7.1 INTRODUCTION

In this Chapter, the Combination Method of Charges, which was evolved from the modified form of CSM and SSM, is applied for practical problems. This method overcomes some of the deficiencies of CSM and SSM. It is capable of solving problems having more than two dielectric regions and thin regions. Results obtained with this Combination Method for a composite insulator used in pollution-prone areas and for a high voltage surge diverter with a floating ring are discussed in this Chapter.

7.2 THREE-DIELECTRIC HIGH VOLTAGE PROBLEMS

7.2.1 Configuration of a HV composite insulator with 3-dielectric regions

A composite insulator used in high voltage transmission lines in polluted areas was taken up for study. Figure 7.1 shows the configuration of the insulator with three different dielectric regions. Studies were conducted with CSM, SSM and the Combination Method.

The numbers in Figure 7.1 indicate different parts of the insulator as follows: 1 and 2 - ground electrode; 3 - FRP rod; 4, 5 and 6 - silicone rubber covering and its small and large sheds; 7 and 8 - HV electrode.
The dimensions of the insulator are: Insulator length = 0.36 m, outer diameter of the electrode caps near the insulator = 0.075 m, electrode shaft diameter = 0.04 m, inner and outer diameters of the silicone rubber covering = 0.026 m and 0.042 m, shed thickness = 0.002 m at the tip and 0.004 m at the root, shed diameter = 0.09 m (smaller) and 0.12 m (larger). Height of the HV conductor from ground = 6m. For the purpose of the study, the potential of the HV electrode was taken as 1 per unit volt. Dielectric constants of the FRP rod and the silicone rubber were taken as 4.5 and 3.0 respectively.

7.2.2 Application of CSM for HV composite insulator without sheds

The silicone rubber sheds of the composite insulator shown in Figure 7.1 are very thin, having sharp edges. Hence attempts to solve this problem with CSM...
were not successful, due to near-singularity. Simulation of the sheds resulted in an extremely large matrix size and the associated computational difficulties.

However, for comparison of results with other methods, sheds were omitted and the problem was solved, assuming that the rubber covering was uniform without sheds. Results obtained with CSM for the potential and field patterns along the insulator surface are shown as broken lines in Figure 7.2.

Figure 7.2 Potential and field patterns with CSM (broken lines) and with SSM (solid lines) omitting the sheds

In this study with CSM, the matrix size was 104x104 and the matrix condition number was 15895. The errors in computation of field (RMS field discrepancies) were, 9.1 % and 6.6 % at the electrode surface and the dielectric interfaces respectively, with AF at 1.4. An attempt was made to solve this problem with increased number of discrete charges, omitting the sheds as above, but the results were not satisfactory due to ill conditioning of the matrix when the number of charges were above 350. The diameter of the FRP rod and the thickness of the rubber covering
of the insulator are very small compared to the length and hence application of CSM was found to be difficult in this case.

7.2.3 Application of SSM for HV composite insulator without sheds

Results obtained with SSM for the problem given in Figure 7.1, omitting the sheds, are given as solid lines in Figure 7.2. The matrix size was 76x76 and its condition number was 6580. The errors in computation were within 3.8%. The matrix condition-number and the percentage errors in computation with SSM were very small, compared to that of CSM. But the computation time with SSM was about 6 times that of CSM. In SSM, surface integration over the boundary elements requires more computer-time.

The curves obtained with CSM (broken lines) slightly deviate from those of SSM (solid lines in Figure 7.2), due to the increased errors in the results with CSM.

7.2.4 Application of the Combination Method for HV composite insulator without sheds

The Combination Method was applied for the HV composite insulator without sheds, by simulating the surfaces of the electrodes with discrete charges (with AF at 1.4) and the dielectric interfaces with distributed charges. The matrix size in this case was 85x85 and the matrix condition number was 7215. The results were found to be almost similar to that of SSM, but the computation time was only about 35% that of SSM. The errors in computation were within 4%.

7.2.5 Application of SSM for HV composite insulator inclusive of sheds

The results obtained with SSM for the configuration in Figure 7.1 inclusive of sheds are given in Figure 7.3. The solid line and the broken line are the
field pattern and the potential distribution respectively, along the interior of the interface of the silicone rubber with air. In this case the matrix size was $121 \times 121$ and the matrix condition number was 8550. The errors in computation were within 4%. Even in this case, the matrix condition number and the errors in computation with SSM were very small, compared to the results with CSM for the insulator without sheds. As already seen, solution to the composite insulator configuration inclusive of sheds is not feasible with CSM.

![Figure 7.3 Potential distribution and field plot obtained with SSM](image)

7.2.6 Application of the Combination Method for HV composite insulator inclusive of sheds

The problem shown in Figure 7.1 inclusive of sheds was solved with the Combination Method. Simulation of discrete charges is advantageous for smooth, bulky regions. The configuration of the electrodes was simulated with discrete charges, adopting AF at 1.4 and the dielectric interfaces with distributed charges.
Results obtained with this method were almost close to the results with SSM shown in Figure 7.3. Differences between the results of SSM and the Combination Method were negligible, since simulation of the dielectric interfaces was similar in both the methods, using distributed charges. The matrix size in this case was 130x130. The errors in computation were within 4\% for both the electrode surface and the dielectric interfaces. The time taken for computation was only about 40\% of the time involved with SSM.

7.2.7 Results with the Combination Method for the insulator with discrete charges for the electrodes and the interface of the FRP rod

The same problem was solved with the Combination Method, by simulating discrete charges for the electrodes and also for the interface between the FRP rod and the silicone rubber covering. Distributed charges were simulated for the interface between the silicone rubber and the surrounding air.

In this case the matrix size increased to 170x 170. This was as expected, since the dielectric interface between the thin, long FRP rod and the silicone rubber requires simulation of a large number of discrete charges on both sides of the interface.

The errors in computation increased to about 8\%. The results were found to be less accurate compared to that given in section 7.2.6. This study indicates the necessity for a judicious choice of the types of charges to be applied for the boundaries, to get a better solution.

Though the matrix size increased in this case, the computation time was only about half that of SSM. The boundary area subjected to surface integration was considerably reduced, while applying discrete charges for both the electrode surfaces
and the interface between the FRP rod and the silicone rubber. Therefore the overall computation time was less than that of SSM.

In the case of the Combination Method, the matrix size is in general smaller, compared to CSM. In complex problems where the number of charges simulated with CSM becomes extremely large, matrix solution takes a very long time. For an increase in matrix size to \(n\) times, the number of matrix elements increases to \(n^2\) times and the time to solve the matrix increases to about \(n^3\) times (William H. Press et. al 1993). In such complicated problems, the computation time with the Combination Method could be less than that of both CSM and SSM.

### 7.3 STUDIES ON A HIGH VOLTAGE SURGE DIVERTER

Many high voltage problems require studies on the effect of floating electrodes over the field pattern. For example, floating rings together with shielding electrodes are used in EHV surge diverters. The influence of the floating electrodes and the shielding rings over the stress along the diverter units has to be accurately determined. The extremely small cross section of the diverter elements and the housing makes it impossible to apply CSM for studies on surge diverters. Hence studies were conducted with the Combination Method and SSM on a 400 kV surge diverter and the results are given below.

#### 7.3.1 Details of the configuration of a 400 kV surge diverter

Figure 7.4 shows a 400 kV surge diverter having four units assembled one over the other. An enlarged view of the top unit together with the metal fittings for stress control is also shown. The dimensions of the surge diverter shown in Figure 7.4 are: \(A = 0.76\) meter, \(B = 0.2\) m, \(C = 0.44\) m (this quantity was varied for the study), \(D = 1.2\) m, \(E = 1.02\) m (this quantity was also varied for the study), \(F = 0.78\) m, \(G = 0.18\) m, \(H = 0.12\) m, \(J = 0.28\) m and \(K = 0.36\) m. The thickness of the metal rods connected to
the rings was assumed as 2.5 cm. Most of the data are within the range of values adopted by some of the manufacturers of surge diverters.

The surge diverter has four identical units, each having cylindrical zinc oxide blocks (ZnO) of diameter 0.065 meter. These ZnO blocks are enclosed by a hollow-cylindrical porcelain insulator whose inner and outer diameters are 0.12 and 0.18 meters respectively, with metal caps at the ends of the porcelain housing. The outer shed diameter of the porcelain block is 0.28 meter. The ZnO blocks under non-conducting state has a dielectric constant of $\varepsilon_r = 800$ approximately (Kojima et al. 1988). For all the studies in this section, AF was assigned with a value of 1.4 for simulation of discrete charges. Floating electrodes were simulated with a fictitious dielectric constant of 45000. The dielectric constant of the porcelain insulator was taken as 5.5.

Figure 7.4  A 400 kV surge diverter and the enlarged view of its top unit (not to scale)
7.3.2 Study with the Combination Method on the bottom unit of the 400 kV surge diverter

For the purpose of determining the influence of the porcelain sheds over the stress pattern on the diverter elements, a study was conducted on the bottom unit of the surge diverter (Figure 7.4). The metal cap on top of this bottom unit was assumed at a potential of 1 per unit volt. The top three units were omitted in this study. The Combination Method of Charges was applied, simulating 39 discrete ring charges for the top and bottom metal parts and distributed charges along the surface of the ZnO elements and along the porcelain-air interfaces.

Figure 7.5 shows the potential and field patterns along the interior of the surface of the ZnO elements, in the absence of the sheds in the porcelain housing. The matrix size was 73x73 and its condition number was 8505. The computational error was 2.69%. The computation time was 22 seconds.

Figure 7.5 Potential and field inside the diverter elements in the absence of sheds in the porcelain housing
Figure 7.6 shows the corresponding graphs with the provision of 8 sheds on the porcelain housing of the bottom unit. The pattern of the graphs in Figures 7.5 and 7.6 are almost similar except that there is a slight oscillation in the stress pattern in Figure 7.6, within the range of about ± 3%, due to the influence of the sheds. In this study, the matrix size was 189x189 and the matrix condition number was 13333. The computational error was 2.58%.

In practical configurations, smaller sheds are also provided in between the larger sheds of the porcelain housing. In this study, only the larger sheds were considered. Moreover, the number of larger sheds in practical configurations is slightly more than that considered in this study. Therefore the overall effect of the sheds on the stress pattern in the ZnO elements in practical conditions will be less than the deviations seen in Figure 7.6.

![Diagram](https://via.placeholder.com/150)

**Figure 7.6** Potential and field inside the surface of the diverter elements including the effect of the porcelain sheds
Figure 7.7 shows the potential and field patterns along the interior of the interface between the porcelain (with 8 sheds) and the outer air region for the bottom unit.

![Diagram of potential and field](image)

**Figure 7.7** Potential and field inside the interface of the porcelain housing and air

**7.3.3 Study with the Combination Method on a 400 kV surge diverter without the shielding and floating rings**

Applying the Combination Method of Charges, a study was conducted on 400 kV surge diverter without the stress control electrodes. All the dimensions and data given in section 7.3.1 for the surge diverter (Figure 7.4) were adopted for the study, except that all the external metal fittings, *i.e.*, the shielding rings, floating ring and the attached metal rods were omitted. Moreover, the sheds on the porcelain housing were also omitted, as their influence on the field pattern in the diverter elements is very little, as seen from the previous study. This study would be useful for comparing the results of the subsequent studies inclusive of the fittings.
The surge diverter was assumed to be at a potential of one per unit volt. All the metal caps, including the intermittent caps at floating potential were simulated with discrete charges. The surface of the surge diverter elements and the porcelain interfaces were simulated with distributed charges. The computed field pattern is given in Figure 7.8. The maximum stress in the diverter elements was about 2.25 V (p.u.)/m. While conducting these studies, it was observed that the field pattern is highly sensitive to the configuration of the metal caps. Even for a small change in the configuration of the caps, a large variation in the field pattern was observed.

![Figure 7.8](image_url)  

**Figure 7.8**  Field inside the surge diverter in the absence of all the shielding electrodes and the floating ring

7.3.4 Study with the Combination Method on 400 kV surge diverter (omitting some of the stress control electrodes)

For a high voltage surge diverter to function satisfactorily, the stress distribution has to be uniform inside the diverter elements. Due to the increased height
of the surge diverters in high voltage applications, the stress distribution becomes highly non-uniform. Shielding electrodes and floating rings are provided to reduce this non-uniformity in the diverter. For the purpose of assessing the effectiveness of the stress-control electrodes, a study was conducted using the Combination Method on the surge diverter, excluding the two shielding rings numbered as 2 and 3 in Figure 7.4. All other fittings were included for the study. All the sheds in the porcelain housing were also omitted.

In this study, the surge diverter was assumed at 1 per unit volt. The metal caps, the shielding and floating rings and the connecting metal rods were simulated with discrete charges. The surface of the ZnO elements and the interface of the porcelain housing were simulated with distributed charges. Results of the studies are given in Figure 7.9. The maximum stress in the ZnO elements in the top arrester unit was about 0.6 V(p.u.)/m. The maximum stress was thus reduced to about 27% of that observed in section 7.3.3. The potential difference across the top arrester unit was 0.561 V(p.u.). Detailed studies on this configuration of the diverter indicated that the thin metal spokes connected to the rings had negligible influence on the field pattern in the ZnO elements.

A further study was conducted on the surge diverter, omitting the shielding rings numbered as 2 & 3 and also the floating ring numbered as 4 (Figure 7.4). The results are shown in Figure 7.10. In this case, the maximum stress in the ZnO elements in the top arrester unit was about 0.58 V(p.u.)/m. The potential difference across the top arrester unit was 0.536 V(p.u.), a reduction by about 0.025 V(p.u.), compared with the results given in Figure 7.9.
Figure 7.9  Field inside the surge diverter in the absence of the shielding electrodes 2 and 3

Figure 7.10  Field inside the surge diverter in the absence of the shielding electrodes 2 & 3 and the floating ring
The effect of the capacitance between the floating ring electrode and the bottom electrodes including the earth is seen to be more predominant than that of the capacitance between the shielding electrode arrangements and the floating ring electrode. Hence omission of the floating ring electrode slightly reduces the potential difference across the top unit in this case.

7.3.5 Study with the Combination Method on surge diverter with all the stress control electrodes

For this study, all the stress control electrodes shown in Figure 7.4 were included. However, the sheds in the porcelain housing were omitted as in the previous study. The dimensions and the data given in section 7.3.1 were adopted for this study. The shielding electrodes numbered as 1, 2 and 3 in Figure 7.4 were at the geometrical locations given in Table 7.1.

Table 7.1 Geometrical locations of the shielding electrodes

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Configuration details &amp; locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter (m)</td>
</tr>
<tr>
<td>Shielding ring -1</td>
<td>1.02</td>
</tr>
<tr>
<td>Shielding ring -2</td>
<td>1.02</td>
</tr>
<tr>
<td>Shielding ring -3</td>
<td>1.02</td>
</tr>
</tbody>
</table>

The Combination Method of Charges was applied for the study. All the electrode surfaces were simulated with discrete charges. The surface of the diverter elements and the interface of the porcelain housing were simulated with distributed charges. The matrix size and the matrix condition number were 188x188 and 483724 respectively. The errors in the computed results were within 4.19%. The computation time was 55 seconds. The maximum stress in the diverter elements in the top unit was
about 0.6 V(p.u.)/m. The computed potential difference across the top diverter unit was found to be 0.38 V (p.u.). The potential and field patterns in the ZnO elements are shown in Figure 7.11.

![Figure 7.11 Potential and Field in the surge diverter with all the shielding electrodes and the floating ring](image)

Figure 7.11 Potential and Field in the surge diverter with all the shielding electrodes and the floating ring

### 7.3.6 Study with SSM on surge diverter with all the stress control electrodes

A study was conducted with SSM on the surge diverter (Figure 7.4) with all the stress control devices, with the same dimensions as in section 7.3.5.

Difficulty was experienced in applying SSM to this configuration. The boundaries of the shielding rings, floating ring and the spokes had to be divided into several elements. This increased the matrix size. This also caused difficulty in computation.
While applying the Combination Method of Charges, simulation of a few discrete ring charges for the ring electrodes were sufficient to yield satisfactory solution. Simulation of the spokes with a few discrete line charges was also sufficient.

But, due to the highly non-uniform charge distribution on the rings (along the periphery of the cross sections) and along the circumference of the rods, division of their surfaces into several elements was necessary for accurate simulation of distributed charges with SSM. Lesser number of boundary elements in such cases resulted in increased errors in computation, while large number of elements led to the computational difficulties like near-singularity.

Near-singularity was often experienced with SSM for this problem. After several attempts to divide the boundaries into suitable boundary elements, the problem was solved with SSM and the results are given in Figure 7.12.

![Graph showing potential and field versus height](image)

**Figure 7.12** Results with SSM for the surge diverter with all the shielding electrodes and floating ring
As the thickness of each of these electrodes is very small, this type of difficulty was experienced with SSM. The possibility of occurrence of such errors with the application of BEM (for a study on the non-uniform field in spherical particles) has been reported in the existing literature too (Boonchai Techaumnat et al. 2003).

Results with SSM are almost similar to that of the Combination Method given in Figure 7.11. However, compared to the results with the Combination Method, application of SSM yielded an increased stress in ZnO elements close to the top electrode. This increase near the top electrode could be due to the coarse boundary elements adopted in SSM in this case.

It is seen from the results with SSM, that the maximum stress in the diverter elements in the top unit was about 0.585 V(p.u.)/m. The potential difference across the top diverter unit was 0.414 V (p.u.). The matrix size and the matrix condition number were 223x223 and 728042 respectively. The errors at the electrode surfaces were within 3.15%. The computation time for this study was 2 minutes.

7.3.7 Study with the Combination Method on surge diverter with modified locations for the shielding electrodes

Studies so far discussed in this Chapter show how the shielding electrodes and floating electrodes could modify the stress distribution in surge diverters. However, despite provision of these electrodes for stress control, the diverter elements in different arrester units experience different levels of electric stress.

The three shielding electrodes- the rings 1, 2 and 3 indicated in Figure 7.4 and in Table 7.1 are of the same size. Their locations, one above the other, are not in a favourable disposition to bring about an appreciable increase in the inter-electrode capacitance between the top electrode and the floating electrode.
Hence, the data given in Table 7.1 in respect of the shielding electrodes were modified for this study with the aim of increasing this inter-electrode capacitance. The modified data are given in Table 7.2. Adopting these revised data for the shielding electrodes and applying all other data that are given in section 7.3.1, a study was conducted with the Combination Method of Charges on the surge diverter. The results of the study are given in Figure 7.13.

Table 7.2 Modified dimensions and locations of the shielding electrodes

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Configuration details &amp; locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter (m)</td>
</tr>
<tr>
<td>Shielding ring -1</td>
<td>1.42</td>
</tr>
<tr>
<td>Shielding ring -2</td>
<td>1.66</td>
</tr>
<tr>
<td>Shielding ring -3</td>
<td>1.90</td>
</tr>
</tbody>
</table>

The matrix condition number in this study was 592176. The results show an improved potential distribution. The potential difference across the diverter elements in the top unit was reduced to 0.271 V (p.u.) in this study. The maximum stress of about 0.42 V(p.u.)/m occurs in the third unit from the ground. Reduction of the stress in the third unit mainly depends on the modification of the floating ring electrode, the ring-4 in Figure 7.4.
A study was conducted on a high voltage composite insulator having a thin FRP rod and silicone rubber insulation around the FRP rod. The thin sheds of the rubber covering could not be simulated with CSM. For the purpose of comparison of results, the sheds were omitted and studies were conducted with CSM, SSM and the Combination Method of Charges. The results with SSM and the Combination Method of Charges are almost similar while the results with CSM are a little less-accurate and slightly deviate from that of the other two methods. Studies were conducted on the insulator inclusive of the sheds, applying SSM and the Combination Method. Results with these two methods are found to be similar, but the time taken by the Combination Method was about half that of SSM or even less in these studies.
Studies were also conducted on a 400 kV surge diverter. CSM could not be applied to this problem, due to the very narrow regions of the diverter elements and the surrounding porcelain housing. While applying the Combination Method for this problem, the floating electrodes were simulated as dielectric regions with a fictitious dielectric constant of 45000.

The effect of the sheds in the porcelain housing on the field inside the diverter elements was studied. It was observed that the field pattern in the diverter elements had fluctuations within the range of about ± 3%, due to the presence of sheds. The sheds in the porcelain housing were omitted while conducting further studies on the surge diverter.

Studies were conducted on the surge diverter, first by omitting all the external stress control electrodes and then omitting only the shielding rings 2 and 3 shown in Figure 7.4. The maximum stress in the latter configuration was only about 27% that of the former.

Computations were made for the surge diverter with all the shielding electrodes and the floating ring electrode shown in Figure 7.4. Both the Combination Method of Charges and SSM were applied for computation. Results of these two methods were found to be almost similar except near the top electrode. Difficulties were also experienced in the application of SSM in simulation of the ring electrodes.

The configuration of the shielding electrodes was slightly altered, increasing their diameters unevenly and lowering their geometrical positions. Computation was made with the Combination Method for this modified configuration. Stress distribution in the diverter elements in this case was found to be comparatively better.
The above studies indicate that appropriate geometrical locations and configurations of HV electrodes and floating electrodes play an important role in bringing down the electric stress.

For simulation of the shielding rings and the rods, only a few discrete charges are required, whereas the number of boundary elements over these conducting surfaces and the associated computer time would be very large if distributed charges are simulated.

Some manufacturers use shielding electrodes with diameters up to 1.5 meters and hence the modified data in Table 7.2 are slightly exaggerated for the purpose of the study. If the actual site conditions of the surge diverters including the bus bars, jumpers and nearby equipments are included, the dimensions of the shielding electrodes could be reduced to get the same desired result.