ATME COLLEGE OF ENGINEERING

13th KM Stone, Bannur Road, Mysore - 570 028

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

NOTES

Course Title: High Voltage and Power System Protection

Course CODE: 21EE71

SEMESTER: VII

Academic Year - 2024-25

INSTITUTIONAL VISION AND MISSION

VISION:

- Development of academically excellent, culturally vibrant, socially responsible and globally competent human resources.

MISSION:

- To keep pace with advancements in knowledge and make the students competitive and capable at the global level.
- To create an environment for the students to acquire the right physical, intellectual, emotional and moral foundations and shine as torchbearers of tomorrow's society.
- To strive to attain ever-higher benchmarks of educational excellence.

Department Vision and Mission

Vision:

To create Electrical & Electronics Engineers who excel to be technically competent and fulfill the cultural and social aspirations of the society.

Mission:

- To provide knowledge to students that builds a strong foundation in the basic principles of electrical engineering, problem solving abilities, analytical skills, soft skills and communication skills for their overall development.
- To offer outcome based technical education.
- To encourage faculty in training & development and to offer consultancy through research & industry interaction.

Program Educational Objectives (PEOs)

PEO1: To produce competent and ethical Electrical and Electronics Engineers who will exhibit the necessary technical and managerial skills to perform their duties in society.

PEO2: To make Graduates continuously acquire and enhance their technical and socio-economic skills.

PEO3: To aspire Graduates on R&D activities leading to offering solutions and excel in various career paths.

PEO4: To produce quality engineers who have the capability to work in teams and contribute to real time projects.

Program Outcomes (POs)

Engineering Graduates will be able to:

PO1: Engineering Knowledge: Apply the knowledge of mathematics, science, engineering fundamentals and an engineering specialization to the solution of complex engineering problems.

PO2: Problem Analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

PO3: Design / Development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

PO4: Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

PO5: Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

PO6: The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

PO7: Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

PO8: Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO9: Individual and team work: Function effectively as an individual and as a member or leader in diverse teams, and in multidisciplinary settings.

PO10: Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

PO11: Project management and finance: Demonstrate knowledge and understanding of the engineering management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

PO12: Life-long learning: Recognize the need for and have the preparation and ability to engage in independent and lifelong learning in the broadest context of technological change.

Program Specific Outcomes (PSOs)

The students will develop an ability to produce the following engineering traits:

PSO1: Apply the concepts of Electrical & Electronics Engineering to evaluate the performance of power systems and also to control industrial drives using power electronics

PSO2: Demonstrate the concepts of process control for Industrial Automation, design models for environmental and social concerns and also exhibit continuous self- learning

High Voltage and Power System Protection

Course Code	Course Title	Core/Elective	Prerequisite	Contact Hours				Total Hrs/ Sessions
				L	T	P	S	
21EE71	**High Voltage and Power System Protection**	**PCC**	Basic Electrical, Engineering Physics, Measuring Instruments	**2**	**0**	**2**	**0**	40 hours Theory + 10 Lab slots
Objectives	1. To discuss conduction and breakdown in gases, liquid dielectrics. 2. To discuss breakdown in solid dielectrics. 3. To discuss generation of high voltages and currents and their measurement. 4. To discuss overvoltage phenomenon and insulation coordination in electric power systems.							

Topics Covered as per Syllabus

Module-1

Introduction to High Voltage Engineering: Advantages, Limitations and applications.

Conduction and Breakdown in Gases: Introduction, Ionization Processes, Townsend's Current Growth Equation and it's Criterion for Breakdown, Streamer Theory of Breakdown in Gases, Paschen's Law, Breakdown in Nonuniform Fields and Corona Discharges.

Conduction and Breakdown in Liquid Dielectrics: Introduction, Conduction and Breakdown in Liquid Dielectrics

Breakdown in Solid Dielectrics: Introduction, Different types of breakdown studies in Solid Dielectrics

Module-2

Generation of High Voltages and Currents: Generation of High Direct Current Voltages, High Alternating Voltages, Impulse Voltages and Impulse Currents.

Measurement of High Voltages and Currents: Measurement of High Direct Current Voltages, High AC and Impulse Voltages, High Currents of Direct, Alternating and Impulse.

Non-Destructive Testing of Materials and Electrical Apparatus: Introduction, Measurement of Dielectric Constant and Loss Factor, Partial Discharge Measurements.

Module-3

Introduction to Power System Protection: Need for protective schemes, Types of Fault and it's Effects, Essential Qualities of Protection, Primary and Backup Protection. Relay Construction and Operating Principles: Introduction, Electromechanical Relays, Static Relays – Merits and Demerits of Static Relays, Numerical Relays, Comparison between Electromechanical Relays and Numerical Relays.

Overcurrent Protection: Introduction, Time–current Characteristics, Current Setting, Time Setting, Directional Relay, Protection of Parallel Feeders and Ring Mains, Earth Fault, Phase Fault Protection and Combined Earth and Phase Fault Protective Scheme, Static Overcurrent Relays, Numerical Overcurrent Relays.

Module-4:

Distance Protection: Introduction, Impedance Relay, Reactance Relay, Mho Relay, Effect of Power Surges, Line Length and Source Impedance on Performance of Distance Relays.

Pilot Relaying Schemes: Introduction, Wire Pilot Protection, Carrier Current Protection**.**

Differential Protection: Introduction, Differential Relays, Percentage Differential Relay, Balanced Voltage Differential Protection.

Protection of Generators, Transformer and Bus zone Protection: Introduction, Protection of Generators. Transformer Protection, Bus zone Protection.

Module- 5:

Circuit Breakers: Introduction, Arc Voltage, Arc Interruption, Restriking Voltage and Recovery Voltage, Current Chopping. Air Circuit Breakers, SF6 Circuit Breakers, Vacuum Circuit Breakers, Rating of Circuit Breakers,
Testing of Circuit Breakers.

Protection against Overvoltage: Causes of Overvoltage, Lightning phenomena, Klydonograph and Magnetic Link, Protection of power stations and Substations, Insulation Coordination.

List of Text Books

TEXT BOOKS:.

1. High Voltage Engineering, M.S.Naidu and Kamaraju- 5th Edition, THM, 2013
2. Power System Protection and Switchgear Badri Ram, D.N. Vishwakarma McGraw Hill 2nd Edition.

List of Reference Books
1. High Voltage Engineering Fundamentals, E. Kuffel, W.S. Zaengl, J. Kuffel, Newnes, 2 nd Edition, 2000 2. High Voltage Engineering, Wadhwa C.L., New Age International, 3 rd Edition, 2012. 3. Protection and Switchgear, Bhavesh et al, Oxford, 1st Edition, 2011. 4. Power System Switchgear and Protection, N. Veerappan, S.R. Krishnamurthy, S. Chand, 1st Edition, 2009

MODULE-1: Conduction and Breakdown in Gases

Syllabus

1.1 Gases as Insulating Media

1.2 Collision Process, Ionization Processes

1.3 Townsend's Current Growth Equation, Current Growth in the Presence of Secondary Processes, Townsend's Criterion for Breakdown

1.4 Experimental Determination of Coefficients α and γ,

1.5 Breakdown in Electronegative Gases

1.6 Time Lags for Breakdown

1.7 Streamer Theory of Breakdown in Gases

1.8 Paschen's Law

1.9 Breakdown in Non-Uniform Fields and Corona Discharges.

1.10 Conduction and Breakdown in Liquid Dielectrics: Liquids as Insulators, Pure Liquids and Commercial Liquids, Conduction and Breakdown in Pure Liquids, Conduction and Breakdown in Commercial Liquids.

1.11 Breakdown in Solid Dielectrics: Introduction, Intrinsic Breakdown, Electromechanical Breakdown, Thermal Breakdown.

Course Objectives

1. To discuss conduction and breakdown in gases, liquid dielectrics.
2. To discuss breakdown in solid dielectrics.

1. Introduction

1. Dielectric material is a poor conductor of electricity.
2. But it can be conducted by applying high electric field.
3. It is an efficient supporter of electric field.
4. Whenever we are applying electric field the position of ions get changed and support for electricity conduction.
5. Examples of dielectric materials are mica, glass, ceramics etc.

a) Dielectric Strength

•The dielectric strength of an insulating material is defined as the maximum dielectric stress with the material can withstand.

b) Factors affecting Dielectric strength

1. Pressure
2. Temperature
3. Humidity
4. Nature of applied voltage
5. Imperfection of material

c) Types of Dielectrics

1. Gas or Vacuum Dielectrics
2. Liquid Dielectrics
3. Solid Dielectrics
4. Composite Dielectrics

1. Gas or Vacuum Dielectrics

1. It has high dielectric strength (10^7 V/cm)
2. Breakdown occur in the gas or vacuum is due to collisional ionization. (Ionization by collision)
3. If the applied voltage is sufficiently large electrons are multiplied in an exponential manner & breakdown will be occurred.
4. Examples- Sulphar Hexa Fluoride, CO_2 etc

2. Liquid Dielectrics

1. The liquid dielectric are used in HV equipment for dual purpose of insulation & heat dissipation.
2. Temporary failure can be quickly re-insulated by the liquid flow to the affected area.
3. Highly purified liquid is more suitable to serve as a dielectric medium.
4. Dielectric strength is up to 1 MV/cm
5. Breakdown strength reduces due to impurities.
6. Selection of liquid dielectric is based on dielectric strength, viscosity, stability, flash point, gas constant etc
7. Examples- Petroleum, transformer oil (Mineral oil) etc
8. **Applications**- Area where equipments is continuously operated like Distribution Transformer.

3. Solid Dielectrics

1. It has good mechanical strength & bonding capability.
2. Dielectric strength – 10MV/cm
3. Examples- Inorganic materials (Ceramics, glass etc) , Organic materials(PVC, Polyethylene, natural rubber etc)
4. Application- Electrical apparatus

4. Composite Dielectrics

1. Combination of more than two kinds of insulators
2. Chemically stable
3. Long life span
4. But dielectric constant of two material should match
5. Two insulators never react together.
6. Examples – Oil impregnated paper, Oil impregnated metalized plastic film.

1. 1 Gases as Insulating Media

1. The simplest and the most commonly found dielectrics are gases.
2. Most of the electrical apparatus use air as the insulating medium, and in a few cases other gases such as **Nitrogen (N_2), Carbon dioxide (CO_2), Freon (CCl_2F_2) and Sulphur hexafluoride (SF_6**) are also used.
3. Various phenomena occur in gaseous dielectrics when a voltage is applied.
4. When the applied voltage is low, small current flow between the conducting electrodes and the insulation keep its electrical properties.
5. Whereas if applied voltage is large, the current flowing through the insulation increases very sharply, and an electrical breakdown occurs.
6. A strongly conducting spark formed during breakdown practically produces a short-circuit between the electrodes.
7. The maximum voltage applied to the insulation at the moment of breakdown is called the **breakdown voltage.**
8. Two types of electrical discharge in gases: **(1) Non-sustaining discharges and (2) Self-sustaining types**.

1.2. Collision Process: Ionization Processes

1. At normal temperature and pressure, a gas acts as good insulating materials.
2. When high voltage applied between the two electrodes immersed in gaseous medium, the gas becomes a conductor an **electrical breakdown** occurs.
3. Ionization by collisions are two type:
   a. **Elastic collisions:** An elastic collision is a collision in which there is no net loss in kinetic energy in the system as a result of the collision.
   b. **Inelastic collisions:** A collision in which the total kinetic energy of the colliding bodies or particles is not the same after the collision as it was before (opposed to elastic collision).

The processes that are primarily responsible for the breakdown of gas are

1. **Primary ionization process**
2. **secondary ionization process**

1. Primary ionization process

1. Ionization by collision
2. Photo ionization

2. Secondary Ionization Process

1. Electron emission due to positive ion impact
2. Thermal ionisation
3. Ionization by interaction of meta stable with neutral atoms
4. Electron detachment

1.2.1. Primary Ionisation

a) Ionization by collision

1. **Ionization is defined as a process** of leaving free electron from a gas molecule with the continuous generation of positive ion.
2. In the process of ionization by collision, a free electron collides with a neutral gas molecule and gives rise to a new electron and a positive ion.
3. If we consider a low-pressure gas column in which an electric field E is applied across two plane parallel electrodes, as shown in Fig. 2.1.
4. If the energy (E) gained during this travel between collision exceeds the ionization potential, Vi, which is the energy required to remove an electron from its atomic shell, then ionization take place. This process can be represented as :

$$e^- + A \xrightarrow{\varepsilon > V_i} e^- + A^+ + e^-$$

Where, A is the atom, A+ the positive ion and e- is the electron.

5. A few electron produce at the cathode by some external means, say by ultra-violet light falling on the cathode, ionize neutral gas particles producing positive ions and additional electrons.
6. The additional electrons, then, themselves make 'ionizing collisions' and thus the process repeats itself.

b) Photo ionisation

The ionization caused by cosmic radiation or photons is called **<u>photo-ionization.</u>**

Photo-ionization occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionization potential.

There are several processes by which radiation can be absorbed by atoms or molecules.

They are **(a) excitation of the atom to a higher energy state, and**

(b) continuous absorption by direct excitation of the atom or dissociation of diatomic molecule or direct ionization, etc.

This reversible process can be expressed as,

$$hv + A \rightleftarrows A^{+} + e^{-}$$

E > Ai; Condition of breakdown Where E = hγ = hc/λ

h – planks constant, c – velocity of light and λ- wave length of radiation

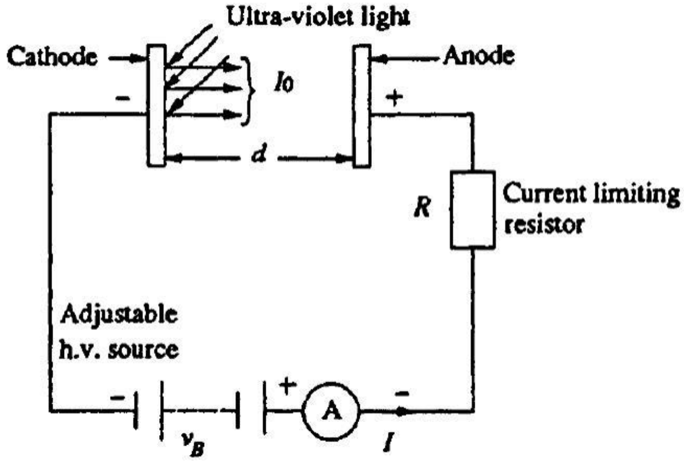


Figure 1.1 :Parallel plate capacitor

The higher the ionization energy, the shorter will be the wavelength of the radiation capable of causing ionization.

Note : It was observed experimentally that a radiation having a wavelength of 1250 Å is capable of causing photo-ionization of almost all gases.

1.2.2 Secondary Ionization

"The process of formation of secondary electrons after completion of ionization by collision & photo ionization"

(a)Electron emission due to positive ion impact

1. Positive ion formation is due to either ionization by collision or photo ionization.
2. Positive ions moves towards cathode
3. The secondary ion is forms such a way that "Total energy >2*work function"
   Where Total energy= KE+ Ionization energy

When positively and negatively charged particles present recombination take place.

This Recombination process is the reverse process of photo ionization and symbolically represented as :

$A^+ + e^- \rightarrow A + hv$

Where,

A^+= positive ion

e^- = an electron or negative ion.

The photon energy released (hv) would be absorbed by a third body C present.

The third body C may be another heavy particle or electron and represented as

$$A^+ + C + e^- \rightarrow A^* + C \rightarrow A + C + hv \frac{d\eta}{dt} = K\eta^2$$

(b) Thermal Ionisation

1. At high electrical stress, the gas filling the gap between the electrodes is heated up.
2. The gases at high temperature some of the gas molecules acquire high kinetic energy.
3. The collision between molecules creates ions due to release of electron from the neutral particles.
4. The electrons and other high speed molecules in- turn collide with each other and release more electrons. Thus the gas gets ionized.

(c)Electron emission due to meta-stable & neutral atoms

1. In the atmosphere, there are some elements or atoms whose life time extends to few seconds, in certain electronic states. Such atoms are called meta-stable atoms.
2. They have high potential energy.
3. Therefore, meta-stable atoms are able to ionize neutral particle.
4. It can be represented by following reaction of intersection:

   $A + B^m = A^+ + e^- + B$

   Where,

   A = the atom to be ionized

   B^m = metastable particle

   A^+ = positive ion of atom

   e^- = negatively charged electron

d) **Deionization by Attachment (Electron Detachment)**

1. Electrons can combine with neutral atoms or molecules to form negative ions, in certain gases.
2. Some of the Gases have a characteristics that are lacking one or two electrons in their outer surface known as electronegative gases.
3. **Electronegative gases** have very high dielectric strength due to formation of negative ion during deionization process.
4. The reaction represented symbolically as

$$AB + e \rightarrow (\mathrm{AB}^-) + \mathrm{hv}$$

It may also be happen that the atom AB will be dissociate into A^+ and B^- ion which will be represented by as below

$$AB + e \rightarrow (\mathrm{AB})^* + \mathrm{e} \rightarrow A^+ + B^- + e$$

1.3 Townsend's Current Growth Equation, Current Growth in the Presence of Secondary Processes, Townsend's Criterion for Breakdown

Why Townsend's theory…………….?

1. We can measure the probability of secondary electron formation by using Townsend's theory
2. Analysis of 'ionization by collision' is carried out by Townsend's theory
3. It is applicable for primary & secondary ionization.

1.3.1 Townsend's first ionization coefficient (α)

1. **α :** is defined as the average number of ionizing collisions made by an electron per centimeter travel in the direction of the field
2. 'α' depends upon Pressure (P) and Electric field in V/cm (E)
3. **' α 'proportional to (E/P)**

- Let us consider a parallel plate capacitor having gas as in insulating medium and separated by a distance as shown in Fig.

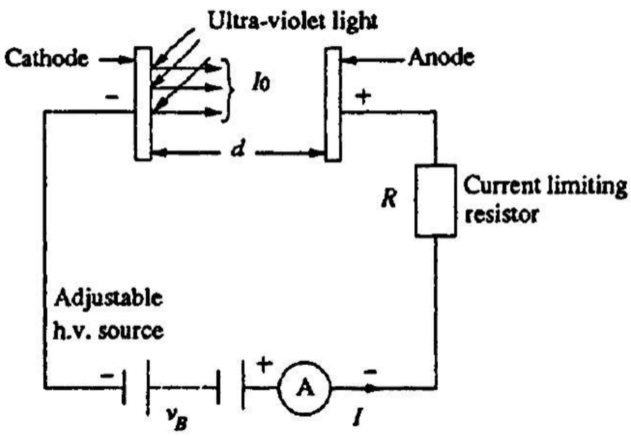
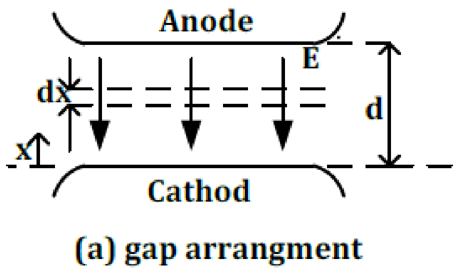


Fig1.2: Parallel plate capacitor



- Let us assume that n_0 **electrons** are emitted from the cathode.
- When one electron collides with a neutral particle, a positive ion and an electron are formed. This is called an ionizing collision.
- Let α be the average number of ionizing collisions made by an electron per centimeter distance travel in the direction of the field (α depends on gas pressure p and E/p, and is called the Townsend's first ionization coefficient).

- Fig. 1.2 illustrates the breakdown phenomenon of a gas and the growth of current in the gas which is responsible for breakdown.
- The curve has three regions:
    1. Ohmic region
    2. Saturation region
    3. Townsend's discharge region

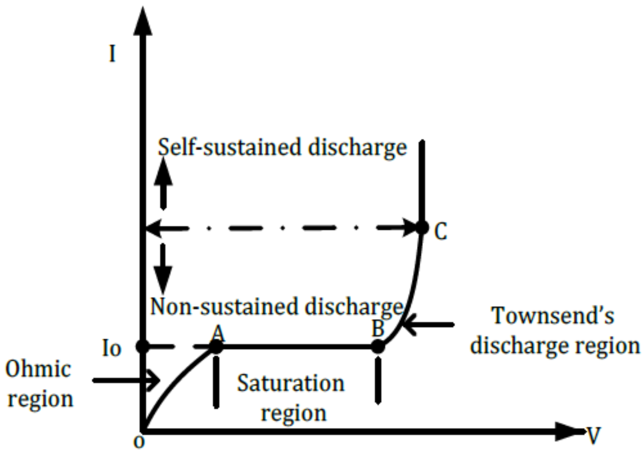


Fig 1.2 : Typical current growth curve In Townsend discharge

- It is observed from the figure that the current at first increases proportionally with the increases in field or voltage. This region is called **ohmic region.**
- After this state, a situation comes when current become constant I_0 even if voltage is increased. The constant current **I_0 is called the saturation current.**
- At still higher voltage, the current increases exponentially.

The exponential increase in current is due to ionization of gas by electron collision with gas molecules.

As the voltage increase, electric field intensity V/d increases and hence the electrons are accelerated more and more and the electron get higher kinetic energy and therefore, knock out more and more electrons.

At any distance x from the cathode, let the number of electrons be n_x.

When these n_x electrons travel a further distance of dx they give rise to $(\alpha n_x dx)$ electrons.

$$dn_x = \alpha n_x dx$$

$$\frac{dn_x}{n} = \alpha dx$$

$$\ln n = \alpha x + A \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(i)}$$

$$(at(x=0), n_x = n_0)$$

$$\therefore A = \ln n_0 \; put \text{ in equation (i)}$$

$$\therefore \ln n = \alpha x + \ln n_0$$

$$\therefore \ln n - \ln n_0 = \alpha x$$

$$\therefore \ln\left(\frac{n}{n_0}\right) = \alpha x$$

$$\therefore \left(\frac{n}{n_0}\right) = e^{\alpha d}, \text{ at x=d distance,}$$

$$\therefore \text{n} = n_0 e^{\alpha d}$$

The average current in the gap, which is equal to the number of electrons travelling from the above equation per second will be

$$I = I_0 e^{\alpha d}$$

Where $e^{\alpha d}$ =electron avalanche, I_0 =initial current Ampere

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Q. **In an experiment in a certain gas it was found that the steady state current is 5.5×10^{-8} A at 8 kV at a distance of 0.4 cm between the plane electrodes. Keeping the field constant and reducing the distance to 0.1 cm results in a current of 5.5×10^{-9}A. Calculate Townsend's primary ionization coefficient α.**

Solution: The current at the anode I is given by

$$I = I_0 \exp(\alpha d)$$

where I_0 is the initial current and d is the gap distance.
Given,

$$d_1 = 0.4 \text{ cm} \qquad d_2 = 0.1 \text{ cm}$$

$$I_1 = 5.5 \times 10^{-8} A \qquad I_2 = 5.5 \times 10^{-9} A$$

$$\frac{I_1}{I_2} = \exp \alpha(d_1 - d_2)$$

i.e., $$10 = \exp(\alpha \times 0.3)$$

i.e., $$0.3\alpha = \ln(10)$$

$\therefore$ $$\alpha = 7.676/\text{cm . torr}$$

1.3.2 Townsend's Second Ionization Co-efficient

1. The single avalanche process described in the previous section becomes complete when the initial set of electrons reaches the anode.
2. The probability amplification of the electrons being release in the gap by other mechanisms increases, and these new electrons create further avalanches.
3. The other mechanisms are
   - (i) The positive ions released may have sufficient energy to cause liberation of electrons from the cathode when they impose on it.
   - (ii) The excited atoms or molecules in avalanches may emit photon, and this will lead to the emission of electrons due to photo-emission.
   - (iii) The meta-stable particles may diffuse back causing electron emission.
4. The electrons produced by these processes are called secondary electrons.

The secondary ionization coefficient γ is defined in the same way as α , as the net number of secondary electrons produced per incident positive ion, photon, exited particle, or metastable particle, and the total value of γ is the sum of the individual coefficients due to the three different processes, i.e. $\gamma = \gamma_1 + \gamma_2 + \gamma_3$.

γ is called Townsend's secondary ionization coefficient and is a function of the gas pressure p and E/p.

Following Townsend's procedure for current growth, let us assume

n_+ = number of secondary electrons produced due to secondary (γ) processes.

($n_0 + n_+$)= total number of electron leaving the cathode.

The total number of electron n reaching the anode becomes,

$$n = (n_0 + n_+) e^{\alpha d} \text{ ....(i)}$$

$$n_+ = \gamma\left[n - (n_0 + n_+)\right]$$

$$n_+ = \gamma n - \gamma n_0 - \gamma n_+$$

$$(1+\gamma) n_+ = \gamma (n - n_0)$$

$$n_+ = \frac{\gamma (n - n_0)}{1+\gamma}$$

Substituting n_+ value in equation (i)

$$n = \left[n_0 + \frac{\gamma (n - n_0)}{1+\gamma}\right] e^{\alpha d}$$

$$n = \left[\frac{n_0 + \gamma n_0 + \gamma n - \gamma n_0}{1+\gamma}\right] e^{\alpha d}$$

$$n = \left[\frac{n_0 + \gamma n}{1+\gamma}\right] e^{\alpha d}$$

$$n(1+\gamma) = (n_0 + \gamma n) e^{\alpha d}$$

$$n + \gamma n = n_0 e^{\alpha d} + \gamma n e^{\alpha d}$$

$$n + \gamma n - \gamma n e^{\alpha d} = n_0 e^{\alpha d}$$

$$n\left[1 + \gamma\left(1 - e^{\alpha d}\right)\right] = n_0 e^{\alpha d}$$

$$n\left[1 - \gamma(e^{\alpha d} - 1)\right] = n_0 e^{\alpha d}$$

$$n = \frac{n_0 e^{\alpha d}}{\left[1 - \gamma(e^{\alpha d} - 1)\right]}$$

$$or\ I = \frac{I_0 e^{\alpha d}}{\left[1 - \gamma(e^{\alpha d} - 1)\right]}$$

This is Townsend’s <u>current growth equation due to primary and secondary ionization</u>

1.3.3 Limitation of Townsend's theory

Townsend theory or Townsend's mechanism applied to gas-discharge phenomenon was found to have some drawback or limitations.

(i) First drawback is that according to Townsend's theory, the current growth occurs as a result of ionization process only. But in practice, breakdown voltages were found to depend on the gas pressure and the geometry of the gap.

(ii) Secondary, the Townsend's mechanism predicts the time-lag of the order of 10^{-5}seconds. While in practice, the breakdown was observed to occur at very short time of the order of 10^{-8} sec.

(iii) Townsend's mechanism predicts the very diffused from of discharge but in practice, it was found to be filament and irregular.

iv) It is applicable for pd value below 1000 torr-cm.

1.4 Condition for Gaseous dielectric breakdown

We know that

$$I=\frac{I_0 e^{\alpha d}}{\left[1-\gamma(e^{\alpha d}-1)\right]}$$

Where, I=current at anode

α =Townsend's first ionization coefficient

γ =Townsend's second ionization coefficient

d = gap-length of electrodes

The current becomes ∞ if

$$1-\gamma\left(e^{\alpha d}-1\right)=0$$

$$\gamma\left(e^{\alpha d}-1\right)=1$$

$$e^{\alpha d}\gg 1$$

$\gamma e^{\alpha d}=1$ defines condition for begining of spark formation.

Three possible condition:

(1) if $\gamma e^{\alpha d}=1$: In this condition, the discharge is said to be Self-sustained because, discharge will sustain itself even if source producing I_0 (as shown in fig.)is removed.

(2) if $\gamma e^{\alpha d}>1$: In this case, the ionization produced by successive avalanche is cumulative. The spark discharge grows more rapidly.

(3) if $\gamma e^{\alpha d}<1$: In this condition, the current is not self-sustained. because, removal of source, the current I_0 is only remain constant.

1.5 Breakdown in Electronegative Gases

- Electronegative gases are the gases that have similarity towards electrons. When electron comes into contact with these gas molecules, the gas molecule attracts the electrons and becomes negative ion.
- The gases, which are lacking in one or two electrons in their outer shell are known as **electronegative gases.**
- The most common attachment processes encountered in gases are :
  a. Direct Attachment: In which an electron directly attaches to form a negative ion.

  $$AB + e^- \rightarrow AB^- + hv$$

  b. Dissociative Attachment: In which gas molecules split into their constituent atoms and

  Electronegative atoms from negative ions.

  $$AB + e \rightarrow A + B^- + e$$

- A simple gas of this types is oxygen. Other gases are Sulphur hexafluoride, Freon, carbon dioxide, and fluorocarbons.
- In this gases, 'A' is usually Sulphur or carbon atom, and 'B' is oxygen atom or one of the halogen atoms or molecules.
- With such gases, the Townsend current growth equation is modified to include ionization and attachment.

An attachment coefficient (η) is defined, similar to α as the number of attaching collisions made by one electron drifting one centimeter in the direction of the filed.

Under these conditions, the current reaching the anode, can be written as

$$I = I_0 \frac{\left[\{\alpha/(\alpha-\eta)\} e^{(\alpha-\eta)d}\right] - \left[\eta/(\alpha-\eta)\right]}{1-\left\{\gamma \frac{\alpha}{(\alpha-\eta)}\left[\left\{e^{(\alpha-\eta)d}\right\}-1\right]\right\}} \text{...(i)}$$

Townsend breakdown criterion for attaching gases can also be find out by equating the denominator in equation (i)

$$\gamma \frac{\alpha}{(\alpha-\eta)}\left[e^{(\alpha-\eta)d}-1\right]=1 \text{..(ii)}$$

This shown that for $\alpha > \eta$, breakdown is always possible irrespective of the values of α, η, and γ.

If on the other hand, $\eta > \alpha$ equation approaches an asymptotic from with increasing value of d,

$$\gamma \frac{\alpha}{(\alpha-\eta)} = 1$$

$$\therefore \gamma\alpha = \alpha - \eta$$

$$\therefore \quad \eta = \alpha - \gamma\alpha$$

$$\therefore \quad \alpha = \frac{\eta}{(1-\gamma)}$$

$$\alpha = \eta \quad (\gamma \text{ is very small } \leq 10^{-4})$$

If the pressure is constant then this condition put the limit of value of E below which no breakdown is possible irrespective of the value of 'd' and the limit value is critical E for that pressure. eg. For SF_6 117V cm^{-1} $torr^{-1}$ at $20^{\circ} C$

1.6 Time Lag of Breakdown

1. Theoretically the mechanism of spark breakdown is considered as a function of ionization processes under **uniform field conditions.**
2. In practical engineering designs, the breakdown due to rapidly changing voltage or impulse voltage is of great importance.
3. Actually there is a time difference in the application of a voltage sufficient to cause breakdown and the occurrence of breakdown itself. This time difference is called as the **time lag.**
4. The Townsend criterion for breakdown is satisfied only if at least one electron is present in the gap between the electrodes as in the case of applied d.c. or slowly varying (50Hz a.c.) voltages. This is no difficulty in satisfying this condition.
5. With rapidly varying voltage of short duration ($\approx 10^{-6}$ s), the initiatory electron may not be present in the gap then the breakdown cannot occur due to not available free electron.

i. Statistical time-lag(ts): is defined as the time lapsed between the application of voltage sufficient to cause breakdown and the appearance of initiating electron is called as statistical time lag.

1. The Statistical time lag depends upon the amount of pre-ionization present in the gap.
2. This in turn depends on the size of the gap and the quantity of radiation that produces the primary electrons.
3. The techniques generally used for irradiating the gaps include ultraviolet radiation, radioactive materials and light sources.

ii. Formative time-lag(tf): After the appearance of electron, the time tf required for the ionization process to develop fully to cause to the breakdown of gap is called as formative time-lag.

The formative time lags depend mostly on the mechanism of the avalanche growth in the gap.

iii. Total time-lag (t): is define as the sum total of Statistical time-lag and formative time-lag T= ts + tf

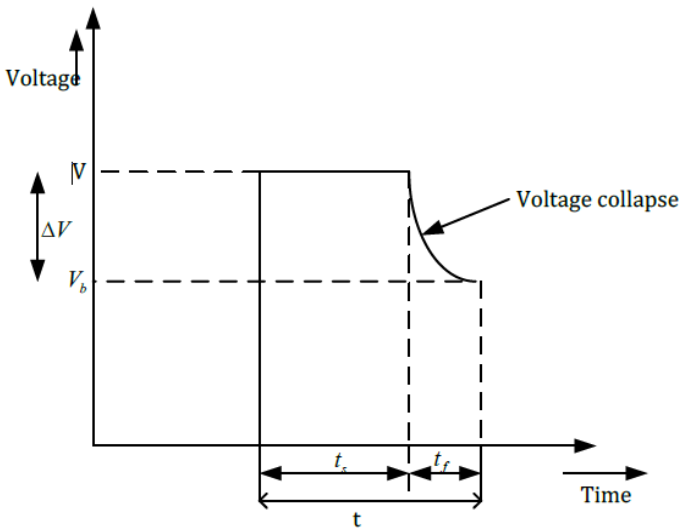


Fig 1.4 : 5Breakdown with a step function voltage pulse

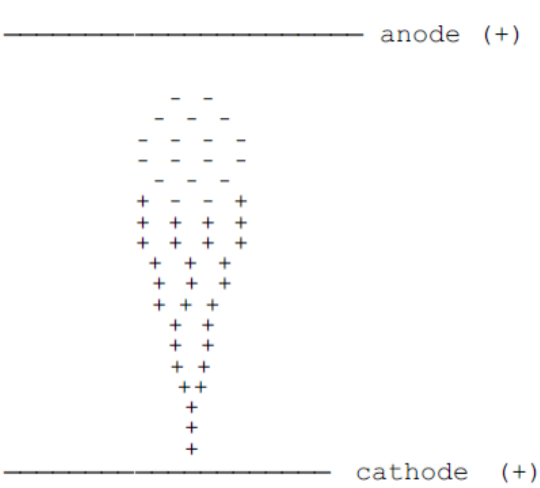
1.7 Streamer or Kanal Mechanism of Breakdown of Spark:

1. The streamer Mechanism of Breakdown is also known as **"<u>Kanal" mechanism of breakdown.</u>**
2. The Streamer theory removes the limitation and drawbacks of Townsend's theory.
3. We know that the charges in between the electrodes separated by a distance d increase by a factor
4. $e^{\alpha d}$ when field between electrodes is uniform
5. This is valid only if we assume that the field $\mathbf{E_0 = V/d}$ is not affected by the space charges of electrons and positive ions.
6. Whenever the concentration exceeds 10^8, the avalanche current is followed by steep rise in current and breakdown of the gap takes place.
7. The weakening of the avalanche at lower concentration and rapid growth of avalanche at higher concentration have been attributed to the modification of the electric field E_0 Due to the space charge field.

Streamer theory of breakdown for gas or Avalanche breakdown :

1. Avalanche breakdown or streamer breakdown is a phenomenon that can occur in both insulating and semiconducting materials.
2. It is a form of electric current multiplication that can allow very large currents within materials & causes dielectric breakdown.
3. Formation of finger like discharge is called as streamer.

"**<u>A streamer discharge</u>**, also known as filamentary discharge, is a type of transient electrical discharge. Streamer discharges can form when an insulating medium (for example air) is exposed to a large potential difference."



Process :

1. Streamer breakdown occur when the dielectric medium is exposed to a high voltage difference.
2. First step is the formation of **avalanche.**
3. Formation avalanche creates **space charge** (collection of charge or cloud of charge).
4. Space charge leads additional electric field.
5. **The electric field** enhance the growth of **new avalanche.**
6. Ionised region grows quickly & expand.
7. Applicable for **non-uniform electric field**
8. **When the energy gained by the electrons greater than lattice ionization potential formation of streamer takes palace. (Condition for streamer breakdown)**
9. Breakdown occur when avalanche exceeds critical size & formation of many avalanche.
10. Streamer ionise the path & production of large current. Breakdown will be occurred.

Detailed Procedure:

Fig. 1.5 shows the electric field around an avalanche as it progresses along the gap and the resultant field i.e., the superposition of the space charge field and the original field $E_{0.}$

A. Since the electrons have higher mobility, the space charge at the head of the avalanche is considered to be negative and is assumed to be concentrated within a spherical volume.
B. It can be seen from Fig. 1.5 that the filed at the head of the avalanche is strengthened.
C. The field between the two assumed charge Centre's i.e., the electrons and positive ions is decreased as the field due to the charge centres opposes the main field E0 and again the field between the positive space charge Centre and the cathode is strengthened as the space charge field aids the main field E_0 in this region.
D. It has been observed that if the charge carrier number exceeds 10^6, the field distortion becomes noticeable.
E. If the distortion of field is of 1%, it would lead to a doubling of the avalanche but as the field distortion is only near the head of the avalanche, it does not have a significance on the discharge phenomenon.
F. However, if the charge carrier exceeds 10^8, the space charge field becomes almost of the same magnitude as the main field E_0 and hence it may lead to **initiation of a streamer.**

G. The space charge field, therefore, plays a very important role in the mechanism of electric discharge in a non-uniform gap.

H. This photon falls on the molecules and again electrons are release which is called photoionization. Photoionization of gas molecules is the secondary mechanism of ionization responsible for breakdown.

I. On the whole, it is observed that due to (i)Enhancement of field (ii)Primary ionization (iii) Photoionization

   A. Size of the electron avalanche is gradually increased and the avalanches are transformed into channels of ionization which proceeds towards the anode.

   B. Such channels are called the **steamer (anode streamer).**

   C. Finally the gas breakdown, at the moment of breakdown the avalanche has got specific size which is called **critical size of avalanche**.

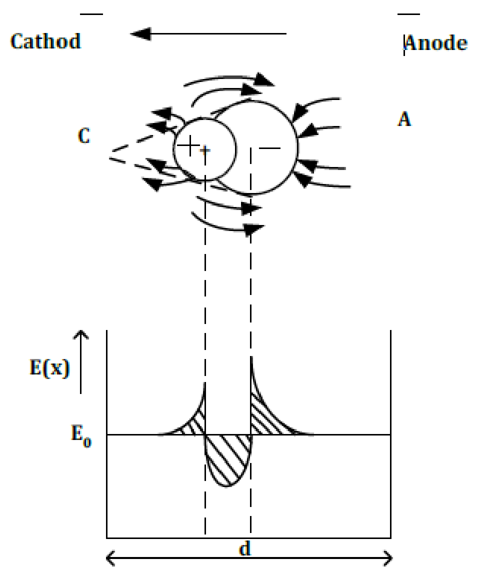


Fig 1.5 : Breakdown with a step function voltage pulse

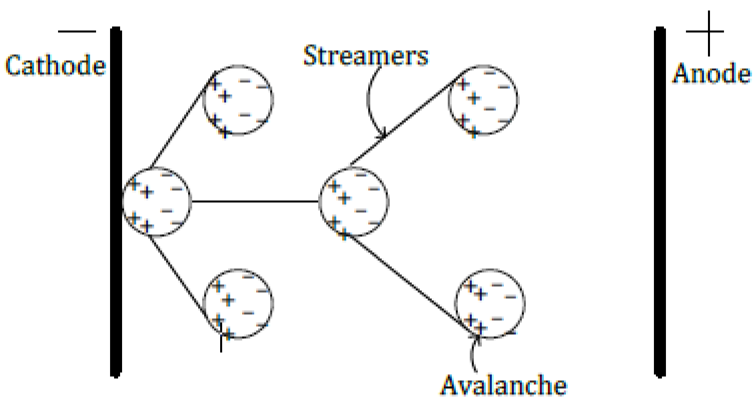


Fig: 1.6 Formation of secondary avalanches due to photo-ionization

Streamer breakdown classification:

- Positive streamer
1. Low electric field
2. Positive streamers propagate in the opposite direction.
- Negative streamer
1. Negative streamers propagate against the direction of the electric field
2. Negative streamers require higher electric fields

Areas of application

1. Ozone production
2. Air purification
3. Plasma medicine

1.8 Paschen's Law

1. Paschen's theory is one of the most important theories related to breakdown of gaseous insulating material.
2. It is widely used in the design of extra high voltage equipments.
3. The gas to be used in the apparatus is matched and studied with operating voltage of the system.
4. The breakdown voltage must be greater than the operating voltage of the system.

Paschen's Law: The law essentially sates that, at higher pressures (above a few torr) the breakdown characteristics of a gap are function (generally not linear) of the product of the gas pressure(p) and gap length(d), usually written as V_b= f(P.d)

The above relation does not imply that breakdown voltage Vb is directly proportional to product the product of p and d.

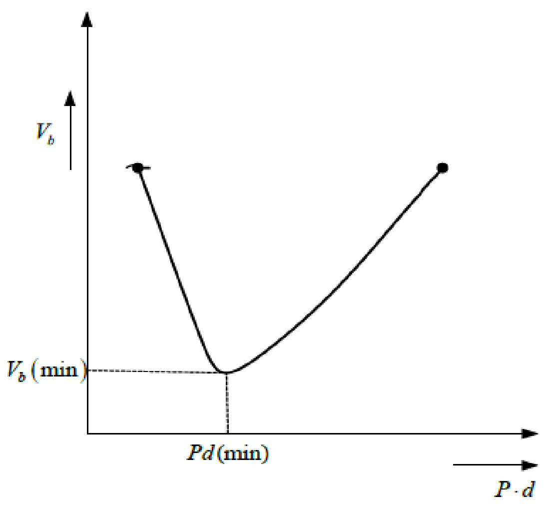
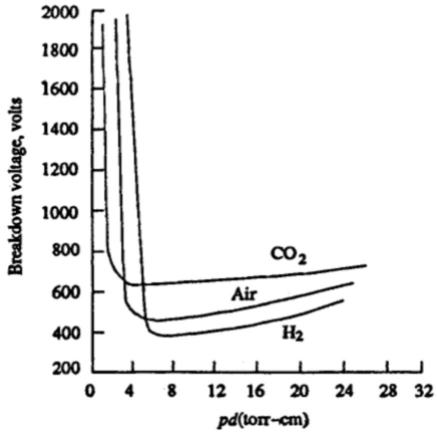


Fig1.7: V_b varies non-linearly with the product Pd

1. Paschen, a scientist studied the breakdown voltage of various gases between the parallel metal plates as the **pressure & distance** where varied.
2. Paschen found that Voltage is a function only of the product of the pressure & gap length(distance).
3. The equation V= f(pd) is called as Paschen's law
4. At higher pressure and air gap length, the breakdown voltage is approximately proportional to product of pressure & air gap.
5. The curve which shows the voltage versus the pressure gap length is called Paschen's curve.
6. Paschen law will be helpful for finding the minimum breakdown voltage of a gas.
7. The minimum pd value for air is 0.567 and 367V.

Paschen's curve



8. Application – based on Paschen's law, we can find the minimum sparking voltage (Breakdown voltage)of various gas.

Minimum Sparking Potential For Various Gases

Gas	V_s min (V)	pd at V_s min (torr-cm)
Air	327	0.567
Argon	137	0.9
H_2	273	1.15
Helium	156	4.0
CO_2	420	0.51
N_2	251	0.67
N_2O	418	0.5
O_2	450	0.7
SO_2	457	0.33
H_2S	414	0.6

1.8.1 Derive an expression for Paschen's Law

pd(min) and Vb(min):

1. The Paschen's curve, the relationship between V and pd is shown in above graph for three gases CO_2, air and H_2. It is seen that the relationship between V and pd is not linear and has a minimum value for any gas.
2. This means that a breakdown voltage of a uniform field gap is a unique function of the product of p, the gas pressure and d, the electrode gap, for a particular gas and for a given electrode material.

The breakdown criterion in gases is given as

$$\gamma\,[\exp(\alpha d) - 1] = 1$$

where the coefficients α and γ are functions of E/p, i.e

$$\frac{\alpha}{p} = f_1\left(\frac{E}{p}\right)$$

and $$\gamma = f_2\left(\frac{E}{p}\right)$$

Also $$E = \frac{V}{d}$$

Substituting for E in the expressions for a and y and rewriting Equation

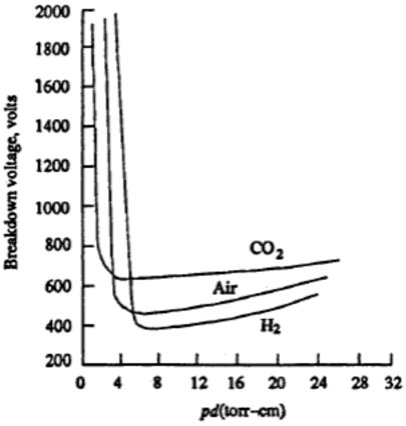
$$f_2\left(\frac{V}{pd}\right)[\exp\left\{pdf_1\left(\frac{V}{pd}\right)\right\} - 1] = 1$$

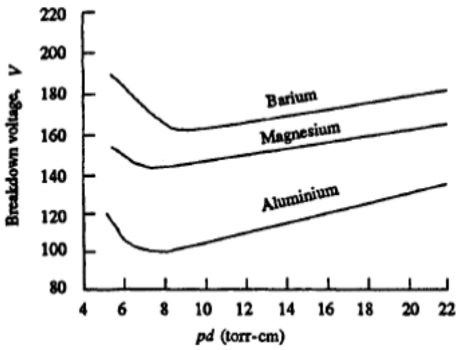
This equation shows a relationship between V and pd, and implies that the breakdown voltage varies as the product pd varies. Knowing the nature of functions f_1 and f_2 we can rewrite

$$V = f(pd)$$

This equation is known as Paschen's law and has been experimentally established for many gases, and it is a very important law in high voltage engineering.

Paschen's curve for different dielectrics





a) Mathematical Analysis

From the definitions of Townsend's first ionization constant, $\frac{\alpha}{p}$ is the function of $\frac{E}{p}$.

That is
$$\frac{\alpha}{p} = f[E/\mathrm{p}]$$
$$\therefore \alpha = f[E/\mathrm{p}] \times p$$

And Townsend's criterion for Breakdown is

$$\gamma\left[e^{\alpha d} - 1\right] = 1$$
$$\gamma e^{\alpha d} - \gamma = 1$$
$$\gamma e^{\alpha d} = 1 + \gamma$$
$$e^{\alpha d} = \frac{1+\gamma}{\gamma} = \left(1 + \frac{1}{\gamma}\right)$$
$$\ln\left(e^{\alpha d}\right) = \ln\left(1 + \frac{1}{\gamma}\right)$$
$$\alpha \cdot d = \ln\left(1 + \frac{1}{\gamma}\right)$$

$$f\left[\frac{E}{p}\right] \cdot p \cdot d = \ln\left(1 + \frac{1}{\gamma}\right) = K$$
$$f\left(\frac{V_b}{p \cdot d}\right) \cdot p \cdot d = K \quad \left(\because E = \frac{V_b}{d}\right)$$
$$f\left(\frac{V_b}{p \cdot d}\right) = \frac{K}{p \cdot d}$$
$$V_b = f(p \cdot d)$$

This is called Paschen's law

NOTE:

Penning effect:

1. Paschen's law does not hold good for many gaseous mixtures. A typical example is that of mixture of Argon in neon.
2. A small percentage of Argon in Neon reduces substantially the dielectric strength of pure Neon.
3. In fact, the dielectric strength is smaller than the dielectric strengths of either pure Neon or Argon.
4. The lowering of dielectric strength is due to the fact that the lowest excited stage of neon is meta-stable and its excitation potential (16eV) is about 0.9eV greater than the ionization potential of Argon.

5. The meta-stable atoms have a long life in neon gas, and on hitting Argon atoms there is a very high probability of ionization them.
6. This phenomenon is known as Penning Effect.

1.9 Breakdown in Non-Uniform Fields and Corona Discharges

1. It is an electric discharge mainly occurring at non uniform electric field
2. Visual and audible discharge
3. The corona will occur when the strength of the electric field around a conductor is high enough to form a conductive region, but not high enough to cause electrical breakdown or arcing to nearby objects.
4. It is often seen as a bluish (or other color) glow in the air adjacent to pointed metal conductors carrying high voltages, and emits light by the same property as a gas discharge lamp.
5. Potential difference between two electrodes should be greater than threshold value (30kV).

Corona Discharge:

1. 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.
2. However, in non-uniform fields, before the spark or breakdown of the medium takes place, there are many sign in the form of visual and audible discharges. These discharges are known as **Corona discharges**.
3. This phenomenon is always accompanied by a hissing noise, and the air surrounding the corona region becomes converted into ozone.
4. Corona is responsible for considerable loss of power from high voltage transmission lines, and it leads to the deterioration of insulation due to the combined action of the bombardment of ions and of the chemical compounds formed during discharges.
5. Corona also gives rise to radio interference.
6. The voltage gradient required to produce visual a.c. corona in air at a conductor surface, called the corona inception field, can be approximately given for the case of parallel wires of radius r as

$$E_w = 30md\left[1+\frac{0.301}{\sqrt{dr}}\right] \quad \text{....................(i)}$$

For the case of coaxial cylinders, whose inner cylinder has a radius r the equation becomes $E_c = 31md\left[1+\frac{0.308}{\sqrt{dr}}\right]$ ....(ii)

Where m is the surface irregularity factor which becomes equal to unity for highly polished smooth wires; d is the relative air density correction factor given by,

$$d = \frac{0.392b}{(273+T)}$$

Where b is the atmospheric pressure in torr, and t is the temperature in $^\circ C$,d = 1 at 760 torr and 250C. The expressions were found to hold good from atmospheric pressure down to a pressure of several torr.

Fig. 1.8 shows the corona inception and breakdown voltages of the sphere-plane arrangement. From the figure, it is clear that—

(i) For small spacing (Zone–I), the field is uniform and the breakdown voltage depends mainly on the gap spacing.

(ii) In zone–II, where the spacing is relatively larger, the electric field is non-uniform and the breakdown voltage depends on both the sphere diameter and the spacing. (iii) For still larger spacing.

(iii) at large spacing(zone-III) the field is non-uniform and the breakdown is preceded by corona and is controlled only by the spacing. The corona inception voltage mainly depends on the sphere diameter.

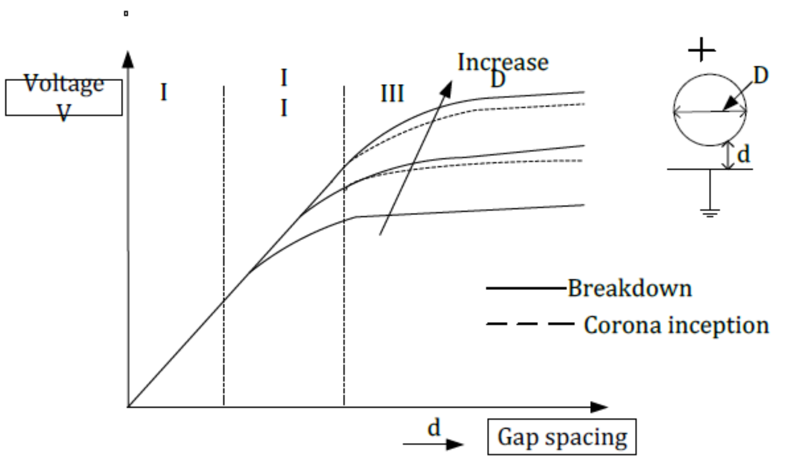


Fig 1.8 :Breakdown and corona inception characteristics for spheres of different diameter in Sphere - plane gap geometry

Results of corona

a. Power loss
b. Hissing noise
c. Ozone formation
d. Chemical activities

Factors affecting corona

a. Air desnsity & Humidity are inversely proportional to corona.
b. Surface conduction is proportional to corona.

Problems associated with corona

a. Ozone (O_3) , Nitric acid & Nitrogen oxide (NO_x) production
b. Electromagnetic interference
c. Audible noise
d. Insulation losses

1.10 Solid Dielectrics

• Solid dielectrics are commonly used all kinds of **electric circuit and devices.**

• Provide insulation for current carrying conductors.

Properties of good solid dielectric material

1. Good mechanical strength
2. Free from gaseous inclusion
3. Free from moisture
4. Resistant to thermal and chemical deterioration
5. Low dielectric loss

Types of breakdown mechanism

(a) Intrinsic or ionic breakdown

1. Electronic breakdown
2. Avalanche breakdown

(b) Electromechanical breakdown

(c) Failure due to treeing and tracking

(d) Thermal breakdown

(e) Electrochemical breakdown

(J) Breakdown due to internal discharges

Types of breakdown mechanism

Intrinsic breakdown

1. Usually a small number of conduction electrons (free electrons) present in the solid dielectric dielectric material.
2. The following reasons such as
   i) Small number of impurities &
   ii) Structural imperfection of dielectric material are responsible for intrinsic breakdown.
3. The impurity atoms, or molecules or both act as traps for the conduction electrons up to certain ranges of **electric fields and temperatures.**
4. When these ranges are exceeded, additional electrons in addition to trapped electrons are released, and these electrons participate in the conduction process.
5. Presence of free electrons which are capable of migration through the lattice of the dielectrics.
6. Process will be repeated until the completion of dielectric breakdown of solid dielectric material.

Types of Intrinsic breakdown

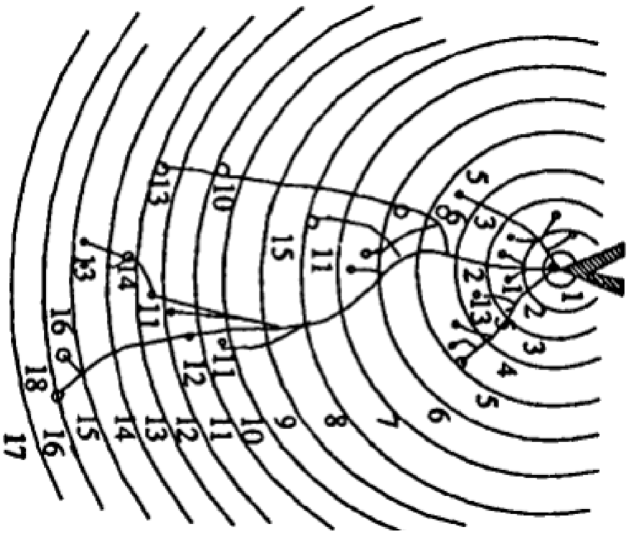
1. Electronic breakdown
2. Avalanche breakdown

(1) Electronic breakdown

1. Due to the presence of large density free electrons in a solid dielectrics
2. Whenever a high voltage is applied, collision between large free electrons will take place.
3. As a result electrons gain energy from the electric field and cross the forbidden energy gap from the valance to the conduction band.
4. Eventually dielectric breakdown takes place

(2) Avalanche or streamer breakdown

1. Similar to the breakdown in gaseous dielectric
2. Avalanche breakdown or streamer breakdown is a phenomenon that can occur in both insulating and semiconducting materials.
3. It is a form of electric current multiplication that can allow very large currents within materials & causes dielectric breakdown.
4. First step is the formation of avalanche.
5. Formation avalanche creates space charge (collection of charge or cloud of charge).
6. Space charge leads additional electric field.
7. The electric field enhance the growth of new avalanche.
8. Ionized region grows quickly & expand.
9. When the energy gained by the electrons greater than lattice ionization potential formation of **avalanche** takes palace. (Condition for avalanche breakdown)
10. Breakdown occur when avalanche exceeds critical size & formation of many avalanche, Breakdown will be occurred



(b) Electro mechanical breakdown

1. Consider the following reasons
   (i) solid dielectrics are subjected to high electric fields
   (ii) electrostatic compressive forces which can exceed the mechanical compressive strength.
2. How do you calculate the 'maximum value of electric field strength' before the breakdown'..?
3. Consider a solid dielectric material
4. The thickness of solid dielectric material=do
5. Applied voltage = V
6. Thickness after the applied voltage = d . That means material is compressed.

$$\varepsilon_0 \varepsilon_r \frac{V^2}{2d^2} = Y \ln\left[\frac{d_0}{d}\right] \qquad \textbf{(1)}$$

7. Equation (1) represents electrically developed compressive stress in equilibrium.
   where Y is the Young's modulus. From (1) find the voltage V^2

$$V^2 = d^2\left[\frac{2Y}{\varepsilon_0 \varepsilon_r}\right]\ln\left[\frac{d_0}{d}\right] \qquad \textbf{(2)}$$

- Usually, mechanical instability occurs when

d/do = 0.6 or do/d= 1.67 ***(3)***

- ***Substitute (3) in (2)***

8. The highest apparent electric stress or maximum value of electric field before breakdown is given by

$$E_{\max} = \frac{V}{d_0}$$

$$E_{\max} = \frac{V}{d_0} = 0.6\left[\frac{Y}{\varepsilon_0 \varepsilon_r}\right]^{\frac{1}{2}}$$

(C) Thermal breakdown

1. Most of the insulation failures in high voltage power apparatus occur due to thermal breakdown.
2. When an electric field is applied to a dielectric, conduction current, however small it may be, flows through the material.
3. The current heats up the specimen and the temperature rises.
4. The heat generated is transferred to the surrounding medium by conduction through the solid dielectric and by radiation from its outer surfaces.

Mathematical expression

• The heat generated under d.c. stress E is given as

$$W_{d.c.} = E^2\sigma \qquad \text{W/cm}^3 \qquad (1)$$

Where 'σ' is the D.C. conductivity of the specimen.

Under A.C. fields, the heat generated

$$W_{a.c.} = \frac{E^2 f \varepsilon_r \tan\delta}{1.8\times 10^{12}} \qquad \text{W/cm}^3 \qquad (2)$$

$f =$ frequency in Hz,

$\delta =$ loss angle of the dielectric material, and

The heat dissipated (WT) is given by

$$W_T = C_V \frac{dT}{dt} + \text{div}\,(K \text{ grad } T) \qquad (3)$$

where, $C_V =$ specific heat of the specimen,

$T =$ temperature of the specimen,

$K =$ thermal conductivity of the specimen, and

$t =$ time over which the heat is dissipated.

• Normally Wac or Wdc equals to WT

• Breakdown occur when Wac or Wdc Greater than WT

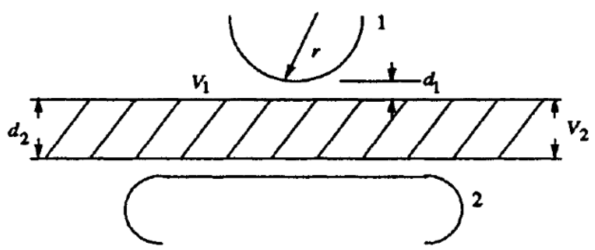
Thermal Breakdown Stresses in Dielectrics

Material	Maximum thermal breakdown stress in MV/cm	
	d.c.	a.c.
Muscovite mica	24	7.18
Rock salt	38	1.4
High grade porcelain	—	2.8
H.V. Steatite	—	9.8
Quartz—perpendicular to axis	1200	—
parallel to axis	66	—
Capacitor paper	—	3.4–4.4
Polythene	—	3.5
Polystryene	—	5.0

c) Breakdown due to treeing & tracking

1. This type of breakdown occurs when a solid dielectric material subjected to electric stress for a long time.
2. Presence of conducting path inside solid dielectric material due to moisture.
3. A mechanism whereby leakage current passes through the conducting path finally leading to the formation of a spark.
4. Insulation deterioration occurs as a result of these sparks, sparks erodes the surface, generates heat & surface becomes dry.
5. The spreading of spark channels said to be **tracking**, in the form of the branches of a tree is called **treeing**
6. As time passes, breakdown channels spread through the insulation in an irregular "tree" like fashion leading to the formation of conducting channels. This kind of channeling is called treeing.
7. Usually, tracking occurs even at very low voltages of the order of about 100 V, whereas treeing requires high voltage.
8. This is a cumulative process, and insulation failure occurs when carbonized tracks bridge the distance between the electrodes.
9. This phenomena happening the layers of Bakelite, paper, cables and similar dielectrics built of laminates.

Breakdown due to treeing & tracking



Arrangement for study of treeing phenomena. 1 and 2 are electrodes

Breakdown due to treeing & tracking

1. When a dielectric material lies between two electrodes as shown in Fig. There is a possibility for two different dielectric media, the air and the dielectric, to come in series.
2. The voltages across the two media are as shown (V_1 across the air gap, and V_2 across the dielectric). The voltage V_1 across the air gap is given as,

$$V_1 = \frac{V d_1}{d_1 + \left(\frac{\varepsilon_1}{\varepsilon_2}\right) d_2}$$

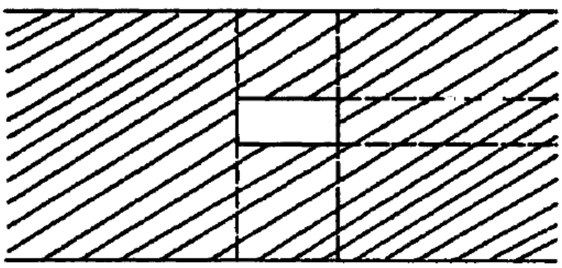
How to prevent treeing & tracking??

1. Treeing can be prevented by having clean, dry, and undamaged surfaces and a clean environment.
2. The materials chosen should be resistant to tracking.
3. Sometimes moisture repellant greases are used. But this needs frequent cleaning and regressing.
4. Increasing creepage distances should prevent tracking, but in practice the presence of moisture films defeat the purpose.
5. Usually, treeing phenomena is observed in capacitors and cables, and extensive work is being done to investigate the real nature and causes of this phenomenon.

Breakdown due to internal discharge

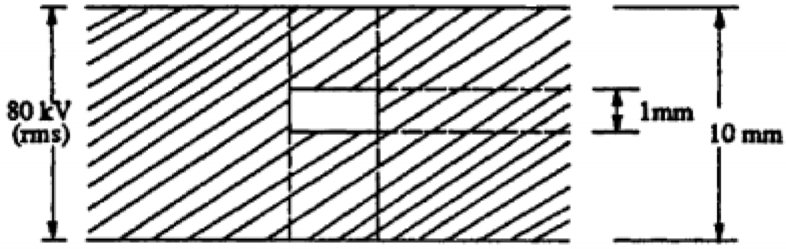
1. Due to voids or cavities present inside the insulating materials.
2. These voids are generally filled with a medium of lower dielectric strength, and the dielectric constant of the medium in the voids is lower than that of the insulation.
3. Hence, the electric field strength in the voids is higher than that across the dielectric.
4. Therefore, even under normal working voltages the field in the voids may exceed their breakdown value, and breakdown may occur.

Breakdown due to internal discharge



Numerical

A solid dielectric specimen of dielectric constant of 4.0 shown in the figure has an internal void of thickness 1 mm. The specimen is 1 cm thick and is subjected to a voltage of 80 kV (rms). If the void is filled with air and if the breakdown strength of air can be taken as 30 k V (peak)/cm, find the voltage at which an internal discharge can occur



Answer:

- The voltage that appears across the void is given as

$$V_1 = \frac{Vd_1}{\left(d_1 + \frac{\varepsilon_0}{\varepsilon_1} d_2\right)}$$

$d_1 =$ 1 mm

$d_2 =$ 9 mm

$\varepsilon_0 = 8.89 \times 10^{-12}$ F/m

$\varepsilon_1 = \varepsilon_r \varepsilon_0 = 4.0\, \varepsilon_0$

$$V_1 = \frac{V \times 1}{\left(1 + \frac{9}{4}\right)}$$

$$= \left(\frac{4V}{13}\right)$$

V- Voltage for the occurrence of Internal discharge.
V1- Voltage require to cause The breakdown in air.

The voltage at which the air void of 1 mm thickness breaks down is 3 kV/mm × 1 mm = 3 kV

$$\therefore V_1 = \frac{13V}{4} = \frac{13 \times 3}{4} = \frac{39}{4}$$

$$= 9.75 \text{ kV (peak)}$$

The internal discharges appear in the sinusoidal voltage 80 sin ωt kV when the voltage reaches a value of 9.75 kV

1.11 Liquid Dielectrics

Properties of **good liquid dielectric material**

1. High density
2. High dielectric strength
3. Should free from moisture
4. Should free from oxidation
5. High resistivity
6. High heat transfer characteristics
7. Chemically stable
8. Applications- Transformer oil, Silicon oil, Synthetic hydro carbon(power cable) & chlorinated hydro carbon

Breakdown in liquid dielectrics

1. Impurities like gas bubbles, suspended particles etc will reason for dielectric breakdown.
2. Breakdown mechanism depends upon nature of electrodes, physical properties of the liquid dielectrics, presence of impurities & gas present in the liquid

Theories supported for dielectric breakdown in **Liquid dielectric material**

1. Suspended particle theory
2. Cavitation & bubble mechanism
3. Electro convection breakdown
4. Electronic breakdown

1. Suspended particle theory

1. Commercial liquids will always contain solid impurities like fibers or dispersed solid particles & gaseous bubbles.
2. Consider the permittivity of liquid dielectrics ε_1 & permittivity of solid impurities being ε_2.
3. $\varepsilon_2 > \varepsilon_1$
4. When the electric field is applied the force is directed towards areas of maximum stress case of the presence of solid particles like paper (solid impurities) in the liquid.
5. On the other hand, if only gas bubbles are present in the liquid ($\varepsilon_2 < \varepsilon_1$).
6. If we consider these impunities (solid or gas) to be spherical particles of radius 'r', and if the applied field is 'E' then the particles experience a force 'F'
$$F = \frac{1}{2r^3}\frac{(\varepsilon_2 - \varepsilon_1)}{2\varepsilon_1 + \varepsilon_2}\text{grad } E^2$$
7. The process of Liquid dielectric breakdown depends up on the size & number of external impurities (either solid or gaseous impurities)
8. If the field exceeds the breakdown strength of the liquids, liquid dielectric breakdown will occur.
9. If the number of impurities present are large, they becomes aligned due to these forces, and thus form a stable chain bridging the electrode gap causing a breakdown between the electrodes.

2. Cavitations (Bubble's theory) theory

1. Theory states that dielectric strength of liquid dielectric material depends up on hydrostatic pressure.
2. Hydrostatic pressure proportional to higher electric field strength & it is responsible for changing the phase of liquid dielectrics & results in liquid dielectric breakdown.
3. A kind of small vapor bubble formed inside the liquid dielectrics reason for dielectric breakdown.
4. The following reasons responsible for the bubble's formation in liquid dielectric material - Gas pockets in the electrode surface - Irregular surface of electrodes - Change in temperature & pressure - Dissociation of product by electron collision
5. Condition of breakdown- " Voltage drop along the length of bubble equals to minimum value of voltage in the Paschen's curve".
6. The value of breakdown field is given by

$$E_0 = \frac{1}{(\varepsilon_1 - \varepsilon_2)}\left[\frac{2\pi\sigma(2\varepsilon_1 + \varepsilon_2)}{r}\left\{\frac{\pi}{4}\sqrt{\left(\frac{V_b}{2rE_0}\right)} - 1\right\}\right]^{\frac{1}{2}}$$

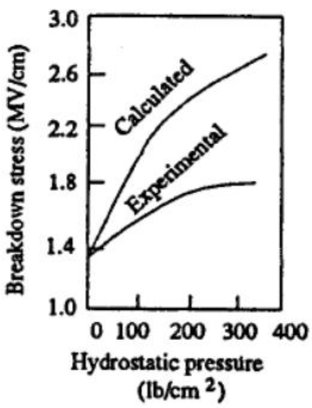
Where σ = surface tension of the liquid, Ɛ1=permittivity of liquid, Ɛ2= permittivity of gaseous bubble, r=initial radios of gas bubble Vb= Voltage drop in the bubble corresponding to the minimum value in the pachen's curve.

1. Breakdown strength depends upon initial size of bubble's, which influence by hydrostatic pressure & temperature.

Limitations

• This theory doesn't mention about the formation of initial bubbles.

• Theoretical & experimental calculation of breakdown strength are different.



3.Electronic breakdown

1. Once the voltage is applied in between two electrodes, electrons are injected to the liquid
2. Electron gains energy from the electric field • Starts the collision process in between other electrons
3. Electrons are accelerated under electric field & would gain a sufficient energy to knock out an electron & beginning the process of avalanche.
4. Condition of breakdown is referred as "Threshold condition"

5. Threshold condition achieved when the energy gained by the electron equals to energy lost during ionisation. • $e*\lambda*E = C* h *\mu$ C=constant

4. Electro-convection breakdown

1. Breakdown in pure insulating fluid under high voltage
2. Charge carrier injected to liquid surface
3. Resulting the formation of space charge region
4. Increase the columbic force
5. Reason for hydrodynamic instability
6. Formation of convection current
7. The interaction between the space charge & the electric field give rise to eddy motion of liquid.

Conclusion

1. It is clear that no single theory can explain all the experimental observation satisfactorily.
2. All the above theories do not consider dependence of breakdown strength on the gap length.
3. Experimental evidence showed that the breakdown strength of liquids depends on the gap length.

Note : Power law

$$V_b = Ad^n$$

d = gap length,
A = constant, and
n = constant, always less than 1.

1. The above equation is termed as 'power law' equation.
2. The breakdown voltage depends on nature of voltage, mode in which the voltage is applied, Gap distance between electrodes & time of application.

Numerical

Example :.In an experiment for determining the breakdown strength of transformer oil, the following observations were made. Determine the power law between the gap spacing and the applied voltage of the oil.

Gap spacing (mm)	:	4	6	10	12
Voltage at breakdown (kV)	:	90	140	210	255

The relationship between the breakdown voltage and gap is normally given as

$$V = Kd^n$$

or, $$\log V = \log K + n \log d$$

i.e., $$\log V - \log K = n \log d$$

or, $$n = \frac{\log V - \log K}{\log d}$$

= slope of the straight line as shown in Fig. E.3.1.

= 0.947

From Fig. E.3.1.,

$$K = 24.5$$

∴ Relationship between the breakdown voltage and the gap spacing for the transformer oil studied is

$$V = 24.5\, d^{0.947}$$

where *V is in kV and d is in mm.*

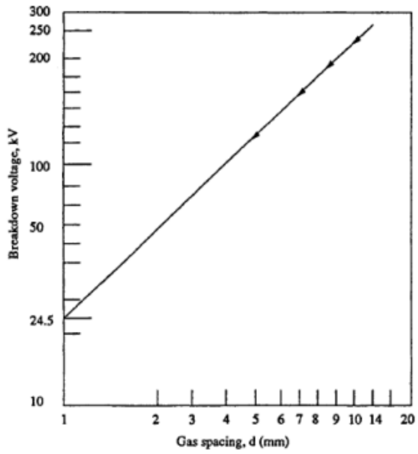


Fig. E.3.1 Breakdown voltage as a function of gap spacing

Note: Solve all numericals solved in class

Course Outcome

At the end of the course the student will be able to:

1. Explain conduction and breakdown phenomenon in gases, liquid dielectrics and in solid dielectrics.