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Fundamental Insulation Characteristic of High-Pressure CO_2 Gas under Actual Equipment Conditions

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ABSTRACT

SF_6 gas has been widely used in electrical power equipment such as circuit breakers and transformers due to its superior insulation and interruption characteristics. However since 1997, SF_6 gas has been designated a greenhouse gas subject to emission restrictions at COP3 (The 3rd session of the Conference Of the Parties to the United Nations Framework Convention on Climate Change) so a new insulating gas is needed as a substitute for SF_6 gas. This research considers the use of high-pressure CO_2 gas as an insulator while stressing the environment aspects. Fundamental insulation data for the insulating gas acquired supposing gas insulated switchgears (GIS) consists of; (1) insulation breakdown characteristics under clean conditions and, (2) insulation breakdown characteristics with metallic particle contamination. The parameters in this case were assumed from an actual apparatus viewpoint, to be a high gas pressure up to 2.0 MPa, an electrode size capable of determining the surface area effect, the electrode surface roughness, and metallic particle length, etc. at the base electrode of the 72 kV GIS. As a result, experiments using these parameters revealed insulation characteristics for high-pressure CO_2 gas and that negative lightning impulse decided the insulation design, as well as the present SF_6 GIS. The need for taking measures to suppress PD under ac voltage and also the need for restricting metallic foreign particles around the central conductor and insulating spacer were recognized.

Index Terms — **Insulating gas, SF_6 substitute, CO_2 gas, gas insulated switchgear (GIS), insulation breakdown characteristics, clean condition, metallic particle.**

1 INTRODUCTION

SF6 gas has been regarded as ideal for electrical power equipment since the 1960's due to its superior insulation and interruption characteristics. Nowadays SF_6 gas is widely used in equipment ranging from a several kV to the EHV class of GIS (gas insulated switchgears), GCB (gas-blast circuit breakers), and GIL (gas insulated transmission lines) [1]. Since 1980's intensive research efforts had been made to find a new gas as a substitute for SF_6, however these new gases failed to surpass SF_6 in overall evaluations that rated items such as insulation characteristics, boiling point, and toxicity, etc. [2,3]. However in 1997, SF_6 gas was labeled by the COP3 as a gas subject to emission restrictions due to being a greenhouse gas [4]. This made finding a substitute insulator gas for SF_6 even more urgent [5]. This situation once again

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spurred research efforts for a substitute for SF_6, where mixed gases were the central cores [6-8]. A portion of this work resulted in the SF_6/N_2 mixed gas in actual use in some GIL [9]. A single substitute gas not containing SF_6 gas was still needed however, especially in view of factors such as stability and recovery during actual operation. When environmental factors such as ozone breakdown and global warming are considered, the selection becomes limited to single gases such as N_2, CO_2 and dry air that as single gases successfully clear the condition of an insulating performance greater than or equal to that of air. Therefore, new researches have tended to focus on these gases [10-12].

This paper gives the environmental aspects a higher priority and therefore considers higher-pressure CO_2 gas as the insulating medium. First acquired are; (1) insulation breakdown (hereafter, referred to just as BD) characteristics under clean conditions for ac voltage and positive and negative lightning impulses (hereafter, abbreviated as LI), and (2) BD characteristics with metallic foreign particles were present on the central conductor and insulating spacer surfaces as basic insulator data for the insulating gas in GIS. Assuming use in actual equipment, various parameters were established, including a high gas pressure of up to 2.0 MPa, electrode sizes capable of determining surface area effect, electrode surface roughness, and metallic foreign particle length, etc, at the base electrode of a 72 kV class GIS.

2 BREAKDOWN CHARACTERISTICS UNDER CLEAN CONDITIONS

This section experimentally evaluates insulation performance for ac voltage as well as LI under clean conditions (namely, quasi-uniform electrical fields), which is fundamental to insulator design, dealing with effects that parameters have on characteristics.

2.1 INSULATION BREAKDOWN CHARACTERISTICS FOR LIGHTNING IMPULSE

2.1.1 EXPERIMENTAL APPARATUS AND CONDITIONS

A coaxial cylindrical electrode for a single-phase bus line for 72 kV class GIS was tested. Figure 1 shows the structure and installed state of the coaxial cylindrical electrode serving as the test electrode. The central conductor applying the high-voltage was 70 mm in diameter, while the diameter of the grounding sheath electrode was 150 mm, and the gap length was consequently 40 mm. Intermediate tanks were formed to partition the gas into multiple compartments by installing gas insulating spacers (pressure differential set to 0.3 MPa for safety) between the test tank and bushing tank (maximum usable pressure: 0.8 MPa) to allow filling the test tank to a maximum of 2.0 MPa. The gas pressure was then gradually raised.

The gas pressure and the electrode surface area were utilized as parameters since their effect on BD in the gas by LI is large. The gas pressures were set at 0.4, 0.7, 1.0, 1.5 and 2.0 MPa, from the equivalent to present GIS using SF_6 to even higher pressures in order to complement the poor insulation performance of CO_2 compared to SF_6. The electrode surface area was set at three conditions, from a maximum consisting of a surface area range where normal SF_6 gas tends to saturate, to a minimum of approximately $1/20^{th}$ of the maximum value as the third condition. The cross sectional profile of the coaxial cylinder was in the same way and their effective lengths were changed to 600, 100, and 35 mm, and the high voltage conductor effective surface areas were set to 1.32×10^5, 2.2×10^4 as well as 7.7×10^3 mm^2 (these electrode geometries are called test electrodes A, B and C respectively). Their electric field (hereafter, described just as EF) utilization was 0.67 but the effective length of test electrode C was shortened as much as possible so the value is 0.77 only in this structure.

Standard positive and negative LI were applied and the 50% BD voltage (hereafter, BDV) and variations (standard deviation: σ) were found with the up-and-down method. The discharge state was filmed via the observation window with a static camera, and it was confirmed that discharges were not concentrated in one spot.

2.1.2 GAS PRESSURE DEPENDENCY

Figure 2 shows the gas pressure dependency of the 50% BD-EF E_{50} on the central conductor surface for positive and negative LI with the test electrode A. The error bar indicates the standard deviation σ (same holds true to figures hereafter). Negative polarity σ are within 2% and within the symbols in the figure. At a negative polarity, the polarity

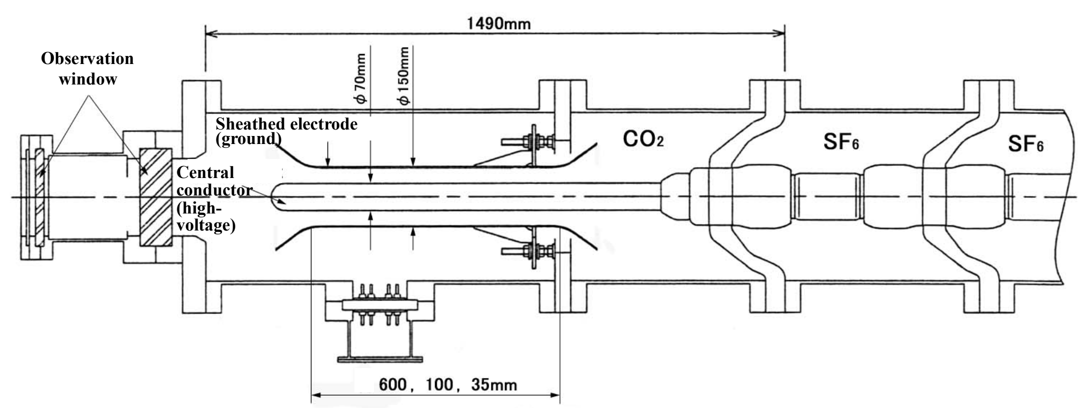

Figure 1. Coaxial cylindrical test electrode of equivalent 72kV class GIS used in lightning impulse test.

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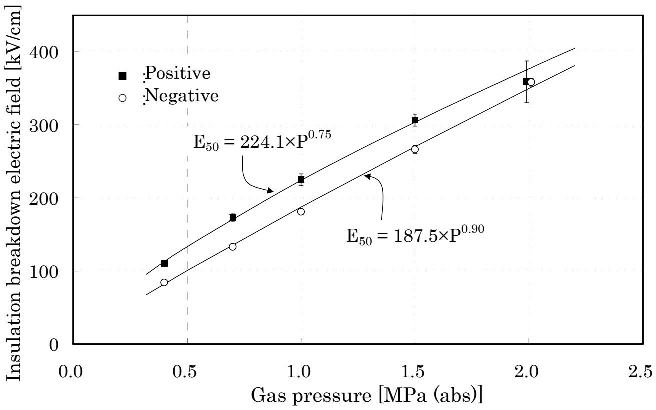

Figure 2. Gas pressure dependency of insulation breakdown electric field for positive and negative lightning impulses.

differential exhibited by E_{50} became lower (largely the same at a gas pressure of 2.0 MPa). Indicating characteristics for E_{50} gas pressure experientially in the figure also shows gas pressure rising to the 0.75 power at a positive polarity, and rising to the 0.90 power at a negative polarity. The E_{50} largely tended to saturate versus pressure at a positive E_{50} gas pressure experientially in the figure also shows gas pressure rising to the 0.75 power at a positive polarity, and rising to the 0.90 power at a negative polarity. The E_{50} largely tended to saturate versus pressure at a positive polarity, and exhibited a comparatively linear rise up to a gas pressure of 2.0 MPa at a negative polarity

Except at a pressure of 2.0 MPa at a positive polarity, the σ was within 4%. Even at high gas pressures, no large differential in gas variations versus those of gas near atmospheric pressure were observed. Testing was performed twice at 2.0 MPa at a positive polarity, however in both cases σ exceeded 7%. The reason why large variations only occurred in this case is currently unclear, however this may be related to peculiar phenomena that appear in high-voltage regions as discussed later in 2.3.

2.1.3 SURFACE AREA EFFECT

Figure 3 shows the relation of the 50% BD-EF, E_{50} versus the high-voltage conductor effective surface area S_E. Characteristics with the test electrode A (S_E on the X-axis = 1.32×10^5 mm^2) are the same as those in Figure 2. The surface area effect on the BD-EF appeared to decline the higher the S_E. In this experiment, the S_E data was acquired on a scale up to 1.32×10^5 mm^2, and checking the BD-EF at a lower negative polarity indicates that the E_{50} tends to nearly saturate at a surface area of 1.32×10^5 mm^2. This fact shows that the test electrode A in this experiment is largely rated with the minimum BD-EF considering the surface area effect.

Checking the standard deviation σ shows that except for a pressure of 2.0 MPa at a positive polarity as described above, the standard variation was comparatively small at less than 4%. The test electrodes B and C also showed the σ of less than 5% in almost all cases, although a portion of the cases were found to exceed 5%. Overall the σ are larger in positive polarity cases than negative ones, and in some cases these positive polarity variations were found to be a maximum of about 10%. The correlation between the electrode surface area or gas pressure is unclear, however caution should be used due to variations in the BD-EF at positive polarities.

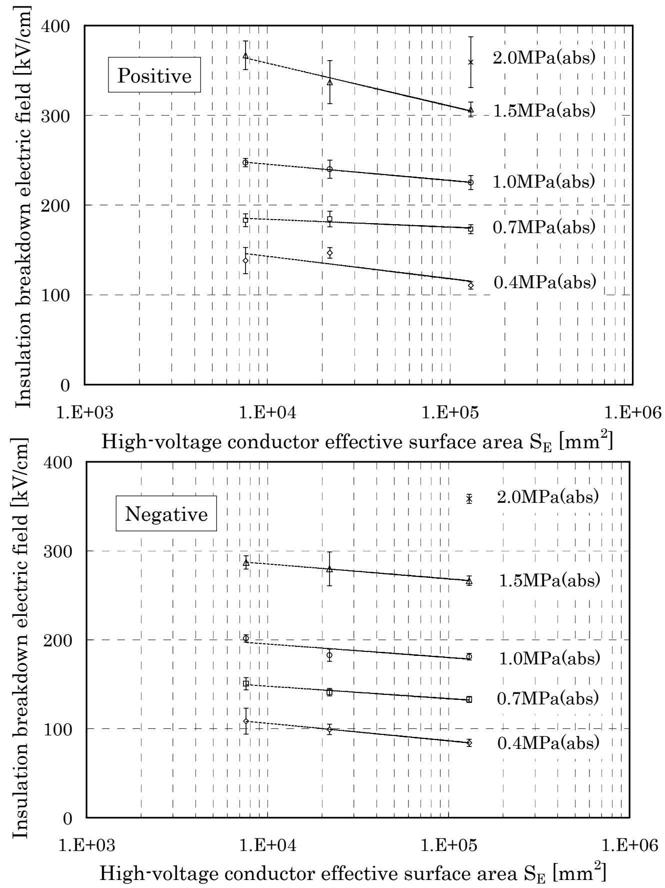

Figure 3. Surface area effect on insulation breakdown electric field for positive and negative lightning impulse.

2.2 INSULATION BREAKDOWN CHARACTERISTICS FOR AC VOLTAGES

2.2.1 EXPERIMENTAL APPARATUS AND CONDITIONS

In this experiment, the test tank was identical to that shown in Figure 2 for the LI test. The test electrode was the same as the A electrode in section 2.1.1, and the coaxial cylindrical electrode for a single-phase bus line for 72 kV class GIS was used. There have been reports of BD occurring via partial discharge (hereafter, just PD) even in the quasi-uniform EFs during ac testing [13], and accordingly PD inception voltages (hereafter, PDIV) as well as BDV were also measured in this ac test. To reduce external noise as much as possible and measure PD with high sensitivity, the voltage transformers for the experiment were connected directly to the test equipment and the test performed with the high-voltage section as a fully sealed structure. The sheathed electrode on the grounded side was insulated from the test tanks, and the signal line from the ground electrode was drawn outside the equipment via an insulation terminal, and the PD measurement device then

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connected. The PD was measured via the ERA method, and the minimum detection sensitivity was a noise level of approximately 1-2 pC.

Gas pressure and the electrode surface roughness were utilized as parameters since their effect on the BD for ac voltage in gas is known to be large. As in the LI test, the gas pressures were set at 0.4, 0.7, 1.0, 1.5 and 2.0 MPa, from the equivalent to present GIS using SF_6 to even higher pressures in order to complement the poor insulation performance of CO_2 compared to SF_6. The electrode surface roughness of the central conductor was set from 25 µm (standard condition) to 5 µm to smooth it as a second condition, and the grounded side cylindrical sheathed electrode was adjusted to a surface roughness of 25 µm or less by sandpaper finishing.

Voltage was applied in 10 kV steps at a voltage lower than the PDIV, maintained there for one minute and then raised to the next step while measuring the PDIV and BDV. Light was observed from the observation widow during discharge, and variations confirmed in discharge points along the periphery of the coaxial cylinder.

2.2.2 GAS PRESSURE DEPENDENCY

BD occurred via PD at all of the gas pressures and that state is described first. Figure 4 shows typical changes in the PD amount when applying an ac voltage. The PDIV for the negative polarity phase of the ac voltage in the same figure is lower than the positive polarity phase PDIV. BD was in some cases observed to occur without PD at a positive polarity. Moreover, the negative polarity PD was observed to greatly increase when a positive polarity phase PD incepted. The PD amount right up to BD was about several dozen pC. At gas pressures up to 1.0 MPa, the negative polarity PDIV was lower than the positive polarity as described above and almost all BDs occurred during the negative polarity phase. However at gas pressures higher than 1.5 MPa, positive phase BDs increased, and at 2.0 MPa there were more cases of BD at positive polarities. As described in section 2.1, in LI cases, the BD-EF for the negative polarity and positive polarity was largely the same at 2.0 MPa, although where the gas pressure was low, the negative polarity had a lower BD-EF in the results (Figure 2). The same trend can be seen in ac cases as well.

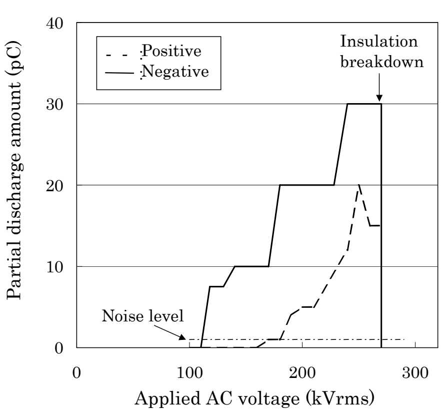

Figure 4. Changes of partial discharge amount toward applied ac voltage (gas pressure: 1.0MPa).

Figure 5 shows gas pressure dependency characteristics for the PDI-EF and the BD-EF. The lowest and highest values are shown for the PDI-EF from among all data taken 10 times. The BD-EF increased along with a rise in the gas pressure, and this can be expressed by the experimental formula listed in the same figure. The PDI-EF on the other hand does not rise much toward an increase in gas pressure. Therefore, the higher the gas pressure, the greater the differential between the PDI-EF and BD-EF. The PD can occur even at comparatively low EF levels so this is also a factor affecting the insulation design. So along with revealing the mechanism causing PD, some type of technical countermeasure must be implemented based on this mechanism.

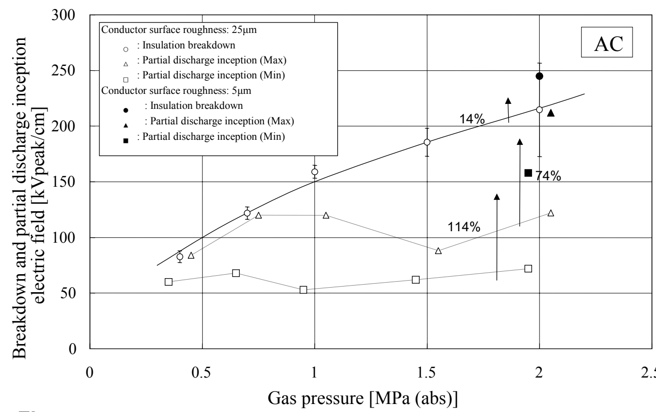

Figure 5. Gas pressure dependence of insulation breakdown electric field and partial discharge inception electric field for ac voltage as well as surface roughness effect (2.0 MPa).

Figure 6 is a Weibull plot of the BDV. This figure clearly shows that variations in the BDV at 2.0 MPa were extremely large compared to the other cases. Even results from the LI test showed a trend as described above for variations in the positive polarity BD-EF to be larger than for the negative polarity. The same trend could also be seen for ac.

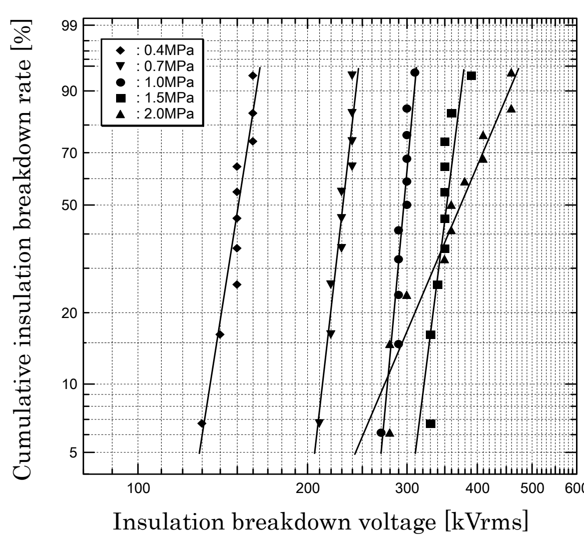

Figure 6. Weibull plot of insulation breakdown electric field for ac voltage.

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2.2.3 ELECTRODE SURFACE ROUGHNESS

PD incepts at a level lower enough than the BD when applying an ac voltage as described above. In order to clarify this phenomenon, and contrive a technical measure to use in the insulator design, this study focused on the electrode surface roughness and an evaluation was made. More specifically, the same ac voltage tests were carried out after smoothing the high voltage section (central conductor) of the test electrode from its previous state (25 µm) to approximately 5 µm. The gas pressure was set to 2.0 MPa where the differential between the PDI-EF and BD-EF was most outstanding.

The PDIV and BDV characteristics at the 2.0 MPa point for the smoothed electrode are also carried in the previous Figure 5. Smoothing the electrode surface raised the PDI-EF 74 to 114%, and the BD-EF to approximately 14%. The rise in the PDI-EF was particularly drastic, and it can be seen that the roughness of the electrode surface has a large effect on causing PD.

Treating the electrode surface and other factors can in this way possibly reduce the occurrence of PD to some extent under clean conditions (quasi-uniform EFs). In these experiments electrode characteristics were compared after smoothing its surface as much as possible. However in view of its use in actual equipment, a practical technical solution should be considered such as coating the conductor surface.

2.3 PECULIAR PHENOMENA AT HIGH-PRESSURE AND POSITIVE POLARITY

BDV characteristics showed a relatively low value and large dispersion at 2.0 MPa for a positive polarity in Figure 2. Further, the saturated area of the area effect increased as the gas pressure became higher for a positive polarity in Figure 3. This peculiar phenomena at high-pressure and positive polarity might be attributed to not gas properties but electrode surface conditions, to think of that no peculiar phenomena in terms of the BDV and dispersion was observed with the small sphere to plane electrodes at 1.8 MPa for the positive polarity LI [14].

As for ac voltage application, similar phenomena were grasped. As the gas pressure increased, BD came to happen in the positive phase, as described in 2.2.2. PDIVs were improved significantly with the smooth electrode surface in Figure 5. Further, the dispersion at 2.0 MPa was extremely large in Figure 6. At high gas pressures, the electrode surface conditions may influence BD in the positive phase, which leads to a whole BD as well as LI.

Field emission is hard to suppose because of a positive polarity, but initial electrons generated near electrodes for some causes may result in this peculiar phenomena of low BDV and large dispersion due to the high electric field applied and fast development of positive streamer and/or leader. It would be expected that this phenomena be clarified in the future.

2.4 IMPULSE RATIO

Figure 7 exhibits results from finding the impulse ratio (BD value for LI / BDpeak value for ac) at positive and negative polarities from the previously described BD for LI characteristic (Figure 2) and BD for ac voltage characteristic (Figure 5). The impulse ratio rises along with the gas pressure, and for example at a negative polarity is about 1.0 at a gas pressure below 1.0 MPa, but rises to 1.67 at 2.0 MPa. This is due to both the BD for LI characteristic and BD for ac voltage characteristic showing a trend to saturate versus the gas pressure, however the latter characteristic shows a larger degree of saturation. Examining the ratio of the current LI and ac breakdown test voltage values [15] shows that the LI is the toughest condition, the same as for the current SF_6 insulation apparatus. In other words, the insulation design for the central conductor is determined by the negative polarity LI.

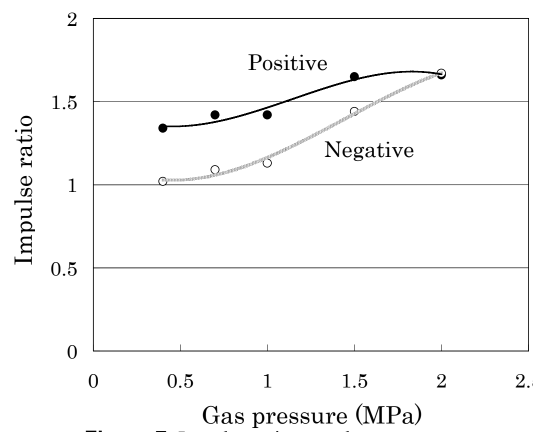

Figure 7. Impulse ratio at each gas pressure.

3 BREAKDOWN CHARACTERISTIC WITH METALLIC FOREIGN OBJECTS

This section experimentally evaluates insulation characteristics for LI when metallic foreign particles are present that must be considered in the insulation design of the gas insulated apparatus. Penetration of metallic substance into the gas (adhering to central conductor) and adhering to the insulating spacer surfaces were assumed as conditions for the presence of metallic foreign objects.

3.1 INSULATION BREAKDOWN CHARACTERISTIC WITH METALLIC PARTICLES ON CENTRAL CONDUCTOR

3.1.1 EXPERIMENTAL APPARATUS AND CONDITIONS

Figure 8 shows a photograph of the test electrode used in the insulation test with metallic foreign object intrusion in the gas. This electrode forms a background EF based on that of the coaxial cylindrical electrode for the test electrode A used in section 2. A protrusion to simulate the metal object was attached to the central conductor of this coaxial cylindrical electrode. The tip of this protrusion (super-hard alloy: G2) was modified to a highly accurate semi-spherical shape, with a diameter 0.25 mm and length from 1 to 10 mm. The test electrode was installed in an insulated model test tank and sealed with CO_2 gas at 1.0 MPa.

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As the BD by LI with foreign metallic particles present (non-uniform EF), of the two polarities, the positive polarity voltage is quite low, so a positive LI was applied. Ten data

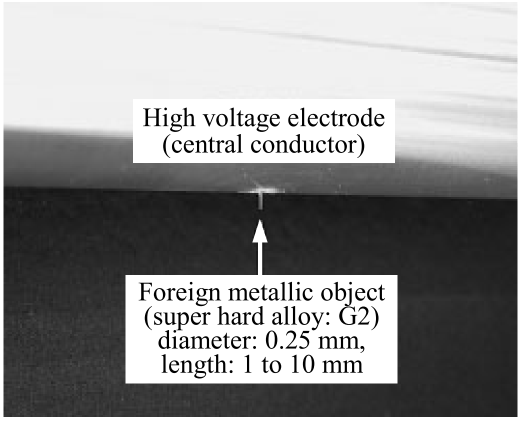

Figure 8. Test electrode for foreign metallic object intrusion test (protruding electrode attached to high-voltage central conductor to simulate foreign metallic object).

were obtained by the step-up method. The discharge state was filmed by static camera via the observation window, and the discharge was confirmed to be based around the foreign metal object.

3.1.2 EXPERIMENTAL RESULTS

The 50%-BDV, V_{50} was converted to a conductor surface (background EF) E_{50} with no foreign metallic objects. The graph in Figure 9 is a plot of the E_{50} and standard deviation σ versus the protrusion length. The characteristics for protrusion length of BD-EF, E_{50} decline largely linearly on the log-log graph. This relation can be expressed by the formula shown in the figure.

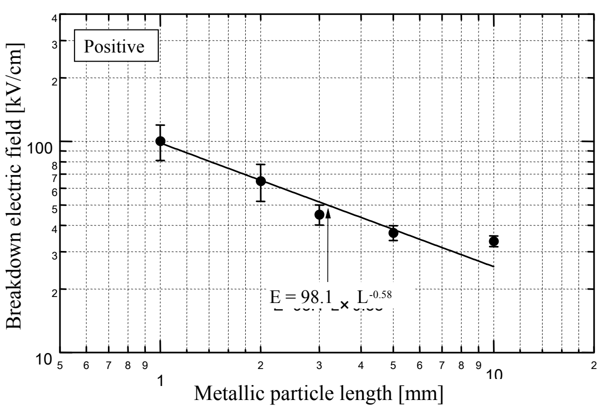

Figure 9. Length of foreign metallic object versus the insulation breakdown electric field.

Figure 10 shows the relation of BD-EF to protrusion length again comparing the experimental data in the separately measured sphere-plane electrode [14]. The sphere-plane electrode was attached to a protruding electrode of the same specifications as the main test. A protruding electrode made to the same specifications as the present experiment was attached to the spherical tip of the 80 mm diameter sphere-plane electrode (gap length: 20 mm, EF utilization factor 0.74) and testing performed. Testing conditions were a CO_2 gas pressure set to 1.0 MPa and 1.8 MPa and for purposes of comparison SF_6 gas was set to 0.5 MPa. This figure shows that even with the sphere-plane electrode, the relation between the BD-EF and protruding length was largely linear on the log-log graph. Compared to SF_6, the BDV can be seen to decline to much the same extent versus the protrusion length. Some differences can be seen in the characteristics revealed in this study versus those in [14] at 1.0 MPa, however finding the EF at the protruding electrode tip by a simple field calculation, and comparing relatively with plotting both these EF values in Figure 9 shows that both are largely the same.

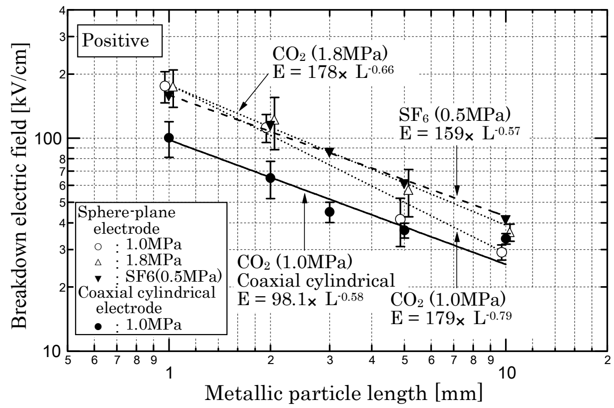

Figure 10. Comparison of foreign metallic object length versus insulation breakdown electric field when using sphere-plane electrode.

3.2 INSULATION BREAKDOWN CHARACTERISTICS WITH METALLIC ADHERES ON INSULATING SPACER SURFACES

3.2.1 EXPERIMENTAL APPARATUS AND CONDITIONS

A test of BD characteristics while metallic objects adhered to the insulating spacer surface was made utilizing a cone insulating spacer model corresponding to a 72 kV class unit. Figure 11 shows the metallic foreign particle installation position and the test insulating spacer model. The test electrode was installed within the installation model test tank as shown in the same figure. The gas pressures were 1.0 MPa and 1.5 MPa. The metallic foreign

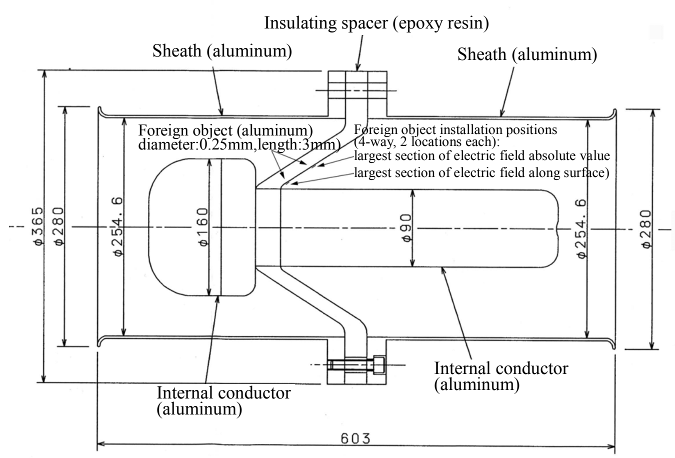

Figure 11. Metallic foreign object installation position and test insulating spacer model.

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objects (aluminum: diameter 0.25 mm, length 3 mm) were installed on two locations each, on the largest section of the EF along insulating spacer surface and largest section of the EF absolute value; for a total of four metallic particles at locations spaced 90 degrees apart on the insulating spacer.

The applied voltage was a positive polarity standard LI. A voltage value somewhat higher than the predicted BDV was applied in order to eliminate effects of static charges on the insulating spacers due to PD from metallic foreign objects in preceding trials. BD was then caused in one shot voltage application. The BDV was evaluated based on the instantaneous voltage at BD at this time.

3.2.2 EXPERIMENTAL RESULTS

BD occurred from foreign objects adhering to the largest section of the EF along surface at gas pressures of both 1.0 MPa and 1.5 MPa. Figure 12 is a photograph showing BD discharge marks along the insulating spacer surface at a pressure of 1.5 MPa. The BDV did not rise much even if the gas pressure was raised, and in the case of 1.0 MPa was 316 kV and in the case of 1.5 MPa was 358 kV. The ratio of the two cases shows a 1.13 times increase, which is small compared to the positive polarity of 1.36 and a negative polarity of 1.47 under clean conditions. Care must be taken in design of the tank bottom surface EF and in quality control during manufacture and assembly the same as in current GIS using SF_6 gas, so that foreign objects do not adhere to the insulating spacers (designated positions).

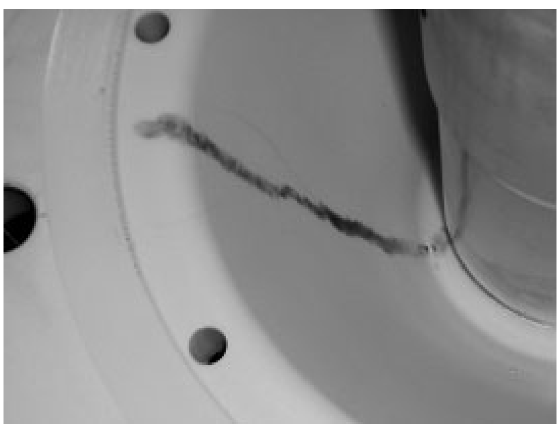

Figure 12. Discharge marks during insulation breakdown along the insulating spacer surface (1.5MPa).

4 CONCLUSION

As fundamental data, the (1) insulation breakdown characteristics under clean conditions, and (2) insulation breakdown characteristics with metallic foreign object intrusion, were obtained on CO_2 gas with a view to finding an insulation gas usable as a substitute for SF_6 gas in gas insulated switchgears (or GIS). In this case, parameters included a high gas pressure up to 2.0 MPa, an electrode size enough for assessing the surface effect, and also the electrode surface roughness, and metallic foreign object length, etc. at the base electrode (coaxial cylindrical electrode) in 72 kV class GIS assuming use in actual equipment.

- The insulation breakdown characteristics for lightning impulses under clean conditions (quasi-uniform field) were measured at a gas pressure of 0.4 to 2.0 MPa. The positive polarity had a higher absolute value however it also tended to saturate greatly toward the gas pressure, and at 2.0 MPa was equivalent to the negative polarity. The variations were large exceeding 7% only at a positive polarity at 2.0 MPa, and in all other cases the standard deviation σ was less than 4%. The high pressure gas also showed no large difference compared to variations in gas near atmospheric pressure. The lower threshold value with the surface area rule was obtained and the design consequently determined by the negative polarity lightning impulse the same as with SF_6.
- The insulation breakdown characteristics for ac voltage under clean conditions (quasi-uniform field) were measured at a gas pressure of 0.4 to 2.0 MPa. The insulation was made to breakdown at a standard surface roughness of 25 μm on the central conductor. The breakdown voltage showed a stronger tendency than the lightning impulse to saturate from gas pressure, and there was almost no increase in the partial discharge inception voltage. Smoothing the surface roughness to 5 μm drastically increased the partial discharge inception voltage.
- The insulation breakdown characteristic for lightning impulses with foreign particles from 1 to 10 mm long was measured at a pressure of 1.0 MPa when a metallic foreign object was attached to the central conductor. The characteristic of the insulation breakdown electric field E_{50} towards protruding length, showed a largely linear drop on a log-log graph.
- The insulation breakdown characteristic versus lightning impulses was measured at gas pressures of 1.0 and 1.5 MPa when a foreign metallic particle was attached to the insulating spacer surface. Insulation breakdown occurred at both gas pressures from foreign particles attached to the largest section of electric field along surface. The breakdown voltage did not rise very much even if the gas pressure was raised.

The following were confirmed as major points for more consideration.

- Testing was performed twice at 2.0 MPa at a positive polarity however in both cases variations exceeded 7%. The reason why large variations only occurred in this case is unclear, however it may be related to peculiar phenomenon that appears in high-voltage regions, so caution is required on this point.
- Processes such as treating the electrode surface can possibly reduce the partial discharge to some extent under clean conditions (quasi-uniform electrical fields). In these tests, electrode characteristics were compared after smoothing its surface as much as possible, however a practical technical solution such as coating the conductor surface should be considered if using in actual equipment.
- Caution must be taken in designing the tank bottom electric field and in quality control during manufacture and

assembly the same as in current GIS using SF_6 gas, so that foreign objects do not adhere to (designated positions on) the insulating spacers.

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