Partial Discharge Activity in Electrical Insulation for High Temperature Superconducting (HTS) Cables

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ABSTRACT
This paper discusses electrical insulation characteristics of liquid nitrogen (LN$_2$) / polypropylene (PP) laminated paper composite insulation system for the practical electrical insulation design of high temperature superconducting (HTS) cables. Partial discharge (PD) inception, propagation and breakdown (BD) characteristics under ac voltage application were obtained and discussed at atmospheric and pressurized conditions. Experimental results were analyzed quantitatively and revealed that void-type discharge was categorized as an important form of discharge to characterize the transition of PD activity leading to BD.

Index Terms — Superconducting cables, dielectric liquids, paper insulation, partial discharges, electrical breakdown, laminated paper.

1 INTRODUCTION
HIGH temperature superconducting (HTS) cables have been developed and demonstrated in field tests in Japan, USA and Korea [1-5]. The electrical insulation system of HTS cables consists of liquid nitrogen (LN$_2$) / polypropylene (PP) laminated paper composite insulation system. However, the electrical insulation design and test schemes of HTS cables have not yet been fully established, due to the lack of dielectric data applicable to the practical development of the HTS cables. Especially, understanding of partial discharge (PD) characteristics is crucial to prevent the degradation of electrical insulation performance.

From the above background, we have been investigating the PD characteristics of LN$_2$ / PP laminated paper composite insulation system under ac voltage application, and evaluated the volume effect of ac PD inception strength at atmospheric and pressurized conditions [6]. We have already proposed a novel technique for PD measurement and analysis, Partial Discharge Current Pulse Waveform Analysis (PD-CPWA), which is expected to elucidate PD mechanisms and physics in different electrical insulating materials [7]. Using PD-CPWA, we can obtain not only individual PD current pulse waveform, but also its transition characteristics of PD activity with the elapse of time and / or for different stresses of electric field and liquid pressure.

In this paper, we describe the transition characteristics of PD activity from PD inception to breakdown (BD) in LN$_2$ / PP laminated paper composite insulation system. Experimental results revealed that PD changed into void-type discharges at a certain applied electric field strength higher than PD inception strength. The results suggested that the large PD in the void-type discharges could be closely related to BD and distinguished from the other PDs. The void-type discharge inception strength (VDIE) can be regarded as the electric field criteria for the electrical insulation design of HTS cables.

2 EXPERIMENTAL SETUP
Figure 1 shows the electrode configuration of coaxial cylindrical cable sample for PD measurement. The coaxial cylindrical cable sample consists of high voltage electrode as an inner cylinder, inner semi-conducting layers, PP laminated paper layers, outer semi-conducting layers, and grounded electrode as an outermost sheath. In this paper, we used 8-layer sample of PP laminated paper layers (0.125 mm thickness / layer). The effective length of quasi-uniform electric field was 150 mm.
3. PARTIAL DISCHARGE ACTIVITY UNDER ATMOSPHERIC CONDITION

3.1 VOID-TYPE DISCHARGE

PDIE of the 8-layer sample was 20-22 kV/mm/mm at the inner electrode surface under atmospheric condition. Figure 3 shows the transition of PD activities when the applied electric field strength $E_a$ was increased from PDIE to BDE; (a) $E_a=20.8$ kV/mm/mm (PDIE), (b) $E_a=24.8$ kV/mm/mm, (c) $E_a=25.9$ kV/mm/mm, (d) $E_a=36.9$ kV/mm/mm (BDE), respectively.

In Figures 3a and 3b, a few PD pulses were generated per cycle at around the peak phase of the applied voltage. In Figure 3c, the number of PD pulses drastically increased and PD pulses appeared at around the zero-crossings of the applied voltage. These results suggest that the PD activity changed into void-type discharges not only in the micro gaps between PP laminated paper layers but also in the butt gaps [8]. The change in PD activity was instantaneous with the increase in $E_a$, which was defined as the void-type discharge inception electric field strength (VDIE). In Figure 3d, the PD activity was void-type discharge with the current level as high as 100 times of the previous ones. It means that PD grew by keeping void-type discharge activity and finally led to BD.

VDIE and BDE of 8-layer sample were 25-26 kV/mm/mm and 37-39 kV/mm/mm, respectively. As indicators to show the transition of PD activity, Figure 4 shows (a) PD generation frequency ($f_{PD}$) and (b) maximum PD current ($I_{max}$) characteristics as a function of applied electric field strength $E_a$ normalized by VDIE. In Figure 4a, the vertical axis is the average of PD generation number per second (pps: pulse per second). In Figure 4b, the vertical axis is the maximum value of positive PD current, where the PD current of 1 mA corresponds to the PD charge of about 20 pC. Bordering on VDIE, $f_{PD}$ and $I_{max}$ increased drastically, which verifies that the transition of PD activity into the void-type discharge was instantaneous with the increase in $E_a$. Furthermore, PD charge at around BDE reached as high as 80 mA, i.e. about 1600 pC.

3.2 PD AND BD TRACES

Figure 5 shows the picture of the decomposed 3-layer sample after BD. BD point was found in the butt gap on the innermost layer at around the center of effective area. Figure 6 shows the picture of the unwrapped PP laminated paper at the 2nd layer of the decomposed 8-layer model at $E_a >$ VDIE. A discolored line was clearly seen on the paper, which corresponded to the spiral-shaped butt gap area in the form of the coaxial cylinder. Such a discolored line was not found at $E_a <$ VDIE. According to the infrared spectroscopy, a methyl group and a methylene group were detected in the discolored line, which were the components of the PP sheet sandwiched by kraft papers. In addition, a BD trace as a hole was found in the discolored line, as shown in Figure 6b at $E_a =$ BDE. The discolored line was attributed to the degradation of PP laminated paper, where successive PD would be generated in the butt gap filled with thermal bubbles. In other words, the discolored line can be regarded as a PD trace as well as an evidence of void-type discharges.
These results on PD and BD traces verified that PD was generated and developed in the butt gap area before BD. Here, our previous research revealed that PD inception could be dominated by micro gaps between PP laminated paper layers rather than butt gaps [6], which seems to be inconsistent with the above results in this paper. It can be interpreted as follows; PD inception at around \( E_a = \text{PDIE} \) would be mainly originated from micro gaps between PP laminated paper layers. PD activity could be developed also in the butt gaps at the higher \( E_a \). Under the reciprocal action of PD generation and bubble formation at around \( E_a = \text{VDIE} \), the butt gap would be filled with bubbles to induce the void-type discharges with much higher \( f_{PD} \) and the discolored line. PD current or charge became much higher at around \( E_a = \text{BDE} \) and finally resulted in BD.

**Figure 3.** Transition of PD activity.

**Figure 4.** PD parameters as a function of applied electric field strength under atmospheric condition.
TIME TRANSITION CHARACTERISTICS

In the previous section, transition characteristics of PD activity were discussed from the viewpoint of applied electric field dependence. On the other hand, in this section, time transition characteristics of PD activity are discussed for the life assessment of electrical insulation of HTS cables.

Our developed PD-CPWA can get each PD current pulse waveform for more than 18000 pulses at one acquisition procedure, which can also be repeated for long time. Statistical parameters of a series of PD current pulse waveform data are analyzed by PD-CPWA. Figure 7 shows Weibull plots of PD current pulse height at different applied electric field strength. The regression line of the Weibull plot at $E_a = PDIE$ in Figure 7a was expressed by a single slope, whereas the regression line at $E_a = VDIE$ in Figure 7b and the higher stress consisted of different slopes. In other words, each PD pulse could be clearly distinguished into small or large PD pulse, respectively, by the PD current pulse height before or after the inflection point. The small PD pulses would be attributed to the void-type discharges, and the large PD pulses would be gaseous discharges in a large bubble formed by a cluster of the void-type small discharges. Hereinafter, we will focus on the large PD pulses which may lead to BD.

Figure 8 shows the time transition characteristics of the generation frequency $f_{PD}$ and the average current value $I_{ave}$ of large PD pulses, where the applied electric field strength $E_a$ was kept constant at a pre-determined stress level up to 3 h. At $E_a > VDIE+2.5$ kV/mm ($E_a/VDIE > 1.1$), BD was caused within 3 h (BD case), and $f_{PD}$ and $I_{ave}$ of large PD increased with the elapse of time. On the other hand, at $E_a < VDIE+2.5$ kV/mm ($E_a/VDIE < 1.1$), BD was not caused within 3 hours (NO-BD case), and large PD activities tended to be shrunk. PD trace on the PP laminated paper as was shown in Fig. 6 was always associated with BD cases. In addition, BDE was measured for some samples exposed to PD in the NO-BD case, which is referred to as the “residual BDE”. The residual BDE was almost the same as BDE of virgin samples, i.e. no
degradation in BDE was confirmed. These results suggest that large PD pulses in void-type discharges would be closely related to BD, i.e. PD beyond the electric field criteria \( E_a = V_{DIE}/2.5 \text{ kV/mm} \) (\( E_a / V_{DIE} = 1.1 \)) might be harmful for the life of HTS cables at atmospheric pressure.

4 PARTIAL DISCHARGE ACTIVITY UNDER PRESSURIZED CONDITION

4.1 PRESSURE DEPENDENCE OF PDIE, VDIE AND BDE

In general, actual HTS cables are operated at the pressurized condition of sub-cooled \( \text{LN}_2 \), so that discussions should be extended to the PD activity under pressurized condition. Figures 9a and 9b show the pressure dependence of PD generation frequency \( f_{PD} \) and maximum PD current \( I_{max} \) in sub-cooled \( \text{LN}_2 \). \( f_{PD} \) increased with the rise of applied electric field strength at each pressure, and the increase rate of \( f_{PD} \) became small with the rise of pressure. \( I_{max} \) increased with the applied electric field strength and decreased with pressure. The transition of PD activity into void-type discharges was also confirmed under pressurized condition. According to the experimental results for different conditions, void-type discharge appeared at \( f_{PD} > 1200 \text{ pps} \), irrespective of the pressure. Then, we defined VDIE quantitatively as the electric field strength where \( f_{PD} \) reached 1200 pps.

Figure 10 shows the pressure dependence of PDIE, VDIE and BDE. PDIE and BDE increased by about 50 % and 25 % from 0.1 MPa to 0.2 MPa, respectively, and tended to be saturated at above 0.2 MPa. This pressure dependence of dielectric characteristics in \( \text{LN}_2 \) can be interpreted by the disappearance of microscopic bubbles and the residual impurities as the main factor for discharge inception under pressurized condition [9].

On the other hand, VDIE increased monotonously with the pressure. The transition into void-type discharge originates from bubble creation in \( \text{LN}_2 \), and is decided by the balance between the electrical discharge energy and the evaporation energy of \( \text{LN}_2 \). Under the pressurized condition, the higher electrical discharge energy is needed for the bubble creation, because of the increase in the evaporation energy of the pressurized sub-cooled \( \text{LN}_2 \). Accordingly, VDIE gradually increased at the higher pressure.
4.2 TIME TRANSITION CHARACTERISTICS

Figure 11 shows the time transition characteristics of \( f_{PD} \) and \( I_{ave} \) of large PD pulses at \( P=0.3 \) MPa. Similarly with those at \( P=0.1 \) MPa, \( f_{PD} \) and \( I_{ave} \) of large PD increased with the elapse of time in the BD-case, but decreased or almost constant in the NO-BD case. The electric field criteria between BD-case and NO-BD case was \( E_a=V_{DIE}-4 \) kV/mm \( (E_a/V_{DIE}=0.9) \) at \( P=0.3 \) MPa, which is lower than the criteria \( (E_a/V_{DIE}=1.1) \) at \( P=0.1 \) MPa. The pressure difference in the criteria may be attributed to the difference between the operating point and the boiling point at each pressure of sub-cooled LN\(_2\) at 77 K. No degradation in BDE of test samples in the NO-BD case was also confirmed by the measurement of residual BDE. In addition, the time from PD inception to BD in the BD case was summarized in Fig. 12 as the V-t characteristics at \( P=0.1 \) MPa and \( P=0.3 \) MPa. Both the lifetime of electrical insulation and its index \( (n \) value) at \( P=0.3 \) MPa increased compared to those at \( P=0.1 \) MPa.

BDE in Fig. 10 was obtained with the increase rate of 1 kV/s in the applied voltage, i.e. short-term criteria (BDE\(_{short}\)) for BD event. On the other hand, the long-term criteria (BDE\(_{long}\)), i.e. V-t characteristics as was shown in Fig. 12, are necessary for the life assessment of electrical insulation of HTS cables. Figure 13 shows the pressure dependence of BDE\(_{long}\) together with PDIE, VDIE and BDE (BDE\(_{short}\)) in Fig. 10, where the applied electric field strength \( E_a \) was kept constant for long time up to 3 hours. BDE\(_{long}\) was lower than BDE\(_{short}\) and nearly equal to VDIE at each pressure.

The above results under pressurized condition reveal that the void-type discharge is an important electrical discharge form to characterize the transition of PD activity leading to BD, and VDIE closely related to BDE\(_{long}\) can be regarded as the electric field criteria for the insulation design of HTS cables.

5 CONCLUSIONS

In this paper, we discussed PD activity for electrical insulation system of HTS cables under atmospheric and pressurized conditions. The main results are summarized as follows:

(1) PD inception would be mainly originated from micro gaps between PP laminated paper layers. At the higher stress, PD activity could be developed into void-type discharges in butt gaps filled with thermal bubbles.

(2) Large PD pulses in the void-type discharges would be closely related to BD, where PD generation frequency and current level increased with the elapse of time.

(3) PD generation frequency \( f_{PD} \) increased with the rise of applied electric field strength at each pressure, and the increase rate of \( f_{PD} \) became small with the rise of pressure. The void-type discharge appeared at \( f_{PD} > 1200 \) pps, irrespective of the pressure.

(4) The void-type discharge is an important electrical discharge form to characterize the transition of PD activity leading to BD, and its inception stress (VDIE) can be regarded as the electric field criteria for the electrical insulation design of HTS cables.
Figure 11. Time transition characteristics of large PD activity at P=0.3 MPa

(a) PD generation frequency of large PD pulses
(b) Average current value of large PD pulses

Figure 12. V-t characteristics at breakdown.

Figure 13. Pressure dependence of PDIE, VDIE, BDE_short and BDE_long.
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