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Design of The Electrical Insulation for The High Temperature Superconducting Cable Based on Model Investigation

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Abstract— **This paper describes the results of a basic study (on a model samples) for the development of 22.9 kV high temperature superconducting (HTS) cable. The authors have established that the factors that decide the performance of HTS cables are butt gaps in tape insulation and carbon particles from semiconductive layer . The insulation performance of HTS cables is determined by size and quality of these elements. In the model tests of HTS cables, the minimum PD inception stress of the tape insulation impregnated with liquid nitrogen was found and insulation thickness was calculated from this result.**

1. INSTRODUCTION

The polypropylene laminated paper tape insulation impregnated with Liquid Nitrogen(LN_2) under multi-laying insulation system has excellent electrical properties such as high breakdown strength and low dissipation factor. However, it contains butt gaps impregnated with LN_2. Due to the small relative dielectric permittivity of LN_2, the electrical stress in a butt gap is intensive. Therefore, butt gap is apt to become a one of the sources of PD. In other words it is a weak point in the insulation system.

We studied the dielectric properties of LN_2 impregnated polypropylene laminated paper and applied this results to the electrical insulation design of HTS Cable.

2. TOPICS FOR THE STUDY IN THE DEVELOPMENT OF 22.9kV HTS CABLE

The insulation thickness design of HTS cable can be done by using equation (1) and (3) bellow. Each equation is used to calculate the insulation thickness t_{AC} in AC case and the insulation thickness t_{IMP} in impulse case, and the greater one of these two values is adopted as the insulation thickness.

In AC case

$$t_{AC} = r \times \left(\exp^{\frac{V_{AC}}{rE_{PD}}} - 1 \right) \tag{1}$$

where r is 14.5mm which is the radius of the internal semiconductive layer on a cable conductor, V_{ac} is AC withstand voltage

$$V_{AC} = \frac{V_{\max}}{\sqrt{3}} \times k_1 \times k_2 \times k_3 \tag{2}$$

V_{max} is maximum line voltage, k_1 is a temperature coefficient, k_2 is a degradation coefficient and k_3 is a design margin.

In impulse case

$$t_{imp} = r \times \left(\exp^{\frac{V_{imp}}{rE_{BDimp}}} - 1 \right) \tag{3}$$

where V_{imp} is impulse withstand voltage

$$V_{imp} = BIL \times k_4 \times k_5 \tag{4}$$

BIL is basic insulation level, k_4 is the uncertainty coefficient and k_5 is a safety coefficient.

In the insulation thickness design, AC and impulse withstand voltages are used by the following causes. First, the intrinsic and atmospheric overvoltage react on insulation during operation. Second, there can be heterogeneity of insulation in a cable (for example, different position of butt gaps and availability of defects by pinches, dents and registration of butt gaps).

3. EXPERIMENTAL RESULTS AND DISCUSSION

The design parameters were determined by using the multi-sheeted tube type model sample with the geometry of “coaxial cylinder” electrode as shown in Fig. 1. The high voltage electrode was smoothly polished stainless-steel tube (27mm in outer diameter and 320 mm in length). On this conductor, two semiconductive carbon paper-tapes(25 mm in width and 0.130 mm in thickness) were wound with 1/3 covering and 1mm butt gaps. Then several layers(2~5) of polypropylene laminated paper–tapes (25 mm in width, 0.119 mm in thickness) were wound on the semiconductive layer with 1/3 covering and 1mm butt gaps. The ground electrode wound on the outside semiconductive layer is the self-gumming cooper foil with 25 mm in width.

3.1. Minimum Partial Discharge (PD) inception electrical stress in the butt gap

PD measurement was carried out according to the electrical location method [1]. The high voltage transformer (Phenix, 100 kV) was used for applying the voltage. The blocking resistance (400 Ω) was applied to decrease a noise level. This resistance and connecting capacitor located in the test cell filled with silicone oil. Digital oscilloscope (Tetronics TDS540) and PDICM System were used to measure PD. To decrease external noise, the measuring circuit was located in the shielded metal box. The sensitivity of PD detection was 5 pC. The PD inception voltage was measured by increasing voltage step by step.

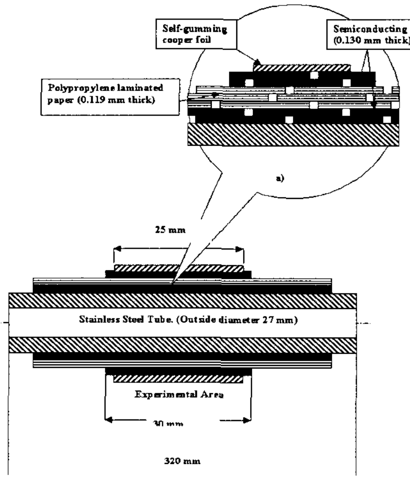

Fig. 1. Design of model sample.

The test voltage step was 500 V during 100 seconds. All measurements were carried out in commercial AC voltage at atmospheric pressure.

Experimental value of PD inception voltage(PDIV) in a model sample was calculated according to the following equation.

$$PDIV = V_{PD} = \frac{V_i + V_{i-1}}{2} \tag{5}$$

V_i is PD inception voltage, which has magnitude of PD more than 50 pC. V_{i-1} is a previous step. Then PD inception electrical stress PDIF in model sample was calculated according to the following equation

$$PDIF = E_{PD} = \frac{V_{PD}}{r_s \ln \frac{r_s + t_s}{r_s}} \tag{6}$$

Where r_s is the radius of internal semiconductive layer on stainless-steel tube and t_s is the thickness of sample insulation (polypropylene laminated paper).

Fig. 2 shows the normal distribution of PDIF in case of three-layer insulation sample impregnated with LN_2 at atmospheric pressure. It was shown that minimum PDIF was 14.4 kV/mm with 95% significance level.

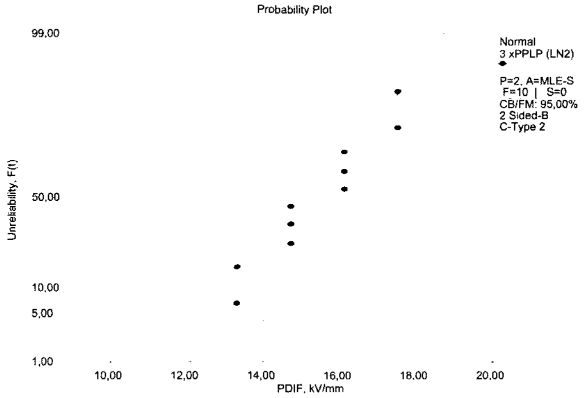

Fig. 2. Normal distribution of PD inception electrical stress of a three layer insulation sample in LN_2.

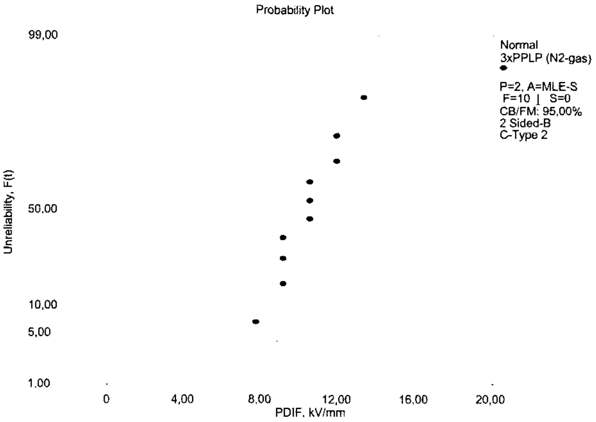

Fig. 3. Normal distributions of PD inception electrical stress of a three layer insulation sample at gaseous N2, 90K.

3.2. Temperature Coefficient k_1

Fig. 3 shows the Normal distribution of PDIF in case of three-layer insulation sample at gas nitrogen and temperature 90K. The minimum PDIF is 9.2kV/mm.

From Fig. 2 and Fig. 3 the temperature coefficient k_1 could be calculated as follows;

$$k_1 = E_{PD\,LN2}/E_{PD\,N2} = 14.4/9.2 = 1.57$$

3.3. Degradation Coefficient k_2

The degradation coefficient (k_2 *– 1hr and 30 yr conversion coefficient)* can be determined by the life exponent (n). The life exponent (n) of PPLP samples at LN_2 was obtained by the progressive stress test [2]. Fig. 4 shows the Weibull distributions of short-term AC breakdown (BD) strength of three-layer test samples at LN_2 with various rates of the test stress (0.56, 1.4, 4.2, 14 kV/mm·s) and it can be predicted by equation (7).

$$P_F(V) = 1 - \exp\left[-C^{\frac{a}{a+b}}\,\dot{V}^{-a}\,V^{a+b}\right] \tag{7}$$

$P_F(V)$ is cumulative probability, C is constant, a and b are shape parameters, V is test voltage, $\dot{V} = V/\tau$ is the rate of the test voltage.

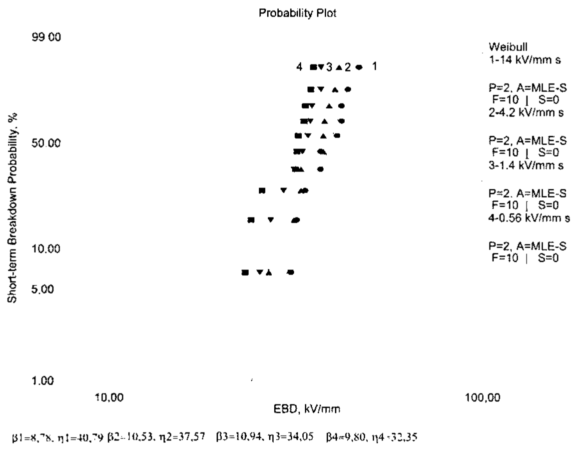

Fig. 4. Weibull distributions of AC BD Strength of a three layer Insulation sample with various rate of the test stress.

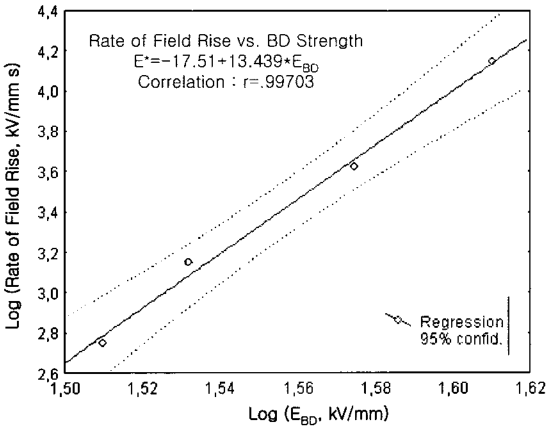

Fig. 5. Log-Log plot of rate of field rise vs. AC BD strength.

All distributions shown in Figure 5 have approximately similar slop of 10.

So

$$a + b = 10$$

The Equation (7) derived from the inverse power law of lifetime as a function of field and the two-parameter Weibull distribution also predicts a power law relationship between the rate of field rise and the BD voltage. A log-log graph of rate of field rise versus BD voltage characteristic is predicted to be a straight line of a slope **(a + b)/a.** Such a graph is presented in Fig. 5 and can be seen to be a good straight line with a slope

$$(a + b)/a = 13.44$$

So

$$n = b/a = 12.5 \approx 13$$

The value of degradation coefficient k_2 is obtained as

$$k_2 = \sqrt[n]{30 \times 365 \times 24} = \sqrt[13]{30 \times 365 \times 24} = 2.6 \ [3]$$

3.4. Design Margin k_3

The value of k_3 was obtained from the published data [3]

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$$k_3 = 1.1$$

4. DETERMINATION OF INSULATION THICKNESS IN AC CONDITION WITH USE OF PD CHARACTERISTICS

AC design parameters for 22.9 kV HTS cable are shown in the Table 1.

$$V_{AC} = \frac{V_{ACL}}{\sqrt{3}} x k_1 x k_2 x k_3 = \frac{25.8}{\sqrt{3}} x 1.57 \times 2.6 \times 1.1 = 67$$

For convenience sake, we decided that V_{ac} was 70 kV.

TABLE 1. AC design parameters for 22.9kV superconducting cable

Parameter	AC	Unit
Max line voltage	25.8	kV
Temperature coefficient	1.57	-
Degradation coefficient	2.6	-
Design margin	1.1	-
Design stress ($E_{PD\,gap}$)	14.4	kV/mm

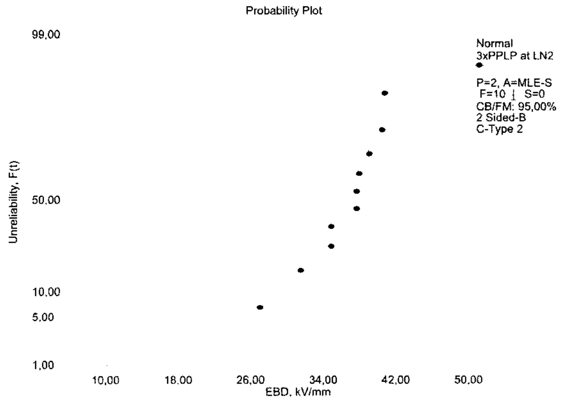


Fig. 6. Normal distribution of short-term BD strength of a three layer insulation sample in LN_2

Insulation thickness (t_{AC}) was calculated as follows

$$t_{AC} = 14.5\left(e^{\frac{70}{14.5 \times 14.4}} - 1\right) = 5.78mm$$

5. DETERMINATION OF INSULATION THICKNESS IN IMPULSE CONDITION

The dielectric thickness of the HTS cable was designed for the insulation to be free from breakdown at design impulse withstand voltage (V_{imp}).

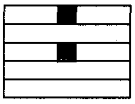
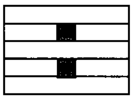
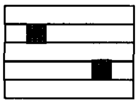
The design impulse withstand voltage is calculated by the equation (4)

$$V_{imp} = BIL\times k_4\times k_5 = 150\times 1.1\times 1.2 = 190kV$$

where *BIL* is basic insulation level (150 kV for 22.9 kV cable), $k_4 = 1.1$ and $k_5 = 1.2$ [3].

Impulse breakdown strength test of the polypropylene laminated paper samples impregnated with LN_2 was carried out and the results are shown in the Table 2.

TABLE 2. Impulse BD strength of laminated polypropylene paper insulation at LN2.

Ref.	Test Sample Design	Total Thickness (mm)	Pressure (Mpa)	Impulse BD strength (kV/mm)
[4]		0.3	0.4	162
[5]		0.375	0.4	140
				146
[4]		0.5	0.4	163
				184

From the result minimum value (140 kV/mm) of impulse BD strength was selected. Impulse design parameters for 22.9 kV HTS cable are shown in the Table 3.

Table 3. Impulse design parameters for 22.9 kV superconducting cable

Parameter	Impulse	Unit
Design withstand voltage	190	kV
Design stress	140	kV/mm

Insulation thickness (t_{imp}) was calculated by the equation (3)

$$t_{imp} = 14.5\left(e^{\frac{190}{14.5\times 140}} - 1\right) = 1.42\,mm$$

6. DETERMINATION OF INSULATION THICKNESS IN ıAC CONDITION WITH USE OF V-t CHARACTERISTICS.

This method is based on the V-t characteristics of the test samples, in particular, a "life curve". Life curve is used to determine the exponent (n) in the well-known inverse power law equation

$$E^n L = const \tag{8}$$

where E is the electrical stress and L is the time to failure of sample.

To obtain the design stress, the short-term AC breakdown strength E_{ACBD} is tested with measuring time ≈ 1 min. and then, the long-term (30-year - design lifetime) breakdown strength E_{w30y} is derived from V-t characteristics.

The long-term breakdown stress E_{w30y} was obtained from the following equation

$$1\times E^n_{ACBD} = 30\times 365\times 24\times 60\times E^n_{w30y} \tag{9}$$

where $n = 13$ is the life exponent.

The value of E_{w30y} is calculated as follows

$$E_{w30y} = (6.34\times 10^{-8})^{1/13}\times E_{ACBD} =$$
$$(6.34\times 10^{-8})^{1/13}\times 33.2 = 9.28 \text{ kV/mm}$$

where E_{ACBD} of 33.2 kV/mm was minimum value of short-term AC BD strength of three-layer insulation test in LN_2. The V-t design parameters of 22.9 kV HTS cable are shown in the Table 4.

Table 4. The V-t design parameters for 22.9 kV superconducting cable

Parameter	V-t	Unit
Life exponent	13	-
long-term breakdown stress	9.28	kV/mm

$$t_{AC(V-t)} = r\left(e^{\frac{V}{rE_{w30y}}} - 1\right)$$

From here

$$t_{AC(V-t)} = 14.5\left(e^{\frac{22.9}{14.5\times 9.28}} - 1\right) = 2.69\,mm$$

7. COMPARISON OF CALCULATED VALUES OF INSULATION THICKNESS

The insulation thickness of HTS cable (22.9 kV) calculated by different methods are shown in the Table 5.

Table 5. Calculated values of insulation thickness

Insulation thickness (mm)		
AC condition		Impulse condition
PD	V – t condition	
5.78	2.69	1.42

The greatest value of insulation thickness t_{ACPD} of 5.78mm was obtained from the PD inception electrical stress in AC condition.

However this value is obtained at atmospheric pressure.

When it comes to consider the LN_2 operating pressure(3~4 bar), it is predicted that PD inception electrical stress is increased. So it is predicted that the insulation thickness obtained from the PD inception electrical stress is decreased under real state condition.

8. CONCLUSION

To design insulation thickness of HTS cable, the various test results (PD and long-term breakdown strength in the AC condition and short-term breakdown strength in the impulse condition) were utilized.

In the three-layer insulation sample test, minimum PD inception electrical stress PDIF was 14.4 kV/mm. And from this result insulation thickness t_{ACPD} of 5.78mm was calculated and determined to the insulation thickness of HTS cable.

In general, dielectric property of the polypropylene laminated paper impregnated with LN_2 is increased with LN_2 pressure. So, it is necessory to investigate the optimum insulation thickness of HTS cable at operating pressure.

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