Optimization of an insulating support in three-dimensional gas insulated systems

B. Techaumnat\textsuperscript{1}, S. Hamada\textsuperscript{1}, T. Takuma\textsuperscript{1} and T. Kawamoto\textsuperscript{2}

\textsuperscript{1}Kyoto University, Japan
\textsuperscript{2}Central Research Institute of Electric Power Industry, Japan

Abstract

Gas insulated systems are widely used nowadays in electric power industry. Practically, solid dielectrics are inevitably required to provide support and separation of a stressed conductor in the systems. The presence of solid dielectrics, called “spacers”, results in complex-dielectric field distributions, which cannot be usually analytically calculated.

This paper describes the optimization of a post-type spacer in a gas insulated bus-bar or a transmission line, which contributes a threedimensional system. We have applied the boundary element method (BEM) for the electric field calculation. As spacers have rounded shapes, calculation models are constructed by second-order isoparametric curved elements. The Marquardt method is an optimization technique to improve the profile (shape) of a spacer from the electric field distribution. Various constraints have been tried, such as maintaining column cross-sections of a spacer circular or elliptical. Spline functions have been applied in some cases in order to maintain smooth surface. The optimization of the spacer has been carried out with respect to two objectives, that are minimizing the tangential electric field strength and the total electric field strength on the spacer surface.
1 Introduction

Insulating characteristics of gas insulated systems decisively depend on the maximum electric field in the system. Hence, the decrease of the maximum field greatly contributes to diminishing the size of such systems as GIS (gas insulated switchgears) and GIL (gas insulated transmission lines). The objective of the optimization is to reduce maximum electric field strength in the system concerned, especially on an electrode or insulator surface. An optimization with respect to electric field requires high accuracy in the calculation of electric field distributions, as electric field is sensitive to the change of surface profiles. Field calculation methods of the boundary subdivision type, such as the charge simulation method and the boundary element method, usually give more accurate results of electric field than those of the domain subdivision type such as the finite difference method and the finite element method. Hence, they are widely utilized in works dealing with the optimization in electric field.

Concerning an objective or a field value to be optimized, there are primarily two objectives in the electric field problem. They are:
1. total electric field strength
2. tangential electric field strength

For the optimization of an electrode profile, normally, only the total electric field strength is the objective to be optimized. For the optimization of a solid dielectric or spacer profile, the selection of an objective depends on the insulating property or condition of the insulation system concerned [1].

Profile optimizations of high voltage insulation systems or their parts with respect to electric field have been under study for many years. Most of the published works on the electric field optimization have been performed for axisymmetrical cases, for example [2, 3]. By contrast, there exist only a few works on the optimization for three-dimensional cases. All of them have been performed for arrangements which consist of only electrodes without a solid dielectric [4, 5]. As the insulation ability along spacer surface (flashover) is usually lower than that in a gas space, it is very important to search for the optimized profile of a spacer.

2 Calculation arrangement

Figure 1 presents the arrangement of a gas insulated system in this optimization. A 1-cm radius inner conductor of potential \( \phi_0 = 1 \, \text{kV} \) is separated from the outer conductor (sheath) by an insulating support (spacer) which has relative permittivity \( \varepsilon_d \). The sheath is grounded, i.e., it possesses zero potential. The gaseous insulation is assumed to have relative permittivity \( \varepsilon_g \) of 1. The calculation has been carried out for a 8-cm long model with a spacer located at the middle of the span. The relative permittivity of the spacer \( \varepsilon_d \) and radius of the outer sheath \( R \) have been varied in the optimization.
As can be seen from Figure 1, electric field in this arrangement is of a three-dimensional distribution and should be calculated by using a full three-dimensional model.

![Figure 1: Calculation arrangement](image)

Figure 2 illustrates an example of mesh subdivision patterns on the conductor and spacer surface. As can be seen from Figure 2, we have concentrated the number of elements near the two junctions where the spacer contacts with the conductor or the sheath. The directions of $x$, $y$, and $z$ in Figure 2 will be referred hereafter when we describe the calculation results.

![Figure 2: Mesh state](image)

The optimization has been carried out for the following objectives and parameters:
objective: total field strength \((E_{tot})\) or tangential field strength \((E_{tan})\) on the spacer surface

\[\varepsilon_d = 4, 6\]
\[R = 3, 4\text{ cm}\]

The values of \(\varepsilon_d\) and \(R\) correspond to the relative permittivity of the epoxy resin (spacer medium) and the radius ratio utilized in practical gas insulated equipment.

It is not easy to define a spacer with constant surface field in a perfectly free condition of a three-dimensional arrangement. For the ease of manufacturing a spacer in practice, we have simplified the problem by adopting a constraint on the cross-section of a spacer as follows:

(a) circular cross-section
(b) elliptical cross-section

It is to be noted that the optimization calculation entails various difficulties not encountered in ordinary electric field calculations. Some of them are that an optimization procedure often requires an additional constraint, and that an optimization condition such as constant surface field is not satisfied in the whole domain or boundary but only in a part. Furthermore, an optimization procedure does not necessarily lead to the global optimal solution, but rather often to a local optimal result or oscillation.

3 Calculation methods

3.1 Electric field calculation methods

We have used the boundary element method (BEM), one of the boundary subdivision methods, to calculate the electric field in the arrangement.

In the BEM, the normal component of electric field and the potential on all the boundary nodes are first determined. Then, potential \(\phi\) at any point \(p\) in the region can be expressed as

\[C\phi(p) = \int_{\Gamma} E_n w d\Gamma + \int_{\Gamma} \phi(\partial w/\partial n)d\Gamma\]

where \(\Gamma\) is the boundaries of the region, \(E_n\) is the normal component of electric field on the boundaries, \(C\) is a constant that depends on the position of \(p\), \(w\) is the fundamental solution, and \(\partial w/\partial n\) is its normal derivative on the boundary.

The boundary element method can be applied to an inhomogeneous domain by subdividing the domain into regions of each homogeneous medium. The boundary element method then is applied to each region. The values between two adjacent regions, region 1 and 2, are related on the boundary surface by,

\[\phi_1 = \phi_2\]
\[\varepsilon_1 E_{n1} = \varepsilon_2 E_{n2}\]
where \( \varepsilon \) is the permittivity of each region and \( E_n \) is the normal component of electric field.

### 3.2 Optimization technique

The Marquardt method has been used as an optimization technique to improve the profile of a spacer. The method is an algorithm for the least-squares approximation of nonlinear parameters. It is a variation of the Gauss-Newton method that introduces a positive number parameter so as to improve the corrective displacement for each iteration step [6].

### 4 Calculation results

A primary data survey was conducted in order to determine an initial profile of a spacer. As the first step, an electric field distribution on a cylindrical column spacer was calculated (without optimization) for various values of its cross-sectional radius. In the optimization, we have selected radii for circular cross-sections and lengths of major and minor axes for elliptical cross-sections as variable parameters while utilizing the Spline functions to maintain smooth surface of the spacer.

For spacers with circular cross-sections, it was found that the optimized profiles were very different from case to case. So an optimized profile for each case was determined with a condition that the radius of the lowermost (sheath-side) cross-section was kept constant. The results give better field distributions than when the radius of the lowermost cross-section is freely modified.

For spacers with elliptical cross-sections, three main cross-sections of the spacer (at the uppermost, lowermost, and middle) were determined first. Subsequently, the number of variable cross-sections was increased in order to determine the optimal profile.

The optimized profiles in the case of \( \varepsilon_d = 4 \) were used as the initial profiles in the corresponding case of \( \varepsilon_d = 6 \).

Table 1 presents maximal and minimal values of electric field strength in coaxial cylindrical arrangements without spacers as well as on the surface of cylindrical column spacers. For each case of the cylindrical spacers, the value \( r \) in Table 1 is the radius of the cylinder that approximately gives the lowest value of the maximum total field strength in a range \( 0.15 < r < 0.9 \) cm. Electric field strength at and near the triple junctions has been excluded from the consideration because it is known that the electric field strength at a triple junction is singular or zero unless the contact angle is equal to \( 0^\circ \) or \( 90^\circ \) [7].

Optimization results for all cases are presented in Table 2. As can be seen in the table, the profiles of the spacers have been significantly optimized for both the objectives (\( E_{tot} \) optimized and \( E_{tan} \) optimized). In the case of \( E_{tot} \) optimized, the maximum field strength has been reduced
Table 1: Electric field in the coaxial cylindrical arrangements and on the cylindrical column spacers

(a) Coaxial cylindrical arrangements

<table>
<thead>
<tr>
<th>R (cm)</th>
<th>E(kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min.</td>
</tr>
<tr>
<td>3</td>
<td>0.303</td>
</tr>
<tr>
<td>4</td>
<td>0.180</td>
</tr>
</tbody>
</table>

(b) Surface of cylindrical column spacers

<table>
<thead>
<tr>
<th>R (cm)</th>
<th>ε_d</th>
<th>r (cm)</th>
<th>E_{tot}(kV/cm)</th>
<th>E_{tan}(kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>min.</td>
<td>max.</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0.20</td>
<td>0.347</td>
<td>0.804</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.25</td>
<td>0.372</td>
<td>0.789</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>0.20</td>
<td>0.205</td>
<td>0.605</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.20</td>
<td>0.211</td>
<td>0.597</td>
</tr>
</tbody>
</table>

around 20 to 28 % for the spacers with circular cross-sections and 28 to 35 % for the spacers with elliptical cross-sections, compared with that in the coaxial cylindrical arrangements without spacers. Note that the field strength has been reduced by about 10 to 22 % compared even with the lowest one of the corresponding cylindrical column spacers with the same values of ε_d and R. The maximal values of E_{tan} in Table 2 are also significantly lower than those in Table 1. Table 2 also shows that the optimized spacers with elliptical cross-sections have better field distributions than those with circular cross-sections.

Concerning the effect of spacer permittivity, the results are quite different between circular cross-section spacers and elliptical cross-section spacers. In the case of circular cross-section spacers, the spacers with higher relative permittivity (ε_d = 6) have lower objective field strength for both E_{tot} optimized and E_{tan} optimized although the difference is very small for E_{tan} optimized. Conversely, in the case of elliptical cross-section spacers, the higher relative permittivity (ε_d = 6) results in higher objective field strength for E_{tan} optimized and very small difference for E_{tot} optimized.

Figure 3 shows the electric field distribution on the surface of a cylindrical column spacer for r = 2.5 cm, R = 3 cm, and ε_d = 6. The electric field distribution is naturally non-uniform as approximately corresponding to an arrangement of coaxial cylinders. We can also notice the change of field strength indicating the triple-junction effect [7] at the uppermost and lowermost parts of the spacer in Figure 3. For the case of a cylindrical column spacer, the electric field approaches zero at the contact between
Figure 5: Electric field distribution on a spacer with elliptical cross-sections for $R = 3$ cm, $\varepsilon_d = 6$, $E_{\text{tot}}$ optimized

Figure 6: Optimized profiles of circular cross-section spacers ($R = 3$ cm)

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References


Figure 7: Optimized profiles of elliptical cross-section spacers ($R = 3$ cm)


