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FEM을 이용한 초전도 직류 케이블의 손실 특성 분석

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Loss characteristics analysis of HTS DC cable using FEM

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Abstract - The authors analyzed harmonic current based loss of a high temperature superconducting (HTS) DC model cable. The loss in HTS DC cable is generated due to the variation of magnetic field caused by harmonic current in a HVDC transmission system. The authors designed and fabricated two meters of HTS DC model cable for verification of real loss characteristic. In this paper, the loss characteristics caused by harmonic current in the HTS DC model cable are analyzed using commercial finite element method software package. The loss of the HTS DC cable is much less than the loss of the HTS AC cable but the loss should be considered to decide a proper capacity of cooling system.

1. Introduction

According to the increasing power demand in urban area, the underground power transmission systems have to be expanded, but it is very difficult to construct new cable tunnels and ducts to install additional underground transmission lines. HTS power cable is one of the most feasible solutions for solving the above problems. And, compared to conventional cables, HTS power cable can offer advantages of higher capacity, lower loss, lighter weight and more compact dimension [1]. Hence, HTS AC power cables are now to be commercialized in practical power grid [2].

Compared to DC HTS power cable, HTS AC power cable has hysteresis and eddy-current losses in the superconductor and its stabilizer caused by the AC magnetic flux; the HTS DC power cable has no such losses [3]. However, the DC current of HVDC system includes harmonic components and the variation of current makes a variation of magnetic field in HTS DC power cable, then the transmission loss is consequently occurred even under DC transport current.

The loss is an important factor for HTS DC power cable design, which decides the capacity of cooling system. Therefore loss should be predicted [4],[5]. In AC transport current, the loss of HTS AC power cable can be calculated using several formulas, however, the loss of HTS DC power cable can't be calculated by general AC loss equations.

This paper describes a FEM analysis model to predict the harmonic current based loss of HTS DC model cable. The analysis results will be compared with experimental results obtained by HTS DC model cable.

2. FEM analysis model

Superconductor has non-linear electric-current density (E-J) characteristics. The non-linearity of superconductor is very severe compared with a normal conductor and it is considered in the FEM model. Also, magnetization of a rolling-assisted biaxially textured substrate (RABiTS) has been considered in the FEM model because it has influence on the loss [2]. Approximation of Maxwell equation in the H-field model was suggested and it showed good performance for the estimation of the AC loss in the superconducting layer [2], [6]. The related equations of the H-field model are shown in (1) to (4).

$$\mu\frac{\partial H_x}{\partial t}+\frac{\partial E}{\partial y}=0,\quad \mu\frac{\partial H_y}{\partial t}-\frac{\partial E}{\partial x}=0 \qquad (1)$$

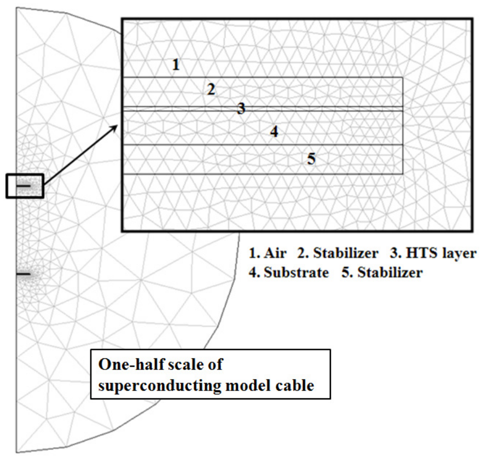
$$E=\rho(J)J \qquad (2)$$

$$J=\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y} \qquad (3)$$

$$P=\int_A E\times J dA[W] \qquad (4)$$

Where, H and E are magnetic field and electric field in 2D domain. μ is the permeability of the each layer. ρ is the electric resistivity, which describes E-J relation of superconductor, and J is the current density in the HTS conductor.

As shown in Fig. 1, the FEM model is a detailed model of superconductor that is composed of four layers of stabilizer, HTS layer, substrate and stabilizer from the outside. The HTS tape has been located symmetrically from the center and the specification of HTS cable model is shown in Table 1.



<Fig. 1> FEM analysis model of HTS DC model cable

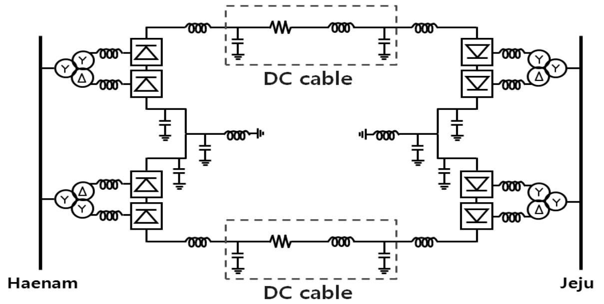
<Table 1> Specification of the HTS cable model

Parameters	YBCO wire
Substrate type	RABiTS
Critical current(Ic)	73.2 A
HTS thickness/width	1 μm/4.32 mm
Substrate thickness	70 μm(weak-magnetic)
Stabilizer	60 μm both side
Between each layer	13.66 mm
Stabilizer material	Brass

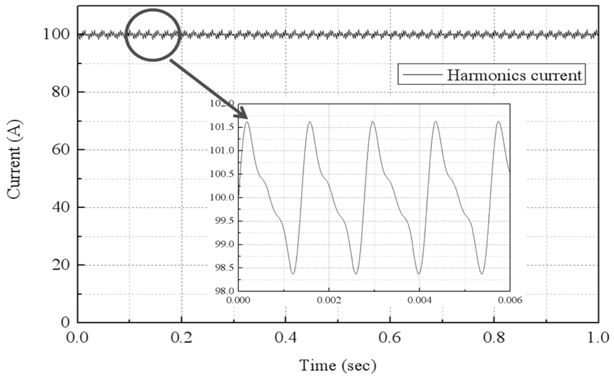
3. Analysis results

The AC/DC converter of HVDC system causes harmonic current in DC side. Because the operation of the thyristor sequential switching results in distortional current waveform. As shown in Fig. 2, the harmonic components for loss analysis have been obtained by the analysis of Jeju and Haenam HVDC system. The harmonic orders are

12th, 24th and 36th, and the harmonic components are shown in Table 2. The loss of HTS DC model cable has been analyzed using the obtained harmonic currents.



(a) Jeju & Haenam HVDC system



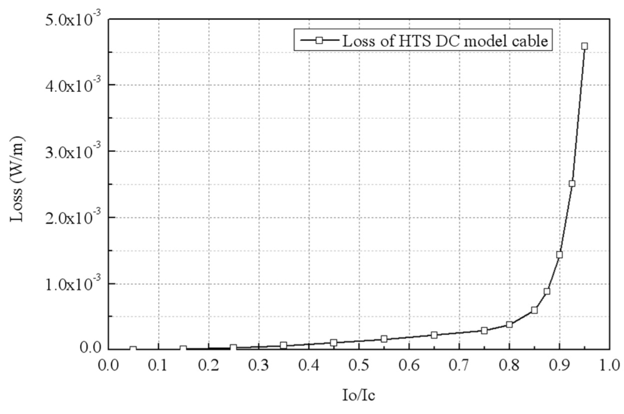
(b) Harmonic current

<Fig. 2> HVDC system & harmonic current for loss analysis

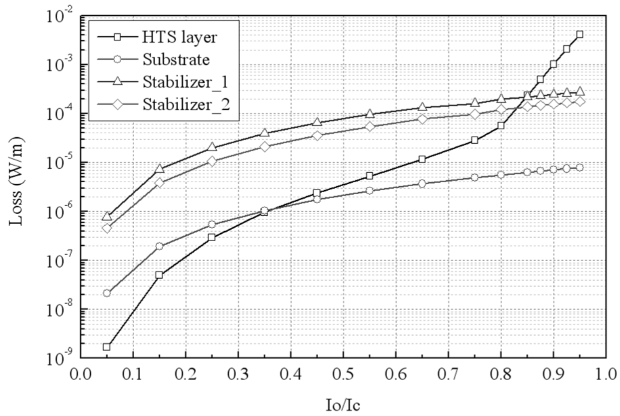
<Table 2> The magnitude of harmonic components

Orders	Frequency(Hz)	Ratio(%)
DC	0	100
Fundamental	60	0
12th	720	1.16
24th	1440	0.61
36th	2160	0.27

As shown in Fig. 3, the loss of the HTS DC model cable has been increased by the increase of the Io/Ic and the harmonic components. The loss of the HTS conductor is composed of iron loss of substrate, stabilizer and magnetization loss of HTS layer. Fig. 4 shows each loss components of HTS layer, substrate and stabilizer. When Io/Ic is less than 0.8, the loss in stabilizer of HTS conductor is the greatest among the loss of HTS conductor.



<Fig. 3> Loss of HTS DC model cable analysis results



<Fig. 4> Loss components of HTS DC model cable

The loss has been increased because the total magnetic flux has been increased by the increases of the Io/Ic and the harmonic components. When Io/Ic is less than 0.8, the loss of stabilizer is the greatest because eddy current loss is proportional to square of the magnetic flux's frequency.

4. Conclusions

In this paper, we have discussed the loss of HTS DC cable which is much smaller than the loss of HTS AC cable. The loss of HTS DC cable, however, can not be ignored due to the large capacity and long distance of HTS DC cable. HTS DC cable losses are mostly caused by the stabilizer of superconductors. To reduce such losses in HTS DC cable, a thin stabilizer and the eddy current free HTS materials should be used. To prove the FEM based analysis results of this paper, the loss needs to be detected using a real HVDC converter and HTS DC model cable.

Acknowledgment

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