High Voltage Engineering

Text Book and Reference Book

- Text Book: High Voltage Engineering by Kuffel and Abdullah
- High Voltage Engineering Fundamentals, By E. Kuffel, 2nd Edition 2000
- Reference: IET Power Energy Series, "Advances in High Voltage Engineering" By Haddad and D. Warne

Lecture contents

- Mechanisms of Air Breakdown
- Introduction
- Physical Mechanism
  - Avalanche development
  - Avalanche properties
  - Applications and many more……

Introduction

- There are two basic ideas existing in breakdown phenomena;
- Lightning – a long spark
- Tree-like discharges, now called corona, across the surface of a conductor
- Indeed, many of the quantities used in discussion of the processes in discharge physics, such as ionisation and attachment coefficients, electron and ion temperatures, diffusion coefficients and so on, have been measured and are quoted in terms of electric field

- Usually, it is assumed that the electric fields being considered are uniform
- In fact, this is very rarely true in practice and the use of these quantities is always subject to such modifications as are dictated by non-uniform electric field conditions
- The concept of breakdown will be assumed to signify the collapse of the dielectric Strength of air between two electrodes, which is in practice defined by the collapse of the voltage that had previously been sustained between them

Basic Breakdown Phenomena

- Over many decades, research has identified concepts which contribute to the formation of a basic picture of breakdown in air
  - Primary Electrons:
  - Free electrons exist only for very short times in air that is not subject to a high electric field; normally they are trapped to form negative ions

- These have a density commonly of the order of a few hundred per cubic centimeter
- However, electrons can be detached again from negative ions by acceleration and resulting collisions with neutral molecules in a strong electric field

Ionization

- The electrons so liberated can themselves accelerate in the field, collide with neutral molecules and settle down to a constant average drift velocity in the direction of the field
- When sufficiently energetic, the collisions may liberate a further electron, so leaving behind a positive ion
- The process is cumulative, quantified initially by Townsend, and resulting in the formation of avalanches of electrons

- The growth in numbers of electrons and positive ions imparts a small conductivity to the air, which does not lead immediately to a breakdown, that is, to a collapse of voltage
- Where electrons are sufficiently energetic to cause ionisation, there is usually a plentiful supply with lower energies that can excite neutral atoms without liberating electrons
- This property is widely used in research to indicate the presence of ionisation

Recombination process

- The electrons created by the growth of ionisation may be trapped, as described above, and so removed from the ionisation process
- This is the attachment process; a net growth of electron and ion population occurs only when the field is sufficiently high for the rate of ionisation to exceed the rate of attachment
- Subsequent detachment of electrons from negative ions occurs at the same time, through collisions with neutrals, with free electrons or by interaction with photons
- Recombination between electrons and positive ions and between positive and negative ions are active in an ionised gas

Electron Attachment

- If a gas molecule has unoccupied energy levels in its outermost group, then a colliding electron may take up one of these levels, converting the molecule into a negative ion
- The negative ion thus formed would be in an excited state, caused by the excess energy
- Note: Electron attachment decreases the number of free electrons, unlike ionisation which increases the free electrons.

Regeneration

- Initially, Townsend postulated that the positive ions could also ionise, a process now recognized as insignificant
- Also, that they move towards the negative electrode to release further electrons by secondary emission, so that the ionisation process could be sustained and grow indefinitely until breakdown occurred
- If primary incident particles of sufficient energy strikes the surface of material emits electrons or ions, called secondary emission

- Experiments showed that breakdown occurs much quickly as compare to this process
- The solution lay in postulating that the positive ions, created by ionisation, are sufficient to create an electric field which, when added to the applied field, intensifies the ionisation process
- Additional initiatory electrons are assumed to be created by ultra-violet radiation from the excited molecules in the electron avalanches in which ionisation takes place

- Electric field strength is determined by the ratio *E/N of electric field E V/cm to the gas density N moles/cm*^{3}*,*known as the reduced field, is now widely used as the reference variable when measuring values of fundamental quantities
- The unit of this ratio is the Townsend (Td), which has the numerical value 10^{-17} Vcm^2
- Older work used the equivalent ratio *E/p where E was in V/cm and p in torr*

- They will also be created by photo-emission from the negative electrode
- In a sufficiently intense field, these events are cumulative and can occur very rapidly
- The current density rises, heating the gas and reducing its density, leading to a rapid increase in energy input and conductivity
- This results in a discharge of very low impedance and causes voltage collapse

Physical mechanism

- Discussion will first be general, in which physical processes are described in relation to the electric field or *E/N value which sustains them*
- *Later, differences will be* discussed when the ionisation growth originates in the field at either a positive or a negative electrode

Avalanche Development

- Analytic treatment of ionisation by collision assumes a continuous process in which the number of electron–ion pairs created by an electron of a given average energy in a given electric field is proportional to the distance that it travels in that field
- The number of new electrons *dn created in distance dx is thus:*
- $dn = \alpha n \, dx$, *where* α *is proportionality constant which is the number of electron-ion pairs created*

- Over a distance *d, starting with one electron at the origin, the total number N of ion* pairs created becomes;
- *Na = exp αd*
- Here *Na is the avalanche number, where originating single electron causes number of ion pairs to be produced.*
- *It increases linearly in the field path*

- The quantity *α embraces complex physical processes which include several types* of collision, including electronic excitations of neutral molecules and the subsequent production of radiation which may itself aid the ionisation process
- These in turn depend on the electric field in relation to the air density or pressure, *E/N or E/p,* for this is an indicator of the energy gained by electrons between collisions with gas molecules

- In round terms, the average energy required for an electron to ionise is of the order of 20 electron volts (eV)
- Some gases, of which the most important in electrical engineering are air and SF_6, exhibit a strong affinity for electrons
- This is the process of attachment to a neutral molecule to form a negative ion

- It is described by an attachment coefficient, *η, defined* as the number of attachments per unit length per electron moving in the direction of the electric field
- This is analogous in form to the definition of the ionisation coefficient, *α, describing the rate of loss of free electrons per unit length, rather than the rate of* increase

- Where attachment is significant, the reverse process of detachment can also occur.
- Two mechanisms are possible:
  - (i) by collisions with neutral molecules in a high electric field
  - (ii) by interaction with radiation

- Process (i) is the mechanism by which it is assumed that primary free electrons are liberated at the outset of the ionisation process
- Since the time between collisions is of the order of a nanosecond, such a mechanism is able to produce free electrons either for the initiation of avalanches or to restore to an avalanche some of the electrons that have been trapped by attachment

- Photodetachment, mechanism (ii), can take place only when avalanches are forming, as a result of the excitations occurring at the same time as the ionisation
- Where the processes of ionisation, attachment and detachment exist together, the basic ionisation growth Equation becomes: $dn = (\alpha - \eta + \delta)n\, dx$

- where δ *is the detachment coefficient, so that:*
- $Na = \exp(\alpha - \eta + \delta)d$
- Data on the values of $(\alpha - \eta + \delta)/N$ *in air, as a function of* E/N
- As an example of the use of previous Equations, we take a value of electric field needed to break down air at normal temperature and pressure
- This is in the order of 3 MVm−1, where E/N *is about 121 Td and* E/p *is about 40* $Vcm^{-1}torr^{-1}$
- *Here,* the value of $(\alpha - \eta + \delta)$ *is about 1800 per meter*
- *Thus, in traversing a gap between* electrodes of 10^{-2} meter, one electron creates about 18 ion pairs

- This may be compared with the total number of collisions made by the electron in crossing the gap, which is in the order of 10^5
- Strictly, the number of positive ions created is $\exp(\alpha - \eta + \delta)d - 1$*, since the integration takes into account the fact* that one electron exists before any ionising collision has occurred

Introduction to Generation and Transmission of Energy

- Generation and Transmission of Energy
- The potential benefits of electrical energy supplied to a number of consumers from a common generating system were recognized shortly after the development of the ‘dynamo’, commonly known as the generator
- The electric power (P) transmitted on an overhead a.c. line increases approximately with the surge impedance loading or the square of the system’s operating voltage

Definition (SIL)

- The surge impedance loading or SIL of a transmission line is the MW loading of a transmission line at which a natural reactive power balance occurs
- A transmission line's surge impedance loading or SIL is simply the MW loading (at a unity power factor) at which the line's Mvar usage is equal to the line's Mvar production. In equation form we can state that the SIL occurs when

Surge Impedance

$$I^2 X_L = \frac{V^2}{X_c} \; or \text{ when } \mathrm{X_L} X_c = \frac{V^2}{I^2};$$

$$\frac{2\pi fL}{2\pi fc} = \frac{V^2}{I^2};$$

$$\sqrt{\frac{V^2}{I^2}} = \sqrt{\frac{L}{c}} = Surge \text{ Impedance}$$

Surge Impedance Loading

$$\text{SIL (in MW)} = \frac{kV_{L-L}^2}{\text{Surge Impedance}}$$

- Thus for a transmission line of surge impedance ZL (=250 ohm) at an operating voltage V, the power transfer capability is approximately P= V^2/ZL, which for an overhead a. c. system leads to the following results;

V(KV)	400	700	1000	1200	1500	
P(MW)	640	2000	4000	5800	9000	

- The rapidly increasing transmission voltage level in recent decades is a result of the growing demand for electrical energy, coupled with the development of large hydroelectric power stations at sites far remote from centers of industrial activity and the need to transmit the energy over long distances to the centers

- The existing transmission system is better utilized using Flexible A.C. Transmission Systems FACTS devices which are based on newly developing high-power electronic devices such as GTOs (Gate Turn off Switch) and IGBTs (Integrated gate bipolar Transistor)
- Examples of FACTS systems include Thyristor Controlled Series Capacitors and STATCOMS
- The FACTS devices improve the utilization of a transmission system by increasing power transfer capability

- Although the majority of the world's electric transmission is carried on a.c. systems, high-voltage direct current (HVDC) transmission by overhead lines, submarine cables, and back-to-back installations provides an attractive alternative for bulk power transfer
- HVDC permits a higher power density on a given right-of-way as compared to a.c. transmission and thus helps the electric utilities in meeting the environmental requirements imposed on the transmission of electric power

- HVDC also provides an attractive technical and economic solution for interconnecting asynchronous a.c. systems and for bulk power transfer requiring long cables

Voltage Stresses

- Normal operating voltage does not severely stress the power system's insulation and only in special circumstances, for example under pollution conditions, may operating voltages cause problems to external insulation
- Nevertheless, the operating voltage determines the dimensions of the insulation which forms part of the generation, transmission and distribution equipment

- The voltage stresses on power systems arise from various overvoltages
- External overvoltages are associated with lightning discharges and are not dependent on the voltage of the system
- As a result, the importance of stresses produced by lightning decreases as the operating voltage increases

- Internal overvoltages are generated by changes in the operating conditions of the system such as switching operations, a fault on the system or fluctuations in the load or generations
- Their magnitude depends on the rated voltage, the instance at which a change in operating conditions occurs, the complexity of the system and so on
- Since the change in the system's conditions is usually associated with switching operations, these overvoltages are generally referred to as switching overvoltages

- In designing the system’s insulation the two areas of specific importance are:
  - (i) determination of the voltage stresses which the insulation must withstand,
  - (ii) determination of the response of the insulation when subjected to these voltage stresses

Testing Voltages

- Power systems equipment must withstand not only the rated voltage (Vm), which corresponds to the highest voltage of a particular system, but also overvoltages
- Accordingly, it is necessary to test h.v. equipment during its development stage and prior to commissioning

- The magnitude and type of test voltage varies with the rated voltage of a particular apparatus
- The standard methods of measurement of high-voltage and the basic techniques for application to all types of apparatus for alternating voltages, direct voltages, switching impulse voltages and lightning impulse voltages are laid down in the relevant national and international standards

Testing with power frequency voltages

- To assess the ability of the apparatus's insulation withstand under the system's power frequency voltage the apparatus is subjected to the 1-minute test under 50 Hz or 60 Hz depending upon the country
- The test voltage is set at a level higher than the expected working voltage in order to be able to simulate the stresses likely to be encountered over the years of service

- For indoor installations the equipment tests are carried out under dry conditions only
- For outdoor equipment tests may be required under conditions of standard rain as prescribed in the appropriate standards

Testing with Lightning Impulse voltages

- Lightning strokes terminating on transmission lines will induce steep rising voltages in the line and set up travelling waves along the line and may damage the system's insulation
- The magnitude of these overvoltages may reach several thousand kilovolts, depending upon the insulation
- Exhaustive measurements and long experience have shown that lightning overvoltages are characterized by short front duration, ranging from a fraction of a microsecond

- The standard impulse voltage has been accepted as an aperiodic impulse that reaches its peak value in 1.2 μsec and then decreases slowly (in about 50 μsec) to half its peak value
- In addition to testing equipment, impulse voltages are extensively used in research laboratories in the fundamental studies of electrical discharge mechanisms, notably when the time to breakdown is of interest

Testing with switching Impulses

- Transient overvoltages accompanying sudden changes in the state of power systems, e.g. switching operations or faults, are known as switching impulse voltages
- It has become generally recognized that switching impulse voltages are usually the dominant factor affecting the design of insulation in h.v. power systems for rated voltages of about 300 kV and above

- Accordingly, the various international standards recommend that equipment designed for voltages above 300 kV be tested for switching impulses
- Although the waveshape of switching overvoltages occurring in the system may vary widely, experience has shown that for flashover distances in atmospheric air of practical interest the lowest withstand values are obtained with surges with front times between 100 and 300 μsec

- Hence, the recommended switching surge voltage has been designated to have a front time of about 250 µsec and half value time of 2500 µsec
- For GIS (gas-insulated switchgear) on-site testing, oscillating switching impulse voltages are recommended for obtaining higher efficiency of the impulse voltage generator

D.C Voltages

- In the past d.c. voltages have been chiefly used for purely scientific research work
- Industrial applications were mainly limited to testing cables with relatively large capacitance, which take a very large current when tested with a.c. voltages, and in testing insulations in which internal discharges may lead to degradation of the insulation under testing conditions

- In recent years, with the rapidly growing interest in HVDC transmission, an increasing number of industrial laboratories are being equipped with sources for producing d.c. high voltages
- Because of the diversity in the application of d.c. high voltages, ranging from basic physics experiments to industrial applications, the requirements on the output voltage will vary accordingly

Testing with very low-frequency voltage

- In the earlier years when electric power distribution systems used mainly paper-insulated lead covered cables (PILC) on-site testing specifications called for tests under d.c. Voltages
- Typically the tests were carried out at 4–4.5V_0
- The tests helped to isolate defective cables without further damaging good cable insulation
- With the widespread use of **extruded** insulation cables of higher dielectric strength, the test voltage levels were increased to 5–8V_0

Generation of High Voltages

- A fundamental knowledge about generators and circuits which are in use for the generation of high voltages belongs to the background of work on h.v. technology
- Generally commercially available h.v. generators are applied in routine testing laboratories; they are used for testing equipment such as transformers, bushings, cables, capacitors, switchgear, etc

- The tests should confirm the efficiency and reliability of the products and therefore the h.v. testing equipment is required to study the insulation behaviour under all conditions which the apparatus is likely to encounter
- The amplitudes and types of the test voltages, which are always higher than the normal or rated voltages of the apparatus under test, are in general prescribed by national or international standards or recommendations, and therefore there is not much freedom in the selection of the h.v. testing equipment

- Quite often, however, routine testing laboratories are also used for the development of new products
- Then even higher voltages might be necessary to determine the factor of safety over the prospective working conditions and to ensure that the working margin is neither too high nor too low

- Most of the h.v. generator circuits can be changed to increase the output voltage levels, if the original circuit was properly designed
- Therefore, even the selection of routine testing equipment should always consider a future extension of the testing capabilities
- The work carried out in research laboratories varies considerably from one
- establishment to another, and the type of equipment needed varies accordingly.
- As there are always some interactions between the h.v. generating circuits used and the test results, the layout of these circuits has to be done very carefully

- The classes of tests may differ from the routine tests, and therefore specially designed circuits are often necessary for such laboratories

- Breakdown concept will be continued