CHAPTER 1
INTRODUCTION

1.1 GENERAL

The reliability of high voltage apparatus depends greatly on the distribution of electric stress across its insulation. The performance and life span of the apparatus are determined mainly by the pattern of the electric stress distribution and the withstand characteristics of the insulation. The life span drastically reduces even if the stress is marginally in excess of the withstand level of insulation. Due to this sensitivity of insulating materials to electric stress, accurate determination of electric field is necessary while designing high voltage apparatus.

An imperfectly designed high voltage apparatus arising out of inaccurate computation of electric field may lead to its poor performance or even premature failure. It is the criticality of the field, which determines the performance of the apparatus. On the other hand, higher margin of safety in insulation would result in increased cost and size of the apparatus, without any assurance of improved performance. Sometimes, provision of over-insulation may adversely affect the thermal equilibrium inside the material due to poor heat conduction. This could lead to uneven expansion in solid insulation, resulting in high mechanical stresses, with the possibility of mechanical damage. Moreover, breakdown of chemical bonds could also occur due to the increase in temperature. Hence, the design of high voltage equipment requires a careful study, with special emphasis on electric stress control.

The non-uniform nature of the electric stress imposes difficulties in insulation design. As the voltage level goes up, the effect of stray capacitance becomes
more pronounced, so is the increased non-uniformity of the stress. This calls for increased insulation requirements. Provision of adequate insulation to EHV equipment is therefore more complicated. As a result, the size of the equipment becomes disproportionately high, with the increase in voltage levels.

Stress grading in high voltage apparatus, especially in gas insulated stations, has attained its importance in terms of achieving reduction in size and cost. Various stress control techniques are adopted to reduce the maximum stress in insulation and in the nonlinear elements of surge diverters. But effective application of stress control techniques primarily depends on the accuracy of computation of stress. Protection offered by surge diverters may not be reliable if the stress control so adopted is not based on precise computation of stress.

An integrated study is required to take into account the influence of every part of the equipment on the resultant stress. Simulation of each and every part demands increased computer-time and memory, besides the requirement of effective algorithms and computational methods.

Provision of floating electrodes and shielding electrodes is aimed at reducing the electric stress. But this increases the complexity of the problem and increases the memory requirements. Neither the potential nor the field at the floating electrodes is known beforehand. By applying the boundary conditions for floating electrodes, the unknown quantities have to be computed. Any approximation in simulation of these floating electrodes results in appreciable deviations in the computed values of electric stress from the actual values. It requires a precise study with more accurate numerical methods, for provision of floating electrodes with appropriate configurations and at appropriate places.

With the advent of high-speed computers with large memory capacity, it is now possible to simulate highly complex configurations of electrical equipment and to
determine the electric field very precisely. Various numerical methods have been developed over the years for computation of electric field. Adaptive computations give optimum solutions and the design process has become easy and fast. Various improvements have also been made to the existing numerical methods for computation of the field more precisely.

The most popular methods that are adopted for computation of electric field are, Finite Element Method (FEM), Boundary Element Method (BEM), Charge Simulation Method (CSM) and Surface-Charge Simulation Method (SSM), also known as Indirect Boundary Element Method. But no single method is fully effective to give precise solutions to all kinds of electric field problems. Research is still going on to improve these methods and to develop new algorithms and techniques for better solutions.

Hybrid methods have also been developed to obtain satisfactory solutions to some of the complicated problems. However, hybrid methods have not become popular and they are seldom applied for electric field computation, due to some difficulties in their application, like ill- conditioning of the matrix and convergence problems.

Among the available methods, choice of a method for computation depends on the nature of the problem to be solved. For example, problems involving space charge distribution or un-isotropic materials could be solved effectively with FEM, compared to the other popular methods. But, in the case of isotropic problems having smooth contours, without any sharp configurations, methods like CSM yield better solutions. Hence it is necessary at first to study the nature of the problem to be solved and identify a method that is more suitable to solve the specific problem. The limitations of the method should also be identified. These limitations should not affect the required accuracy of results.
CSM and SSM are the two numerical methods, which are applied to solve electric field problems through simulation of charges. The efficacy of these two methods has been proved over the years, by their successful application to several high voltage field problems. The objective of this thesis is to explore the possibility of more effective computation of electric field through simulation of charges. Details of the studies are given in this thesis. Improvements and new techniques arising out of these studies are also given. In the present study, combining CSM with SSM, a hybrid method has been developed to overcome some of the deficiencies of the individual methods.

1.2 CHARGE SIMULATION METHOD

In CSM, discrete charges are employed to represent the free and bound charges at the surfaces of the electrodes and the dielectric interfaces respectively. Point, line and ring charges are most commonly used to replace the distributed charges at the boundaries. The magnitudes of these discrete charges are such that they satisfy the boundary conditions of the electrodes and the dielectric interfaces. These charges are simulated just inside the electrode surfaces and on both sides of the dielectric interfaces. During computation in a specific dielectric region, the charges simulated inside that region are omitted and all other charges are taken for computation.

With the known values of the applied potential at the electrodes and from the continuity relationship of the potential values and also of the normal flux densities across the dielectric interfaces, potential and field coefficients for each of the simulated charges are calculated and linear equations are formed. The unknown values of the simulated charges are evolved, by solving the linear equations. The computed values of the charges are then applied to find the potential and field in any region of interest.
Soon after the development of CSM, its deficiencies were also realized. Surface-Charge Simulation method (SSM), which is applied to simulate distributed charges at the boundaries, has now become popular.

1.3 SURFACE-CHARGE SIMULATION METHOD

In SSM, distributed charges with varying charge densities are simulated at the electrode surfaces and dielectric interfaces. This is in contrast to the simulation of discrete charges in CSM. The boundaries are divided into a number of convenient sections, called boundary elements. The integral effect of the distributed charges in these boundary elements has to satisfy the boundary conditions of a given problem. This requires numerical surface-integration to determine the potential and field coefficients due to the varying charge densities simulated at the boundary elements.

In view of the numerical double integration involved over each of the boundary elements, computation-time with this method is very long. However, since distributed charges are simulated exactly over the boundaries, simulation is very close to the actual physical conditions and this method gives very precise results. The matrix size is also small with this method for most of the problems, compared to CSM.

1.4 LITERATURE SURVEY

1.4.1 Charge Simulation Method

Singer et al. (1974) published a comprehensive paper on CSM, employing point, line and ring charges to solve electric field problems through numerical computation. This method became popular soon after the publication of this paper. This method is seen to be an improvement over the earlier works by many researchers including Steinbigler, on numerical computation through simulation of charges (Nazar H. Malik 1989 and Kuffel et al. 2000). Steinbigler’s work in 1969 is seen to be a major contribution to the evolution of this method (Tadasu Takuma et al. 1997 a).
In view of the simplicity and accuracy of this method, it has been applied to different kinds of electric field problems. Successful application of CSM to several complicated problems led to a series of publications. Nazar H. Malik (1989) has given the details of these publications, the nature of the studies conducted with CSM, the advantages of this method, improvements to this method by various researchers etc., as review work. The merits of CSM have been established through various studies, comparing its results with those of other methods (Steinbigler et al. 1991).

Tadasu Takuma et al. (1978) applied CSM for determination of the field behavior near singular-points (at sharp edges of the boundaries and triple junctions) in composite insulators. Tadasu Takuma (1991) further extended this study through a semi-analytical approach, inclusive of the application of CSM for determination of enhanced field behavior at triple-junctions due to the ‘Takagi effect’. Sivathanu Pillai et al. (1983) studied the influence of the radius of curvature of the dielectric interfaces at triple-junctions on the field pattern.

Landers (1979) applied CSM for problems involving electrodes with known potential, along with electrodes having known total charges but with unknown potential and for other complicated problems. Utmischi (1979) introduced the application of ring charges having sectorial-constant charge density in CSM for computation of asymmetric fields.

CSM has been found useful to compute the field pattern for open boundary problems. Sendaula et al. (1983) applied this method to determine the field pattern in irregular terrain under a transmission line. Using this method, Shao Fang-yin et al. (1983) studied the field pattern in substation arrangements.

This method was applied for the study on the effects of recessed electrodes (Pillai et al. 1984 a and 1984 b), on the effects of insulator sheds (Kaana-Nkusi et al.

Tadasu Takuma et al. (1979) introduced a technique to CSM for computation of the complex (capacitive-resistive) field in problems having finite surface resistance. Bachmann (1979) has worked out a different form of determination of mixed (complex) fields with the application of CSM.

Abdel-Salam et al. (1987) and Chakravorti et al. (1993) conducted studies on problems involving complex fields and on uniform and non-uniform surface pollution on HV insulators. El-Kishky et al. (1996 a and 1996 b) studied the effect of water droplets on the insulator surfaces using this method.

Metz (1979) applied CSM for optimization of high voltage fields through an iterative process in which electrode surfaces are divided into separate regions for fixed contours and variable contours. The sections of the electrodes with variable contours are moved in the desired direction in each iteration process to achieve the optimized configuration, to have the field level close to the chosen value. Elmoursi et al. (1983) have also conducted a study for determination of electrode configuration, for uniform field on a portion of its surface.

Mazen Abdel-Salam et al. (1986), Abdel-Salam et al. (1987), Kato et al. (1997) and Kato et al. (2001) have made studies on optimization of insulator and electrode geometries, with the application of CSM.

CSM has been applied together with artificial neural network simulation (Chakravorti et al. 1994 and Mukherjee et al. 1996) and fuzzy inference system (Chatterjee et al. 2001) for optimization of electrode contour.
Several researchers have made modifications to CSM to solve many complicated problems. El-Kishky et al. (1994) introduced a modified Charge Simulation Method for calculation of field over non-ceramic and ceramic suspension insulators. They have given the drawbacks of the earlier optimization technique in CSM, its limitations from the point of view of more computer memory requirements and computation time as well as convergence and stability issues. They have also suggested suitable techniques to reduce errors due to ill-conditioned matrix. They have claimed that their method could use less number of charges by proper choice of Assignment Factor. They have also discussed in their paper, the technique of solving floating electrode-problems.

Tadasu Takuma et al. (1997 b) pointed out the inconsistency of the results with CSM for floating conductor problems and suggested modifications. They applied this method for solid insulator problems having surface and volume conduction.

Some modifications to CSM have been made for easy adoptability to complicated problems and for better results (Abdel-Salam et al. 1987, Blaszczyk et al. 1994, Blaszczyk 1996, Andreas Blaszczyk 2000 and Palaniswamy et al. 2001).

Hybrid methods have been evolved, by combining CSM with other methods and they were applied for some complicated problems (Okubo et al. 1982, Sharmene Ali et al. 2000 and Cao Yundong et al. 2001). A combination method of CSM with SSM, developed in the present study, is seen to give accurate solutions to problems involving thin regions and sharp corners, for which CSM alone cannot be applied (Palaniswamy et al. 2003 a and 2003 b). This combination method is also found to be much faster in computation than SSM.

Yildirim et al. (2003) applied CSM for computation of corona inception voltage through simulation of electron avalanche above the critical field.
1.4.2 Surface-Charge Simulation Method

During the seventies, integral equations were applied to solve some axisymmetric configurations (Daffe et al. 1979). Subsequent improvements to this Integral Equation Method led to the development of SSM. In this method, the interfaces are divided into many sections, over which surface integrations are carried out. By this time, another method known as Boundary Element Method (BEM) was also evolved (Brebbia 1978) and it closely resembled SSM in some aspects. In the course of the development of BEM, different formulations like Variational formulation, Collocation technique etc., were adopted and hence it has many variations (Ren et al. 1988, Taher Ahmed et al. 1989 and Christophe Geuzaine et al. 2001).

Because of the close resemblance of SSM with BEM in some aspects, the former came to be known as Indirect Boundary Element Method; sometimes it is merely referred as a variant of BEM (Gin et al. 1990, Mukherjee et al. 1999 and Tiebin Zhao et al. 2000).

Misaki et al. (1982 and 1983) made some improvements to SSM and applied this method for optimum electrode and insulator design.

Sautter et al. (1983) applied spline functions to represent the contours of the electrodes and for simulation of charge density distribution with SSM. Sato et al. (1983) introduced a fast algorithm to SSM.

Shuji Sato (1987) introduced fast computation techniques for this method and applied Tchebycheff Polynomials to represent the variations in charge distribution at the interfaces, to get more accurate results.
Gin et al. (1990) applied this method with fast toroidal-function computation and high speed integral to determine the stress pattern inside a transformer. They applied this method for thin layer insulation regions. Mirko et al. (1994) introduced adaptive refinement for the integral method to get better solutions.

Cardelli et al. (1997) simulated surface charges for a single dielectric problem with suitable modified formulations to avoid singularity and compared the results with that of FEM. Jawad Faiz et al. (2000) suggested techniques to avoid singularity situations in SSM and studied the field inside a power transformer.

Skopec et al. (1994) applied integral equations to compute the field on an axially symmetric insulator with surface contamination. Mukherjee et al. (1999) made a study on the electric field distortion due to asymmetric pollution.

Chakravorti et al. (1998 and 2000) conducted studies on capacitive-resistive field on HV bushings and axis-symmetric insulators. They have studied the effect of insulator sheds and pollution on the field pattern.

Tiebin Zhao et al. (2000) applied this method for calculation of the field in non-ceramic, transmission line insulators. In their study, the effect of conductors and transmission towers was also taken into account. The effect of weather sheds and grading rings on the field pattern in the composite insulators was also studied.

Shoji Hamada et al. (2003) applied SSM adopting Fast Multi-pole Method for calculation of the field around bare stranded wire. Tatematsu et al. (2003) applied SSM adopting Fast Multi-pole Method along with multi-point charge measurement using an electrostatic probe for calculation of the field and hence the determination of charge accumulation on the surface of high voltage insulating supports.
1.5 OBJECTIVES OF THE THESIS

Electric power is transmitted through extra high voltage (EHV)-grid network with the aim of economical distribution of power. This type of power transmission demands trouble-free performance of EHV equipment. These equipments are costly, because of the increased complexity in insulation requirements. Any power failure arising out of failure of these equipments results in huge capital loss and revenue loss. The very scope of the EHV transmission is lost if such failures are more. The time to repair the EHV equipment is usually very long and the time to normalize the EHV grid back to the original condition without any make shift arrangement is also long.

It has been noticed that in utilities like the Tamilnadu Electricity Board, the failure rate of HV equipments is on the higher side, as seen from Appendix 1. Though various causes exist for their failure, the major cause of failure is found to be due to the breakdown of insulation. Failure of insulation occurs either due to lightning and other types of over-voltages, or due to the faulty design and manufacture. This again raises a question on the effectiveness of the protection offered by surge diverters in case the failure is due to lightning. In fact, the failure rate of HV surge diverters is also felt to be high in electric utilities like the Tamilnadu Electricity Board.

There is enough scope to reduce the failure rate of HV equipment. The conditions prevailing in some electric power utilities prompted the author of the present dissertation, to work in the area of computation of electric field. Studies were conducted by the author on effective computation of electric field for some practical insulator geometries and surge diverters. An attempt was also made for improvement in computation.

In high voltage systems, sharp corners have to be necessarily avoided to reduce the electric stress. Hence electrodes and dielectric interfaces in high voltage
systems are, to the extent possible, free from sharp curvatures. CSM is very effective in simulation of curved boundaries without sharp corners. This method has been reported to be fast and accurate. Hence CSM was chosen in this study for improved computation of electric field. SSM resembles CSM to a limited extent, in meeting the boundary conditions through simulation of charges. But the resemblance is less while the differences between them are more. For example, boundary division adopted in SSM is not applicable to CSM. Distributed charge-simulation is not possible in CSM. Some disadvantages found in CSM can be easily overcome with SSM. SSM was also taken up for study on the field pattern in high voltage insulators.

- The first objective of the thesis was to identify the strength and weakness of CSM and categorize those types of problems where its application is more advantageous.

- The second objective was to make a quantitative assessment of errors in computation with CSM and to identify the ways of minimization of the errors. With this objective, studies were made on some specific problems, to determine the influence of some factors affecting accuracy. Minimization of errors depends on proper choice of the locations of the discrete charges.

- The third objective was to study the possibility of further improvement to CSM, for accurate solution to multi-dielectric problems. Over a period of time, several improvements have been made to this method by different researchers. Yet CSM is found to be incapable of solving problems with more than two dielectric regions. In this study, the possibility of effective application of CSM for these problems was explored. A modification was introduced to CSM in the present study to get accurate results for problems having more than two-dielectric regions.

- The fourth objective was to achieve accurate computation of electric field for floating electrode problems, with the application of CSM. In stress control
techniques, floating electrodes like grading rings and shielding electrodes play a major role. So far, application of CSM for these problems has not been completely successful and hence CSM requires modifications (Tadasu Takuma et al. 1997 b). A new technique was introduced to CSM in the present study for improved solutions to floating electrode problems.

- The fifth objective was to study the possibility of better solutions to electric field problems by applying CSM in combination with any of the other numerical methods. With this objective in mind, the merits and demerits of different numerical methods were studied and SSM was chosen for combination with CSM. Both CSM and SSM have some deficiencies but some of the deficiencies noticed in one method are not present in the other. An attempt was made in this study to develop a hybrid algorithm and combine CSM and SSM. The Combination Method of Charges evolved out of these two methods in the present study eliminates or minimizes some of the deficiencies of the individual methods and gives better results. With this combination method, matrix conditioning was found to be better. The results obtained with the Combination Method and its constituent methods (CSM and SSM) were compared.

1.6 ORGANIZATION OF THE THESIS

A brief outline of the contents given in Chapters 2 to 8 of this thesis is given below. The details of the studies with CSM, SSM and the Combination Method of Charges are given in these chapters.

In Chapter 2, the methodology of application of CSM is given. The governing equations for simulation of different types of discrete charges in CSM, the method of simulation of charges and the matrix formulation are discussed. The advantages and limitations of this method and the method of assessment of errors in
the results are given. A comparison of CSM with FEM is made, from the results obtained with these methods.

In Chapter 3, the effect of Assignment Factor and the number of simulated-charges over the results are given. Also, the necessity for proper locations of charges, conditions for minimum level of errors and the near-singular situations in some cases during computation with CSM are discussed.

In Chapter 4, an improvement to CSM is made to get better solution for multi-dielectric field problems. Comparison is made with the results obtained from the conventional CSM and the modified CSM. A comparison is also made between the modified CSM and FEM.

In Chapter 5, the method adopted by various researchers for floating electrode problems is explained. Difficulty in the application of CSM for problems with floating electrodes and the ways of overcoming this difficulty through the application of a different technique are discussed. Results obtained for a floating electrode problem with the introduction of this technique to CSM are given.

In Chapter 6, the merits and demerits of some of the popular methods are given. The advantages and disadvantages of SSM are discussed. The methodology of application of this method is given. The details of the Combination method of Charges developed from CSM and SSM are given. The steps involved in the hybrid algorithm in combining CSM and SSM are given.

In Chapter 7, results obtained for practical electric field problems, with the application of CSM, SSM and the Combination Method of Charges are given. The results with these methods are compared. The advantages of the Combination Method are given.

Chapter 8 is the concluding chapter, in which the salient features of the present study and the scope for further study are given.