액체 질소에서의 반합성지 AC 파괴 강도에 미치는 부분 방전의 영향

Study of Partial Discharge Influence on AC Breakdown Strength of Laminated Ploypropylene Paper(PPLP) at Liquid Nitrogen

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Abstract: The short-term AC breakdown strength of laminated polypropylene insulating paper (PPLP) has been studied for cold dielectric of high temperature superconductivity power cables. The design and operating conditions of the electrode system for studying of short-term breakdown strength of one-layer and multi-layer PPLP samples are discussed in liquid nitrogen(LN2) state. The influence of various operating factors (geometry and dimension of electrodes, speed of tested voltage, thickness of test sample) on the value of short-term AC breakdown strength at cryogenic temperature has been established.

Key Words: short-term AC breakdown strength, insulation of high temperature superconductivity cable, liquid nitrogen, PPLP, partial discharge.

1. Introduction

The high temperature superconductivity (HTS) power cable is one of the promising ways for handling huge electric power in the future. It is necessary to study the behavior of different types of electrical insulation at cryogenic temperature to evaluate not only short-term characteristics but also long-term reliability for HTS cable application.

HTS cable insulation can be the tape type[1,2] or the extruded dielectric type [3,4]. Both types have some advantages and some shortcomings. The taped insulation which resembles oil-impregnated synthetic paper insulation can be easily impregnated with LN2. If the taped insulation is properly selected, it can combine excellent dielectric properties. However, taped insulation contains some gaps between insulating layers that could become a source of partial discharge (PD).

So, it is very important to investigate the influence of PD on breakdown strength of PPLP.

The laminated papers are made of various polymeric films and Kraft-papers, representing the greatest interest. These combined insulating material materials have excellent properties, compared with Kraft-paper and high porosity that provides the opportunity of impregnating in cryogenic liquids. Those have a low dielectric factor and relative permittivity, as polymeric films.

The PPLP has the low dielectric loss (ε·tan δ = 0.002) and the high breakdown strength, so it may be considered a good candidate for HTS power cable applications.

2. Experiments

The test samples are commercially available PPLP. The basic properties of tested PPLP are given in Table 1.

Table 1. Basic Properties of PPLP

Density, g/cm^3	0.98
Tensile strength, kN/m	
- machine direction	11.3
- cross direction	6.1
Elongation, %	
- machine direction	2.5
- cross direction	12.9
Dissipation factor, tanδ(100°C), %	0.080
Relative permittivity, ε	2.7

The test sample of PPLP consists of two layers of cellulose paper by different thickness (one layer - 0.04 mm, second layer - 0.07 mm) and rough polypropylene film by thickness 0.085 mm. The technological cycle of fabrication of synthetic paper contains the thermal calendering operation, so total thickness of PPLP forms 0.160 mm. Consequently, the factor Kf (volumetric share of polymeric film) is 53%, that is the optimum value for this type of synthetic insulating papers.

A new design of electrode system has been developed. This device enables to research ten and more identical samples without periodic change of LN2 in the cryostat, so the reliable and consistent test could be carried out. The experiments were carried out in a 4.6 liter stainless steel cryostat at

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atmospheric pressure. Its use to investigate short-term AC breakdown strength of PPLP at cryogenic conditions has been examined.

3. Results and discussion

3.1. Short-term dielectric strength of PPLP at Room Temperature(RT) in air and at 77K in LN2

The breakdown test was conducted on standard method [5] at scaling-up of test voltage with the increasing rate of 1.5 kV/s. High voltage(HV) electrode was brass cylinder by diameter 25 mm, the ground electrode was brass cylinder by diameter 35 mm and the schematic diagram of electrode system for this experiment was showed in fig.1 .

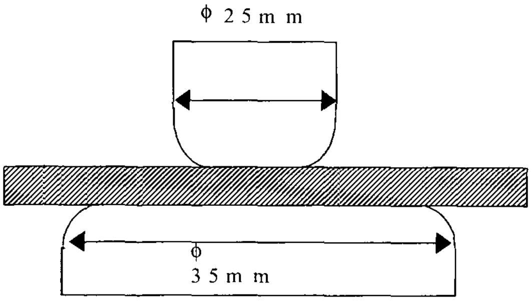


Fig. 1. Cylindrical HV electrode system

The breakdown strength distribution of one layer PPLP is plotted in Figure 2.

In order to analyze these data, statistical techniques such as normal distribution are commonly applied.

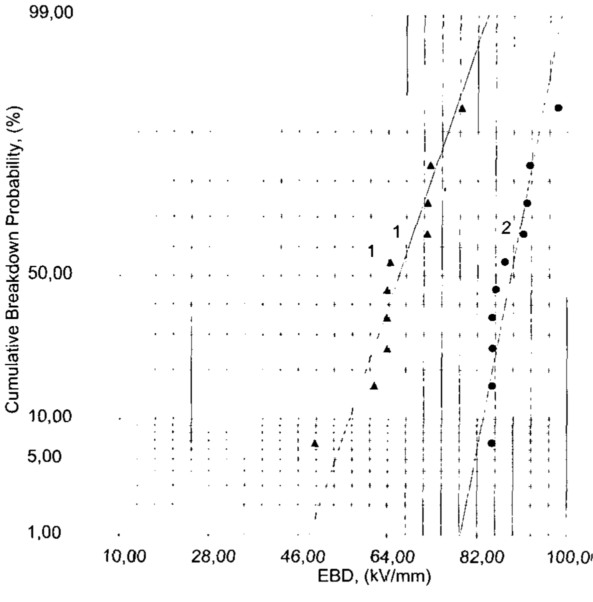


Fig. 2. Normal plots of the short-term AC breakdown strength of PPLP-sample (0.16 mm): No.1 at Room temperature in air; No.2 at 77 K in liquid nitrogen.

The Kolmogorov-Smirnov test has showed that the electrical breakdown values of PPLP can be adequately modeled by a normal distribution. The corresponding normal parameters are listed in Table 2.

The values of short-term breakdown strength of a sample at 77K are higher in comparison with short-term breakdown strength at RT in air. These results are similar to another researchers work[1,6]. It is possible to explain this phenomenon by two reasons.

Table 2. Normal parameters of the short-term breakdown strength distributions for PPLP.

Tested condition	Air(RT)	LN_2(77K)
Mean, E[kV/mm]	66.1	83.7
StDev, σ[kV/mm]	7.7	4.3

Firstly, at cryogenic temperature PPLP sample has the glass form. Here the electronic mechanism of breakdown process is known to be dominant; therefore values of breakdown strength in this temperature region are essentially increased [6].

Secondly, in air at RT, partial discharge occurs easily near the edge of HV electrode due to the enhancement of electric field as can be seen in Figure 3 and finally leads to the breakdown of PPLP sample. But the possibility of PD in LN2 is lower than at RT in air, that is why the dielectric strength in LN2 is higher than in air at RT [1,8].

3.2. The effect of electrode area and increasing rate of test voltage on short-term AC dielectric strength

In order to study the influence of electrode area and the increasing rate of test voltage on short-term breakdown strength of PPLP in LN2, three different types of high voltage electrodes (cylindrical type with diameter 10, 25 mm and spherical type with diameter 6 mm) were prepared. In these tests, the increasing rate of test voltage was changed from 0.45 to 3.0kV/s.

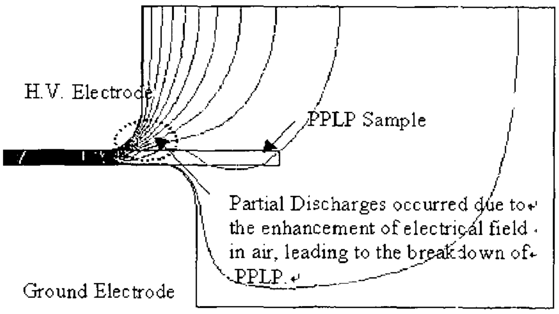


Fig. 3. The equi-potential profile of the electrode system

The dependences of short-term AC breakdown strength of PPLP on HV electrode area are plotted

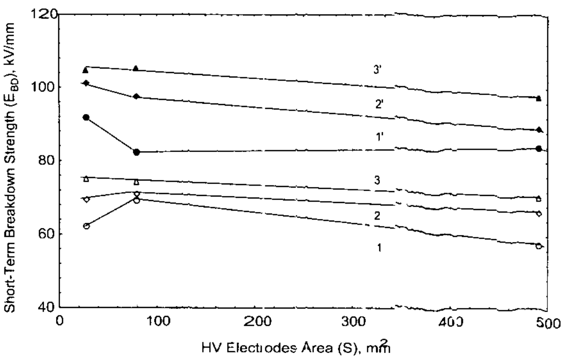


Fig. 4. AC breakdown strength of PPLP (0.16 mm) versus HV electrode areas for different increasing rates of test voltages: 1,1' - 0.45 kV/s; 2,2' - 1.5 kV/s; 3,3' - 3.0 kV/s. Empty symbols indicate measurements at RT and filled symbols at 77K

in Figure 4. In both cases (in air and LN2) the minimal value of short-term breakdown strength of PPLP is observed for HV electrode with the largest area (25 mm diameter). The major reason of this result is high probability of defects of PPLP-structure under large HV electrode area. For the smallest area of HV electrode(spherical electrode with diameter 6 mm) dependences of $E_{BD} = f(S)$ is different.

In LN2, the breakdown strength of PPLP increased with decreasing of HV electrode areas. In case of a spherical electrode at RT in air, the short-term breakdown strength of PPLP was reduced at lower increasing rate of test voltage because PD occurs during the time required to breakdown, which is somewhat longer due to lower increasing rate. At the higher rate, this time is shorter for PD and we observed the higher short-term AC breakdown strength of PPLP at 77K in LN2

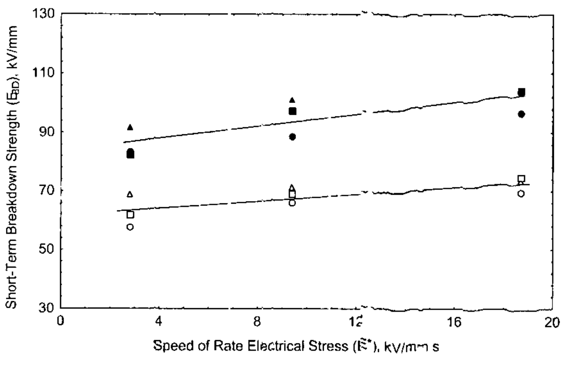


Fig. 5. AC breakdown strength of PPLP (0.16 mm) versus increasing rate of electrical stress. Empty symbols indicate measurements at RT and filled symbols at 77K

Figure 5 shows that at RT and 77K the short-term breakdown strength of one sheet PPLP specimen increased with the rate of test voltage according to the following equation:

$$E_{BD} = Av + Bv \cdot E^* \quad \text{--- (eqn.1)}$$

$$E^* = \frac{v}{t}$$

E^* : calculated value of increased electrical stress, v : increasing speed of test voltage, t: thickness of specimen, Av and Bv: calculated parameters of regression model

Table 3. Calculated values of parameters, Av and Bv

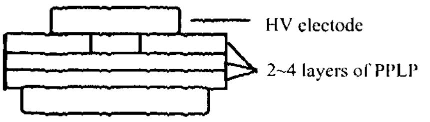
Parameter	Air(RT)	LN2(77K)	N
A_v[kV/mm]	61.8	84.2	30
B_v[s]	0.62	1.01	30

The results in Figure 5 and Table 3 indicate that the investigated dependences are identical in both cases. So, in LN_2 the failure of PPLP-samples occurs due to the action of PD. The increase of PD action (at lower increasing rate of test voltage) reduces value of short-term AC breakdown strength of PPLP.

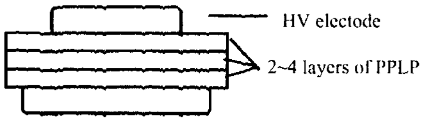
3.3. Intrinsic Breakdown and PD leading to breakdown strength

In order to study about the influence of PD on the short-term dielectric strength of PPLP, in LN_2 two different types of PPLP specimens were prepared : one type has artificial gaps 4mm wide between PPLP turns. And this is more realistic model of HTS cable insulation, and the other type is without gaps. The schematic drawings of these samples and insulation model of HTS cable are represented in Figure 6.

(a) Insulation model of HTS cable



(b) Samples with artificial gap



(c) Samples without artificial gap

Fig. 6. Insulation model of HTS cable and sample preparation

The breakdowns occured on PPLP specimens at RT and at 77 K is different. In air most of breakdowns of samples are at outside(from 1 up to5 mm) to edges of HV electrode. On the other hand, breakdowns of samples in LN2 take place on the surface of HV electrode.

Hence, the breakdown of PPLP in air-especial in case of a spherical electrode- is originated from the PD in the gap. Although the PD has influence on breakdown process in LN2 as Figure 7 shows, it is not so much.

3.4. Thickness effect on short-term AC dielectric strength

In LN2 the short-term AC breakdown strength decreased with increasing thickness (t) of PPLP-specimens without and with artificial gap (Figure 7) and complied with the following equation:

$$E_{BD} = A_t\ t^{-\alpha}\ [\mathrm{kV/mm}] \quad --- \quad (\mathrm{eqn.}2)$$

A_t and α are calculated parameters of regression model listed in Table 4.

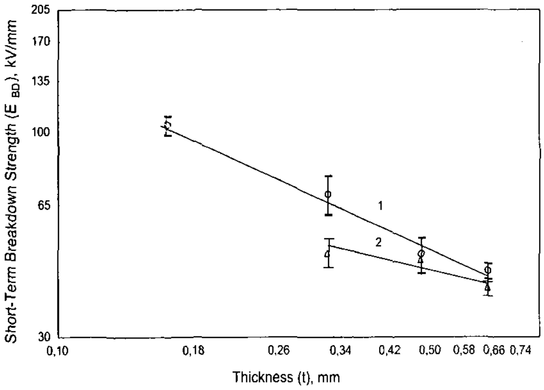


Fig. 7. AC breakdown strength of PPLP specimens without (No. 1) and with (No. 2) artificial gap (4mm wide) in LN2 (77K) versus insulation thicknesses. Configuration of HV electrode is spherical by diameter 6 mm and speed of test voltage is 1.5 kV/s

Table 4. Calculated parameters At and α for dependences in Figure 7

Parameter	PPLP specimen without artificial gap	PPLP specimen with artificial gap
A_t[kV/mm]	32.4	37.6
α	0.64	0.27

The equation 2 is valid for various layers insulating materials in air with respect to influence of the intensive PD. For this case the value of parameter α is ranged from 0.50 to 0.55 [7]. As it is visible from Table 4, for specimens without artificial gap in LN2, value α is larger than that in case of with artificial gap.

4. Conclusions

Short-term AC breakdown voltage characteristics of PPLP were studied under different kinds of test conditions.

The following results are obtained:

(1) The AC breakdown strength of PPLP in LN2(77K) is higher than at RT in air. The electrical breakdown values of PPLP have narrow dispersions. Hence, PPLP-samples have homogeneous structure and high quality. The laminated insulating paper with polypropylene is a good candidate for HTS power cable applications.

(2) The influence of PD on short-term AC breakdown strength of one and multi-layer PPLP specimens without and with artificial gap was investigated. The increase of duration of PD action reduces breakdown strength of PPLP in LN2. For specimens with artificial gap this influence is revealed sharply.

(3) Empirical equations 1 and 2 for dependences $E_{BD} = f(E^*)$ and $E_{BD} = f(t)$ were derived. The value of breakdown strength of one layer PPLP specimens increased with increasing rate of electrical stress (E^*). The value of breakdown strength of multi-layer PPLP specimens without and with artificial gap decreased with increasing thickness of specimens. These equations are very important and will be used in determining optimal operating electrical stress in cold dielectric design of HTS power cables.

감사의 글

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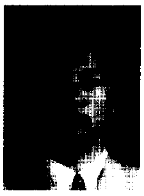

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