COATING AND BARRIER WITHIN MEDIUM VOLTAGE GIS
(GAS INSULATED SWITCHGEAR)

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ABSTRACT

The main purpose of this paper is to investigate cases with atmospheric air and hybrid insulation, where solid insulation is used in addition to air. For solid insulation, convenient polymeric materials are used. With hybrid insulation it is typically two options: Coating or barriers. The properties of convenient polymeric materials are in somewhat extent unknown and less examined for this type of application. Therefore an investigation of the dielectrical behaviour of materials used in medium voltage switchgear on a section with parallel conductors has been carried out. For the execution, experiments were done with power frequency test and lightning impulse voltage. The experiments with coating were done with Raychem heat-shrink tubes. Two types of plastic material where used as barrier. Observations from experiments showed that hybrid insulation with coating gives an increase in breakdown strength compared to air only. Coating should be preferred based on the increase in dielectric strength of the system. However, if the barrier can be used as a mechanical support for the conductors, the barrier could be preferred as the solid insulation.

INTRODUCTION

Air/polymer insulation is becoming increasingly attractive because of environmental consideration and advance of polymer technique. For air insulated equipment with compact design an improvement of the electrical performance is needed because the insulation capability provided by air alone is not sufficient to ensure a compact design. In recent years extensive investigations on dielectric barriers and coated conductors have been carried out [1, 2, 3]. The work described in this paper has focused on hybrid solutions within medium voltage systems. The main purpose of this paper is to investigate cases with atmospheric air and hybrid insulation, where solid insulation is used in addition to air. For solid insulation, convenient thermoplastic materials are used. With hybrid insulation it is typically two options: Coating or barrier. The experimental setup described in this paper is comparable with the physical size of a typical medium voltage switchgear.

TEST OBJECTS AND EXPERIMENTAL SET UP

The main objectives of the experiments was to find some design guidelines for an optimized solution of air/polymer insulation based on the measures as described below. To reduce the likelihood of unwanted breakdown as much as possible, the test object was made with great care. A simplified adaptation from the switchgear section was made. The test object was made for investigation of the critical path from outer connection to ground-plane. The test object itself was held up on a metal rack on wheels with two insulators. The whole test object was insulated from earth. A good and predictable control of the behaviour of breakdown was achieved. The bus bar profile was replaced as the ground plane and connected to earth potential, while the conductor was insulated from earth with non conductive material. Typical distances from high potential to earth plane in medium voltage switchgears is 45 - 100 mm. Gap distances used in the experiments are based on this dimensions. The critical path would be the shortest distance from conductor to ground-plane. Therefore, the outer connection to ground-plane was chosen. If a breakdown occurred on the first impulse, it was not counted in the analysis. Accumulated charges can occur in the experiments and as a consequence influence the test results. Three actions were done to reduce the effect between experiments. A 3M Scotch-Brite™ cloth was used to rub off possible roughness on the surface of the conductor. Furthermore, a cloth was used to clean the test objects. Also, compressed air was used on the test object to remove particles. For tests with coated electrodes, visual inspection was done in order to see whether the breakdown had made roughness on the insulation surface. The coating was replaced if roughness was observed on the insulated surface. Experimental setups were tested for both lightening impulse voltage test and 50 Hz power frequency test. An arbitrary gap distance of x=58 mm was held constant in experiment setups with barrier and coating.

Experiment setup 1: Conductor crossing earth electrode with air as the insulating material.

The $U_{50\%}$ as a function of gap distance, $x$, is investigated in this setup.

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Figure 1 Experimental setup 1 showing gap distance x from earth electrode to the conductor that is held up by non conductive material.

**Experiment setup 2: Barrier placed between earth electrode and conductor.**

Figure 2 Experimental setup 2 showing barrier of 3mm placed in the middle of the air gap between earth electrode and conductor with constant gap distance of x = 58mm

**Experiment setup 3: Coated conductor**

Figure 3 Experimental setup 3 showing a coated conductor with constant gap of x = 58mm. The thickness of coating was 1.4, 2.1 and 3.1 mm.

**STATISTICAL METHODS**

When an increasing voltage is applied between two electrodes, a breakdown will eventually occur at a certain value - the breakdown voltage. If the test is repeated with the same test conditions, it will normally be seen that the breakdown now happens at a different voltage. The observed breakdown voltage would then vary stochastic or random from test to test. Two different statistical methods are used in this paper for the electrical breakdown testing, the Up-and-down method and Weibull analysis.

**Up-and-down method**

The Up-and-down method of Dixon and Mood permits a quite reliable estimation of the 50 % breakdown voltage named $U_{50\%}$ when the breakdown voltage belongs to the normal distribution. This method [4] also provides an estimate of the standard deviation. If the breakdown voltage cannot be assumed to be normal distributed, indication of the dispersion should be abandoned. The $U_{50\%}$ voltage can be calculated using [4]:

$$ U_{50\%} = U_{\text{max}} + U_{\text{step}} \left( \frac{\sum k \cdot n_k + 1}{\sum n_k} \right) $$

$U_{\text{step}}$: The constant step between each test voltage.
$U_{\text{min}}$: The lowest U at which there is a breakdown.
$k$: Indicates the number of the step where $k=0$ for the lowest voltage step with a breakdown.
$n_k$: The number of breaks at each step k.
$r$: The number of steps with breakdowns minus 1.

Withstand voltage can be calculated using:

$$ U_W = U_{50\%} - 2\sigma $$

**Weibull analysis**

The primary advantage of Weibull analysis is the ability to provide reasonably accurate failure analysis and failure forecasts with extremely small samples. The Weibull distribution should be used when the objective is to find the weakest link of the system. This is preferable in the case of the power frequency test. The three-parameter cumulative distribution function (CDF) by Weibull [5] is in case of electrical breakdown tests:

$$ CDF(U) = 1 - e^\left(\left(\frac{U - U_0}{\eta}\right)^\beta\right), \ U \geq 0 $$

Where:
$U =$ breakdown voltage
$U_0 =$ limit value for breakdown voltage
$\eta =$ characteristic breakdown voltage
$\beta =$ shape parameter

Experience has shown that the fit to experiment data is little dependent upon $U_0$. It is therefore common to choose $U_0=0$, [6]. The well-known three-parameter Weibull distribution is thus reduced to the two-parameter cumulative distribution function:

$$ CDF(U) = 1 - e\left(\left(\frac{U}{\eta}\right)^\beta\right), \ U \geq 0 $$
EXPERIMENTAL RESULTS

The test program has been performed in 4 steps: initial tests 1 to 3 with applications for lightning impulse voltage tests, then an experiment with 50 Hz power frequency tests according to IEC 60060-1 [7]. All the experiment results was achieved at approximately 23°C, 760 mmHg, and 30 % relative humidity.

Experiment setup 1 Air

With air only as the insulating material, Figure 4 as shown below has been drawn. At each test for experiment setup 1 to 3; 60 impulses with positive polarity and a voltage increment of \( U_{\text{step}} = 2 \text{kV} \) were applied. The positive polarity is normally the limiting voltage. Figure 4 shows the \( U_{50\%} \), of experiment setup 1 with a change in the gap distance \( x \). The gap distance \( x \) (from surface of conductor to surface of ground-plane) was varied from 45.5 mm to 98 mm.

![Figure 4 The \( U_{50\%} \) of experiment setup 1 with change in gap distance \( x \) for positive polarity.](image)

It can be seen that the 50 % breakdown voltage at a typical gap distance of 58 mm, was found to be 111 kV for positive impulse. Based on the experiment results with air only, the air gap distance of 58 mm, and the rated lightning impulse withstand voltage of 125 kV for 24 kV switchgear [8], an increase in breakdown strength of the system is necessary. To have a satisfactory safety margin for 24 kV switchgear, a gap distance of minimum 90 mm is required.

Experiment setup 2 Barrier

Investigation in setup 2 was done with the use of barriers with both positive and negative polarity. The investigation of the effect of the barriers was done on different types of material. The plate with thickness of 3 mm was positioned in the middle of the air gap of 58 mm as shown in Figure 2.

The effect of barrier material was investigated with two different thermoplastic materials PETG (Polyethylene Terephthalate Glycol) and POM-C (Polyoxymethylene). Figure 5 shows the experiment results of the different materials compared with results from test setup 1 (air).

![Figure 5 The \( U_{50\%} \) for both polarities at three different experiment setups. The bars indicate two standard deviations.](image)

Figure 5 indicates that the material PETG shows an increase of the \( U_{50\%} \) for both positive and negative polarity. The effect of a barrier with relatively high relative permittivity such as POM-C gives almost no increase in the \( U_{50\%} \). A lower permittivity of the solid insulation gives a higher breakdown voltage of the hybrid system. The air gaps will be more stressed as the relative permittivity of the barrier increases. Sjöberg [3] concludes that the permittivity of the solid insulation should be as low as possible in order to achieve low capacitance and thereby minimise the required quantity of surface charges needed to quench air gap discharges.

The bars in Figure 5 indicate two standard deviations. The standard deviation, \( \sigma \), for both materials increases compared to air only. For air, the standard deviation is relatively small. A large enhance in the standard deviation can be seen by introducing a polymer material in the form of a barrier into the gap. For PETG positive polarity and POM-C negative polarity the standard deviation, \( \sigma \), was calculated to be 6 kV and 8 kV respectively. The increase in standard deviation, \( \sigma \), gives a withstand voltage, \( U_W \), value of about 113 kV for POM-C negative polarity. This is lower than the \( U_W \) for air only. Table 1 shows the given values for two standard deviations from Figure 5.

<table>
<thead>
<tr>
<th>Polarity</th>
<th>Air [kV]</th>
<th>PETG [kV]</th>
<th>POM-C [kV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>3</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>Negative</td>
<td>3</td>
<td>6</td>
<td>16</td>
</tr>
</tbody>
</table>

Experiment setup 3 Coating

For investigations the effects of coated conductors, Raychem heat-shrink tubes were used to coat the conductors. In this section three tubes with different thicknesses were used. This is the BBIT 40/16, BBIT 25/10, and BPTM 30/12 from Raychem with relative permittivity of 5. It was only used already commercial available material in the experiments. The gap distance from the surface of conductor to ground plane was kept constant at \( x = 58 \) mm.
As a consequence: the air gap is decreasing as the thickness of the coating increases. The experimental results are shown in Figure 6.

Figure 6 Three different types of coating compared to air for both polarities. The bars indicate two standard deviations.

The $U_{50\%}$ increased in all tests for both polarities compared to air. A maximum increase of 35 kV in breakdown voltage, compared to air, was achieved for positive polarity with BBIT 25/10. The evaluating of the standard deviations should be done with great care as seen for BPTM positive polarity in Figure 6. The standard deviations are very large and quite surprising. A normal distribution may not be existing because of the change in test condition.

**Power frequency tests**

Power frequency tests were done with 7 test objects at each test for air, barrier, and coating. In power frequency experiment setup the voltage started at zero and was increased at a rate of about 1.7 kV/s until breakdown occurred. Experimental results using Weibull distribution is shown in Table 2.

Table 2 Values from 6 different sets using Weibull distribution.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [mm]</th>
<th>$\beta$ [kV]</th>
<th>$\eta$ (= \frac{U_{50%}}{\sigma}) [kV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>-</td>
<td>22</td>
<td>68</td>
</tr>
<tr>
<td>Coating (BBIT 25/10)</td>
<td>2.1</td>
<td>18</td>
<td>102</td>
</tr>
<tr>
<td>Coating (BBIT 40/16)</td>
<td>3.1</td>
<td>19</td>
<td>104</td>
</tr>
<tr>
<td>Coating (BPTM 30/12)</td>
<td>1.4</td>
<td>39</td>
<td>94</td>
</tr>
<tr>
<td>Barrier (PETG)</td>
<td>3</td>
<td>43</td>
<td>92</td>
</tr>
<tr>
<td>Barrier (POM-C)</td>
<td>3</td>
<td>20</td>
<td>96</td>
</tr>
</tbody>
</table>

A significant difference was found for air only compared to coating or barrier. The increase of the breakdown voltage was 36 kV compared to air for coating with BBIT 40/16. Between coating and barrier the differences are relatively small. The effect of the material properties has small impact on the disruptive discharge of the system using power frequency test.

The $\beta$ in Table 2 is a measure of scatter from Weibull distribution. Comparing $\beta$ in Table 2 with $2\sigma$ from Figure 5 and 6, a similarity can be seen in the value of the scatter. For positive polarity, BPTM in Figure 6 and PETG in Figure 5 has a relative large enhance in the standard deviation. This is also verified with the Weibull distribution.

**CONCLUSION**

The results from the experiments showed an increase in the breakdown voltage compared to air, under certain conditions. This was achieved by coating the conductor or using a polymeric barrier in the air gap. The maximum increase in $U_{50\%}$ compared to air with the same gap distance was 35 kV when the conductor was coated. No significant difference could be seen between coating and barrier in power frequency tests. The permittivity of the solid insulation should be as low as possible. Furthermore, a material with lower permittivity than the heat-shrink tubes used in these experiments should be developed and investigated.

The experiments also show that to achieve a improved dielectrical withstand, the coating and barrier must be designed in a correct way. Based on the increase of the dielectric strength of the system with lightning impulse, coating can be preferred as the solid insulation. If the barrier, however, can be used as a mechanical support for the conductors, the barrier could be preferred as solid insulation.

**REFERENCES**