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Electrical Insulation Design of a 154 kV-Class HTS Power Cable

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Abstract-- **A 154 kV class high-temperature supercond -ucting (HTS) power cable system is developing in Korea. For insulation design of this cable, it is important that study on cryogenic electrical insulation design to develop the cold dielectric type HTS cable because the cable is operated under the high voltage environment in cryogenic temperature. Therefore, this paper describes a design method for the electrical insulation layer of the cold dielectric type HTS cable adopting the partial discharge-free design under ac stress, based on the experimental results such a ac breakdown strength, partial discharge inception stress, V_{ac}-t characteristics, V_{imp}-n characteristics, and impulse breakdown strength of liquid nitrogen / laminated polypropylene paper (LPP) composite insulation system in which the mini-model cable is immersed into pressurized liquid nitrogen.**

1. INTRODUCTION

The 154 kV-class HTS cable being developed in Korea has the highest voltage level in the world and is expected to face most difficult challenges of electrical insulation hard to deal with. The electrical insulation of the HTS cable has selected the cold dielectric (CD) type that several layers of thin insulation paper wrapped around the superconductor to segment it in LN_2. And the insulation materials are used with the laminated polypropylene paper (LPP) that can reduce the dielectric loss in the ac cable and heightens the insulation strength under the cryogenic temperature. Electrical insulation is one of the key research topic and in particular, insulation design is one of the critical technologies in development, as in a CD type HTS cable, not only extra high-voltage (EHV) is applied, but also insulation material works at a cryogenic temperature (77 K) of LN_2.

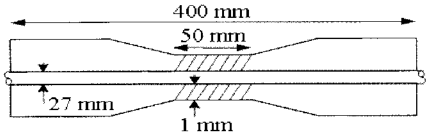
Previous studies have proposed basic data for insulation design of 154 kV-class with grading insulation method using two kinds of insulation paper and another method using one kind of insulation paper [1]. Due to incomplete the manufacturing of samples and the experimental method and conditions for EHV insulation design, however, insulation thickness was designed too thick, which raised an economical problem. Therefore, to improve experimental conditions, structure and operating conditions of the cable were more closely analyzed, and target voltage and design electrical stress for insulation design were re-calculated. In addition, mini-model experimental sample was manufactured to meet conditions for pattern and operating conditions of HTS cable, and experiment was conducted again in pressurized LN_2.

This paper proposes three kinds of design method to carry out the optimal insulation design for a 154 kV-class HTS cable. The proposed insulation design method takes into consideration AC and lightning impulse withstand voltage so as to prevent partial discharge and breakdown for power frequency operating voltage and breakdown for lightning impulse voltage during operating the cable. The final insulation thickness is determined by selecting more thick value out of insulation thickness calculated through the three insulation design methods. This paper referenced the existent papers about insulation design of HTS cable and progressed to satisfy in Korean Industrial Standards.

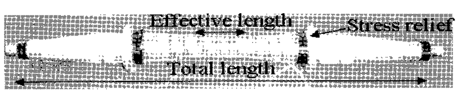
2. INSULATION THICKNESS DESIGN

2.1. Fabrication of mini-model cable

A mini-model cable as shown in Fig. 1 was manufactured for a basic characteristics experiment to design insulation thickness of a 154 kV-class HTS cable. The structure of the mini-model cable has the stainless steel former of 27 mm of



(a)



(b)

Fig. 1. Manufactured mini-model cable for insulation test; (a) Schematic, (b) Photograph.

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diameter, inner screen layer wrapped two layers of carbon paper with the thickness of 130 ㎛ and the width of 25 mm, insulation layer, and outer screen layer with the same method as the inner screen. The insulation layer provides the butt-gap of 1 mm between LPP that is cut in same width with the carbon paper. It wraps in overlap for approximately 30 % between the upper and lower layer. Also, in order to moderate the electrical stress in the terminal part of cable, the same insulation paper is used for the reinforcement insulation and attaches the aluminium stress relief to shield. The insulation thickness of the mini-model cable is 1 mm, total length of 400 mm and effective length of 50 mm. LPP used in the experiment are dried for four hours at 105 ℃ by using the drier to completely remove the moisture.

2.2. Determination of target withstand voltage

AC target withstand voltage V_{ac}, partial discharge target withstand voltage V_{PD} and lightning impulse target withstand voltage V_{imp} to withstand insulation test of 154 kV-class HTS cable are calculated in the following;

$$V_{ac} = ACWV \times M \quad (1)$$

$$V_{PD} = \frac{U_m}{\sqrt{3}} \times K_1 \times K_2 \times K_3 \quad (2)$$

$$V_{imp} = LIWV \times L_1 \times L_2 \times L_3 \quad (3)$$

Here, ACWV means a short time ac withstand voltage, and it is 300 kV by Standard Technical Specification of KEPCO in Korea. U_m refers to ac maximum system voltage, and 154 kV-class series highest voltage is 170 kV. LIWV means lightning impulse withstand voltage value; lightning impulse test voltage BIL is usually applied, and to a 154 kV-class, 750 kV is applied. In addition, K_1, L_1 is degradation coefficient occurring in use, K_2, L_2 is temperature coefficient of breakdown voltage, and M, K_3, L_3 is design margin by unfixed elements.

First of all, ac degradation coefficient K_1 is calculated by V-t characteristics test, and Fig. 2 shows V-t characteristics curve of LPP mini-model cable. V-t characteristics, as relationship between voltage V and life t, is expressed as

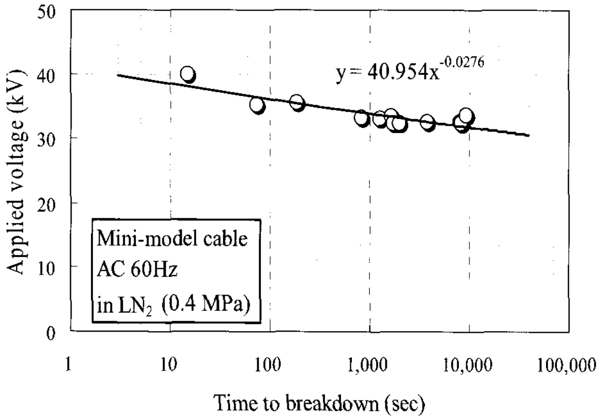

Fig. 2. V-t characteristics of LPP in LN_2 .

'$V^n \cdot t$ = constant ', where n means life exponent. Previous studies have reported that life exponent n value of insulation materials such as PPLP®, Kraft paper, Nomex, and OPPL, used for superconducting cables is determined in a range of 19~49, through V-t characteristics test [2-4]. According to the results of Fig. 2, life exponent of LPP was determined 'n=36', and ac degradation coefficient is 'K_1=1.18' by the following (4), on the conditions of 30 years of cable operating duration and 30 days of testing duration.

$$K_1 = \left(\frac{\text{Operating duration}}{\text{Testing duration}}\right)^{\frac{1}{n}} \quad (4)$$

Lightning impulse degradation coefficient L_1 by lightning impulse can be obtained by V-n characteristics test. In this study, degradation never happened, even in case of 2,000 shots or over applications of lightning impulse voltage to LPP in LN_2, which has been reported in a paper of H. Suzuki [5]. Accordingly, lightning impulse degradation coefficient 'L_1=1.0' was applied.

For temperature coefficient K_2, L_2, as a measure of how the life of insulation material decreases by the heat as a result of Joule loss and dielectric loss during cable operation, the '1.1~1.2' scale was applied to existing power cable, but for HTS cable operating at cryogenic temperature, '1.0' was applied [6].

In addition, design margin M, K_3, L_3, as margin for unfixed elements such as thickness and volume of insulator and shape of electrode, '1.2' was applied [3,6].

By applying coefficients obtained through an experiment, target voltage of a 154 kV-class HTS cable are 'V_{ac}=360 kV' for ac breakdown, 'V_{PD}=140 kV' for partial discharge free, and 'V_{imp}=900 kV' for lightning impulse breakdown.

2.3. Determination of maximum design electrical stress

Insulation thickness in ac voltage at 30 years of life of power cable is designed to prevent partial discharge in ac maximum operating voltage (U_m) during operating duration. In addition, insulation thickness by ac and lightning impulse are designed to prevent breakdown for cable operating duration. Therefore, maximum design electrical stress for ac and lightning impulse is determined by measuring partial discharge inception stress and lightning impulse breakdown strength under cable operating pressure.

Fig. 3 shows characteristics of partial discharge inception stress of mini-model by increase in pressure of LN_2. Partial discharge inception stress can be obtained as in (5) below, using calculation method for electrical stress in case of coaxial cylinder electrode arrangement.

$$E = \frac{PDIV}{r_1 \cdot \ln\left(\frac{r_2}{r_1}\right)} \quad [kV/mm] \quad (5)$$

Here, PDIV refers to ac applied voltage starting point of partial discharge inception, r_1 to radius of inner conductor (13.76 mm), and r_2 to outer radius of insulation layer (14.76 mm). As shown in Fig., partial discharge inception stress increases as pressure of LN_2 goes up, tending to be saturated at around 0.3 MPa, which may because growing pressure applied to the liquid prevents bubbles from being generated in LN_2 and butt-gap of sheet sample filled with LN_2. Considering average operating pressure of HTS cable is around 0.3~0.4 MPa, ac maximum design electrical stress $E_{max(PD)}$ is set to '20 kV/mm'.

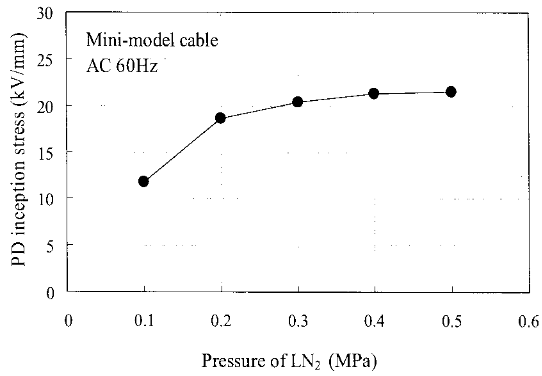

Fig. 3. Partial discharge inception stress of mini-model cable by increase in pressure of LN_2.

Maximum design electrical stress $E_{max(ac)}$ and $E_{max(imp)}$ for ac and lightning impulse can be obtained by the weibull distribution of the ac and lightning impulse breakdown strength for insulation material under cable operating pressure. Probability P in which insulation material is broken down at electrical stress E is as in the following equation;

$$P = 1 - \exp\left[-\left(\frac{E - E_L}{E_0}\right)^m\right] \qquad (E \geq E_L) \qquad (6a)$$

$$= 0 \qquad (E \leq E_L) \qquad (6b)$$

Here, E_L refers location parameter, E_0 to scale parameter, m to shape parameter, and (6b) to the distribution '0' where insulation material E_L can be breakdown at E_L or below. Based on E_L value obtained from extensive data of repeated tests, insulation thickness is designed.

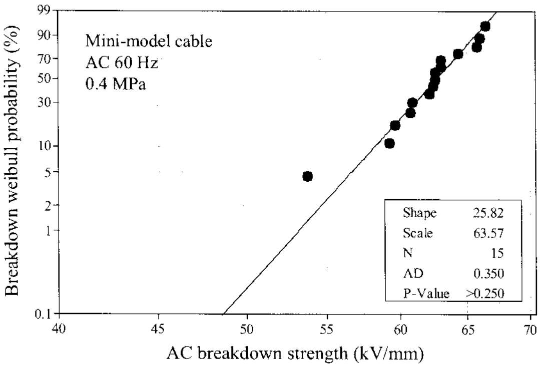

Fig. 4. Weibull probability plots for ac breakdown strength of LPP in LN_2 (0.4 MPa).

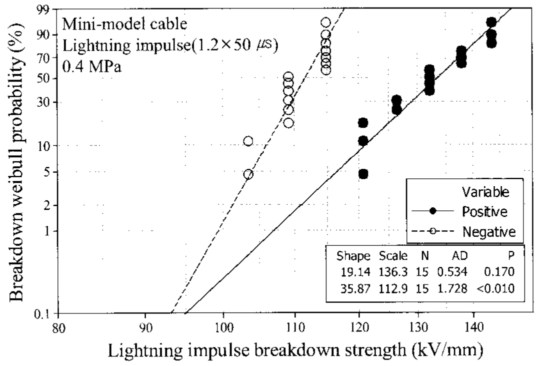

Fig. 5. Weibull probability plots for lightning impulse breakdown strength of LPP in LN_2 (0.4 MPa).

Fig. 4 and Fig. 5 show weibull probability plot for ac and lightning impulse breakdown strength in pressurized LN_2 (0.4 MPa) of LPP. In the weibull probability plot, breakdown strength of the 0.1 % breakdown probability point is set as maximum design electrical stress. In previous studies, the experiments were done at atmospheric pressure, and the insulation thickness was designed very high [1]. In the experiment of design electrical stress of LPP based on impacts on pressure, ac was '49 kV/mm', positive impulse was '95 kV/mm', and negative impulse was '93 kV/mm'. Accordingly, ac '49 kV/mm' was selected as ac maximum design electrical stress $E_{max(ac)}$. Furthermore, negative '93 kV/mm', which was smaller, was selected as impulse maximum design electrical stress $E_{max(imp)}$.

2.4. Calculation of insulation thickness

The insulation thickness of EHV power cable is designed to meet set target performance, considering breakdown strength or degradation properties of cable. In determining target performance, both power frequency withstand voltage and lightning impulse withstand voltage are considered in general. The target voltage for ac breakdown was set to '360 kV', PD inception to '140 kV', and lightning impulse breakdown to '900 kV'. The maximum design electrical stress was '49 kV/mm', '20 kV/mm' and '93 kV/mm' for ac, PD and lightning impulse, respectively, at minimum operating pressure of superconducting cable, or 0.4 MPa.

The insulation thickness of HTS power cable *t* is calculated by (7) and based on calculating equation of maximum electrical stress in coaxial cylinder electrode arrangement.

$$t = r_c \cdot \left[\exp\left(\frac{V}{E_{max} \cdot r_c}\right) - 1\right] \qquad (7)$$

Here, r_c is a radius of inner conductor of insulation layer (r_c=15.2 mm), V is a target withstand voltage, and E_{max} is maximum design electrical stress of insulation material.

The insulation thickness of a 154 kV-class HTS cable is calculated into '8.9 mm' by PD inception , '9.5 mm' by ac breakdown and '14 mm' by lightning impulse breakdown, and the final insulation thickness is determined as '14 mm', which is highest.

3. CONCLUSION

The 154 kV / 1 GVA-class HTS cable, being developed in Korea as part of the DAPAS program, is highest in its voltage level in the world and one of the highly important technologies not only for large-capacity conductor, but also electrical insulation design in terms of cable core design.

Therefore, this paper established design method of insulation thickness of HTS cable applied with EHV, by reviewing, comparing and analyzing previous cable insulation design data. In addition, parameters of HTS cable insulation design were examined through ac and lightning impulse experiments in pressurized LN_2, and finally insulation thickness of a 154 kV-class HTS power cable was designed as '14 mm'. In the future, to validate data of this design, insulation test model cable will be manufactured and evaluated.

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