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Introduction

The subject, "High Voltage Engineering," is the knowledge of the behavior of dielectrics—electrical insulation when subjected to high voltage. Performance of dielectrics is electric field dependent. The electric field configuration, to which a dielectric is subjected, determines its life and function in the long run. It is always desirable to minimize the volume of the electrical insulation requirements yet a long and trouble-free life of all high voltage apparatus should be ensured. For an apparatus to be economically viable, its desirable life expectancy is 30–40 years, depending upon the cost and technology of production involved.

The world has seen rapid advancement in the technology applied in high voltage apparatus in the second half of the twentieth century. Manufacturing of gas insulated sub-stations (GIS), power transformers, cables, and switchgears at the highest rated voltages up to 1100 kV involve the most sophisticated technologies. Such a development has taken place with dedicated efforts to understand the behavior of dielectrics, gaseous, solid, liquid, and vacuum.

The last half century has also seen prominent advancement in the technology of dielectric finishes on equipment. To a limited extent, insulating materials with better dielectric properties and performance have been developed. Knowledge of electric field dependent behavior of dielectrics has led to better use of the insulating materials. Advancement in techniques of evaluating the quality of the finish of electrical insulation in an apparatus has contributed to producing quality power apparatus with more reliability up to the highest rated voltages. The non-destructive testing and condition monitoring techniques of equipment/insulation have improved considerably. The high voltage test apparatus and measuring instrumentation and their respective technologies have also made big advances. These have led to the production of more dependable and economical high voltage apparatus with sophisticated technologies.

The contents of this book was initially developed at the High Voltage Laboratory of Technische Universität Dresden, Germany, which is well known in the continent of Europe for its dedicated research and development work for more

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than one and a half centuries. These were published for the first time in English in our earlier book, "High Voltage Insulation Engineering," in 1995. Advances in this subject, at TU Dresden, Germany and Indian Institute of Technology Kanpur (India) and in many other countries in the world, are being incorporated into this second book.

While delivering the lectures based on our first book, interaction with the students revealed a number of lacunae in interpreting the basic concepts essential for understanding the behavior of dielectrics. Hence, some fundamental terminologies used commonly in this subject are explained in the following pages. Explanation of these terms has been mainly derived from various English-language dictionaries [1–4] that describe the same terminology in slightly different ways. Hence, a number of similar expressions available for a particular term are compiled. These descriptions are bulleted in the following text. A clear interpretation of these terms will help the reader to better understand the high voltage phenomena.

1.1 Electric Charge, Discharge, Current, and Potential

Electron

- an elementary particle consisting of negative charge, found outside the nucleus of an atom
- negatively charged sub-atomic particle found in all atoms and acting as the primary carrier of electricity in solids

Proton

- a subatomic particle with a positive electric charge occurring in all atomic nuclei-origin Greek, "first thing"
- a nuclear particle with positive charge equal and opposite to that of an electron negative charge

Ion

- an electrified atom having either a positive or negative charge
- an electrified atom which has increased or decreased its number of electrons after electrolysis (ionization)
- an atom or molecule with a net electric charge produced through loss or gain of electrons

Ionize

- convert an atom, molecule, or substance into an ion or ions
- to convert into an ion form
- to convert wholly or partly into ions—to become ionized

Ionization

- the process of formation of ions

Electric Charge

- the presence of an uncancelled excess of either positive subatomic particles (protons), or negative subatomic particles (electrons) in a substance
- electricity in free subatomic particles of a polarity, positive or negative

The behavior of electric charge can be explained with the following typical characteristics:

- ionization is a process by which charges build up
- accumulation of charge (q) builds up potential φ
- concentration of like polarity charge (in dielectrics) is known as "**space charge**"
- when the positive and the negative charges are uniformly distributed in a dielectric, the volume charge density "ρ_v," is equal to zero
- on the contrary, when there is a concentration of any one polarity charge, ρ_v is not equal to zero
- the electric charge is at rest in dielectrics; however, it is restless in conductors
- the electric charge always acquires the least resistance path to flow
- flow of charge is electric current
- the electric charge finds its ultimate peace only inside the earth, the mother earth

Electric Discharge

- to get rid of a charge of electricity
- withdrawing or transference of an electric charge
- release or neutralize the electric charge
- a flow of electricity through the air or other gas
- a sudden movement of charge

Electric Current

- the rate of flow of electric charge carriers, or the charged particles, over a point or a region
- flow of one coulomb of charge per second is a measure of one "ampere" of current in SI units

Electric Potential

- the amount of work done per unit charge to move the charge from a point of reference to a specified point
- the work done measured in "joules per coulomb" is known as "volts"

  The electric discharge process can be typically described by the following:
- ionization is the process by which electric charges—hence potential builds up; while discharge involves movement of charge—hence loss of potential

- ionization builds up potential on a body while discharge tends to lose it
- electric discharge leads to equalization of the difference of electric potential built by the charge between any two bodies/electrodes

1.2 Electric and Magnetic Fields

Field is a quantity that is a function of space. The presence of a field is sensed by the force exerted on a particle or body. A wave can be defined as a function of both time and space [5, 6].

Electric Field

- a quantitative description of the attraction or repulsion of one electric charge by another at any one point
- the ratio of the force exerted on a positive test charge, placed at that point, to the magnitude of the charge
- the source of electric field intensity is electric charge

Magnetic Field

- the portion of space near a magnetic body or a current carrying body in which the forces from the body or current can be detected
- a region around a magnet within which the force of magnetism acts
- any space or region in which magnetic forces are present, as the space or region in or around a piece of magnetized steel, or in or around an electrical current

1.3 Electromagnetism

Electromagnetism is defined as an interaction between electricity and magnetism. For example, when a changing magnetic field generates an electric field or vice versa. It is also explained as:

- magnetism developed by a current of electricity
- branch of physical science that deals with the physical relations between electricity and magnetism
- the study of the relation between electric currents and magnetism
- magnetism caused by electric current

Electromagnetic

- relating to the inter-relation of electric and magnetic fields
- pertaining to electromagnetism or an electromagnet

Electromagnetic Radiation

- radiation in which electric and magnetic fields vary at the same time

Electromagnetic Wave

- a wave whose characteristics are variations of electric and magnetic fields, such as a radio wave or a light wave
- one of the waves that are propagated by simultaneous periodic variations of electric and magnetic field intensity and that include radio wave, infrared, visible light, ultraviolet, X-rays, and gamma rays

Electromagnetic waves can also be explained as follows:

- time varying magnetic field produces an electric field (Maxwell's equation)
- time varying electric field also produces a magnetic field, even in the absence of flow of electric current
- time varying electric and magnetic fields form electromagnetic waves that are characterized by their impedance, energy and velocity of propagation, etc.

Electromagnetic Induction

- discovered by Michael Faraday in 1830s, electromagnetic induction is the phenomenon by which the generation of electromotive force (emf) or voltage takes place in a conductor due to changing magnetic field
- it is the principle used in "electro-magnetic energy conversion" (emec) process in electrical machines

Electromagnetic Force

- the force, associated with electric and magnetic fields, may be attractive or repulsive force
- carried by the photon, it is responsible for atomic structure and chemical reactions

Electromagnetic Field

- An electromagnetic field comprised of both electric and magnetic fields. The two fields are related to each other theoretically such that Maxwell's equations are satisfied under the given boundary conditions. An electromagnetic field itself has no mathematical symbol and it is not a measurable quantity as such.

1.4 Dielectric and Electrical Insulation

Electric

- electricus produced from amber (a resin) by friction
- amber's substance that develops electricity under friction
- pertaining to, consisting of, or containing electric charge or electric current
- charged with or capable of developing electricity

Dielectric

- **Archaic:** A non-conductor of electricity used to excite or accumulate electricity
- **Dia + electric**: Non-conductor of direct electric current
- insulating (medium or substance), non-conductive, non-conductor, through which electricity is transmitted (without conduction).
- a non-conducting or insulating material; a material that admits electrostatic and magnetic lines of force but resists passage of electric current.

However, there is no dielectric which does not have any conduction of charge or current. Conduction currents through dielectrics mainly depend upon their relative permittivity number ε_r and the type and amplitude of the voltage applied.

Before pico-, nano-, or micro-ampere of current magnitudes could not be detected or measured, the electrical insulating materials were considered to be totally non-conducting, hence called "dielectric."

Insulator

- one that insulates; a material that is a poor conductor of electricity

Electrical Insulant

- an electrical insulating material, insulation, the material used for insulating

Insulate

- to separate from conducting bodies by means of nonconductors so as to prevent transfer of electricity

The first and foremost enemy of an electrical insulator is water. It is the most **bitter** enemy of liquid and solid dielectrics.

1.5 Electrical Breakdown

Failure of electrical insulation properties of insulating materials is known as "breakdown." The electrical breakdown of dielectrics can be distinguished between "Global" and "Local" breakdowns, described in the following text.

1.5.1 Global Breakdown

The complete rupture or failure of the electrical insulation between two electrodes is described as "breakdown." It is generally termed as "electrical breakdown," or simply "breakdown."

1.5.2 Local Breakdown or Partial Breakdown

The phenomenon of failure of insulating properties confined locally to a part of the total insulation system provided between two electrodes is known as local breakdown. Since it takes place partially, not globally, it is described as "partial breakdown" (PB) in an electrical insulation. The healthy part of the dielectric continues to provide electrical insulation between the two electrodes in spite of failure of insulating properties in some limited part. The terminology, used very widely so far, for describing this phenomenon has been "Partial Discharge" (PD) in the literature. Since the word discharge has several meanings, it is more appropriate to describe this phenomenon as "partial breakdown" (PB). This phenomenon can occur in any dielectric under adverse conditions. Like breakdown, the PB phenomenon is injurious for the dielectrics. Hence it is most undesirable and should be prevented as much as possible.

1.5.3 Breakdown Strength or Electric Strength

The qualitative definition of breakdown strength of a dielectric is "the highest magnitude of electric stress withstood" when the voltage applied across the dielectric is raised gradually. It is given in kV/mm or kV/cm. The quantitative value, however, is rather precarious since it depends upon a number of parameters of measurements and the composition and quality of the dielectric, most importantly, the type of electric field determined by the electrode shape, size, and gap distance and even the electrode material. It varies widely for the type (dc, ac, impulse) and the duration of applied voltage it is measured with. Atmospheric conditions, like temperature, pressure, and humidity, besides the physical conditions of the dielectric influence too.

1.6 Corona, Streamer, Star, and Leader

Corona

- the gaseous envelope of the sun or star
- a small circle of light seen around the sun or moon
- origin Latin; crown, cornice, garland

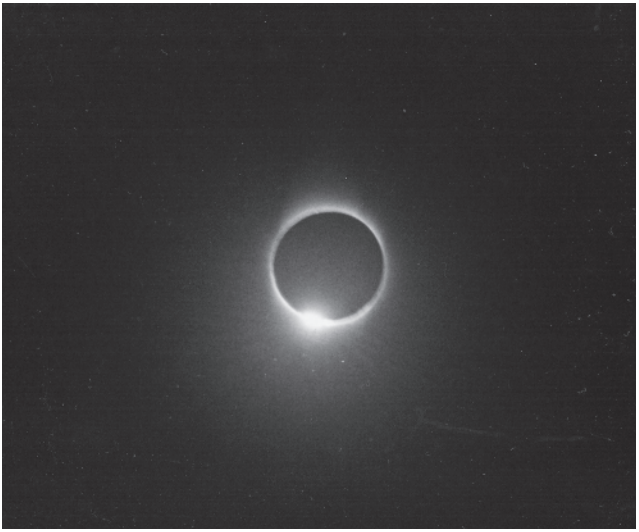


Figure 1.1 Diamond ring with long extension of the solar corona seen at total eclipse taken by the author in 1995.

- halo of white light seen around the black disc of moon in total eclipse of sun, Figure 1.1
- the brush discharge of electricity
- a circle of light made by the apparent convergence of the streamers of the aurora borealis
- a faint glow adjacent to the surface of an electrical conductor at high voltage
- a crown or garland, especially that bestowed upon the ancient Romans as a reward for distinguished services
- white or colored circle of light seen around a luminous body, the sun or moon
- the thin, hot outer atmosphere of the sun that is shaped by solar magnetic fields
  The stable PB phenomenon in gaseous dielectrics/mediums is known as corona.

Streamer

- a long, narrow strip of material used as a decoration or flag
- a Pennon, ribbon attached at one end and floating or waving at the other
- column of light shooting up in aurora
- any long narrow wavy strip resembling or suggesting a banner floating in the wind
- a long extension of the solar corona visible only during a total solar eclipse
- Aurora Borealis
- anything which streams
- stream of light shooting upward from the horizon, as in some forms of the aurora borealis

Streamer Corona

- The stable PB phenomenon in gaseous dielectrics at hemispherical rods, spherical or similar electrodes, appear like a streamer or a shower of discharge, are known as "Streamer Corona." It takes place when the avalanches are able to acquire above critical amplification.

Star Corona

- Stable PB in gaseous dielectrics at extremely sharp electrodes, needle tips, brims or thin wires appear like a star in the sky in dark, is known as "Star Corona." It takes place when the avalanches are not able to acquire critical amplification, or to say with avalanches of below critical amplification.

Leader Corona

- The vigorous streamer corona may undergo an abrupt transformation, the so called constriction of its trajectories on increasing the applied voltage in case of gap distances above 1 m, giving rise to "Leader Corona," which has a fewer but very bright trajectories.

The PB phenomenon in gaseous dielectrics at hemispherical rods, spherical or similar electrodes, which appear like a streamer or a shower of discharge, are known as streamer corona.

1.6.1 Aurora

- luminous atmospheric (prob. electrical) phenomenon radiating from earths northern or southern magnetic pole; down; color of sky at sunrise
- Roman goddess of dawn (morning)
- a luminous phenomenon that consists of streamers or arches of light appearing in the upper atmosphere of a planet's polar regions and is caused by the emission of light from atoms excited by electrons accelerated along the planets magnetic field lines
- the sporadic radiant emission of light from the upper atmosphere over middle and high latitudes

Auroras are spectacular displays of luminous radiation in the sky near polar regions, their symmetry defined by the earth's magnetic field. Aurora lights are emitted when atoms in the ionosphere are struck by high energy electrons coming from the sun [7].

The well-known "Faraday glow" is nothing but emission of light from atoms excited by electrons accelerated along a tube having atmospheric pressures, as in high latitudes at an altitude of hundreds of kilometers above the ground (earth), on application of voltage.

Aurora Australis

- an aurora that occurs in earth's southern hemisphere
- the southern lights
- streamers of colored light seen in the sky near the South Pole origin: Latin

Aurora Borealis

- an aurora that occurs in earth's northern hemisphere
- the northern lights
- streamers of colored light seen in the sky near the North Pole origin: Latin
- the northern down in Latin, meaning the light generated by electrons and ions bombarding the upper atmosphere at high latitudes

1.6.2 Electric Arc

- "arched column of horizontal electrical discharge in air between two charcoal electrodes"—Davy
- when an electrically conductive channel acquires plasma state
- arc columns produced due to high short-circuit currents in power systems and lightning

1.7 Capacitance and Capacitor

Conductors have resistance; coils have inductance; and dielectrics have capacitance. A dielectric between two electrodes gives rise to a capacitor having a capacitance. The exact value of capacitance (in Farads) of a capacitor is difficult to determine analytically. It depends upon the shape and size of the electrodes, the volume of the dielectric between them, and the condition of the dielectric.

Figure 1.2 shows a typical parallel plate capacitor. The capacitance "C" of this capacitor is analytically calculated as,

$$C = \varepsilon_o \varepsilon_r \frac{A}{d} \quad \text{F}$$

where

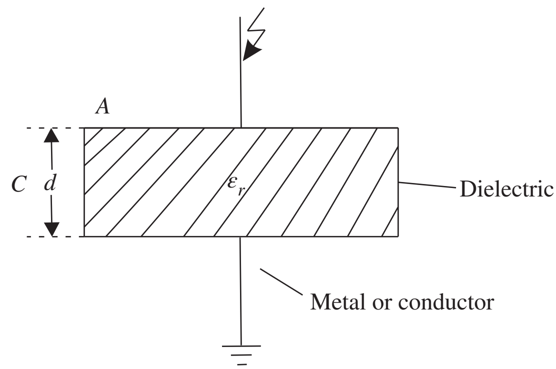
ε_o = the absolute permittivity or dielectric constant equal to 8.854×10^{-12} or $1/36\pi \times 10^{-9}$ F/m

ε_r = the relative permittivity number, a dimension less quantity, which is a function of the temperature of the dielectric and also the magnitude and frequency of the voltage applied to it

A = area of the plates (considered to be identical) in m^2

d = gap distance between the plates in m

Figure 1.2 A capacitor.



This analytical formula for the calculation of capacitance has been derived with a very important assumption that the electric field between the plates is a "uniform" field. However, if the two plates are of limited size, the fringing effect of the plate ends would not render uniform field in between. Hence, many authors have described it to be valid for two "infinite" size plates in the literature. In that case, the field in the "center" of the plates may be uniform but when the area "*A*" tends to infinity, this formula is not valid for determining capacitance of this capacitor. Even if one considers two very large area plates, the field may be uniform only in the middle of the plates, not throughout the area "*A*." Uniform field between two electrodes is only an ideal condition, one that is very difficult to achieve in practice.

Another lacuna in this formula is that "ε" the permittivity of the dielectric is often considered to be a constant. As mentioned, the relative permittivity varies with temperature and applied magnitude of voltage and its frequency. Since $\varepsilon = \varepsilon_0 \varepsilon_r$, it would be wrong to describe ε to be a constant.

The formula for the calculation of capacitance of the parallel plate capacitor should therefore be applied for a rough estimation of the capacitance. It is always advisable for the actual value of capacitance formed by a dielectric between two electrodes to be determined by measurement.

1.7.1 Stray Capacitance

A capacitor, depending upon its physical location, forms capacitance with other wholly or partially conducting bodies.

As shown in Figure 1.3, the stray capacitances could be constituted by one or more dielectrics. The stray capacitances may vary in magnitude with respect to the location of the main capacitor. Air is the dielectric that constitutes most often the stray capacitances. To minimize the effect of stray capacitance, often screens (grounded concentric electrodes) are used in practice.

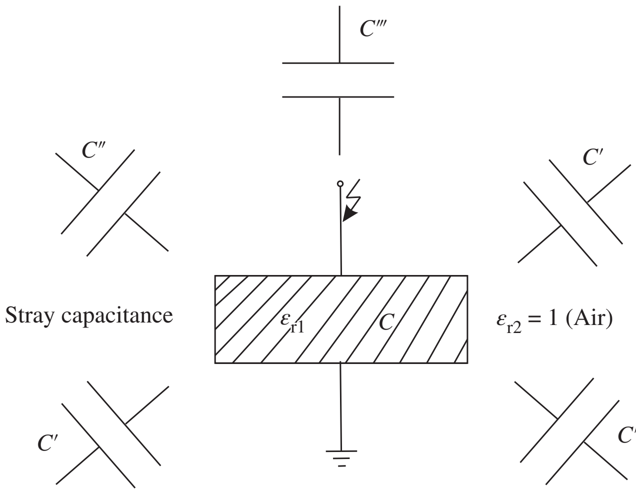


Figure 1.3 A capacitor with its stray capacitance.

1.8 Forms of Voltages and Currents

The power systems come across basically three forms of voltages and currents:

Alternating Current (ac)

- Alternating current and also voltage have a frequency of 50 Hz, known as "power frequency" in India and in most of the countries in the world. But in the United States and in some other countries it is 60 Hz. The oscillating magnitude varies in a sinusoidal cycle wave form with respect to time. The symbol used is (~).

Direct Current (dc)

- Direct current and also voltage have ideally a constant magnitude with respect to time. It may have a positive or a negative polarity. A dc system could be either mono-polar or bi-polar. The symbol used is (=).

Impulse Voltage and Current

- A unidirectional voltage or current that rises rapidly to a peak value and then decays comparatively slow. These are represented as a quotient of the time required to acquire the peak value to the time required to decay to its 50% magnitude of the peak value. The duration of their time is normally in μs or ms in power systems. These may have either positive or negative polarity.

The transient over-voltages in power systems have an impulse wave form. They are generated by (1) External source, the “Lightning,” (li) and (2) Internal source within the network, “Switching,” (si). The symbol used is (^).

1.8.1 Traveling Waves

The impulse voltages and currents, generated at a location in power systems over and above the rated voltage and current, spread and propagate in every direction in the form of “traveling waves.” The magnitude of individual waves is proportional to the resistance/impedance offered by the conductive path. While propagating, there is an attenuation in their magnitudes due to losses in the conductor, reflections at the junctions, and also due to actuation of the protective devices and flash-overs.

1.8.2 Neutral and Ground

The “star” point or the “tri-junction” in a three phase star connected system is called the “neutral.” Depending upon the circuit characteristics, the neutral point may be required to be grounded (earthed). If so, it is grounded only at the device/apparatus.

The ground conductor, laid along with three and single phase power distribution circuits, is a completely independent conductor used for personnel safety.

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