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A study on the eddy current losses on the high-Tc superconducting power cable system

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***Abstract*— The structure of a high-Tc superconducting power cable system is composed of these parts; (from the outer section) a liquid nitrogen cryostat, a vacuum cryostat, multi-layer high-Tc superconducting cable cores and a stabilizer which is used as the current bypasses during the quench period. In this paper, the eddy current losses in the stabilizer and both cryostats during the stable operating period of the high-Tc superconducting power cable system are calculated by the numerical method. And the optimal conditions of the stabilizer and both cryostats, that minimize the eddy current losses, are derived from the analyzed results. The optimal results can be applied to the design and manufacture of the high-Tc superconducting power cable system.**

***Index Terms*—cryostat, eddy current loss, high-Tc superconducting power cable system, numerical method, quench, stabilizer**

1. INTRODUCTION

Since 1987 when a high-Tc superconductor that could be driven at liquid nitrogen temperature was found and since the middle of the 1990s, high-Tc superconducting cables which could be used in electric power systems developed and universal cable manufacturers and electric power companies have recently been spurring to develop a common use for the high-Tc superconducting power cables.[1]

The high-Tc superconducting power cable system is an environment-friendly system. So, it can solve electric power supply problems in big cities, because conventional copper cables are replaced by high-Tc superconductors for the purpose of low-loss & high-capacity power transport.[2]~[3]

Because of the lower electrical capacitance of the superconducting power cable compared to that of conventional cable, there's no limitation on the power transmission distance

and capacity. So, it is possible to transfer a high capacity of electrical power.

Therefore, it is possible to secure power transmission capacity using a lower voltage, and to reduce the system operation costs by decreasing the number of power transmission lines as well as decreasing the condensation of insulation design or the reduction of transmission loss.

When the transmission currents pass through a superconducting power cable, eddy current losses occur in the stabilizer and cryostats around superconducting cables, and these eddy current losses affect the whole superconducting power cable system greatly.

In this paper, the eddy current losses that occured in the superconducting power cable systems were, first, numerically modeled by using OPERA-3d (a commercial electromagnetic field analysis program), and then, eddy current losses from each part were calculated.

2. BASIC THEORY

2.1. Eddy current loss

A superconducting power cable system usually has the following electromagnetic structure. It consists of multi-layers of superconducting cores for power transmission, stabilizers that bypass the transmission current in case of quench and outer cryostats for liquid nitrogen and vacuum.

The structure and shape of the superconducting power cable system are shown in Fig.1 and Fig.2.

When the voltage is applied to the ends of the cable, there is a transport current in each superconducting layer and that current makes the magnetic fields around the whole superconducting power cable system.

Through these magnetic fields, eddy current losses occur in the stabilizer of the interior and 2 layers of cryostats.

Eddy current losses in the vacuum layer can be ignored, and loss in the silver base is also negligible because it was insulated mutually. Therefore, most of the loss in the superconducting power cable system occurs in the stabilizer.

2.2. Electromagnetic Analysis

The superconducting power cable system can be F.E.M. modeled by the Poisson equation or the Laplace equation that are derived from the Maxwell equation.

These equations are given in the form of partial difference equations that have boundary conditions, in most cases, it is impossible to solve those using an analytical method. So, generally, a numerical analysis method is used to obtain the solutions.

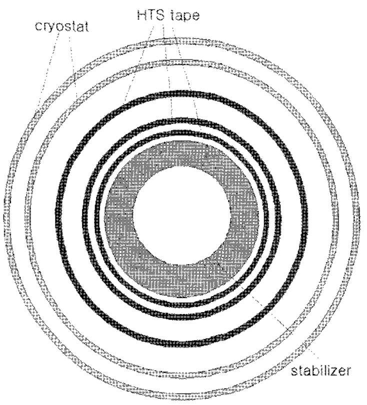

Fig. 1. A cut-view of a superconducting power cable system.

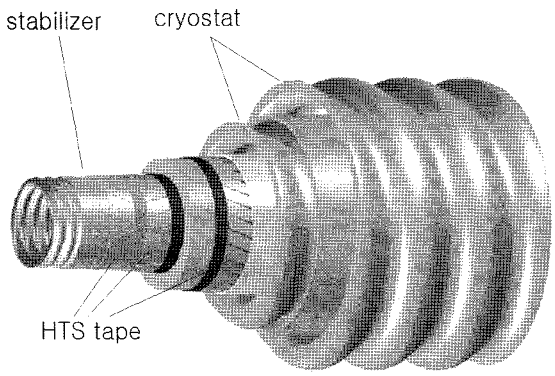

Fig. 2. A structure of superconducting power cable system

Methods for numerical analysis which can yield a solution from the partial difference equation that has a boundary condition are the finite difference method, the boundary element method and so on. There are various kinds, but the one method used most widely is the finite element method.

The finite element method divides the whole area where the equation is applied to a small area, and after, it supposes that a solution is fixed in each fraction. And then, it yields a solution which satisfies the equation. The solution of each area is used to yield a solution of the whole system by using first or second polynomial approximations.

Most commonly used programs at present have been developed based on this method.

In this paper, OPERA-3d is used to analyze an electromagnetic field analysis of the superconducting power cable system..

There are methods to analyze the time-varying electromagnetic problem. In this paper, the method of magnetic scalar potential is used to reduce analysis time and memory capacity.

3. F.E.M MODEL

Skin-depth must be considered to analyze an electromagnetic analysis model. Skin effect is the property of the induced current and magnetic field confined to the surface of a conductor when the frequency increases. By this effect, the current and magnetic field in a conductor decreases exponentially from a conductor surface. Skin-depth decreases as the frequency of, an electrical conductivity and magnetic permeability of material increases.

In this paper, skin-depth is considered to improve the accuracy of the Analytical Results. That is, the analysis model has enough mesh within its skin-depth at mesh creation according to the change in several design parameters that influence on the skin-depth of the analysis model.[4]

Fig. 3 is an analysis model image using OPERA-3d.

The cores of the superconducting power cables are composed of 2 layers for the transmission current and 1 layer for shielding.

The 2-layer cryostat is situated on the outside of the superconducting cores for the liquid nitrogen and the vacuum charging, stabilizer is situated on the inside of core.

Fig. 4 is the image of the stabilizer. As can be seen in Fig. 4, there are 2 types of stabilizer models, one is a bulk cylinder type and another is a divided cylinder type. If the stabilizer, such as in Fig. 4(b), has sections that are disaffiliated and given enough space from each other, the

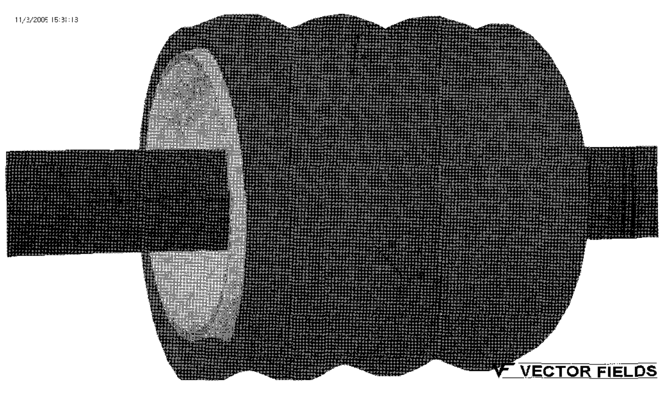

Fig. 3. Superconducting power cable system using by OPERA-3d

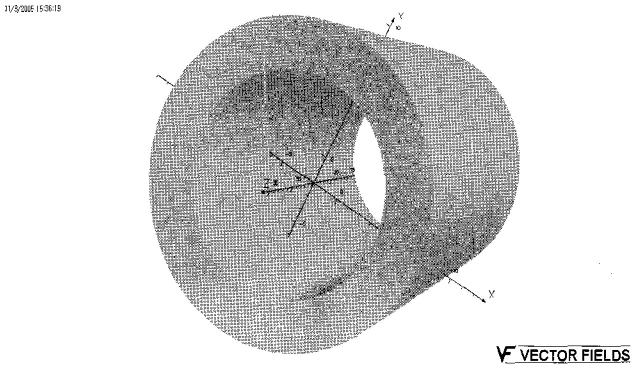

Fig. 4(a). Bulk cylinder type stabilizer

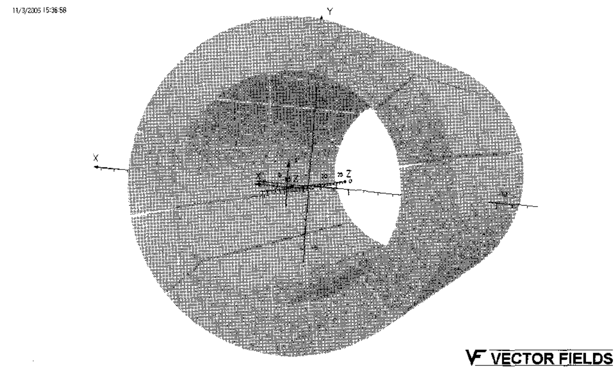

Fig. 4.(b). Divided cylinder type stabilizer.

eddy currents on the stabilizer may be limited to each section in perpendicular to the magnetic fields.

These 2 types of stabilizer are analyzed by the F.E.M and the results are compared to find out the suitable structure which can reduce eddy current loss.

The transmission current for analysis is 1260 [A], 60 [Hz].

4. ANALYTICAL RESULTS

Fig. 5 and Fig. 6 are pictures that display magnetic field distribution of the superconducting power cable system that has stabilizers of model 1 and model 2.

Analytical Results show that most magnetic fields exist between the superconducting cable and the shield layer, and that the magnetic field of the axial direction is formed in the interior of the superconducting cable core.

In Fig.7, the stabilizer is magnified and the magnetic field in a stabilizer and the eddy current distribution are shown.

The parameters and characteristics of HTS cable for computer simulations are shown in Table I. The twisted directions are opposite to one another. Table II is the Analytical Results of eddy current losses in the stabilizer and cryostats. As expected in the basic theory, very small amounts of losses in outer cryostats appear, and losses in a stabilizer occupy most of the eddy current losses.

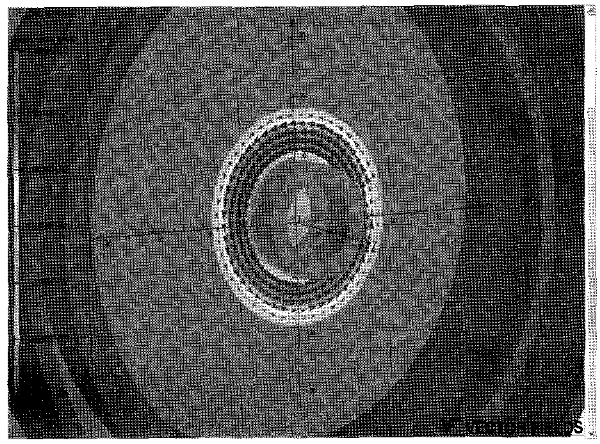

Fig. 5. Magnetic field distribution of Bulk cylindrical type stabilizer.

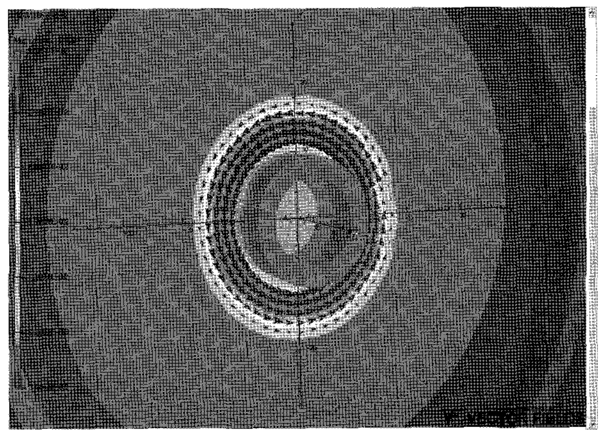

Fig. 6. Magnetic field distribution of divided cylindrical type stabilizer.

As the analysis model refers in advance, if the shield layer exists, then the magnetic field is very small on the outside of the superconducting power cable.

Also, the distance between the superconductivity cable core and cryostats in Fig. 3 is reason for the very low losses in cryostats.

As shown in the Analytical Results, the losses of model1 and model2 are large for a difference of 50 times.

Although the stabilizers of model1 and model2 have the same diameter and thickness, in the case of model1, the eddy current shows the forming of a single loop, but in the case of model2, the eddy current makes a loop in each divided stabilizer.

Model2's stabilizer is divided into 10 sections with a space of 0.078[mm] from each other. It is profitable to reduce the eddy current losses in the superconducting cable system by increasing the number of sections of the stabilizer within the present-day manufacturing limitations.

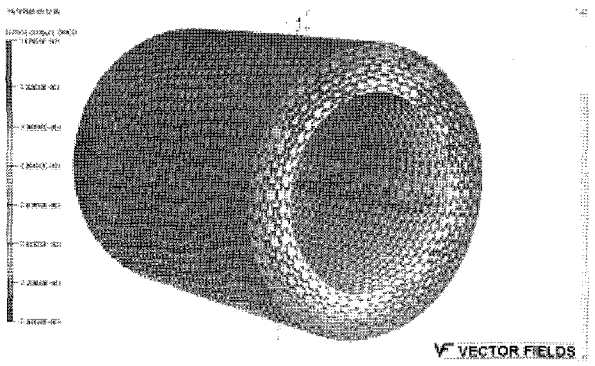

Fig. 7. Eddy current distribution of Bulk cylindrical type stabilizer.

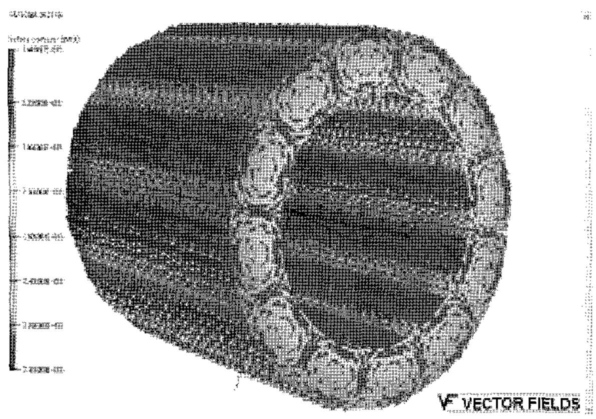

Fig. 8. Eddy current distribution of divided cylindrical type stabilizer.

TABLE I
PARAMETERS & CHARACTERSISTICS OF HTS CALBE FOR SIMULATION ITS

Parameters Layer	Inner radius [mm]	Pitch [mm]	Current [A]
1st conductor	10.3	450	1260/2
2nd conductor	10.9	540	1260/2
1st shield	16.65	510	-1260

TABLE II
EDDY CURRENT LOSSES IN THE STABILIZER AND CRYOSTATs

Parts Model	Stabilizer [W/m]	Inner Cryostat [W/m]	Outer Cryostat [W/m]
Model 1	0.10188	1.5721e-4	2.0212e-5
Model 2	0.002638	1.6529e-4	2.1245e-5

Also, the eddy current losses can be diminished by using the material with good magnetic permeability and small conducting

Although there are limitations to the number of sections that can be divided in order to get a profitable result.

5. CONCLUSION

The eddy current losses in the stabilizer and outer cryostats of superconducting power cable system are analyzed in this paper.

In the case of cryostats, eddy current losses are not important to the whole system loss, and most eddy current loss dissipation occurs in the stabilizer.

Also, with varying forms of the stabilizer, there are large differences in eddy current losses.

Absolutely, it is profitable to reduce the eddy current losses in the superconducting cable system by dividing of the stabilizer. but, we can judge the extent of effect of stabilizer separation on the eddy current loss using this analysis.

In this paper, a parametric F.E.M. model is constructed according to the change in design value of the superconducting cable, and stabilizer and cryostats, and can be utilized in the manufacture of stabilizer and cryostats.

ACKNOWLED GMENT

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