Chapter 2
Electric Field Intensity, Stress Control, and Types of Breakdown in Dielectrics

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Introduction

- The performance of a dielectric over its life span depends mainly upon the type of electric field and the magnitude of electric field intensity.

Objective

Electric field strength (Electric stress)

- Basic definition: Quantitative and qualitative approach
- Classification of electric field
- Better utilization of insulating properties of dielectric

Electric Fields

- The 'electric field intensity', also known as the' electric field strength', is defined as the electrostatic force F exerted by the field on a unit positive test charge q, placed at a particular point P in a dielectric. It is denoted by E, and expressed in unit 'Newtons per Coulomb', that is, the force per unit charge
- The electric field intensity is measured in its practical units of 'Volts per meter' (V/m or kV/mm).
- The electric field intensity is often more specifically mentioned as 'electric stress' experienced by a dielectric or an electrical insulating material.

Electric Fields (Continued..)

- Faraday described the space around a magnet to be filled with 'lines of magnetic force'.
- Similarly, the region around an ***electrified object*** may be considered to be filled with 'lines of electric force'.
- To Faraday, these lines existed as mechanical structures in the surrounding medium (the dielectric) and could exert force on an object placed therein.

Electric Fields (Continued..)

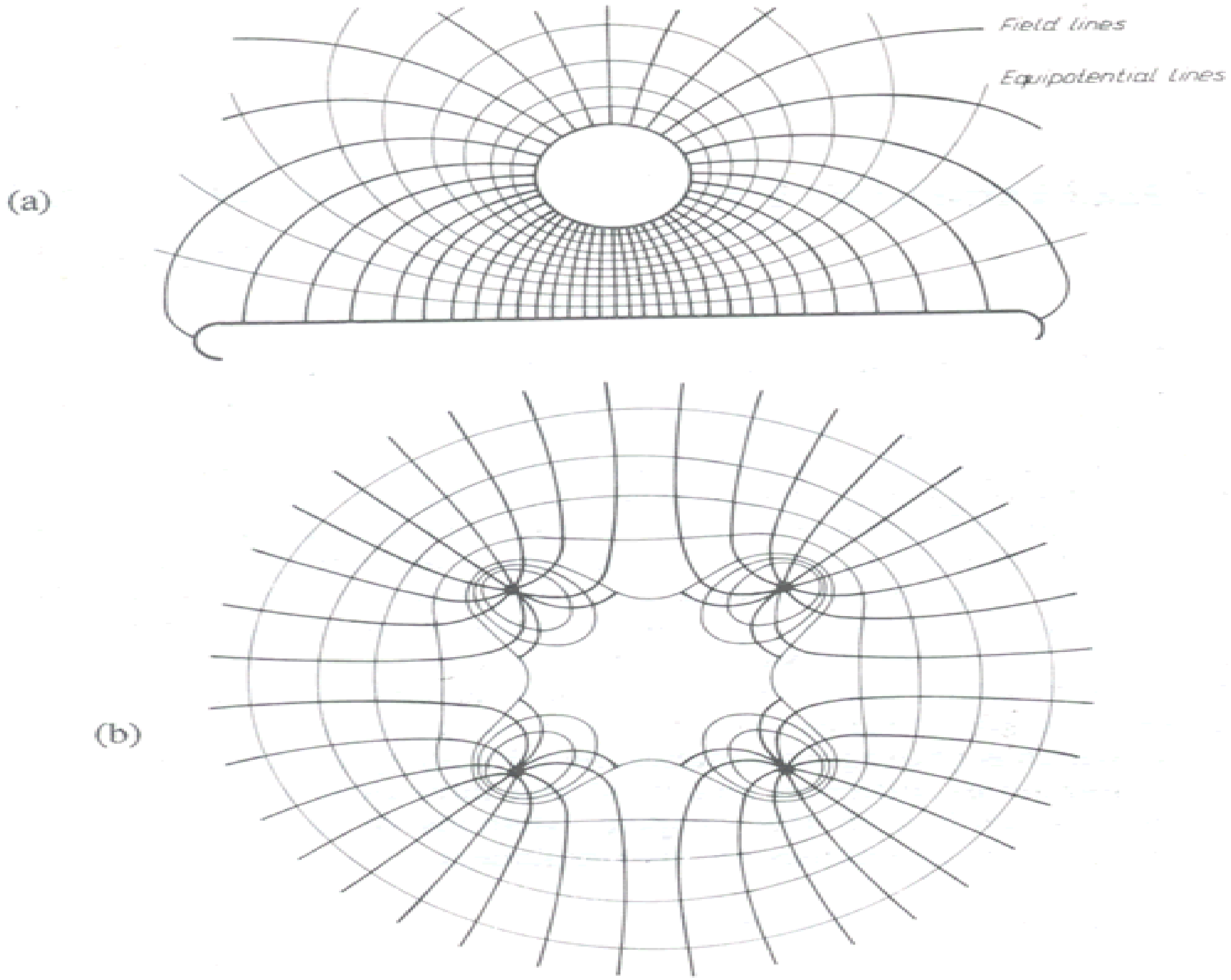


Fig 2.1 Typical electrostatic field configurations.
(a) Field between sphere or cylinder and plane,
(b) Field on a bundle of four conductors.

Electric Fields (Continued..)

The potential difference between two points a and b, having scalar potential in a space charge free electric field , is defined as the work done by an external source in moving a unit positive charge from b to a,

$$U_{ab} = -\int_b^a \left| \vec{E} \right| dx = \left(\phi_a - \phi_b \right)$$

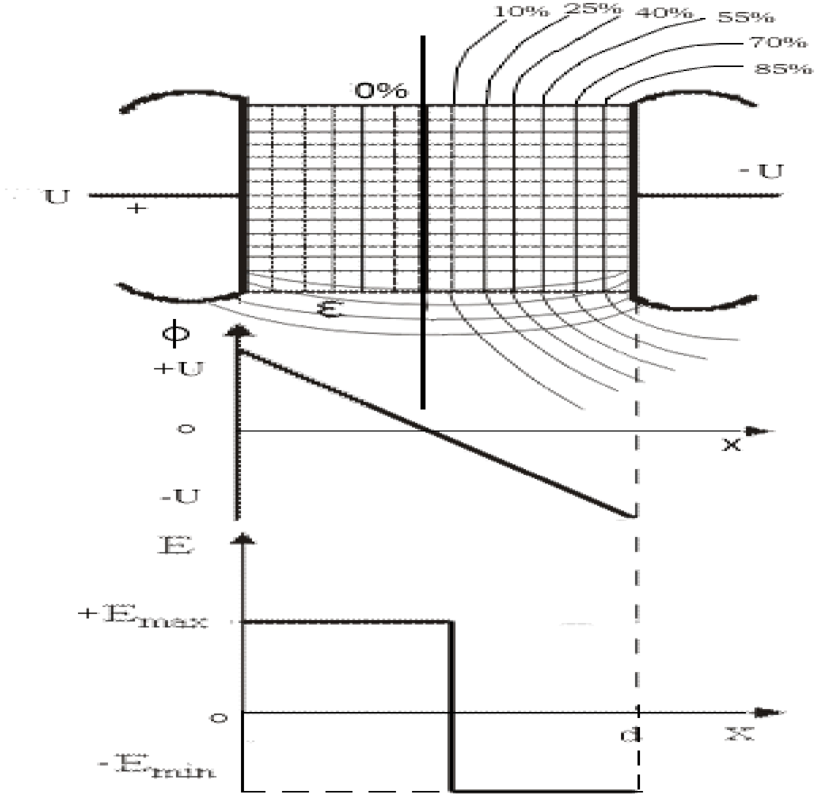
Electric Fields (Continued..)

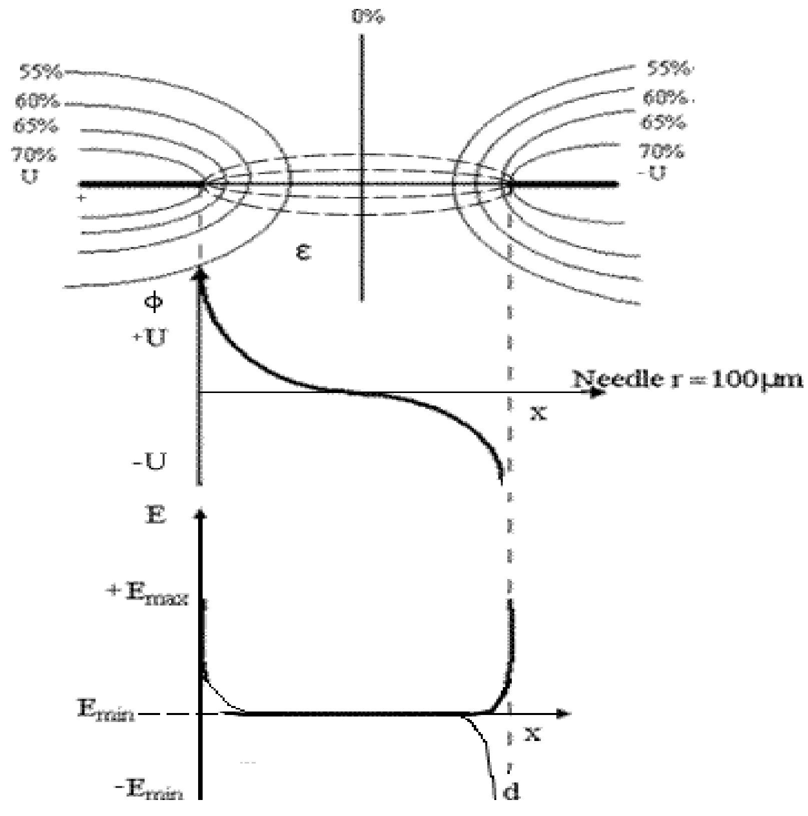
U_{ab} is positive if the work is done in carrying the positive charge from b to a. The maximum magnitude of electric field intensity is therefore, ***given by the maximum value of the rate of change of potential with distance.***

It is obtained when the direction of the increment of distance is opposite to the direction of , in other words, the maximum value of the rate of change of potential is obtained when the direction of is opposite to the direction in which the potential is increasing most rapidly,

$$\frac{dU_{ab}}{dx}\Big|_{max} = -|\bar{E}|_{max} \qquad \bar{E} = -\text{grad}\,\phi$$

Electric Fields (Continued..)





Electric Strength of Dielectrics

•The qualitative definition of 'electric strength' of a dielectric is 'the maximum electric stress a dielectric can withstand'.

•A large number of factors affect the electric breakdown of a dielectric, these include ***pressure, humidity, temperature, electric field configuration (electrode shape and size) electrode material, applied voltage waveform, its duration and magnitude, presence of impurities and imperfections in the dielectric, the composition of dielectric material***. Hence a quantitative definition is complicated.

Electric Strength of Dielectrics

•In a time varying ac power frequency field (quasi stationary field), the maximum electric stress occur at the peak value of the applied voltage.

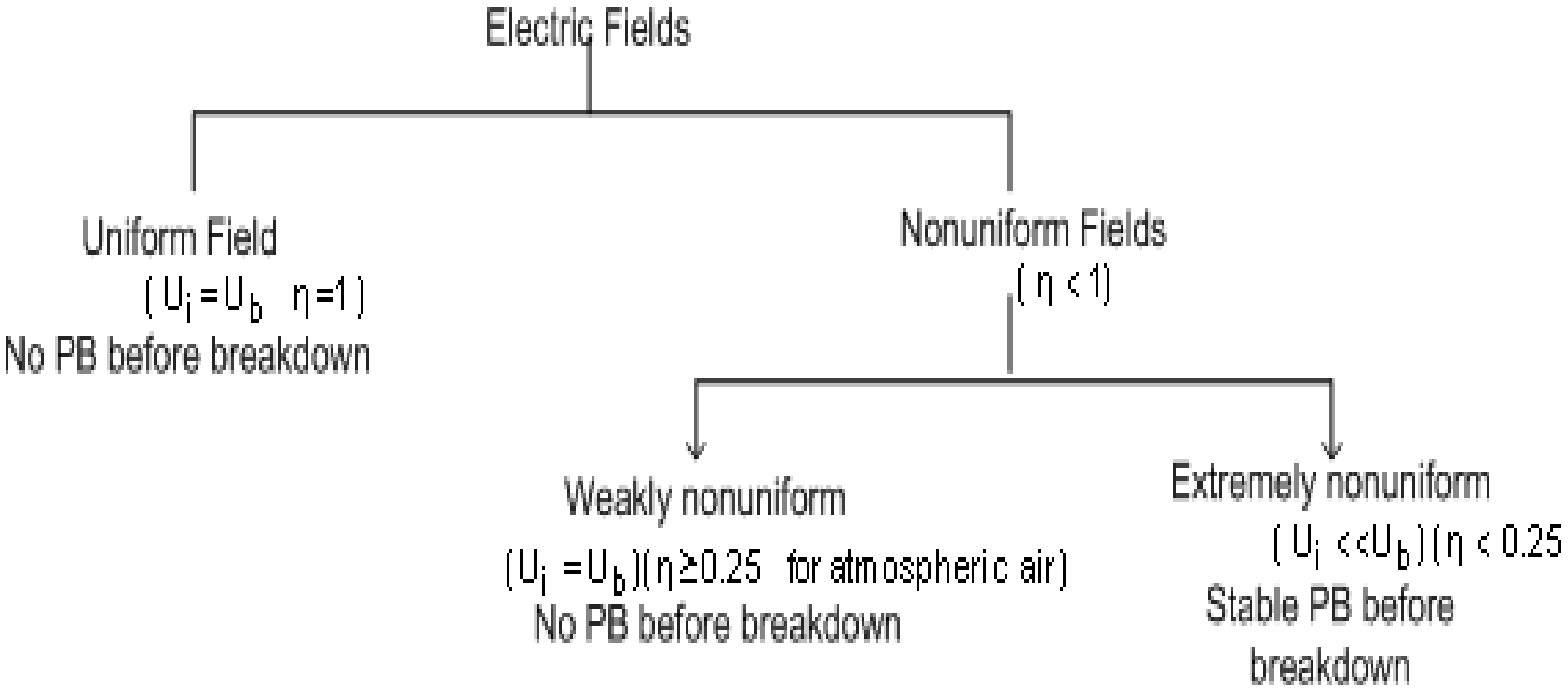
•Intrinsic strength of a dielectric: It is defined for gaseous and other than gaseous dielectric differently.

- Gaseous dielectric: It is the magnitude of breakdown voltage measured across a gap distance of one cm in uniform field ($\eta = 1$) at normal temperature and pressure.

- Liquid and Solid dielectrics: It is the highest value of breakdown strength obtained after eliminating all known secondary effects which may influence the breakdown adversely.

  It is measured for the ideal conditions of the dielectric in uniform field. Since it is very very high for solid and liquid dielectrics compared to gaseous dielectrics, it is measured for mm and µm thin films of the liquid and solid dielectrics respectively instead of 1 cm gap distance in case of gaseous dielectrics.

Classification of Electric Fields



PB – Partial Breakdown

U_i – PB inception voltage

U_b – complete breakdown voltage

η – Schwaiger Factor

Classification of Electric Fields (Continued..)

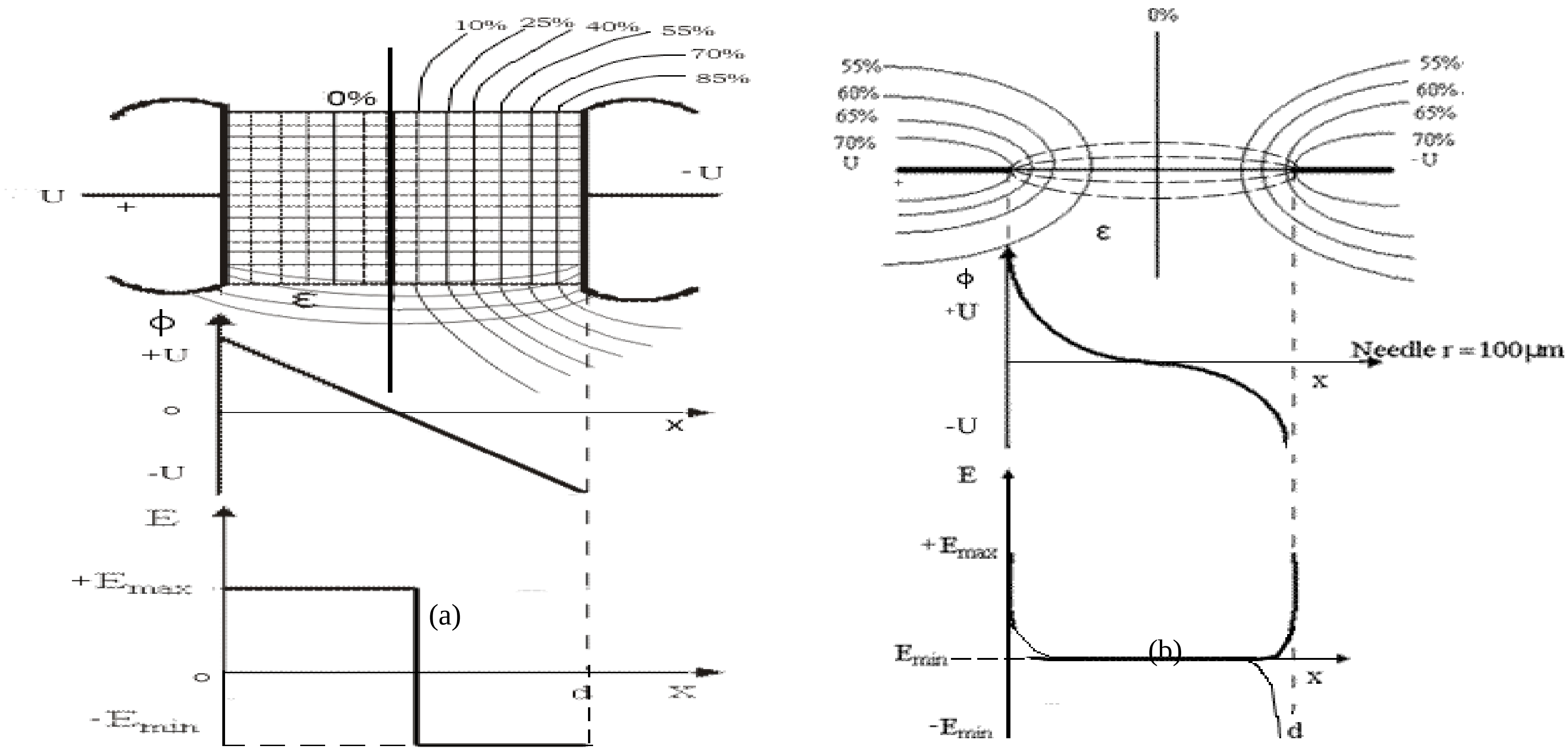


Fig 3.1 The extreme field configurations (a)Uniform field between two parallel plates.
(b) Extremely non uniform field between needle-needle electrodes.
(Effect of grounding is neglected in these plots)

Degree of Uniformity of Electric Fields

•The degree of uniformity η introduced by Schwaiger in 1922 as a measure of the uniformity of a field, is defined as following

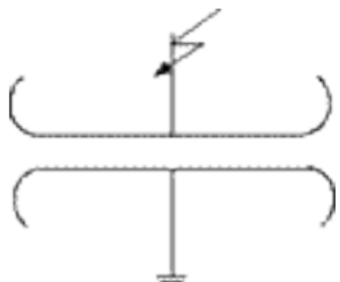
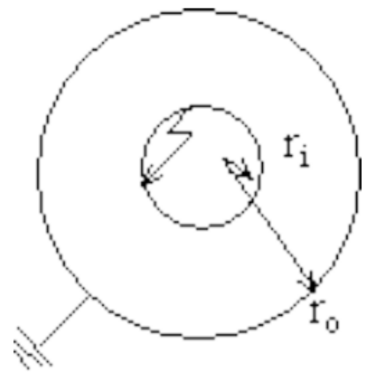
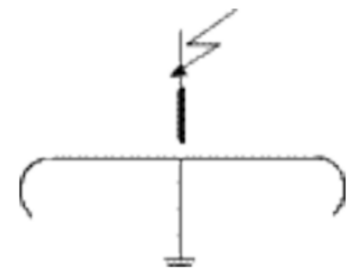
$$\eta = \frac{\hat{E}_{mean}}{\hat{E}_{max}} = \frac{\hat{U}}{d} \cdot \frac{1}{\hat{E}_{max}} \qquad \hat{U} = \hat{E}_{max} \cdot \eta \cdot d$$

$\hat{E}_{mean}$ and $\hat{E}_{max}$ are the peak values of the Mean and the Maximum field Intensities in a dielectric respectively. U is the peak value of potential difference applied between the two electrodes at a distance *'d '* apart.

The value of η also represents the degree of utilization of the dielectric in between two electrodes. A higher value of η represents better utilization of the insulating properties of a dielectric. Thus η, a dimensionless quantity enables a comparison of the uniformity of field configuration formed between different electrodes. Table 3.1 gives the values of η for typical fields. The value of η lies between, $0 \leq \eta \leq 1$

Degree of Uniformity of Electric Fields (Continued..)

Table 2.1 Typical values of η in the three types of electric fields

Field Classification	Uniform	Weakly non-uniform	Extremely non-uniform
Electrode Configuration	Parallel plates 	Concentric cylinders  $r_i = 0.25\ r_o$	Needle-plane 
Schwaiger Factor 'η'	1	≤ 0.25	$<<0.01$

Degree of Uniformity of Electric Fields (Continued..)

•Schwaiger also introduced 'p', a geometrical characteristics for an electrode configuration and established that it is possible to represent η as a function of 'p',

$$p = \frac{r+d}{r} \qquad (1.5)$$

$$(1 \le p < \infty)$$

$$\text{and} \quad \eta = f(p) \qquad (1.6)$$

where r is the radius of curvature of the sharpest electrode and d the shortest gap distance between the two electrodes under consideration.

For some common and practical electrode configurations, the equation (1.6) is represented graphically in Figure 2.2 in double logarithmic scale. These are known as 'Schwaiger curves'.

Degree of Uniformity of Electric Fields (Continued..)

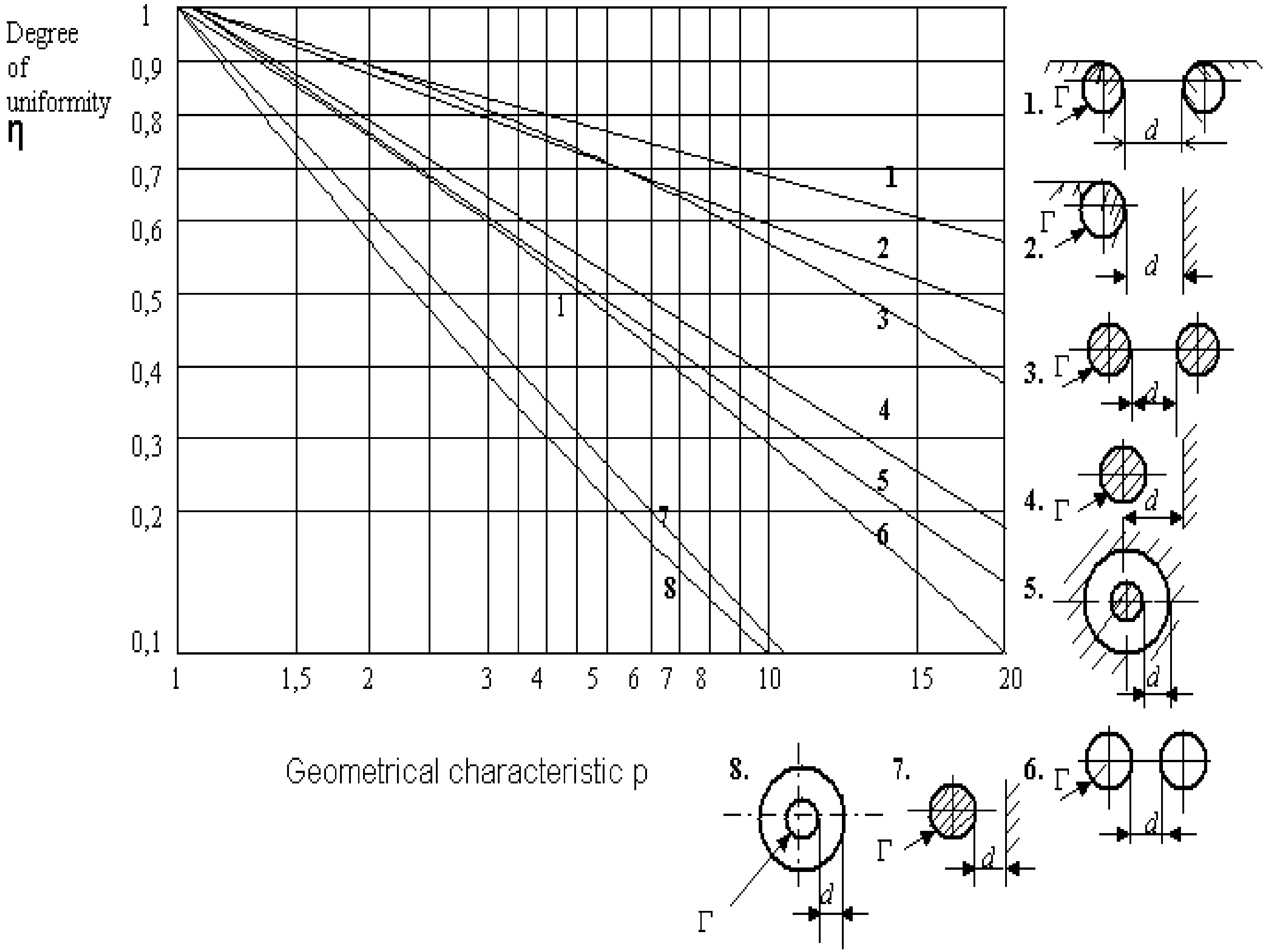


Fig Schwaiger curves for spherical, cylindrical and curved electrode field configurations.

Utilization of Dielectric Properties

- The value of η also represents the degree of utilization of the dielectric in between two elecrtodes.
- A higher value of η represents better utilization of the insulating properties of a dielectric.
- It compares the ideal condition of electric field intensity (uniform field between electrodes at the same distance *d* apart) with the existing actual maximum field intensity.
- Thus η, a dimensionless quantity enables a comparison of the degree of uniformity of field configurations formed between different electrodes. Table 2.1 gives the values of η for typical fields. The value of η lies between, $0 \leq \eta \leq 1$

Utilization of Dielectric Properties (Continued..)

- With the knowledge of the value of η for a particular field configuration, the maximum electric field intensity or the maximum electric stress on a dielectric can easily be estimated.
- η serves as a ready reference which is an important information for insulation design in equipment.
- However, for determining the exact magnitude of maximum electric stress, at different shapes of electrodes used in the equipment, ***numerical estimation techniques*** have to be applied .

Stress Control

- More the uniformity in field, better is the utilisation of the dielectric.
- An ideal utilisation is accomplished only where η is equal to one, which is not possible in practice.
- More nonuniform field represents higher electric stress in the dielectric. It could be at only a particular location. Insulation design in an equipment is made with due consideration to the value of estimated maximum electric field intensity.
- By shaping the conductors to reduce stress concentrations,
- By insertion of higher dielectric strength insulation at higher stress points, and,
- By selection of materials appropriate permittivity's to obtain more uniform voltage gradients.

Stress Control(Continued..)

- It is possible to achieve a higher degree of uniformity of fields by giving suitable shapes and sizes to various electrodes in an equipment.
- For example, abrupt interruption of electrodes, both anode or cathode, in high voltage equipment leads to concentration of electric field at the brim, resulting in a tremendous enhancement of electric stress on the dielectric. The dielectric in the vicinity thus becomes highly vulnerable to breakdown.

Stress Control(Continued..)

•The electrodes must be given a suitable shape at the brim to control the stress.

•For stress control, in principle the electrodes are extended and formed in such a way that higher field intensity than in the main field region does not appear anywhere in the dielectric.

•Rogowski suggested in 1923, a shape by which the electrodes could be extended, known as 'Rogowski Profile', Fig. 4.1(a).

•One can see in this figure that the field intensity continuously reduces beyond the main field region.

•Another shape of the electrode credited to Borda known as 'Borda Profile' , Fig 4.1(b), was actually worked out by him in as early as 1766 in France, more than 200 years ago.

Stress Control(Continued..)

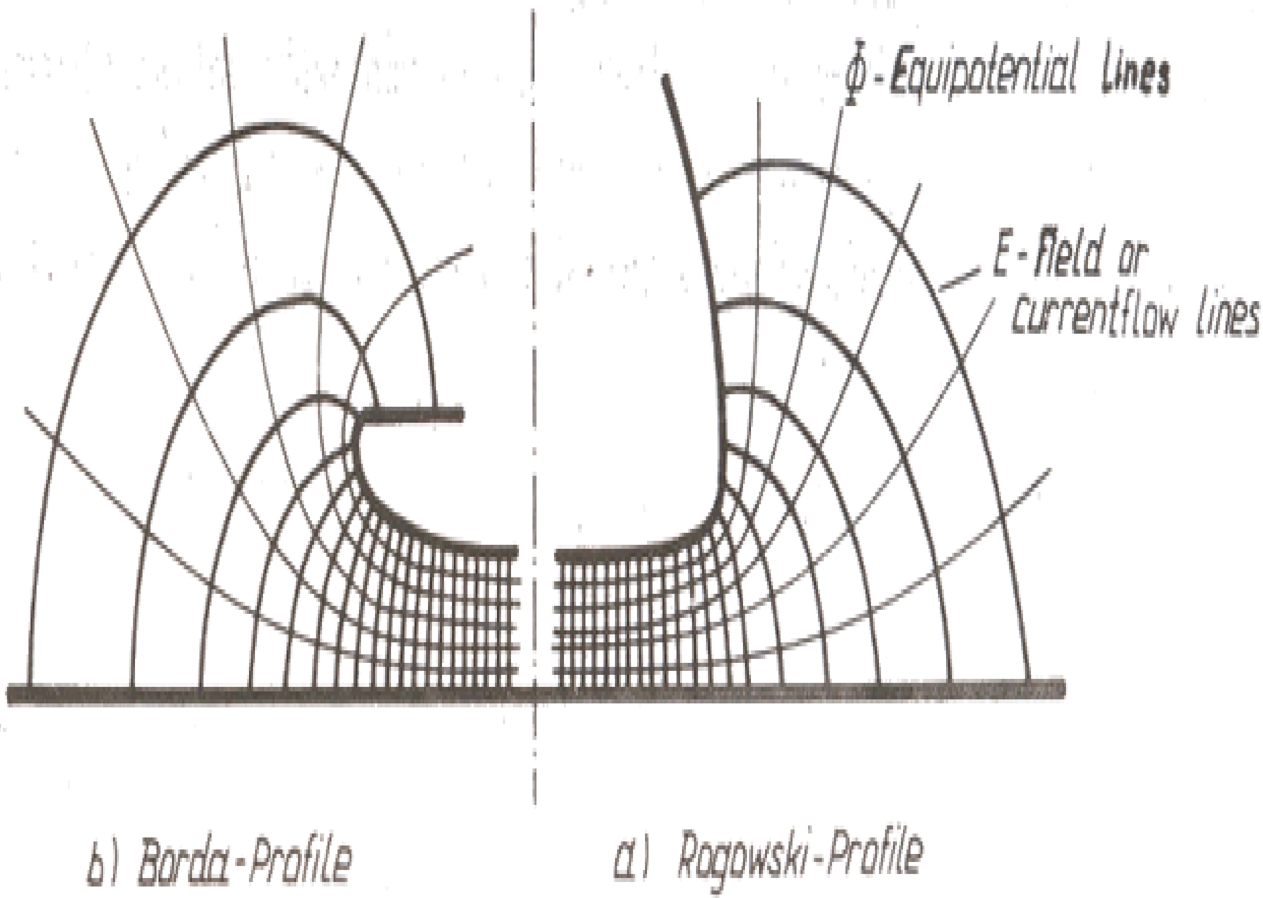


Fig 4.1 Equipotential and Field (current flow) lines between plane and brim field

Stress Control(Continued..)

- Electrodes at high potentials in the laboratory are given large, smooth shaped dome like bodies or shapes like toroids to bring down electric stress on the atmospheric air (dielectric).
- The modern trend in such electrode design includes 'segmented electrodes', constituting a number of small, identical, smooth discs given a large desired continuous shape as per requirement. The curvatures of the individual segment discs are worked out by optimisation of the suggested profiles.

Segmented electrodes(Complete HV lab (600 kV AC))

Single metallic body (DC Generator 900 kV)

Stress Control(Continued..)

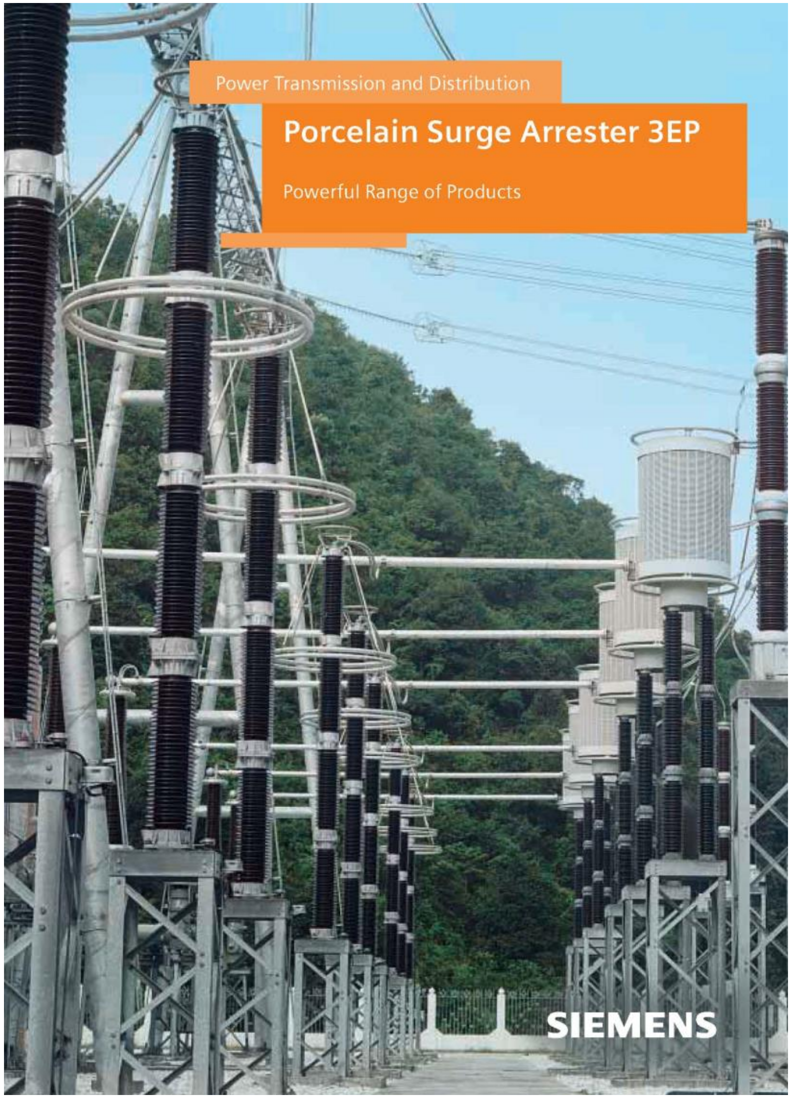
- Extended shapes of electrodes, also known as 'shields', are suitably provided on high voltage apparatus for electric stress control as shown in Fig 4.3.
- Sharp contacts are often enveloped by a large diameter hemispherical electrode having an aperture, or provided with concentric toroidal rings (doughnut shaped ring). Spheres with smooth holes are provided at bends for the connections of circular and tubular electrodes.
- Instead of wires, tubular electrodes of large diameters are used for connections in high voltage laboratories which bring down the field intensity at higher voltages considerably. These measures are necessary not only to prevent any partial breakdown(corona) occurring in the laboratory but also to check radio interference.
- It is a common practice to use bundles of two or more number of conductors at the same potential instead of a single conductor, to bring down the electric stress, i.e., for stress control,

Lightning Arresters

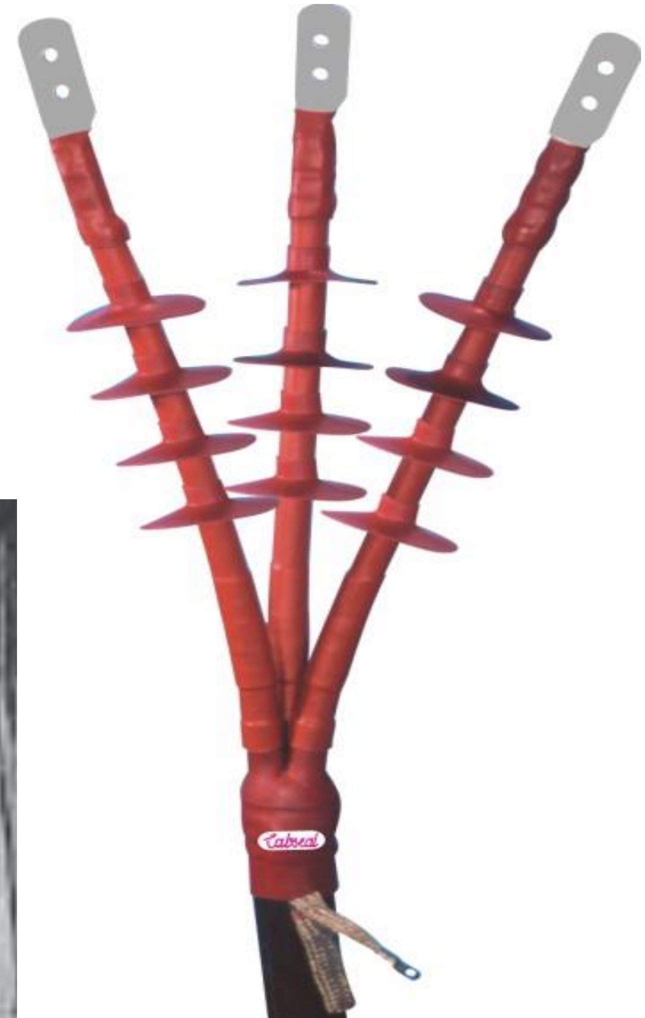
- It is connected between the line and earth so diverts the incoming high voltage wave to earth.
- Lightning arresters act as safety valves designed to discharge electric surges resulting from lightning strokes, switching or other disturbance.
- Lightning arrestors directly connected at one end to the transmission system.

Lightning Arresters (Continued..)

- Rod arrester
- Horn gap arrester
- Multi gap arrester
- Expulsion type lightning arrester
- Valve type lightning arrester
- Silicon Carbide Arrestor
- Metal Oxide Arrestor



Cable Termination and Stress Cone



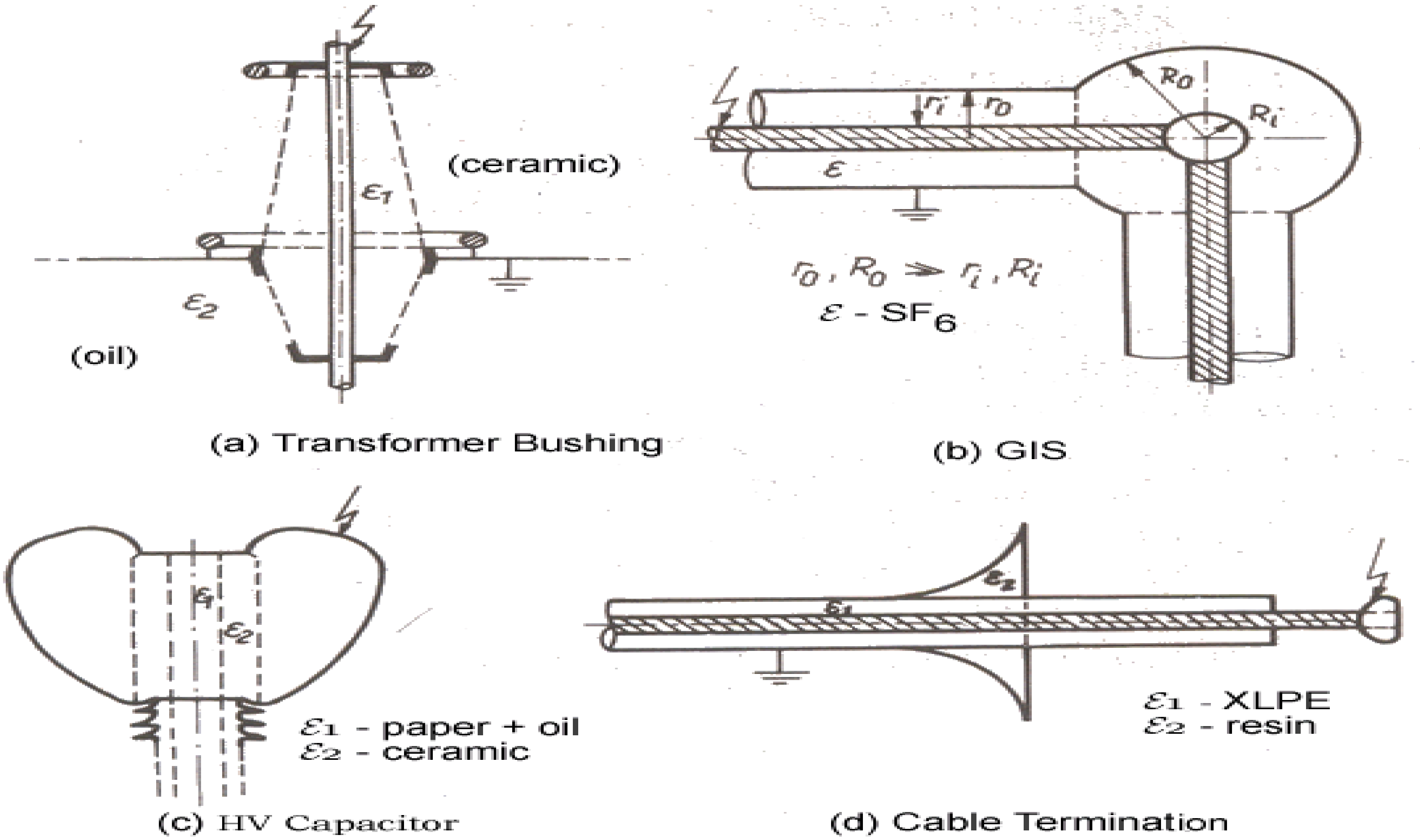


Fig Extended shapes of electrodes for stress control (a) A bushing with toroids (b) Right angle bend of a bus bar in gas insulated switchgear (GIS), (c) HV electrode on a condenser, (d) stress cone at a screened cable end.

Stress Control(Continued..)

- Capacitive grading is provided in high voltage bushings, potential transformers and cable terminations in order to achieve a better potential distribution leading to a more uniform field distribution in the dielectric.
- Use of screen (also known as concentric conductor at ground potential) over the insulation in coaxial high voltage cables is made to control the electric stress.
- A modest thumb rule to control electric stress in high voltage apparatus is to avoid sharp points and edges. Symmetrical, smooth shaped and large electrodes are preferable.
- Furthermore, microprotrusions may grow and penetrate deeper in the dielectric leading to excessive field enhancement. These must be prevented from developing, firstly during manufacturing stage and subsequently during service and maintenance.

Stress Control(Continued..)

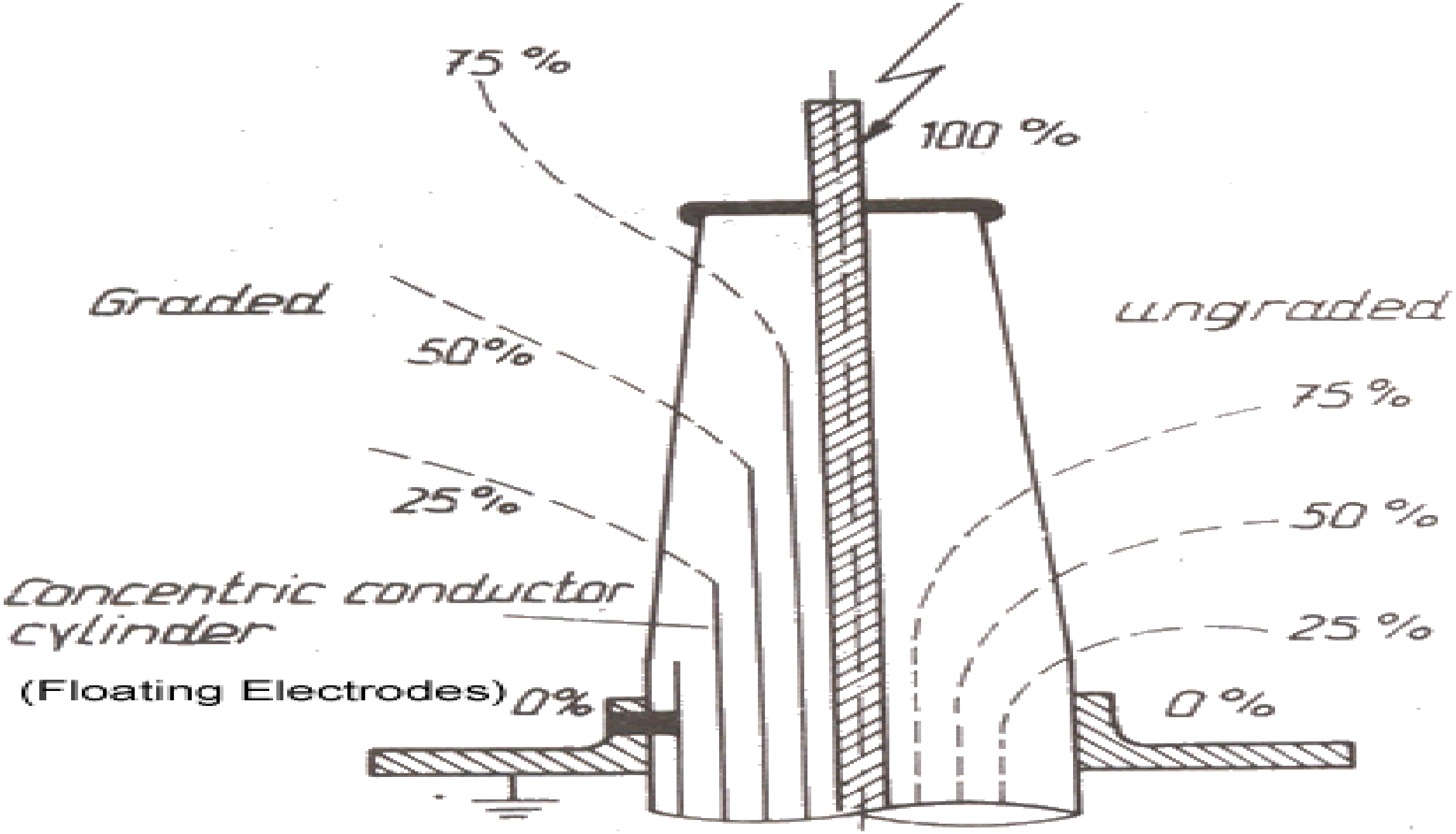


Fig 4.4 Potential distribution in a bushing with and without capacitive grading

Thank You
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