2E1-5

AC Resistance of Copper Clad Aluminum Wires

Ning Guan [1], Chihiro Kamidaki [1], Takashi Shinmoto [1], Ken'ichiro Yashiro [2]
[1] Power & Telecomm. Cable System R&D Center, Fujikura Ltd.
2153–1, Oota, Sakura, 285-0808, Japan, ning.guan@jp.fujikura.com
[2] Faculty of Engineering, Chiba University
1–33, Yayoi-cho, Inage-ku, Chiba, 863-8522, Japan

1. Introduction

Recently, wireless power transfer has attracted much attention for power supplying on not only small electric devices but also large equipments such as electric and hybrid vehicles [1]. Coils are key components in a power transfer system and the AC resistance determines the transferring efficiency. The AC resistance of wires used in coils is required as lower as possible for high efficiency systems.

We have proposed a copper clad aluminum (CCA) wire shown in Fig. 1 where an aluminum wire is surrounded by a thin copper layer. CCA wires are mainly composed from aluminum that is rich in the earth and are light-weight and easy for soldering. In addition, they have lower loss caused by the proximity effect [2] than commonly used copper wires at high frequencies.

In this paper, the AC resistance caused by the skin and proximity effects of a CCA wire with circular cross-section is numerically analyzed. The theory agrees well with experiments and it is demonstrated that coils wound by CCA wires have lower AC resistance than those by copper wires under some circumstances.

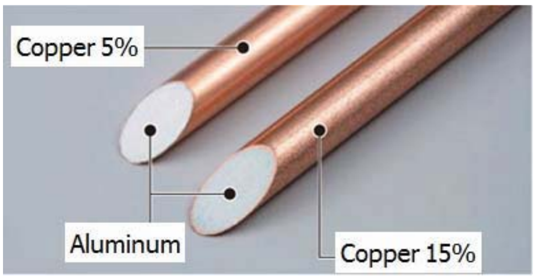

Figure 1: Copper clad aluminum wires.

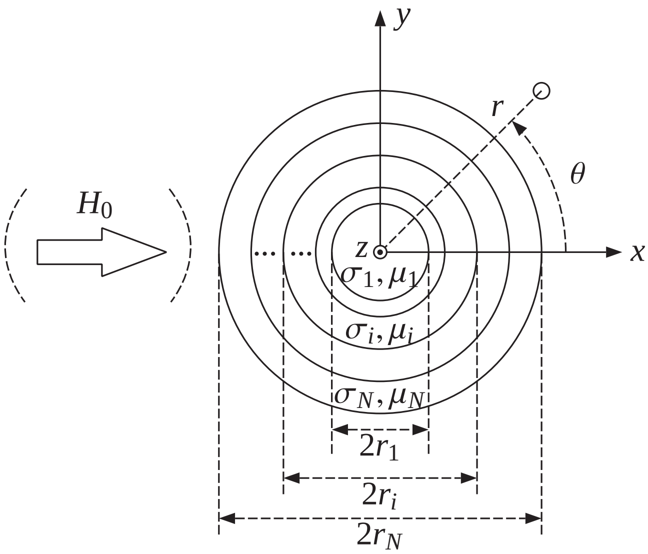

Figure 2: Wire model for analysis.

2. Formulation

2.1 AC Resistance Related to the Skin Effect

Figure 2 shows the model of a circular wire uniformly distributed along z-direction with N layers where the i-th layer has a conductivity of σ_i and relative permeability of μ_i. Assuming a time factor of $e^{j\omega t}$, the z-component of electric field E_z at the i-th layer satisfies

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} - j\omega\mu_i\mu_0\sigma_i E_z = 0. \tag{1}$$

It follows that

$$E_z = \begin{cases} A_1 J_0(k_1 r), & (r \leqq r_1) \\ A_i J_0(k_i r) + B_i Y_0(k_i r), & (r_{i-1} < r \leqq r_i, \quad i = 2, \ldots, N) \end{cases}, \tag{2}$$

where J_ν and Y_ν are the Bessel and Neumann functions of the ν-th order, respectively, $k_i^2 = -j\omega\mu_i\mu_0\sigma_i$ and A_i, B_i are constants.

Boundary condition requires

$$E_z|_{r=r_i-} = E_z|_{r=r_i+}, \tag{3}$$

$$\frac{1}{\mu_i}\left.\frac{\partial E_z}{\partial r}\right|_{r=r_i-} = \frac{1}{\mu_{i+1}}\left.\frac{\partial E_z}{\partial r}\right|_{r=r_i+}. \tag{4}$$

According to Ampére's law, total current I in the wire is given by enclosed integral of the magnetic field at the surface of the wire as

$$I = \oint H_\theta|_{r=r_N}\, dl = \frac{2\pi\xi}{j\omega\mu_N\mu_0}\left[A_N J_0'(\xi) + B_N Y_0'(\xi)\right], \tag{5}$$

where $\xi = k_N r_N$. Then all the constants are related to I.

On the other hand, loss of a wire with a length of l is obtained by the power flow passing into the wire through the surface as

$$\overline{P}_s = -\frac{1}{2}\oint \boldsymbol{E}\times\boldsymbol{H}^*\cdot d\boldsymbol{S} = \frac{j\omega\mu_N\mu_0 l|I|^2}{4\pi\xi}\cdot\frac{A_N J_0(\xi) + B_N Y_0(\xi)}{A_N J_0'(\xi) + B_N Y_0'(\xi)}. \tag{6}$$

Equating $\overline{P}_s = \frac{1}{2}(R + j\omega L)|I|^2$ yields the resistance per unit length of

$$R_s = \Re\left[\frac{j\omega\mu_N\mu_0}{2\pi\xi}\cdot\frac{A_N J_0(\xi) + B_N Y_0(\xi)}{A_N J_0'(\xi) + B_N Y_0'(\xi)}\right], \tag{7}$$

where $\Re$ denotes the real part of a complex number.

2.2 Loss Caused by the Proximity Effect

Assume that an AC magnetic field H_0 is applied to the wire along x-direction, as shown in Fig. 2. The z-component of a magnetic potential A satisfies

$$\frac{\partial^2 A}{\partial r^2} + \frac{1}{r}\frac{\partial A}{\partial r} + \frac{1}{r^2}\frac{\partial^2 A}{\partial\theta^2} + k_i^2 A = 0 \tag{8}$$

which has a solution of

$$A = \sin\theta \times \begin{cases} C_1 J_1(k_1 r), & (r \leqq r_1) \\ C_i J_1(k_i r) + D_i Y_1(k_i r), & (r_{i-1} < r \leqq r_i, \quad i = 2, \ldots, N) \\ C_{N+1} r + D_{N+1}/r, & (r_N < r) \end{cases}. \tag{9}$$

Constants C_i, D_i are related to H_0 by the boundary condition of

$$\mu_i\, A|_{r=r_i-} = \mu_{i+1}\, A|_{r=r_i+}, \tag{10}$$

$$\left.\frac{\partial A}{\partial r}\right|_{r=r_i-} = \left.\frac{\partial A}{\partial r}\right|_{r=r_i+}. \tag{11}$$

Loss due to the eddy current in the wire with a length of l is calculated by the power flow passing through the surface of the wire as

$$\overline{P}_p = -\frac{1}{2}\oint \boldsymbol{E}\times\boldsymbol{H}^*\cdot d\boldsymbol{S} = -\frac{2\pi l|\xi|^2|H_0|^2}{\sigma_N}\frac{\xi X Y^*}{|Z|^2}, \tag{12}$$

where

$$X = C_N J_1(\xi) + D_N Y_1(\xi), \tag{13}$$

$$Y = C_N J_1'(\xi) + D_N Y_1'(\xi), \tag{14}$$

$$Z = (\mu_N - 1)X + \xi\left[C_N J_0(\xi) + D_N Y_0(\xi)\right]. \tag{15}$$

2.3 AC Resistance of Coils

For a coil wound by wire, magnetic field is generated by the current flowing in the wire. Therefore, the magnitude of the field is proportional to the magnitude of the current, i.e.

$$|H_0| = \alpha |I|, \tag{16}$$

where α is a shape factor which depends on the structure of the coil. By introducing this factor, the total AC resistance of the wire is given by

$$R_{ac} = R_s + \alpha^2 D_p, \tag{17}$$

where D_p is associated with the loss caused by the proximity effect per unit length and given by

$$D_p = -\frac{4\pi|\xi|^2}{\sigma_N}\Re\left(\xi\frac{XY^*}{|Z|^2}\right). \tag{18}$$

3. Numerical Results

AC magnetic field applied to a metallic wire with finite conductivity will penetrate into the wire to induce eddy current inside. This effect depends on the applied frequency as well as the wire material and can be evaluated by the skin-depth of $\delta = \sqrt{2/(\omega\mu\sigma)}$, where σ and μ are the conductivity and permeability of the wire, respectively. In order to quantitatively understand the behaviour of the proximity effect for different wire materials, let us confine ourselves to consider a wire with a radius of a made by only one kind of material. In this case, (18) is simplified to [3]

$$D_p = 2\pi\omega\mu a^2 f_{\text{prox}}(\zeta), \quad f_{\text{prox}}(\zeta) = -\frac{1}{\zeta}\frac{\text{ber}_2\zeta\cdot\text{ber}'\zeta + \text{bei}_2\zeta\cdot\text{bei}'\zeta}{\text{ber}^2\zeta + \text{bei}^2\zeta},$$

where $\zeta = \sqrt{2}a/\delta = \sqrt{\omega\mu\sigma}a$ is the normalized radius and ber, bei are the Kelvin functions.

Function f_{prox} can be regarded as the loss dependence on σ at a fixed frequency and is plotted in Fig. 3. We may obtain a very interesting conclusion from the plot: the larger the conductivity of σ is, the higher the loss of D_p, provided $\zeta < 2.5$. It is implied that an aluminum wire may have lower proximity-effect-caused loss than a copper (Cu) one for thin wires in terms of the skin-depth. The CCA wires we have proposed show an unique electrical property based on this simple fact.

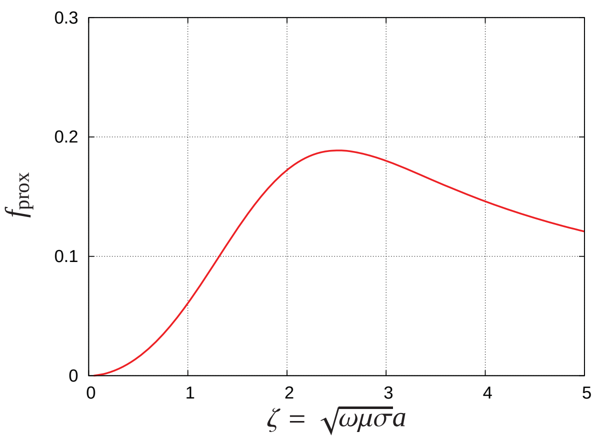

Figure 3: Function for proximity effect.

Figures 4 and 5 show the calculated R_s and D_p, respectively, for a Cu wire of Φ0.4 mm and a CCA one with the same diameter where the area ratio of copper to aluminum is 5%. It is shown that the CCA wire has higher R_s but lower D_p than the Cu wire as the frequency is lower than 420 kHz.

The fact that the CCA wire has lower D_p than the Cu one is explained as follows. Concentration of magnetic field to the wire surface is less significant in the CCA wire than in the Cu one thanks to the lower conductivity of aluminum and this reduces the loss of the eddy current in CCA wires. Figure 6

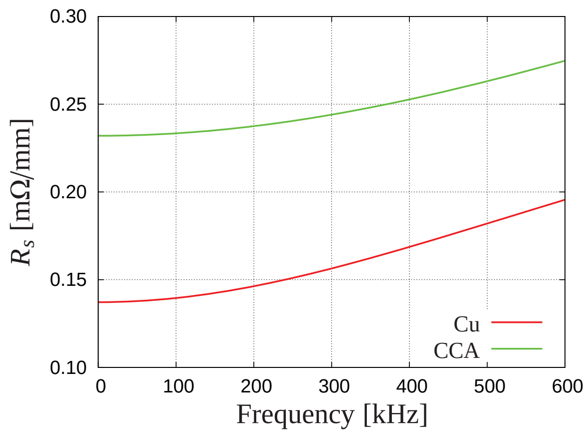

Figure 4: Calculated AC resistance related to the skin effect.

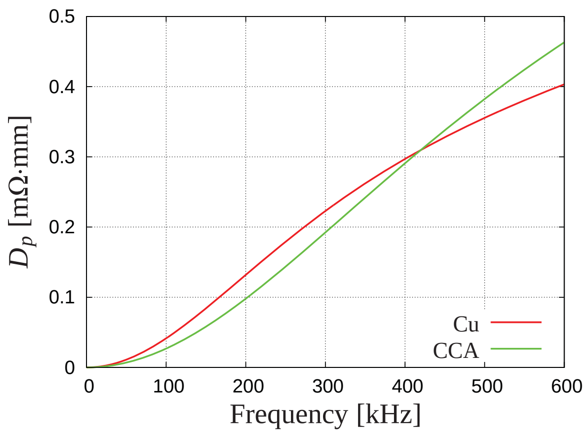

Figure 5: Calculated loss caused by the proximity effect.

shows the loss density on y-axis when a magnetic field of 100 kHz is applied and verifies the explanation. However, as frequency increases further, the magnetic field is only localized on the surface and the losses reverse in magnitude.

Figure 7 compares the calculated and measured AC resistances for a coil wound by a cable stranded with 14 wires of Φ0.4 mm for 8 layers of 10 turns on a bobbin of Φ20 mm, where the shape factor α is set to 11.8 mm^{-1}. It is shown that the theory agrees well with the measurement and the resistance of CCA wire is less than that of Cu wire when frequency is between 15 and 350 kHz.

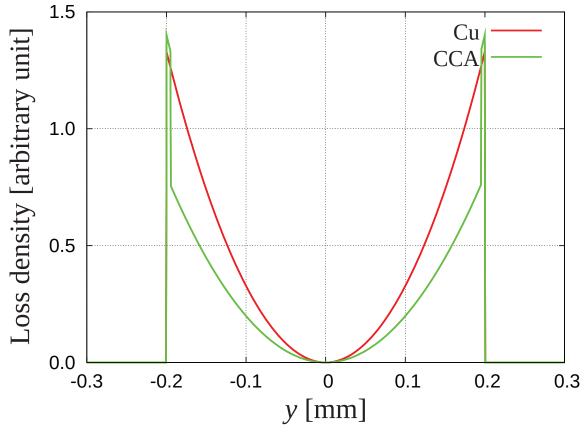

Figure 6: Loss density on y-axis at 100 kHz.

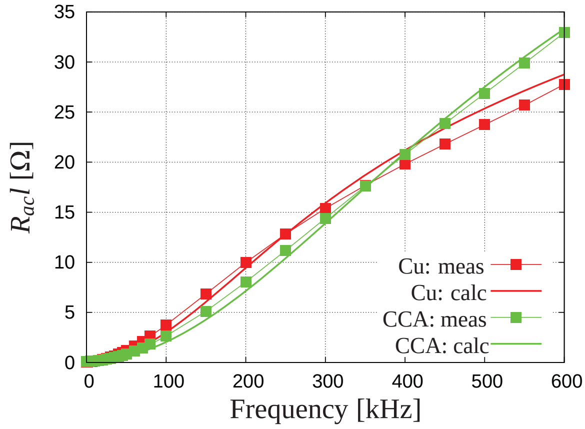

Figure 7: Comparison of AC resistance.

4. Conclusion

We have numerically analyzed the AC resistance caused by the skin and proximity effects for a circular wire. It is experimentally and theoretically demonstrated that CCA wires have lower resistance than Cu ones at some circumstances. The CCA wires will be very useful in power transfer systems because they are light-weight, cost-effective and even low-loss.

References

[1] N. Shinohara, "Power without wires," *IEEE Microw. Magazine*, vol. 12, pp. S65–S73, 2011.

[2] H. B. Dwight, *Electrical Coils and Conductors*, McGraw-Hill, 1945.

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