UNIT II

BREAKDOWN

GASES, SOLIDS and LIQUIDS

GASEOUS BREAKDOWN

Introduction

- Gaseous dielectrics
  - Air
  - Nitrogen (N_2)
  - Carbon Dioxide (CO_2)
  - Freon (CCl_2F_2)
  - Sulphur hexafluoride (SF_6)

Gaseous Breakdown

- For High voltages, current increases between the electrode in dielectric then breakdown occurs.
- Breakdown Voltage – maximum voltage applied to the insulation at the moment of breakdown
- Types
  - Self sustaining
  - Non sustaining
- Theories
  - Townsend theory
  - Streamer Theory

Ionization: Townsend's Theory

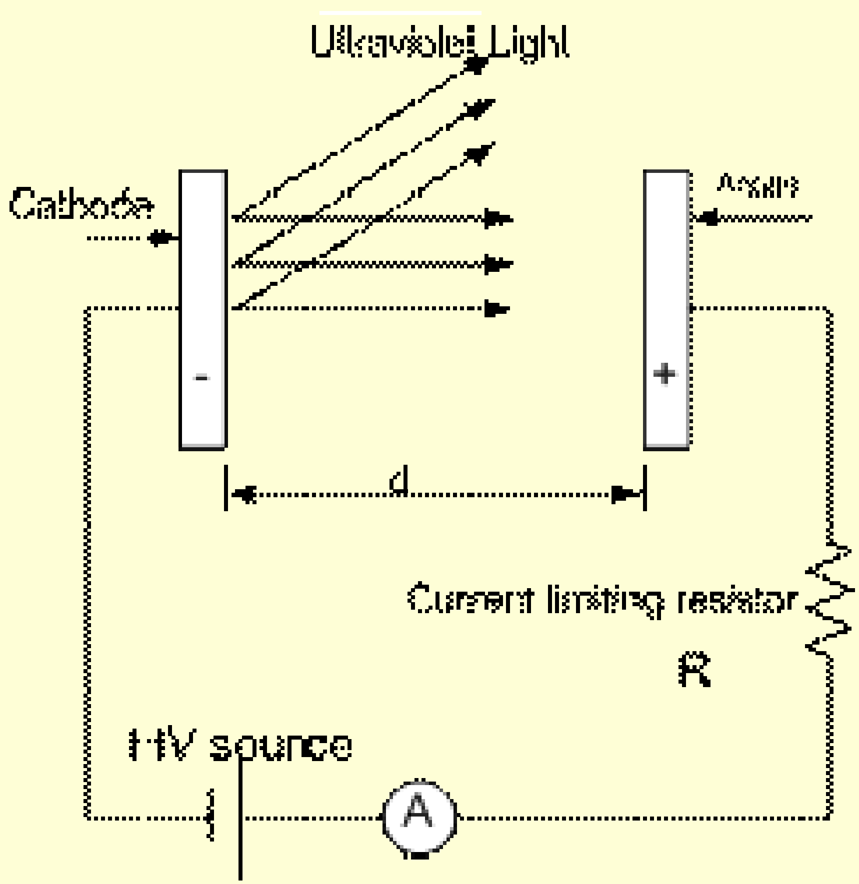
- Liberating an electron from a gas molecule with the simultaneous protection of a positive ion- ionization
  - By Collision
  - Photo Ionization
  - Secondary Ionization
  - Electron Attachment Process

Ionisation by Collision

- Free electron collides with a neutral gas molecule and gives rise to anew electron and a positive ion
- If the energy gained during this travel between collisions exceeds ionisation potential, which is the energy required to dislodge an electron from its atomic shell then ionisation takes place.

$$e^- + A \text{---------}\rightarrow e^- + A^+ + e^-$$

- Electrons produced at cathode by UV light falling on cathode.
- No of electrons reaching the anode is greater than that liberated from cathode



Ultraviolet Light
Cathode
-
+
d
Current limiting resistor
R
HV source
A

Photo Ionisation

- Involves radiation of matter
- Occurs when the radiation energy absorbed by atom exceeds ionisation potential
- Process
  - Excitation of the atom to a higher energy state
  - Continuous absorption by direct excitation of the atom or dissociation of diatomic molecule or direct ionisation etc

$$h\nu + A \leftarrow\text{----------}\rightarrow A^*$$

- Ionisation occurs when

$$\lambda = c.h/V_i$$

$$\lambda = 1.27X10^{-6}/V_i \text{ cm}$$

Where,

h -> Plank's Constant

λ -> Wavelength of Incident radiation

c -> Velocity of Light

V_i->Electron Volts

- Photo ionisation occurs with a radiation of 1250 A^o

Secondary Ionisation:

- It sustain a discharge after it is established due to ionisation by previous process
  - Electron emission due to Positive Ion Impact
  - Electron emission due to Photons
  - Electron emission due to Metastable and Neutral Atoms

Positive Ion Impact

- Positive ion can cause emission of electrons from the cathode by giving up its K.E on impact
- It Total Energy (I.E+K.E) is greater than twice the work function, than one electron will be ejected and a secondary electron will neutralise the ion

Electron Emission due to Photons

- Energy (in the form of photons) by UV light cause electron to escape from a metal
- It occurs if $h\nu \geq \varphi$, where φ is the work function and ν is the threshold frequency
- Clean nickel surface with φ=4.5eV threshold frequency correspond wavelength λ=2755 A^0

Emission due to Metastable and Neutral Atoms

- Metastable- excited particle whose lifetime (10^{-3}s) is large compared to that of an ordinary one (10^{-8}).
- Electrons ejected due to metastable atoms by sufficient energy
- Yields be large (nearly 100%) for interactions of excited He atom with molybdenum, nickel or magnesium.
- Neutral atoms in the ground state also gives rise to secondary electrons if K.E is High (1000 eV)

Townsend's Current Growth Equation

- Number of electrons travels at a distance x (from the cathode) is given by

$$n_x = n_o \exp(\alpha x)$$

No of electrons reaching the anode,

$$n_d = n_o \exp(\alpha d)$$

$$I = I_o \exp(\alpha x)$$

Where, n_o - No of electrons emitted from cathode

α – Avg no of ionizing collisions made by an electron per cm level in the field (Townsend's First Ionization Coefficient depends pressure (p) and Field per pressure (E/p))

Current Growth through Secondary Process

- Let n_0'=no of secondary electrons

  n_0''=total no of electrons leaving the cathode.

$$n_0'' = n_0' + n_0$$

No of electrons reaching the anode

$$n = n_0'' \exp(\alpha d) = (n_0' + n_0) \exp(\alpha d)$$

and

$$n_0' = \gamma(n - n_0' - n_0)$$

Eliminating n_0'

$$n = \frac{n_0 \exp(\alpha d)}{1 - \gamma[\exp(\alpha d) - 1]}$$

$$I = \frac{I_0 \exp(\alpha d)}{1 - \gamma[\exp(\alpha d) - 1]}$$

Townsend's Criterion for Breakdown

- Current at particular distance makes infinity and it is limited by ext circuit.

From previous equation,

$$1-\gamma(\exp(\alpha d)-1)=0$$

$$\gamma\exp(\alpha d)=1.$$

- Voltage gives the value of γ, α satisfying above eqn, -spark breakdown voltage.
- Corresponding Distance- Sparking distance.

Electron Attachment Process: Breakdown in Electro Negative Gases

- Collisions in which electrons attached to atoms to form negative ions.
- Electrically insulating gases, O_2, CO_2, Cl_2, F_2, C_2F_6, C_3F_8, C_4F_{10}, CCl_2F_2 and SF_6 exhibit this property

$$A + e^- + k \dashrightarrow A^- + E_a + K$$

Where, A-Atom, A^- Negative atomic ion, k-Kinetic Energy, E_a - Electron Affinity

- It removes free electrons from an ionised gas when arc interruption occurs in gas insulated switchgear.

Process

- Direct Attachment in which an electron directly attaches to form a negative ion

$$AB + e \longrightarrow AB^-$$

- Dissociative attachment in which the as molecules split into their constituent atoms and the electronegative atom forms a negative ion

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

- A - Sulphur or Carbon Atom
- B – Oxygen / Halogen atom / molecules

Townsend's criterion

$$I = I_0 \frac{[\{\alpha/(\alpha-\eta)\}\exp((\alpha-\eta)d)]-[\eta/(\alpha-\eta)]}{1-\left\{\gamma\frac{\alpha}{(\alpha-\eta)}[\exp((\alpha-\eta)d)-1]\right\}}$$

$$Criterion:::\gamma\frac{\alpha}{(\alpha-\eta)}[\exp((\alpha-\eta)d)-1]=1$$

$$if, \alpha<\eta; then$$

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

η=attachment coefficient=no of attaching collisions made by one electron drifting one cm in the direction of field

Results

- γ is small, so $\alpha=\eta$.
- It puts a limit called critical E/p, below which no B.D is possible irrespective of ‘d’
- Critical E/p:->
  - SF6->117 $cm^{-1}torr^{-1}$
  - CCl_2F_2->121 $cm^{-1}torr^{-1}$ (20^oC)

Drawbacks in Townsend's theory

- Drawbacks in Townsend's theory
  - BD voltage depends on pressure and geometry of gap
  - Time lags: theory - 10^{-5}, Practical - 10^{-8},
  - Diffused form of discharge in theory / Filamentary and irregular form in practice

Paschen's Law

- In Townsend's criterion, α, γ are the function of E/p

$$\frac{\alpha}{p} = f_1\left(\frac{E}{p}\right); \gamma = f_2\left(\frac{E}{p}\right); E = \frac{V}{d}$$

substituting

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

$$V = f(pd)$$

Minimum Sparking Potential

Gas	Vmin (V)	Pd (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

Experimental Results

Breakdown potential of air is expressed as a power function in pd as

$$V = 24.22\left[\frac{293pd}{760T}\right] + 6.08\left[\frac{293pd}{760T}\right]^{1/2}$$

At 760 torr and 293^{o}K

$$E = 24.22 + 6.08\sqrt{d} \text{ kV/cm}$$

Corona Discharge

- In nonuniform fields, Voltage rise cause Discharge in gas to appear at points with highest electric field intensity, namely at sharp points or where the electrodes are curved or on transmission lines. It observed as bluish luminence
- Hissing noise and air surrounding corona becomes ozone
- It gives line loss
- Rise to radio interference

Corona inception field

- Voltage gradient to produce visual ac corona in air at a conductor.
- For parallel wires of radius r

$$E_w=30md[1+(0.301/\sqrt{dr}\ )]$$

- For coaxial cylinders

$$E_c=31md[1+(.308\sqrt{dr})]$$

Where, m-surface irregularity factor (1-high polished smooth wires)

d- Relative Air density correction factor

$$d=0.392b/(273+t)$$

Where b – atmospheric pressure, t – temperature ^{o}C

- d=1 @ 760 torr, $25^{0}C$

Breakdown and Corona inception characteristics

- At small spacing the field is uniform, BD voltage depends spacing
- At fairly large spacing, field is non uniform, BD Voltage depends sphere diameter
- At large spacing, field is non uniform, BD Voltage preceded by corona and controlled by spacing
- Corona inception voltage depends sphere diameter

BD – Non Uniform Field

- Coaxial cylinders, point-plane and sphere plane gaps.
- Townsend criterion is varies

$$\gamma\left\{\exp\left[\int_0^d \alpha dx\right]-1\right\}=1$$

- Meek's Equation for radial field

$$E_r = \frac{5.27\times10^{-7}\alpha_x \exp\left(\int_0^x \alpha dx\right)}{(x/p)^{1/2}} V/cm$$

Contd.,

- Rod-rod, sphere-sphere gap – Measurement of HV and Protection of Electrical apparatus such as transformers
- B.D. Voltages high for negative polarity
- Depends humidity in air
- Rod-rod gaps is non uniform, so sphere gap is used

Vacuum Breakdown

- Applications
  - Vacuum contractors, interrupters, High frequency Capacitors and Relays, Electrostatic Generators, Microwave tubes.
- Vacuum pressures
  - High vacuum : $1X10^{-3}$ to $1X10^{-6}$ Torr
  - Very high vacuum : $1X10^{-6}$ to $1X10^{-8}$ Torr
  - Ultra High vacuum : $1X10^{-9}$ Torr and Below.

Vacuum Breakdown

- Unlike gaseous breakdown, electron crosses the gap without encountering any collisions
- Classifications
  - Particle Exchange Mechanism
  - Field Emission Mechanism
  - Clump Theory

Particle Exchange Mechanism

- Charged particle emission, impinges on other electrode, liberation of opposite charges
- Involves electrons, positive ions, photons, absorbed gases
- Anode releases positive ions and photons
- Photons and Positive ions liberates the electrons called secondary electrons
- Break down criterion

  (AB+CD)>1
- Modifications (AB+EF)>1
- Where A-no of positive ions, C-no of photons, B-No of electrons liberated by positive ions, D- B-No of electrons liberated by positive ions photons. E-No of electrons liberated by negative ions, F-No of electrons liberation by +v ions
- Product Ef closer to unity for copper, aluminium, and Stainless electrodes.

Field Emission Theory

- **Anode Heating Mechanism**
  - Field emission bombard, anode temperature rise-gases and vapors released
  - Ionise the atoms into +ve
  - Secondary electrons formed due to positive ions in cathode
- **Cathode Heating Mechanism**
  - Pre-breakdown current
  - Resistive heating
  - Vacuum discharge
  - BDS-10^6 to 10^7 V/cm

Clump Mechanism

- A loosely bound particle (Clump) exist on one of the electrode
- On HV, particles gets charged, detached from mother electrode, accelerated across gap
- BD occurs due to a discharge in vapour or gas released by impact of particle at target electrode.

LIQUID BREAKDOWN

INTRODUCTION

- Liquids and solids-10^3 times denser than gases
- Dielectric strength in the order of 10^7V/cm
- Used as impregnants in HV cables and capacitors and filling up transformers (heat transfer agent) and circuit breakers (Arc quenching media)
- Petroleum Oils (TF), Synthetic and Halogenated Hydrocarbons, Silicon Oils, Fluorinated hydrocarbons, Vegetable oils, esters are the examples of liquid dielectrics

Transformer Oil

- Mixture of hydrocarbons with Paraffins, Iso-paraffins, Napthalenes and Aromatics.
- Subjected to prolonged heating at high temperature about 95^0C, undergoes a gradual ageing process
- Darker due to formation of acids, resins, and sludges

Electrical Properties

- Capacitance pu volume (Permittivity)
  - Petroleum oils – 2-2.6
  - Askerals – 4.5-5
  - Silicone oils – 2-73
- Resistivity
  - In the order of 10^{16} Ohm metre
- Loss Tangent or Power factor
  - 10^{-4} at 20^{0}C and 10^{-3} at 90^{0}C
- Withstand ability of high electric stresses
  - Depends atomic and molecular properties
  - Material of electrodes, temperature, type of voltage, gas content of the liquid

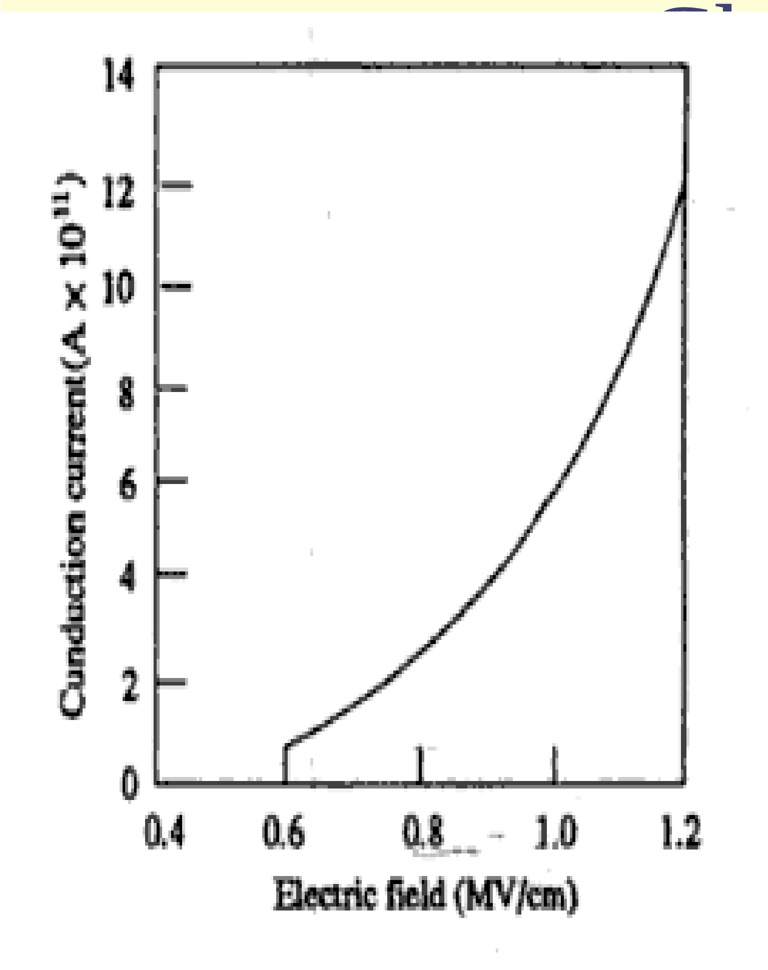
PURE AND COMMERCIAL LIQUIDS

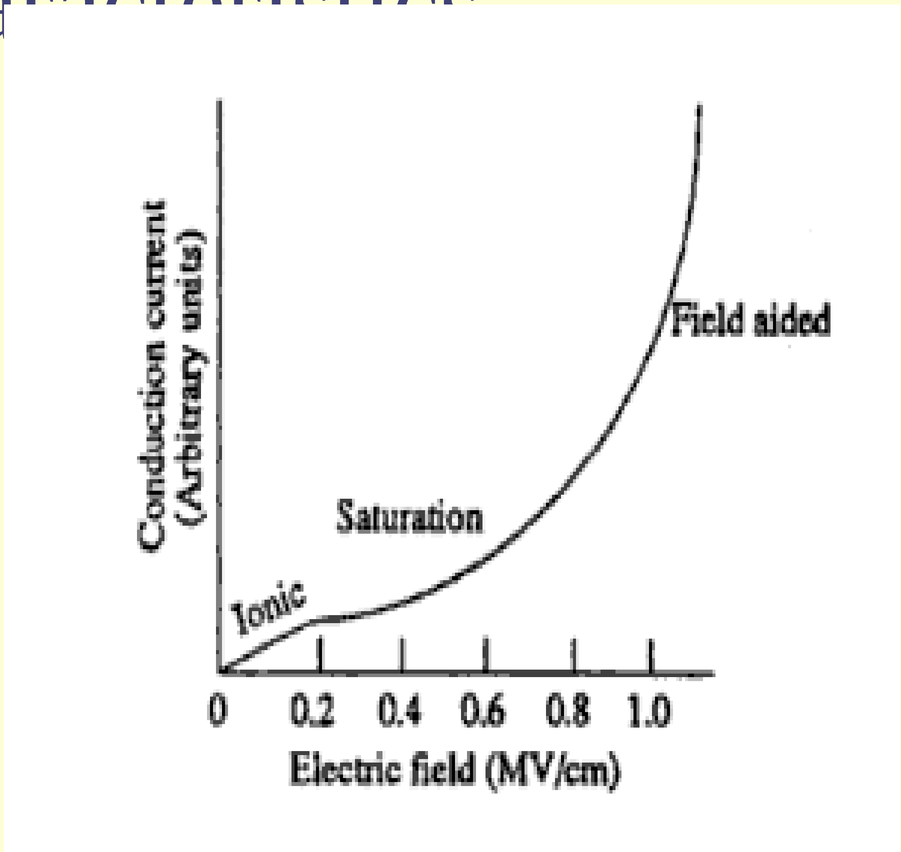
- Pure Liquids do not contain any chemical impurities.
- n-hexane (C_6H_{14}), n-heptane (C_7H_{16}) and other paraffin hydrocarbons
- Easier to separate out various factors that influence conduction and breakdown in them
- Commercial liquids are not chemically pure, consists of mixtures of complex organic molecules which cannot be specified or reproduced in a series of experiments

Conduction and Breakdown in Pure Liquids

Liquid	Max BD Strength (MV/cm)
Hexane	1.1-1.3
Benzene	1.1
Transformer Oil	1.0
Silicone	1.0-1.2
Liquid Oxygen	2.4
Liquid Nitrogen	1.6-1.9
Liquid Hydrogen	1.0
Liquid Helium	0.7
Liquid Argon	1.1-1.42

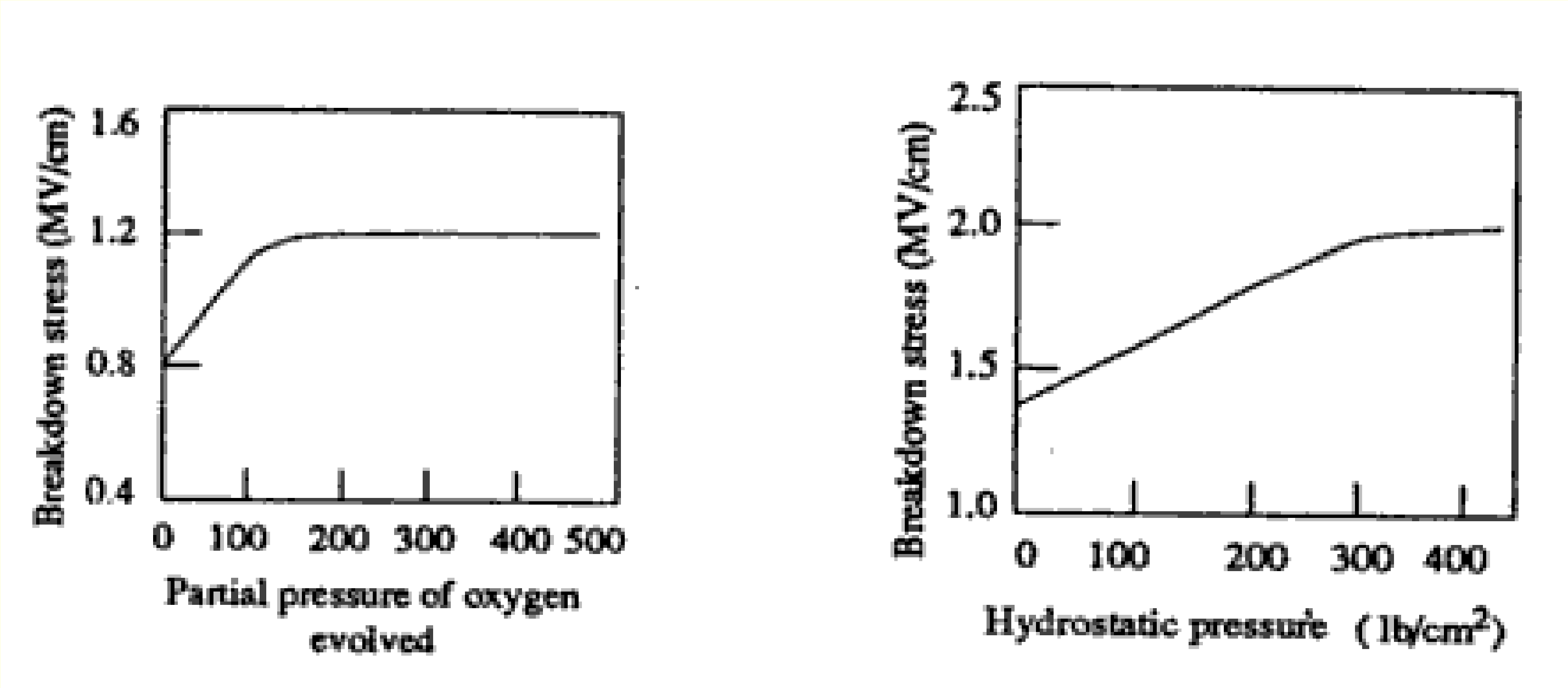
Conduction Current Electrical Field Characteristics





a) Hexane at high fields

b) Hydro carbon liquid



a. Effect of oxygen gas evolved on the breakdown stress in n-hexane
b. Effect of hydrostatic pressure on the breakdown stress in n-hexane

Conduction and Breakdown in commercial liquids

- BD mechanism influenced by presence of impurities
- Additional gases and gas bubbles are evolved and solid decomposition products are formed
- Depends nature, condition of electrodes, physical properties of liquid etc.,
- Theories
  - Suspended Particle Theory
  - Cavitation and Bubble Mechanism
  - Stressed Oil Mechanism

Suspended Particle Theory

- Impurities considered as spherical wirh radius r and field E then it experiences a force of

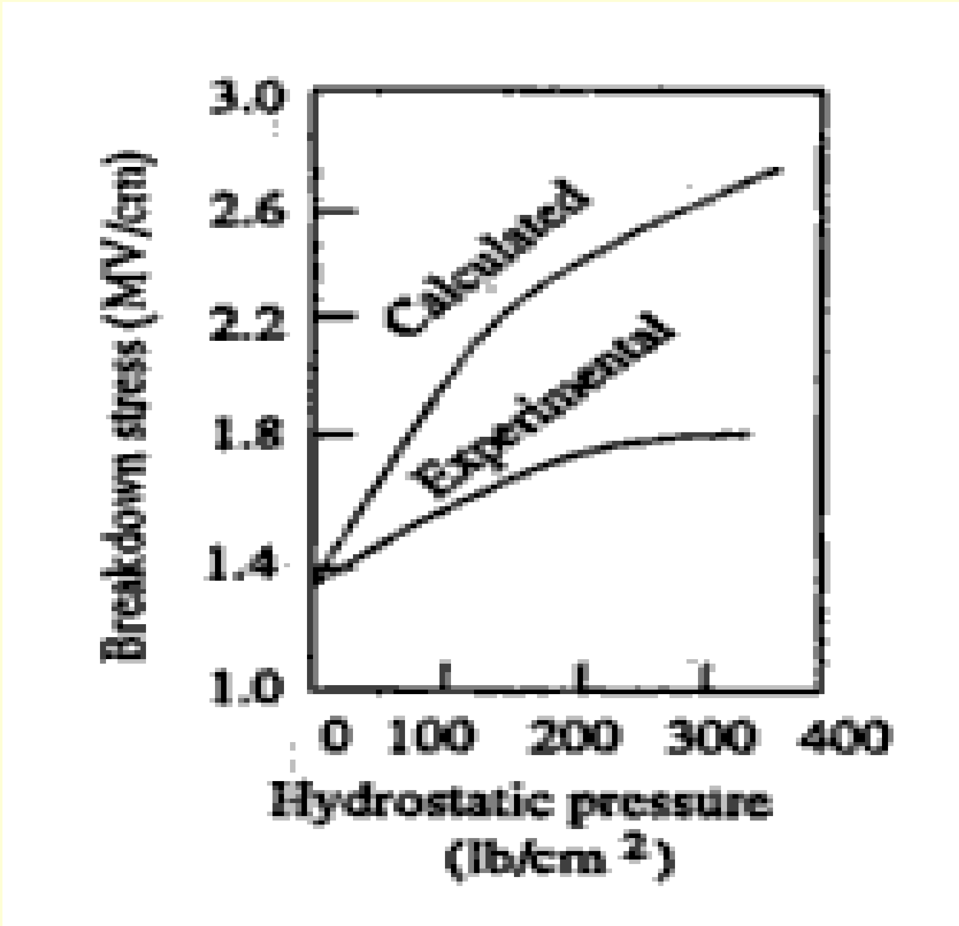
  $F=(1/2r^3)\ ((\varepsilon_2 - \varepsilon_1)/(2\ \varepsilon_1 + \varepsilon_2)).\ \text{Grad}\ E^2$

- Force is directed towards max stress
- If no of particles large, they aligned and form a stable chain bridging the electrode gap causing a breakdown between electrodes

Cavitation and Bubble Mechanism

- Formation of vapour bubbles:
  - Gas pockets at the surface of the electrodes
  - Electrostatic repulsive forces between space charges which may be sufficient to overcome the surface tension
  - Gaseous products due to dissociation of liquid molecules by electron collisions
  - Vapourization of the liquid by corona type discharge from sharp points and irregularities on the electrode surfaces.

Theoretical and Experimental breakdown stresses in n-hexane



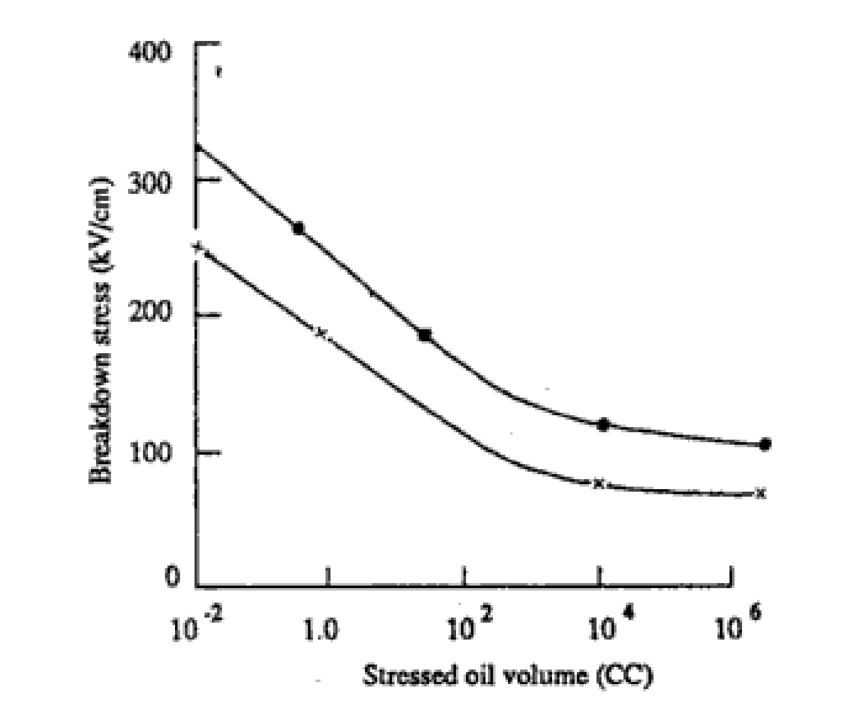
Thermal Mechanism of Breakdown

- High current pulses (before BD) originate from the tips of microscopic projections on the cathode surface ($1A/cm^3$)
- Localised heating , formation of vapour bubbles
- Energy limit $10^7 W/cm^2$
- BD strength depends pressure and molecular structure of the liquid.

Stressed Oil Volume Theory

- Largest Possible Impurity or Weak Link
- Weakest region- which is stressed to the maximum.
- Stressed oil volume- between max stress contour and 0.9 E_{max} contour.
- BDS inversely proportional to SOV

P.F AC breakdown stress as a function of stressed oil volume



- With steady voltage rise

x One minute withstand voltage

Solid Breakdown

- Low dielectric loss, high mech strength, and free from gaseous inclusions, and moisture resistant to thermal and chemical deterioration
- Mechanisms
  - Intrinsic or Ionic
  - Electromechanical
  - Failure due to treeing and tracking
  - Thermal
  - Electrochemical
  - Internal discharges

INTRINSIC BREAKDOWN

- Intrinsic electric strength (10^{-8} s)
  - 15 MV/cm polyvinyl alcohol at -196^0C
- Free electrons presence
- Electronic breakdown:
  - Initial density of free electrons be large
  - They cross forbidden energy gap from valency to conduction band when voltage is applied.

Intrinsic breakdown – Avalanche or Streamer

- Cumulative ionization
- If electrons embedded in specimen, b.d will occur when an electron avalanche bridges the electrode gap
- Breakdown does not occur by the formation of single avalanche
- Demo in lab by applying impulse voltage between point plane electrodes with point embedded in transparent solid dielectric such as Perspex

Electromechanical Breakdown

- Electrostatic compressive forces exceeds mech comp strength.
- At equilibrium,

$$\varepsilon_0 \varepsilon_r V^2/(2d^2)=Y \ln (d_0/d)$$

Y-> Young Modulus

$$V^2=d^2(2Y/\varepsilon_0\varepsilon_r) \ln(d_0/d)$$

Mechanical instability occurs

when $d/d_0=0.6$ or 1.67

$E_{max}= V/d_0 =0.6. (Y/\varepsilon_0\varepsilon_r)^{1/2}$

Thermal Breakdown

- Equilibrium is reached when the heat used to raise the temperature of dielectric plus heat radiated out equals heat generated.
- Heat generated

$$W_{dc}=E^2 \sigma \ W/cm^3$$

σ-dc conductivity of the specimen

$$W_{ac}= (E^2 f \varepsilon_r \tan \delta) / (1.8 \times 10^{12}) \ \ W/cm^3$$

Where

f-frequency, δ – loss angle of dielectrics material, E rms value

Heat dissipated, $W_T = C_V \ dT/dt + div \ (K \ grad \ T)$

Where, C_V specific Heat, T-Temperature, K-Thermal Conductivity

Breakdown occurs W_{dc} or W_{ac} exceeds W_T