CHAPTER 5

CHARGE SIMULATION METHOD FOR FLOATING ELECTRODE PROBLEMS

5.1 INTRODUCTION

Various stress control techniques are adopted for reduction of electric stress in high voltage equipment. One of the most important techniques of stress control is the provision of floating electrodes. Suitable configurations and locations for these electrodes have to be determined, to achieve better stress control. Some researchers have reported that CSM cannot be effectively applied to floating electrode problems. However, not enough work has been done for modification or improvement to CSM, to get satisfactory solutions to floating electrode problems.

In this chapter, the methodology of successful application of CSM for floating electrode problems is discussed.

5.2 FLOATING ELECTRODE PROBLEMS

5.2.1 Boundary conditions for simulation of floating electrodes

Floating electrodes are not directly connected to any potential source. Under static conditions, induced charges would appear at the surface of the floating electrodes in the presence of an external electric field. Due to these induced charges, the field pattern around the electrodes is altered. These induced charges have to be simulated to determine the altered potential and field pattern due to the floating
electrodes. The determination of this altered field pattern is more important in the design of high voltage equipment. Hence accurate simulation of floating electrodes plays an important role.

Boundary conditions have to be applied to solve any electrostatic field problem. The boundary conditions for a floating electrode are, i) its surface is at equipotential and ii) the sum of the induced charges at its surface is zero. The second condition does not include the charges transferred to its surface from an external source through a leaky or conductive surrounding medium. If however, such accumulated charges are also present, then this condition is modified and the net charge at the surface of the floating conductor is equated to the charge so transferred. To apply this modified condition, knowledge of the quantum of charges so transferred is required. These two conditions are used in many numerical methods including CSM, to solve the floating electrode problems.

As a conductor, a floating electrode exhibits the following properties under static conditions.

i) Electric field terminates perpendicularly at the exterior of its surface. This also means that no tangential component of the field could exist at its surface.

ii) Electric field inside the floating electrode is zero. This means that charges if any, would appear only at the surface of the electrode.

The first property is the alternative form of the first boundary condition stated above. The second property is more explicit in explaining how the charges would redistribute among themselves at the surface of the floating electrode in the presence of an external field, without violating the first property. These two properties could also be used as alternative forms of boundary conditions, though it is a little difficult to simulate them.
5.2.2 Simulation of floating electrodes in CSM

If \( nf \) number of discrete charges are simulated inside a floating electrode, an equal number of potential equations could be formed, one each for the respective contour point. However, potential values at the contour points are unknown beforehand.

Nazar H. Malik (1989) has given the details of the earlier studies with CSM for problems involving floating electrodes. Solutions have been attempted for these problems, with the inclusion of the supplementary condition that the sum of the inner charges on each floating electrode is zero. If the floating electrode has a net charge, then the sum of its inner charges is equated to the known net charge value.

El-Kishky et al. (1994) have discussed the method of solving floating electrode problems by equating the sum of the induced charges at the floating electrodes to zero. They have cautioned that the coefficient matrix may change to an ill conditioned one or it would be numerically nearly singular unless the locations of charges and boundary points are judiciously chosen.

The potential equations, one for each contour point at the surface of the floating electrode are of the form

\[
\sum_{j=1}^{\delta} P_{ij} Q_j = V_k
\]  

(5.1)

where

\( V_k \) is the unknown uniform potential at the floating electrode.

If \( ne, nf, nd \) and \( na \) are the number of charges simulated inside the electrodes, floating electrodes, dielectric region and air medium respectively in a two dielectric problem, the potential equation for each contour point at the surface of the floating electrode can be written as
\[ \sum_{j=1}^{ne+nf+nd} P_{ij} Q_j - V_i = 0.0 \quad (5.2) \]
to satisfy the boundary conditions at the contour points of the floating electrode on
the air side, and

\[ \sum_{j=1}^{ne+nf+nd} P_{ij} Q_j - V_i = 0.0 \quad (5.3) \]
to satisfy the conditions at the contour points on the dielectric side.

Equations (5.2) and (5.3) are obtained by writing down the difference
between two equations satisfying the boundary conditions (equi-potential surface) of a
given floating electrode. Thus, the unknown value of the floating-electrode potential
on the right hand side of the equation (5.1) is eliminated. In this process, a total of \((nf-1)\) linear independent equations are obtained for a floating electrode with \(nf\) number of
simulated charges.

An additional equation is formed, by introducing the condition that the net
charge inside a given floating electrode is zero (or a known value, in case this
electrode possesses some accumulated charge). This supplementary equation for a
given floating electrode with \(nf\) number of charges is

\[ Q = \sum_{j=1}^{nf} Q_j = 0.0 \quad (5.4) \]
where \(Q\) is the sum of all the charges inside a floating electrode.

Equations (5.2), (5.3) and (5.4), satisfying the boundary conditions of
floating electrodes, together with the equations applicable for other boundaries, form a
set of linear equations. Solution to this set of equations gives the unknown values of
charges, from which the floating electrode potential is computed. However, matrix ill-
conditioning or near singular situations occur in many cases and it is difficult to get a
satisfactory solution to floating electrode problems with CSM.
5.2.3 Simulation of floating electrodes in other numerical methods

Equation (5.4) used in CSM for floating electrode problems is applied in other methods also. In the Fast Adaptive Multi-pole - Boundary Element Method (FAM-BEM), Andre Buchau et al. (2001) have applied this equation for simulation of a floating conducting particle. In this case, summation is carried out through surface-integration as shown below.

\[ Q = \oint D_n ds = 0.0 \]  

(5.5)

In the case of FEM and Finite Difference Method too, application of equation (5.5) is stated to be one of the techniques to solve floating electrode problems (Tadasu Takuma et al. 1997 b).

5.2.4 Application of a different technique in an Analytical-Numerical Method

Morales et al. (1997), in their paper on computation of field with an Analytical- Numerical Method, have introduced a different technique to solve floating electrode problems.

In this technique, floating conductors are modelled as closed dielectric regions of very large dielectric permittivity, when compared to the permittivity of any practical dielectric region. The fictitious dielectric constants \( \varepsilon' \) of the floating electrodes will be in the range of 1000. This range of values ensures that the simulated boundary condition is almost identical to that of a conductor (floating electrode). This type of simulation of floating electrodes is almost equivalent to the application of the alternative forms of boundary conditions (or the properties of the electrodes) given in section 5.2.1.
It is observed from the existing literature that no serious attempt has been made so far to adopt this technique for Charge Simulation Method, despite the simplicity of this technique.

5.2.5 A study by Tadasu Takuma et al. on floating electrode problems

Tadasu Takuma et al. (1997 b) made a detailed study on floating electrode problems. They observed that in composite dielectric arrangements where a floating conductor is in contact with two dielectrics, application of equation (5.4) in CSM does not yield correct results.

They studied the effect of an axis-symmetric floating conductor together with a support insulator, placed in a uniform external electric field $E_0$, as shown in the top of Figure 5.1. This uniform external field $E_0$ was assumed to have a downward direction.

Applying CSM, they obtained the curves in broken lines, shown in Figure 5.1, which represent the variation of floating electrode potential with variation of the relative permittivity $\varepsilon_r$ of the insulator column. They came to the conclusion that the increase in the computed floating electrode potential shown by the broken lines, with the increase in $\varepsilon_r$ of the insulator column, indicated the wrong formulation of equation (5.4) in CSM. For very high values of $\varepsilon_r$, a dielectric would behave more like a conductor. Hence there will be a reduction of floating electrode potential on increasing the relative permittivity $\varepsilon_r$ of the insulator. But the computed results were found contrary to this concept.

These researchers further observed that the fictitious charges in CSM do not correspond to the true charge on the surface but represent the equivalent charge
including the effect of dipole charge. They modified equation (5.4) for the charge inside the floating electrode and the modified form is given below.

\[ Q = \varepsilon_g \int \left[ \sum_{\ell} F_{n\ell} q_{\ell} + \sum_{\ell} F_{n\ell} q_d \right] ds + \varepsilon_d \int \left[ \sum_{\ell} F_{n\ell} q_{\ell} + \sum_{\ell} F_{n\ell} q_g \right] ds + \int (\varepsilon_d - \varepsilon_g) F_{n\ell} ds \]

(5.6)

where \( \varepsilon_d \) and \( \varepsilon_g \) are the relative permittivities of the dielectric and the surrounding gas medium.

Figure 5.1 Potential pattern of a floating electrode in a uniform field as a function of \( \varepsilon_d \) (courtesy Tadasu Takuma et al. 1997 b)
$F_{en}$, $F_{ed}$ and $F_{eg}$ are the normal field coefficients for the electrode, dielectric and gas medium respectively,

$q_e$, $q_d$ and $q_g$ are the densities of charges in the electrode, dielectric and gas medium respectively,

$\Gamma$ and $ds$ are the corresponding surface area and the incremental area,

$Q$ is the net charge inside the floating electrode

and $E_{no}$ is the normal component of the external uniform field.

The revised solutions arrived at by Tadasu Takuma et al. (1997 b) with equation (5.6) yielded the drooping solid curves shown in Figure 5.1 and the results were in agreement with the expected behavior of the potential pattern. However, their paper does not indicate the range of values adopted for the Assignment Factor or the number of charges simulated in their studies with CSM. From the formulation of equation (5.6), involving surface integrations, it is not known whether they applied the Integral Equation Method to arrive at the solution shown as solid curves. Their paper does not explicitly state the method in which the modified equation was adopted to obtain the correct solution.

The study by Tadasu Takuma et al. (1997 b) shows that CSM requires modification in the methodology of simulation for floating electrode problems.

5.3 SUITABILITY OF THE TECHNIQUES FOR SIMULATION OF FLOATING ELECTRODES

In CSM, the areas of the boundaries are not demarcated for each of the discrete charges, which are simulated at a definite distance from these boundaries. The aggregate effect of all these discrete charges is such that it satisfies the boundary conditions. The summation of the discrete charges simulated inside a floating
electrode could not always be exactly equal to zero due to their locations lying a little away from the boundaries and due to the computational round-off of values while evolving these charges.

If the condition given in equation (5.4) is expected to be satisfied in CSM, by incorporating this equation in the matrix formation, it results in some sort of compromise on the accuracy of the computed results. In view of these situations and sometimes due to the ill conditioning of the matrix generally occurring in floating electrode problems, application of CSM for floating electrode problems does not always give satisfactory results. Also, due to the wrong formulation, as pointed out by Tadasu Takuma et al. (1997 b) for multi-dielectric boundaries, application of the condition in equation (5.4) gives unexpected results.

An attempt has been made in the present study to adopt the technique used by Morales et al. (1997) in their studies and treat the floating electrodes as dielectrics, as seen in section 5.2.4, in place of the technique of equating the sum of the simulated charges within the floating electrodes to zero. From the continuity relationship of the normal flux density (equation (2.6)) across a dielectric interface, it is evident that the normal component of field inside a dielectric with a larger dielectric constant becomes lesser. With very large values of this fictitious dielectric constant \( \varepsilon \), the field inside the floating electrode (simulated as a dielectric) becomes negligibly small, approaching zero, as seen in equation (3.2). Hence, the potential inside it becomes almost constant, while the field at the exterior of its surface becomes almost normal. The larger the dielectric constant, the more closeness of the external field will be to the perpendicularity at the boundary.

In other words a floating electrode can be simulated as a dielectric with a very large dielectric constant in electrostatic problems. This type of simulation is equivalent to the application of the alternative forms of boundary conditions given in section 5.2.1 and yields better results.
In Chapter 3 (section 3.4.2), it was observed that simulation of a spherical dielectric with a large dielectric constant (=10^6) yielded results very close to the analytical results for an identical floating spherical electrode.

If the values adopted for the fictitious dielectric constant $\varepsilon_r'$ of the floating electrodes are in the range of $10^4$, errors introduced in equating the normal flux densities across the boundaries of the floating electrodes would be only in the range of a few parts in $10^4$. However, higher accuracy could be achieved by performing computation in double precision, with the adoption of larger values of dielectric constants and applying special techniques for matrix solution.

5.4 SIMULATION OF FLOATING ELECTRODE AS A DIELECTRIC

Studies were conducted in the present work to ascertain the validity of the simulation of floating electrodes as dielectric regions, by comparing the results with that obtained by Tadasu Takuma et al. (1997 b) and given in Figure 5.1. The details of the studies are given below.

5.4.1 Floating electrode configuration in a uniform field

The floating electrode cum insulator column arrangement shown in Figure 5.1 was taken up for study. For this study, the height 'h' of the insulator column, its radius $R_e$, the thickness 'D' and the radius 'R' of the floating electrode shown in Figure 5.1 are 3.0, 1.0, 1.5 and 1.5 meters respectively.

A disc shaped main electrode arrangement similar to the one discussed in Chapter 3 (section 3.4) was simulated to produce a uniform field of -1.0 V/m. This main electrode was at a potential of 100 volts, with a radius of 300 meters and at a height of 100 meters above the ground. The floating electrode together with the
insulator column shown in figure 5.1 was assumed axially symmetric to and below the main electrode.

Different values were assigned to the assumed dielectric constant $\varepsilon_r$ of the floating electrode, in the range from $10^3$ to $10^6$. The results are compared with the corresponding upper solid curve of Figure 5.1, with $h/R = 2$.

### 5.4.2 Floating electrode as a dielectric with a dielectric constant $\varepsilon_r = 10^4$

The floating electrode in a uniform field of $-1.0$ V/m, as seen in section 5.4.1, was simulated with a fictitious dielectric constant $\varepsilon_r = 10^4$. Computation was performed for different values of the dielectric constant $\varepsilon_i$ of the insulator column, varying from 1 to 100. Assignment Factor (AF) was also varied, to determine its influence on the results. A total of 414 charges were simulated, 186 charges for the main electrode and the balance for the floating electrode cum insulating column arrangement. The results are given in Figure 5.2.

Curves 1 to 5 in Figure 5.2 were obtained with AF at 1.0, 1.2, 1.3, 1.4 and 1.5 respectively. They show the relationship between the ratio $V/R$ and the relative permittivity $\varepsilon_i$ of the insulator column, where $V$ and $R$ are the floating potential and the radius of the floating electrode respectively. These curves correspond to the upper solid curve shown in Figure 5.1, with $h/R = 2$.

In the above computations, the matrix condition numbers were in six digits with AF at 1.5, whereas they rarely crossed five digits with AF at or below 1.3. With AF at 1.4, the matrix condition numbers were in five digits or in the lower ranges of six digit figures.
Curve 5 (for AF at 1.5) is almost similar to the upper solid curve in Figure 5.1, only for larger values of $\varepsilon_r$. It has an upward shift for lower range of $\varepsilon_r$. This could be due to errors in computation due to bad conditioning of the matrix. Curve 4 (for AF = 1.4) is almost closer to the upper solid curve in Figure 5.1. Curve 1 (for AF at 1.0) is drooping only slightly, deviating very much from Figure 5.1.

Figure 5.2 Results for the floating electrode as a dielectric with a fictitious dielectric constant $\varepsilon'_r=10^4$

5.4.3 Floating electrode with reduced dielectric constant ($\varepsilon'_r=10^3$)

Reducing $\varepsilon'_r$ to $10^3$, the floating electrode problem discussed in section 5.4.1 was again simulated with 414 charges. The patterns of the floating electrode potential (ratio V/R) against $\varepsilon_r$ of the insulator column, with AF at 1.2, 1.3, 1.4 and 1.5 are shown in Figure 5.3. Of the two curves sandwiched between the outer curves, the
curve with AF at 1.3 lies closer to the upper curve and the curve with AF at 1.4 is closer to the lower curve.

All the four curves shown in this figure are close to one another, especially for the lower range of $\varepsilon$ (in the range where the dielectric constants of almost all the HV insulators lie). They are almost similar to the pattern of the upper solid curve in Figure 5.1. These graphs show consistency in results with only a slight deviation for different values of AF from 1.2 to 1.5, thereby indicating higher accuracy in computation. With AF at 1.5, the resulting curve is much more closer to the curve in Figure 5.1. The matrix condition numbers were found to be comparatively less in this study. The numbers were in the lower ranges of 6 digit figures with AF at 1.5.

Figure 5.3 Results for the floating electrode with reduced fictitious dielectric constant ($\varepsilon' = 10^3$)
It was observed that the simulation of floating electrodes with $\varepsilon_r'$ close to $10^3$ (the value suggested by Morales et al. 1997), would give more accurate results. However, a higher value (around $10^4$ or higher) may have to be chosen for $\varepsilon_r'$, if the relative permittivity ($\varepsilon_r$) of the insulator column is above 100, though such a situation does not arise in high voltage engineering problems.

5.4.4 Floating electrode with increased dielectric constant ($\varepsilon_r' \geq 10^5$)

The floating electrode problem was again simulated with the same 414 charges, as given in sections 5.4.2 and 5.4.3, but increasing the dielectric constant $\varepsilon_r'$ to $10^5$. Results were found to be erroneous with oscillations in the pattern of the curves, even for a lower range of AF. Increased matrix condition numbers were observed in this case and this ill conditioning is found to seriously affect the results.

The results were found to worsen, on increasing $\varepsilon_r'$ still further. These erroneous results are not shown here. As El-Kishky et al. (1994) observed, problems in computation could arise if the matrix condition number exceeds $10^5$ and if the number of charges exceeds 400 (leading to ill conditioning of the matrix).

5.4.5 The effect of reduced number of charges with increased dielectric constant ($\varepsilon_r' = 10^5$)

The same floating electrode arrangement was simulated again, keeping $\varepsilon_r'$ at $10^5$ but reducing the number of charges to a half (simulating 207 charges only), to determine the influence of the variation in the number of charges. The results are given in Figure 5.4.

In Figure 5.4, the potential pattern with AF at 1.4 is close to the upper solid curve of Figure 5.1. But the curve with AF at 1.3 is less- inclined and deviates much
from the upper solid curve of Figure 5.1. Potential patterns with AF at 1.2 or less, and at 1.5 or more, were found to deviate very much from the graph in Figure 5.1 and they are not shown in Figure 5.4.

These studies indicate that both the number of charges and AF adopted in CSM affect the results very much, if \( \varepsilon_r' \) of the floating electrode is around \( 10^5 \). With AF in the range of 1.3 to 1.5 and \( \varepsilon_r' \) at \( 10^5 \), the matrix condition numbers were all in six digits. Though the matrix condition numbers were in 5 digits with AF at or less than 1.2, the results were not satisfactory, due to the inappropriate low values of AF and weak formulation of the matrix due to the increased value of the constant \( \varepsilon_r' \).
5.4.6 Floating electrode with reduced number of charges and $\varepsilon'_r \leq 10^4$

Results obtained with lesser number of charges (207 charges) and with lesser values of $\varepsilon'_r$ for the configuration described in section 5.4.1 are given below.

Figure 5.5 shows the results with AF at 1.3 and 1.4 and with $\varepsilon'_r$ at $10^4$. With AF at 1.5, oscillation in the potential pattern was observed and that result is not shown here. For lesser values of AF, the potential patterns were almost similar to those in Figure 5.2.
Figure 5.6 shows the results with AF at 1.3 and 1.5 and with $\varepsilon'$ at $10^3$. No oscillation was noticed in this case. The patterns of the graphs are similar to those given in Figure 5.3. The patterns of the curves with AF at 1.2 and 1.4 (not shown in Figure 5.6) were also similar to those given in Figure 5.3. The results were not affected much with variations in AF or the number of charges, when the floating electrode was simulated as a dielectric with $\varepsilon'$ at $10^3$.

Figure 5.6 Results for the floating electrode with reduced number of charges ($\varepsilon'=10^3$)
5.4.7 The pattern of errors in simulation of floating electrode as a dielectric in a uniform field

The results given in sections 5.4.2 to 5.4.6 show that the simulation of the floating electrode as a dielectric with a dielectric constant $\varepsilon^*$ close to $10^3$ gives satisfactory results. The results are consistent, without appreciable variation, despite variations in the number of charges simulated or in the value assigned to AF in the range of 1.2 to 1.5. With the increase in AF from 1.2 to 1.5, the results become closer to the upper solid curve in Figure 5.1.

When $\varepsilon^*$ is $10^4$, only the results pertaining to AF at 1.4 were found satisfactory and close to the upper solid curve in Figure 5.1.

With $\varepsilon^*$ at $10^5$, results were inconsistent, highly sensitive to the variation in AF and also sensitive to the number of charges simulated. Generally the matrix is found to be ill conditioned in this case. Also, only when the number of simulated charges is at a favorable level and only when the AF is close to 1.4, the result would be satisfactory.

5.5 SIMULATION OF FLOATING ELECTRODE AS A DIELECTRIC FOR PRACTICAL PROBLEMS

In this section, the computed results for a high voltage insulator unit with a floating ring electrode are discussed.

5.5.1 Study on a high voltage insulator with a floating electrode ($\varepsilon^* = 10^3$)

Figure 5.7 shows a high voltage insulator unit with a floating ring electrode. The cross sectional diameter $D$ of the tube of the ring electrode was taken as
1.5 meters and the relative permittivity of the insulator column was assumed as 4.5. Calculations were performed for this unit with a potential of 1 MV at the top electrode and simulating the floating electrode as a dielectric with $\varepsilon_r' = 10^3$.

Curves 1 and 2 (solid curves) in Figure 5.8 are the potential and field patterns respectively along the surface of the insulator column with AF at 1.5, in the absence of the floating ring. A total of 147 charges were simulated for this study.

Curve 3 (dotted line) in Figure 5.8 is the field pattern with the inclusion of the floating ring electrode; the field at the electrode triple junction was 0.224 MV/m. In this case, a total of 207 charges were simulated, adopting AF at 1.5. The potential distribution for this arrangement was almost close to the curve-1 and hence it is not shown here.

The increased field intensity near the top electrode with the inclusion of floating electrode was due to the capacitance between the floating electrode and the ground aggravating the field pattern. The computed floating electrode potential was about 0.496 MV.

Figure 5.7  High voltage insulator unit with a floating electrode
Further studies were conducted for this arrangement, with AF at 1.0, 1.2, 1.3 and 1.4, keeping the height of the floating electrode at 8 meters. The computed results are given in Table 5.1. Both the maximum values of potential at some locations on the surface of the floating electrode and the minimum values at some other locations are given in the Table, to check the consistency of the results.

Table 5.1 shows that the computed values of potential at the floating electrode are almost uniform for different values of AF. The results were found to be more consistent with AF in the range of 1.2 to 1.5.
Table 5.1 Results for the HV insulator unit with floating electrode (Dielectric constant $\varepsilon_r'$ for the floating electrode: $10^3$)

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Assignment Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>% RMS potential error at the top-electrode surface</td>
<td>0.197</td>
</tr>
<tr>
<td>% RMS field discrepancy at the dielectric interface</td>
<td>0.120</td>
</tr>
<tr>
<td>Matrix condition number</td>
<td>12733</td>
</tr>
<tr>
<td>Floating electrode potential:</td>
<td></td>
</tr>
<tr>
<td>a) Maximum (MV)</td>
<td>0.4962</td>
</tr>
<tr>
<td>b) Minimum (MV)</td>
<td>0.4947</td>
</tr>
<tr>
<td>Difference (a - b): (MV)</td>
<td>0.0015</td>
</tr>
</tbody>
</table>

5.5.2 The effect of increasing the height of the floating electrode in HV insulator unit

Further studies were conducted, by increasing the height of the floating electrode to 9 meters from the ground, without changing other data for the problem given in section 5.5.1. The potential and field patterns were obtained with AF at 1.5 and shown in Figure 5.9. In this case, there was a favorable reduction in the field to 0.207 MV/m at the dielectric interface close to the top electrode, as seen from Figure 5.9. The non-uniformity of the field pattern in this case was found to be less, compared to the field pattern indicated by curve 3 in Figure 5.8.
Further studies were conducted for this configuration by adopting different values for AF. Field patterns obtained with AF in the range of 1.2 to 1.5 were found to be almost identical. The floating electrode potential was found to be in the range from 0.6642 to 0.6654 MV with AF=1.2 and in the range from 0.6648 to 0.6656 MV with AF=1.5. The results were found to be consistent. This increase in the floating electrode potential close to 0.665 MV, as against the value of around 0.496 MV obtained in section 5.5.1, was due to the increase in the inter-electrode capacitance and reduction in the capacitance between the floating electrode and the ground, with the increase in the height of the floating electrode.

These studies indicate how floating electrodes could aggravate the field pattern (curve 3 in Figure 5.8) instead of bringing down the maximum stress if their locations are improperly chosen. The configurations of the floating electrodes also play an important role in bringing down the maximum stress.
5.5.3 Study on HV floating electrode problem with increased dielectric constant $\varepsilon_r'$

Further studies were conducted for the configuration in Figure 5.7, with increased values of $\varepsilon_r'$ for the floating electrode. The tube cross sectional diameter $D$ of the floating electrode (at a height of 8 meters from the ground) was taken as 1.5 meters and the relative permittivity $\varepsilon_r$ of the insulator column was assumed as 4.5. Computations were performed, keeping the potential of the top electrode at 1 MV. A total of 207 charges were simulated. The results are given in Tables 5.2 and 5.3.

The results given in Table 5.2 correspond to the simulation of the floating electrode as a dielectric with $\varepsilon_r'$ at $10^5$. Table 5.3 shows the results with $\varepsilon_r'$ at $10^6$. The results for both the two cases were found to be satisfactory. The computed floating electrode potential was within the range from 0.494 to 0.496 MV in all the cases. The matrix condition numbers for these studies did not exceed five digits. The results were consistent, despite large values of $\varepsilon_r'$ and variation of AF from 1.2 to 1.5.

Table 5.2 Results for the HV insulator unit with floating electrode (Dielectric constant $\varepsilon_r'$ for the floating electrode: $10^5$)

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Assignment Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>% RMS potential error at the top-electrode surface</td>
<td>0.196</td>
</tr>
<tr>
<td>% RMS field discrepancy at the dielectric interface</td>
<td>0.120</td>
</tr>
<tr>
<td>Matrix condition number</td>
<td>13447</td>
</tr>
<tr>
<td>Floating electrode potential</td>
<td></td>
</tr>
<tr>
<td>(a) Maximum (MV)</td>
<td>0.4956</td>
</tr>
<tr>
<td>(b) Minimum (MV)</td>
<td>0.4945</td>
</tr>
<tr>
<td>Difference (a - b): (MV)</td>
<td>0.0011</td>
</tr>
</tbody>
</table>
Table 5.3 Results for the HV insulator unit with floating electrode (Dielectric constant $\varepsilon_r$ for the floating electrode: $10^6$)

<table>
<thead>
<tr>
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<td>0.120</td>
</tr>
<tr>
<td>Matrix condition number</td>
<td>13447</td>
</tr>
<tr>
<td>Floating electrode potential</td>
<td>0.4955</td>
</tr>
<tr>
<td>(b) Minimum (MV)</td>
<td>0.4945</td>
</tr>
<tr>
<td>Difference (a - b): (MV)</td>
<td>0.0010</td>
</tr>
</tbody>
</table>

These results are also in conformity with those given in Table 5.1. AF in the range of 1.2 to 1.5 gave more consistent results. However, the average values of the floating electrode potential given in Tables 5.2 and 5.3 are slightly less than those in Table 5.1 by about 0.3%. The results given in Tables 5.1 to 5.3 also indicate that with AF at 1.0, the RMS potential error at the electrode surface is somewhat high.

5.6 SUMMARY

Existing literature shows that not much work has been done with CSM in the case of floating electrode problems. The technique of equating the net charge at the surface of the floating electrode to zero, applicable to other methods, could not give satisfactory solutions when it was adopted in CSM. Some researchers have pointed out the reason for the failure of this condition in CSM.
In the present study, a different technique of treating the floating electrode as a dielectric, with a very large dielectric constant, was applied to CSM. This technique was found to give satisfactory results. Results from this technique are in close conformity with that given by Tadasu Takuma et al. (1997 b), when AF is close to 1.4 and the fictitious dielectric constant $\varepsilon_r'$ of the floating electrode is in the range from $10^3$ to $10^5$. However, with $\varepsilon_r'$ at $10^3$, AF can have a value in the range of 1.2 to 1.5 for satisfactory results. With very large values of $\varepsilon_r'$ ($\geq 10^5$), results are sometimes affected by the ill conditioning of the matrix.

A typical HV insulator unit with a floating electrode was taken up for study with this technique. The results were found to be consistent and accurate with this technique, with AF in the range of 1.2 to 1.5 and $\varepsilon_r'$ in the range from $10^3$ to $10^6$. The matrix condition numbers were at a satisfactory level (not exceeding $10^5$) in this case.

These studies also indicate that proper locations and configurations of floating electrodes play an important role in controlling the maximum levels of electric stress in insulator regions. Improper locations of the floating electrodes could aggravate the stress pattern.