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Reduction of Eddy Current Loss in Metal Sheath of 154 kV Transmission Cable

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The power cables in underground transmission lines consist of a conductor, an insulator, and a metallic sheath. The metallic sheath serves to protect the cable from external physical impacts. When a large fault current is applied to the transmission line owing to an accident, the metallic sheath prevents the fault current from penetrating into the transmission-line current and thus enhances the reliability of the transmission line. However, owing to the alternating current flowing through the conductor, an eddy current is generated in the sheath and a loss occurs. Thus, the overall transmission efficiency is reduced. In this paper, an eddy current loss in a metallic sheath was analyzed using an analytical method, and the results thus obtained were verified by comparing them with those obtained using the finite element method. In addition, a design was proposed for reducing the eddy current loss.

Keywords : eddy current, eddy current loss, 154 kV cable, sheath

1. Introduction

Improving the efficiency of power systems has received increasing attention recently; the prediction of losses occurring in power-system transmission lines (shown in Fig. 1) has become important. Transmission efficiency can be calculated by measuring the power of the input and output terminals and then calculating the total loss. Among the total losses, the transformer losses are measurable. However, as the loss caused by the internal and external structures of the power cable comprise hysteresis and eddy current losses, it is difficult to measure the loss. However, in order to improve the transmission efficiency, it is necessary to accurately predict the loss of each structure, and the design for reducing loss should be developed based on the predicted loss [1-4].

In previous studies, research was conducted on the hysteresis loss and eddy current loss that occurred in the metal fittings around the cable [5]. However, there is insufficient research on the loss occurring inside the cable.

The power cable used in an underground transmission line consists of a conductor, an insulating layer, and a metallic sheath. In the conductor, an AC current transmits electrical power, and the insulating layer serves to prevent any leakage of the current. The metallic sheath protects the transmission line from external physical shocks and fault current. In the case of conductors, the copper loss can be predicted from the resistance and current. However, in the metal sheath, the magnetic field generated by the AC current flowing through the conductor crosses the metal sheath and according to Faraday's law, the eddy current is generated in the direction to reduce the change in the magnetic flux, thus resulting in an eddy current loss. Furthermore, there exists a limitation in the measurement of eddy current loss.

Therefore, it is necessary to study the eddy current loss that occurs in the metal sheath. In addition, research is

Fig. 1. (Color online) Underground transmission lines.

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required to be conducted to reduce the eddy current loss by considering the analyzed eddy current loss in order to improve transmission efficiency.

In this paper, the eddy current loss in the metal sheath was analyzed, and a structure of metal sheath for reducing the loss was proposed. First, based on the Maxwell equation, an equation was derived for evaluating the eddy current loss induced in the metal sheath of the power cable. The obtained result was then compared with that obtained using the finite element analysis and thus verified. Furthermore, based on the analysis results, a method was proposed for reducing the eddy current loss.

2. Analysis of Eddy Current Loss in Metal Sheath

2.1. Structure and material of 154 kV cable

The structure of a typical 154-kV cable is presented in Fig. 2. The inside of the cable consists of a conductor through which current flows, an insulating layer for protection, and a metal sheath. However, as only the conductor and metal sheath have conductivity, an alternating current flows in the conductor, and thereby an eddy current flows in the metal sheath. Therefore, only the conductor and sheath are required to be considered in the eddy current loss calculation and finite element method (FEM). Table 1 lists the size of each component. In this study, the loss was analyzed while considering conductor and metallic sheath.

Table 1. Sizes of cable components.

	Inner diameter	Outer diameter
Conductor	-	54 mm
Metallic Sheath	112.8 mm	118 mm

2.2. Computational analysis

A general method is developed for calculating the current distribution in the conductor and metallic sheath by starting from the quasi-static Maxwell equations. The system to be studied is shown in Fig. 3.

Ω_1 represents a conductor fabricated using copper, Ω_2 and Ω_4 represent air, and Ω_3 represents a metallic sheath composed of aluminum. At low-frequency conditions below 60 Hz, the Maxwell equation is as follows.

$$\nabla^2 \vec{E} - jk^2 \vec{E} = 0 \tag{1}$$

where $\vec{E}$ is the electric field, k^2 is $2\pi f \mu \sigma$, and f is the frequency. μ is the permeability, and σ is the conductivity. If we use cylindrical coordinates, the equation can be written as follows.

$$\frac{\partial^2 \vec{E}}{\partial^2 r^2} + \frac{1}{r}\frac{\partial \vec{E}}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \vec{E}}{\partial \phi^2} = jk^2 \vec{E} \tag{2}$$

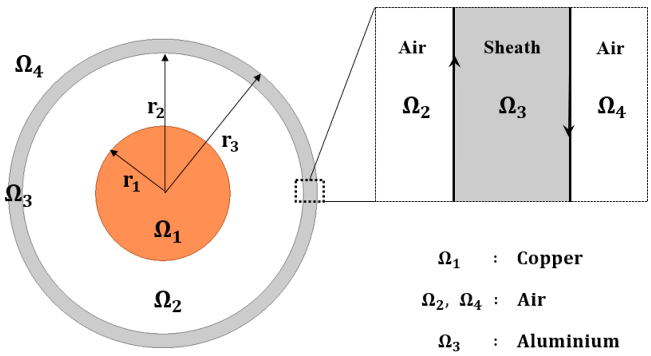


Fig. 3. (Color online) Model for underground power cable.

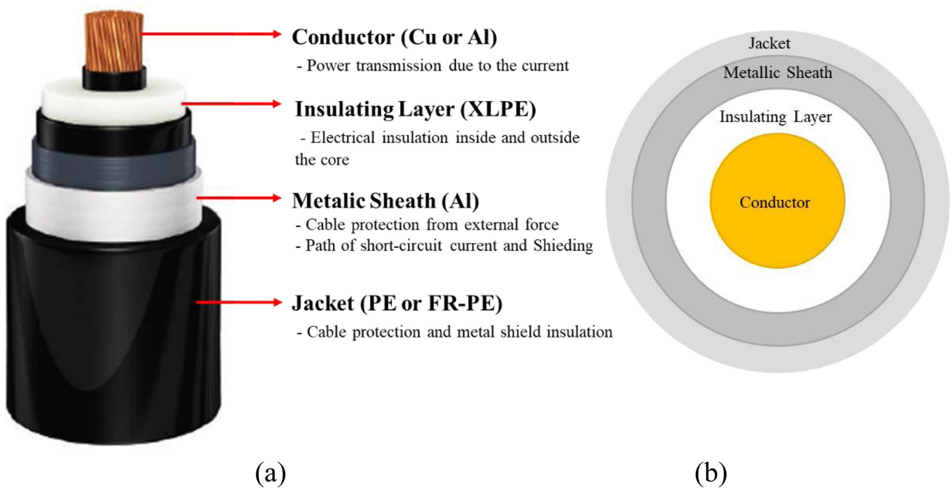


Fig. 2. (Color online) Structure of 154-kV power cable. (a) Structure of power cable. (b) Model of power cable.

In this case, the solution of equation (2) can be expressed in the form of the Bessel function [6]. On considering boundary conditions, the electric field in the sheath is as follows.

$$\overrightarrow{E_3}(r) = C_3 J_0(j^{1.5}kr) + B_2 Y_0(j^{1.5}kr) \tag{3}$$

where C_3 and B_3 are constant, and J_0 and Y_0 represent the Bessel equation. As the permeability of aluminum equals that of air, the magnetic field strength inside the sheath changes linearly. However, as the Bessel equation component exists in the electric field equation, it is difficult to calculate the eddy current loss directly via the integration of the square of the eddy current density. Therefore, the eddy current loss in the metallic sheath is represented by the following expression using pointing vector theory.

$$S = \oint(\vec{E} \times \vec{H}) \cdot dS \tag{4}$$

The real component of the energy of electromagnetic waves in the sheath is eddy current loss. If only the real part was considered, it can be expressed as in Eq. (5), and finally the eddy current loss occurring in the sheath can be expressed in Eq. (6).

$$< S >= \frac{1}{2}\mathrm{Re}(\oint(\vec{E} \times \vec{H}^*) \cdot d\Omega_3) \tag{5}$$

$$\begin{aligned} P_{loss} = -\frac{1}{2}\mathrm{Re}[C_3\{J_0(j^{1.5}kr_3) - J_0(j^{1.5}kr_2)\} \\ + B_3\{Y_0(j^{1.5}kr_3) - Y_0(j^{1.5}kr_2)\}] \end{aligned} \tag{6}$$

P_{loss} is the eddy current loss in the metallic sheath, r_2 is the inner radius of the sheath, and r_3 is the outer radius of the sheath. C_3 is –4.5887+4.4649i and B_3 is –4.465-1.5887i, respectively. Therefore, the eddy current loss in

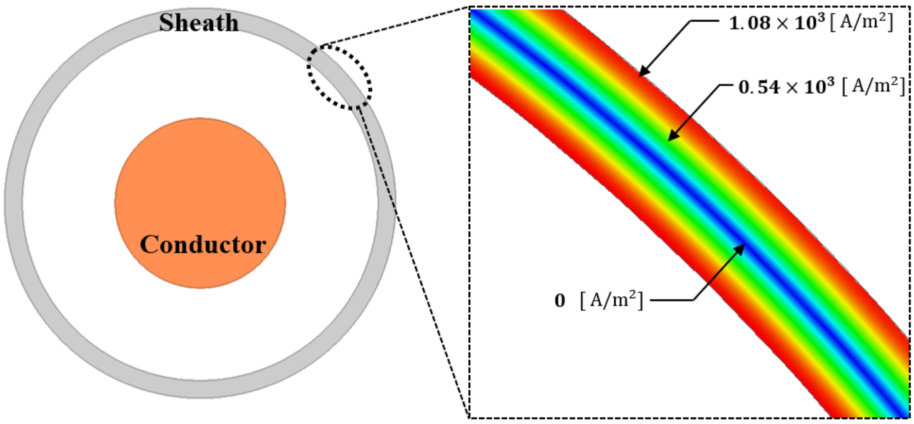


Fig. 4. (Color online) Magnitude of cable-sheath eddy current density (ωt = 0°) obtained using analytical method.

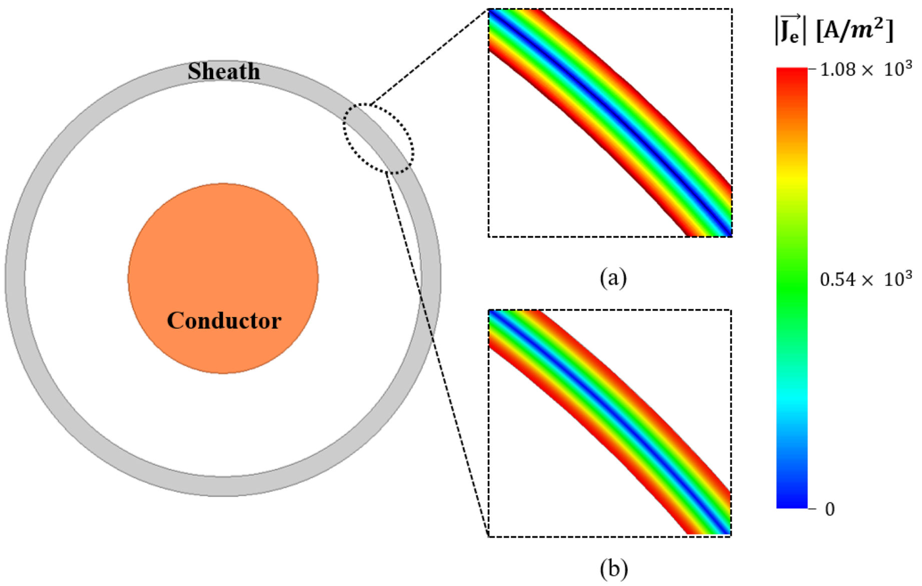


Fig. 5. (Color online) Magnitude of cable-sheath eddy current density (ωt = 0°) according to methods. (a) FEM (Finite Element Method) (b) Analytical method.

Table 2. Eddy current loss obtained with each method.

	Analytical method	FEM
Eddy current loss	23.05 [W/km]	23.05 [W/km]

the metallic sheath can be expressed as a function of the sheath width.

Figure 4 shows the contour of the magnitude of the eddy current density in the metallic sheath. On considering the distribution of the current density, it can be observed that the eddy current flows intensively toward the inside and outside of the sheath.

2.3. Comparison of metallic-sheath eddy current loss obtained using analytical method and FEM

The equation of the eddy current loss in the power-cable metallic sheath was derived using the Maxwell equation. In order to verify the metallic-sheath eddy current loss equation, the eddy current loss calculated using the analytical method and the eddy current loss data obtained from the 2D FEM were compared. Both the methods had the same power conditions. The maximum value of the current applied to the conductor was 1156 A, and the frequency was 60 Hz. The considered geometric parameters (r_2 = 56.4 mm, and r_3 = 59 mm) were also the same.

Figure 5(a) and (b) presents the contour of the magnitude of the eddy-current density in the metallic sheath according to the FEM and analytical method, respectively. Considering the distribution of the current density, it can be observed that the eddy current flows intensively toward the inside and outside of the sheath. It can be observed that the magnitude of the eddy current loss according to the change in the sheath width is the same in both methods.

Table 2 presents a comparison of the eddy current loss according to the eddy current calculation method. It can be observed that an eddy current loss of 23.05 W/km was calculated in the case of both methods.

3. Reduction of Eddy Current Loss in Metal Sheath

Figure 6 presents the flow of eddy current in a metal sheath. The eddy current flows in a direction parallel to the conductor along the metal sheath and in the direction of being blocked at both edges.

3.1. Previous research

The eddy current loss from the metal sheath results in a reduction in the overall efficiency of the power transmission system. Accordingly, increasing resistance of sheath and reduction structures have been proposed for

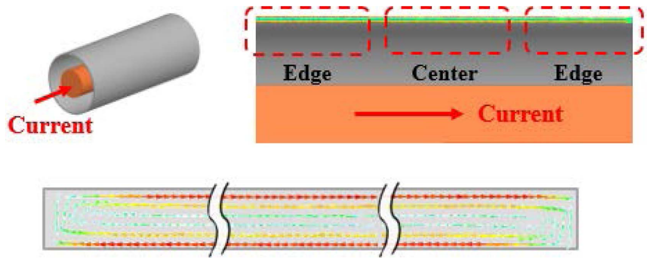
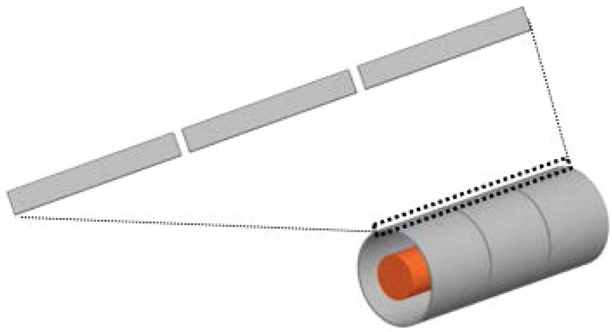
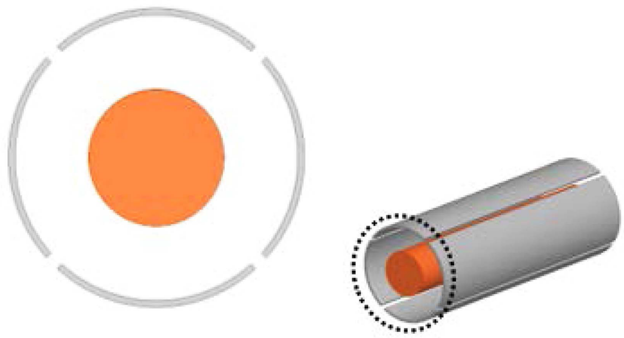


Fig. 6. (Color online) Eddy current vector in metal sheath.



(a)



(b)

Fig. 7. (Color online) Model types considered for reducing eddy current loss: (a) Model A. (b) Model B.

reducing eddy current losses [7-9]. However, these do not appropriately take into consideration the flow of the eddy currents, and thus, have limitations.

Figure 7 presents the model type used for reducing the eddy current loss. Model A comprises a structure with a metal sheath cut along the length of the cable. Model B comprises a cut in the circumferential direction of the sheath. Model A was first proposed because it can cut the flow of the eddy currents. However, its structure does not actually block the eddy currents.

Figure 8 presents the eddy current path according to model type. L represents the length of the sheath, and D is the thickness. As such a cable is thousands of kilometers in length, L has a value close to infinity. We consider that the length of the eddy current path in the

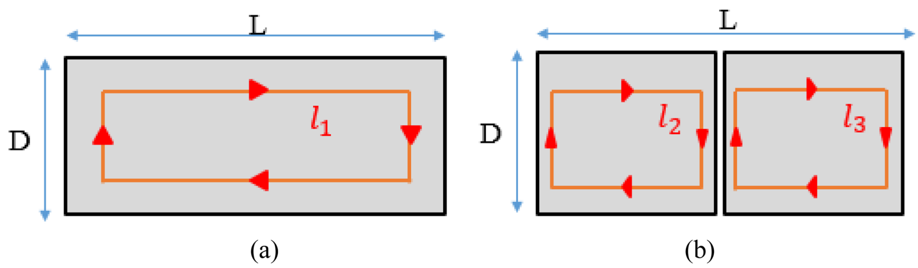


Fig. 8. (Color online) Eddy current path equivalent model. (a) Reference Model. (b) Model A.

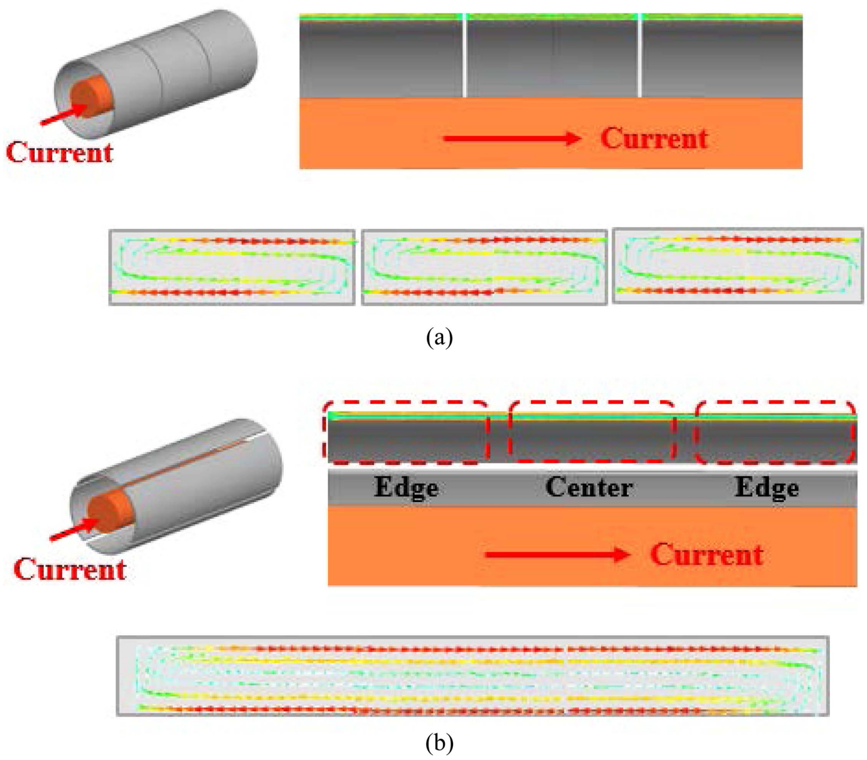


Fig. 9. (Color online) Analysis of eddy current vector according to FEM. (a) Model A. (b) Model B.

reference model is l1. As model A was blocked in the longitudinal direction, the path was divided into several paths. However, as L is very long, the overall length was almost the same as that of the reference model. In addition, model B does not interfere with the flow of the eddy currents, and thus, it has the same length as that of the reference model. As the total length is the same, the total resistance is the same, and accordingly, the eddy current flow equally.

Figure 9 presents the eddy current vector obtained from the FEM. Figure 9(a) shows model A, and it can be observed that the magnitude of the eddy current was similar to that of the reference model. Moreover, model B shows similar results.

3.2. Design for reduction of eddy current loss

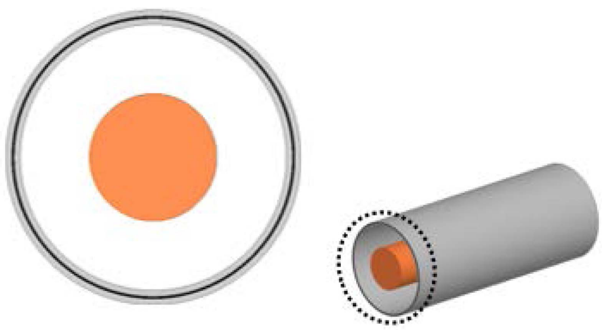


Fig. 10. (Color online) Proposed model for reducing eddy current loss.

In order to reduce the eddy current loss occurring in the metal sheath, a method is required for increasing the resistance by increasing the total length of the eddy

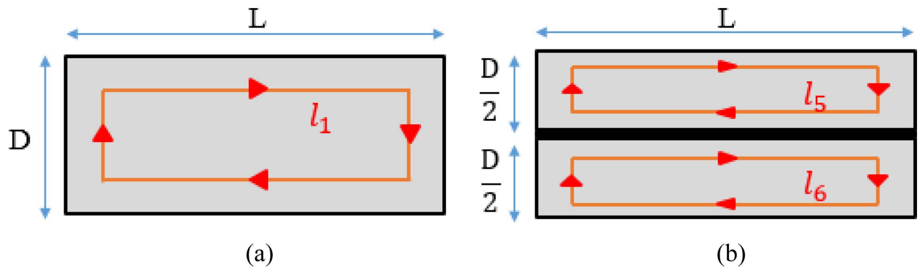


Fig. 11. (Color online) Analysis of eddy current vector according to FEM. (a) Reference Model. (b) Proposed Model.

current path.

Figure 10 presents the proposed model for reducing the eddy current loss. In contrast to the previous models, the proposed model was designed to stack metal sheaths in a manner similar to the stacking used in transformers.

Figure 11 presents the comparison of the total length of the eddy current flowing in the reference and proposed models. The proposed model has two paths for eddy current flow, in contrast to that in the reference model, where it flows along one path. Each path through which the eddy current flows is equal to L in the cable direction and D in the thickness direction is halved. However, as there are two paths in total, the path length in the D direction is almost the same for both models, and in the L direction, it is twice as long as that in the reference model.

As the overall length is doubled, the total resistance is also doubled. When the resistance is doubled, the eddy current is reduced by 2 times and the loss is reduced by 4 times.

Figure 12 shows the eddy current in the proposed model. Since the sheath was divided into two plates and insulated, eddy currents flows through each of the upper and lower plates, forming a path, respectively. Accordingly, as the length of the entire eddy current path increased by about 2 times, and the resistance is increased, thereby reducing the eddy current. It can be observed that the eddy current magnitude was reduced from the color of the eddy current path being blue as compared to that in the previous model.

Table 3 lists the eddy current loss for each model. In the reference model, 23.05 W/km of eddy current loss was

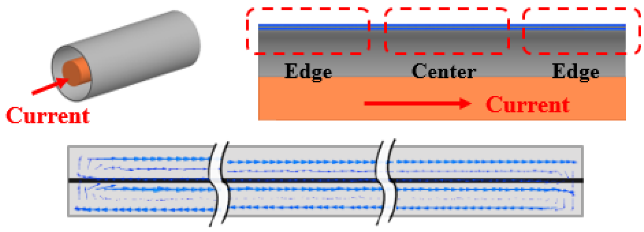


Fig. 12. (Color online) Analysis of eddy current vector according to FEM in proposed model.

Table 3. Eddy current loss according to models.

Model Type	Eddy Current Loss	Reduction Rate
Reference	23.05 [W/km]	-
Model A	21.28 [W/km]	7.7 %
Model B	22.92 [W/km]	0.6 %
Proposed	4.56 [W/km]	80.2 %

generated. Models A and B demonstrate losses of 21.28 W/km and 22.92 W/km, respectively, which are similar to that of the reference model.

In contrast, in the case of the proposed model, a loss of 4.56 W/km was generated, which indicates a reduction of 80.2 % as compared to that of the reference model.

4. Conclusion

In this paper, an equation was proposed for predicting the eddy current loss that occurs in the metal sheath of a 154-kV power cable and verified using the FEM. An eddy current loss of 23.05 W per kilometer was observed in the metal sheath. When considering the length of the entire power cable, an eddy current loss that cannot be ignored is generated, and the cable transmission efficiency is deteriorated accordingly.

Therefore, this paper presented a design that can reduce the eddy current loss by analyzing the loss distribution. By dividing the path along which the eddy current flows, the total eddy current path length is doubled, which increases the total resistance and decreases the eddy current accordingly.

Acknowledgments

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References

[1] P. A. Hargreaves, B. C. Mecrow, and R. Hall, IEEE Trans. Ind. Appl. **48**, 1460 (2012).

[2] K. S. Seo, H. D. Kim, K. H. Lee, and I. H. Park, IEEE Trans. Magn. **51**, 1 (2015).
[3] J. J. H. Paulides, K. J. Meessen, and E. A. Lomonova, IEEE Trans. Magn. **44**, 4373 (2008).
[4] M. Majoros, M. D. Sumption, M. A. Susner, M. Tomsic, M. Rindfleisch, and E. W. Collings, IEEE Trans. Appl. Supercond. **19**, 3106 (2009).
[5] H. E. Song, S. H. Im, K. Y. Kim, and G. S. Park, Kepco Journal on Electric Power and Energy **4**, 9 (2018).
[6] W. Moutassem and G. J. Anders, IEEE Trans. Power Delivery **25**, 2054 (2010).
[7] C. S, G. W, A. V, A. B, L. O, M. T, and R. R, IEEE Trans. Appl. Supercond. **19**, 2463 (2009).
[8] R. D. Rindlay and J. H. Dableh, Proceedings of Canadian Conference on Electrical and Computer Engineering **2**, 794 (1993).
[9] J. H. Dableh, R. D. Findlay, R. T. H Alden, and B. Szabados, IEEE Trans. Power Del. **5**, 1 (1990).