Introduction:-

The demand for the generation and transmission of large amounts of electric power today, necessitates transmission at extra-high voltages.

In developed countries like USA, power transmission voltages have reached 765KV / 1100KV & 1500KV systems are also being built.

In modern times, high voltages are used for a wide variety of application covering the power systems, industry, and research laboratories. such applications have become essential to sustain modern civilization.

High voltages are applied in laboratories in nuclear research, in particle accelerators, and Van de Graaff generators. For transmission of large bulks of power over long distances, high voltages are used.

Also, voltages up to 100KV are used in electrostatic precipitators, in automobile ignition coils etc. x-ray equipment for medical and industrial applications also use high voltages. Modern high voltage test laboratories employ voltage up to 6MV or more.

For use of high voltage the maintance and construction cost is more and the Electric stress offered by high voltage equipment is also more. so achieving reliability and economy we increase the voltage stress for optimal design in the insulating materials.

1-) Electric field stresses:-

Like in mechanical designs where the criterion for design depends on the mechanical strength of the materials and the stress that are generated during their operation, in high voltage applications, the dielectric strength of insulating material and the electric field stress developed in them when subjected to high voltages are important factors in high voltage system.

In a high voltage apparatus, the important material used are conductors and insulators. While the conductor carry the current, the insulator prevent the flow of currents in undesired paths. The electric stress to which an insulating material is subjected to is numerically equal to the voltage gradient, and is equal to the electric field intensity

$$E = -\nabla \phi$$

$E \rightarrow$ Electric field intensity

$\phi \rightarrow$ applied potential

$\nabla \rightarrow a_x \frac{\partial}{\partial x} + a_y \frac{\partial}{\partial y} + a_z \frac{\partial}{\partial z}$

voltage gradient

a_x, a_y & a_z are components of position vector $r = a_x x + a_y y + a_z z$

The most common cause of insulation failure is the presence of discharges either within the insulation or over the surface of insulation

Gas/vacuum as Insulator:-

Air at atmospheric pressure is the most common gaseous insulation. Breakdown occurs in gases due to the process of collisional ionization.

In some gases, free electrons are removed by attachment to neutral gas molecules: the breakdown strength of such gases is substantially large. An example of such a gas, with larger dielectric strength is sulphur hexafluoride (SF_6).

Using gases at high pressures, field gradient up to 29 MV/m have been realized. Nitrogen (N_2) was the gas first used at high pressures because of its inertness and chemical stability, but its dielectric strength is the same as of air. Other important insulating gases are carbon dioxide (CO_2) dichlorodifluoromethane (CCl_2F_2) (freon), and sulphur hexafluoride (SF_6)

However, in recent years pure SF_6 gas has been found to be a green house gas causing environment hazards. So they focussed on finding a replacement gas or gas mixture which is environmental friendly. Pure nitrogen, air and SF_6/N_2 mixtures shows good potential to replace SF_6 gas in high voltage apparatus.

Vacuum is the best insulator with field strength up to 10^7 V/cm limited only be emission from the electrode surfaces.

2-1

Liquid Dielectrics:-

Liquids are used in high voltage equipment to serve the dual purpose of insulation and heat dissipation.

They have the advantage that a puncture path itself healing. Temporary failures due to overvoltages are reinsulated by liquid flow to the affected area.

Highly purified liquids have dielectric strength as high as 1 MV/cm. under actual service conditions, the breakdown strength reduces considerably due to presence of impurities.

Solid Dielectrics:-

A good solid dielectric should have some of the properties mentioned earlier for gases and liquids and it should also posses good mechanical and bonding strength. many organic and inorganic materials are used for high voltage insulation purposes. widely used inorganic materials are ceramic & glass.

The most widely used organic materials are thermosetting epoxy resins such as polyvinyl chloride (P.V.C), polyethylene (PE) or cross-linked polyethylene (XLPE). Kraft paper, natural rubber, silicon rubber and polypropylene rubber are some of the other materials widely used as Insulators in electrical equipment.

Solid Insulating materials have breakdown stress will be as high as 10 MV/cm.

Estimation and control of Electric stress:-

The electric field distribution is usually governed by the Poisson's equation

$$\nabla^2 \varphi = -\frac{\rho}{\varepsilon_0}$$

$\varphi \rightarrow$ Potential

$\rho \rightarrow$ space charge density

$\varepsilon_0 \rightarrow$ electric Permittivity of free space.

However, in most of the high voltage apparatus, space charges are not normally present, and hence the potential distribution is governed by the Laplace's equation

$$\nabla^2 \varphi = 0$$

There are many methods available for determining the potential distribution. The most commonly used methods are

i) electrolytic tank method, and

2) Numerical methods.

The potential distribution can also be calculated directly. However, this is very difficult except for simple geometries.

The important rules are

~~i) the equipotent~~

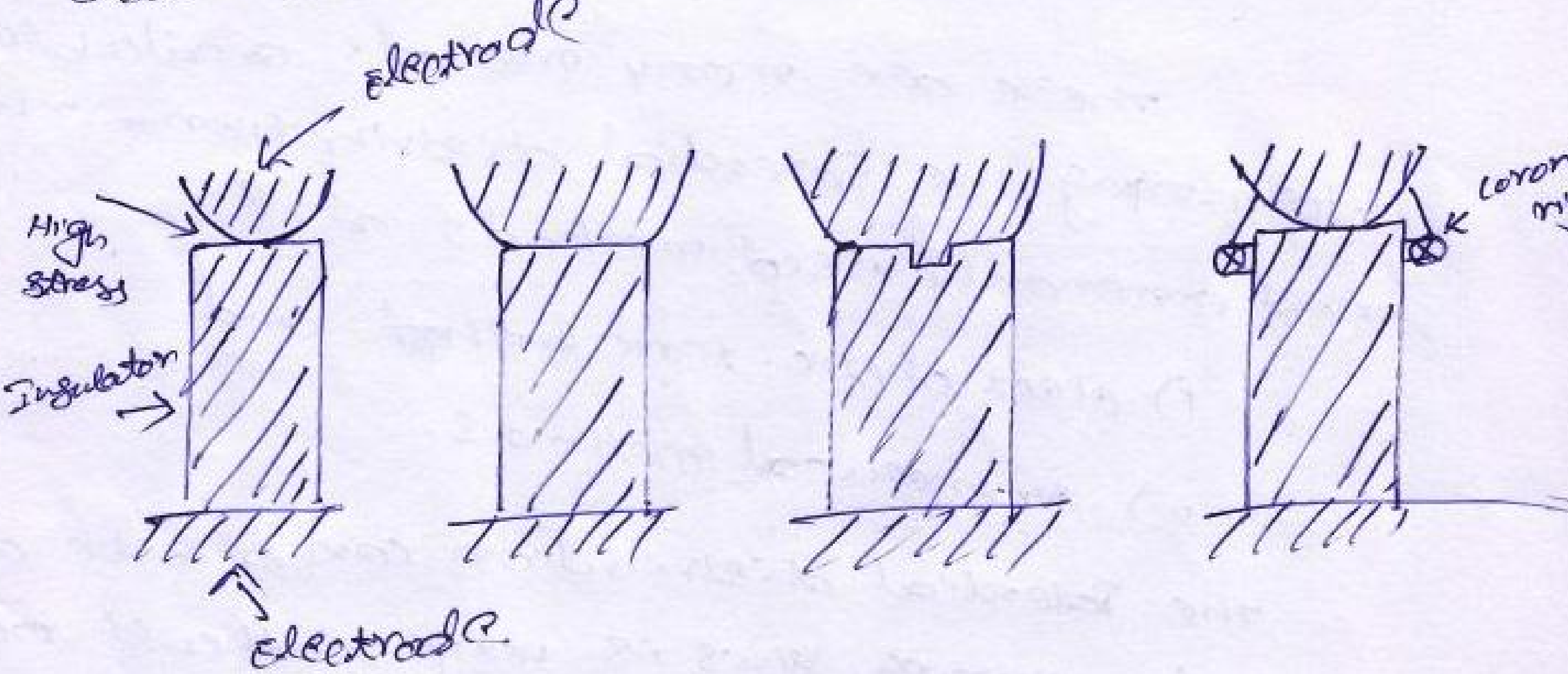
i) The equipotentials cut the field lines at right angles, 3-1

2) When the equipotentials and field lines are drawn to form curvilinear squares, the density of the field lines is an indication of the electric stress in a given region, and

3) in any region, the maximum electric field is given by dv/dx where dv is the voltage difference between two successive equipotentials.

Considerable amount of labor and time can be saved by properly choosing the planes of symmetry and shaping the electrodes accordingly.

The other methods of stress control are shown in the below diagram.



Electric Field:-

The field intensity 'E' at any location in an electrostatic field is the ratio of the force on an infinitely small charge at that location to the charge itself as the charge decreases to zero. The force 'F' on any charge 'q' at that point in the field is given by

$$F = qE$$

The electric flux density 'D' associated with the field intensity 'E' is

$$D = \epsilon E$$

The potential $\varphi = -\int_l E \cdot dl$

'l' is the path through which the charge is moved.

~~Theory~~

$$D = \epsilon E$$

$$\varphi = -\int_l E \cdot dl$$

$$E = \frac{F}{q}$$

$$\iint_s E \cdot ds = \frac{q}{\epsilon_0} \text{ (Gauss theorem)}$$

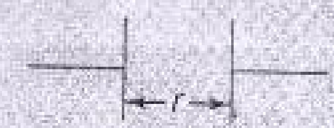
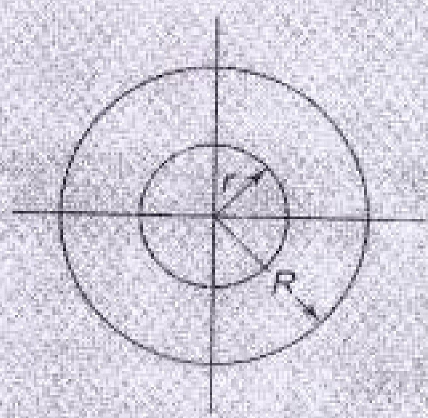
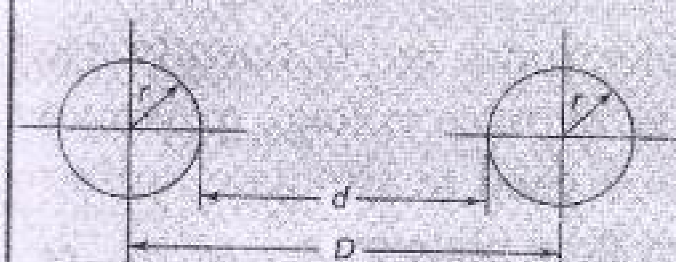
$$\nabla \cdot D = \rho \text{ (charge density)}$$

$$\nabla^2 \varphi = -\frac{\rho}{\epsilon_0} \text{ (Poisson's equation)}$$

$$\nabla^2 \varphi = 0 \text{ (Laplace's equation)}$$

where 'F' is the force exerted on a charge 'q' in the electric field 'E', and 's' is the closed surface containing charge 'q'.

u-1 Estimation of electric field in some Geometric Boundaries:-

Geometrical configuration	Maximum electric field E_m	Field enhancement factor $f = E_m / E_{av}$
 Parallel plates	$\frac{V}{r}$	1.0
 Concentric cylinders	$\frac{V}{r \ln \frac{R}{r}}$	$\frac{(R-r)}{r \ln \frac{R}{r}}$
Figure same as above Concentric spheres	$\frac{VR}{r\,(R-r)}$	$\frac{R}{r}$
 Parallel cylinders of equal diameter	$\frac{V\sqrt{D^2 - 4r^2}}{2r\,(D-r)\cosh^{-1}(D/2r)} \approx$ $= \frac{V}{2r} \ln \frac{d}{r}$ if $D >> r$	$\frac{d}{2r \ln \frac{d}{r}}$ (if $d >> r$)
Equal spheres with dimensions as above	$\frac{V}{d} f$ $\approx \frac{V}{2r}$, if $d >> r$ For other configurations like sphere-plane and cylinder-plane f is approximately given by $f = 0.94\,\frac{d}{r} = 0.8$ (sphere-plane) $f = 0.25\,\frac{d}{r} + 1.0$ (cylinder-plane)	$f = \frac{\left(\frac{d}{r}+1\right) + \sqrt{\left(\frac{d}{r}+1\right)^2 + 8}}{4}$ $\approx \frac{d}{2r}$, if $d >> r$

Numerical methods for Electric field computation:-

There are 3 types of numerical methods are commonly used in high voltage applications

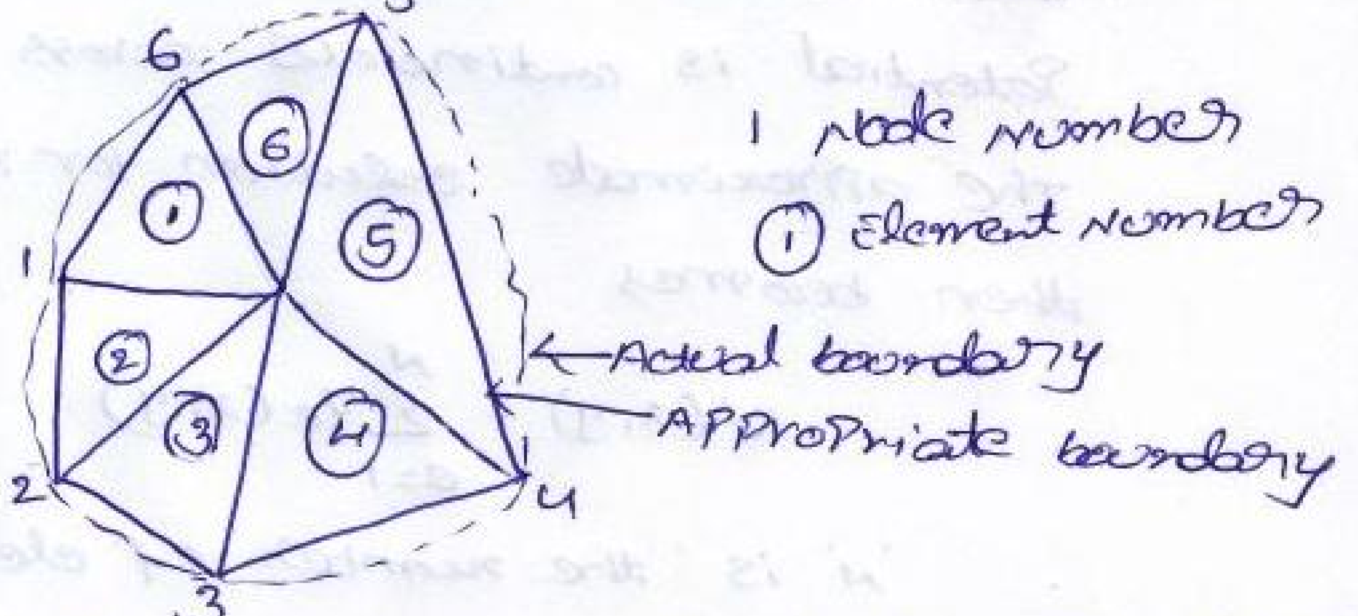
1. Finite Element method (FEM)
2. Charge simulation method (CSM)
3. surface charge simulation method (SSM)

1. Finite Element method (FEM):-

a) Finite Element Discretization
b) Governing Equations
c) Assembling of all Elements
d) Solving the Resulting Equations.

a) Finite Element Discretization:-

To start with, the whole problem domain is fictiously divided into small areas/volumes called elements



The potential, which is unknown throughout the problem domain, is approximated in each of these elements in terms of the potential at the vertices called nodes. As a result of this the potential functions will be unknown only at nodes. Normally a certain class of polynomials, is used for the

5.1 interpolation of the Potential inside each element in terms of their nodal values. The coefficients of this interpolation function are then expressed in terms of the unknown nodal Potentials. As a result of this, the interpolation can be directly carried out in terms of the nodal values. The associated algebric functions called <u>shape functions</u>.

Ex:

bar Elements → one dimension

Triangle & Quadrilateral → 2 Dimension

Tetrahedron & Hexahedron → 3 Dimension

b) Governing Equations:-

The Potential V_e within an element is first approximated and then interrelated to the Potential distribution in various elements such that the Potential is continuous across inter-element boundaries. The approximate solution for the whole region then becomes

$$V(x,y) = \sum_{e=1}^{N} V_e(x,y)$$

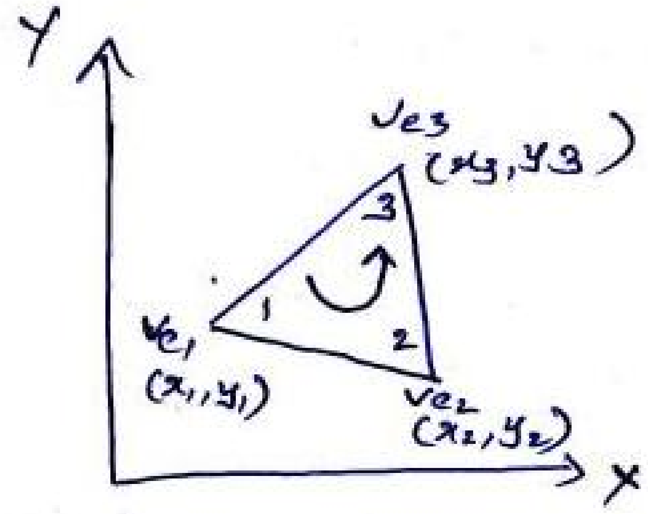
'N' is the number of elements into which the solution region is divided.

The most common form of approximation for the voltage 'V' within an element is a polynomial approximation

$$V_e(x,y) = a + bx + cy$$

for triangular elements

$$V_e(x,y) = a + bx + cy + dxy$$



The above triangular element shows the potentials V_{e1}, V_{e2} & V_{e3} at nodes 1, 2 & 3 are obtained from

eqn. $V_e(x,y) = a + bx + cy$

$$\begin{bmatrix} V_{e1} \\ V_{e2} \\ V_{e3} \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

$$\Rightarrow \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix}^{-1} \begin{bmatrix} V_{e1} \\ V_{e2} \\ V_{e3} \end{bmatrix}$$

Substitute this eqn in

$$V_e(x,y) = a + bx + cy + dxy$$

$$V_e = \begin{bmatrix} 1 & x & y \end{bmatrix} \frac{1}{2A}$$

$$\begin{bmatrix} (x_2y_3 - x_3y_2) & (x_3y_1 - x_1y_3) & (x_1y_2 - x_2y_2) \\ (y_2 - y_3) & (y_3 - y_1) & (y_1 - y_2) \\ (x_3 - x_2) & (x_1 - x_3) & (x_2 - x_1) \end{bmatrix} \begin{bmatrix} V_{e1} \\ V_{e2} \\ V_{e3} \end{bmatrix}$$

(or) $$V_e = \sum_{i=1}^{N} \alpha_i(x,y) V_{ei}$$

where

$$\alpha_1 = (1/2A)\left[(x_2y_3 - x_3y_2) + (y_2 - y_3)x + (x_3 - x_2)y\right]$$

$$\alpha_2 = (1/2A)\left[(x_3y_1 - x_1y_3) + (y_3 - y_1)x + (x_1 - x_3)y\right]$$

$$\alpha_3 = (1/2A)\left[(x_1y_2 - x_2y_1) + (y_1 - y_2)x + (x_2 - x_1)y\right]$$

and A is the area of the element e, that is,

$$2A = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix}$$

$$= (x_1 y_2 - x_2 y_1) + (x_3 y_1 - x_1 y_3) + (x_2 y_3 - x_3 y_2)$$

$$A = \tfrac{1}{2}\left[(x_2 - x_1)(y_3 - y_1) - (x_3 - x_1)(y_2 - y_1)\right]$$

$$\alpha_1 (x_1, y_1) = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} i = j \\ i \neq j \end{bmatrix}$$

$$V_e = \sum_{i=1}^{3} \alpha_i (x, y) = 1$$

The energy per unit length associated with the element 'e' is given by the following equation

$$W_e = \tfrac{1}{2} \epsilon [V_e]^T [C^{(e)}][V_e]$$

where, T denotes the transpose of the matrix

$$[V_e] = \begin{bmatrix} V_{e1} \\ V_{e2} \\ V_{e3} \end{bmatrix}$$

and $$[C^{(e)}] = \begin{bmatrix} C_{11}^{(e)} & C_{12}^{(e)} & C_{13}^{(e)} \\ C_{21}^{(e)} & C_{22}^{(e)} & C_{23}^{(e)} \\ C_{31}^{(e)} & C_{32}^{(e)} & C_{33}^{(e)} \end{bmatrix}$$

The matrix given above is normally called as element coefficient matrix. The matrix element $C_{ij}^{(e)}$ of the coefficient matrix is considered as the coupling between nodes $i \neq j$.

(c) Assembling of all Elements:-

Having considered a typical element, the next stage is to assemble all such elements in the solution region. The energy associated with all the elements will then be

$$W_e = \sum_{e=1}^{N} W_e = \frac{1}{2} \epsilon [V]^T [C] [V]$$

where $[V] = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix}$

$n \rightarrow$ no. of nodes

$N \rightarrow$ no. of Elements

$[C] \rightarrow$ global coefficient matrix.

(d) Solving the Resulting Equation:-

It can be shown that the laplace's (and poisson's) equation is satisfied when the total energy in the total energy in the solution region is minimum. Thus, we require that the partial derivatives of 'W' with respect to each nodal value of the potential is zero

$$\delta W/\delta V_1 = \delta W/\delta V_2 = \cdots \delta W/\delta V_n = 0$$

$$\delta W/\delta V_k = 0 \quad \text{if } k = 1, 2 \cdots n$$

In general $\delta W/\delta V_k = 0$ lead's to

$$0 = \sum_{e=1}^{n} V_i C_{ik}$$

7-1 2) charge simulation method (CSM):-

charge simulation method belongs to the family of integral methods for calculation of electric fields. There are two variations of this method: CSM with discrete charges and CSM with area charges.

(a) Basic principle of CSM:-

When the conductor is excited by an applied voltage charges appear on the surface of conductor. These charges produce an electric field outside the conductor, while at the same time maintains the conductor equipotential. Similarly when a dielectric is excited by an external field, it gets polarized i.e the charged particles of the molecules of the dielectric get shifted from their neutral state to produce a volume of dipoles. In essence, it is possible to replace this volume polarization by the charged surface. The values of these discrete charges are evaluated to forcing the specified voltages at some selected points called contour points on the surface of the conductor by forcing the material ~~surface~~ interface conditions at some selected points on the dielectric interface.

It is required that at any of these contour points on the electrode, the potential resulting from the superposition of the charges is equal to the electrode potential φ.

Thus $$\varphi_i = \sum_{j=1}^{N} P_{ij} Q_j$$

8-1 conductors are replaced by n_c ~~functions~~ fictitious charges placed inside or outside the conductors. The types and positions of these charges are assumed. In order to determine their magnitudes, n_b contour points are selected on the surfaces of the conductors, as known or fixed potentials and it is required that at any of these contour points the potential resulting from superposition of all simulation charges is equal to the known conductor potential. The number of contour points is selected equal to the number of fictitious charges i.e $n_b = n_c = n$. Therefore, the charges are determined from

$$[P]_{n,n}[Q]_n = [\varphi]_n$$

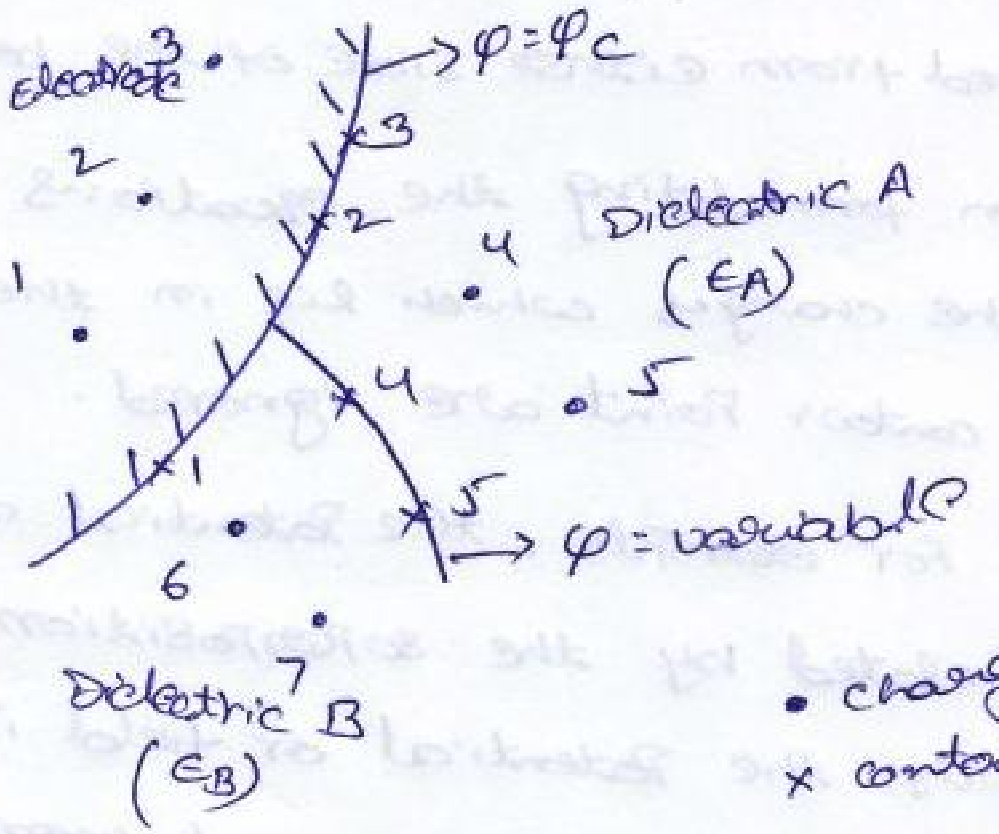
$[P]$ = Potential coefficient matrix

$[Q]$ = column vector of values of unknown charges

$[\varphi]$ = Potential of the boundary points.

After solving the above equation to determine the magnitudes of simulation charges, it is necessary to check whether the set of calculated charges produces the actual boundary conditions everywhere on the electrode surfaces. It is possible that the potential at any point other than the contour points can be different from the actual conductor potential.

(C) CSM for a multi-Dielectric medium:-



The field computations for a multi-dielectric system are more complicated than for a single dielectric. This is due to the fact that, under the influence of applied voltage, the dipoles are realigned in a dielectric, and this realignment has the effect of producing a net surface charge on the dielectric. Thus in addition to the electrodes, each dielectric-dielectric interface needs to be simulated by the discrete charges.

In the simple example the above diagram shows charges 1 to 3 are used to simulate the electrode while charges 4 to 7 are used to simulate the dielectric boundary. Contour points 1 to 3 are selected on the electrode surface whereas only two contour points (i.e 4 & 5) are selected on the dielectric boundary. In order to determine the simulation charges, a system of equations is formulated by imposing the following boundary conditions

-> at each electrode boundary, potential must be equal to the known conductor potential, and

9-1 → at each dielectric boundary, potential and normal component of the flux density must be same, when viewed from either side of the boundary.

In formulating the equations at a given contour point, the charges which lie in the same dielectric as the contour point are ignored.

For example, the potential at ~~contour~~ contour point '1' is calculated by the superposition of charges 1 to 5. Similarly, the potential or field intensity at contour point '5' when viewed from the side of the dielectric 'A' will be due to the superposition of charges 1 to 3 and 6 & 7. Thus when the first boundary condition is applied to contour points 1 to 3 the following eqn. are obtained.

$$\sum_{j=1}^{5} P_{ij} Q_j = \varphi_C \ (i=1)$$

$$\sum_{j=1}^{3} P_{ij} Q_j + \sum_{j=6}^{7} P_{ij} Q_j = \varphi_C \ (i=2,3)$$

When the secondary boundary condition is applied for potential and the flux densit at $i = 4$ to 5

$$\sum_{j=4}^{5} P_{ij} Q_j + \sum_{j=6}^{7} P_{ij} Q_j = 0$$

$$(\epsilon_A - \epsilon_B) \sum_{j=1}^{3} f_{ij} Q_j + \epsilon_A \sum_{j=6}^{7} f_{ij} Q_j - \epsilon_B \sum_{j=4}^{5} f_{ij} Q_j = 0$$

f_{ij} → field coefficients in a direction which is normal to the dielectric boundary.

3) Boundary Element Method (BEM)

Though the charge simulation method is known for its accuracy and speed, it is not very efficient in case of multi dielectric problems and very thin electrodes, which are often used to control and get the electric field strength in condenser bushings, transformers etc.

Such problems can be solved using the surface charge simulation method (SSM) which is also called Boundary Element method (BEM)

In many cases, electrodes and insulators used in high voltage equipment consist of cylinders, spheres, cones, and plane electrodes.

Principle of BEM:-

BEM, in principle, is very similar to CSM with area elements. Like in CSM, the BEM uses area charge simulation elements to replace the real charges. However, BEM does not require that the system components should have axial symmetry.

Basic formulation of BEM:-

Boundary element formulation calls for the scalar potential due to surface charge density which is written as

$$\phi(\xi) = 1/(2\alpha\pi\epsilon_0) \int \rho_s(x)\phi'(\xi, x)\, dP(x).$$

ϕ' -> fundamental solution

$\alpha = 1$ or 2 for two or 3-D Problems

$\rho_s(x)$ -> surface charge density

10.1 Advantages & Disadvantages of the various Numerical Methods:-

-> Finite Element method is very general method and has been used for solving a variety of problems. Any non linearity / inhomogenity can be modelled and the solution will be available on the entire surface of domain. material interface conditions are automatically satisfied. However, it needs a powerful graphic user interface for processing disadvantage.

-> open geometry does not pose any problem with the charge simulation method. since the surface of conductor is the only one that is discretized. In addition, as the solution satisfies the Laplace's/Poisson's equation, it will be very smooth. However, due to the application of superposition principle, non-linearities and non-homogeneity cannot be modelled using this method.

-> A unique feature of BEM is that the electric fields are proportional to charge densities on an enclosed electrode which is simulated by real charges. This direct field derivation is based on a well known Gauss's area integral. There are programming complexity and the need for large amount of computational time to execute an improper integral.

		2 D	3 D
Accuracy for	BEM & CSM combination	1%.	2%.
	BEM & FEM combination	2%.	3%.

Surge voltages, Their Distribution and control:-

The design of Power apparatus particularly at high voltages is governed by their transient behaviour. The transient high voltages or surge voltages originate in Power systems due to lighting and switching operations. The effect of the surge voltages is severe in all Power apparatuses.

The response of Power apparatus to the impulse or surge voltage depends on capacitance between the coils of windings and between the different phase windings of the multi-phase machines. The transient voltage distribution in the windings as a whole are generally very non-uniform and are complicated by travelling wave voltage oscillations setup within the winding.

Generally, improvements can be affected in the following ways:

i) By shaping the conductors to reduce stress concentrations

ii) By insertion of higher dielectric strength insulation at high stress points

iii) By selection of materials of appropriate permittivities to obtain more uniform voltage gradients.