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Winding Insulation Characteristics of Gas Filled Transformers With SF_6 Alternative Gas

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SUMMARY

In recent years, gas-filled transformers that use SF_6 gas as an insulation and cooling medium have been attracting attention from the viewpoint of preventing fires caused by accidents inside the transformer tank and preventing environmental pollution due to oil leakage [1]. However, SF_6 gas has a high global warming potential, therefore, there is a demand for gas-filled transformers that SF_6 alternate gases such as dry air [2] and N_2 [3][4] that have a low global warming potential and are easy to handle. In this paper, we report the following findings obtained by investigating the basic insulation characteristics of the disk windings of gas-insulated transformers with these gases.

From the investigation of the basic insulation characteristics simulating between the sections of the disk winding, it became clear that the SF_6 alternative gas has an insulation performance of about 60 to 70 % of that of the SF_6 gas, although it depends on the gas pressure. Based on the above results, the dielectric breakdown characteristics of N_2 gas were obtained using a main gap model that simulated the winding configuration of an actual transformer, and the dielectric breakdown electric field exceeded the theoretical breakdown electric field of N_2 gas at 30 kV/mm. The reason for this is considered to be that the insulating material prevented the discharge propagation. In addition, the following was clarified with N_2 gas. It has no electron attachment and the discharge uniformity is lower than that of dry air. Even if 1.1 times the partial discharge inception voltage is applied between the winding sections, the discharge does not propagate and the dielectric breakdown does not occur.

KEYWORDS

Gas filled transformer - Disk winding - Partial discharge - Alternative Gas - N_2 - Dry air

1 INTRODUCTION

Gas-filled transformers that use nonflammable SF_6 gas as the insulating and cooling medium are used in underground substations in urban areas due to its high disaster prevention. In recent years, it has been increasingly applied to outdoor substations because of its advantages such as high environmental performance without oil leakage and the need for disaster prevention equipment.

On the other hand, SF_6 gas has a high global warming potential, so the care must be taken in handling such as countermeasures against gas leaks. For this reason, there is a demand for gas-insulated transformers that use SF_6 alternative gases such as dry air and N_2, which have a low global warming potential and are easy to handle. However, dry air and N_2 have extremely low insulation performance and different insulation characteristics compared to SF_6 gas. Therfore, it is necessary to understand the basic insulation characteristics of these gases.

In this paper, we report the survey results on the basic insulation characteristics of disk windings of gas-insulated transformers.

2 EXAMINATION METHOD

The basic insulation characteristics of disk windings, which are important for transformer insulation design, are the insulation properties between the disc winding sections shown in Figure 1 and the main gap insulation characteristics between low voltage and high voltage windings. Therefore, the insulation characteristics between the winding sections in the basic model and the insulation characteristics of the main gap in the actual scale model simulating the actual transformer configuration were investigated with dry air, N_2 and SF_6.

In addition, among the gases described above, N_2 is the only gas that does not have electron attachment characteristics, and when a partial discharge occurs in N_2, the discharge easily propagate, and there is a possibility that dielectric breakdown can easily occur. Therefore, the probability of discharge propagation in covered electrode of the gas-filled transformer was compared and investigated with dry air and N_2.

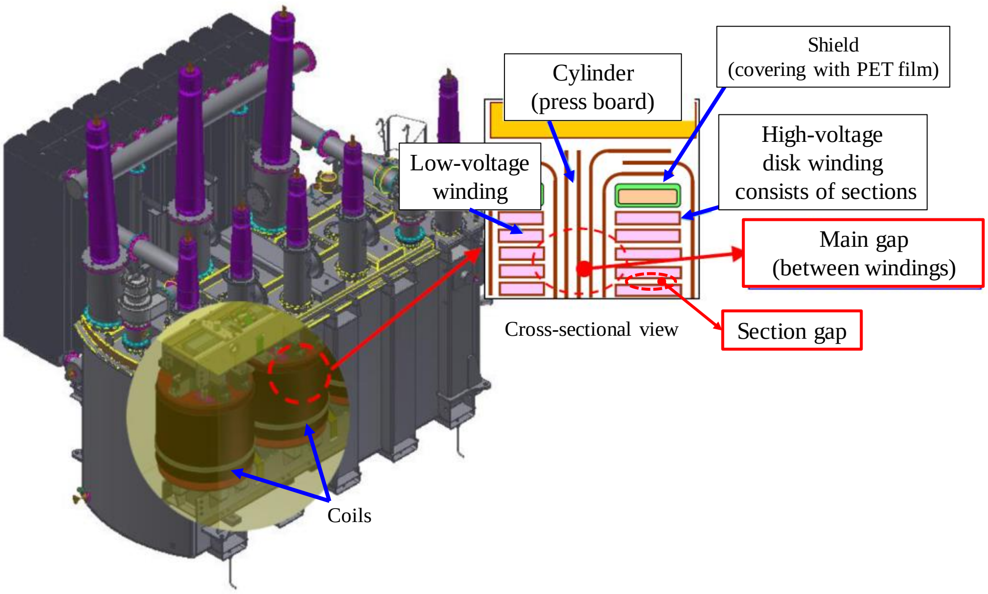
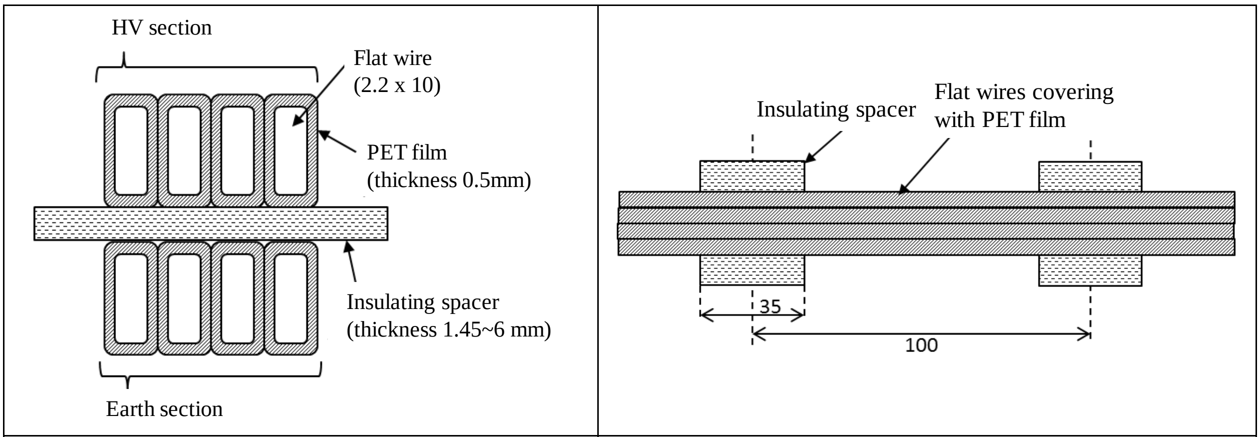


Fig.1 Configuration of gas-filled transformer disk winding

2.1 Winding section gap model (between sections of disk-winding)

The winding section model is a model simulating the inter-section insulation configuration in the transformer disk winding, and the model configuration is shown in Figure 2. The model consisted of two sets of four flat copper wires covered with polyethylene terephthalate (PET) film, with pressboard insulation spacers between these sections. The wedge-shaped gas gap (triple junction gas gap) is formed between the copper wires and the insulating spacers, where the electric field is concentrated. The thickness of the pressboard insulation spacer was 1.45 mm to 6 mm. Models consisting of conductors and spacers are supported by acrylic stands. Figure 3 shows the appearance of the model.

The model is installed in a test tank, and the conditions of the filled gas are pressures of 0.22 MPa and 0.5 MPa, and the gas type is dry air, N_2 or SF_6 gas. A negative lightning impulse voltage was applied to the model and the partial discharge inception voltage (PDIV) and breakdown voltage (BDV) were measured. The PDIV was determined by optical observation using an image intensifier through the observation window of the test tank.



(a) Cross-sectional View | (b) Top view

Fig.2 Winding section model (between sections of disc-winding)

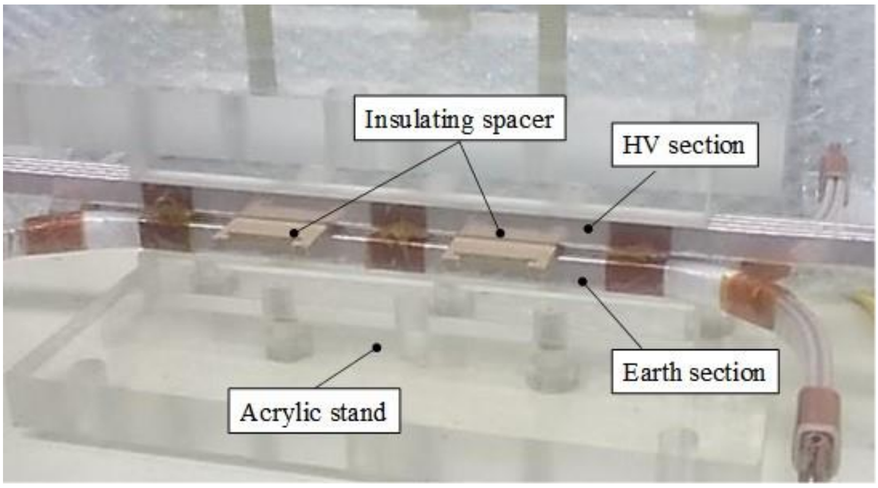


Fig.3 The appearance of the winding section model

2.2 Main gap model (between low and high voltage windings)

The main gap model simulates the low and high voltage windings of a transformer and the insulation configration between them, and the model configuration is shown in Figure 4. The low voltage winding was simulated by wrapping a 1 mm thick PET film around an aluminum cylinder with a ground potential. The high-pressure winding was simulated by winding a flat copper wire around a press board cylinder to form three sections. The flat copper wire had a cross-sectional dimension of 2.2 x 10 mm, and a 0.06 mm thick PET film was wound 10 times, and a 0.38 mm insulating paper was wound 3 times on the outside of the PET film. Transformers generally have a gap between the pressboard cylinder and the winding to circulate the cooling medium. However, in consideration of the evaluation of the gas-filled transformer, in order to prevent the discharge propagation due to electron acceleration from the high electric field part of the wedge gap of the winding, the winding is wound directly around the cylinder in this model. Five press board cylinders were placed in the main gap between the low and high pressure windings, and the main gap distance was 135 mm.

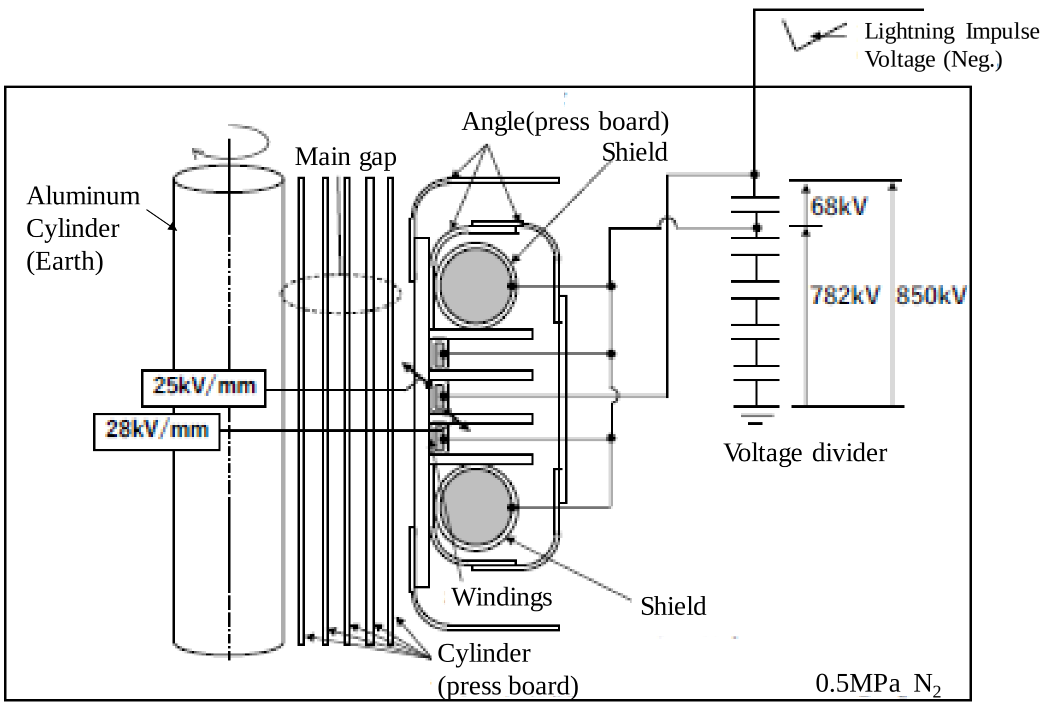
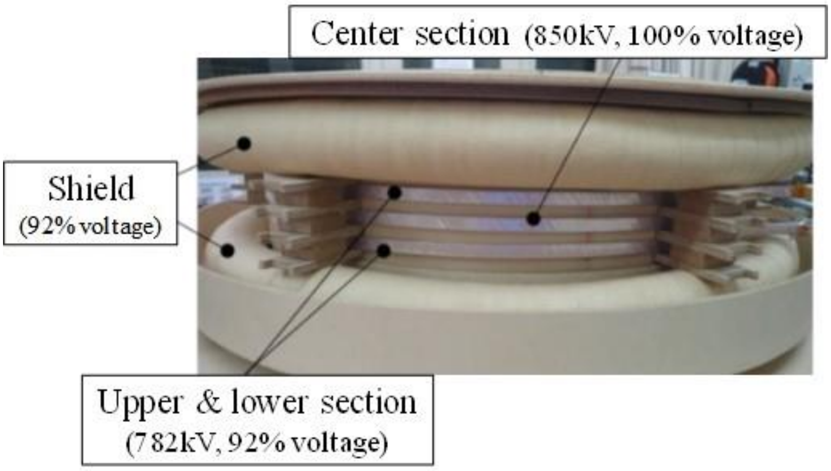
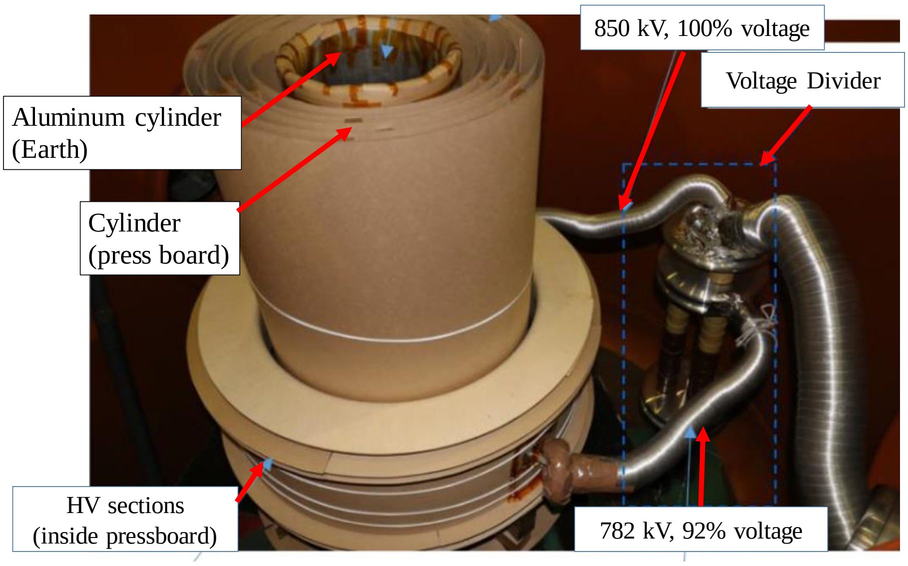


Fig.4 Main gap model (between low and high voltage windings)

The model was installed in a test tank filled with 0.5 MPa N_2 gas and BDV was measured by applying a negative lightning impulse voltage. Only N_2 gas was verified as a typical alternative gas in this model. In order to simulate an electric field distribution close to that of an actual transformer, the applied voltage was divided by a capacitor voltage divider at 100 % in the center section and 92 % in the upper and lower sections. Figure 5 shows a) the appearance of winding section and b) the overall installed in the test tank of the winding main gap model.



(a) the appearance of winding section



(b) overall model arrangement installed in the test tank

Fig.5 Appearace of main gap model

2.3 Discharge propagation survey with winding section model

The discharge progress of partial discharge was investigated using the same model as the winding section model described in 2.1. The negative impulse voltage was applied to a model with an insulating spacer thickness of 6 mm and a gas pressure was 0.5 MPa of dry air and N_2. The voltage of 110 % of PDIV in the test of 2.1 was applied 100 times under each condition, the propagation of partial discharge was optically observed by the image intensifier.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Winding section model (between sections of disk-winding)

Figure 6 shows the PDIV and BDV measurement results at a gas pressure of 0.22 MPa. As the thickness of the insulation spacer increases, PDIV increases with SF_6 gas, N_2, and dry air. The PDIV of N_2 and dry air is about 60 % of SF_6, which is consistent with the theoretical solution of air in the dotted line in the figure.The theoretical solution is obtained from the following streamer conditional expression from the effective ionization coefficient α' and the streamer coefficient K.

$$\int \alpha' dx = K \qquad (1)$$

where α' is the effective ionization coefficient [5], x is coordinate along an electric field line, and K is dimensionless number, K=10 for dry air, K=4.5 for N_2, and K=10.5 for SF_6. On the other hand, BDV has a constant voltage regardless of the spacer thickness.

Figure 7 shows the PDIV and BDV measurement results at a gas pressure of 0.5 MPa. Both PDIV and BDV increase as the spacer thickness increases, PDIV for N_2 and dry air is about 70% of that of SF_6. These results tend to be consistent with the results of theoretical analysis by the streamer conditional expression, as in the case of 0.22 MPa. BDV shows different aspects under the conditions of 0.22 MPa and 0.5 MPa, and the reason is considered to be as follows. At 0.22 MPa, gas dielectric breakdown occurs at PDIV and higher voltages, but at that voltage it cannot penetrate the PET film and the progress of discharge is stopped by the PET film. Therefore, BDV at 0.22 MPa is determined by the voltage penetrating the PET film and becomes a constant value regardless of the gas type. On the other hand, at 0.5 MPa, the voltage at which the gas dielectric breakdown occurs is high, and the discharge penetrates the PET film. Therefore, the BDV at 0.5 MPa becomes a value close to the voltage penetrating the PET film, and the BDV increases as the thickness of the insulating spacer increases.

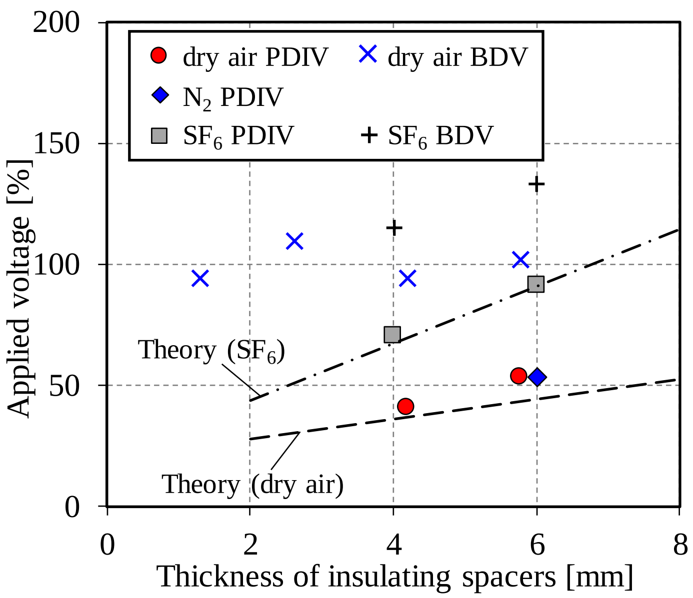


Fig.6 PDIV and BDV measurment results at 0.22 MPa

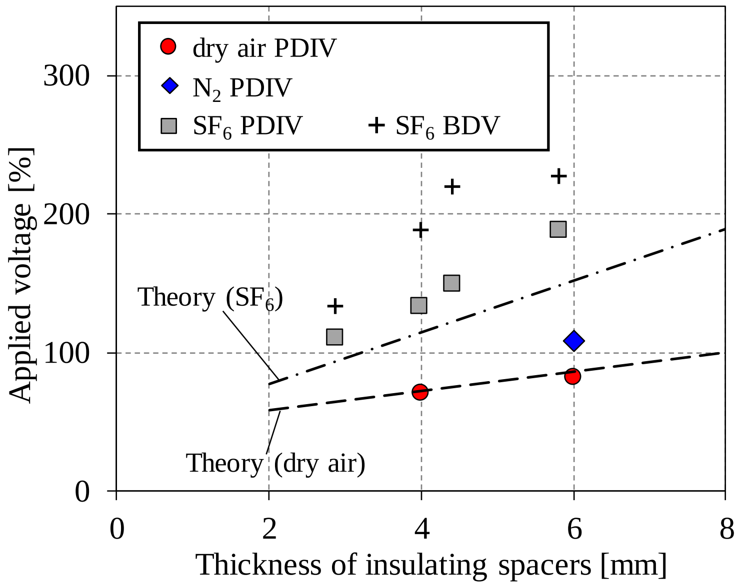


Fig.7 PDIV and BDV measurment results at 0.5 MPa

3.2 Winding main gap model (between low and high voltage windings)

The waveform of the test voltage applied to the main gap model did not change due to partial discharge up to 850 kV, and dielectric breakdown occurred in the next voltage step of 900 kV. Figure 8 shows the discharge trace of dielectric breakdown of the model. When dielectric breakdown occurs, the discharge starts at the end of the copper wire in the central section that simulates a high-voltage winding, penetrates the pressboard cylinder, and progresses to an aluminum cylinder with a ground potential that simulates a low-voltage winding. It is assumed that the test voltage was applied, the conductor end became a high electric field strength, and a discharge occurred. As a result of electric field calculation, when 900 kV was applied, the maximum electric field strength at the end of the simulated winding was 30 kV/mm, which greatly exceeds the theoretical dielectric breakdown electric field 10 kV/mm (N_2, 0.5 MPa) caluculated from the effective ionization coefficient [5]. We consider that solid insulating materials with high insulation performance such as PET film and press board are effective in preventing the initial discharge propagation due to dielectric breakdown of the local high electric field with a gas having lower insulation performance than SF_6 gas such as dry air.

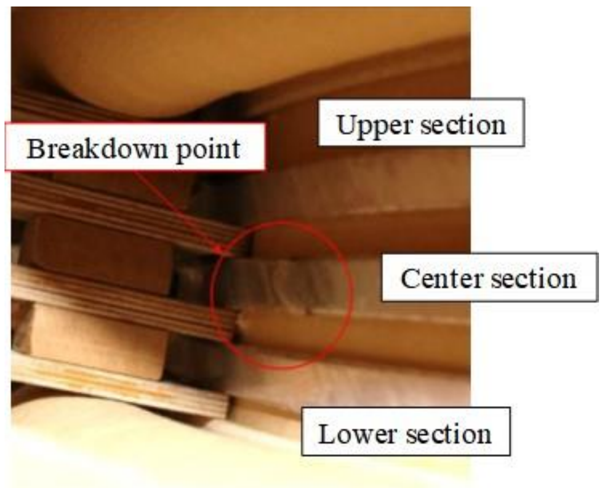


Fig.8 Discharge trace of the model

3.3 Discharge propagation survey with winding section model

Figure 9 shows an example of optical observation of partial discharge by applying repeated voltage with dry air and N_2. The applied voltage is 1.1 times that of the PDIV of the winding section model, and the number of repetitions is 100. Since the applied voltage exceeds PDIV, partial discharge occurs at the triple junction between the winding and the insulating spacer. However, discharge propagation that causes dielectric breakdown does not occur. In dry air, uniform partial discharge emission was observed at triple junctions at all 100 times voltage applications. On the other hand, in N_2, discharge emission was observed only 32 times out of 100 times, and the discharge emission itself was often not uniform.

From the above results, the aspect of partial discharge of N_2 is not uniform discharge compared with dry air because N_2 has no electron attachment. However, at the voltage of 1.1 times that of PDIV for both dry air and N_2, partial discharge does not proceed and lead to dielectric breakdown.

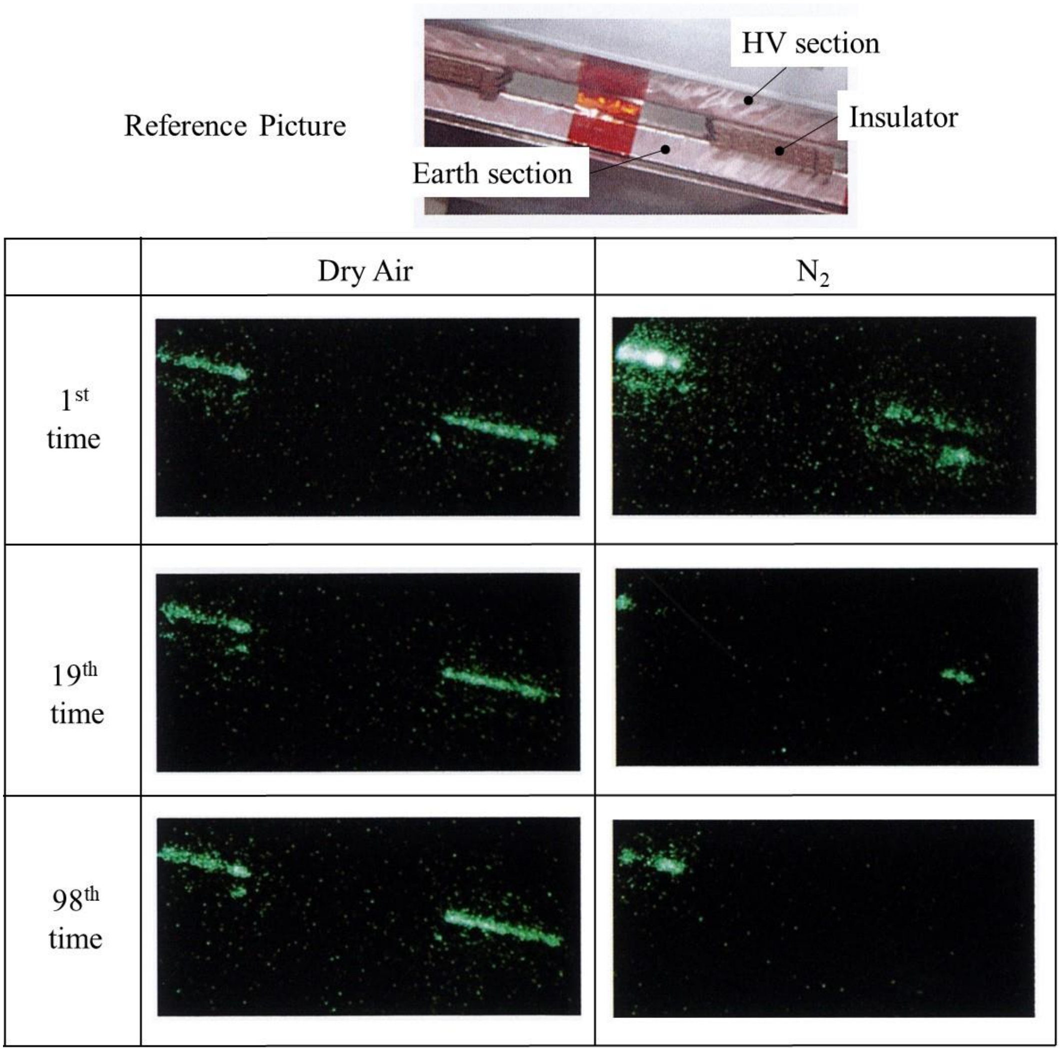


Fig.9 Comparison of partial discharge aspect of N_2 and dry air

4 CONCLUSION

Between the sections of the transformer disk winding, a partial discharge occurs at the triple junction gas formed by the covered insulation of the winding and the insulating spacer between the sections. The partial discharge inception voltage PDIV is about 60 % of SF_6 at 0.22 MPa and about 70 % of SF_6 at 0.5 MPa for N_2 and dry air, and increases according to the thickness of the insulating spacer. PDIV trends can be explained by theoretical value calculated from the streamer breakdown criterion. The breakdown voltage BDV at 0.5 MPa is determined by the insulation performance of the gas, and tend to increase as the insulating spacer thickness increases. However, the BDV at 0.22 MPa was determined by the penetration voltage of the PET film, and resulted in a constant value regardless of the section gap.

From the test results of winding main gap model simulating the actual transformer winding configuration, the electric field strength of dielectric breakdown was 30 kV/mm, which exceeds the theoretical breakdown electric field of N_2 gas. We consider the discharge propagation due to N_2 gas dielectric breakdown in the high electric field part was prevented by the PET film and press board.

In addition, the partial discharge in N_2, which has no electron attachment, is considered to have a large variation compared to dry air, which has electron adhesion. Nevertheless, at a voltage of about 1.1 times that of PDIV, dielectric breakdown due to discharge propagation does not occur in both gases.

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