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The Effect of Butt gaps on Dielectric Strength of Taped Insulation in Superconducting Cable

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***Abstract*- This paper discusses several electrical properties of tape-type insulation impregnated with liquid nitrogen (LN_2) in superconducting cable. Synthetic polypropylene laminated paper has been tested for its short-term breakdown strength and partial discharge(PD) characteristics under AC voltage. Furthermore, the effect of winding parameter on breakdown strength, PD incepti on and extinction electrical stress with different test samples are discussed.**

1. INTRODUCTION

Recently, the application of high temperature superconductivity(HTS) to power system has been highlighted because of the advantage of achieving large power delivery with negligible electrical loss in compared with conventional power system [1]. The taped insulation, which resembles the oil-impregnated one, can be impregnated with LN_2 easily, so it is regarded the one of main types of HTS cable insulation. In this kind of cryogenic insulation, the high flexibility for reeling and installation as well as the ability to absorb the shrinkage during cool-down process from room temperature to cryogenic temperature is the required feature.

Taped dielectrics such as different kinds of synthetic laminated papers can combine high breakdown strength, low dissipation factor and low relative dielectric permittivity at LN_2. However, taped insulation contains butt gaps impregnated with LN_2. Due to the small relative permittivity of LN_2(around 1.4) in compared with the one of solid dielectrics(more than 2.4), the electric stress in a butt gap is more intensive than that in solid dielectric. Therefore, butt gap is liable to become one of the sources of PD. In other words, PD may occur and then generate gas-filled thermal bubbles in cryogenic liquid. Prolonged PD activity erodes the solid insulation surface and can eventually result in electrical breakdown. Also, this result can generate heat which makes the refrigeration resistance in cryogenic temperature.

So, it is very important to investigate the effect of butt gap on main electrical properties of the taped cable insulation at cryogenic temperature.

2. EXPERIMENTS

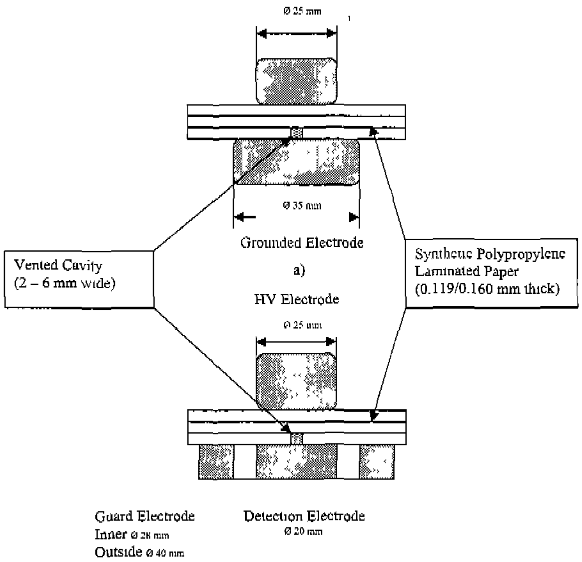
The experimental studies have been conducted by using two types of small-scale model samples (one is flat type and the other is tube type) and two kinds of commercially available synthetic polypropylene laminated papers were tested for the object of cryogenic insulation material (TABLE I).

TABLE I Basic Properties of tested synthetic polypropylene laminated papers

THICKNESS(MM)	0.160	0.119
DENSITY(g/㎤)	0.98	0.89
PP-RATIO(%)	53	57
TENSILE STRENGTH(kN/cm^2) (MACHINE/CROSS DIRECTION)	11.3/6.1	7.4/4.4
ELONGATION(%) (MACHINE/CROSS DIRECTION)	2.5/12.9	2.8/6.5
DISSIFATION FACTOR(100℃), %	0.080	0.055
RELATIVE PERMITTIVITY	2.7	2.7

Synthetic polypropylene laminated paper has low dielectric loss and high electrical breakdown strength, so it may be considered as good insulating materials for HTS power cable application [2,3].

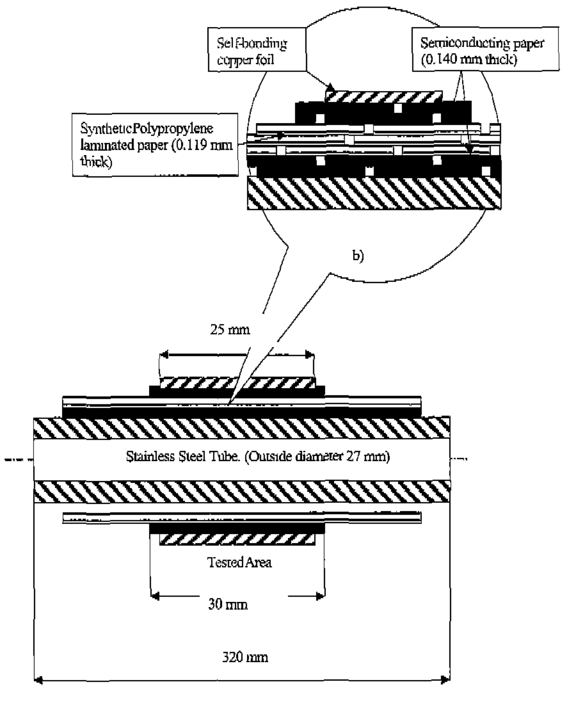
The flat type sample with "plane - plane" electrodes geometry was used for breakdown and PD tests with and without artificial cavities. The electrode geometry of this sample is shown in Fig. 1, at there the guard electrode was used for eliminating a edge discharge phenomenon for study of PD.



b)

Fig. 1. Electrode geometries
a) for short-term breakdown strength
b) for PD characteristics

The second model is a multi-sheeted tube type sample with "coaxial cylinders" electrode geometry. Preliminary design of tube type sample is shown in Fig.2



a)

Fig. 2. a) Tube sample used stainless steel tube
b) detailed frame of tube sample

The high voltage conductor is used by smoothly polished stainless steel tube of 27mm in outer diameter. and of 320mm in length. On the conductor, two semiconducting carbon paper tapes(25 mm in width) were wound with 1/3 covering and with 1 mm butt gaps. Next, on this surface, 2~5 layers of polypropylene laminated paper tapes(25 mm in width) were wound with various covering at constant tension. The grounded electrode is the self-bonding copper foil(25 mm in width).

The both test samples were put into a vertical cryostat containing LN_2 and maintained for 15 minutes to be constant cryogenic temperature before experiment.

The breakdown test was conducted according to standard method and repeated several times in same condition and specimen(10 for tube types and 25 for flat types) [4]. The voltage was raised from zero until breakdown occurrance at constant rate of 1.5kV/s. After breakdown, each specimen was disassembled and examined to ascertain the exact position of breakdown.

PD measurement was carried out according to electrical location method[5]. The sensitivity of PD detection was 5 pC and the measuring circuit is PD free. The PD inception voltage measurements are carried out by increasing(step by step - 500 V during 100 seconds) voltage applied to the sample until the required magnitude of PD(10 pC) was observed. Then the PD extinction voltage was measured when the voltage was decreased to zero. Measurement was repeated several times(5-6) for each type model in order to determine any variation with design or impregnation.

All measurements are carried out in commercial AC voltage at atmospheric pressure. The results of breakdown strength and PD characteristics were analyzed by using the normal distribution.

3. RESULTS AND DISCUSSION

3.1 The effect of cavity size and location on short-term AC breakdown strength

The result of short-term AC breakdown strength of flat type sample with artificial cavities that have various width and location is shown in Fig.3 and Fig.4. The short-term AC breakdown strength decreased with increasing cavity width and the number of cavities. The cavity location in the four-layer of flat type sample has very little effect on breakdown strength and the number of artificial cavities has much higher effect on breakdown strength (Fig.5). It's seen that the breakdown strength of four-layer sample increases and standard deviation of the breakdown strength decreases as the distance between neighboring artificial cavities increase. The breakdown channel in the sample that has small distance between sample that has small distance

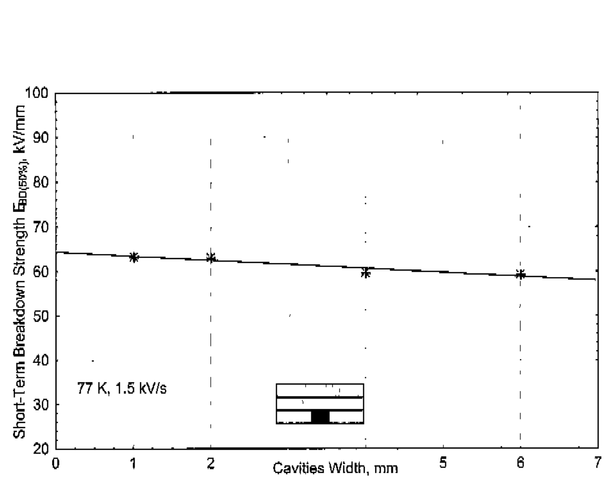


Fig. 3. Effect of cavities width on E_{BD} of three layer(0.119mm) flat sample impregnated with LN_2

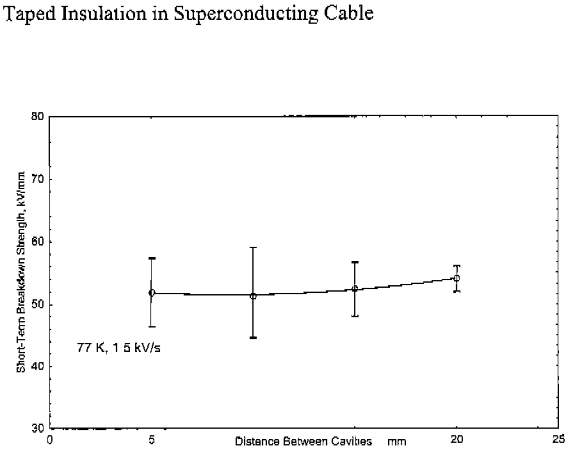


Fig. 5. Effect of distance between neighboring artificial cavities (2 mm wide) on E_{BD} of four layer(0.119 mm thick) flat sample impregnated with LN_2

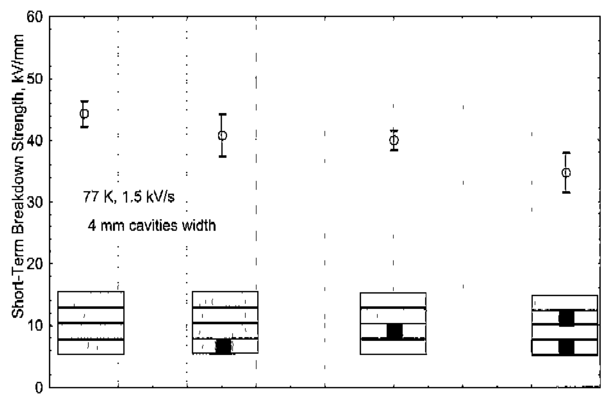


Fig. 4. Effect of cavities location on EBD of four layer(0.160 mm thick) flat sample impregnated with LN_2

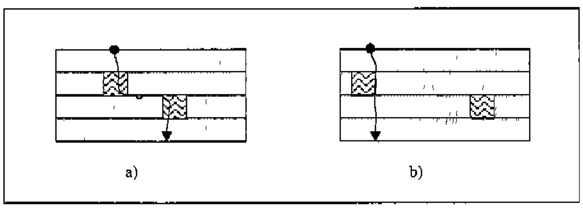


Fig. 6. Scheme of breakdown channel in four layer samples with various distances between cavities: a) small distance; b) large distance.

between cavities shows very complex way (Fig.6a). It means that the breakdown channel is formed between insulating layers and finished in the next cavity. This phenomenon is not observed in the multi-layer samples at room temperature, but only at LN_2 temperature. The discharge is apparently broken at impact with a solid dielectric at LN_2 temperature. The variety of electron mobility and the surface charge will be formed, then the electric field is distorted. The dielectric strength of synthetic polypropylene laminated paper is higher at cryogenic temperature than room temperature, so its surface maintains this impact and the discharge runs between insulating layers.

The increase of the distance between cavities reduces a probability of originating of the ramified breakdown channel. The discharge breaks through the insulating layers one by one from top to bottom as shown in Fig. 6b. This phenomenon has great importance for the choice of the optimal width of insulating tapes, so more than 20 mm is recommendable for the width of polypropylene laminated paper tapes in the HTS cable design.

3-2. Thickness effect

In the HTS cable design, the insulation has to consist of the tapes that have different thickness to be compatible with the optimal cost and design. Fig. 7 shows the short-term breakdown strength with thickness variation for both flat and tube type samples. It's shown that each graph has a linear log-log relationship over the range. Therefore, the relation between the short-term AC breakdown strength(E_{BD}) and thickness(t) can be expressed simply by following equation.

$$E_{BD}=A_t(t)^{-\alpha} \quad [\text{kV/mm}] \quad \cdots\text{(eqn.1)}$$

A_t and α are calculated parameters of regression model of E_{BD} listed in Table 2.

It's seen that E_{BD} which is measured in the flat type sample without artificial cavity shows the maximum value, provide that those thicknesses are less than about 0.5mm.

The exponent α for this sample is larger than for the sample with cavity. The breakdown mechanisms differ from each other. In case of the flat type sample without cavity, breakdown resulted from PD process in the edge of HV electrode.

TABLE Ⅱ Calculated parameters At and α for dependence in Fig. 7

Sample		Thickness of paper[mm]	A_t [kV/mm]	α
Flat type	Without cavity	0.119 0.160	34.6	0.60
	With cavity (4mm)	0.119	44.14	0.24
		0.160	37.6	0.27
Tube type		0.119	25.0	0.28

In cases of the tube and the flat type samples with artificial cavity, breakdown resulted from PD process into the cavity and the butt gaps. The value of E_{BD} in the flat type sample made of thin polypropylene laminated paper (0.119 mm) is larger than E_{BD} of sample made of thick paper (0.160 mm). This phenomenon provides an important result that if the thinner thickness is used, the higher dielectric strength is acquired.

The breakdown strength of tube type sample is the smallest among test samples (Fig.7). This resulted from the large contents in LN_2 into the sample as shown in Fig.8. The short-term AC break-down strength of tube type sample decreases with increasing covering rate.

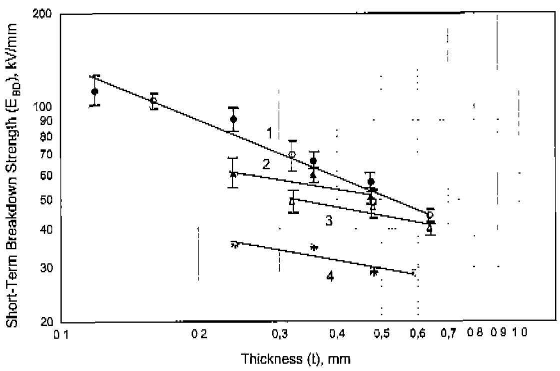


Fig. 7. E_{BD} of different model samples; at LN_2 versus thickness; (No.1) flat sample without artificial cavity: (No.2 and No.3) flat samples with single artificial cavity (4 mm wide); (No.4) tube samples at LN_2 versus insulation thickness. Full symbols for laminated paper (0.119 mm thick); empty symbols for (0.160 mm thick)

In Fig. 9 the short-term AC breakdown strength at LN_2 is expressed as a function of stressed volume (SV) for each test sample. Stressed volume is calculated from multiplying the volume of cavity by the acquired volume (i.e. the volume to determine the electric field region to which the insulating design covers). The short-term AC breakdown strength of each test sample linearly decreases with increasing parameter SV in a log-log scale. It means that the following correlation exists between E_{BD} and SV (correlation coefficient r = - 0.949):

$$E_{BD}=240(SV)^{-0.20} \quad \cdots \text{(Eqn.2)}$$

It is possible to see that parameter SV takes into account the both influence of sample thickness and LN_2 volume simultaneously[6].

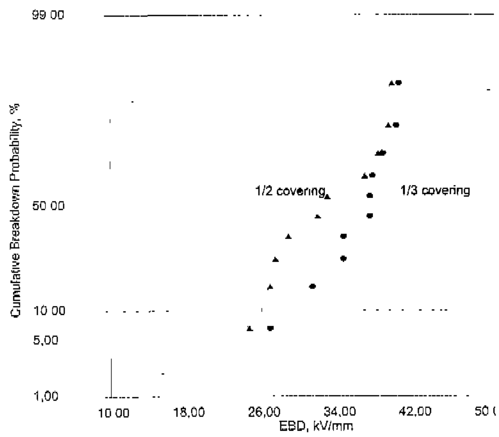


Fig. 8. Normal plots of the short-term AC breakdown strength of three layer tube samples, manufactured from polypropylene laminated paper (0.119 mm thick, 25 mm wide) with different covering

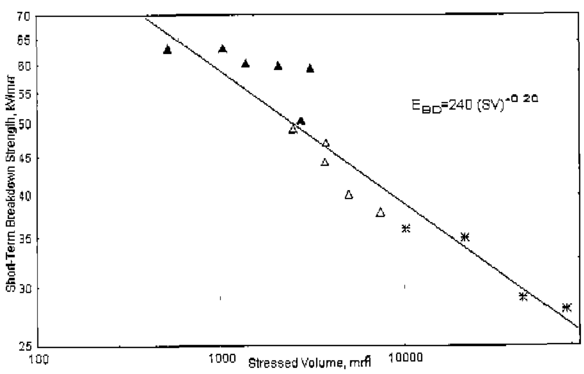


Fig. 9. Correlation between E_{BD} and stressed volume of model samples. Full symbols for laminated paper (0.119 mm thick); empty symbols for (0.160 mm thick)

3-3. Effect of thickness for PD inception / extinction electrical stress

The measurement of PD characteristics was conducted by using the flat type sample made of synthetic polypropylene laminated paper (0.119 mm thick) with artificial cavity (2 mm wide), which is adjacent to the ground electrode. The maximum apparent charge (Qmax) of PD detection at the PD inception voltage was less than 50 pC. These PD are initiated in the microscopic gas bubbles within LN_2 [7] or directly in LN_2 [2]. The initiation of PD and the associated energy release cause the vaporization of LN_2 which generates many gas bubbles, that time Qmax increases more than 500 pC. The number of PD tends to increase rapidly with increasing test voltage They also increase with time and persist at lower voltage to give PD extinction stress as low as (10 - 15)% of the PD inception stress (Fig.10).

The PD inception/extinction electrical stress (E_{IPD} /E_{EPD}) of the flat type sample both decreased with increasing sample thickness and this variation can be expressed by Eqn.1. In this case, the calculated parameters of regression model of E_{IPD}/E_{EPD} are shown in Table 3. The intensive PD at extinction voltage can be generated at interfaces between solid and liquid (LN_2) insulation to produce conducting paths known as tracking. Prolonged PD activity erodes the synthetic polypropylene laminated paper surface and can initiate the breakdown process.

TABLE III Calculated parameters At and α for dependences E_{IPD} = f(t) and E_{EPD} = f(t) in Fig. 10

Parameter	Dependence	
	$E_{IPD}=At(t)^{-\alpha}$	$E_{EPD}=At(t)^{-\alpha}$
A_t, kV/mm	12.5	9.9
α	-0.52	-0.59

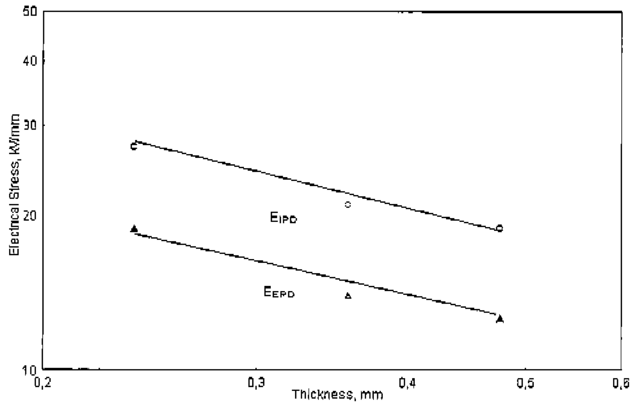


Fig. 10. Dependence of PD inception stress (E_{IPD}) and PD extinction stress (E_{EPD}) on thickness of flat samples with artificial cavity (2 mm wide) at liquid nitrogen.

4. CONCLUSION

The short-term AC breakdown strength and PD characteristics (inception and extinction electrical stress) of tube and flat samples made of the synthetic polypropylene laminated paper were studied. The influence of size and location of the butt gaps on electrical characteristics of tape insulation at LN_2 temperature was analyzed.

The following results are obtained:

(1) The size and number of artificial cavities influence on the short-term AC breakdown strength of multi-layer flat type sample at LN_2. The location of cavity does not influence on the breakdown strength practically.

(2) The distance between artificial cavities in neighboring layers of the sample influences on the short-term AC breakdown strength and breakdown dynamics very much. The breakdown channel passes between layers and then is finished in the next cavity in the case of small distance. An increase of the distance between cavities decreases the probability of growth of ramified discharge, so E_{BD} increases.

(3) The short-term AC breakdown strength of multi-layer samples without and with butt gaps decreases with increasing thickness according to Eqn.1. The discrepancy in breakdown mechanisms of different samples was analyzed. The correlative dependence between short-term AC breakdown strength and parameter SV was established.

(4) In the flat type sample with cavity, the PD extinction electrical stress is 10 - 15% lower than the PD inception electrical stress. The basic cause of this phenomenon is discrepancy in the physical nature of PD at the various voltages. The discharge at PD extinction stress takes place in thermally gaseous bubbles, which have high intensity and can initiated breakdown in short time. So, first of all, it is necessary to take into account the PD extinction electrical stress dependence to calculate operating working strength.

(5) The main results of this investigation can be used for an optimal design of winding parameter of taped superconducting insulation.

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