Field Analysis of SF₆ Gas Insulated Cables and Its Application to Spacer Design

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Synopsis

This paper describes the spacer design for SF₆ gas insulated cables. The maximum electric stress within the cable is calculated by a numerical method, and it is recognized that the breakdown voltage depends linearly on the calculated values. Moreover, the effects of varying the shape of the spacer are made clear in this study for designing an optimum spacer.

1. Introduction

The problem of compressed gas insulated cables has been studied by many researchers from different points of view. Lately, the number of these reports has been increasing. The authors were given many useful suggestions by several papers which explained the breakdown characteristics in a compressed gas such as SF₆ [1,2,3,4].

The purpose of this paper is to investigate by calculation and experiment the effects of the insulating spacers upon the breakdown characteristics and also to present basic data of a practical spacer design. Each phase of the cable system consists of a single conductor, a cylindrical metal sheath, the spacers which support the conductor within the sheath, and SF₆ gas between two metal electrodes. In this case two relative dielectric constants exist: that of the epoxy spacers and that of the surrounding SF₆ gas.

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The spacers have direct effects upon the breakdown characteristics. One of the effects is caused by its cohesion with electrodes and shielding electrodes. These problems and countermeasures are presented in an IEEE paper. [5]

The problem treated here is the effects of varying the shape of the spacer upon the field distribution in the cable. If epoxy spacers are introduced into a uniform field, the field is distorted. The potential distribution becomes complicated, and the maximum electric stress occurs near the spacers. A numerical analysis based on digital computation is helpful in solving such a problem. [6,7,8,9] Here, equations to be used in the calculations are derived directly from the familiar Gauss’ theorem.

After calculating the potential distribution, the point where the maximum electric stress occurs and its value are obtained. Then the relation between the shape of the spacer and the breakdown voltage can be estimated. Comparing the calculations with the breakdown tests, the effects of varying the shape of the spacer upon the breakdown characteristics may be made clear, and these results may be used in a practical spacer design.

2. Procedure of Numerical Analysis

Fig.1 shows the cross section of SF₆ gas insulated cables. This cable has axial symmetry and has two different dielectrics; that is, epoxy resin and SF₆ gas.

The problem region, that is, R-Z plane, is subdivided by a rectangular mesh, and each grid-intersection point is numbered. A set of algebraic equations is obtained by using Gauss’ theorem around a point \((i,j)\) as shown in Fig.2.
a_1V(i,j+1)+a_2V(i-1,j)+a_3V(i,j-1)+a_4V(i+1,j)-a_5V(i,j)=0 \quad (1)

where

\[
\begin{align*}
a_1 &= \frac{1}{h_1}(\epsilon_1 h_2 (1-\frac{h_2}{4R(i,j)})+\epsilon_8 h_4 (1+\frac{h_4}{4R(i,j)}) ) \\
a_2 &= \frac{1}{h_2}(\epsilon_2 h_1 +\epsilon_3 h_3)(1-\frac{h_2}{2R(i,j)}) \\
a_3 &= \frac{1}{h_3}(\epsilon_4 h_2 (1-\frac{h_2}{4R(i,j)})+\epsilon_5 h_4 (1+\frac{h_4}{4R(i,j)}) ) \\
a_4 &= \frac{1}{h_4}(\epsilon_8 h_3 +\epsilon_7 h_1)(1+\frac{h_4}{2R(i,j)}) \\
a_5 &= a_1 + a_2 + a_3 + a_4
\end{align*}
\]

\(R(i,j)\) represents the radial distance from a point \((i,j)\) to the Z axis. \(\epsilon_1, \epsilon_2, \ldots, \epsilon_7\) and \(\epsilon_8\) are the relative dielectric constants, and \(h_1, h_2, h_3,\) and \(h_4\) are the distance between grid-intersection points on the rectangular region. The boundary conditions are as follows:

1. The potential \(V\) on the \(R=R_i\) line in Fig. 3 is given by \(V=V_a\)
   where \(V_a\) is the applied voltage.
2. The potential \(V\) on the \(R=R_o\) line in Fig. 3 is given by \(V=0\).
3. It can be considered that there is no effect of the spacer near the line \(Z=Z_c\). The potential \(V\) on the \(Z=Z_o\) line in Fig. 3 is given by...
The potential $V$ on the $Z=Z_p$ line and the potential $V$ on the $Z=Z_m$ line are symmetric with respect to the $R$ axis.

The usual method of solving Eq. (1) by iteration techniques is to set up the iteration procedure.

$$V_{k+1}^{(i,j)} = V_k^{(i,j)} + \omega \left( a_1 V_k^{(i,j-1)} + a_2 V_k^{(i+1,j)} - a_3 V_k^{(i,j-1)} - a_4 V_k^{(i+1,j)} - a_5 V_k^{(i,j)} \right)$$

where

$\omega =$ accelerating factor

$k =$ order of iteration

3. Computer Solutions and Discussion

Making use of the above method, the potential distributions within SF$_6$ gas insulated cables may be calculated.
Fig. 5 Potential distributions within cables
Now the cable chosen as a numerical example consists of a single conductor of radius=20mm, a cylindrical metal sheath of radius=45mm, the epoxy spacers of relative dielectric constant=5, and the surrounding SF6 gas of relative dielectric constant=1. The typical profiles of the spacers are shown in Fig.4. By using the above method, the potential distributions within the cable are obtained as shown in Fig.5.

The value of the maximum electric stress can be obtained from the potential distributions, and also the effects upon the maximum electric stress of varying the shape of the spacer can be made clear. Table 1 shows the values of the maximum electric stress obtained by the calculation. Where $\beta$ is normalized stress in case the applied voltage is 100. From these results, it is predicted that the breakdown voltage of spacer No.1 will be highest and that of spacer No.3 lowest. Table 2 shows the test results. In the tests, 60-Hz AC voltage was applied between two electrodes. Fig.6 gives the relationship between maximum electric stress (Table 1) and breakdown voltage (Table 2). In this figure, it is recognized that the breakdown voltage depends linearly on the calculated values. Moreover, the traces of flashover in the tests are shown in Fig.7. With the No. 1 spacer, the flashover occurs directly through the gas. However, with the No.3 spacer, the flashover occurs along the surface of the spacer. These results correspond to the predicted results from Fig.5. Therefore this method may be very useful for designing an optimum spacer.

Table 1 Numerical results of model spacers

<table>
<thead>
<tr>
<th>Spacer Number</th>
<th>Maximum Electric Stress($\beta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>8.5</td>
</tr>
<tr>
<td>No.2</td>
<td>8.65</td>
</tr>
<tr>
<td>No.3</td>
<td>9.67</td>
</tr>
</tbody>
</table>

Table 2 Test results of model spacers

<table>
<thead>
<tr>
<th>Spacer Number</th>
<th>Test 1 (kVeff)</th>
<th>Test 2 (kVeff)</th>
<th>Test 3 (kVeff)</th>
<th>Test 4 (kVeff)</th>
<th>Test 5 (kVeff)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>160</td>
<td>150</td>
<td>175</td>
<td>165</td>
<td>-</td>
</tr>
<tr>
<td>No.2</td>
<td>160</td>
<td>170</td>
<td>160</td>
<td>150</td>
<td>-</td>
</tr>
<tr>
<td>No.3</td>
<td>100</td>
<td>130</td>
<td>100</td>
<td>130</td>
<td>120</td>
</tr>
</tbody>
</table>

SF6 Gas Pressure : 1.5 kg/cm² Gauge
Fig. 6 Relations between maximum electric stress and breakdown voltage

Fig. 8 to Fig. 15 shows an example of spacer design. In this design, parameters selected are as follows:

- **case 1**
  - $R_3 / R_2$, $R_4 / R_3$, $Z_2 / Z_1$ in Fig. 8

- **case 2**
  - $Z_3 / Z_1$, $R_5 / R_1$, $R_6 / R_5$ in Fig. 12

In each case, the results obtained are shown in Fig. 9 to Fig. 11 and Fig. 13 to Fig. 15. In Fig. 9, when $R_3 / R_2 = 5/17$, $8/17$, the maximum electric stress occurs near the point B, and when $R_3 / R_2 = 9/17$, the maximum electric stress shifts to the point A. When $R_3 / R_2 = 10/17$, the maximum electric stress changes to the point C, and in this case, the value of stress becomes highest. From all the results obtained (Fig. 9 to Fig. 11 and Fig. 13 to Fig. 15), the spacer shown in Fig. 12 is most preferable with respect to its shape. As for $R_5$ in Fig. 12, the smaller the value is, the better the dielectric characteristic is, and in this case, the value of $Z_3$ should be about 5 times that of $Z_1$. 

![SPACER NO.1](image1.png)

![SPACER NO.3](image2.png)
Moreover, it was made clear that in case the shielding electrode on sheath is smaller the maximum electric stress near the spacer is also decreased.

![Diagram of spacer design](image1)

![Graph of calculated results](image2)

![Graph of calculated results](image3)

![Graph of calculated results](image4)
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Fig. 12 Example of spacer design

Fig. 13 Calculated results

Fig. 14 Calculated results

Fig. 15 Calculated results
4. Conclusions

In this paper, the potential distribution and the maximum electric stress within SF\textsubscript{6} gas insulated cables having various shaped spacers were obtained by using a numerical method. The conclusions can be summarized as follows:

1. It is recognized that the breakdown voltage depends linearly on the calculated values.
2. If electric stresses for the various parameters are obtained by a numerical method, optimum spacer design may become possible.
3. For the application to the EHV cables, it will be necessary to continue experiments to get full scale data.

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References


