perp}$. Therefore, the values of the external magnetic field $H_{L\perp}$ in (2) should be calculated for predicting the AC resistance of the Litz wire planer spiral coil.

Therefore, this paper utilized the 2-dimensional FEM magnetic field analysis to determine the external magnetic field $H_{L\perp}$. Hence, the planer spiral coil is approximated to windings of concentric circles for simplicity. In addition, A current in the Litz wire flows almost uniformly in the cross section of the Litz wire even if a current in the strands and bundles is biased by the skin and proximity effect. Therefore, the Litz wire is replaced by a round wire with a uniform current distribution and analyzed by the FEM static magnetic field analysis.

In the analysis result by the FEM analysis, the magnetic field $\mathbf{H}_{FEM\perp}$ in the Litz wire is expressed at the sum of the internal magnetic field vector $\mathbf{H}_{int\perp}$ and the external magnetic field vector $\mathbf{H}_{L\perp}$. The internal magnetic field vector $\mathbf{H}_{int\perp}$ generated by the AC current flowing through the Litz wire. Hence,

$$\mathbf{H}_{FEM\perp} = \mathbf{H}_{int\perp} + \mathbf{H}_{L\perp}. \tag{11}$$

Therefore, in order to utilize the external magnetic field $\mathbf{H}_{L\perp}$ in the analysis loss model, the internal magnetic field and the external magnetic field should be separated from the analytical result by the FEM analysis.

In the wire at the edge of the spiral coil, since the external magnetic field generated from other wires are the same vector, the total sum of the external magnetic fields becomes large. On the other hand, in the intermediate wire of the spiral coil, since the external magnetic fields generated from the wires on both sides are inverted vectors, the external magnetic field becomes cancel out. Hence, the external magnetic field is simply approximated to be the uniform field, Therefore, in the area where the external magnetic field becomes large, the external magnetic field $\mathbf{H}_{L\perp}$ is simply approximated to be the uniform field. And, in the area where the external magnetic field becomes cancel out, the internal magnetic field is dominant. In addition, because the circular cross-section geometry has the axisymmetry, $\mathbf{H}_{int\perp}$ also has the axisymmetry. Therefore, the following relation can be obtained:

$$\begin{aligned}\int_{S_L} |\mathbf{H}_{FEM\perp}|^2 dS_L &= \int_{S_L} |\mathbf{H}_{int\perp} + \mathbf{H}_{L\perp}|^2 dS_L \\ &= \int_{S_L} |\mathbf{H}_{int\perp}|^2 dS_L + \int_{S_L} |\mathbf{H}_{L\perp}|^2 dS_L,\end{aligned} \tag{12}$$

where S_L is the cross-section area of the Litz wire, respectively.

Replace (14) and divide by S_L, we obtain

$$\begin{aligned}\overline{H_{L\perp}^2} &= \frac{1}{S_L}\int_{S_L} |\mathbf{H}_{L\perp}|^2 dS_L \\ &= \frac{1}{S_L}\int_{S_L} |\mathbf{H}_{FEM\perp}|^2 dS_L - \frac{1}{S_L}\int_{S_L} |\mathbf{H}_{int\perp}|^2 dS_L,\end{aligned} \tag{13}$$

where factor $\overline{H_{L\perp}^2}$ is Area integral mean of square of the external magnetic field $\mathbf{H}_{L\perp}$. Since the external magnetic field is assumed to be nearly uniform, $\overline{H_{L\perp}^2}$ and H_L^2 have almost the same value. Therefore, the AC resistance of the coil can be calculated by substituting $\overline{H_{L\perp}^2}$ into (2).

The second term of (13) can be calculated by the current I_L and the radius a_L of the Litz wire because the internal magnetic field H_{int} in the Litz wire is determined by the current I_L. Hence,

$$\overline{H_{\text{int}\perp}^2} = \frac{1}{S_L}\int_{S_L} \left|\mathbf{H}_{int\perp}\right|^2 dS_L = \frac{\int_0^{a_L}\int_0^{2\pi} H_{\text{int}\perp}^2 \, d\phi \, dr}{\pi a_L^2} = \frac{I_L{}^2}{8\pi^2 a_L^2}, \quad (14)$$

$$H_{\text{int}\perp} = \frac{I_L}{2\pi r}, \quad (15)$$

where factor $\overline{H_{\text{int}\perp}^2}$ is Area integral mean of square of the internal magnetic field $\mathbf{H}_{\text{int}\perp}$, $H_{int\perp}$ is scholar of the root-mean-square internal magnetic field of Litz wire, I_L is the AC current flowing through the Litz wire, r is the radius in the Litz wire.

Therefore, the external magnetic field $\overline{H_{L\perp}^2}$ of the planer spiral coil can be derived by subtracting the calculated value of $\overline{H_{\text{int}\perp}^2}$ in Equation (14) from the FEM analysis result.

Finally, the copper loss of the planer spiral coil $R_{coil}i_L{}^2$ can be obtained as

$$R_{coil}i_L{}^2 = \sum_k l_k \left\{ R_L i_L{}^2 + G_{L\perp}\overline{H_{L\perp,k}}^2 \right\}, \quad (16)$$

where l_k is the wire length of k^{th} turn of the coil. In addition, the copper loss when the coil current I_L is set to $1A_{\text{rms}}$ becomes the AC resistance R_{coil} of the planer spiral coil.

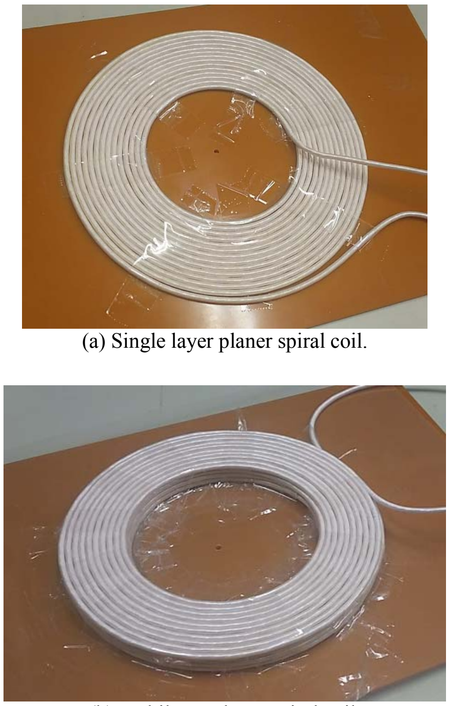
IV. Experiment

Figure 3 shows planar spiral coils for the experiments. Fig. 3(A) shows a single-layer coil simulating a WPT coil, and Fig. 3(b) shows a multi-layer coil simulating an IH coil. Besides, the specifications of the Litz wires are shown in Table I. Based on the dimensions of these coils and a Litz wire, FEM analysis is performed by approximating them to concentric coils and round wire as shown in Fig. 4. In addition, a uniform current of $1.414A(1A_{\text{rms}})$ is applied to each round wires. The 2-dimensional FEM static magnetic field analysis is performed using JMAG-Designer 18.1 (JSOL Corp.).

Figure 5 shows results of the 2-dimensional FEM static magnetic field analysis. From these results, Fig. 6 shows the classification of the $\overline{H_{\perp}^2}$ in each winding. The FEM analysis calculates the sum of the $\overline{H_{\text{int}\perp}^2}$ and $\overline{H_{L\perp}^2}$, and the $\overline{H_{\text{int}\perp}^2}$ is derived from (14). Therefore, the $\overline{H_{L\perp}^2}$ is the difference between the calculation result of the FEM analysis and that of (8). The $\overline{H_{\text{int}\perp}^2}$ of the Litz wire is $6.9\text{kA}^2/\text{m}^2$.

The planer coils of the Litz wire is connected to the LCR meter (NF Corp. ZM2376 with attachment ZM2363) to measure the AC resistance in the frequency region from 10kHz to 1MHz. Fig. 7 shows the comparison result of the measured AC resistance of the planer spiral coil with the analytically predicted R_{coil}.

In the single-layer planer spiral coil shown in Fig. 7(a), the relative error is about 10% (Max:15.0% @700kHz). On the other hand, in the multilayer planer spiral coil of Fig. 7(b), the relative error exceeds 10% at 100 kH or more. This is attributed to the parallel resonance of the coil. The parallel resonance in the coil is about 1.5 MHz. As can be seen in the Fig.7 , the Litz wire loss model is found to well predict the measured AC resistance of the Litz wire planer spiral coil, supporting the appropriateness of the Litz wire loss model.



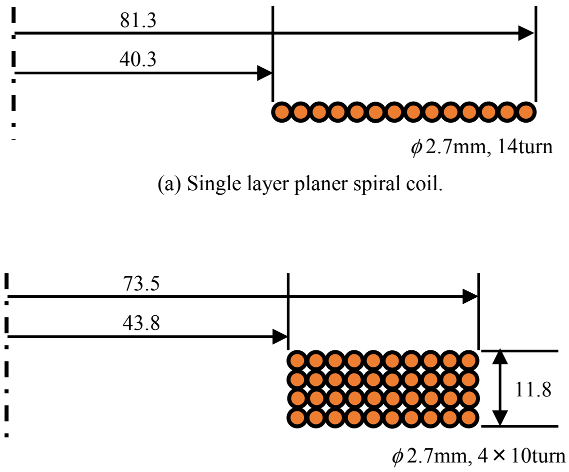
(a) Single layer planer spiral coil.

(b) multilayer planer spiral coil.

Fig. 3. Photographs of the planer spiral coils.

TABLE I
Specifications of The Experimental Litz Wire

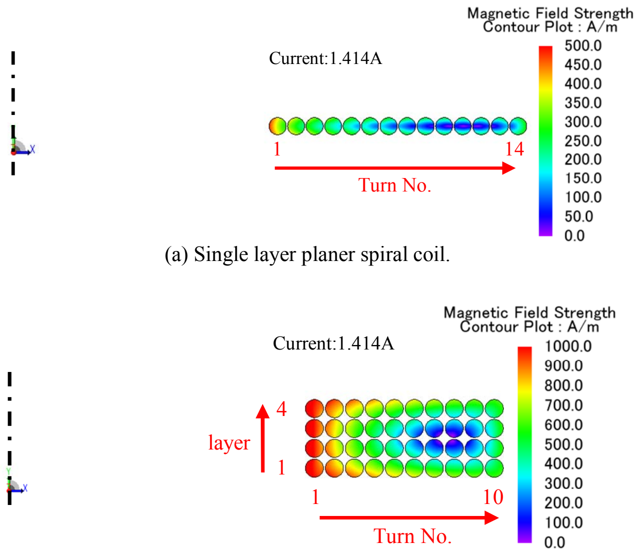
Parameter	Wire A
Strand radius a_s	0.0355mm
Litz wire radius a_L	1.35mm
Total number of strands	800
Number of 1st level bundles n_b	32
Parameter m	1.077



(a) Single layer planer spiral coil.

(b) multilayer planer spiral coil.

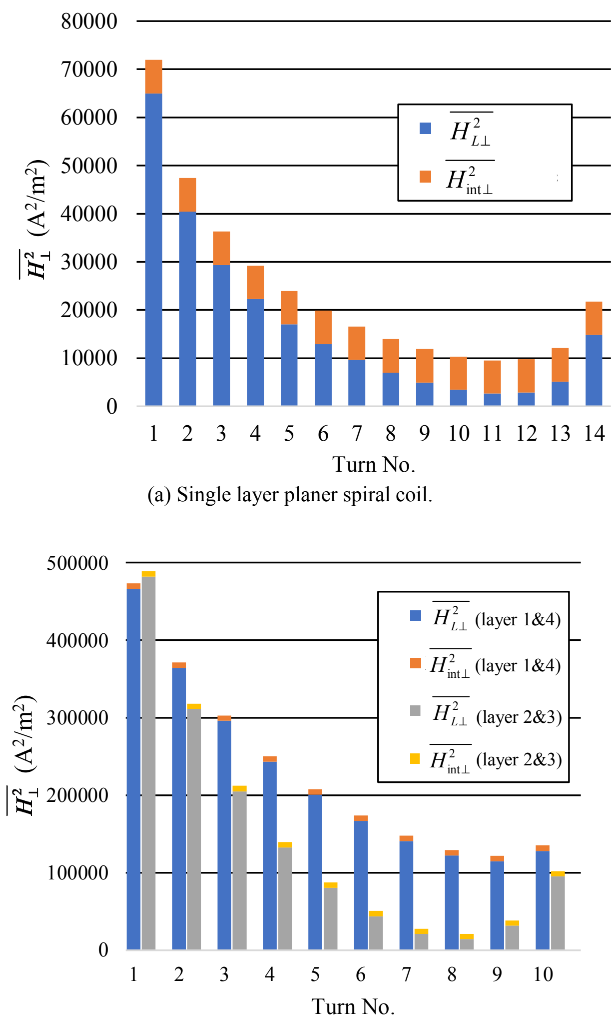
Fig. 4. Cross section structure and dimensions of the planer spiral coils.



(a) Single layer planer spiral coil.

(b) multilayer planer spiral coil.

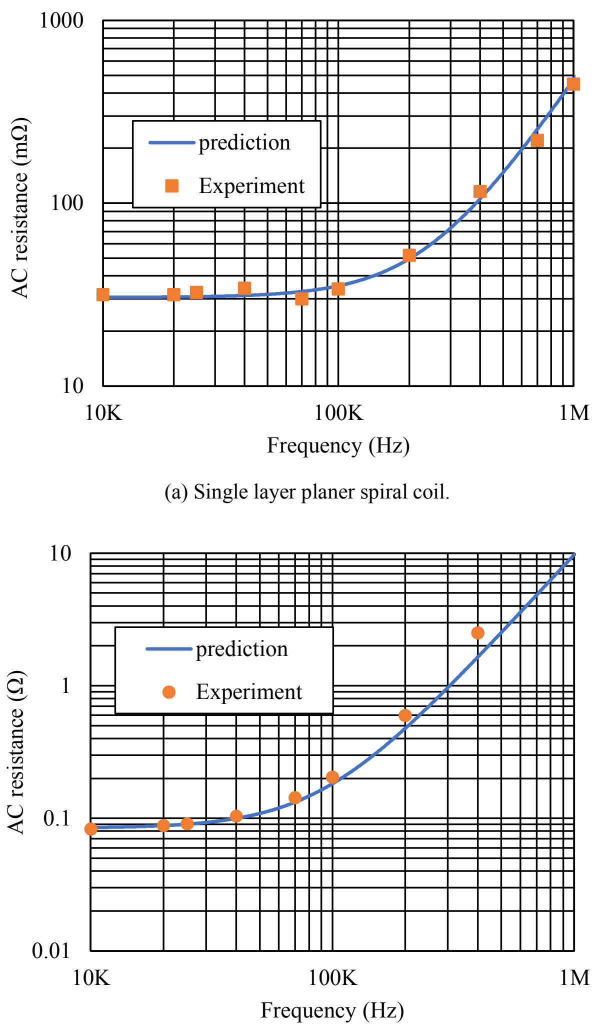
Fig. 5. Results of the 2-dimensional FEM static magnetic field analysis.



(a) Single layer planer spiral coil.

(b) multilayer planer spiral coil.

Fig. 6. Classification of the $\overline{H^2_{\perp}}$ in each winding.



(a) Single layer planer spiral coil.

(b) multilayer planer spiral coil.

Fig. 7. Comparison result between the theoretically predicted and experimentally measured R_{coil}.

V. CONCLUSIONS

Recently, the analytical prediction method of the AC resistance of the Litz wire has been proposed for design optimization of the Litz wire. However, verification in practical coils using the Litz wire is still insufficient.The purpose of this paper is to verify the prediction accuracy of AC resistance using a full analytical model in a practical coil. For practical coil, planer spiral coils are selected, and AC resistance of the planer spiral coil is calculated by combining with the loss model and the FEM analysis. As a result, the Litz wire loss model is found to well predict the measured AC resistance of the Litz wire planer spiral coil, supporting the appropriateness of the Litz wire loss model.

REFERENCES

[1] B. Klaus, D. Barth, B. Sillmann, and T. Leibfried, "Design and implementation of a transmission system for high-performance contactless electric vehicle charging," *Proc. IEEE Transportation Electrification Conference and Expo (ITEC)*, Jun. 2017, pp. 39–44.

[2] I. Lope, J. Acero, and C. Carretero, "Analysis and optimization of the efficiency of induction heating applications with litz-wire planar and solenoidal coils," IEEE Trans. Power Electron., vol. 31, no. 7, pp.5089-5101, Jul. 2016.

[3] M. Hataya, K. Kamaeguchi, E. Hiraki, K. Umetani, T. Hirokawa, M. Imai, and S. Sadakata, "Verification of the reduction of the copper loss by the thin coil structure for induction cookers," in Proc. IEEE Intl. Power Electron. Conf. (IPEC2018), Niigata, Japan, May 2018, pp. 410–415.

[4] C. R. Sullivan and R. Y. Zhang, "Simplified design method for litz wire," *Proc. IEEE Applied Power Electronics Conference and Expositions (APEC2014)*, Mar. 2014, pp. 2667-2674.

[5] A. Roßkopf, E. Bär, and C. Joffe, "Influence of inner skin- and proximity effects on conduction in litz wires," IEEE Trans. Power Electron., vol. 29, no. 10, pp. 5454-5461, Oct. 2014.

[6] A. Roßkopf, E. Bär, C. Joffe, and C. Bonse, "Calculation of power losses in litz wire systems by coupling FEM and PEEC method," *IEEE Trans. Power Electron.*, vol. 31, no. 9, pp. 6442-6449, Sept. 2016.

[7] S. Hiruma and H. Igarashi, "Fast 3-D analysis of eddy current in litz wire using integral equation," IEEE Trans. Magn., vol. 53, no. 6, pp. 7000704, Jun. 2017.

[8] P. L. Dowell, "Effects of eddy currents in transformer windings," *Proc. IEE*, vol. 113, no. 8, pp. 1387–1394, Aug. 1966.

[9] J. A. Ferreira, "Improved analytical modeling of conductive losses in magnetic components," *IEEE Trans. Power Electron.*, vol. 9, no. 1, pp. 127–131, Jan. 1994.

[10] C. R. Sullivan, "Computationally efficient winding loss calculation with multiple windings, arbitrary waveforms, and two-dimensional or three-dimensional field geometry," *IEEE Trans. Power Electron.*, vol. 16, no. 1, pp. 142–150, Jan. 2001.

[11] R. P. Wojda and M. K. Kazimierczuk, "Winding resistance of litz-wire and multi-strand inductors," *IET Power Electronics*, vol. 5, no. 2, pp. 257-268, Jan. 2012.

[12] J. Acero, R. Alonso, J. M. Burdio, L. A. Barragan, C. Carretero, "A model of losses in twisted-multistranded wires for planar windings used in domestic induction heating appliances," in Proc. IEEE Appl. Power Electron. Conf. and Expo., 2007, pp. 1247-1253.

[13] D. Sinha, P. K. Sadhu, N. Pal, and A. Bandyopadhyay, "Computation of inductance and AC resistance of a twisted litz-wire for high frequency induction cooker," in Proc. Intl. Conf. Ind. Electron. Control Robotics, 2010, pp. 85-90.

[14] C. R. Sullivan and R. Y. Zhang, "Analytical model for effects of twisting on litz-wire losses" *Proc. IEEE Workshop on Control and Modeling for Power Electronics (COMPEL)*, 2014, pp. 1-10.

[15] K. Umetani, J. Acero, H. Sarnago, O. Lucia, and E. Hiraki, "Simple fully analytical copper loss model of Litz wire made of strands twisted in multiple levels," *Proc. IEEE Applied Power Electronics Conference and Expositions (APEC2019)*, Mar. 2019, pp. 1257-1264.

[16] M. Lu and K. D. T. Ngo, "An analytical method to calculate winding resistance for planar coil with ferrite plate and litz wire in inductive power transfer." *Proc. IEEE Energy Conversion Congress and Exposition (ECCE2017)*, Oct. 2017.

[17] M. Lu and K. D. T. Ngo, "Analytical calculation of proximity-effect resistance for planar coil with litz wire and ferrite plate in inductive power transfer," *IEEE Trans. Ind. Appl.*, vol. 55, no. 3, pp. 2984-2991, May-Jun. 2019.

[18] S. Gyimóthy, et al. "Loss computation method for litz cables with emphasis on bundle-level skin effect." *IEEE Trans. Magn.*, vol. 55, no. 6, Jun. 2019.