Characteristics of Surface Field Strength and Discharge Path by Medium Effect in Eco-friendly Insulating Gas

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Abstract

Gaseous medium as an insulation material cannot completely perform insulation at high voltage (HV) power equipment. Consequently, the composite insulation using solid dielectric has been applied to the power equipment. However, one of the major problems of the composite insulation is surface discharge. Therefore, it is necessary to study the surface discharge examined in gaseous medium. In order to design eco-friendly HV power equipment (EHPE), this paper presents the characteristics of surface field strength \( (E_s) \), surface discharge voltage \( (V_d) \) and discharge path by the medium effect in \( \text{N}_2 \) and \( \text{N}_2/\text{O}_2 \) mixture gas under AC HV. Effects of gas pressure, mixture ratio of \( \text{O}_2 \) and the relative permittivity of the solid dielectric on \( E_s \) and \( V_d \) characteristics are reviewed. According to experimental results, the important factor which influences to \( E_s \) and \( V_d \) is the insulation performance of ambient gas. The decisive factor of discharge path progress is the pressure of the ambient gas. Moreover, the points of discharge inception \( (D_{ip}) \) are the triple junction and the weak point of an electrode where an electric field is concentrated. Due to these main factors, there are three types of discharge path patterns \( (D_{ip}) \). Critical pressure which leads to change \( D_{ip} \) and \( D_{ip} \) was 0.3 MPa. These results will be useful not only for the EHPE insulation design but also for the improvement of surface dielectric strength of the equipment.

Key words: Discharge path, Insulation performance, Medium effect, \( \text{N}_2/\text{O}_2 \) mixture gas, Solid dielectric, Surface discharge

1. Introduction

\( \text{SF}_6 \) gas \( (\text{SF}_6) \) has been used for high voltage \( (\text{HV}) \) power equipment such as gas insulated switchgear \( \text{(GIS)} \), gas insulated transmission line \( \text{(GIL)} \) and gas circuit breaker \( \text{(GCB)} \) because of its excellent insulation and arc extinction performance. However, since \( \text{SF}_6 \) was classified as a greenhouse gas at COP3 in 1997, its usage has then become limited. Moreover, it has a problem which causes a breakdown accident in cold region due to its liquefaction characteristic in a high temperature range (Eun-Hyeok et al. 2012). Consequently, \( \text{N}_2 \), \( \text{N}_2/\text{O}_2 \) mixture gas, and Dry-air have been examined as the alternative insulation medium of \( \text{SF}_6 \).

The life cycle assessment \( \text{(LCA)} \) which systematically examines alternative gases concluded that these gases are only composed of \( \text{N}_2 \) and \( \text{O}_2 \) (Lutz Niemeyer, 1998). Since insulation design techniques should be based on the understanding of discharge mechanism in insulating gases (H.Okubo and N.Hayakawa, 2004), insulation properties of the alternative gases have been studied in both Korea and Japan (He-Rie Park et al., 2009)(Eun-Hyeok Choi et al., 2009)(Seok-Ho Nam and Hyoung-ku Kang, 2011)(Toshiaki Rokunohe et al., 2006).

It is necessary to utilize spacer and solid insulation with these gases, because the gaseous medium as an insulation material cannot completely perform insulation in eco-friendly HV power equipment \( \text{(EHPE)} \) and HV power equipment. However, applying the spacers and the solid insulation causes surface discharge which occurs on a boundary surface between insulating gas and solid dielectric, when composite insulation was formed due to the use of the solid dielectric. Furthermore, the surface discharge caused by the spacers treated a special problem at GIS (M.S. Naidu, 2008). Accordingly, the insulation design technique of the EHPE must sufficiently consider the surface discharge and its characteristics caused by the spacers and the solid insulation. Nevertheless, it is relatively insufficient to investigate the surface discharge for the EHPE in the alternative gases.

Therefore, to design the insulation of the EHPE and to improve its surface dielectric strength, this paper experimentally examines the characteristics of surface field strength \( (E_s) \), surface discharge voltage \( (V_d) \) and discharge path in \( \text{N}_2/\text{O}_2 \) mixture gas. This paper deals with the following subjects.
(1) Effect of ambient gas pressure and mixing ratio of O₂ on $E_s$.
(2) Effect of ambient gas pressure, mixing ratio of O₂ and relative permittivity of solid dielectric on $V_s$.
(3) Discharge path patterns ($D_p$) by the medium effect and points of discharge inception ($D_{ip}$) in N₂/O₂ mixture gas.

2. Experimental apparatus and procedure

Figure 1 shows experimental apparatus and a circuit diagram for this study. The experimental apparatus used are an AC power supply, a test chamber and a HV divider.

The AC power supply (DY-106, AC 300 kV/120 mA) consists of an AC HV transformer and an AC HV device, which generates AC HV of 60 Hz. The increased voltage from the HV transformer was applied to the test chamber via the AC HV device. The test chamber is capable of enduring AC HV up to 300 kV and a temperature variation from -90 to 100 °C.

A pressure gauge was installed to measure the pressure of the test chamber and to manufacture N₂/O₂ mixture gas by specific pressure ratios. The pressure of N₂ and N₂/O₂ mixture gas in the test chamber was based on the pressure gauge during experimentation.

In Figure 1, $R_2$ and $R_3$ are the HV divider (High Voltage Probe EP-100K, 3000:1). The divider was used to measure the AC HV applied to the test chamber. Also, $R_1$ is to measure waveform of discharge current, when surface discharge occurs in the test chamber.

Besides the mentioned experimental apparatus, other materials for experiments are electrodes, solid dielectrics, N₂ and O₂ gases. The electrode and the solid dielectric were vertically placed for effective occurrence of the surface discharge. Figure 2 shows the vertical arrangement as well as the shape, the material and the size of the electrodes. The used solid dielectrics were Teflon (TE), Polyethylene (PE) and Bakelite (BE) of disc-shaped, and their relative permittivity was 2.1, 2.2, 5.0, respectively. In the experiment for $E_s$ and $V_s$ characteristics, the size of the solid dielectrics was 1T 70 Ф and that for discharge path characteristics was 3T 100 Ф. The solid dielectrics were applied as considering relative permittivity of the actual spacers. This relative permittivity was from 2.1 to 4.7 (J.R.Laghari , 1985). N₂/O₂ mixture gas was used as eco-friendly insulating gas.

Fig. 1. Experiment apparatus and circuit

Fig. 2. Vertical arrangement of electrode inside the test chamber
Experimental procedure comprised of installation of electrodes and solid dielectrics, injection of N$_2$/O$_2$ mixture gas, AC HV application and $V_x$ measurement. As seen in Figure 2, the electrodes were placed on vertical arrangement inside the test chamber. The solid dielectrics were inserted between the sphere electrode and the circular type plane electrode. In order to inject pure N$_2$ and N$_2$/O$_2$ mixture gas to the test chamber, the chamber was vacuumed about $5 \times 10^{-4}$ Torr by a vacuum pump (SINKU KIKO Co.LTd, Gud-050A, Pumping seed 60[ l/min]) and then, N$_2$ and N$_2$/O$_2$ mixture gas were pressurized into the chamber. Mixing ratios of N$_2$ and O$_2$ gas were 100:0, 80:20, 60:40 and 40:60 %; N$_2$/O$_2$ mixture gas which corresponded to the mixing ratios named N$_2$, MA$_1$, MA$_2$ and MA$_3$ respectively. The mixing ratios were applied according to the law of partial pressures on the basis of a pressure gauge. These N$_2$/O$_2$ mixture gases were pressurized into the test chamber in the order of N$_2$ and O$_2$.

After AC HV rising speed of voltage of 3.15 kV/sec was applied to the test chamber, $V_x$ was measured five times at each pressure level, when surface discharge occurred along solid dielectrics. Experimental data used $E_x$ and $V_x$, $E_x$ was calculated by equation (1).

$$E_x = \frac{V_x}{d_x}$$  \hspace{1cm} (1) \\

Where $V_x$ is surface discharge voltage (kV), $d_x$ is surface distance (mm). $V_x$ used the average value of five times of measurement. The constant value of $d_x$ was 41.5 mm. Every each 20~30 s should be passed in order to measure $V_x$, after N$_2$/O$_2$ mixture gas was pressurized into the test chamber; and after the surface discharge occurred in the test chamber. This is because $V_x$ must be measured in a steady state of N$_2$/O$_2$ mixture gas.

3. Experimental result and discussion

3.1 Surface Discharge Characteristics by Solid Dielectric and Mixing Ratio of O$_2$

Surface discharge is initiated from partial discharge (PD) of ambient gas due to a concentrated electric field at the triple junction. The insulation performance of the ambient gas and the concentrated electric field at this junction contribute to a PD initiation. Thus, this section describes the effects of the mixing ratio of N$_2$/O$_2$ gases and the relative permittivity of solid dielectrics on the surface discharge.

Figure 3 shows the surface discharge characteristics as functions of the ambient gas pressure and solid dielectrics (TE, PE, BE) in N$_2$/O$_2$ mixture gas. $E_x$ of the solid dielectrics increased with the increase of the ambient gas pressure. Since the increasing gas pressure enhances the insulation performance of the ambient gas which surrounds electrodes and solid dielectrics, the $V_x$ also increases with the increase of the gas pressure. Because $ds$ is a constant value in the experimental condition, increasing $V_x$ leads to increase $E_x$. In other words, both the $V_x$ and the $E_x$ increase due to the medium effect. It can confirm that the medium effect appears on the solid dielectrics in Figure 3.

Figure 3(a), 3(b) and 3(c) show that $E_x$ is varied through the different mixing ratios of O$_2$ on the solid dielectrics. $E_x$ appeared in order of the MA$_1$, MA$_2$, MA$_3$ and N$_2$. This order is in good agreement with experimental results in (Eun-Hyeok Choi et al., 2009) that breakdown voltage of these gases was investigated as a function of the gas pressure under an uniform field. It means that the insulation performance of the ambient gas plays a significant role to determine $V_x$ and that the insulation performance of the ambient gas can be improved by a suitable addition of electronegative gas (O$_2$) in buffer gas (N$_2$).

The insulation performance of N$_2$/O$_2$ mixture gases was higher than that of N$_2$. It is due to the electron attachment effect of O$_2$ which is electronegative gas. The effective ionization coefficient can be reduced by the effect, so that a mixture of O$_2$ enhances insulation performance of N$_2$/O$_2$ mixture gases, and $V_x$ increases by the effect. Among given N$_2$/O$_2$ mixture gases, the $V_x$ of the MA$_1$ which has similar composition of the air which is the highest.

Figure 4 shows $V_x$ characteristics as functions of the gas pressure and the solid dielectrics in MA$_1$ and N$_2$. The surface discharge is developed from the PD in ambient gas due to the concentration of a local electric field. It means that the electric field which applied the ambient gas is significant. The location where the electric field is concentrated is the triple junction. It is clear that the electric field at the location depends on relative permittivity.
Fig. 3. The $E_s$ characteristics of TE, PE and BE by gas pressure and mixing ratio of $N_2/O_2$ of solid dielectric, because the permittivity of the ambient gas is nearly '1'. With the increase of the relative permittivity of the solid dielectric, the electric field becomes more intense, and $V_s$ decreases. Since the relative permittivity of BE is higher than TE and PE, the $V_s$ of BE was lower than that of TE and PE among the used solid dielectrics.
Although it is known that an electrical characteristic (dielectric breakdown strength and relative permittivity) of TE is superior to that of PE, $V_S$ of TE is lower than that of PE. It shows that $V_S$ does not completely depend on the dielectric breakdown strength or the relative permittivity. Moreover, this result can be interpreted by the medium effect. Liquid dielectrics, such as transformer oil is used as ambient medium for the test of dielectric breakdown strength of different solid dielectrics. However, in this study, the gaseous dielectric ($N_2/O_2$ mixture gas) was used as the ambient medium instead of the liquid dielectrics. As a result, it appears obvious that $V_S$ is different from the different dielectric breakdown strength due to the medium effect. In addition, the medium effect by gas pressure of $MA_1$ and $N_2$ is significantly observed on TE that an increasing rate of $V_S$ is higher than other solid dielectrics.

According to these results, the insulation performance of the ambient medium and the medium effect has to be considered for the improvement of surface dielectrics strength at the EHPE

### 3.2 Discharge Path Characteristics by Medium Effect in $N_2/O_2$ Mixture Gas

A discharge path by flashover in GIS is progressed along a spacer surface at a triple junction (K. Itaka T. Hara and T. Misaki H. Tsuboi, 1983). However, in this study, it was observed that there are three different types of the discharge paths by the medium effect (variation of ambient gas pressure) in GIS. Hence, this section examined the discharge paths by the medium effect, especially in $MA_1$.

In this experiment, the authors found that there are two patterns of the discharge path patterns ($D_P$), which are initiated at a triple junction and a weak point of the used sphere electrode. In detail, $D_P$ are classified by three points of discharge inception ($D_{ip}$). $D_{ip}$ are the triple junction and the weak point of the sphere electrode. Figure 5 illustrates $D_{ip}$ determining $D_P$. In Figure 5, $W_1$ is the triple junction, and $W_2$ and $W_3$ are the weak point of the electrode.
$D_P$ are determined according to $W_1$, $W_2$ and $W_3$. $D_P$ which corresponds to the $W_1$, $W_2$ and $W_3$ are defined as pattern 1, pattern 2 and pattern 3, respectively. Their propagation patterns are described as follows.

- Pattern 1: PD is initiated at $W_1$. The discharge path is progressed along the surface of the solid dielectric.
- Pattern 2: PD is initiated at $W_2$. The discharge path is progressed along the surface of the solid dielectric.
- Pattern 3: PD is initiated at $W_3$. The discharge path is progressed through MA1.

**Photo 1.** Discharge patterns ($D_P$) by points of discharge inception ($D_{IP}$) in MA1

Photo 1 depicts these $D_P$. It is obvious that the discharge path can be separated from $D_{IP}$. As mentioned in section 3.1, the surface discharge is initiated from PD due to the concentrated electric field at the triple junction. Discharge path progress is affected by the insulation performance of ambient gas, the surface roughness and pollution of solid dielectric and a local electric field by a particle. In this experiment, the ambient gas pressure was changed. Therefore, we can interpret that $D_{IP}$ and the pressure of the ambient gas pressure influence $D_P$.

$D_{IP}$ are the points where electric field is concentrated. The points are the triple junction and the weak point of the sphere electrode due to solid dielectric and the surface roughness of the electrode, respectively. These points correspond to $W_1$, $W_2$ and $W_3$ in Figure 5.
To analyze $D_p$ influenced by medium effect, the $V_s$-$P$ characteristics and $D_{ip}$ were studied and listed in Table 1. It shows that both $V_s$ and $D_p$ are affected by the medium effect. Due to the medium effect, $V_s$ becomes higher with the increase of the ambient gas pressure. As the ambient gas pressure decreases, the points of $D_p$ are transited from $W_1$ to $W_2$ and $W_3$. It is due to that the initial discharge easily arises from the sphere electrode surface because of the lower insulation performance of the ambient gas around the electrode. Consequently, the medium effect plays an important role in an interpretation of $D_p$ and the discharge path.

A discharge path in SF$_6$ follows the pattern 1. Typically, the discharge path has characteristics which progresses through a part of an electric field distortion, a high conductivity and a low dielectric strength. So, the discharge path of SF$_6$ progresses through a boundary between ambient gas and solid dielectric because of its excellent insulation performance. However, if ambient gas which has relatively low insulation performance is applied, the discharge path can be progressed through the ambient gas at the weak point of an electrode such as the pattern 2 and 3. The insulation performance of MA$_1$ is enhanced from the increased ambient gas pressure. Therefore, as the ambient gas pressure increases, due to PD at a triple junction, the discharge path is progressed from $W_1$ to a solid dielectric surface such as the pattern 1. On the other hand, if the insulation performance of MA$_1$ is lower due to the decreased ambient gas pressure, the discharge path is easier to progress from the sphere electrode surface to MA$_1$. The reason is that PD arises from the weak point of the electrode due to the lowered insulation performance of MA$_1$. This discharge path corresponds to the patterns 2 and 3.

<table>
<thead>
<tr>
<th>Pressure of ambient gas</th>
<th>$V_s$ (kV)</th>
<th>$D_p$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 MPa</td>
<td>38</td>
<td>$W_1$</td>
</tr>
<tr>
<td>0.2 MPa</td>
<td>40</td>
<td>$W_2$</td>
</tr>
<tr>
<td>0.3 MPa</td>
<td>42</td>
<td>$W_2$</td>
</tr>
<tr>
<td>0.4 MPa</td>
<td>43</td>
<td>$W_1$</td>
</tr>
<tr>
<td>0.5 MPa</td>
<td>44</td>
<td>$W_1$</td>
</tr>
<tr>
<td>0.6 MPa</td>
<td>45</td>
<td>$W_1$</td>
</tr>
</tbody>
</table>

From these results, we can know that the $D_p$ can be determined by the medium effect and $D_{ip}$. In particular, the medium effect by the ambient gas pressure is more dominant on a decision of $D_p$. In addition, the reproducibility of $D_p$ was confirmed by several successive experiments.

In order to analyze $D_p$, the ambient gas pressure was defined as $P_H$, $P_M$ and $P_L$. The pressure ranges of $P_H$, $P_M$ and $P_L$ are 0.4-0.6 MPa, 0.3 MPa and 0.2-0.1 MPa, respectively. The discharge paths of each pressure range correspond to the patterns 1, 2 and 3, respectively. Table 2 shows the relationship among the pressure, $D_p$ and $D_{ip}$. $D_p$ and $D_{ip}$ could be seen to be separated from the pressure, and critical pressure which leads to change $D_p$ and $D_{ip}$ was 0.3 MPa. From Table 2, it is obvious that the ambient gas pressure determines $D_p$ and $D_{ip}$. That is, it can be concluded from Table 2 that the medium effect is dominant in determining $D_p$ and $D_{ip}$.

From these discharge path characteristics, the EHPE applying N$_2$/O$_2$ mixture gas (MA$_1$) must be designed to be pressurized at least over 0.4 MPa. The increasing gas pressure can induce improvement of a dielectric strength as well as the discharge path characteristics. From discussions in section 3.1 and 3.2, the medium effect can be significant in the EHPE to improve surface dielectric strength and the discharge path characteristics.

Table 2. Discharge patterns($D_p$) and points of discharge inception($D_{ip}$) according to defined pressure

<table>
<thead>
<tr>
<th>$D_p$</th>
<th>$P_H$</th>
<th>$P_M$</th>
<th>$P_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pattern 1</td>
<td>pattern 2</td>
<td>pattern 3</td>
</tr>
</tbody>
</table>

4. Conclusion

For the insulation of eco-friendly high voltage power equipment (EHPE), this paper experimentally investigated the characteristics of surface discharge and discharge path in N$_2$ and N$_2$/O$_2$ mixture gas. From this study, the obtained conclusions are as follows.

1) Surface discharge voltage ($V_s$) increased with the increase of ambient gas pressure, and the medium effect induced the increase of both $V_s$ and surface field strength ($E_s$).

2) $V_s$ was determined by the insulation performance of ambient gas. Due to the electron attachment effect of O$_2$, $V_s$ of N$_2$/O$_2$ mixture gas was higher than that of N$_2$. Compared with other gases, $V_s$ of MA$_1$(N$_2$/O$_2 = 8/2$) which is similar to the composition of the air was the highest.
3) The order of $V_t$ of solid dielectrics was PE>TE>BE. This order was determined by the medium effect and the relative permittivity of the solid dielectrics.

4) The discharge path of MA differed from that of SF$_6$. There were three type of the discharge path due to the medium effect. The medium effect and the points of discharge inception($D_{IP}$) determined discharge path patterns($D_P$)

5) $D_{IP}$ were the triple junction and the weak point of the used sphere electrode surface. The medium effect was a factor which determines $D_P$ and $D_{IP}$. When ambient gas pressure decreased, $D_P$ were changed from the triple junction to the weak point of the electrode as the pattern 2 and 3.

6) $D_P$ were separated from the medium effect. $D_P$ in gas pressure range of 0.4-0.6 MPa, 0.3 MPa and 0.2-0.1 MPa corresponded to the pattern 1, 2 and 3 respectively.

7) It was shown that the medium effect is dominant in $D_P$ and $D_{IP}$. Critical pressure changing $D_P$ and $D_{IP}$ was 0.3 MPa.

It is expected that the results of this paper will be useful for the composite insulation design and the surface dielectric strength of the EHPE.

References


Dong-Young Lim was born in Korea in 1983. He received the B.S. degree in electronic engineering in 2009 from Gyeongju University, Korea. He received the M.S. and Ph.D. degree in electrical engineering from Yeungnam University, in 2011 and 2015, respectively. His research interests include high voltage phenomena, surface flashover and insulation design of gas insulated switchgears.