On AC Resistance of Two-Layered Wires

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***Abstract* - In this paper, AC resistance of a two-layered wire is numerically analyzed. The resistance is caused by the skin effect and proximity effect which are theoretically formulated, respectively. It is demonstrated by the numerical results that a high-resistive wire covered by copper layer such as a copper-clad-steel (CCS) wire can suppress an increase of resistance with increasing frequency. A CCS wire is evaluated theoretically and experimentally. It is shown that the CCS wire has a lower resistance even than a pure copper wire in a specific frequency range. The range is demonstrated to depend on thickness of Cu layer and is able to compute by our simple formula. This surprising phenomenon is satisfactorily explained by the theory.**

***Index Terms* — Wireless energy transmission, Coils, Skin effect, Proximity effect, Copper clad steel wire.**

I. INTRODUCTION

As efficiency of wireless energy transmission (WPT) is improved with increasing quality factor (Q) of the circuit, coils used in inductive coupling WPT system require high $Q = \omega L/R$, where ω, L and R are the angular frequency, inductance and AC resistance, respectively. Since usable frequencies band for WPT is determined by regulation or law restriction, ISM band such as 6.78 MHz is one of the candidates because of its toleration for electromagnetic interference and compatibility. However, AC resistance arises with frequency due to skin and proximity effects.

A copper clad steel (CCS) wire is steel wire covered with copper (Cu) layer to utilize characteristic features of inner metal such as strength, and makes up for conductivity by Cu (Fig.1 (*a*)). At high frequency, they are used like Cu wire because current flows only surface of wire. However, their resistance frequency characteristics have not been checked well enough yet, especially for cases that thickness of Cu layer and skin depth are the same scale.

In this study we demonstrate numerical analysis by theoretical formula on AC resistance of a wire with two layers. A CCS wire is evaluated by measurement and calculation and these results show its superiority to Cu one in the aspect of AC resistance in particular frequency range that are described as a function of thickness of Cu layer.

II. THEORETICAL FORMULA

A CCS wire is modeled as wire composed of two different materials with conductivities of σ_1 and σ_2, relative magnetic permeabilities of μ_1 and μ_2, and diameters of $2r_1$ and $2r_2$, respectively (Fig.1 (*b*)). AC resistance of a coil is given as summation of resistance due to Joule effect by the carrying current in the wire and eddy current induced by external magnetic field from vicinity wire [1];

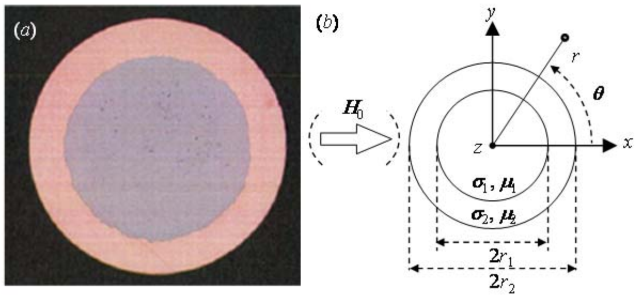

Fig. 1. Cross section of a CCS wire (*a*). It is modeled as wire composed of two different material layers (*b*).

$$R_{ac} l = (R_s + \alpha^2 D_p) l \ , \quad (1)$$

where l is the length of a wire and R_s is associated with the skin effect including DC resistance, and D_p is associated with the eddy current loss caused by a magnetic field generated by the proximity effect, and α is a shape factor that represents magnitude of magnetic field applied to the coil [2]. For a coil, the magnitude of magnetic field is proportional to the magnitude of current flowing in the winding wires, and depends on the structure of the coil. Therefore, $\alpha^2 D_p$ is the resistance due to the proximity effect, which is proportional to square of magnitude of magnetic field.

III. NUMERICAL RESULTS

Figs. 2 and 3 show R_s and D_p of 33% CCS (the area ratio of Cu to the total area of the wire is 33%) and Cu wire with a same diameter of 0.6 mm, where the conductivities of Cu and steel are 5.8×10^7 and 6.4×10^6 S/m, and the relative permeabilities are 1 and 80, respectively. The R_s and D_p ratio of CCS to Cu are also shown. The CCS wire shows lower R_s and D_p from 2 to 11 MHz and 2.2 to 11 MHz than Cu, and the lowest ratio of them at 3.8 MHz and 4.0 MHz, respectively. Thus, AC resistances due to both the skin and proximity effects are reduced at almost the same frequency range.

Fig. 4 shows AC resistance of one-loop coils with length of 500 mm made of CCS and Cu. The calculation is evaluated by using $\alpha = 0.13$ mm^{-1}. The calculation agrees measurement well and simulates superiority of the CCS wire.

The fact that CCS wires show lower resistance than Cu one is explained as follows. At high frequency, the magnitude of current density gets larger and the phase shifts as that close to surface of wire due to the skin effect as described by following approximate expression.

$$J(r) \propto e^{-d/\delta} e^{j(\omega t - d/\delta)}, \tag{2}$$

where $\delta = \sqrt{2/\omega\sigma\mu}$ is the skin depth and d is the depth from surface of wire. As shown in (2), internal current flows in a same direction just in the range of $0 < d < \pi\delta/2$, but reverses its direction when $d > \pi\delta/2$. The reversed current causes extra loss and hence increases resistance. Therefore, in order to minimize the reverse current, thickness of Cu should meet the following condition:

$$t = \pi\delta/2\ . \tag{3}$$

Fig.5 shows frequency at which R_s and D_p of a CCS wire with 0.6 mm diameter show the minimum ratio to a Cu wire with the same diameter depends on the area ratio of Cu. Plot for R_s shows good agreement and that of D_p also approximately matches with a CCS wire with thickness of (3).

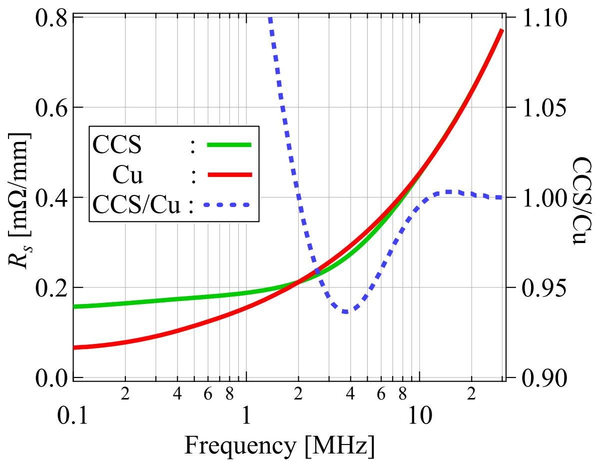

Fig. 2. Comparison of R_s.

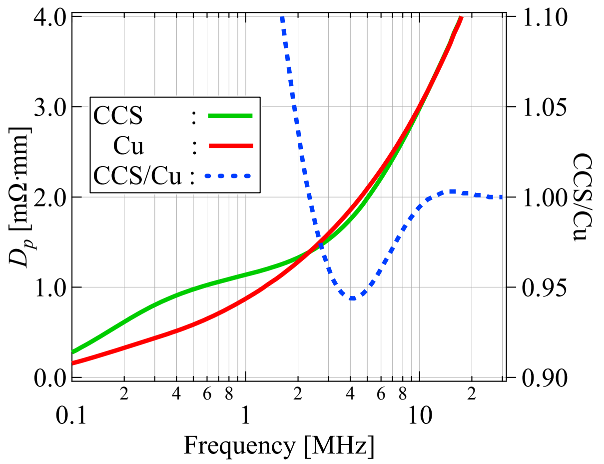

Fig. 3. Comparison of D_p.

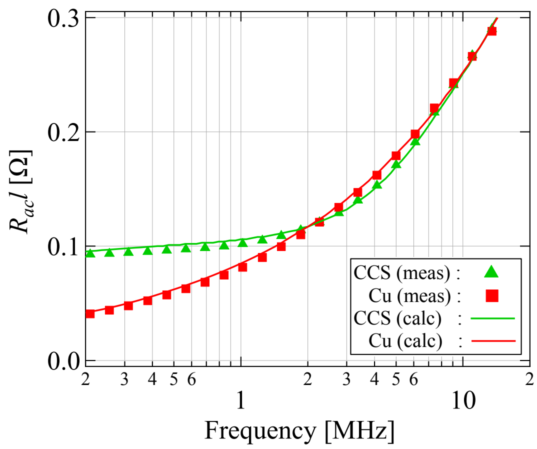

Fig. 4. Comparison of R_{ac}.

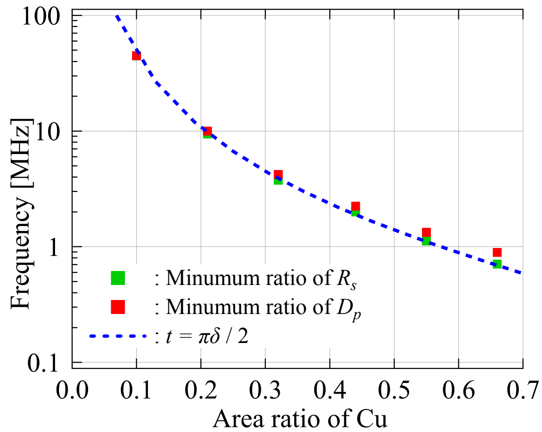

Fig. 5. Numerical analysis of the minimum ratio of R_s and D_p, and computation of that by (3).

IV. Conclusion

The AC resistance due to the skin and proximity effects of a CCS wire is numerically analyzed and verified by measurement. There exists a frequency range where a CCS wire shows lower resistance than Cu one described as function of thickness of Cu layer. Thus, two-layered wires are useful in WPT coil thanks to not only their mechanical characteristics but also low AC losses.

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