CHAPTER 8

CONCLUSIONS

8.1 GENERAL

This Chapter aims at reviewing the contributions made during the course of this work and proposing some suggestions for further study.

It was observed from the literature survey that despite the developments that have taken place in the area of numerical computation for electric field problems, the methods available at present do not meet the present requirements of high voltage engineering. Accuracy in computation is the main criterion for the studies related to the optimization of high voltage apparatus in terms of reduction of cost and size. But, it is seen that no single method is effective enough to give precise solutions to all kinds of electric field problems. Different methods have different features and their capability to give satisfactory solutions depends on the types of electric field problems.

In view of the direct application of the Coulomb's Law and Gauss Theorem, CSM ensures accuracy in results, provided the problem is less complicated. From the studies made by several researchers it is seen that this method is simple to apply, fast in computation, applicable to open boundary problems, capable of generating smooth contours of high voltage problems and several other advantages, as detailed in Chapter 2. Hence CSM was chosen as the main theme of this work. The
study was aimed at exploring the reasons for the failure of this method in some cases and introducing new techniques to improve the results with this method.

8.2 SUMMARY OF THE WORK DONE

In Chapter 2, the results of the studies with CSM (using the code developed in the present study) and FEM (using Ansoft package) on two asymmetric high voltage problems were compared. Computation time with CSM was found to be very short, in the range of only about 3 to 5% that of FEM.

In the studies with CSM on the above two problems, the maximum potential errors in computation were within 3.2% and the RMS values of field discrepancies were about 12%. The corresponding errors with FEM were not known, but from the shapes of the field patterns obtained with FEM, it was observed that the field discrepancy with FEM could not be of a negligible value. The maximum difference between the computed values of potential with CSM and FEM was only about 3%.

The results obtained with CSM for an axis-symmetric high voltage problem were found to be very accurate. The maximum potential error at the electrode surface, the maximum potential discrepancy at the dielectric interface and the RMS field discrepancy were at 0.1%, 0.015% and 0.83% respectively. Hence it is seen that CSM gives very accurate results for axis-symmetric problems.

In Chapter 3, the influence of an empirical formula known as Assignment Factor (AF) over the accuracy in results with CSM was discussed. This factor together with another formula known as Curvature Criterion determines how deep the discrete charges have to be simulated inside the electrodes and the dielectric regions from the boundaries, in relation to the distance between two adjacent charges. Hence the locations of the charges to be simulated are decided by AF. Since the range of values
adopted for AF by several researchers is too wide (1.0 to 2.0), studies were conducted to determine the influence of AF on accuracy.

Studies in the present research have shown that the most suitable range of values for AF to give more accurate results is between 1.2 and 1.5. It was observed from the studies that with an increase in AF and also with an increase in the number of charges simulated, the matrix condition number increases, with the possibility of near-singular situation with AF above 1.5.

In case near-singularity occurs with AF at or below 1.5 in any complicated problem, the upper limit for the above range of AF has to be slightly reduced, to avoid computational difficulty. Matrix condition number within $10^5$ normally yields results free from computational difficulty.

It was observed from the above studies that with AF above 1.5, more accurate results are possible in some cases. But the additional increase in accuracy in such cases is negligible and it has no practical significance. Hence, to avoid computational difficulty for most of the practical problems, the upper limit for AF has to be restricted to 1.5.

It was further observed that with an increase in the number of charges up to a certain level, accuracy increases. But, a further increase in the number of charges (above 600 in this study) leads to more round-off errors during computation and it sometimes results in matrix ill-conditioning and the associated computational difficulties.

In order to quantitatively determine the levels of errors that could occur with CSM, a test problem was chosen for study. Computed results obtained with CSM for this problem were compared with the analytical results. With AF at 1.2, the maximum error in the field was about 0.27%. With AF at 1.5, the maximum error was
about 0.034% only. AF in the range of 1.2 to 1.5 gave accurate results for this problem too. Within this range, an increase in the value of AF increases accuracy. However, in some complex problems, AF at 1.5 resulted in near-singularity.

In chapter 4, details of the studies conducted on multi-dielectric field problems were discussed.

Due to an ambiguity in simulation of charges with the conventional CSM, this method could not give satisfactory solutions to problems having more than two dielectric regions. This ambiguity was removed in the present work by modifying the method with the introduction of a criterion for simulation of charges. Studies with the modified CSM and FEM showed that computation time with FEM was more than 25 times that of the modified CSM. Also, besides increased accuracy, computation time with the modified CSM was less than that of the conventional CSM by about 5 to 10%.

Results with the modified CSM for an axis-symmetric three-dielectric problem were found to be more accurate with AF in the range of 1.2 to 1.4. RMS field discrepancies at the dielectric interfaces were predominant (about 3.12% with AF at 1.2 and with 300 ring charges) compared to the potential errors and RMS field discrepancies at the electrode surface. Increase in the number of charges resulted in increased accuracy. Results with the modified CSM for this problem were found to be satisfactory, but the conventional CSM gave highly erroneous and unsatisfactory results.

For this axis-symmetric problem, errors with the modified CSM increased gradually with the increase in AF beyond 1.2. This was due to the effect of the increased matrix condition number and the increased complexity of the problem, with three dielectric regions.
Results with the modified CSM for an asymmetric problem with three dielectric regions are also given in Chapter 4. In this case, the RMS field discrepancies at the electrode surfaces were more predominant (about 9.5% with AF at 1.6, but 16.4% with AF at 1.0). RMS field discrepancies at the dielectric interfaces were minimum (below 1.1%) with AF in the range of 1.3 to 1.5. AF at 1.2 gave results with a slightly reduced accuracy. For this problem too, the suitable range of values for AF was found to be between 1.2 and 1.5. This range has to be narrowed down, depending on the error level and the matrix conditionality. Matrix conditionality was found to be very sensitive to the increase in AF in this case.

In chapter 5, the details of an improved technique for floating electrode problems and the results with the modified CSM with this improved technique were discussed.

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 in the case of CSM. Some researchers have pointed out the reason for the failure of this condition in CSM.

A different technique of treating the floating electrode as a dielectric, with a large fictitious dielectric constant (in the range of $10^3$ to $10^5$), was incorporated into the modified CSM. When AF was close to 1.4, results with the modified CSM (inclusive of this technique) were in close conformity with that given by Tadasu Takuma et al. (1997 b) for a specific floating electrode problem. Simulation of the floating electrode with a fictitious dielectric constant of $10^3$ and AF in the range of 1.2 to 1.5 gave results closer to that of the above researchers.
A typical HV insulator unit with a floating electrode was also taken up for study with the modified CSM. The results were found to be consistent and accurate with this method, with the fictitious dielectric constant for the floating electrode lying in the range of $10^3$ to $10^6$ and with AF in the range of 1.2 to 1.5. The matrix condition numbers were at a satisfactory level (not exceeding $10^5$) in this case.

The above study was also made to determine the influence of the geometrical location of a floating electrode on the field pattern along the dielectric interface. Results of the study indicated that improper locations of floating electrodes would aggravate the field pattern.

In Chapter 6, the merits and demerits of different numerical methods were analyzed. SSM was found to be suitable for combination with CSM for the purpose of overcoming the deficiencies of the latter. A hybrid algorithm was developed for combination of the modified CSM with SSM. The resulting Combination Method of Charges is capable of simulating thin regions and sharp corners, for which CSM cannot be applied. The Combination Method applies both discrete charges and distributed charges for simulation of the boundary conditions and avails the advantages of both the modified CSM and SSM.

In Chapter 7, the Combination Method of Charges was applied to solve some practical problems.

A high voltage composite insulator with a central FRP rod insulator surrounded by a silicone rubber covering was taken up for study. The thin sharp sheds of the silicone rubber covering could not be simulated with the conventional CSM and also with the modified CSM. For comparison purposes, the sheds of the silicone rubber covering were omitted and a study was conducted with the modified CSM, SSM and the Combination Method. In this study, the errors with the modified CSM (RMS field discrepancies at 9.1 %) were more than double that of the other two
methods. But the computation time with the modified CSM was about one sixth that of SSM and about half that of the Combination Method. The Combination Method was found to be faster than SSM for this problem, while the error levels were the same for both the methods.

Applying SSM and the Combination Method of Charges, a study was conducted on the composite insulator, inclusive of the sheds on the silicone rubber covering. The results with SSM and the Combination Method were similar. But the Combination Method was found to be faster in computation, taking only about 40% of the time taken with SSM.

A 400 kV surge diverter was taken up for study, applying the Combination Method. A study was conducted to determine the influence of the sheds of the porcelain housing over the field pattern inside the Zinc Oxide elements of the surge diverter. The study showed that the fluctuations in the field due to the sheds were within the range of ±3%. This variation being small, further studies were conducted on the surge diverter, omitting the sheds of the porcelain housing.

Using the Combination Method, a study was conducted on the surge diverter, omitting all the externally attached stress control electrodes. The maximum field in the diverter elements at the point of contact with the top metal cap was about 2.25 V(per unit)/m. The field pattern was found to be highly sensitive to the configuration and the size of the metal caps.

Further studies were conducted on the surge diverter, including the stress control electrodes. Applying the Combination Method, the influence of the shielding rings over the field pattern in the surge diverter elements was determined. A few discrete ring charges were sufficient to accurately simulate the ring electrodes. Hence the matrix size and the computation time were low with the Combination Method. The maximum stress in the diverter elements was about 0.6 V(per unit)/m in this case.
But, while applying SSM to the above problem, difficulty was experienced in choosing an appropriate number of boundary elements for the stress control electrodes (the shielding and floating rings and the metal spokes connected to the rings) and this led to computational difficulties. Several boundary elements were required to represent the non-uniform charge distribution on the rings and the spokes. Too many boundary elements resulted in near-singularity and computational difficulties, while too few elements resulted in increased errors. Computation with SSM with a reasonable level of accuracy was possible only after a few attempts in choosing a suitable number of boundary elements for the stress control electrodes. The matrix size was larger with SSM, compared to that of the Combination Method.

The results obtained with the application of the Combination Method and SSM for the surge diverter were compared. The field pattern with both the methods were almost similar except near the top HV electrode. The computation time with SSM was about twice that of the Combination Method.

With a slight modification to the geometrical locations and the diameters of the stress control electrodes of the surge diverter, computation was made, using the Combination Method of Charges. The maximum stress in the diverter elements was brought down to 0.42 V(per unit)/m in this case. This study indicates the importance of proper configurations and locations of the stress control devices in bringing down the stress in HV apparatus.

These studies show that the Combination Method of Charges is more effective in solving electric field problems, some of which are difficult to be solved with CSM or SSM.

8.3 SCOPE FOR FURTHER STUDY

Several papers have been published over the last four decades on numerical computation of electric field and improvements to the methods of computation. Special techniques have been introduced to solve highly complex problems.
As far as electrostatic problems are concerned, hybrid methods developed earlier have not become popular. The main reason for this is that those hybrid methods, which were developed by combining a domain division method like FEM with an entirely different type of method like CSM, pose some difficulties in computation, like matrix ill conditioning, convergence problems etc. However, such hybrid methods were developed mainly to solve some specific and highly complex electric field problems like those involving space charge, ion flow etc. Hence their usefulness cannot be underestimated.

Conventional methods are found to be ineffective in solving some of the less complicated field problems too. A method, which is capable of giving better solutions to some problems, may not be suitable for some other problems that are effectively solved by some other methods. Hence, there lies the necessity to identify a method, which is more suitable to solve a given problem. Instead of such identification of suitable methods and application of different methods for different problems, a hybrid method can be developed and used in place of the conventional methods, to solve different varieties of problems. In some cases, the overall efficiency in computation with a hybrid method could be more than that of any individual method.

The Combination Method of Charges developed out of CSM (together with the new techniques and modifications) and SSM, is only in its initial stages of development. Yet the present work discussed in this dissertation shows the capability of this combination to solve some problems, which are difficult to be solved with either CSM or SSM. This Combination Method is at present restricted to axisymmetric studies only. More research is necessary to develop a sophisticated and powerful hybrid method, which could replace several conventional methods.

Besides the necessity to develop a powerful hybrid method to replace the conventional methods, there is also the necessity to incorporate advanced techniques for more accurate matrix solution. An ineffective technique for matrix solution,
especially for large sizes of matrix, yields unsatisfactory results despite the application of a powerful numerical method for electric field studies. Different algorithms are adopted for matrix solution, depending upon the constitution of the matrix. Further research is necessary to adopt a suitable technique for better solution to the matrix that is formed while applying a hybrid method.

There is also a scope for application of effective adaptive techniques for the studies aimed at optimum design of high voltage apparatus. Further research is necessary to improve the existing techniques on adaptive computation and optimization.