초전도 케이블에서 반합성지의 전기적 특성에 관한 설계 인자 연구

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The Study of Design Factors on the Main Electrical Properties of the Tape Insulation

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Abstract - The partial pischarge(PP) process in synthetic laminated paper insulation was studied at cryogenic condition using different types of the test samples(flat and tube type). The influence of semiconducting carbon paper was also evaluated by studying the electrical properties of superconducting cable.

1. Introduction

The high temperature superconducting(HTS) power cable is one of the potential ways for handling huge electric power in the future. It is necessary to study the behavior of electrical insulation for the design and fabrication of HTS cable at cryogenic condition.

Taped insulation such as laminated polypropylene(PP) paper has excellent electrical properties, however, also companies the butt gaps when impregnated in liquid nitrogen(LN_2). The relative permittivity of LN_2 is close to 1.4 while the surrounding solid dielectric is more than 2 so the electric stress in a butt gap is more intensive than the average electric stress of electrical insulation. Therefore, butt gap could become a source of PD. Prolonged PD activity erodes a solid dielectric surface and can eventually initiate failure of cryogenic insulation.

In this paper, the effects of butt gaps in LN_2 were investigated for the optimal design of HTS cable.

2. Experiment

2.1 Design of test sample

Two types of test samples were prepared with laminated PP paper(25 mm wide, 0.119 mm thick). One is a multi-layer flat type sample which has the plane to plane electrode geometry and butt gap(2 mm wide) near ground electrode. Fig.1 shows the electrode configuration of the flat type sample.

The other is a multi-layer tube type sample which has the cylindrical electrode geometry. Fig. 2 shows the configuration of this sample. High voltage conductor is smoothly polished stainless steel tube with outside diameter 27 mm and 320 mm long. Two semiconducting carbon paper tapes(25 mm wide, 0.130 mm thick) are wound on the conductor with 1/3 registration and 1 mm wide butt gaps. Then PP laminated paper was wound on this semiconduc-

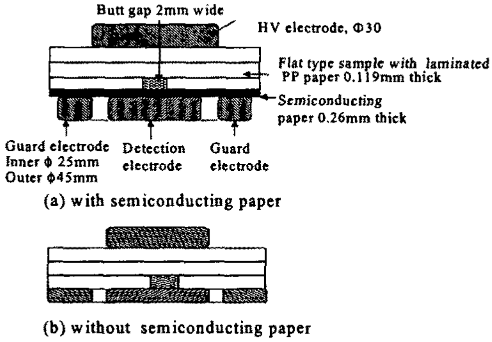

Fig. 1 Configuration of the flat type sample

-ting layer. The self-bonding copper foil, 25mm wide was used for ground electrode by winding on the outmost layer.

Each test sample was impregnated into LN_2 vessel and maintained for 15 minutes to cool down. PD measurement was carried out according to Fig. 3. Blocking resistance (400 Ohm) which is filled with silicone oil was applied to decrease a noise level and digital oscilloscope was used. To decrease the external noise, measuring circuit was located in the shielded metal box. Sensitivity of PD detector was below 5 pC.

The measurement of PD inception voltage was carried out by increasing voltage step by step. Then, the voltage was lowered to zero until the PD extinction voltage was measured. Degree

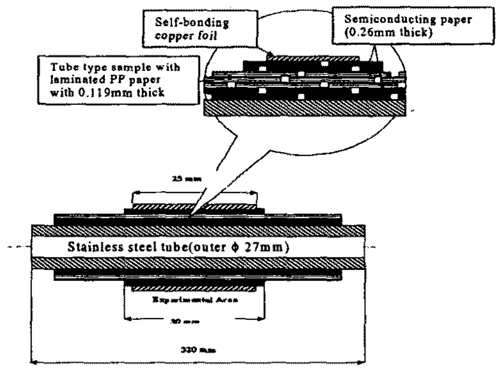

Fig. 2 Configuration of the tube type sample

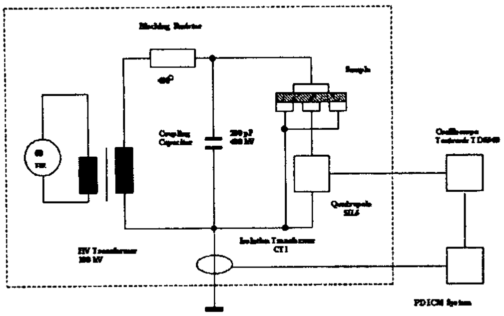

Fig. 3 Schematic system of PD detector

of the step was 500 V during 100 s.

PD inception voltage (PDIV) and PD extinction voltage (PDEV) were calculated according to the following equations:

$$PDIV=\frac{U_i+U_{i-1}}{2}, \quad PDEV=\frac{U_e+U_{e-1}}{2} \qquad (1)$$

U_i and U_e is the PD inception & extinction voltage when PD magnitude is 50pC. U_{i-1} and U_{e-1} are the values of previous step. PD magnitude at PDIV is 100~200pC. All these measurements were repeated 5 times and carried out by using commercial AC voltage at atmospheric pressure and average current, occurrence rate of PD were calculated according to following equation.

$$I_{PD}=\sum_i Q_i\frac{N_i}{\tau}, \quad N_{PD}=\sum_i\frac{N_i}{\tau} \qquad (2)$$

(where I_{PD} : average current, N_{PD} : occurrence rate of PD, Q_i : Apparent PD charge, N_i : the number of PD, τ: measuring time)

2.2 Study of PD process

2.2.1 PD Process in the flat sample

PD in multi-layer flat type sample with butt gaps was measured. PD inception stress(PDIF, E_{IPD}) and PD extinction stress (PDEF, E_{EPD}) have large difference with same thickness in the absence of semiconducting paper..

Fig. 4 shows the dependency of PD magnitude versus test stress for 3 layers flat type sample. PD magnitude increases up to several thousand pC as test stress increases. Then the reverse trace reveals the different path compared with forward trace

Fig. 5 shows the effects of thickness of insulation layer on PDIF and on PDEF and both dependencies could be expresses in the following equation:

$$E_{IPD}=12.5(t)^{-0.52} \ [\mathrm{kV/mm}]$$
$$E_{IPD}=9.9(t)^{-0.59} \ [\mathrm{kV/mm}] \qquad (3)$$

The value PDEF is 13~15% less than PDIF for all tested samples.

In case of sample which includes

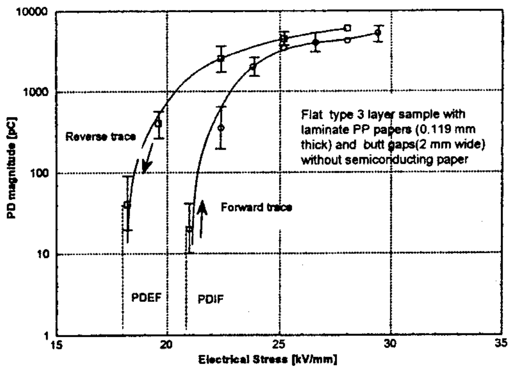

Fig. 4 PD magnitude *vs* test stress in 3 layer flat sample without semiconducting layer

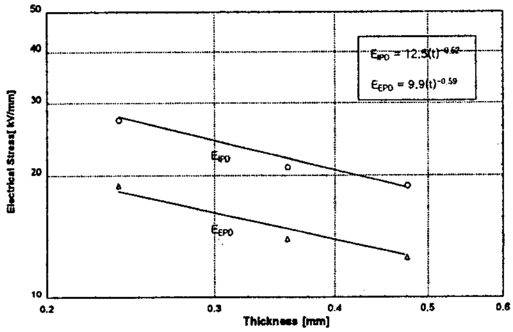

Fig. 5 Effect of insulation thickness on PDIF and PDEF

semiconducting layer, the PD inception and PD extinction essentially differ from the previous case. Fig. 6 shows the relation of PD magnitude versus test stress in flat type 3-layer sample with semiconducting layer. As test stress increases, PD magnitude also increases at forward trace.

When the test voltage decreases, the PD magnitude also decreases like the former result without semiconducting layer. But the case of samples with semiconducting layer, the value of PEEF is close to the PDEF at various thickness.

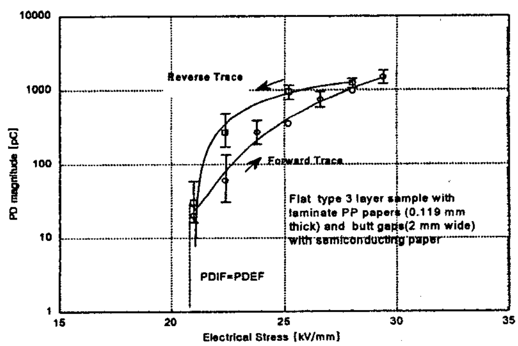

Fig. 6 PD magnitude *vs* test stress in flat type 3 layer sample with semiconducting layer

The dependencies of PDIF and PDEF can be designed by the identical reverse power equation with similar regression factors.

$$E_{IPD} \cong E_{EPD} = 12.2(t)^{-0.55}\,[\text{kV/mm}] \qquad (4)$$

Main reason of these differences results from carbon tracks. These tracks were shown on the surface of laminated PP paper after initiating PD as a result of an interaction between discharges and LN_2. But these are not founded in case of only discharge at atmospheric condition and only LN_2 condition without discharge. Once carbon particles is attached on surface of a synthetic paper, the track formed quickly. This phenomenon may cause the negative consequences as below

- Increase of dielectric losses at cryogenic condition
- Diffusion of carbon particles between layers of laminated PP papers

Also, this phenomenon can accelerate the aging process and the breakdown of the insulation at cryogenic condition.

2.2.2 PD Process in the tube type sample

The PD processes in the tube samples at liquid nitrogen were studied. The tube type sample with 2~5 layers of laminated PP papers was used. For comparison between liquid and gaseous nitrogen(GN_2), tube type 3 layers sample was tested in a gaseous nitrogen condition about 85~90 K.

Fig. 7 shows the influence of maximum PD magnitude versus test stress. PD magnitude in LN_2 increases very quickly from PDIF as test stress increases. The reason of this phenomenon is the generation and the growth of thermal bubbles with increasing test stress[2],[3]. In case of GN_2, PD magnitude is not practically changed with increasing test stress, so PD magnitude depends on the generation of thermal bubbles. The occurrence rate of PD and PD current in tube sample increased with test stress(Fig. 8). The occurrence rate of PD and the PD current increased with the number of layers proportional to the volume of butt gaps. These

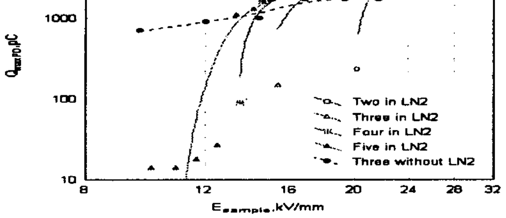

Fig. 7 PD Magnitude in tube samples at LN_2

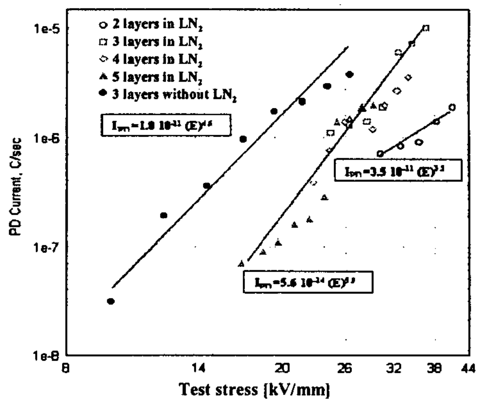

Fig. 8 PD occurrence rate and current in tube type samples at LN_2

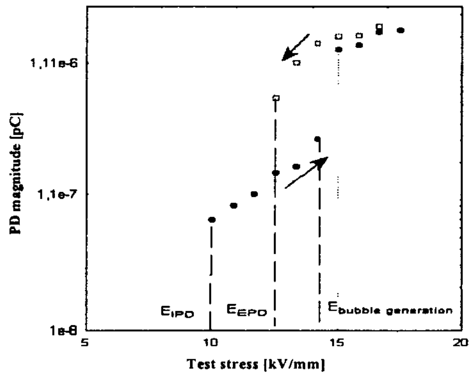

Fig. 9 PD magnitude VS test stress with tube type 5 layer sample

values in LN_2 are higher than maximum values at GN_2.

Fig. 9 shows forward and reverse traces of PD magnitude versus test stress at the five layer tube type sample in LN_2. At the forward trace, we can see the increase of PD magnitude with increasing the test stress.

The sharp extension of PD magnitude takes place at the moment of the generation of thermal bubbles. At reverse trace, PD magnitude decreases with test stress. For this

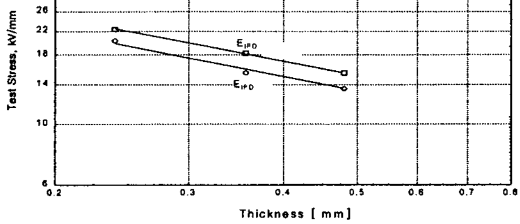

Fig. 10 Effects of sample thickness VS test stress

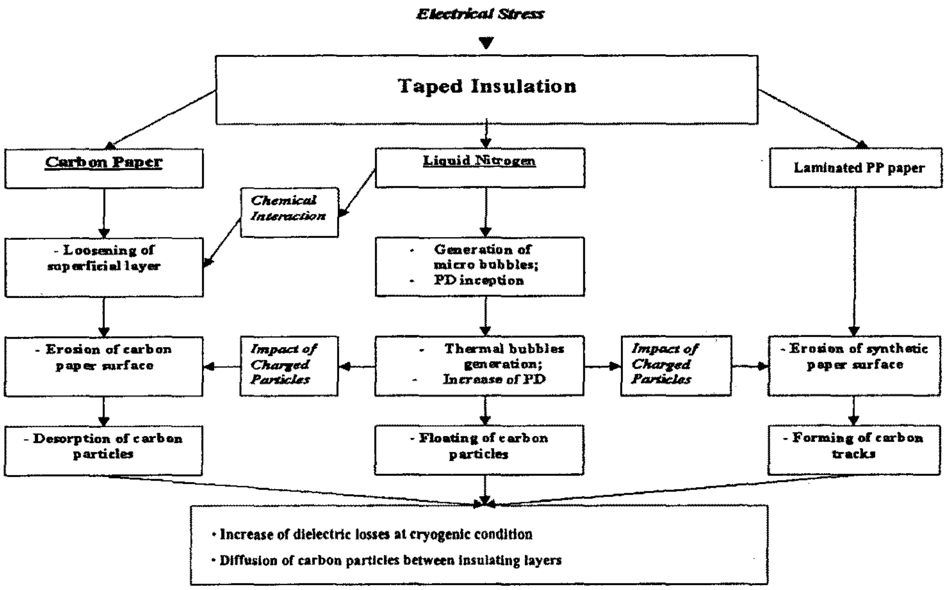

Fig. 11 Generation of carbon tracks into butt gap in LN_2

case, the value of PDEF is larger than that of PDIF. This phenomenon is related to carbon tracks into butt gaps.

Effects of sample thickness on PDIF and PDEF are shown in the Fig. 10. It can be shown that these influences correspond to the reverse power laws,

$$E_{IPD}=8.7(t)^{-0.59}\ [\mathrm{kV/mm}]$$
$$E_{EPD}=10.5(t)^{-0.53}\ [\mathrm{kV/mm}] \qquad (4)$$

The hypothesis model of carbon track in butt gaps of the tape is shown in the Figure 11.

The impacts of charged particles such as ions, electrons from surface of carbon paper can increase the PD activity into thermal bubbles. Simultaneously charged particles adhere to surface of laminated PP paper, causing its erosion. The separated carbon particles float inside butt gaps and then cause PD activity These negative effects may accelerate the aging of cryogenic tape insulation.

3. Conclusion

The PD characteristics such as inception and extinction electrical stress, the average current, the occurrence rate of PD were studied using flat and the tube samples made with laminated PP paper. The influences of butt gaps and semiconducting paper on PD characteristics were analyzed in LN_2.

The effects of the discharge results in following mechanisms.

- Increase of dielectric losses at cryogenic condition
- Diffusion of carbon particles between insulating layers

[Reference]

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