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Electromagnetic & its Application to Insulation Breakdown in Pulsed Power Technology

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***Abstract*—This paper deals with the electromagnetic law which explains break down and the behavior of insulation while break down. An electrostatic field produced due to a potential on an electrode, stresses the electrical insulation in contact with electric stresses. The performance of a dielectric depends mainly upon the magnitude of electric field intensity it is stressed with .For an optimum design of insulation requirement in different equipment's the knowledge of electric field intensity in of great importance in high voltage engineering .The dielectric strength of insulating materials and the electric field stresses developed in them when subjected to high voltage systems .In high voltage apparatus the important materials used are conductors and insulators. While the conductors carry the current and insulators prevent the flow of current in undesired path.**

***Index Terms*— Insulation, Break down, Electric Field Intensity, Dielectric Strength, High Voltage.**

I. INTRODUCTION

The most important material used in a high voltage apparatus is the insulator. The dielectric strength of an insulating material can be defined as the maximum dielectric stress which the material can with stand. The electric breakdown strength of insulating materials depends on a variety of parameters such as pressure, temperature ,humidity, field configuration, nature of applied voltage imperfection in dielectric materials , materials of electrode and surface condition of electrode etc.,

II. INSULATION

All electrical appliances are insulated with gaseous or liquid or solid or a suitable combination of these materials. The insulation is provided between live parts or between live part and grounded part of the appliance. The materials may be subjected to varying degrees of voltages, temperatures and frequencies and it is expected of these materials to work satisfactorily over these ranges which may occur occasionally in the system. The dielectric losses must be low and the insulation resistance high in order to prevent thermal breakdown of these materials. The void formation within the insulating materials must be avoided as these deteriorate the dielectric materials. When an insulating material is subjected to a voltage for investigation, it is usually not possible to draw conclusion regarding the cause of breakdown from the knowledge of the breakdown voltage particularly in solid materials.

Earlier, the quality of insulation was judged, mainly by the insulation resistance and its dielectric strength. However, these days high voltage equipment's and installations are subjected to various tests. These tests should also yield information regarding the life expectancy and the long term stability of the insulating materials. One of the possible testing procedures is to over-stress insulation with high A.C. and/ or D.C. or surge voltages. However, the disadvantage of the technique is that during the process of testing the equipment may be damaged if the insulation is faulty. For this reason, following non-destructive testing methods that permit early detection for insulation faults are used:

a) Measurement of the insulation resistance under D.C. voltages.
b) Determination of loss factor tan δ and the capacitance *C*.
c) Measurement of partial discharges.

Classification of Electric Fields

The electric field configurations are classified between two extreme fields, the uniform and the extremely non-uniform fields. In a uniform field the potential is linearly distributed and the electric field intensity is constant throughout the space between the two electrodes and the break down takes place without any partial discharge

There is an extreme nonlinear distribution of potential in the space between two needle electrodes, leading to strong non-uniformity in electric field intensity. This is a typical case of an extremely non-uniform fields, the insulation breakdown in extremely non-uniform field takes place after stable partial discharge. The pre-discharges are rendered unstable only just before the breakdown. At the tip of the electrode the dielectric is subjected to a very high electric stress, but elsewhere between the electrodes it is stressed moderately. For a given electrode gap distance, the uniform field has the highest breakdown voltage, however, it is difficult to realize a uniform in practice.

Degree of Uniformity of Electric Fields:

The degree of uniformity η is a measure of the uniformity of a field, is defined as following;

$$\eta = \frac{E_{mean}}{E_{max}} = \frac{U}{d.E_{max}} \quad (1)$$

Where, E_{mean} and E_{max} are the peak values of the mean and maximum field intensities respectively. U is the peak value of the 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 any two electrodes. Thus, a dimensionless quantity enables to make a comparison of the uniformity of field formed between different electrode configurations. The value of η lies between,

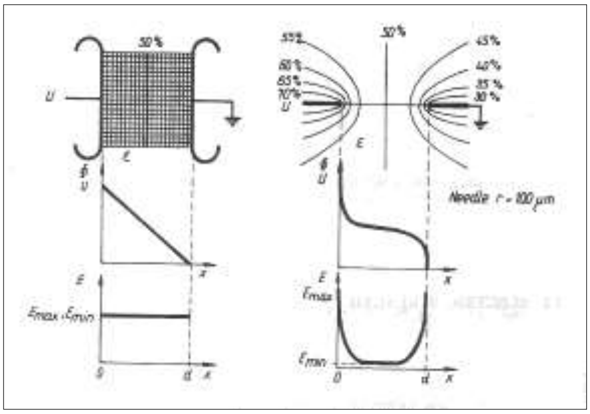

Fig.1 Uniform and non-uniform fields

$$0 \leq \eta \leq 1$$

Knowing the value of η for a particular field configuration, the maximum electric field intensity or the maximum electric stress on a dielectric can be easily estimated. The reciprocal of η represents the degree of non-uniformity of an electric field. The figure shows field configuration.

III. MAXWELL'S EQUATION

The Electromagnetic unfolds as a logical deduction from eight postulated equations, namely, Maxwell's four field equations and four medium-dependent equations. Magneto-static problems are problems in which the fields are time-invariant. In this case, the field intensity (H) and flux density (B) must obey:

$$\nabla \times H = J \quad (2)$$

$$\nabla x\, B = 0 \quad (3)$$

Subject to a constitutive relationship between B and H for each material:

$$B = \mu\ x\ H \quad (4)$$

If a material is nonlinear (*e.g.* saturating iron or alnico magnets), the permeability, μ is actually a function of B. Flux density is written in terms of the vector potential, A, as:

$$B = \nabla \times A \quad (5)$$

If the magnetic field is time-varying, eddy currents can be induced in materials with a non-zero conductivity. Denoting the electric field intensity as E and the current density as J, E and J obey the constitutive relationship:

$$J = \sigma \times E \quad (6)$$

The induced electric field then obeys

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (7)$$

Electrostatic problems consider the behavior of electric field intensity, E, and electric flux density (alternatively electric displacement), D. There are two conditions that these quantities must obey. The first condition is the differential form of Gauss' Law, which says that the flux out of any closed volume is equal to the charge contained within the volume:

$$\nabla \times D = \rho \quad (8)$$

Where, ρ represents charge density. The second is the differential form of Ampere's loop law:

$$\nabla\ x\ E = 0 \quad (9)$$

Displacement and field intensity are also related to one another via the constitutive relationship:

$$D = \varepsilon \times E \quad (10)$$

Where, ε is the electrical permittivity. Maxwell's equations are coupled first-order differential equations which are difficult to apply when solving boundary-value problems. The difficulty is overcome by decoupling the first-order equations, thereby obtaining the wave equation, a second-order differential equation which is useful for solving problems.
The wave equations are as follows;

$$\nabla^2 E = \in \mu \frac{\partial^2 E}{\partial t^2} \quad (11)$$

$$\nabla^2 H = \in \mu \frac{\partial^2 H}{\partial t^2} \quad (12)$$

Boundary Conditions:

The material medium in which an EM field exists is usually characterized by its constitutive parameters ρ, μ and Є the medium is said to be linear if ρ, μ and Є are independent of E and H or nonlinear otherwise. It is homogeneous if ρ, μ and Є are not functions of space variables or inhomogeneous otherwise. It is isotropic if ρ, μ and Є are independent of direction (scalars) or anisotropic otherwise.

Dirichlet type of boundary condition, the value of potential A or V is explicitly defined on the boundary, *e.g.* $A = 0$. The most common use of Dirichlet-type boundary conditions in magnetic problems is to define $A = 0$ along a boundary to keep magnetic flux from crossing the boundary. In electrostatic problems, Dirichlet conditions are used to fix the voltage of a surface in the problem domain.

Neumann boundary condition specifies the normal derivative of potential along the boundary. In magnetic problems, the homogeneous Neumann boundary condition, $\partial A/\partial n = 0$ is defined along a boundary to force flux to pass the boundary at exactly a 90^o angle to the boundary. This sort of boundary condition is consistent with an interface with a very highly permeable metal.

Breakdown Mechanism:

At normal temperature and pressure, the gases are excellent insulators. The current conduction is of the order of 10–10 A/cm2. This current conduction results from the ionization of air by the cosmic radiation and the radioactive substances present in the atmosphere and the earth. At higher fields, charged particles may gain sufficient energy between collisions to cause ionization on impact with neutral molecules. It is known that during an elastic collision, an electron loses little energy and rapidly builds up its kinetic energy which is supplied by an external electric field. On the other hand, during elastic collision, a large part of the kinetic energy is transformed into potential energy by ionizing the molecule struck by the electron. Ionization by electron impact under strong electric field is the most important process leading to breakdown of gases.

The Townsend's Criterion

$$v(e^{\alpha d} - 1) = 1 \quad (13)$$

enables the evaluation of breakdown voltage of the gap by the use of appropriate values of α/p and v corresponding to the values E/p when the current is too low to damage the cathode and also the space charge distortions are minimum. A close agreement between the calculated and experimentally determined values is obtained when the gaps are short or long and the pressure is relatively low.

An expression for the breakdown voltage for uniform field gaps as a function of gap length and gas pressure can be derived from the threshold equation by expressing the ionization coefficient α/p as a function of field strength E and gas pressure p

$$\frac{\alpha}{p} = f\left(\frac{E}{p}\right) \quad (14)$$

By substituting this we get

$$f\left(\frac{V_b}{pd}\right) = \frac{K}{pd} \quad (15)$$

$$V_b = F\,(p \times d) \quad (16)$$

This shows that the breakdown voltage of a uniform field gap is a unique function of the product of gas pressure and the gap length for a particular gas and electrode material. This relation is known as *Paschen's law*. This relation does not mean that the breakdown voltage is directly proportional to product *pd* even though it is found that for some region of the product *pd* the relation is linear *i.e.*, the breakdown voltage varies linearly with the product *pd*. The variation over a large range is shown in Fig.1

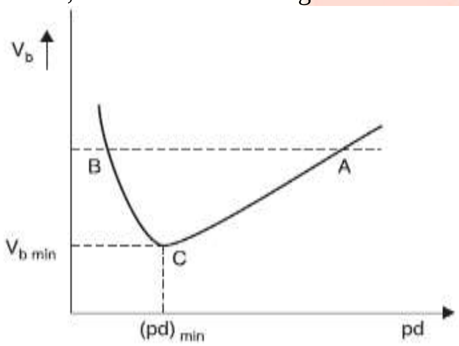

Fig.2 Paschen's Curve

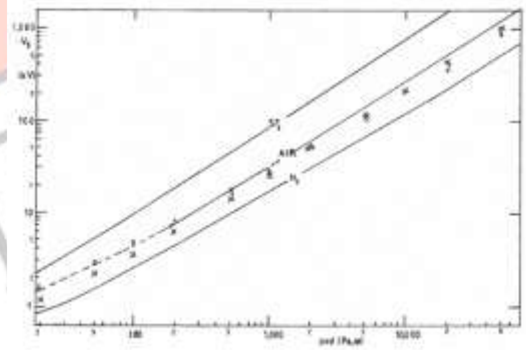

Fig.3 Paschen Characteristics of Six Gases

If the electric field is uniform and if the field is increased gradually, just when measurable ionization begins, the ionization leads to complete breakdown of the gap. However, in non-uniform fields, before the spark or breakdown of the medium takes place, there are many manifestations in the form of visual and audible discharges. These discharges are known as *Corona discharges*.

Table 1 Minimum Sparking Constant for Various Gases

Sr. No.	**Gas**	***(pd)* minimum**	**V_b Minimum Volts**
1	Air	0.55	352
2	Nitrogen	0.65	240
3	Hydrogen	1.05	230
4	SF_6	0.26	507
5	CO_2	0.57	420
6	O_2	0.70	450
7	Neon	4.0	245
8	Helium	4.0	155

In fact Corona is defined as a self-sustained electric discharge in which the field intensified ionization is localized only over a portion of the distance (non-uniform fields) between the electrodes. The phenomenon is of particular importance in high voltage engineering where most of the fields encountered are non-uniform fields unless of course some design features are involved to make the field almost uniform. Corona is responsible for power loss and interference of power lines with the communication lines as corona frequency lies between 20 Hz and 20 kHz. This also leads to deterioration of insulation by the combined action of the discharge ion bombarding the surface and the action of chemical compounds that are formed by the corona discharge.

IV. APPLICATION TO PULSED POWER TECHNOLOGY

Generation of short duration pulse is the main application of the breakdown study. Electromagnetic solver can give the electromagnetic field distribution for the breakdown phenomenon.

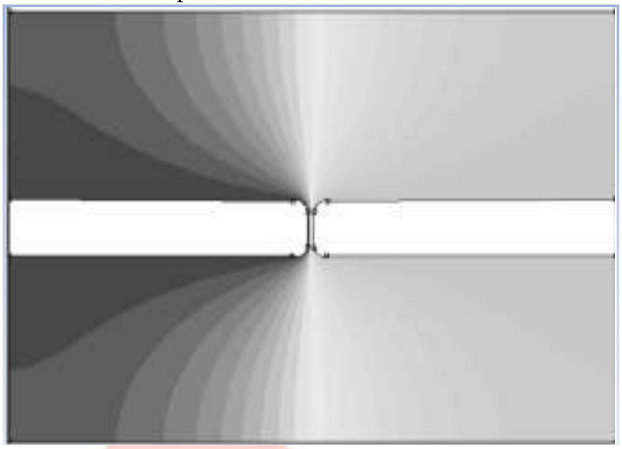

Fig.5 Finite Element Model of Rogowski Profile Electrode

Above figure shows potential distribution because of Rogowski profile electrodes. This can be achieved using Finite element method software. The output of the system is short duration pulse. According to the requirement the change in electrode configuration can be made. Many microscopic models (partial physics) and macroscopic models (thermal, dynamic, electrical) have been developed. In a microscopic model the charge density distribution is obtained using any numerical technique. This gives the arc voltage, arc current and resistance of arc. Thus in this model the arc resistance forms the equivalent circuit element. In this, the particle in cell method simulations, have to be carried out.

The generally used macroscopic models are Ayrton, wherein the voltage of the arc is a function of the arc current and distance between electrodes and the model proposed by Mayr and Cassie describes the rate of change of energy in terms of power input to the arc and the power dissipated in the environment. The Mayr and Cassie model is widely used. In this method the arc is modeled dynamically as a function of arc impedance, arc time constant, input power and cooling power. Using these modeling techniques and above theoretical background of breakdown theory the generation of short duration pulse can be more clearly understood.

V. CONCLUSION

Behavior of dielectric when subjected to electric stress in very important aspects for insulation system design in high voltage engineering. It is not only essential to know the existing maximum field intensity in the electrode system of an equipment but also the maximum permissible electric stress for the dielectric in use .A perfect integration of these two may prove a safe, secure, reliable and economically insulation system. This paper discussed the basic equation for potential and field intensity in electrostatic fields. It also covers the classification of electric fields under different electrode shapes.

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