154kV급 고온초전도 전력케이블의 전기절연 설계

Insulation Design for a 154 kV Class HTS Power Cable

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Abstract: *A 154 kV class high temperature superconducting (HTS) power cable system is developing in Korea. For insulation design of this cable, the grading method of insulating paper is proposed. The use of graded insulation gives improved bending properties of the cable. Therefore, we discussed the electrical stress distribution and calculation for grading insulation design of a HTS cable. Also, the basic insulation design of 154 kV class HTS power cable was done.*

Key Words: HTS cable, Insulation design, PPLP, Graded insulation.

1. Introduction

The application of a HTS cable have been studied and developed because of the advantage of achieving large power delivery with negligible AC loss compared with conventional power cables [1-3]. The Korea Electrotechnology Research Institute (KERI) and LS Cable Ltd. are developing a 154 kV class HTS power cable in one of 21st century superconducting frontier projects in Korea.

The HTS cable system is composed of conductor, cooling system and electrical insulation. A study of electrical insulation is important to develop a HTS cable because the cable is operated in a high voltage environment. Generally, the electrical insulation of a HTS cable is composite insulation type, made of dielectric paper and liquid nitrogen(LN_2), which is similar to the dielectric structure of oil-filled cables [4-5]. The advantage of composite insulation is that contraction of the HTS cable due to cooling down to LN_2 temperature can be absorbed readily because the insulation is composed of dielectric tapes wound spirally around a conductor. For this reason, the composite insulation system was selected for the insulation design of a 22.9 kV class HTS cable in Korea [6-8]. Also, the electrical insulation material of a 154 kV class HTS power cable has been used two kinds of polypropylene laminated paper (PPLP) that has different thickness. It gives improved bending properties of the cable.

In this paper, the impulse breakdown strength of the PPLP sheet sample and mini-model cable is investigated. Based on these data, we designed insulation thickness of a 154 kV class HTS power cable. Also, the electrical stress distribution of designed cable was examined.

2. Experiment

Two kind of PPLP that have different thickness were used in this experiment to determine a composite insulation thickness of a 154 kV class HTS power cable. The impulse breakdown characteristics of the PPLP impregnated with LN_2 were investigated using a sheet sample including butt-gap. The basic properties of tested PPLP are given in Table 1.

Table 1. Basic properties of the insulation paper.

Materials	Thickness (㎛)	Permittivity (ε)	tan δ (%)
$PPLP_1$	125	2.6	0.062
$PPLP_2$	170	2.6	0.061
Kraft paper	100	3.4	0.120

Fig. 1 shows the sheet sample and mini-model cable that was used to measure the impulse breakdown voltage. In case of butt-gap, the center of the sheet samples has been cut off in the shape of circular hole with a diameter of 2 mm. The electrodes used in the breakdown test are plane electrode of a diameter of 25 mm and 75 mm, respectively [9]. The high voltage electrode is molded with epoxy resin to avoid the edge effect. The sheet sample that was used in the breakdown test has done not exceeding 0.1 % of moisture and dried around 105 ℃ ('NREL Standard Procedures #001' Measurement Method). The holder of the electrode system was made by fiberglass reinforced

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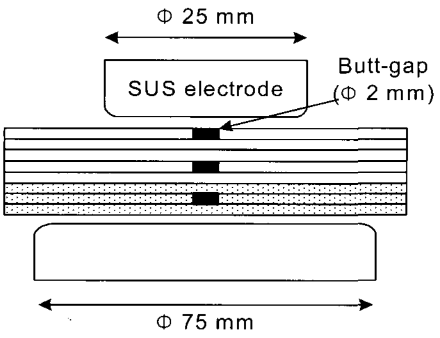
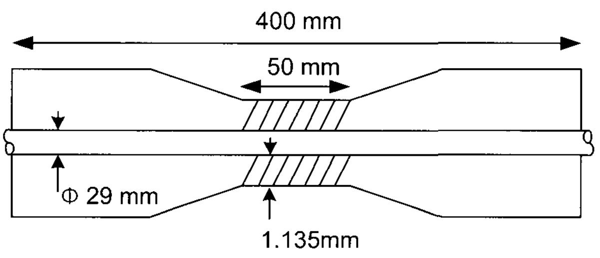
plastic (FRP) to achieve high durability in the cryogenic environment. Also, the mini-cable is first wrapped with carbon paper on a flexible SUS former serially from the first layer and then insulation paper is wrapped with 30 % overlap between insulation layers. The mini-model cable has the total length of 400 mm and the total insulation thickness of 1.135 mm ($PPLP_1$ 125 ㎛ × 5 sheets and $PPLP_2$ 170 ㎛ × 3 sheets). The stress cone of the cable terminal was reinforced with the insulation paper to prevent the concentration of electric field at the end. The main electrode was used as carbon paper that has a length of 50 mm.



(a) Sheet sample



(b) Mini-model cable

Fig. 1. Sample specimens for breakdown test.

3. Results and discussion

Fig. 2 shows a typical Weibull probability plot of the impulse breakdown strength of 3 sheets of $PPLP_1$ and $PPLP_2$. As this figure indicates, the calculated impulse breakdown strength at 50 % probability of $PPLP_1$ and $PPLP_2$ are 114 kV/mm and 99 kV/mm, respectively. However, the maximum impulse breakdown strength were set at 78 kV/mm and 73 kV/mm. It shows the breakdown strength of $PPLP_1$ is higher than that of $PPLP_2$.

Fig. 3 shows the impulse breakdown strength versus the composite ratio of PPLP in LN_2. This experiment is to determine the optimum mixture ratio of two insulation materials. In this figure, the composite ratio of $PPLP_1$ and $PPLP_2$ was decided as 5:3 considering the maximizing breakdown strength of a 154 kV class HTS power cable. Therefore, the composite thickness ratio is 625 ㎛ : 510 ㎛.

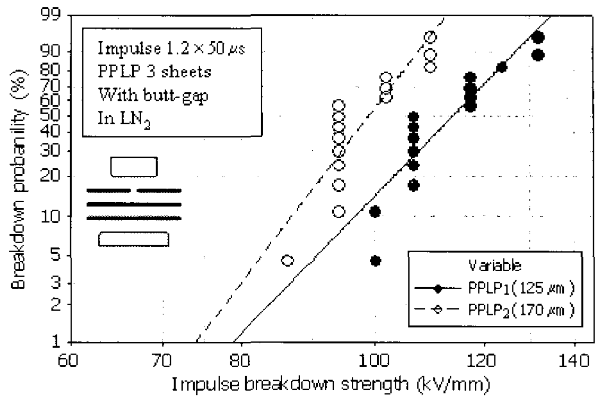


Fig. 2. Weibull probability plot of the impulse breakdown strength of PPLP 3 sheets.

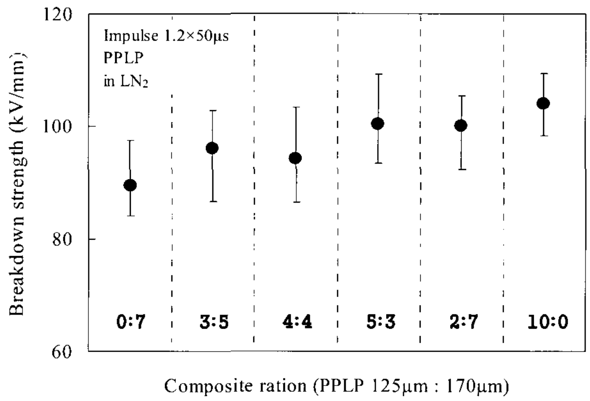


Fig. 3. Impulse breakdown strength versus the composite ratio of PPLP.

Fig. 4 shows a typical Weibull probability plot of the impulse breakdown strength of multilayered sheet sample of $PPLP_1$ 5 sheets and $PPLP_2$ 3 sheets. The calculated impulse breakdown strength at 50 % probability is 74 kV/mm and the shape parameter is 14.79. However, the maximum impulse breakdown strength (E_{max}) was set at 56 kV/mm for the cable design to ensure the stability of cable insulation.

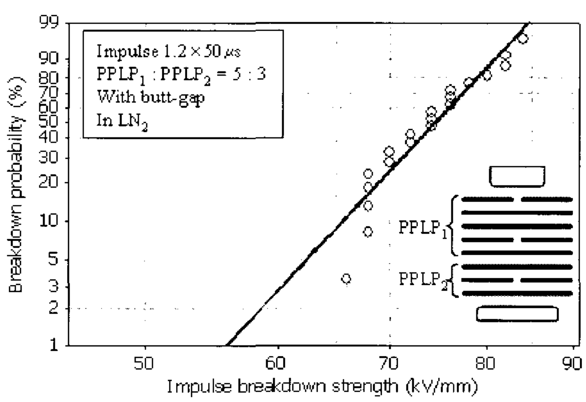


Fig. 4. Weibull probability plot of the impulse breakdown strength of PPLP.

Fig. 5 shows the conversion coefficient (M) on the impulse breakdown strength of the sheet sample and mini-model cable. It considers the size effect and shape effect of electrode. The conversion coefficient that is calculated through ratio of the impulse breakdown strength is '0.8'. Therefore, this conversion coefficient of '0.8' should be multiplied in maximum impulse breakdown strength.

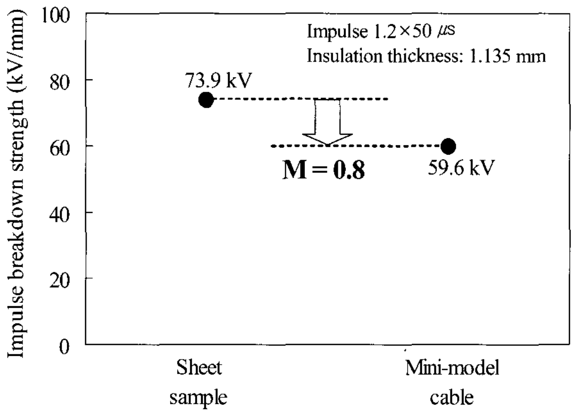


Fig. 5. Impulse conversion coefficient of the sheet sample and mini-model cable.

Based on the above experimental results, the electrical insulation thickness design of a 154 kV class HTS power cable was examined. The insulation design is assumed to be carried out in a similar way as that of a conventional oil-filled cable. The insulation thickness of the HTS cable is estimated by (1)

$$t = \frac{BIL \times K_1 \times K_1 \times K_1}{E_{\max} \times M} \quad (1)$$

Where, the line impulse withstand voltage (basic insulation level: BIL) of a 154 kV class is 750 kV. K_1 is a degradation coefficient with a value of '1.1', K_2 is a temperature coefficient with a value of '1.0', K_3 is an impulse design margin with a value of '1.2'. E_{max} is the maximum impulse breakdown strength of PPLP with a value of '56 kV/mm' and M is the conversion coefficient with a value of '0.8'.

The insulation thickness of a 154 kV class HTS power cable is established at 23 mm to prevent electrical breakdown. The insulation thickness t is determined by the ratio V/E. Therefore, the insulation thickness of $PPLP_1$ and $PPLP_2$ are designed 12.7 mm and 10.3 mm according to composite thickness ratio of 625 ㎛ : 510 ㎛. Also, the outside of insulation layer was reinforced with the Kraft paper of 4 mm to prevent from the mechanical stress. The equivalent circuit of the designed 154 kV class HTS power cable shown in Fig. 6.

The capacitance and voltage division of the cable is given by

$$C_n = \frac{\varepsilon_n}{18 \cdot \ln\left(\frac{r_n}{r_{n-1}}\right)} \quad (2)$$

$$V_n = \frac{C}{C_n} \times V \quad (3)$$

Where, r_n = radius over the insulation of n layer
r_{n-1} = radius over the insulation of n-1 layer
ε_n = relative dielectric permittivity of n layer
V = impulse withstand voltage (990kV)

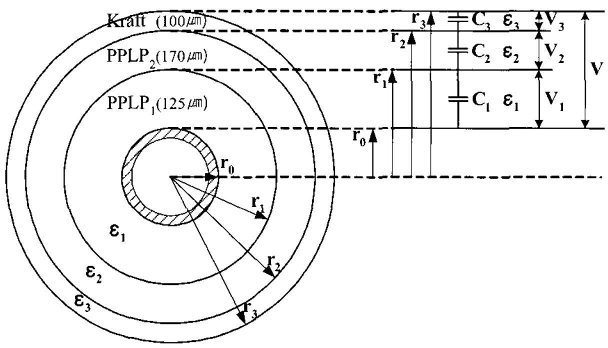


Fig. 6. Equivalent circuit of the designed 154 kV HTS power cable.

Also, the calculated electrical impulse stress distribution curve of 154 kV HTS cable shown in Fig. 7. The impulse stress distribution of the cable is calculated by

$$E_{\max(n)} = \frac{V_n}{r_{n-1} \cdot \ln\left(\frac{r_n}{r_{n-1}}\right)} \quad (4)$$

$$E_{\min(n)} = \frac{V_n}{r_n \cdot \ln\left(\frac{r_n}{r_{n-1}}\right)} \quad (5)$$

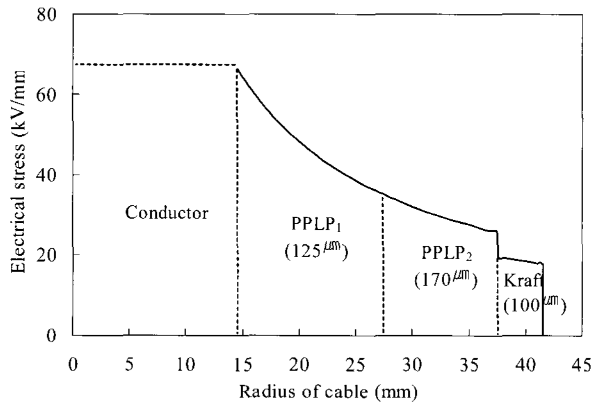


Fig. 7. Electrical impulse stress distribution curve of a 154 kV HTS cable.

The electrical stress is maximum at the conductor surface and varies throughout the insulation, *decreasing from the conductor surface.*

Table 2 shows the calculated insulation thickness, capacitance and impulse division voltage of a 154 kV class HTS power cable.

Table 2. The calculation of the impulse stress distribution on the insulation designed 154 kV class HTS power cable.

Materials		Inner conductor	$PPLP_1$ (125㎛)	$PPLP_2$ (170㎛)	Kraft paper (100㎛)
Radius of cable core (mm)		14.5 (r_0)	27.2 (r_1)	37.5 (r_2)	41.5 (r_3)
Insulation thickness (mm)			12.7	10.3	4
ε_n			2.6	2.6	3.4
C_n (μF)			0.2296	0.4498	1.8637
V_n (kV)			606	309	75
E_n (kV/mm)	E_{max}		66	35	20
	E_{min}		35	25	18

4. Conclusions

For the insulation thickness design of a 154 kV class HTS power cable, the impulse breakdown properties of two kind of PPLP were investigated. The composite ratio of $PPLP_1$ (125 ㎛) and $PPLP_2$ (170 ㎛) was decided by 5:3 considering the maximizing breakdown strength of the cable. The maximum impulse breakdown strength was set at 56 kV/mm for the cable design to ensure the stability of cable insulation. Also, the conversion coefficient that is calculated through ratio of the impulse breakdown strength of sheet sample and mini-model cable is '0.8'.

Based on these data, the total insulation thickness of a 154 kV class HTS power cable is established at 23 mm to prevent electrical breakdown. Therefore, the insulation thickness of $PPLP_1$ and $PPLP_2$ are designed 12.7 mm and 10.3 mm, respectively.

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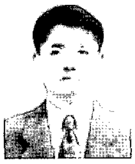

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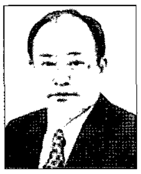

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