Boundary Element Studies on Insulator Shape and Electric Field around HV Insulators with or without Pollution

S. Chakravorti

Electrical Engineering Department
Jadavpur University, Calcutta, India

H. Steinbigler

Institute of HV Engineering & Electric Power Transmission
Technical University Munich, Munich, Germany

ABSTRACT

Capacitive-resistive field computations are carried out around post-type HV insulators of varying shapes. The boundary element method (BEM) has been employed for electric field computations. Different insulator shapes have been obtained by varying several parameters, which define the shape of the HV insulator contour. For each insulator shape, the maximum stress occurring on the insulator surface has been determined with no surface pollution, uniform surface pollution and also partial surface pollution. For partial pollution, several cases have been studied, in which different sections of the insulator surface are polluted. Furthermore, the effect of electrode radius on the maximum stress on insulator surface has been investigated. The results obtained are presented in this paper in detail.

1 INTRODUCTION

Improvement of HV insulating system reliability demands progress in the design criteria of insulators. Failures of outdoor HV insulators most often involve the solid-air interface of insulators. As a result, a knowledge of the field distribution around HV insulators is very important to determine the electric stresses occurring on the insulator surface, particularly on the air side of the interface.

Several researchers have computed the field distribution around HV insulators under pollution free condition. Mukherjee and Roy [1] calculated the field distribution around a disc insulator of simple geometry. Khan and Alexander [2] accurately modeled a practical disc insulator geometry and Kaana-Nkusi et al. [3] studied the field distribution around a section of a practical post-type insulator. Hazzad et al. [4] and Irvani et al. [5] calculated the field around a string of disc insulators. All these works have been carried out using the charge simulation method [6].

In outdoor applications, HV insulator surfaces are exposed to atmospheric as well as industrial pollution. Hence, the surface of outdoor insulators may get other uniformly polluted or partially polluted. The field around an insulator with no surface pollution is quite different from that with uniform or partial surface pollution. Therefore, it is essential to know the changes in the field distribution around an outdoor insulator caused by surface pollution of different nature and severity.

Considering uniform surface pollution, Abdel-Salam and Saneck [7] computed the field distribution around an insulator having simple geometry, andinger [8] computed the same around a porcelain support insulator. Takuma et al. [9] computed the field, including either volume resistance or surface resistance, around an axi-symmetric spacer, while Kumar and Nagabhushana [10] computed the same around an impulse generator wave-tail resistor. Chakravorti and Mukherjee [11] computed the field around a post type insulator with uniform or non-uniform surface pollution. However, all these studies have been carried out using the charge simulation method. Tang and Raghuvan [12] calculated the field around a HVDC wall bushing with nonuniform surface pollution using the finite element method (FEM).

It has been observed by researchers that the analysis of axi-symmetric electric field distribution by integral methods such as the charge simulation method (CSM) or boundary element method (BEM) is more convenient than by differential techniques such as FEM. It has further been noted that a major problem in CSM is the uncomfortable and subjective placement of simulation charges, which can be obviated by the use of BEM. In recent years the BEM has been successfully employed for electric field calculation in complex 2-D and 3-D systems [13-15] and field calculations including volume and surface resistivities by BEM have also been reported [16-20]. Because the field distribution around an insulator is axi-symmetric in nature and depends upon the insulator geometry, the influence of insulator shape on the field distri-
bution around a post-type insulator has been studied by BEM. Several parameters, which define the shape of insulator contour, are varied and their effects on the stresses occurring on the insulator surface are studied, in the presence as well as in the absence of surface pollution.

In the case of partial surface pollution, the effects of the zone which is polluted also are determined. In addition, for a given insulator shape, the effects of electrode radius on electric stresses with or without surface pollution have been studied. The results of all these studies are presented in detail in this paper.

2 INSULATOR CONFIGURATIONS

Two types of post-insulator configurations, as shown in Figures 1(a) and (b), respectively, are considered for capacitive-resistive field calculations. In both cases, the following are taken into consideration:

1. The insulator is made of porcelain and is surrounded by air.
2. The insulator is stressed between a pair of electrodes, as shown in Figures 1(a) and (b).
3. The bottom electrode is taken as grounded, while the voltage applied to the live electrode is of unity magnitude.
4. The applied voltage is sinusoidal, with frequency of 50 Hz.

Therefore, the insulator-electrode arrangements under consideration have axi-symmetric configuration with two dielectrics. The two configurations shown in Figures 1(a) and (b) differ in the shape of the insulator sheds. For configuration 1 as shown in Figure 1(a), upper as well as lower insulator surfaces have negative slopes, and the slope angle for the upper surface \( \theta_u \) is always higher than that for the lower surface \( \theta_l \). In the case of configuration 2, as shown in Figure 1(b), the upper insulator surface has a negative slope and the lower surface a positive one. However, the slope angle \( \theta \) for both these surfaces are taken to be equal.

3 METHOD OF SIMULATION

The technique described below for the calculation of axi-symmetric capacitive-resistive field distribution is based on the BEM [21]. In this method the electrode and dielectric boundaries are discretized into several boundary elements and a suitable distribution function is introduced for the equivalent surface charges along the discrete boundary.

\[ \phi(i) = \frac{1}{4\pi \varepsilon_0} \int \int \frac{\sigma(M)}{s_{ij}} dS_p + \int \int \frac{\sigma(N)}{s_{ij}} dS_d \]  \( i \in S_p \), \( p = 1, 2, \ldots, P \), \( \sigma \) is the equivalent surface charge density at any node, \( S_p \) the conductor boundary, \( p = 1, 2, \ldots, P \), \( S_d \) the dielectric-dielectric boundary, and \( M \) the index of the boundary nodes lying on the conductor boundary, \( N \) the index of the boundary nodes lying on the dielectric-dielectric interface.

For any point \( I \) on the electrode surface, the potential in the capacitive-resistive field distribution is calculated according to the relationship

\[ \bar{E}(i) = \frac{1}{4\pi \varepsilon_0} \left[ \sum_{p=1}^{P} \int \frac{\sigma(M)}{s_{ij}} dS_p + \sum_{d=1}^{D} \int \frac{\sigma(N)}{s_{ij}} dS_d \right] \]  \( i \in S_p \) , \( p = 1, 2, \ldots, P \), \( M \) is the index of the boundary nodes lying on the conductor boundary, \( N \) the index of the boundary nodes lying on the dielectric-dielectric interface.

In Equation (1), the potential and charge densities are taken as complex quantities instead of having real values, only for calculating the capacitive-resistive field. The complex quantities are marked by an overbar (as in \( \bar{\sigma} \)) in this paper.

If \( \sigma_s \) is the bound surface charge density on the dielectric-dielectric boundary, then the boundary condition at any point \( i \) on the interface of two dielectrics can be written as

\[ \epsilon_1 | \bar{E}_{1in}(i) - \epsilon_2 | \bar{E}_{2in}(i) | = \sigma_s(i) \]  \( i \in S_i, \) \( x = 1, 2 \), \( \bar{E}_{1in} \) and \( \bar{E}_{2in} \) at the point \( i \) can be calculated with orientation towards the dielectric 1 side, as in [21].

\[ \bar{E}_{1in}(i) = \bar{E}_{1n}(i) + \frac{\sigma(i)}{2\epsilon_1} \]  \( i \in S_i, \) \( x = 1 \), \( \frac{\sigma(i)}{2\epsilon_1} \) is the normal component of the electric field intensity at the node \( i \) by charge densities at all the nodes on \( S_i \) [14, 15].

For fields including volume and surface resistivities, \( \sigma_s(i) \) is to be determined from the general condition of the current density vector at the point \( i \) [22]. Considering isotropic materials and sinusoidal fields, this condition can be written as follows [16]

\[ \frac{\bar{E}_{1n}(i) - \bar{E}_{2n}(i)}{\rho_{21}} + \Delta J_s (i) + \text{i} \omega \epsilon_0 \bar{G}_s = 0 \]  \( i \in S_i, \) \( x = 1, 2 \), \( \rho_{21} \) is the volume resistivity of dielectric 2, \( x = 1, 2 \), and \( \Delta J_s(i) = \frac{1}{\rho_{21}} \left[ \frac{\phi(i)}{s(i)} \left\{ \frac{1}{\bar{R}(i)} + \frac{1}{\bar{R}(i+1)} \right\} \right] \]  \( i \in S_i, \) \( x = 1, 2 \), \( \rho_{21} \) is the volume resistivity of dielectric 2, \( x = 1, 2 \), and \( \Delta J_s(i) = \frac{1}{\rho_{21}} \left[ \frac{\phi(i)}{s(i)} \left\{ \frac{1}{\bar{R}(i)} + \frac{1}{\bar{R}(i+1)} \right\} \right] \)  \( i \in S_i, \) \( x = 1, 2 \).
Equations (2) to (5) can be combined together in the following form:
\[
\frac{2(\varepsilon_1 - \varepsilon_2)}{\varepsilon_1 + \varepsilon_2} \nabla \phi_i = -\frac{2\iota}{\omega S(i)}(\varepsilon_1 + \varepsilon_2) \times \left[ \frac{1}{R(i)} \left( \frac{1}{R(i+1)} + \frac{1}{R(i-1)} \right) - \frac{1}{R(i+1)} - \frac{1}{R(i-1)} \right] \varepsilon_3 + \sigma_x = 0 \quad (6)
\]
where
\[
\varepsilon_\omega = \varepsilon_0 \varepsilon_r - \frac{1}{\omega \rho_\omega} \quad (7)
\]
and where \( x = 1, 2 \), \( \omega = 2\pi f \), \( f \) is the frequency, \( S(i) \) is a small area, \( R(i) \) and \( R(i + 1) \) are surface resistances around the node \( i \), respectively. The methods of calculation of \( S(i) \), \( R(i) \) and \( R(i + 1) \) are described in [11]. The nodes with the indices \( i - 1 \), \( i \) and \( i + 1 \) are three consecutive nodes on the dielectric-dielectric boundary. The ordering of the nodes for the use of indices \( i - 1 \), \( i \) and \( i + 1 \) has been discussed in [9].

For the calculation of axisymmetric fields, straight line and elliptic arc elements are used. A linear basis function is assumed for the description of charge distribution along the boundary element between the nodes. For the definition of boundary nodes and elements, adaptive discretization in conformity with electric stress variation has been implemented in this work and the same discretization criterion has been used in all investigations presented in this paper.

For capacitive-resistive field calculation, uniform surface pollution is simulated by a uniform resistivity \( \rho_s \) along the insulator contour. Non-uniform pollution of the insulator surface is simulated by considering different values of \( \rho_s \) at different locations on the insulator surface. No volume conduction has been considered in this purpose and, hence, volume resistivities for both porcelain and air have been taken to be infinite.

A comprehensive program named TWIN based on the formulations described above has been developed and the investigation results described here have been obtained using this program.

4 RESULTS AND DISCUSSION

For an insulator with surface pollution, the field distribution may be capacitive, capacitive-resistive or resistive, depending upon the severity of surface pollution, while for a pollution-free insulator the field is capacitive in nature. The severity of surface pollution has been represented quantitatively by earlier researchers [9, 10, 11] by the range of \( \rho_s \) within which changes in the nature of field distribution take place. Hence, considering uniform surface pollution, field computations are at first carried out to determine the range of \( \rho_s \) within which the field distribution changes from capacitive to capacitive-resistive in nature. It has been observed here that the field is capacitive for \( \rho_s \geq 10^{14}\Omega \) and is resistive for \( \rho_s \leq 10^7\Omega \). For the intermediate values of \( \rho_s \), the field is capacitive-resistive.

Field computations are carried out for different shapes of the two types of insulator contours described in Figures 1(a) and (b). These different shapes are obtained by varying several parameters, which define the shape of insulator contours. The parameters studied in this work are the slope angle of the insulator shed \( \theta_m \), \( \theta_c \) and \( \theta_i \), the insulator shed radius \( r_m \), the insulator core radius \( r_c \), the axial height \( h_s \), the insulator shed outer corner radius \( r_{oc} \), and the inner corner radius \( r_{ic} \). To investigate the influences of various parameters on the electric field distribution, the values of the parameters under consideration are varied within the range of practical applications. It may be noted here that the number of insulator sheds is taken to be 3 in all cases under consideration from the point of view of actual usage. However, neither the formulations presented nor the program mentioned earlier is limited to a given number of sheds only, but are of generalized nature. For each of these insulator shapes, electric stresses are calculated along the insulator surface for three different cases as follows

1. no surface pollution, i.e. capacitive field with \( \rho_s = 10^{14}\Omega \),
2. uniform surface pollution with \( \rho_s = 10^7\Omega \),
3. partial surface pollution for which \( \rho_s \) is set at \( 10^7\Omega \) along the section and of the insulator surface, i.e. from the point of contact of the insulator with the live electrode, to the tip of the topmost insulator shed, while \( \rho_s = \infty \) along the rest of the insulator surface.

The highest stresses occurring on the insulator surface are denoted by \( E_{max} \) for no surface pollution, \( E_{max} \) for uniform surface pollution and \( E_{max} \) for partial surface pollution and are presented in this paper for different insulator shapes. The electric stresses are calculated on the air-side of the porcelain-air interface and are presented in a normalized format \((V/m)/V\), i.e. as electric field intensity per unit magnitude of applied potential difference. For each insulator contour considered, the creepage length \( L_c \) has been calculated also, and is presented here in m. The results obtained are discussed in detail in the following Sections.

4.1 EFFECT OF THE SLOPE ANGLE

For field computations in this case, the following parameters have been kept constant: \( r_m = 0.08 \) m, \( r_c = 0.025 \) m, \( h_s = 0.15 \) m, \( r_{oc} = 0.002 \) m and \( r_{ic} = 0.0045 \) m. The electrode dimensions also are kept constant as follows: electrode radius \( r_e = 0.035 \) m, electrode corner radius \( r_{ec} = 0.005 \) m and electrode height \( h_e = 0.05 \) m.

For configuration 1 as shown in Figure 1(a), results have been obtained for different values of \( \theta_m \) and \( \theta_c \). The values of \( \theta_m \) considered are 0°, 5° and 10° respectively and for each \( \theta_m \) the values of \( \theta_m \) are chosen such that \( \theta_m - \theta_c \) varies from 5° to 20° in steps of 5°. Table 1 presents the values of \( L_c \), \( E_{max} \) for \( E_{max} \) and \( F_{max} \) for all the insulator shapes thus obtained. From Table 1 it may be noted that as \( \theta_m \) decreases, within the range given above, for a given \( \theta_c \), \( L_c \) decreases by 5.7% to 8.8%, \( E_{max} \) increases by 18.7% to 19%, \( E_{max} \) decreases by 4.2% to 4.8% and \( E_{max} \) decreases by 2.2% to 4.3%. On the other hand, when \( \theta_m \) increases from 0° to 10° for a given value of \( \theta_m \), e.g. 23°, \( L_c \) decreases by 9.7%, \( E_{max} \) increases by 14.1%, \( E_{max} \) increases by 3.6% and \( F_{max} \) decreases by 7.2%.

The computed values thus indicate that a higher \( \theta_m \) for a given \( \theta_c \) does not yield notable reduction in stresses, but does lower \( L_c \). On the other hand, a higher \( \theta_c \) for a given \( \theta_m \), with the condition that \( \theta_m > \theta_c \), does give improved stresses and higher \( L_c \).

For configuration 2 as shown in Figure 1(b), the values used for \( \theta_c \) vary from 3° to 15° in steps of 3° and the results of computations are presented in Table 2. In this case it may be noted that as \( \theta_c \) increases, \( L_c \) decreases by 11.6%, \( E_{max} \) increases strongly by 36%, \( E_{max} \) and \( E_{max} \) decrease by 5.7% and 3.7% respectively. Analysis of the results thus shows that an increase in \( \theta_c \) for configuration 2 does not provide notable improvement in electric stresses, but does reduce \( L_c \).
4.2 EFFECT OF INSULATOR SHEDE RADIUS

The following parameters are kept constant for field computations, in this case $r_1 = 0.025$ m, $h_1 = 0.15$ m, $r_{nc} = 0.002$ m, $r_2 = 0.0045$ m, $r_3 = 0.035$ m, $r_4 = 0.005$ m and $h_2 = 0.05$ m. The values of insulator shed radius $r_o$ are varied from 0.06 m to 0.1 m in steps of 0.01 m.

Results have been computed for several shapes of configuration 1 and configuration 2 as reported in Tables 1 and 2 respectively, but the results for only two representative shapes are given in Table 3 onwards. These two cases are configuration 1 with $\theta_1 = 20^\circ$ and $\theta_0 = 0^\circ$ and configuration 2 with $\theta = 30^\circ$ respectively. Table 3 shows that for configuration 1, when $r_o$ increases within the given range, $L_{cr}$ increases by 86.2%, $E_{app}$ decreases strongly by 22.8%, $E_{app}$ decreases by 6.5% and $\delta_{app}$ decreases significantly by 15.2%. Again, for configuration 2 as $r_o$ increases within the same range, $L_{cr}$ increases by 90.2%, notably $E_{app}$ increases and $E_{app}$ decreases by 13.6% and 13.1% respectively, while $\delta_{app}$ decreases by a relatively smaller amount, 4.9%.

A higher value of $r_o$, in addition to increasing $L_{cr}$, does improve the results considerably for configurations 1 and 2 causing lower stresses in the presence of surface pollution, but at the same time increases the stress in the absence of surface pollution.

It may also be observed that, for a given $r_o$ within the specified range, $E_{app}$ for configuration 1 is greater than $E_{app}$ for configuration 2 in the range 0.06 m $\leq r_o \leq 0.08$ m and the difference gradually decreases from 26.9% to 1.2% as $r_o$ increases from 0.06 m to 0.08 m. For $r_o = 0.09$ m, $E_{app}$ values are almost equal for configuration 1 and 2, while for $r_o = 0.1$ m, $E_{app}$ for configuration 2 is 7.7% higher than that for configuration 1. Further, for a given $r_o$ within the specified range $E_{app}$ values are nearly the same for both configuration 1 and 2, the values of configuration 2 being slightly on the higher side and $E_{app}$ for configuration 1 is less than that for configuration 2, the difference increasing from 4.0% to 9.7% with increasing $r_o$.

4.3 EFFECT OF INSULATOR CORE RADIUS

In this case the constant parameters for field computations are as follows: $r_1 = 0.08$ m, $h_1 = 0.15$ m, $r_{nc} = 0.002$ m, $r_2 = 0.0045$ m, $r_3 = 0.035$ m, $r_4 = 0.005$ m and $h_2 = 0.05$ m. Insulator core radius $r_i$ is varied from 0.015 to 0.025 m in steps of 0.002 m.

The results of computations are tabulated in Table 4. For configuration 1 as in Table 4, $L_{cr}$ decreases by 13.1% and $E_{app}$ increases by 1.6% with the increase in $r_i$ within the range mentioned above. On the other hand, as $r_i$ increases within the same range, $E_{app}$ and $E_{app}$ for configuration 1 increase by 0.18% and 4.5% respectively. For configuration 2 as in Table 4, with the increase in $r_i$ within the same range, $L_{cr}$ decreases by 13.4% and $E_{app}$, $E_{app}$ and $E_{app}$ increase by 1.3%, 0.36% and 0.83% respectively.

The results discussed here show that as $r_i$ is increased, $L_{cr}$ decreases and the stresses are increased for configuration 1 as well as for configuration 2, leaving aside $E_{app}$ for configuration 1. However, the incremental changes in the stresses are comparatively low. Again, for a given $r_i$ within the specified range, $E_{app}$ and $E_{app}$ for configuration 1 are greater than those for configuration 2 and $E_{app}$ for configuration 1 is less than that for configuration 2. The differences vary between 8.8% to 11.5%, 0.6% to 0.8% and 6.2% to 10.1% for $E_{app}$, $E_{app}$ and $E_{app}$ respectively.
A higher $h_t$ increases $L_{cr}$ and reduces the stresses for both configuration 1 and 2 in the presence as well as in the absence of surface pollution.

Further, for a given $h_t$ within the range specified above, $E_{\text{inlp}}$ and $E_{\text{outlp}}$ for configuration 1 are lower than those for configuration 2, the differences being in the ranges of 0.6% to 3.9% and 6.1% to 8.9% for $E_{\text{inlp}}$ and $E_{\text{outlp}}$ respectively. But $E_{\text{inlp}}$ for configuration 1 is greater than that for configuration 2, the difference being in the range 0.9% to 17.0%.

### 4.5 EFFECT OF INSULATOR SHED OUTER CORNER RADIUS

In this case the following parameters are kept constant for field computations: $r_o = 0.08$ m, $r_e = 0.0125$ m, $h_t = 0.15$ m, $r_1 = 0.0045$ m, $r_c = 0.035$ m, $r_{\text{ri}} = 0.005$ m and $h_c = 0.05$ m. Insulator shed outer corner radius $r_{\text{oc}}$ is varied from 0.0015 m to 0.0045 m in steps of 0.0005 m.

The computational results are presented in Table 6. Table 6 shows that for configuration 1, as $r_{\text{oc}}$ increases within the range mentioned above, $L_{cr}$ decreases by 1.5%, $E_{\text{inlp}}$ increases by 9.6% and $E_{\text{outlp}}$ and $E_{\text{ripp}}$ decrease by 33.6% and 30.7% respectively. Similarly in the case of configuration 2, with the increase in $r_{\text{oc}}$ within the same range, $L_{cr}$ decreases by 1.6%, $E_{\text{inlp}}$ increases by 12.5% and $E_{\text{outlp}}$ and $E_{\text{ripp}}$ decrease by 38.8% and 32.1% respectively. It is significant to note here that for both configuration 1 and 2, the maximum stresses on the insulator surface in the presence of surface pollution is greatly reduced as $r_{\text{oc}}$ is increased. However, an increased $r_{\text{oc}}$ also reduce $L_{cr}$ to some extent.

Again it may also be noted that, for a given $r_{\text{oc}}$ within the specified range, $E_{\text{inlp}}$ for configuration 1 is greater than $E_{\text{outlp}}$ for configuration 2, the difference being in the range 6.5% to 9.5%. On the other hand, $E_{\text{inlp}}$ and $E_{\text{outlp}}$ for configuration 1 are lower than those for configuration 2, the ranges of difference being 0.3% to 1.4% and 5.8% to 8.3% for $E_{\text{inlp}}$ and $E_{\text{outlp}}$ respectively.

### 4.6 EFFECT OF INSULATOR SHED INNER CORNER RADIUS

There are two inner corners of the insulator shed to be considered, one each at the upper surface and lower surface of the insulator shed respectively. The radii of both the inner corners are taken to be equal in the present study. The value of the insulator shed inner corner radius $r_{\text{ic}}$ is varied from 0.003 to 0.006 m in steps of 0.001 m. The other parameters, which are considered to be constant for field computations are as follows: $r_o = 0.08$ m, $r_e = 0.0125$ m, $h_t = 0.15$ m, $r_{\text{ri}} = 0.005$ m and $h_c = 0.05$ m.

The computed results are tabulated in Table 7. The results show that as $r_{\text{ic}}$ is increased within the range given above, for configuration 1, $L_{cr}$ decreases by 13.3%, $E_{\text{inlp}}$ and $E_{\text{outlp}}$ decrease by 1.9% and 0.15% respectively and $E_{\text{ripp}}$ is maximum for $r_{\text{ic}} = 0.0045$ m. But
Table 6. Effect of the insulator shed outer corner radius on the creepage length and maximum stress on the insulator surface. $\theta_a, \theta_m$, and $\theta$ are in degree ($^\circ$).

<table>
<thead>
<tr>
<th>$r_{oc}$ m</th>
<th>Config 1</th>
<th>Config 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Theta_m = 20$, $\Theta_a = 10$</td>
<td>$\Theta = 3$</td>
</tr>
<tr>
<td>0.0015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{oc}$</td>
<td>6.3174</td>
<td>5.3675</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>21.24</td>
<td>19.21</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>67.94</td>
<td>60.18</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>77.35</td>
<td>83.41</td>
</tr>
<tr>
<td>0.0002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{oc}$</td>
<td>0.3708</td>
<td>0.3493</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>24.70</td>
<td>20.79</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>51.77</td>
<td>52.23</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>70.52</td>
<td>74.92</td>
</tr>
<tr>
<td>0.0005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{oc}$</td>
<td>0.3748</td>
<td>0.3621</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>22.33</td>
<td>20.79</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>52.98</td>
<td>53.37</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>63.73</td>
<td>68.85</td>
</tr>
<tr>
<td>0.0003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{oc}$</td>
<td>0.3784</td>
<td>0.3923</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>22.80</td>
<td>21.23</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>40.04</td>
<td>40.43</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>56.30</td>
<td>56.85</td>
</tr>
<tr>
<td>0.0004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{oc}$</td>
<td>0.3732</td>
<td>0.3618</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>22.68</td>
<td>21.61</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>37.74</td>
<td>38.19</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>55.55</td>
<td>56.65</td>
</tr>
</tbody>
</table>

The difference between the minimum value of $E_{mp}$, which occurs for $r_{oc} = 0.003$ m and this maximum value of $E_{mp}$, is 2.7%. Again, for configuration 2, with the increase in $r_{oc}$ within the same range, $L_{oc}$ decreases by 15.5%, $E_{mp}$ decreases by 8.3%, $E_{mp}$ increases by 0.25% and $E_{mp}$ is minimum for $r_{oc} = 0.0045$ m. The difference between this minimum value of $E_{mp}$ and the maximum value of $E_{mp}$, which occurs for $r_{oc} = 0.006$ m is only 0.46%. It may thus be noted that $r_{oc}$ has very little effect on the maximum stresses occurring on the insulator surface, particularly with surface pollution. But an increased $r_{oc}$ reduces $L_{oc}$ by a significant amount.

4.7 EFFECT OF ELECTRODE RADIUS

Apart from studying the effects of various parameters defining the shape of the insulator contour, the effects of the electrode radius on the electric stresses occurring on the insulator surface have also been studied. The value of electrode radius $r_e$ is varied from 0.035 to 0.06 m in steps of 0.005 m. The parameters kept constant for field computations in this case are as follows: $r_c = 0.05$ m, $r_t = 0.025$ m, $h_i = 0.15$ m, $r_{oc} = 0.002$ m, $r_{nc} = 0.0045$ m, $r_{nc} = 0.005$ m and $h_a = 0.05$ m.

The results of computations for different values of $r_e$ are presented in Table 8. Table 8 shows that, as $r_e$ is increased within the range mentioned above, for configuration 1 $E_{mp}$ increases by 22.1%, $E_{mp}$ and $E_{mp}$ decrease by 11.2% and 6.5% respectively and for configuration 2 $E_{mp}$ and $E_{mp}$ decrease by 13.7% and 8.4% respectively. $E_{mp}$ for configuration 2 is minimum for $r_e = 0.05$ m and the difference between this minimum value and the maximum value of $E_{mp}$, which occurs for $r_e = 0.035$ m, is 19.1%. Thus it is found that a higher value of $r_e$ reduces the maximum stress on the insulator surface in the presence of surface pollution. Further, for a given $r_e$ within the specified range, $E_{mp}$ for configuration 1 is higher than that for configuration 2 and $E_{mp}$ for configuration 1 is lower than that for configuration 2, the difference being in the range of 8.8% to 33.4% and 4.1% to 61% for $E_{mp}$ and $E_{mp}$ respectively. $E_{mp}$ for configuration 1 is nearly equal to $E_{mp}$ for configuration 2 when $r_e = 0.045$ m. Again, for a given $r_e$, $E_{mp}$ for configuration 1 is less than that for configuration 2 when $r_e < 0.045$ m and is higher than that for configuration 2 when $r_e > 0.045$ m, the differences lying within 0.35% to 2.8%.
Table 9. Effect of the partial surface pollution zone on the maximum stress on the insulator surface. \( \theta_0 \), \( \theta_1 \), and \( \theta_2 \) are in degree (°).

<table>
<thead>
<tr>
<th>Partial poll zone</th>
<th>Conf 1</th>
<th>Conf 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-d</td>
<td>76.50</td>
<td>50.71</td>
</tr>
<tr>
<td>b-f</td>
<td>51.82</td>
<td>61.71</td>
</tr>
<tr>
<td>a-g</td>
<td>52.92</td>
<td>37.54</td>
</tr>
<tr>
<td>c-i</td>
<td>73.83</td>
<td>60.23</td>
</tr>
<tr>
<td>a-k</td>
<td>60.72</td>
<td>57.95</td>
</tr>
</tbody>
</table>

4.8 EFFECT OF THE ZONE OF PARTIAL SURFACE POLLUTION

In the earlier Sections of this paper, the zone of partial surface pollution is considered to be the section a-d of the insulator surface, Figure 1. In addition to this zone, studies have been carried out also for several other zones of partial surface pollution. These studies include cases, where multiple sections of the insulator surface, which need not be continuous, are considered to be polluted simultaneously. In each case \( \mu_p \), in the polluted zone is taken to be \( 10^7 \Omega \) and that be infinite in the other parts of the insulator surface. Table 9 presents the results of these computations. In all these field computations the following parameters are taken to be constant: \( r_c = 0.08 \) m, \( r_1 = 0.015 \) m, \( r_c = 0.002 \) m, \( r_c = 0.0045 \) m, \( r_c = 0.035 \) m, \( r_c = 0.005 \) m, and \( h_c = 0.05 \) m.

In Table 9, results for six different cases of partially polluted insulator surface where the polluted sections are taken to be continuous, are given. For both configuration 1 and 2, \( E_{\text{app}} \) is highest in the case, when the section a-d of Figure 1 is the insulator surface is polluted. Compared to the values of \( E_{\text{app}} \) in the case when the section a-d of Figure 1 is polluted, which are discussed in the earlier Sections, these highest values of \( E_{\text{app}} \) are 66.2% and 48.7% higher for configuration 1 and 2, respectively. Results for four different cases of discontinuous multiple insulator sections, which are polluted simultaneously are also reported in Table 9. Compared to the case when the section a-d of Figure 1 is polluted, \( E_{\text{app}} \) for multiple polluted zones for configuration 1 are lower or nearly equal and the same for configuration 2 are higher. In other words, for simultaneous multiple polluted zones on the insulator surface, \( E_{\text{app}} \) for configuration 1 is lower than that for configuration 2. For multiple polluted zones, worst results are obtained when the sections a-d, b-f and k-n of Figure 1 are polluted simultaneously. However, the stresses for this case are much lower, compared to the case when the section a-d of Figure 1 is polluted only.

5 CONCLUSIONS

Effects of various parameters, which define the shape of insulator contour, on the electric stresses occurring on the insulator surface with or without surface pollution have been studied by IEM. Considering the maximum stress on insulator surface it has been found that better results may be obtained in the case of configuration 1 and 2 for (1) a higher \( r_c \), particularly in the presence of surface pollution, and (2) higher \( h_c \) and \( r_c \), both with or without surface pollution.

Similarly in the case of configuration 1, better results may be obtained for a higher \( \theta_0 \) for a given \( \theta_0 \), with the condition \( \theta_0 > \theta_0 \). It has also been noted that \( r_c \) and \( \theta_0 \) have negligible effects on the maximum stresses. Studies also show that the zone of partial surface pollution influence the maximum stresses significantly. For a given insulator shape, a higher value of electrode radius is found to reduce the maximum stresses in the presence of surface pollution for both configuration 1 and 2.

ACKNOWLEDGMENT

The authors wish to thank Alexander von Humboldt-Stiftung, Germany, as the work has been carried out at the Technical University Munich, Germany, where Dr. S. Chakravorti worked as Alexander von Humboldt-Stiftung research fellow.

REFERENCES


Manuscript was received on 28 May 1998, in final form 2 October 1999.