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HIGH VOLTAGE ENGINEERING

UNIT-I - OVER VOLTAGES IN ELECTRICAL POWER SYSTEMS

1.1 Causes of Over Voltages and its effects on Power system

→ It is essential for electrical power engineers to reduce the number of outages and preserve the continuity of electric supply.

→ Therefore, to protect transmission line and power apparatus by direct special attenuation from causes of overvoltages like lightning overvoltages and switching overvoltages.

→ Lightning overvoltage is a natural phenomenon, while switching overvoltages originate in the system itself by connection and disconnection of circuit breaker contacts (or) due to initiation (or) interruption of faults.

→ Switching overvoltages are highly damped short duration overvoltages. They are "temporary overvoltages" of power frequency (or) its

outages - non-functions

attenuation - decrement

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harmonic frequency, either sustained (or) weakly damped and originate in switching and fault clearing proces in power systems.

→ Both switching and power frequency overvoltages have no common origin, they may occur together, and their combined effect is important in insulation design.

→ Magnitude of lightning voltages does not depend on line design & hence lighting phenomenon performance to improve with increasing insulation level (ie) with system voltage.

→ Switching overvoltages are proportional to operating voltage, at which emphasis changes from lightning to switching surge design, being important above 500 kV.

emphasis importance

→ In range of 300kV to 765 kV, both switching & lightning overvoltages have to be considered, while for ultra high voltages (>700kV) switching surges may be the chief condition for design considerations.

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1.2 Lightning :

→ Lightning phenomenon is a peak discharge in which charge accumulated in clouds discharges into neighbouring cloud (or) to ground

→ Electrode seperation (ie) cloud to cloud (or) cloud to ground is very large (ie) 10 km (or) more.

① Charge formation in the clouds :

→ Factors that contribute for charge accumulation in clouds are uncertain.

→ During thunder storms, positive & negative charges become seperated by heavy air currents with ice crystals in upper part and rain in lower parts of the cloud.

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→ This charge seperation depends on height of clouds, which range from 200 to 10000 m, with their charge centres probably at distance of about 300 to 2000 m.

⇒ Charge inside the cloud may be as high as 1 to 100 C.

→ clouds may have a potential as high as 10^7 to 10^8 V with field gradient ranging

gradient - slidin

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from 100 V/cm to as high as 10 kV/cm at initial discharge point.

→ Energies associated is 250 KWh.

→ It is believed that upper regions are usually positively charged in clouds, whereas lower region are negatively charged.

→ Maximum gradient reached at ground level due to charged cloud may be as high as 300 V/cm, while the fair weather gradients are about 1V/cm.

Probable field gradient near ground corresponding to probable charge distribution in cloud

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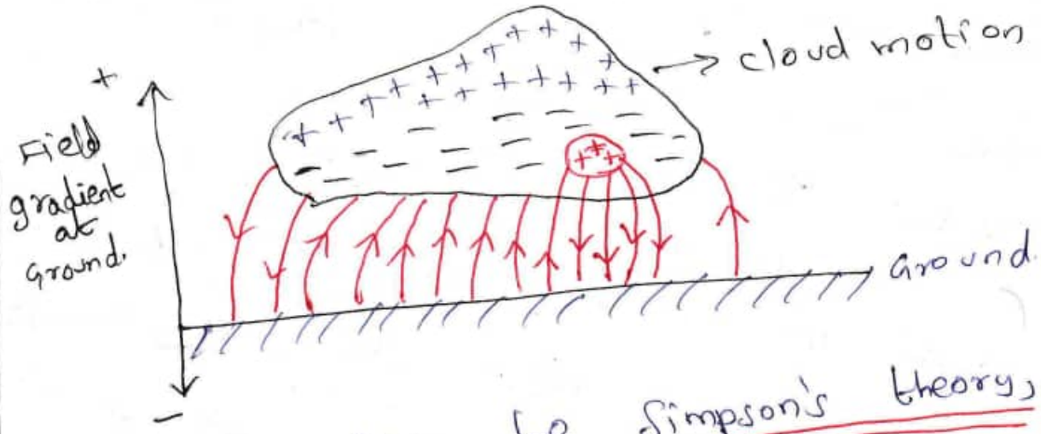

→ According to Simpson's theory, there are 3 essential regions for charge formation in clouds

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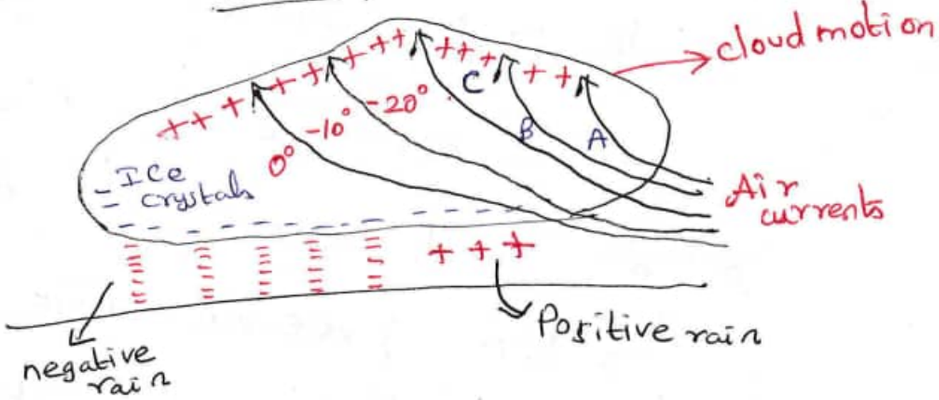
→ Below region A, air currents travel above 800 cm/s & no rain drops fall through.

Cloud model according to Simpson's theory



→ In region A, air velocity is high to break falling rain drops causing positive charge spray in cloud & negative charge in air

→ Spray is blown upwards, as velocity decrease positively charged water drops recombine with large drops & fall again.

→ Thus region A, eventually becomes positively charged, while region B above it, becomes negatively charged by air currents.

→ In upper regions, temperature is low and only ice crystals exist.

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→ Recently, Reynolds & Mason proposed modification, according to which thunder clouds are developed at heights 1 to 2 km above ground level & may extend upto 12 to 14 km above ground.

→ Temperature is 0°C at about 4 km & may reach −50°C at about 12 km.

→ they freeze below −40°C on which crystalline ice patterns develop & grow.

→ In cloud effective freezing temperature range is ground −33°C to −40°C.

→ Thunder cloud consists of supercooled water droplets moving upwards & large hail stones moving downwards. carry negative charge.

→ According to Mason, ice splinters should carry only positive charge upwards.

→ In an ice slab, lower portion which is warmer will have negative charge density & hence the upper portion which

crystalline — vapour

hailstones — ice balls

icesplinters — ice splinters

iceslab — wall of cloud

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is cooler will have net positive charge density.

→ According to Reynolds theory, which is based on experimental results, hail packets get negatively charged when impinged upon by warmer ice crystals.

hail packets - ice packets

impinged - ~~blocked~~ noticeable effect

(i) Rate of Charging of Thunder Clouds

→ Mason considered thunder clouds as a uniform mixture of positive & negative charges.

→ If λ is a factor depends on conductivity of medium, E be the electric field intensity, v be velocity of seperation of charges, ρ be the charge density in cloud, then,

$$\frac{dE}{dt} + \lambda = \rho v$$

Hence $$E = \frac{\rho v}{\lambda}\left[1 - \exp(-\lambda t)\right] \quad - (1)$$

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→ Let Q be seperated charge & Q_g be the generated charge, then

$$\rho = \frac{Q_g}{Ah} \quad - (2), \qquad E = \frac{Q_s}{A\varepsilon_0} \quad - (3).$$

where A → cloud area, h → height of charged

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region, ε_0 → permittivity

→ Sub (2) & (3) in (1),

$$\frac{Q_s}{A\varepsilon_0} = \frac{Q_g}{Ah}\frac{V}{\lambda}\left[1-\exp(-\lambda t)\right]$$

$$Q_g = \frac{Q_s h}{\varepsilon_0}\frac{\lambda}{V}\left[\frac{1}{1-\exp(-\lambda t)}\right]$$

Sub $\boxed{Q_s h = M}$ = electric moment of thunderstorm,

$$\therefore Q_g = \frac{M}{\varepsilon_0}\frac{\lambda}{V}\left[\frac{1}{1-\exp(-\lambda t)}\right]$$

(2) Mechanism of Lightning strokes:

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→ when electric field intensity at some point in charge concentrated cloud exceeds the breakdown value (≈ 10 kV/cm), an electric streamer with plasma starts towards ground with velocity of about $\frac{1}{10}$ times that of light, but may progress only about 50 m (or) so before it, comes to a halt emitting a bright flash of light.

→ After a short interval of about 100 μs, streamer again starts out repeating its performance.

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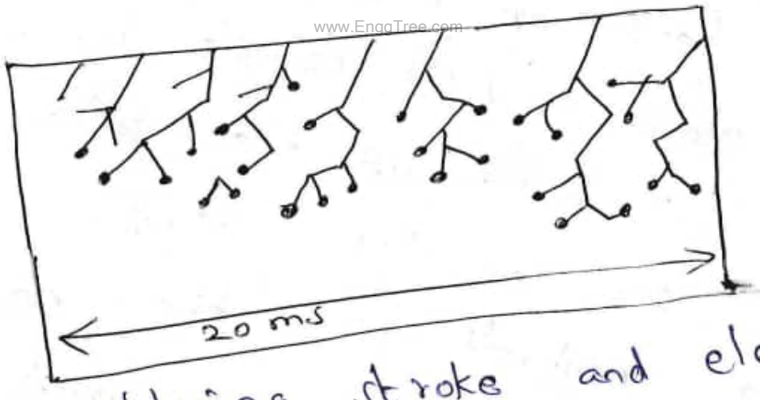
→ Total time for such stepped leader to reach ground may be 20 ms.

→ The path may be quite lustrous, depending on air conditions & electric field gradients.

→ Branches from initial leader may also be formed.

→ Since the progress of this leader stroke is by a series of jumps, it is referred as stepped leader.

Propagation of a stepped leader stroke

→ lightning stroke and electrical discharge due to lightning are explained based on 'Streamer' (or) 'kanel' theory for spark discharges in long gaps with non-uniform electric fields.

→ lightning consists of a few seperate

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culminates height of climatic point

stroke - charge reverses

canal - ways

discharges from leader discharge & culminates in return stroke (or) main discharges.

→ Velocity of leader stroke of first discharge may be 1.5×10^7 cm/s, of succeeding leader strokes about 1.5×10^8 cm/s & of return strokes may be 1.5×10^9 cm/s to 1.5×10^{10} cm/s

→ After leader touches the ground, return stroke follows..

→ As leader moves towards the ground, positive charge is directly accumulated under head of the stroke (or) canal. and electric field intensity is sufficiently large to build up the path.

→ Hence positive charge returns to ground neutralizing the negative charge and hence heavy current flows through the path.

→ Velocity of return (or) main stroke ranges from 0.05 to 0.5 time the velocity of light & current will be of order of 10,00A to 2,50,000A.

→ The return strokes vanish before

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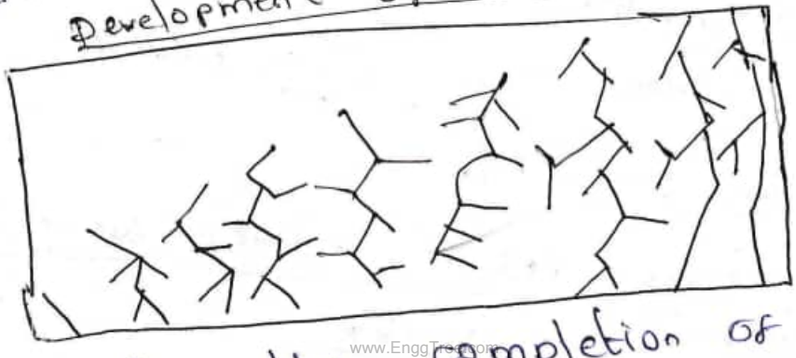
they reach the cloud.

→ duration of main (or) return stroke is about 100 μs (or) more

→ diameter of return strokes is about 1 to 2 cm.

→ Return strokes also may develop branches but the charges are neutralised in successive branches.

Development of main (or) return stroke



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→ After the completion of return stroke, smaller current of 100 A to 1000 A may flow persists approximately for 20 ms.

→ By these currents, initial breakdown are considerably reduced & discharges.

→ therefore, additional reservoirs of charge become available due to penetration of cloud mass known as preferred paths and lead to repeated strokes.

→ Leader strokes of the repeated strokes progress with much less velocity

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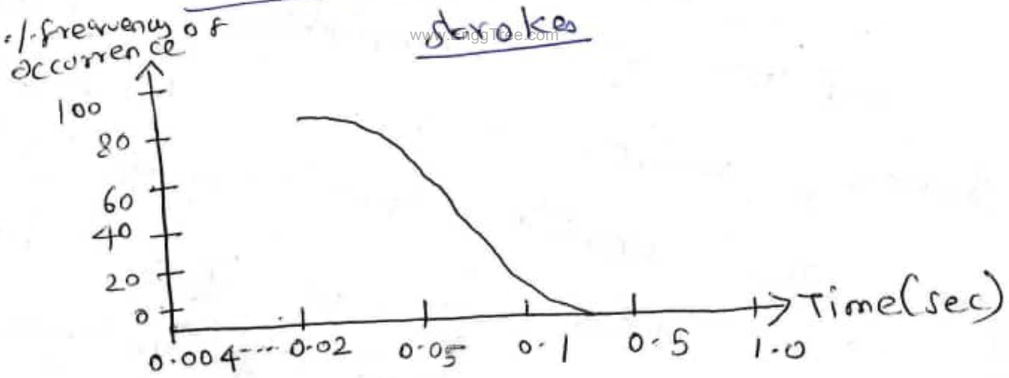
($\approx$ 1% of that of light) & donot branch. This stroke is called continuous leader and return stroke for this leader follows with much less current.

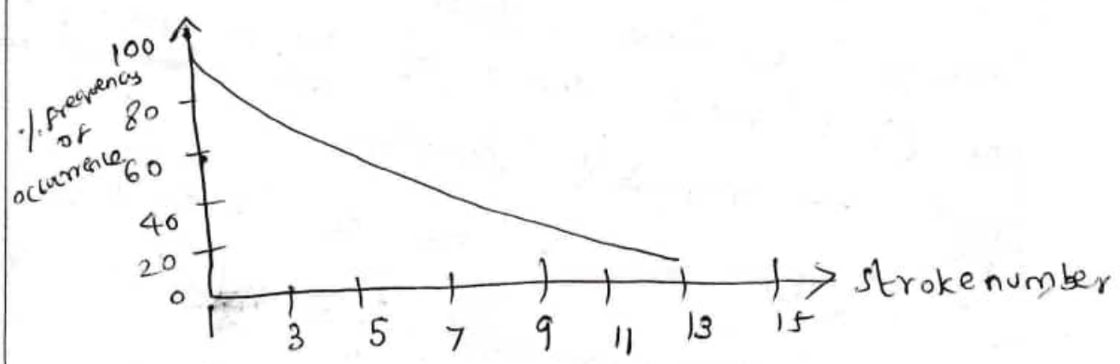
→ Interval between repeated strokes may be from 0.6 ms to 500 ms with an average of 30 ms

→ current from ground by main return stroke may have 2,50,000 A & rate of rise as 100 KA/μs.

Time interval between succesive strokes



Number of strokes in lightning discharges



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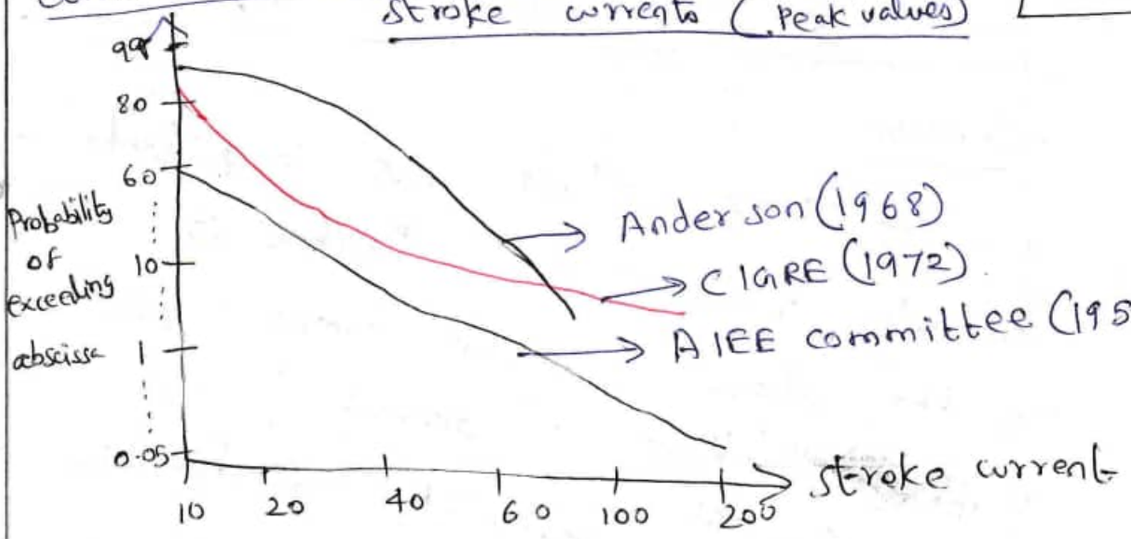
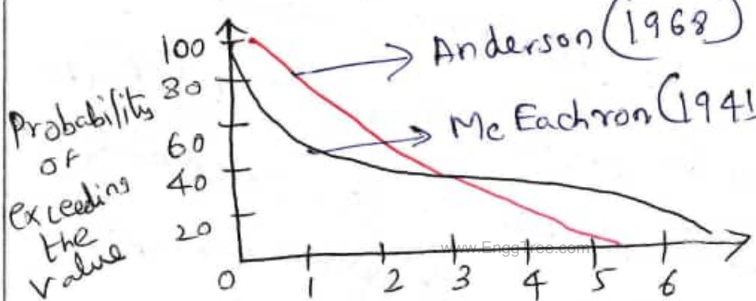
Cumulative distributions of lightning stroke currents (Peak values)



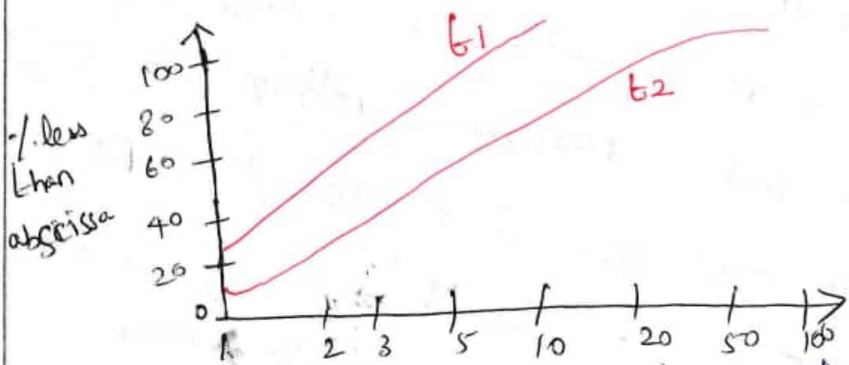
AIEE – American Institute of Electrical Engineers

CIGRE – International Council on Large Electric Systems

Time to Peak of lightning stroke currents

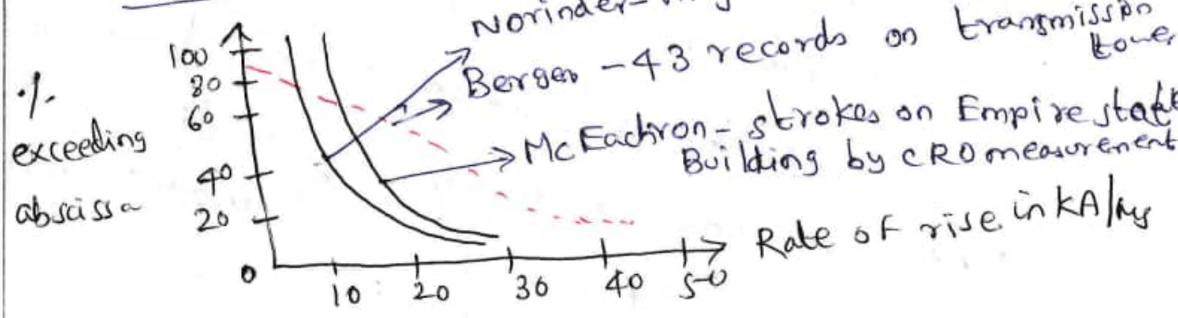


Wavefront & wave tail times of lightning strokes



abscissa – point in graph

Rate of rise of current of lightning strokes



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(3) Parameters and characteristics of the Lightning Strokes:

→ These include the amplitude of the currents, rate of rise, probability distribution of the above & the wave shapes of the lightning voltages and currents.

→ Other important characteristics are time to peak value and its rate of rise.

→ 50% of lightning stroke currents have rate of rise greater than 7-5 kA/μs & for 10% of stroke, it exceeded 25 kA/μs.

→ Duration of stroke currents above half value is more than 30 μs.

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→ Measurement of surge voltages indicated that Maximum voltage is 5000 kV, but on average it is less than 1000 kV on line.

→ Time to front is 2 to 10 μs & tail times is from 20 to 100 μs.

→ Rate of rise of voltage is about 1 MV/μs.

→ Lightning stroke on transmission line are of 2 groups → direct stroke, induced stroke

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→ when a thunder cloud directly discharges onto a transmission line tower (or) line wires, it is called direct stroke. This is the most severe form of the stroke.

→ When the thunderstorm generates negative charge at its ground, earth objects develop induced positive charges. The transmission line and ground will act as a huge capacitor charged with positive charge & hence overvoltage occur which result in a stroke called induced lightning stroke.

→ when a direct lightning stroke occurs on tower, tower carry high impulse currents. If there is tower footing resistance, potential rises to a large value and so flashover takes place called back flashover.

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(4) Mathematical Model for Lightning:

→ During charge formation process, cloud may be considered to be non conductor. So various potentials may be assumed.

→ If charging process is continued, it is probable that gradient exceeds

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breakdown strength. Hence, local breakdown takes place within the cloud.

→ when streamer discharge occurs to ground by first leader stroke, followed by main strokes, lightning stroke may be thought to be a current source I_0 with source impedance Z_0 discharging to earth.

→ $V = IZ$

$= I_0 \frac{ZZ_0}{Z+Z_0}$

$= I_0 \frac{Z}{\frac{Z+Z_0}{Z_0}}$

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$V = I_0 \frac{Z}{\frac{Z}{Z_0}+\frac{Z_0}{Z_0}}$

$V = I_0 \frac{Z}{\frac{Z}{Z_0}+1}$

→ Z_0 is estimated to about 1000 Ω to 3000Ω.

→ $\frac{Z}{Z_0} < 0.1$ & hence can be neglected.

→ $V = I_0 Z$ where I_0 → lightning stroke current, Z → line surge impedance

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→ If lightning stroke current of 10,000 A strikes a line of 400 Ω surge impedance, over voltage of 4000 kV occurs.

→ This heavy over voltage cause immediate flashover.

→ The incidence of lightning stroke on transmission lines & substations is related to degree of thunderstorm activity.

→ It is based on level of Thunderstorm Days (TD) known as Isokeraunic Level defined as number of days in a year when thunder is heard (or) recorded in a particular location.

→ If measure of ground flashover density (N_g) is obtained, then number of ground flashovers can be computed from TD level.

→ From past records,

$N_g = (0.1 \text{ to } 0.2)\, TD$ / strokes / km^2 - year

→ $N_g = K_1 (TD)^b$

where $K_1 = 0.04$ & $b = 1.25$ (Anderson)

(or) $K_1 = 0.054$ & $b = 1.1$ (Mac Gorman)

→ From experimental data,

Number of lightning strokes (or) flashes is given by,

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$$N = N_g \left(2.8\, h^{0.6} + \frac{b}{10}\right)$$

where h → height of tower (m)

b → width of base of tower

(a) Overvoltages due to Indirect strokes:

→ Direct lightning stroke is one that hits either a

(i) shielding wire
(ii) tower (or)
(iii) Phase conductor of a overhead power line

→ An indirect stroke is defined as one that strikes the ground, a nearby object around power line (or) an earthed structure longer & higher than the power line and cause induced voltage.

→ Voltage induced by an indirect stroke can be due to following reasons:

① Charged cloud above power line induces bound charge when cloud discharges. gives rise to travelling waves

② Charges released by stepped leader strokes gives rise to above effect

③ Residual charge in return stroke induces

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overvoltages (electrostatic effect)

④ Rate of change of current in return stroke induces overvoltage due to electromagnetic effects.

$$V_i = \left[\nabla\varphi + \frac{\delta A}{\delta t}\right] h$$

where V_i → induced voltage

φ → electrostatic potential

A → electromagnetic vector

h → height of conductor above ground.

(b) Model of Lightning stroke Effect and Computation of Induced voltages:

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→ A model based on lightning return stroke is given which assumes that the lightning channel is straight, vertical to and normal ground plane

→ Return stroke current $I(z,t)$ is assumed as function of vertical coordinate z & time t,

$$i(z,t) = i\left(t - z/v\right) \quad , \; z < vt$$

$$i(z,t) = 0 \quad , \; z > vt \;,$$

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where v → return stroke velocity

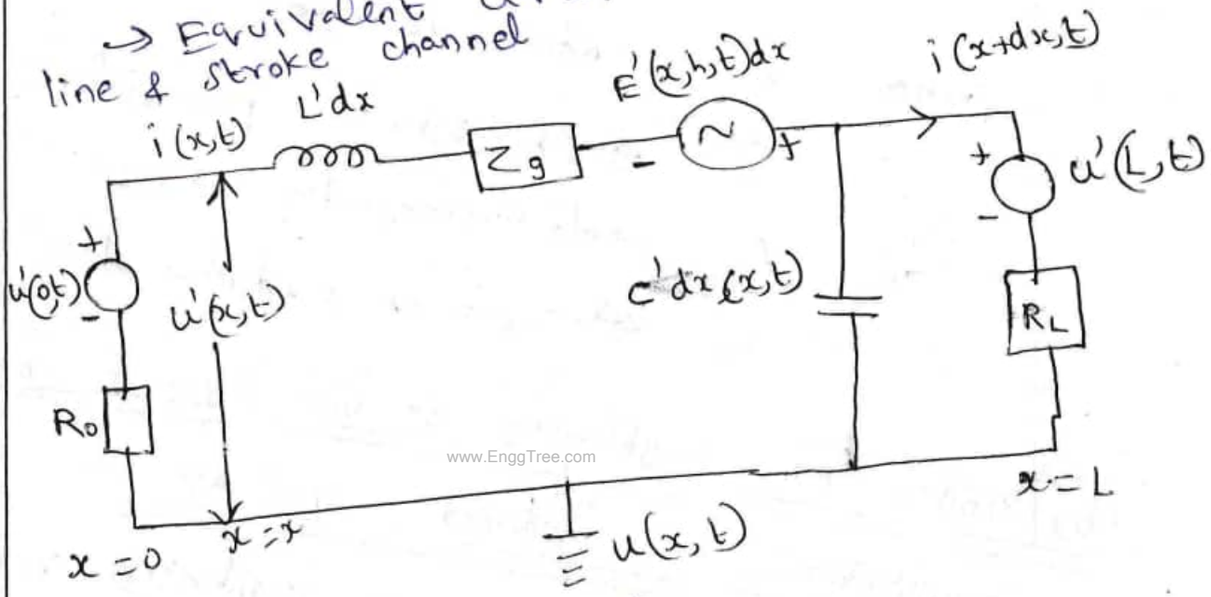
→ Factors that influence the lightning induced voltages are

(i) ground conductivity

(ii) leader stroke current

(iii) corona.

→ Equivalent circuit for coupling between line & stroke channel



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where L → Length of Line

R_0, R_L → Terminating resistance

L', C' → inductance & capacitance of line per unit length

$u'(x,t)$ → voltage developed at any distance x

$i'(x,t)$ → current through line at any distance x

$E'(x,h,t)$ → Electric field in x direction at height h

Z_g → equivalent ground impedance

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1-3 Switching surges and temporary over voltages:

(1) Introduction:

→ In insulation co-ordination, the protective level of surge diverter is proportional to maximum voltage, insulation level and cost of equipment depends on magnitude of over voltages (400 kv & above)

→ In EHV range, it is the switching surge & other types of overvoltages that determine insulation level of lines and other equipment & they also determine dimensions & costs

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(2) Origin of switching surges:

→ The making and breaking of electric circuits with switchgear may result in abnormal overvoltages having large inductances & capacitances.

→ Overvoltage may go as high as '6' times normal power frequency voltage.

→ In circuit breaking operation, switching surges with a high rate of rise of voltage may cause repeated

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restriking of arc between contacts of a circuit breaker, thereby causing destruction of circuit breaker contacts.

→ switching surges may include high natural frequencies, damped normal frequency voltage component (or) restriking and recovery voltage with successive reflected waves from terminations.

(3) Characteristics of switching surges:

→ waveshapes of switching surges origin from any of the following sources.

(i) Deenergizing of transmission lines, cables etc
(ii) Disconnection of unloaded transformers, reactors etc
(iii) Energization (or) reclosing of lines & reactive loads
(iv) Sudden switching off of loads
(v) Short circuits & fault clearances
(vi) Resonance phenomenon like ferroresonance, arcing grounds etc

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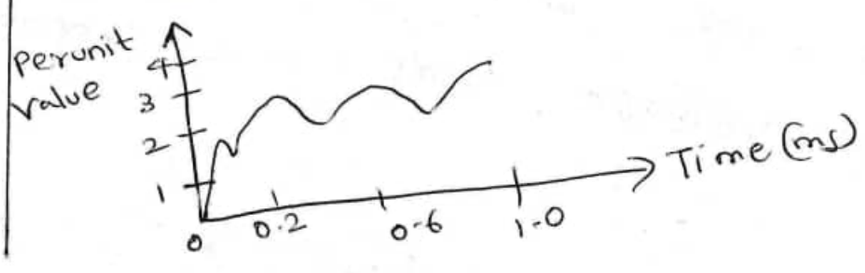
Typical waveshapes of switching surge voltages

a) Recovery voltage after fault clearing



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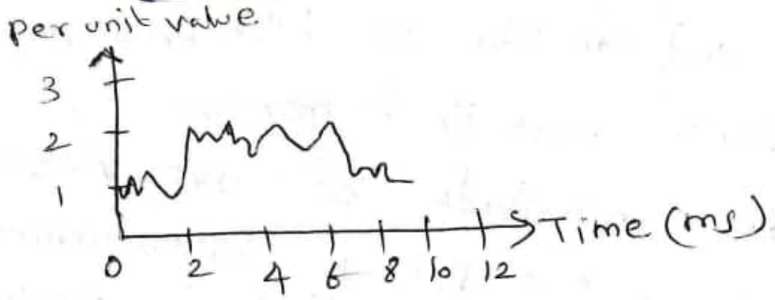
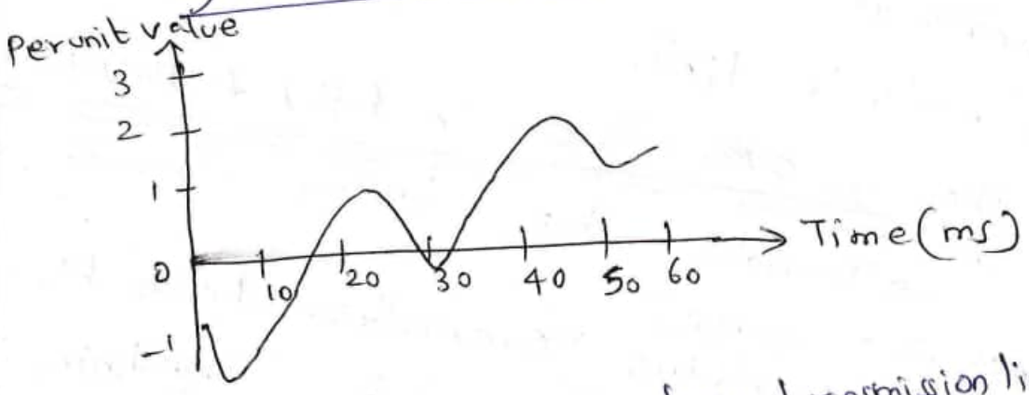
b) Fault initiation



c) Overvoltage at line end after fault clearing



d) Energization of long transmission line

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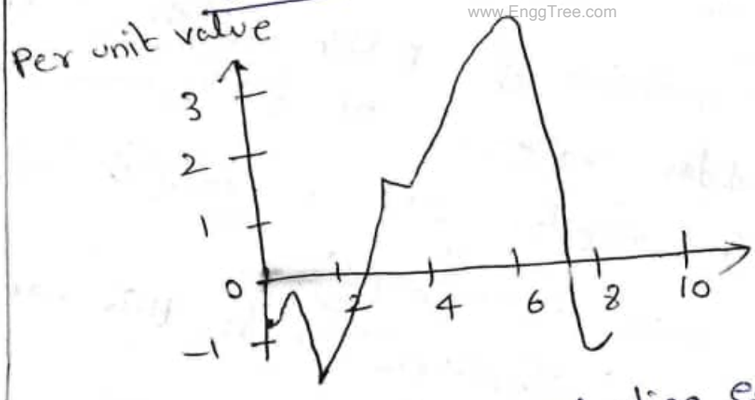
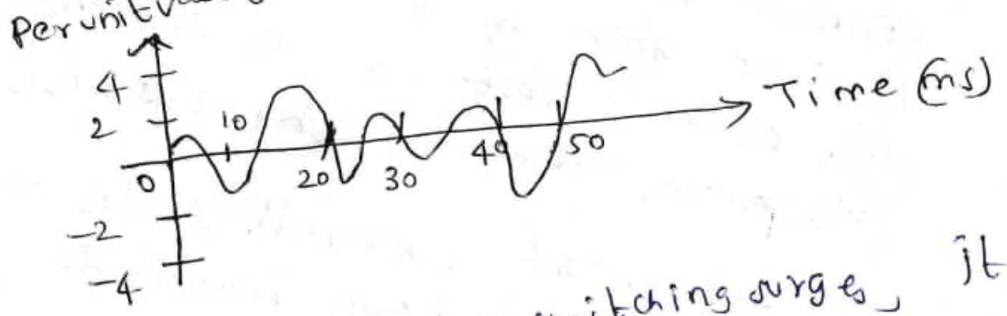


e) Overvoltage at line end during (d)



→ From figure of switching surges, it is

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clear that overvoltages are irregular (oscillatory or unipolar) and can be of high frequency (or) power frequency with its harmonics.

→ Relative magnitudes of overvoltages may be about 2-4 pu in transformer energizing and 1.4 to 2 pu in switching transmission line

a) Switching overvoltages in EHV & UHV systems:

→ Insulation has lowest strength for switching surges.

→ switching overvoltages have high magnitudes as compared to lightning overvoltages for UHV system.

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→ Overvoltage in EHV systems when there is a sudden release of internal energy stored either in elederostatic form (in 'C') (or) in electromagnetic form (in 'L')

→ Different situation under this happens

(i) interruption of low Inductive current
(ii) interruption of low capacitive currents
(iii) ferro resonance conditions.
(iv) energisation of long EHV (or) UHV lines

→ Transient overvoltages is of order 1 to 3.3 pu & have magnitude 1200kV to

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2000 kV.

→ Duration of these overvoltages varies from 1 to 10 ms.

→ Situations that rise to switching overvoltages of 0-5 to 5ms & low magnitude of 2 to 2-5 pu are

a) Single pole closing of circuit breaker
b) interruption of fault current when L-G (or) L-L fault is cleared.
c) resistance switching in circuit breaker
d) switching line by transformer
e) series capacitor compensated lines
f) sparking of surge diverter.

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→ overvoltage are studied from
a) mathematical modeling using computers
b) scale modeling using transient analysers
c) by conducting field tests

→ Main factors that are investigated from above studies are
a) line parameters effect on transients
b) damping factors
c) effect of circuit breakers
d) lightning arrester sparkover characteristics

→ Measures taken to control (or) reduce

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over voltages are

(i) energisation of lines by preinsertion of resistors
(ii) phase controlled closing (or) circuit breaker with proper sensors
(iii) drain of charges before reclosing the line
(iv) limiting overvoltages by surge diverters

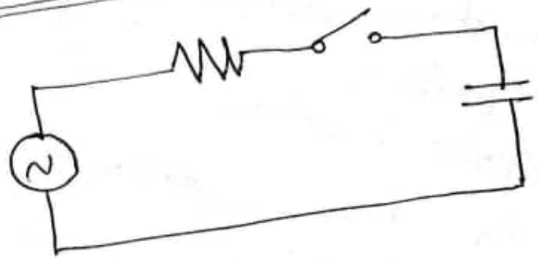
b) Overvoltage due to switching operations in Gas-Insulated Sub-stations =

→ Nowadays gas insulated substations & systems in voltage ranges from 33 kv to 400 kv due to land limitations in urban.

→ very fast transient voltages are generated during (i) closing ground switch
(ii) fault clearing
(iii) opening (or) closing disconnector switch.

Switching behaviour & pattern of voltages during disconnector switching

a) Equivalent circuit



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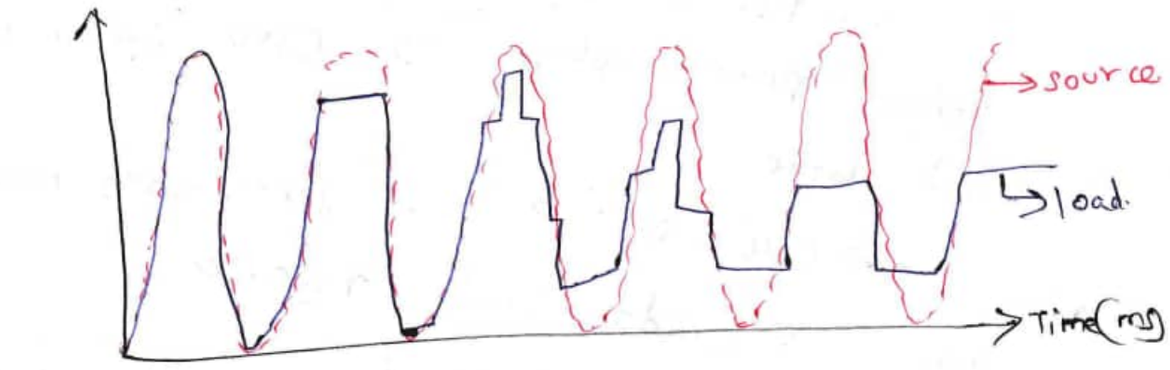
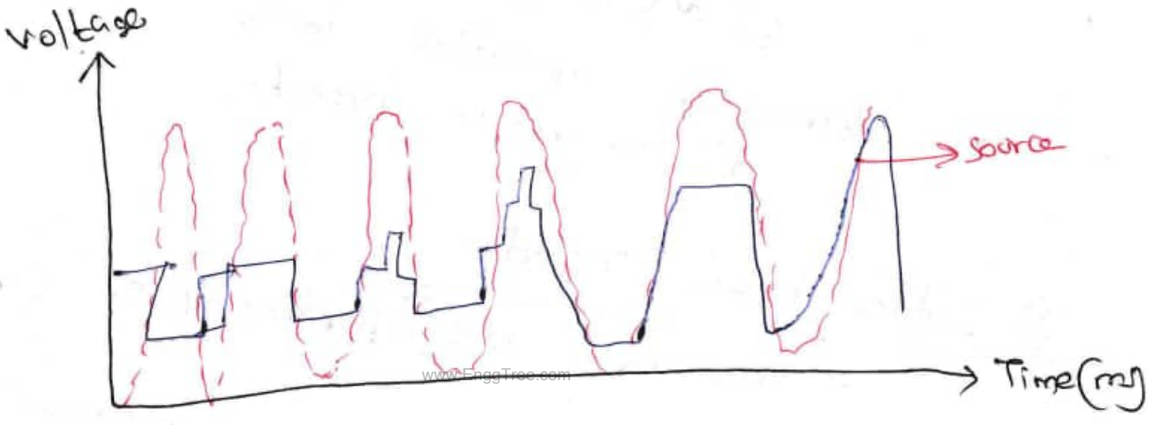
a) opening operation



b) closing operation

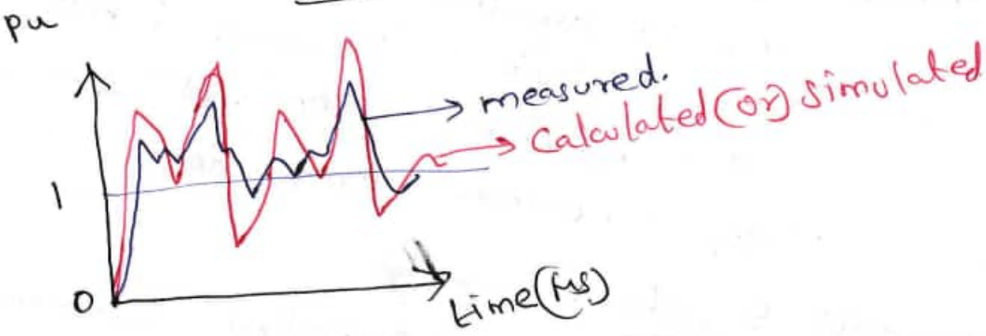


→ Frequency of pulse $f = \frac{1}{4T} \approx \frac{75}{d}$ (MHz)

where T → transit time (μs)

d → duct length (m)

Transient voltage of overvoltage in GIS at closing a switch



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(4) Power frequency overvoltages in power systems

→ Power frequency overvoltages occur in large power system in EHV system of 400kV and above

→ Causes of power frequency overvoltages are
a) Sudden load rejection
b) Ferranti effect
c) disconnect of inductive loads (or) connection of capacitive loads
d) Saturation effects.

a) Sudden Load rejection:

→ It causes the speeding up of generator prime movers

→ speed governor & automatic voltage regulators will restore to normal conditions

→ approximate voltage rise

$$V = \frac{f}{f_0} E' \left(\left(1 - \frac{f}{f_0} \right) \frac{x_s}{x_c} \right)$$

where x_s → reactance of generator
x_c → capacitive reactance
E' → voltage generated before overspeeding
f → instantaneous increased frequency
f_0 → normal frequency

b) Ferranti Effect:

→ Long uncompensated transmission

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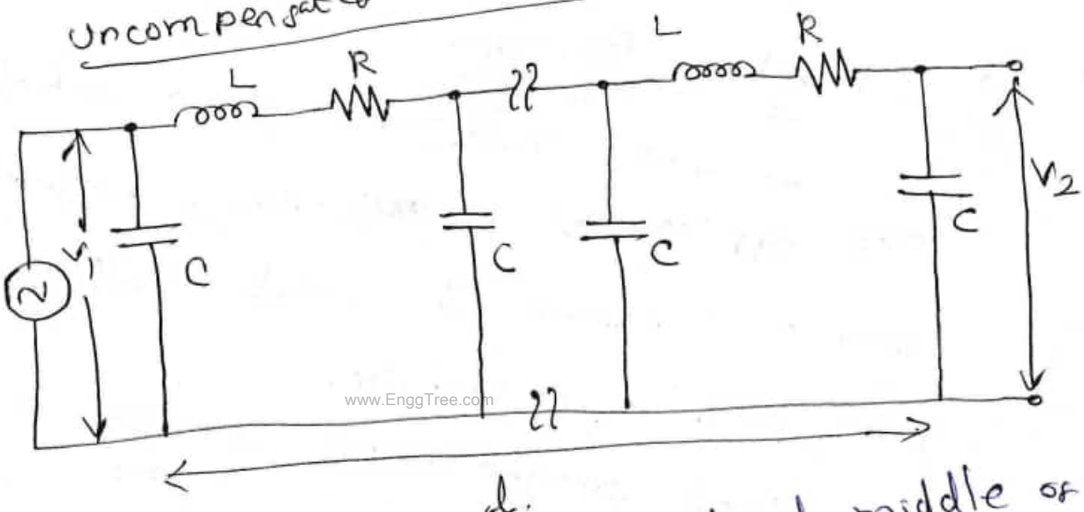
lines exhibit voltage rise at receiving end (V_2)

$$V_2 = \frac{V_1}{\cos \beta l}$$

where
V_1 → sending end voltage
β → phase constant
l → length of line

uncompensated long transmission line



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→ consider line capacitance is at middle of line, $I_C = j\omega C V_1 = \frac{V_1}{X_C}$

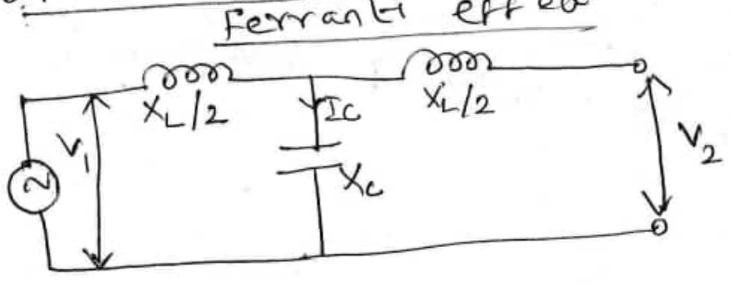
where ω → angular frequency

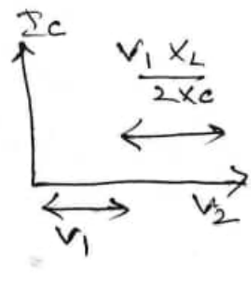
$$V_2 \approx V_1 \left[1 - \frac{X_L}{2X_C}\right]$$

where X_L → line inductive reactance
X_C → line capacitive reactance

Ferranti - voltage rise at receiving end than sending end

Open circuited uncompensated line showing Ferranti effect





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(c) Ground faults & their effects

→ With effectively ground systems

(ie) with $\frac{X_0}{X_1} \leq 3.0$ & $\frac{R_0}{X_1} \leq 1.0$, rise in voltage does not exceed 1.4 PU.

where R_0, X_0 → zero sequence R & X

X_1 → positive sequence X.

(d) Saturation Effects:

→ when voltages above rated value are applied to transformers, magnetizing currents increase to about full load current for 50% over voltage.

→ These magnetizing current are not sinusoidal having harmonics & delta connected windings with impedance suppress them

→ But shunt capacitors & line capacitors can form resonant circuits & cause 3rd harmonic over voltages.

→ For higher harmonics, a series resonance between transformer inductance & line capacitance can occur which produce even high voltage

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(5) Control of overvoltages due to switching:

→ Overvoltages due to switching and power frequency may be controlled by

a) Insertion of Resistors
b) Phase Controlled switching
c) Drainage of Trapped charge
d) Shunt reactors
e) Surge diverters

a) Insertion of Resistors:

→ By inserting resistance R in series with contacts when switching on with circuit breaker
→ this will reduce transients
→ voltage step applied is first reduced to $\frac{Z_0}{R+Z_0}$ pu where Z_0 → surge impedance
→ It is refleted from far end & again reflected back from near end with reflection factor $\frac{R-Z_0}{R+Z_0}$ pu.
→ If $R = Z_0$, there is no reflection from far end.
→ If resistor is kept for large than 5ms, it is shown from succesive reflections & transmissions, that over voltage may reach as high as 1.2 pu for lengths of 500 km.

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→ preinsertion of resistor is done to limit over voltage to less than 2 to 2.5 pu

→ Normal time of insertion is 6 to 10ms

b) Phase Controlled Switching:

→ over voltage can be avoided by controlling exact instances of closing of 3 phases seperately. by help of complicated controlling equipment which is not adopted.

c) Drainage of Trapped Charge:

→ when lines are suddenly switching off, electric charge may left on capacitors & line conductors and this charge will leak through insulator path

→ conventional potential transformers may also help the drainage of charge

→ Effective ways to reduce trapped charges before reclosing is by temporary insertion of resistors to ground (or) inseries with shunt reactors & removing before closure of switches

(d) Shunt Reactors:

→ normally, all EHV lines will have shunt reactors to limit voltage rise due to

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Ferranti effect.

→ This help in reducing surges due to sudden energizing.

→ shunt reactors cannot drain trapped charge but will give rise to oscillations with the capacitance of the system.

→ Since compensation given by reactors is less than 100·/. , frequency of oscillation will less than power frequency & overvoltages may be high as 1.2 pu.

→ Resistor in series with reactors will suppress oscillations & limit overvoltage

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e) Surge diverters:

→ Switching & Power Frequency overvoltages are limited by surge diverters

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1.4 Reflection and Refraction of Travelling waves

Bewley lattice diagram:

(i) Reflection and Transmission of waves at Transition Points:

→ whenever there is an abrupt change in parameters of transmission line, such as open circuit (or) termination, travelling wave undergoes a transition, part of wave is reflected (or) sent back, and only a portion is transmitted forward.

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→ At Transition point, voltage (or) current wave may attain a value which can vary from zero to 2 times its initial value.

→ The incoming wave is called incident wave and other waves are called the

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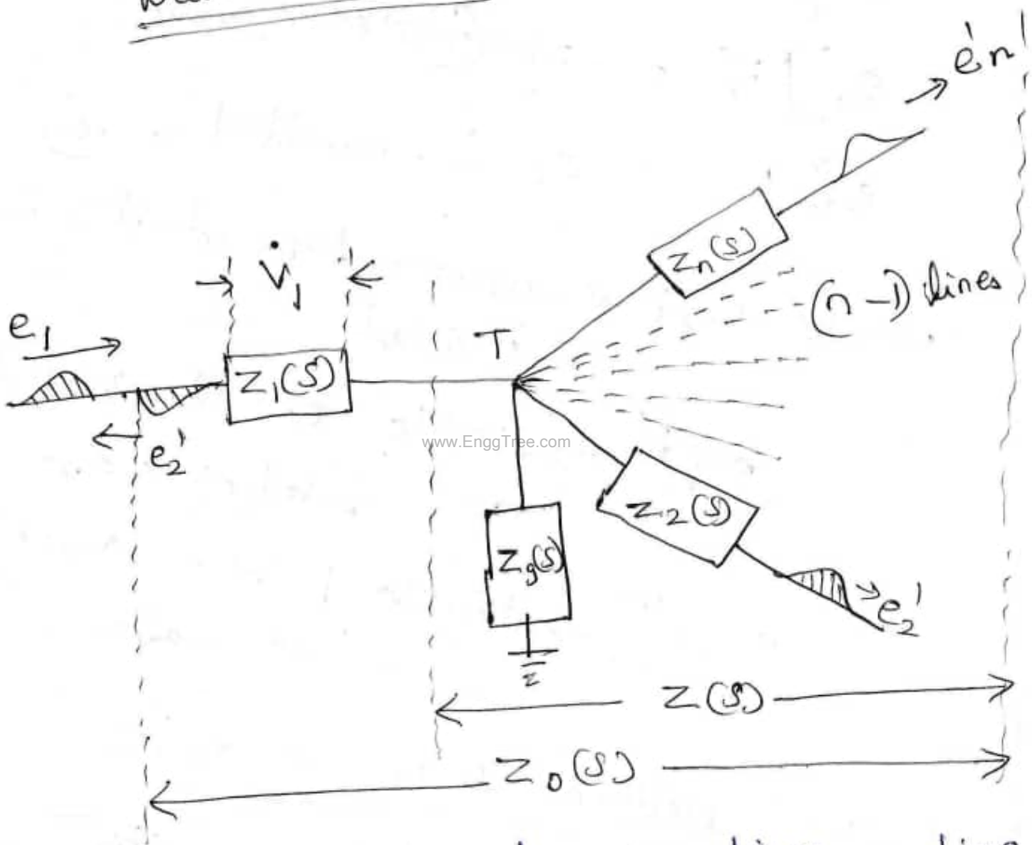
reflected & transmitted waves at transition point.

→ Such waves are formed according to Kirchhoff's laws & they satisfy the line differential equations

Transition point (T) & Propagation of wave at (T)



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→ Let transformed equations of line impedances be $Z_1(s)$, $Z_2(s)$ ... $Z_n(s)$ & impedances to ground $Z_g(s)$ be the total impedance as seen from transition point $Z(s)$ & looking beyond transition point $Z_0(s)$

→ Taking transition point (T) as reference,

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distance along the line away from transition point of line is taken as negative, so that incoming wave towards transition point is counted as travelling in positive direction

→ Taking lines as lossless lines, relations are

$e_1 / i_1 = Z_1$ (incident wave)

$e_1' / i_1' = -Z_1$ (reflected wave)

$e_k'' / i_k'' = Z_k$ (transmitted wave)

where e, i ⇒ unprimed quantities for incident waves

e', i' ⇒ single primed quantities for reflected waves

e'', i'' ⇒ double primed quantities for transmitted waves.

(ii) Successive Reflections & Lattice Diagrams:

→ In many problems involving short cable lengths (or) lines tapped at intervals, travelling waves encounter successive reflections at transition point.

→ It is exceedingly difficult to calculate multiplicity of these reflections, and

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Bewley has given the lattice (or) time-space diagrams from which the motion of reflected & transmitted waves & their positions at every instant can be obtained.

(iii) Principles observed in lattice diagrams:

a) All waves travel down hill (ie) into positive time

b) The position of the wave at any instant is given by means of time scale at the left of lattice diagram

c) Total potential at any instant of time is the superposition of all the waves which arrive at that point until that instant of time, displaced in position from each other by time intervals equal to the time differences of their arrival

d) Attenuation is included so that the amount by which a wave is reduced is taken care of.

e) Previous history of the wave, if desired can be easily traced. If the computation is to be carried out at a point, where operations cannot be directly placed on

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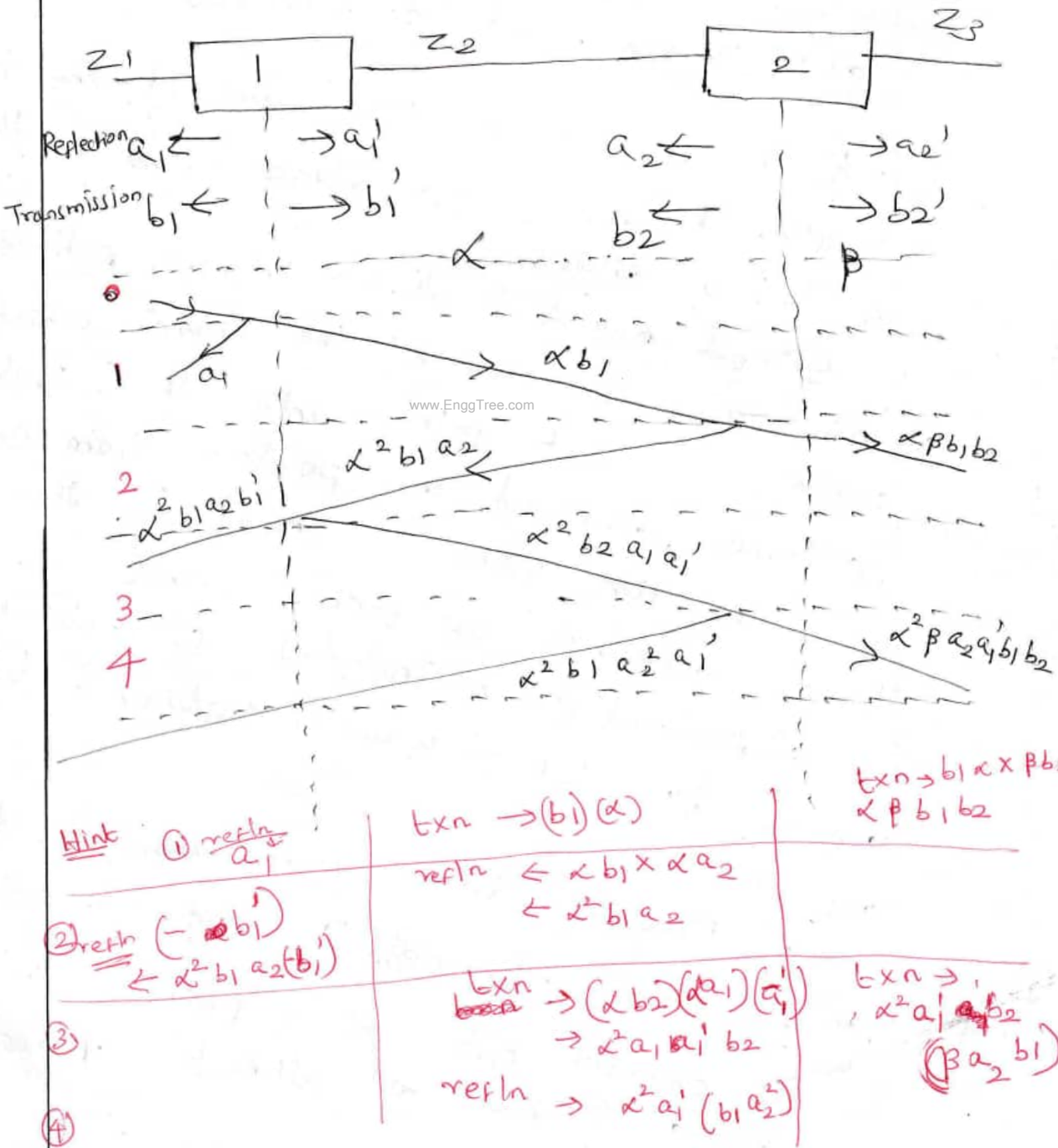
lattice diagram, the arms can be numbered & the quantity can be tabulated & computed.

→ The above comprehensive description can be understood by considering example

Reflection lattice of a travelling wave



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Hint	txn → (b1)(α)	txn → b1 α × β b2 = α β b1 b2
① refln a_1	refln ← α b1 × α a2 ← α² b1 a2	
② refln (− b1') ← α² b1 a2 (b1')		
③	txn → (α b2)(α a1)(a1') → α² a1 a1' b2	txn → α² a1' b2 (β a2 b1)
④	refln → α² a1' (b1 a2²)	

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→ Here there are 2 junctions 1 & 2

→ The travel times for waves are different through Z_1, Z_2 & Z_3 (surge impedances) which are connected on either side of junctions.

→ Let α & β be the attenuation coefficients for Z_2 & Z_3

→ Let a_1 & a_1' be reflection coefficients for waves approaching from left & right at junction 1 & a_2 & a_2' be the corresponding reflection coefficients at junction 2

→ Let b_1 & b_1' be transmission coefficients for waves approaching from left & right at juction 1 & corresponding coefficients be b_2 & b_2' at junction 2. for transmission

→ To construct lattice diagram, position '0' is taken when wave coming from Z_1 reaches junction 1

→ Junction 2 is taken to scale at time interval equal to travel time through the Z_2 between junctions 1 & 2

→ Diagram is drawn by choosing a suitable time scale.

→ Process of calculation is indicated on

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slope of lines in diagram upto required time interval.

Pblm A long transmission line is energised by unit step voltage 1.0 V at sending end & is open circuited at receiving end. Construct Bewley lattice diagram & obtain value of voltage at receiving end after a long time. Take the attenuation factor $\alpha = 0.8$

Soln: Let time of travel of wave = 1 unit

At receiving end,

Reflection coefficient $\gamma = (Z_0 - Z)/(Z_0 + Z) = 1.0 = a$

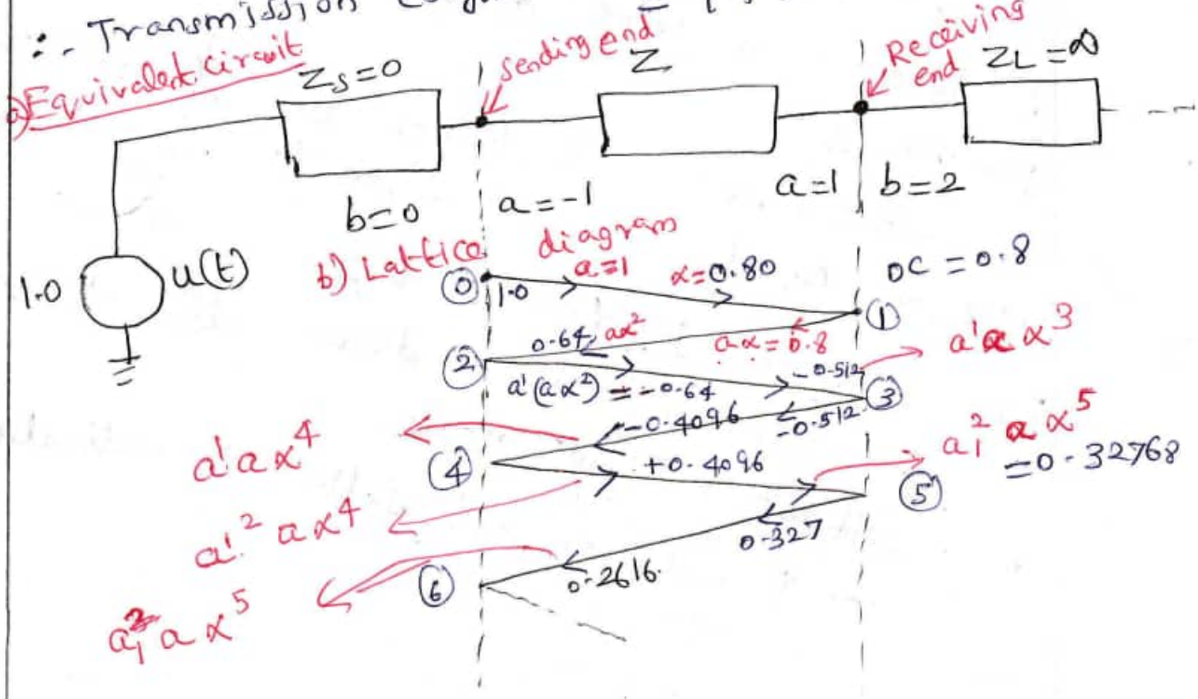
∴ Transmission coefficient $= 1 + \gamma = 2.0 = b$

At sending end,

Reflection coefficient $\gamma = (0 - Z)/(0 + Z) = -1.0 = a$

∴ Transmission coefficient $= 1 + \gamma = +1 + (-1) = 0 = b$

a) Equivalent circuit



b) Lattice diagram

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→ Since source impedance $Z_s = 0$,

Z_2 (open receiving end impedance) $= \infty$

From lattice diagram, wave magnitudes are shown below

At receiving end	At sending end	Time unit
1	0	0
1	1	α
$1+\alpha^2$	2	2α
1	3	$2\alpha - \alpha^3$
$1-\alpha^4$	4	$2\alpha - 2\alpha^3$
1	5	$2\alpha - 2\alpha^3 + \alpha^5$
$1+\alpha^6$	6	$2\alpha - 2\alpha^3 + 2\alpha^5$

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→ Voltage at receiving end after 4n units of time is

$$V = 2\left(\alpha - \alpha^3 + \alpha^5 - + \cdots\right) u(t)$$

$$= 2\alpha \left[\frac{1 - \alpha^{4(n+1)}}{1+\alpha^2}\right] u(t)$$

→ Voltage at receiving end after a long time (ie) $t = \infty$ is,

$$V_u(t) = \left[2\alpha/(1+\alpha^2)\right] u(t)$$

Sub $\alpha = 0.8$,

$$V_\infty = \frac{2(0.8)}{1+(0.8)^2} u(t) = 0.9756\, u(t)$$

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1-6 Protection against Overvoltages:

→ Protection of transmission lines against natural (or) lightning overvoltages are done by
① suitable line design
② Guard & ground wires
③ surge diverters.

→ Switching surges & power frequency over voltages are considered for greater insulation levels & with proper insulation coordination.

→ Overvoltages due to lightning strokes can be minimized by
a) sheilding by ground wires above phase wires
b) Using ground rods & counter-poise wires
c) Protective devices like expulsion gaps, Protector tubes, Rod gaps and Surge Arresters.

a) Protection using shielded wires (or) Ground wires:

→ Ground wire is a conductor run parallel to main conductor of transmission line on same tower & earthed at every equally & regularly spaced towers. It is run above main conductor of line.

→ Ground wire shields the transmission line conductor from induced charges, from

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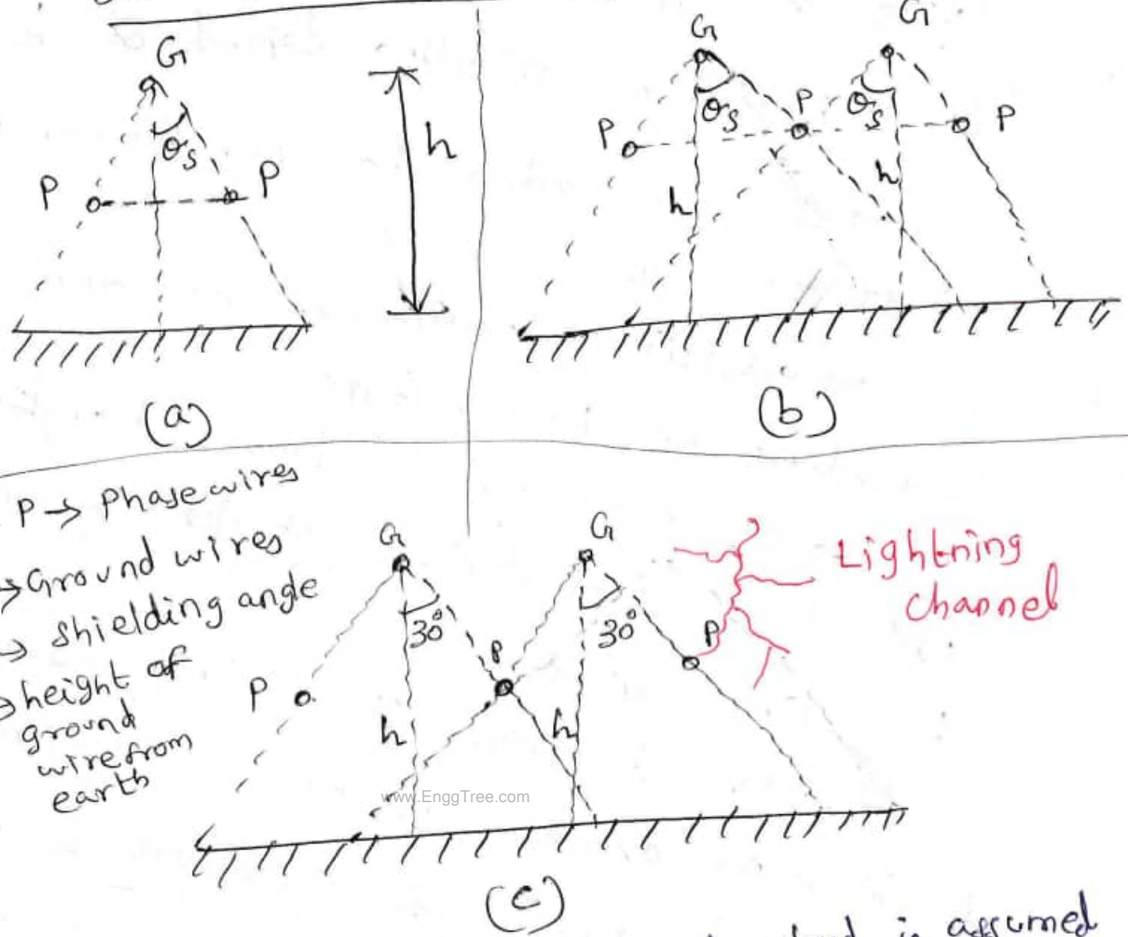
clouds as well as from lightning discharge.

Shielding of overhead lines by ground wires



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⇒ If a positively charged cloud is assumed to be above line, it induces negative charge below it of transmission line.

→ with ground wire, both ground wire & line conductor get induced charge.

→ Ground wire is earthed at regular intervals & so induced charge is drained to earth; only the potential difference between ground & cloud & between ground & transmission line will be inverse ratio of respective capacitances.

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→ As ground wire is near to line wire, induced charge is much less & hence potential rise is small.

→ Effective shielding depends on h & $\theta_s (\approx 30^\circ)$

→ θ_s was adequate for tower height of 30 m (or) less.

→ shielding wires may be of one or more depending on tower type.

→ for EHV lines, tower heights are upto 50 m & lightning strokes occur directly to line wires.

→ Present trend in fixing tower heights & shielding angle is by considering flashover rates, & failure probabilities.

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b) Protection using Ground rods and Counter-Poise wires:

→ when line is shielded, lightning strikes either tower (or) ground wire.

→ path for charge drainage & lightning current is
(a) through tower frame to ground
(b) through ground line in opposite directions from striking point.

→ Thus ground wire reduces

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Potential, to which tower top rises, as current path is in 3 directions.

→ instantaneous potential $V_T = \frac{I_0 Z_T}{\left(1 + \frac{Z_T}{Z_S}\right)}$

where Z_T → Surge impedance of tower
Z_S → Surge impedance of ground wire.

→ If Z_T, which is effective tower footing resistance reduced, surge voltage is also reduced. This is done by providing ground rods & counter poise wires at tower legs.

→ Ground rods are of 15 mm diameter & 2.5 to 3 m long.

→ In hard soils, rods are long of 50 m.

→ It is made of galvanised iron (or) copper-bearing steel.

galvanised

→ Spacing, number & depth of rods depend on tower footing resistance.

→ With 10 rods of 4m long & 5m space, the effective resistance is reduced to low.

→ Above effect is achieved by using counter-poise wires which are buried at a depth of 0.5 to 1.0 m, parallel to

counter-poise

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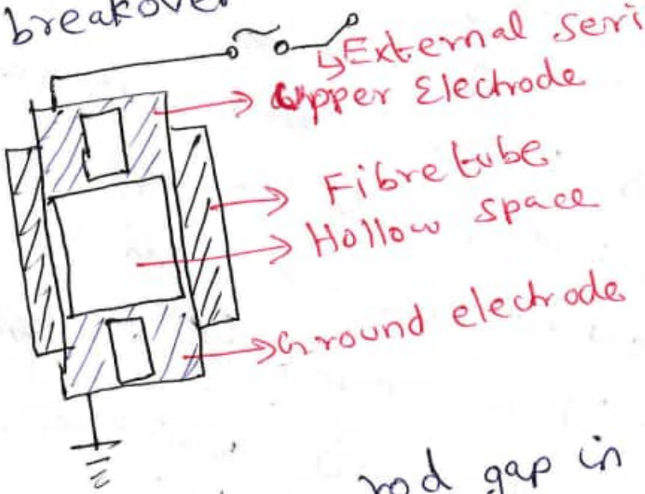
transmission line of 50 to 100 m long.
→ These are more effective & so Z_T is reduced to 25Ω
→ But it is difficult to lay these wires than ground wires.

(c) Protective Devices:

→ On line, 2 devices like expulsion gaps & protector tubes are used.
→ Line terminations, junctions & substations are fitted with surge arrestors.

(i) Expulsion Gaps:

→ Expulsion gap is a device which has spark gap together with arc quenching device to extinguishes current arc when gaps breakover due to overvoltages.



→ It has rod gap in series with second gap enclosed with fibre tube.
→ During over voltage, both spark gaps

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breakdown & current is limited by tower footing resistance & Z_s.

→ Internal arc in fibre tube vapourizes fibre material

→ Gas thus formed, being a mix of water vapour & decomposed fibre product, drive away the arc products & ionized air.

→ when power frequency current passes through zero value, arc is extinguished & path becomes open. & at this time, insulation recovers dielectric strength & normal conditions are established.

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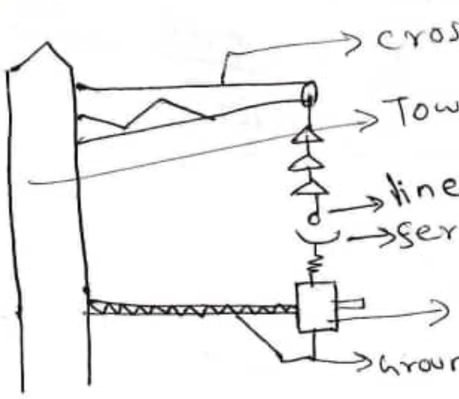
(ii) Protector Tubes

→ It is similar to expulsion gap in construction & principle.

→ It has rod (or) spark gap, mounted under line on tower.



→ hollow gap in expulsion is replaced by nonlinear element which has very high

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impedance at low currents but low impedance for high current.

→ During over voltage, spark gap breaks down, current is limited by tower footing resistance.

→ After surge current is discharged to ground, it is limited by resistance.

→ After current zero, spark gap recovers insulation strength quickly.

→ Flashover voltage of protector tube is less than that of line insulation & so it discharge overvoltage effectively

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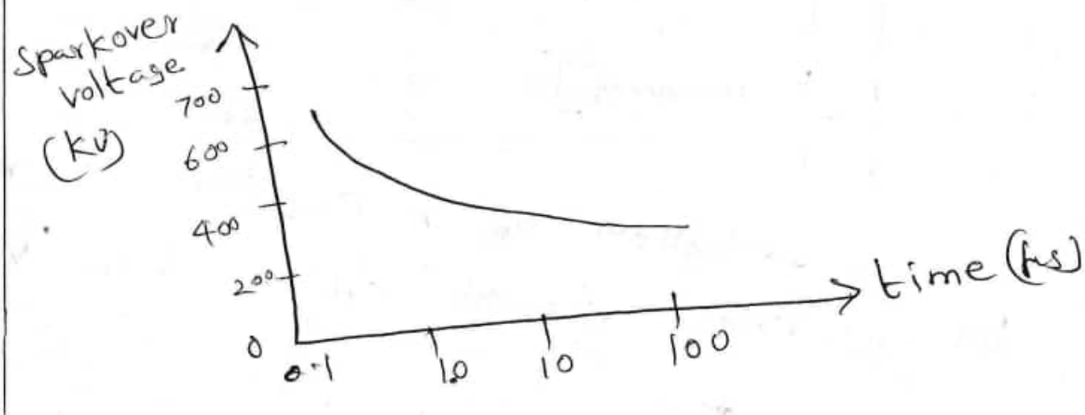
(iii) Rod Gaps:

→ simpler & effective protection device is rod gap.

→ Sparkover voltage depends on atmospheric conditions.

volt time characteristic of standard rod gap (67 cm)



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→ There is no current limiting device to limit current after sparkover & so series resistance is used.

→ without this, impulse voltage collapse to zero thus create steep-step voltage, which is very dangerous to apparatus like transformer or machine winding.

→ Rod gap provide efficient protection when thunderstorm activity is less & lines are protected by ground wires.

(iv) Surge Arresters (or) Lightning Arresters:

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→ These are devices used at substations & at line terminations to discharge over voltages & switching surges.

→ These are usually mount at line end at nearest point to substation

→ They have flashover voltage lower than of any insulation at substation.

→ These are capable of 10 to 20 kA of long duration surge (8/20 μs) & 100 to 250 kA of short duration surge currents (1/5 μs)

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5.7 Insulation Coordination :

→ Generally substations contain transformers, switchgear & other valuable equipment with non-self restoring insulation, which have to be protected against failures & internal destruction.

→ Lightning and switching surge protection requires establishment of protective voltage levels called Shunt Protection levels by protective devices like lightning arresters.

→ Lightning impulse withstand level known as Basic Impulse Level (BIL) is established for each system nominal voltage for different apparatus.

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→ For higher system voltages, switching surges are of importance & following criterion is to be adopted.

(i) BIL has to be higher because the overvoltages cause thermal overloading due to leakage currents

(ii) At present, there are surge arresters, which operate for overvoltage due to lightning and switching surges. It is preferable to assign to each protective

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equipment, a Switching Impulse Level (SIL) like surge diverter. Normally rod gaps and lightning arresters are used as protective devices.

→ Ideal requirements of a protective device are

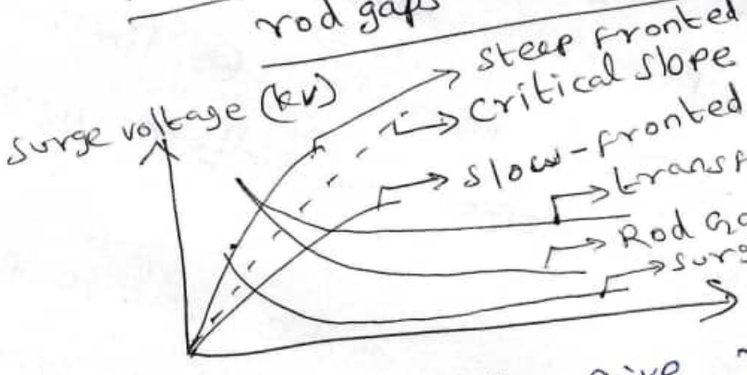
a) It should not flashover for power frequency overvoltage

b) Volt time characteristics must lie below withstand voltage of protected insulation

c) It should be capable of discharging high energy in surges & recover insulation strength quickly.

d) It should not allow power frequency follow on current to flow.

Volt time characteristic of transformer rod gaps and surge diverters



→ Rod gaps may give rise to very steep impulse waves on transformer as chopped waves, because no current limiting

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resistance is used.

→ Chopped impulse waves may lead to destruction of transformer turn-to-turn insulation

(i) Surge Arresters:

→ These are non-linear resistors in series with spark gaps which acts as fast switches.

→ Volt ampere characteristics of a resistive element is of form $I_d = kV^a$

where I_d → discharge current

k, a → constant depend on material & dimension.

V → voltage across element

→ When surge voltage (V_i) is applied to surge arrester, it breaks down giving discharge current I_d & maintain a voltage V_d across it. & thus it provides protection to the apparatus above protective level (V_p).

→ It is possible to limit power frequency and other overvoltages using surge arresters.

→ The permissible voltage & duration depend on thermal capacity of arrester.

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→ Selection of surge arrester voltage depends on
(i) rate of rise of voltage
(ii) type of grounded systems
(iii) operating characteristics of arrester.

→ Usual type of surge arresters are
(i) silicon carbide arresters with spark gaps
(ii) silicon carbide arresters with current limiting gaps
(iii) gapless metal oxide arresters

→ surge arresters have severe requirements like
(i) Have to protect from overvoltages
(ii) should be capable of withstanding surges & dissipate energy without damage
(iii) offer low resistance during surges & offer high resistance during normal operation.

a) Protection of Lines with surge Arresters:

→ Spark gap inside arrester acts as fast acting switch while non linear arrester elements provide low impedance ground path.

→ Arrester voltage $V = \left[2 \frac{(R+r)}{R+r+Z}\right] u(t)$
where Z → line surge impedance,

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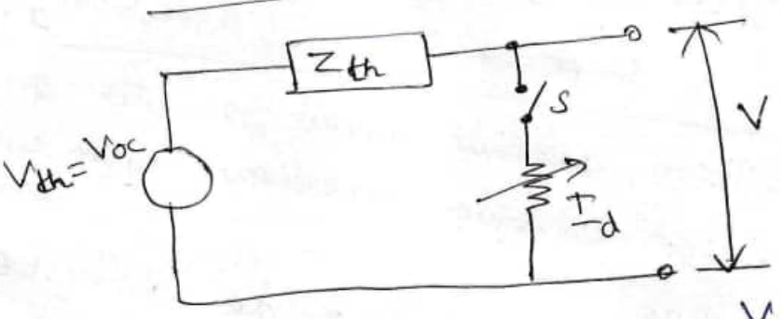
R → Resistance of non linear element
r → resistance of ground to earth
u(t) → surge voltage.

Equivalent circuit of surge Arrester



Zth ⇒ impedance viewed from terminals of protective device

→ switch S is open when V < sparkover voltage Vs and closed when V > Vs.

(ii) Insulation Levels at substation with Protective zones:

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a) Magnitude & shape of Incoming voltage surges:

→ voltage wave is estimated by assuming voltage magnitude as equal to 1-3 times negative critical flashover voltage.

b) Equipment Insulation Level:

→ Basic Impulse level (BIL) is determined as 1.25 to 1.30 times the protective level offered by surge arrester.

→ when surge arresters are to be used for BIL, a margin of 15% to 20% is allowed over protective level

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c) Distance Effect:-

→ when surge arrester, breaker and transformer are in line, voltage at distance D is $V(D) = V_p + 2ST$ where

V_p → Spark over voltage at protective level

S → steepness of wave front

T → Travel time = D/V

where V → velocity of wave travel.

→ Surge diverter (or) lightning arrester is the main device to limit overvoltages and it must have proper

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(i) MCOV = Maximum power frequency Continuous Operating Voltage

(ii) TOV = Temporary Overvoltage that can appear on it

(iii) Energy = energy dissipating capacity (ie) energy to be absorbed when limiting surge voltages.

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UNIT II

DIELECTRIC BREAKDOWN

Gaseous Breakdown

i) Gases dielectrics

* Air
* Nitrogen (N_2)
* Carbon Dioxide (CO_2)
* Freon (CCl_2F_2)
* sulphur hexafluoride (SF_6)

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⇒ For High voltages, current increases between the electrode In dielectric the breakdown occurs.

⇒ Spark formed during breakdown Produces short circuit between electrode

⇒ Maximum voltage applied to the insulation at the moment of breakdown is called as Breakdown voltage

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⇒ The Electrical discharges in gases are two types

* A self sustaining
* Non sustaining

⇒ The buidup of high current in a breakdown is due to process known as ionization.

⇒ Two theories are used as follows

① Townsend theory
② streamer theory

Ionization Process : Townsend's theory.

Liberating an electron from a gas molecle with the simultaneous protection of a positive ion - ionization

1. By collision
2. photo ionization
3. secondary ionization
4. Electron Attachment Process

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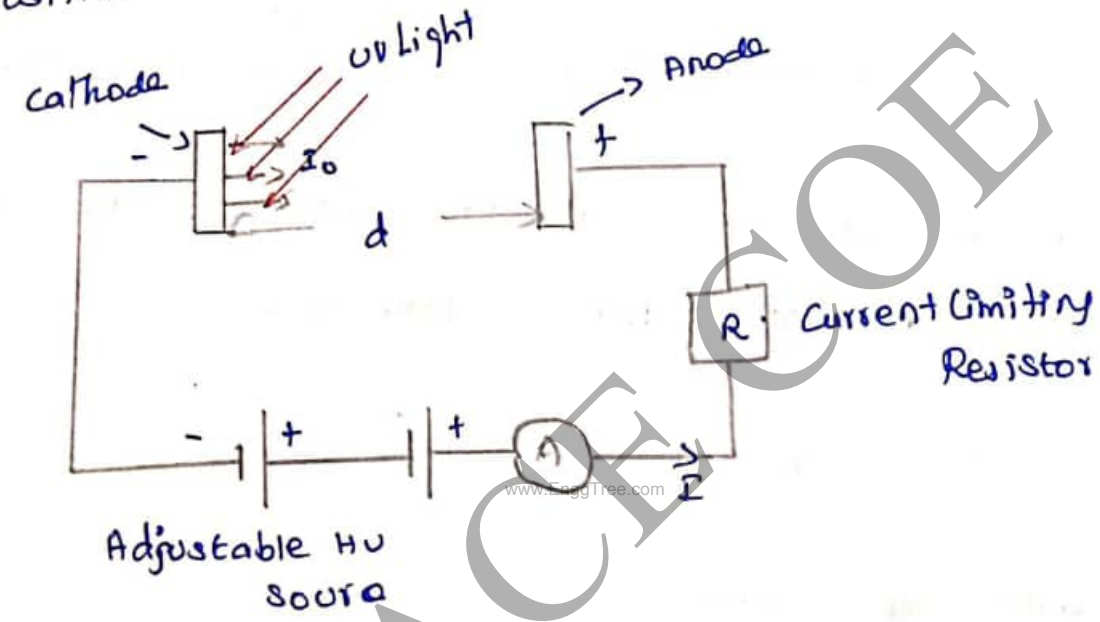
i) Ionisation By collision

⇒ Free electron collides with a neutral gas molecule and gives rise to a new electron and a positive ion.



⇒ Electric field E is applied between 2 parallel electrodes, electrons at cathode will be under collisions towards anode.

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

where e^- → electron, A → Atom, A^+ → Positive ion

Σ → Energy, V_i → ionization potential

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ii) Photo Ionisation

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

Process :

* excitation to the atom to a higher energy state
* Continuous absorption by direct excitation of the atom (or) direct ionisation

$$h\nu + A \rightleftharpoons A^*$$

Ionization occur when

$$\lambda \leq c \cdot \frac{h}{V_i}$$

where h is the planck's constant

c → velocity of light

λ → wavelength of the incident radiation

V_i → Ionization energy of the atom

⇒ photo ionization occurs with a radiation of 1250 A°

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Secondary Ionization Process :

=> It sustain a discharge after it is established due to ionization by previous process

(1) Electron emission due to positive ion impact

(2) Electron emission due to photons

(3) Electron emission due to metastable and neutral atoms.

(1) Positive Ion Impact

=> Positive ion can cause of electrons from the cathode by giving up its kinetic energy on impact

=> If the total energy (kinetic energy and ionisation energy) is greater than the work function, than one electron will be ejected and a secondary electron will neutralize the ion.

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Electron Emission due to photons

=> Electrons can be ejected from the metal surface by impact of metastable atoms

=> If Electron to escape from a metal, it should be given enough energy to overcome the surface potential barrier.

=> It occurs if $h\nu > \phi$, where ϕ is the work function, ν is the threshold frequency

=> clean nickel surface with $\phi = 4.5$ eV threshold frequency correspond wavelength $\lambda = 2755\ A^{\circ}$

Electron Emission due to Metastable & 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

=> Neutral atoms in the ground state also give rise to secondary electrons if Kinetic energy is high (1000 eV)

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Electron Attachment Process

⇒ Electrons become attached to atoms to form negative ions are called attachment collisions.

⇒ Electron attachment process depends on the electron energy and the nature of the gas

$$Atom + e^- + k \longrightarrow \text{negative atomic ion} + [E_a + K]$$

Townsend's Current growth Equation

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

$$n_x = n_0 \exp(\alpha x)$$

Number of electrons reaching the anode

$$n_d = n_0 \exp(\alpha d)$$

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

where, n_0 - no of electrons emitted from cathode

α - Avg number of ionizing collisions

I_0 - intial current at the cathode

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Townsend's criterion for Breakdown

The current will be limited only by the resistance of the power supply and the external circuit.

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

$\Rightarrow \alpha$ and $\alpha \rightarrow$ Breakdown criterion

$ds \rightarrow$ sparking distance

Breakdown in Electronegative Gases

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The gases in which attachment processes encountered in gases are

a) Direct attachment

$$AB + e \rightarrow AB^- + h\nu$$

b) Dissociative attachment

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

A → Sulphur (or) Carbon Atom

B → Oxygen / Molecules

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Drawbacks in Townsend's theory

=> Breakdown voltage depends on Pressure and geometry of the gap

=> Time lags : Theory - 10^{-5}, Practical - 10^{-8}

=> Discharges were found to be filamentary and irregular.

Paschen's Law

The breakdown creterion in gases is given as

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

where the co-efficients α and γ are functions 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 for E in the above equation

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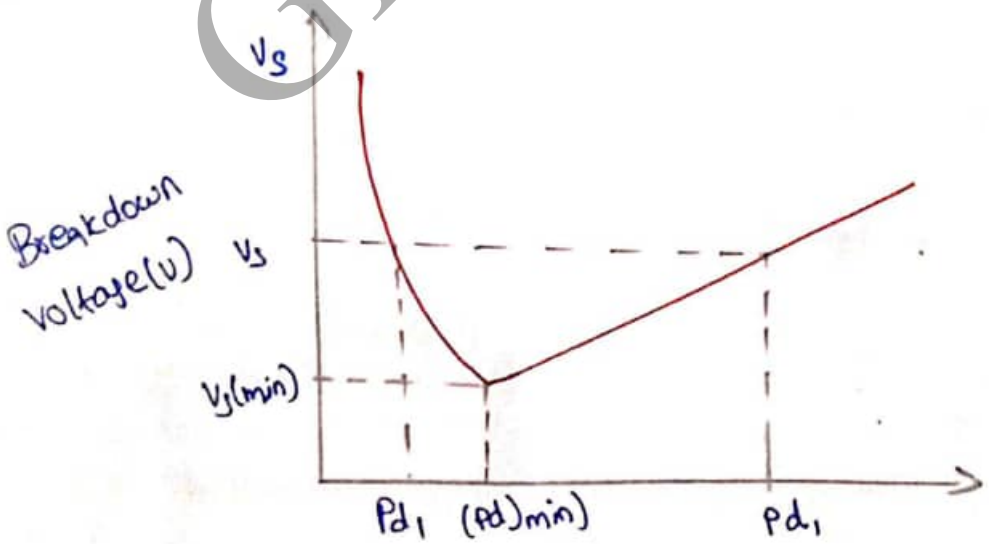
$$f_2\left(\frac{V}{Pd}\right)\left[\exp\left\{Pd f_1\left(\frac{V}{Pd}\right)\right\} - 1\right] = 1$$

This equation shows a relationship between V & Pd. The above equation can be rewritten as.

$$V = f(Pd)$$

This Equation is know as Paschen's law

⇒ The Paschen's curve, the relationship between V & Pd is show in Figure. The Figure shows that the relationship between V & Pd is not linear and has a minimum value for any gas.



Breakdown voltage -Pd curve (Pagichen's law)

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Corona Discharges

⇒ In nonuniform electric field, an increase in voltage will cause a discharge in gas to appear at points with highest electric field intensity on transmission lines. This form of discharge is called a corona discharge.

⇒ It accompanied by hissing noise and air surrounding corona become ozone

⇒ Corona also gives rise to Radio interference and line losses

⇒ The voltage gradient to produce visual AC corona in air at a conductor

For parallel wires of radius r

$$E_w = 30\, m\delta \left[1 + (0.301/\sqrt{\delta r})\right]$$

Fo co-axial cylinders

$$E_c = 31\, m\delta \left[1 + (0.308/\sqrt{\delta r})\right]$$

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Where m - surface irregularity factor

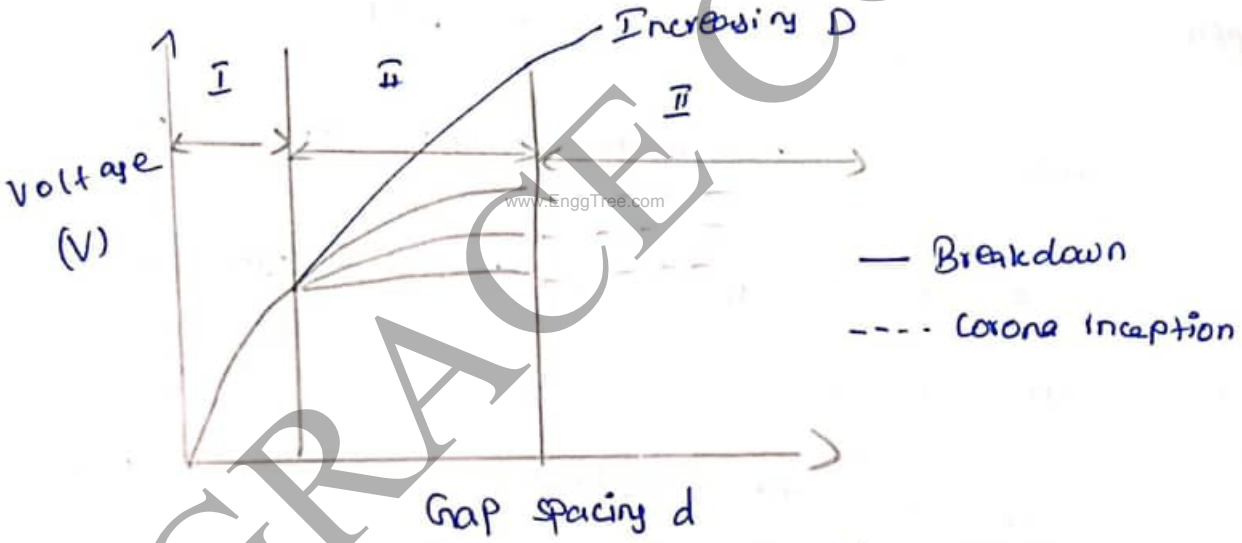
d - Relative Air density correction factor

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

where b- atmospheric pressure

t - temperature °c

d = 1 @ 760 torr, 25°c



Breakdown and corona inception characteristics

=> at small spacing (region I), the field is uniform, and the breakdown voltage is depend on the spacing

=> At fairly large spacing (region II), the field is nonuniform, and the breakdown voltage is depends on the sphere diameter and spacing

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Breakdown in non-uniform fields.

=> co-axial cylinders, point plane and sphere-plane gaps, the applied field varies across the gap. The Townsend's creterion for breakdown now,

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

=> Rod gap - rod gap, sphere - sphere gap are used for the measurement of high voltages and protection of electrical apparatus.

=> The breakdown voltage do depends on humidity in air.

=> In the case of rod gaps the field is non-uniform, so sphere gap is used

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Vacuum Breakdown

Unlike gaseous breakdown, an electron crosses the gap without encountering any collisions.

Collision:

a) Particle exchange Mechanism
b) Field emission mechanism
c) clump theory

a) Particle exchange mechanism

=> charge particle emitted from one electrode and impings from other electrode, and liberates opposite charged particles due to ionization.

=> It involves electron, positive ion, photons and the absorbed gases at the electrode surface

=> An electron present in the vaccum gap is accelerated towards the anode and on impact releases A positive ions and C photons.

=> Both photons and positive ions liberates an electron(B) called secondary electron (liberate on electron (B))

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⇒ The Breakdown criterion can be written as

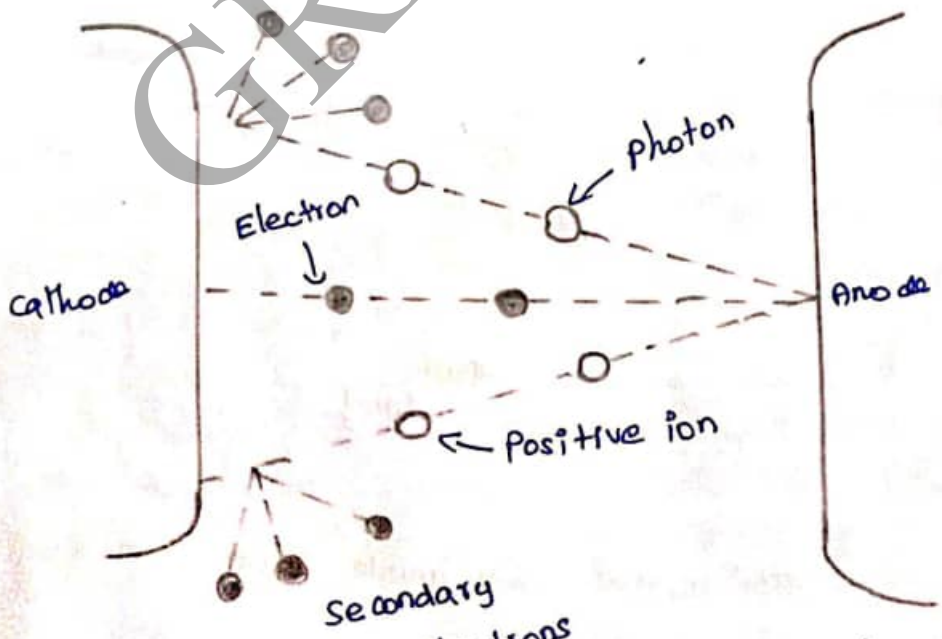
$$AB + CD => 1$$

⇒ the theory Modified to allow the presence of negative ions an the Breakdown criterion becomes

$$AB + EF > 1$$

⇒ where E & F are the co-efficient for negative and positive ion liberation by positive and negative ion.

⇒ Product EF were close to unity for Copper, aluminium and stainless electrodes.



Particle exchange mechanism of vaccum breakdown

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b) Field Emission Theory :

i) Anode Heating Mechanism

=> Due to field emission bombard the anode causing a local rise in temperature and release gas is vapours into the vacuum cap.

=> These electron ionize the atoms of the gas and produce positive ions.

=> These Positive ions arrive at Cathode and Produce secodary electrons.

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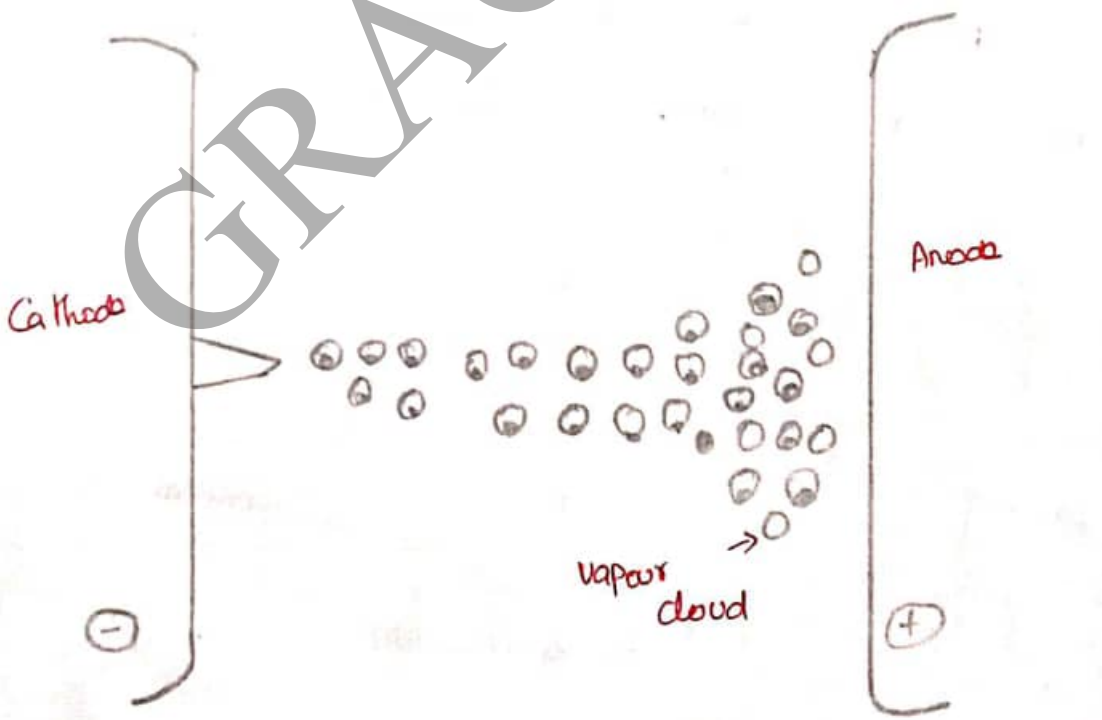

Vapour Electron beam anode heating mechanism

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ii) Cathode heating mechanism .

⇒ The mechanism creates breakdown voltage on the gap, sharp points on the surface are ~~exist~~ existence the pre-breakdown current

⇒ This current cause resistive heating, thus ~~initiative~~ initiating vacuum discharge.

⇒ The Breakdown ~~Discha~~ take place by the process of effective cathode electric field is 10^6 to 10^7 V/cm.

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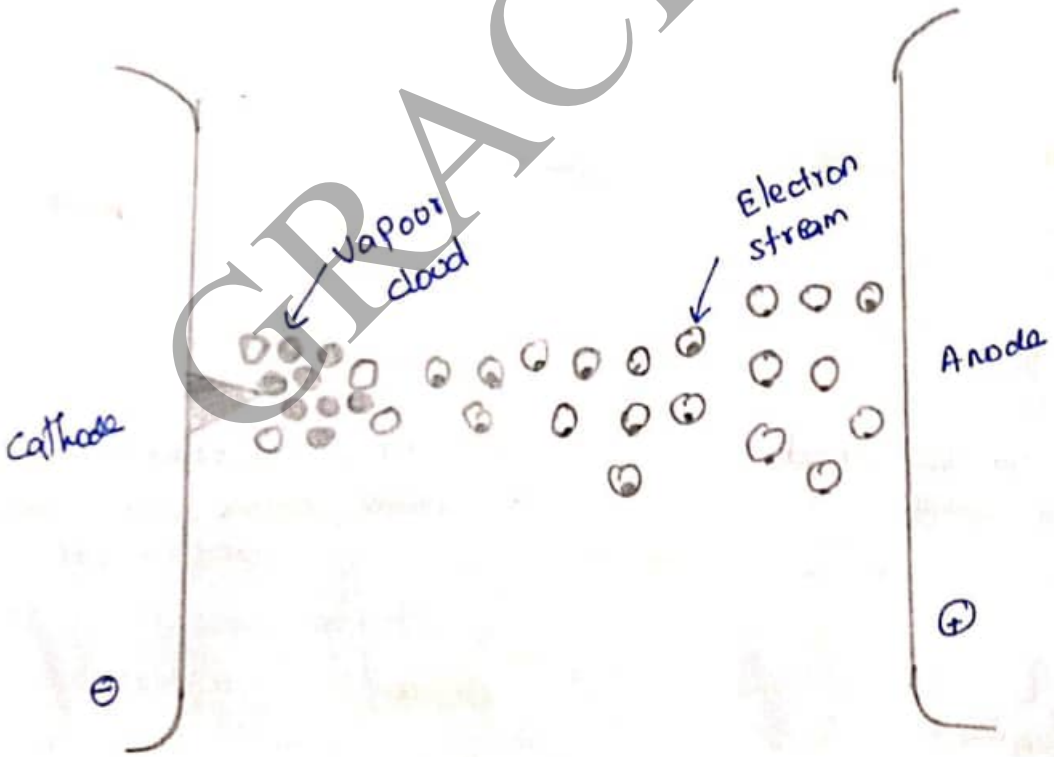

Breakdown in vacuum caused by heating of a microprojection on the cathode

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c) clump Mechanism

i) A loasely bound particle exist on one the electrode surface.

ii) on High voltage, the particle get charged, detached from mother electrode and is accelerated across the gap.

iii) The Breakdown occor due to a discharge vapour released by the impact on the particle

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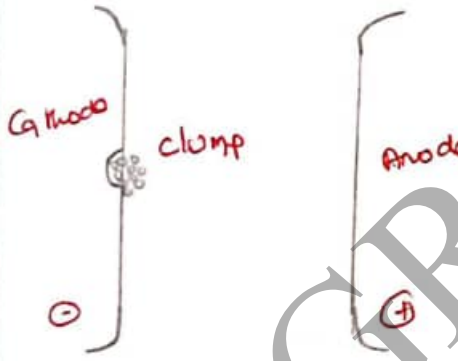
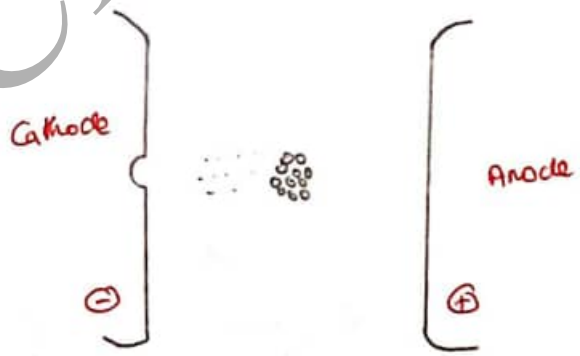


(a) clump is loosely attached to the surface



(b) clump is detached from the cathode surface and it accelerated across the gap

Impact of the clump on the anode gives out a cloud of metal vapour

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Liquids as Breakdown

=> Liquid dielectrics more useful as insulating materials than solids (or) gases

=> Liquids and solids are 10^3 times denser than gases.

=> Liquids dielectric strength in the order of 10^7 V/cm

=> Mostly used as impregnants in high-voltage Cables, capacitors and for filling up of transformers, and as a circuit Breakers.

classification:

a) Transformer oil (Petroleom oils)

b) Synthetic Hydrocarbons

c) Chlorinated Hydrocarbons

d) Silicone Oils

e) Esters

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Characteristics of Liquid Dielectrics

a) Electrical Properties

i) Permittivities → Petroleum oils vary from 2 to 2.6 & silicon oil vary from 2.0 to 73.

2) Resistivities → used for high voltage applications should be more than 10^{16} Ω-m.

3) Power factor → varying between 10^{-4} at 20°C and 10^{-3} at 90°C at a frequency of 50 Hz.

4) Dielectric strength → depends on the atomic and molecular properties of the liquid itself.

b) ~~Heat~~ Heat Transfer

⇒ Heat is transferred mainly by convection

⇒ under natural atmospheric cooling conditions

Convection (N) is given by

$$N = f\left[k^3 A C / \nu\right]^n$$

where k → thermal conductivity, A → co-efficient of expansion

C → specific heat per unit volume, ν → kinetic viscosity

$n = 0.25 \sim 0.33$

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c) Chemical stability.

⇒ ability to withstand high electrical stresses in the presence of materials like O_2, water, fibres and decomposition products of solid insulation

Pure Liquids and Commertial Liquids.

⇒ Pure Liquids are chemically pure do not contain any other impority. Example [C_6H_{14}, C_7H_{16}]

⇒ Commertial liquids are not chemically pure, consists of mixtures of complex organic molecules.

Purification :-

⇒ The liquid dielectric impurities are dust, moisture, dissolved gase and ionic impurities.

⇒ Various methods employed for purification, are filration, centrifuging, degassing, distillation and chemical treatment.

⇒ The System Provides for cycling the liquid. the liquid from reservoir flows through the distillation

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Column where ionic impurities are removed.

⇒ water is removed by drying agents in the low temperature path.

⇒ The gases dissolved in the liquid are removed by passing them through the cooling tower and pumped out by the vacuum pumps.

⇒ The liquid then passes through the filter where dust particles are removed.

⇒ The vaccum system helps to remove moisture and other gaseous impurities.

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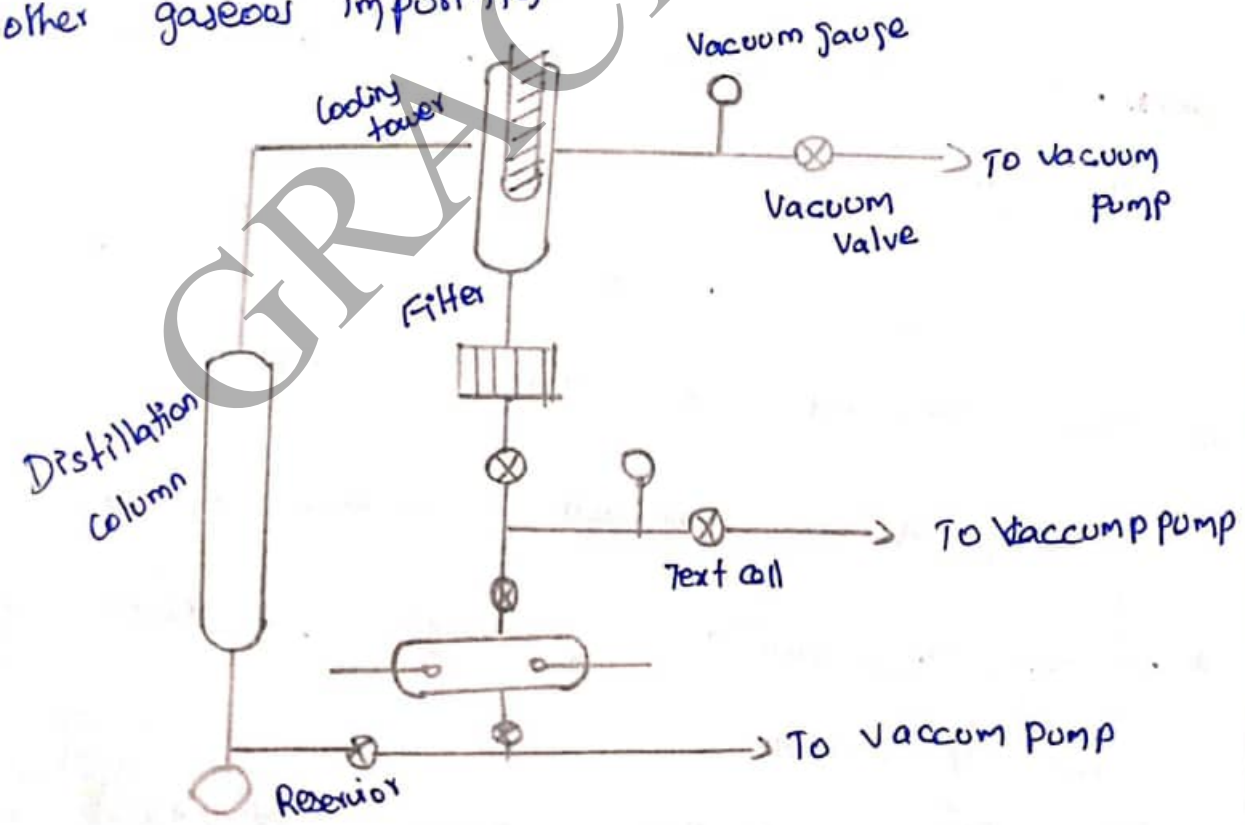

Liquid Purification system with test cell.

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Breakdown tests

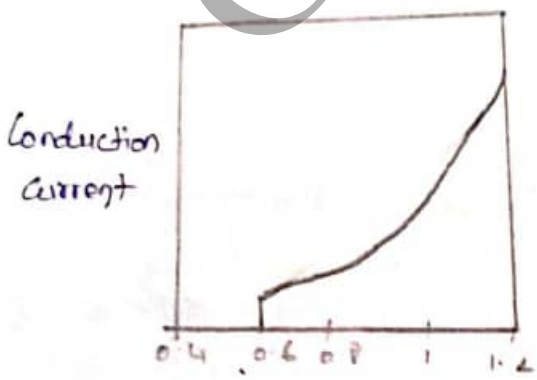
⇒ Breakdown tests are normally conducted using test cells.

⇒ For testing pure liquids, the test cells are used are small so that less quantity of liquid is used during testing.

⇒ The electrodes used for breakdown voltage measurement are usually spheres of 0.5 - 1 cm in diameter with gap spacing about 100-200 nm.

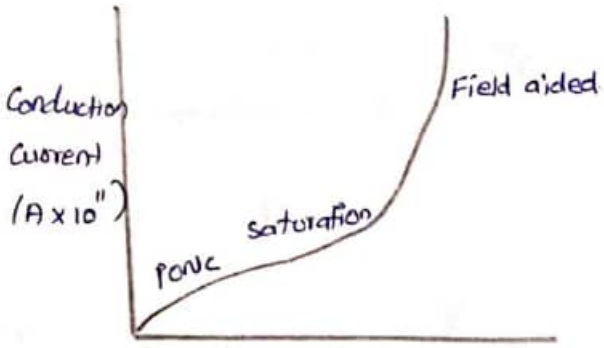
⇒ The test voltage required for these tests are usually low, of the order of 50-100 kV.

Conduction and Breakdown in pure liquids.



Electric field (MV/cm)

Conduction current in hexane



Electric field (MV/cm)

in hydrocarbon liquid.

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③ [The Breakdown voltage depends on the field, gap seperation, cathod work function and the temp of the Cathode]

③ ⇒ when low electric fields less than 1 kV/cm are applied, Conductivities of $10^{-18} - 10^{-20}$ mho/cm are obtained These are Probably due to impurities remaining after purification. ④ [As Breakdow field approach, the current Incresed rapidly due to process similar to Primary ionization Process, and also the positive ion reaching Cathode generate secondary electrons, leading to Break down.

④ However, when the fields are high (>100 kV/cm) the currents not only increase rapidly, but also undergo violent fluctuations.

Conduction and Breakdown in Commercial liquids.

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The Breakdown mechanism in commercial liquids is dependent, ~~as~~ on nature, condition of the electrodes, physical Properties and impurities.

The liquid breakdown theories can classified as

a) suspended Particle Mechanism

b) Cavitation and Bubble Mechanism

c) stressed oil volume Mechanism

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i) Suspended particle theory :-

⇒ The commertial liquids, the presence of solid impurities cannot be avoided. These impurities will be present as fibres.

⇒ The permittivity of these particle (ε_2) will be different from the permittivity of the liquid (ε_1)

$$\text{Force} = \frac{1}{2} r^3 \frac{(\varepsilon_2 - \varepsilon_1)}{2\varepsilon_1 + \varepsilon_2} \text{grad } E^2$$

⇒ If $\varepsilon_2 > \varepsilon_1$, the force is directed towards of maximum stress. If $\varepsilon_2 < \varepsilon_1$, the force will be in the direction of low stress.

⇒ If the voltage appl is continuously applied, the the force drives the particle towards the areas of maximum stress. than causing the Breakdown between two electrodes.

cultivation and the Bubble theory

⇒ The Breakdown strength depends on applied hydrostatic pressure, vapour bubble and Breakdown proces.

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The Process of formation of vapour bubbles:

a) gas pockets at the surfaces of the electrodes

b) electrostatic repulsive forces

c) gaeous product due to dissociation of liquid molecules.

d) vapourization of the liquid by corona type discharge

⇒ the Breakdown occurs when the voltage drop along the length of the bubble becomes equal to the maximum value of the Paschen's curve for the gas in the bubble. The Breakdown field is.

$$E_0 = \frac{1}{\varepsilon_1 - \varepsilon_2}\left[\frac{2\pi\sigma(2\varepsilon_1+\varepsilon_2)}{r}\left\{\frac{\pi}{4}\sqrt{\left(\frac{V_b}{2r\varepsilon_0}\right)}-1\right\}\right]^{1/2}$$

where $\sigma \rightarrow$ Surface tension

$\varepsilon_1 \rightarrow$ Permittivity of liquid

ε_2 - Permitivity of gas bubble

$r \rightarrow$ radius

$V_b \rightarrow$ voltage drop.

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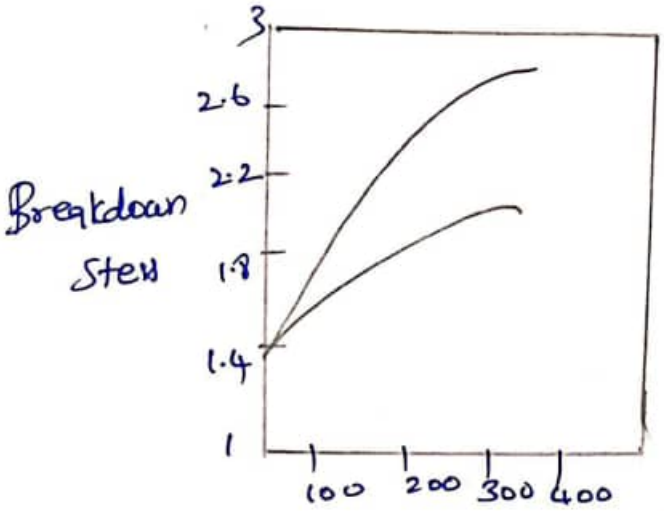

The Breakdown stess in n-hexane

(iii) Stress oil volume theory :

⇒ The Breakdown strength is determined by the largest possible impurity (or) weak link.

⇒ The Breakdown strength is inversly proportional to stressed oil volome.

⇒ The Breakdown voltage is highly influenced by the gas content in the oil, viscosity of the oil, and presence of othe impuritig.

⇒ If increase the stressed oil volume consequently results in reduction in the Breakdown Voltage.

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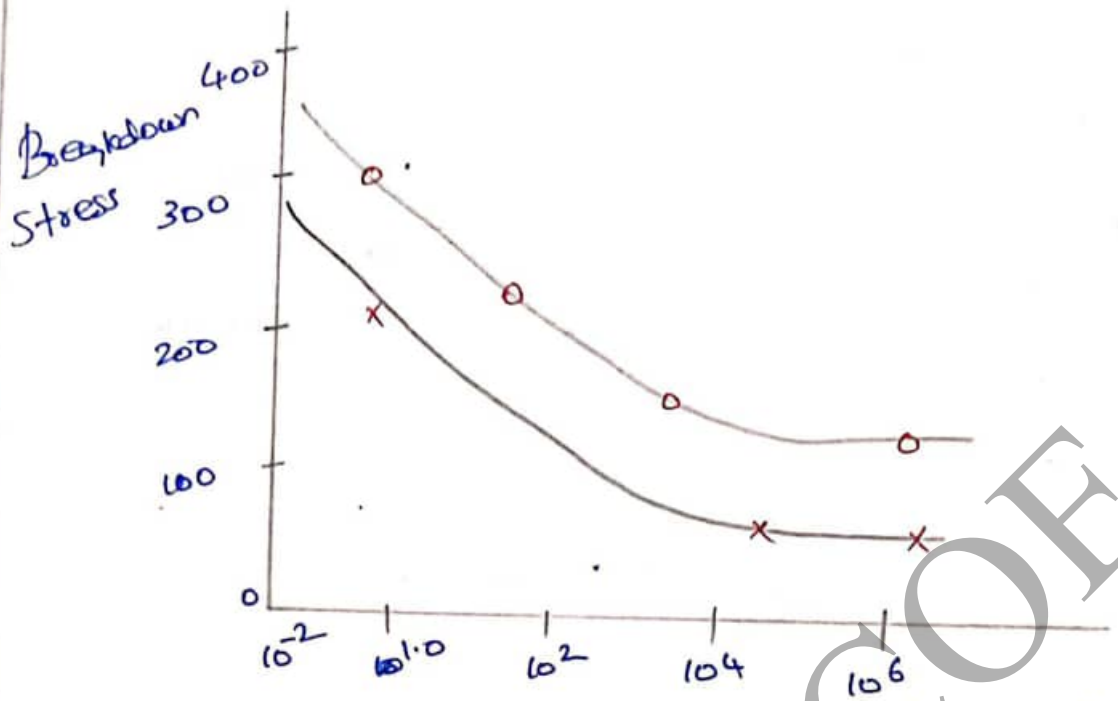

[AC Breakdown stress as a function of stressed oil volume.

Solid Dielectric Breakdown

⇒ Solid dielectrics have higher breakdown strength compared to liquids and gas.

⇒ solid insulating materials are paper, wood, rubber, mica, glass, porocelain, PV.

⇒ The mechanism of breakdown is depending on the time of application of voltage.

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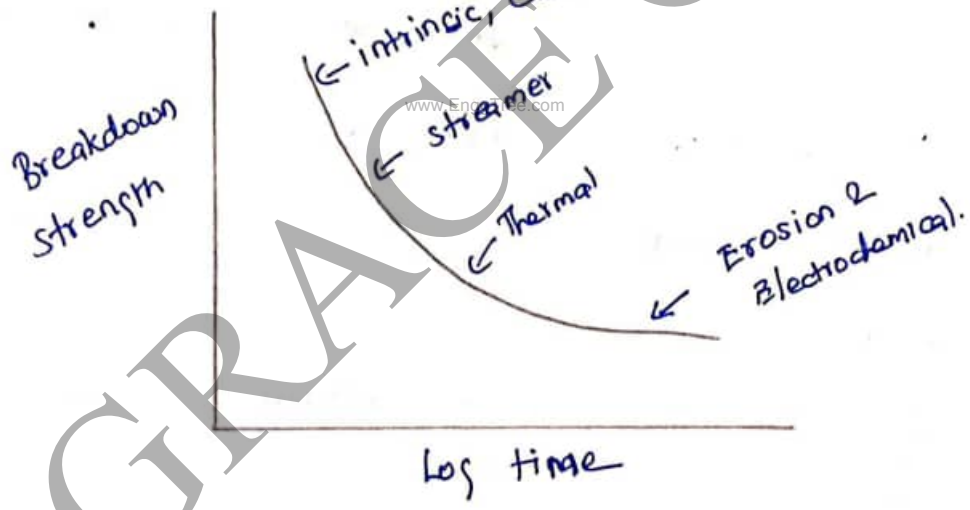
The various breakdown mechanisms are classified as.

a) Intrinsic breakdown
b) electromechanical breakdown
c) failure due to treeing and tracking
d) thermal breakdown
e) electrochemical breakdown
d) Internal Discharges.



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i) Intrinsic Breakdown.

=> when voltages are applied only for short durations of the order of 10^{-8} s, the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the Intrinsic electric strength

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=> Intrinsic breakdown depends on the presence of free electrons.

=> A small number of Conduction electrons are present in solid dielectrics along with impurities

=> The Impurity molecules act as traps for the Conduction electron up to certain range of electric fields and temperatures.

=> when these ranges of ~~electric~~ ~~fs~~ are exceeded additional electrons in addition to trapped electrons are released. and these electrons participate in the conduction process.

=> The Two types of intrinsic breakdown are

i) electronic breakdown
ii) steamer breakdown

ii) Electromechanical Breakdown

when solid dielectrics are subjected to high electric fields, failure occurs due to

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Electrostatic Compressive forces.

=> If the thickness of the specimen is d_o and is Compressed to a thickness 'd' under an applied voltage V, then the electrically ~~compress~~ developed Compressive stress is in equilibrium if

$$\varepsilon_o \varepsilon_r \frac{V^2}{2d^2} = Y \ln\left[\frac{d_o}{d}\right]$$

where Y is the young's modules.

$$V^2 = d^2 \left[\frac{2Y}{\varepsilon_o \varepsilon_r}\right] \ln\left[\frac{d_o}{d}\right].$$

Mechanical instability occurs when

$$d/d_o = 0.6 \text{ (or) } d_o/d = 1.67$$

The highest apparent electric stress before breakdown

$$E_{max} = \frac{V}{d_o} = 0.6 \left[\frac{Y}{\varepsilon_o \varepsilon_r}\right]^{1/2}$$

Y is depends on the mechanical stress.

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Thermal Breakdown

⇒ when electric field is applied to a dielectric, Conduction current, flows through the material.

⇒ The current heats up the specimen and the temperature rises.

⇒ The heat generated is transferred to the surrounding medium by conduction through the solid dielectr.

⇒ Equilibrium is reacheached when the heat used to raise the temperature of dielectric.

under DC, The stea E is

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

σ ⇒ DC conductivity

under AC, The heat Generated $W_{AC} = \dfrac{E^2 f \varepsilon_r \tan\delta}{1.8 \times 10^{12}} \ W/cm^3$

f = freq , δ = loss angle , E = rms value

Heat dissipated $(W_T) = C_v \dfrac{dT}{dt} + div\,(k\,grad\,T)$

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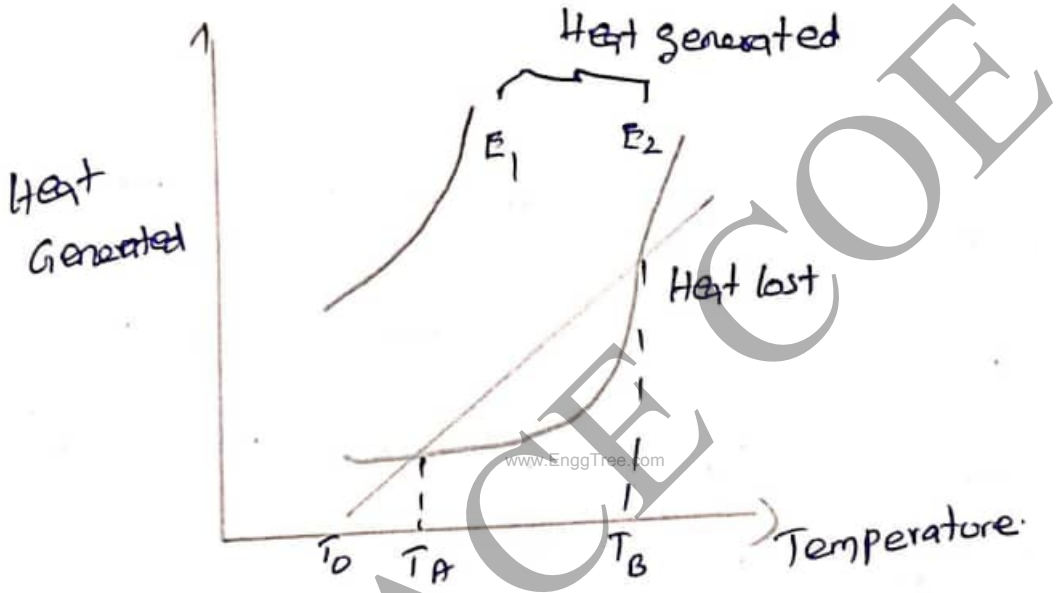
C_v = specific heat of the specimen

T = temperature of the specimen

K = thermal conductivity of the specimen

t = time over.



=> Equilibrium is reached when W_{DC} (or) W_{AC} is equal to (W_T)

=> Breakdown occurs when W_{DC} (or) W_{AC} exceeds (W_T).

=> The heat lost is shown by a straight line & the heat generated at fields E_1 & E_2 are shown by separate curve

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=> At region of T_A and T_B heat generated is less than the heat lost for the field E_2 and hence the breakdown will not occur.

=> At field E_2 breakdown occur between both temperatures T_A and T_B.

=> as most of the insulation failures in high-voltage Power apparatus occur due to thermal breakdown

=> Thermal breakdown sets up an upper limit for increasing the breakdown voltage when the thickness of the insulation is increased.

=> Thermal breakdown stresses are lower under AC conditions than DC conditions.

=> Thermal Breakdown stress in dielectric

Material	DC	AC
Mica	24	7·28
Rock salt	38	1·4
Porcelain	-	2·8
ITU steatite	-	9·8

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Generation of High Dc Voltages

=> High Dc voltages are needed in insulation tests on cable and capacitors.

=> Impulse generator charging units also required high voltages of about 100 to 200 kV.

=> The generation of DC voltages of up to 100 kV, electronic valve rectifiers are used and the output current is 100 mA.

i) Half and Full wave Rectifier

=> Rectifier circuits producing high DC voltages from Ac sources may be a) half wave b) Full wave c) voltage doubler type recifiers.

=> The rectifier may be an electron tube are available for peak voltages up to 250 kV.

=> Number of units are used in series, transient voltage distribution along each unit becomes non uniform.

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=> The half wave rectifier, the capacitors is charged to Vmax, the maximum AC voltage of the secondary of the high voltage transformer in the conducting half cycle

=> In the other land capacitor is discharged into the load.

=> The rectifier valve must have a peak inverse rating of at least 2Vmax. To limit the charging current an additional resistance R is provided in series with the secondary of the transformer.

=> In the full wave rectifier; the positive half-cycle, the rectifier A conducts and charges the capacitor C. In the negative half cycle, the rectifier B conducts and charges the capacitor.

=> The source transformer required a centre-tapped secondary with a rating of 2V.

=> For applications at high voltages of 50 kV and above, the rectifier valves used are of special construction.

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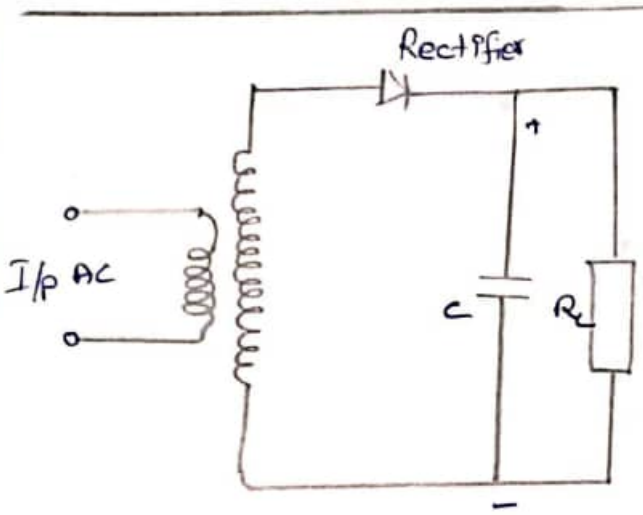
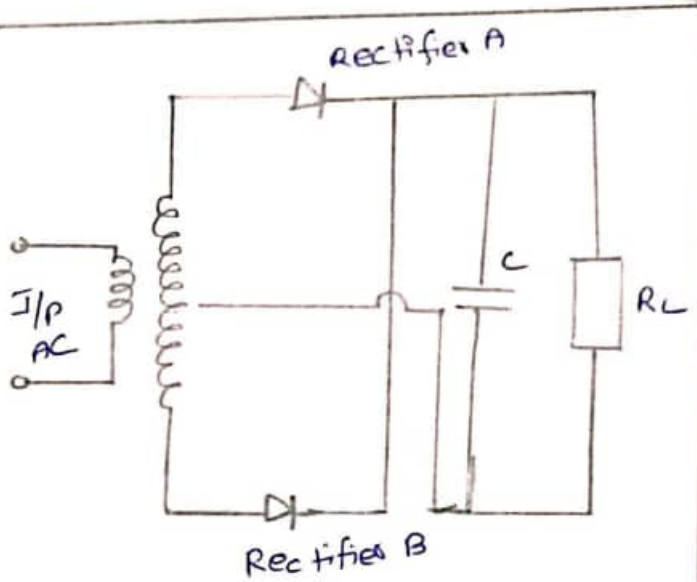


(a) Half wave Rectifier

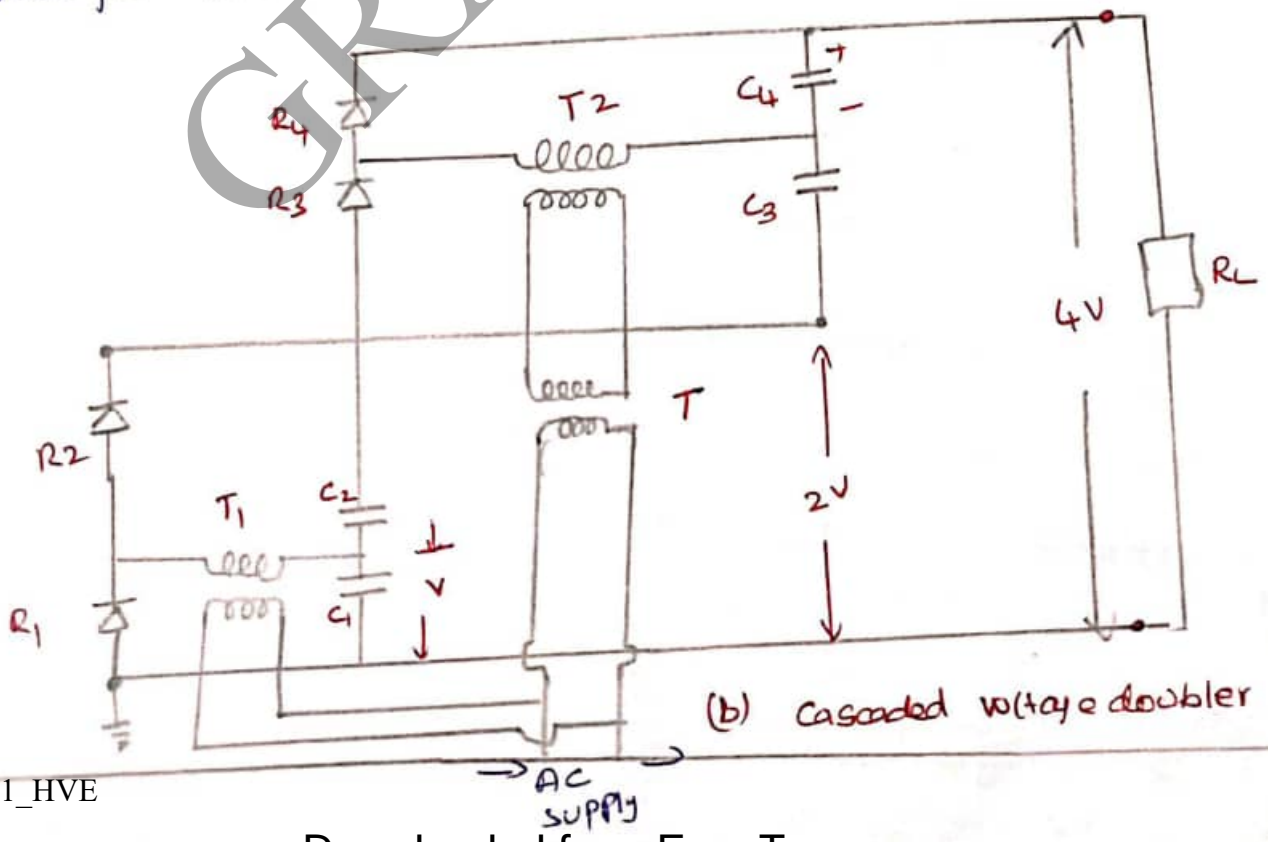


(b) Full wave Rectifier

Voltage Double circuits

=> Both full wave and Half wave rectifier Produces a DC voltage less than the AC maximum voltage

=> when higher DC voltages are needed, a voltage doubler circuits are used.



(b) Cascaded voltage doubler

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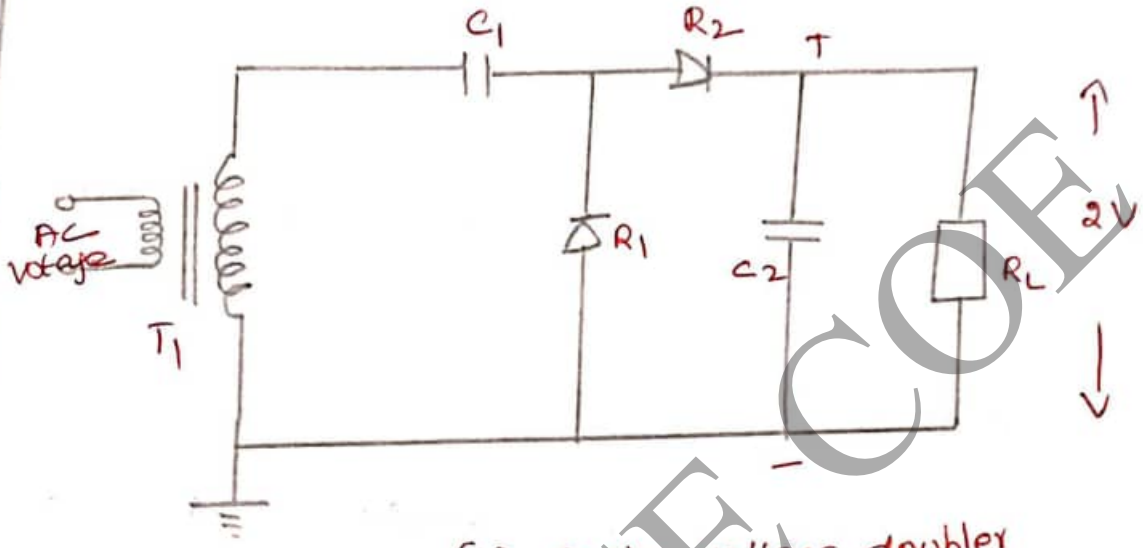
T_1, T_2 → hv transformer

C_1 C_2 C_3 C_4 → Capacitors

T → isolating transformer

R_1 R_2 R_3 R_4 - Rectifiers

R_L - Load Resistance



(a) Simple voltage doubler

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⇒ The Capacitor C_1 is charged through rectifier R_1 to a voltage of $+V_{max}$ during negative half cycle

⇒ As the voltage of the transformer raises to positive $+V_{max}$ during the next cycle, the potential of the other terminal of C_1 raises to a voltage of $+2V_{max}$.

⇒ Cascaded voltage doublers are used when larger output voltages are needed without changing the input transformer voltage level.

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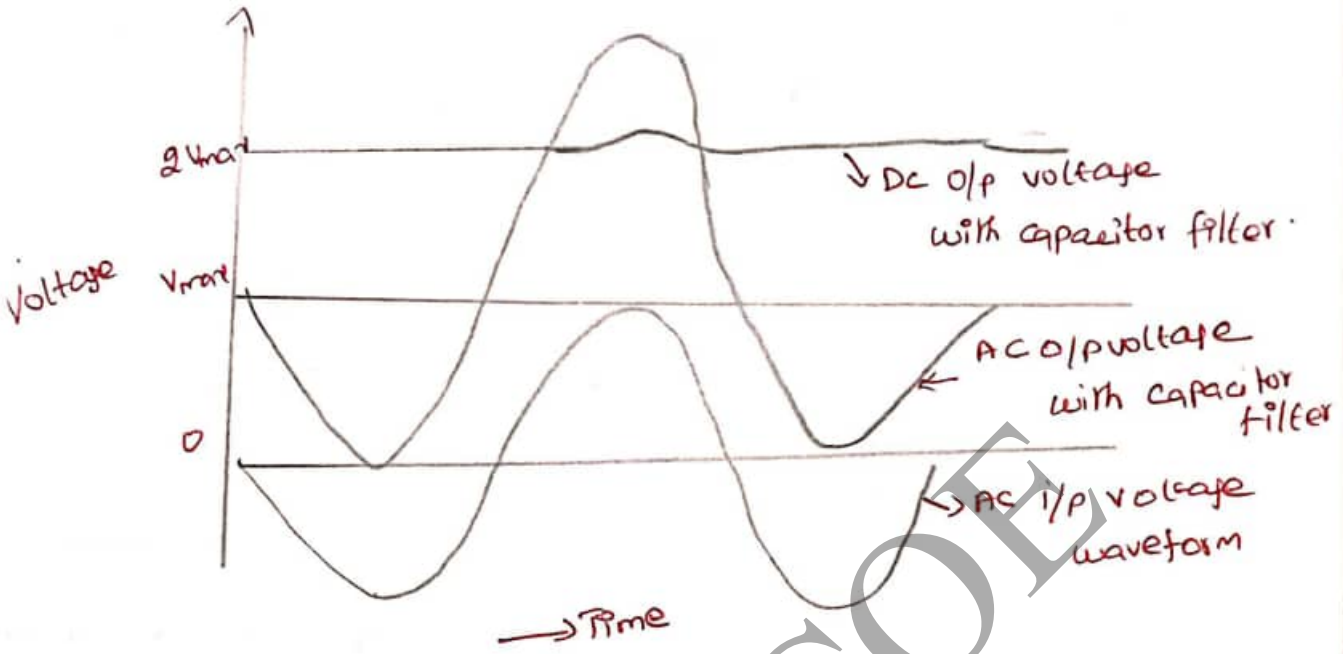

Voltage Multiplier circuit

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=> Cascaded voltage multiplier circuits for high voltages are cumbersome and require too many supply and isolating transformers

=> It is possible to generate very high DC voltages from single supply transformers by extending the voltage doubler circuits.

=> The valve-type pulse generators may be used instead of conventional AC supply and the circuit become compact.

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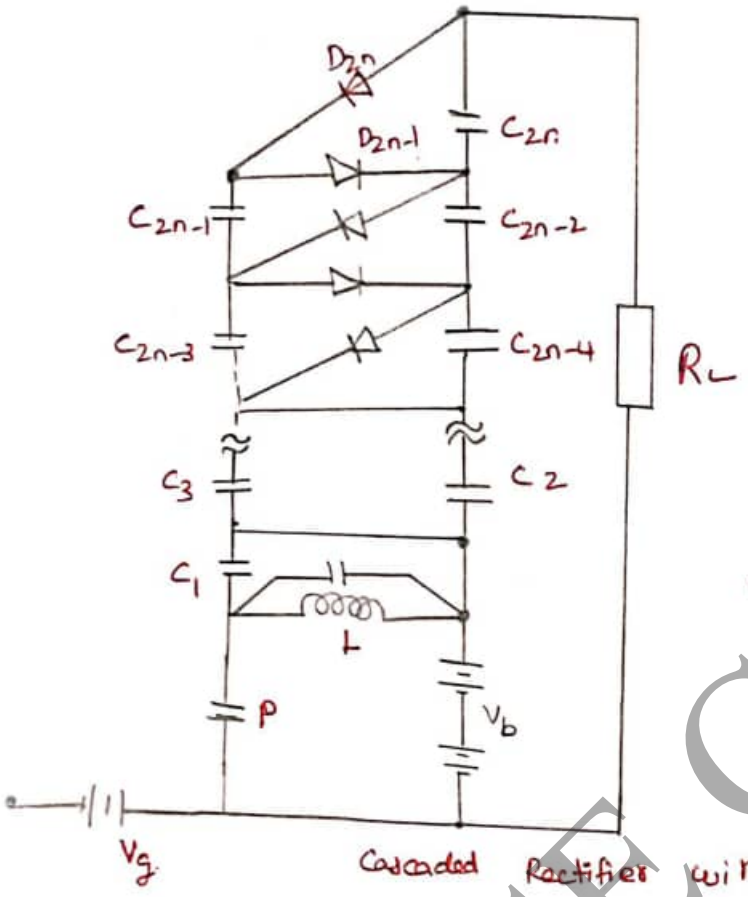

P - Pulse Generator

V_b - Dc supply to pulse Generator

V_s - Bias voltage.

Cascaded Rectifier with Pulse generator

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Electrostatic machines

⇒ In electrostatic machine, current-carrying conductors are moved in a magnetic field, so that the mechanical energy is converted into electrical energy.

⇒ The charged bodies are moved in an electric field against the electrostatic field in order that mechanical energy is converted into electrical energy.

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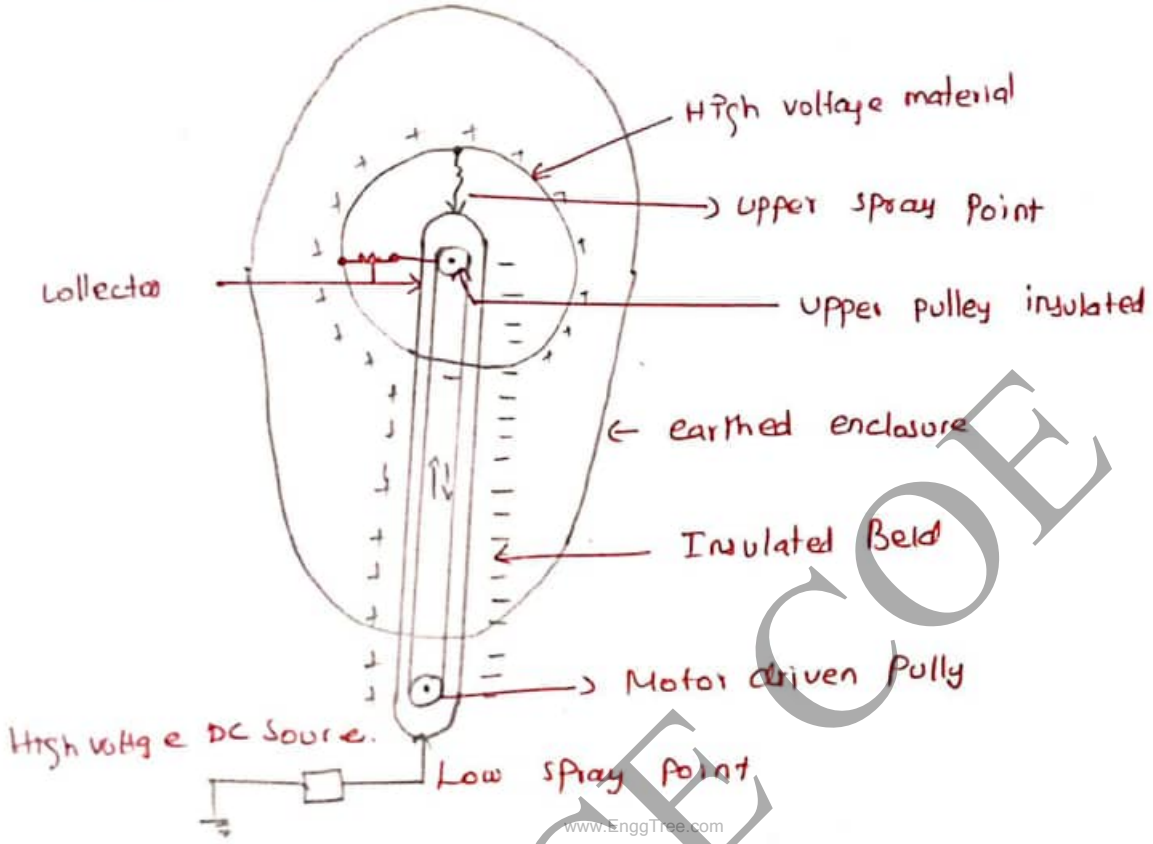
a) Van de Graaff Generator



⇒ The generator is usually enclosed in an earthed metallic cylindrical vessel and is operated under pressure.

⇒ Charge is sprayed onto and insulating moving belt from corona points at a potential of 10 to 100 kV.

⇒ The belt is driven by an electric motor at a speed of 1000 to 2000 metres per minute.

⇒ The potential of high-voltage electrode rises at a rate

$$\frac{dv}{dt} = \frac{1}{C}\frac{dQ}{dt} = \frac{I}{C}, \quad I \rightarrow \text{net charging current}$$

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=> Van de Graff generators are useful for very high voltage and low voltage applications.

=> The output voltage is easily controlled by controlling the corona source voltage and rate of charging

=> The voltage can be stabilized to 0.01 %

=> These are extremely flexible and precise machines for voltage control.

Generation of High Alternating voltages.

=> when test voltage requirments are less than about 300 kV, a single transformer can be used for test purpose.

=> for higher voltage requirements, a single-unit construction becomes difficult and costly due to insulation problems. Moreover transportation and erection of large transformers become difficult.

=> These drawbacks are overcome by series connection or cascading of the several identical units of transformers.

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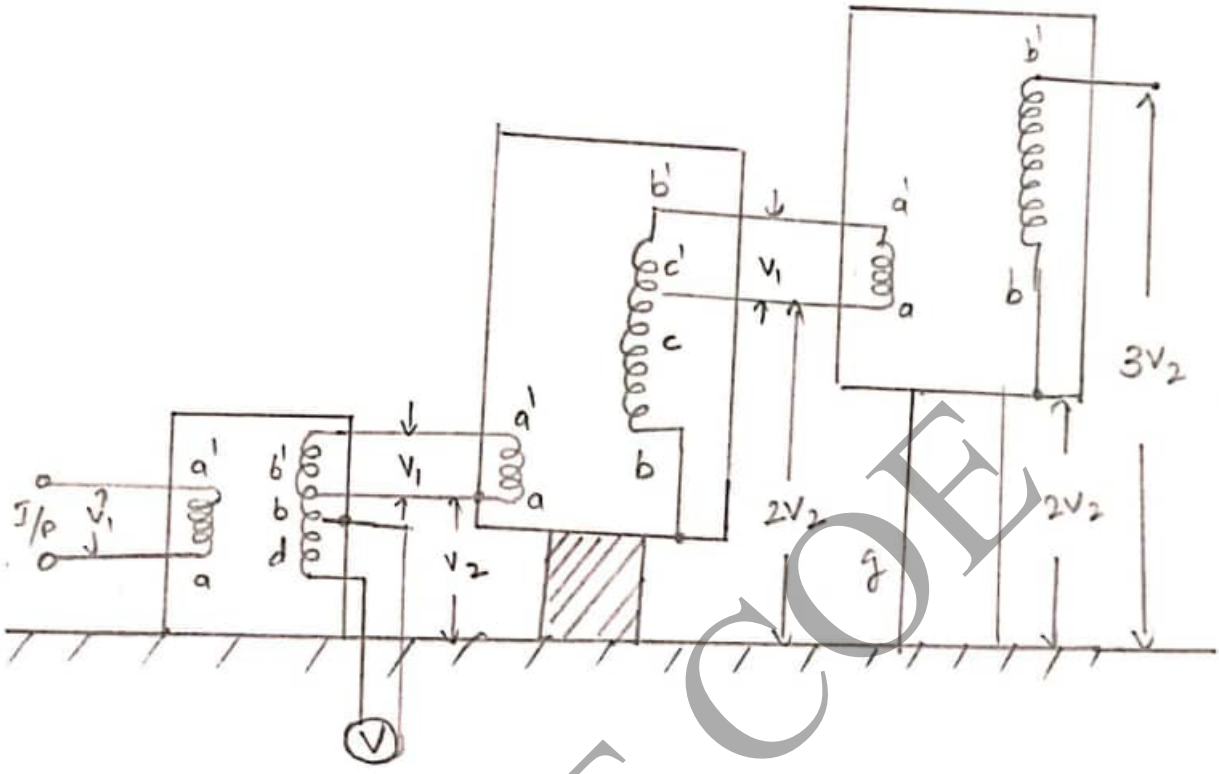
Cascade transformer Connection



V_1 – Input voltage V_2 – output voltage

g – Insulation support aa' – LV primary winding

bb' – HV secondary winding cc' → excitation winding

bd → Meter winding (200 to 500V)

⇒ The first transformer is at the ground potential along with its tank. The second transformer is kept on insulators and maintained at a potential of V_2, the output voltage of the first unit above the ground.

⇒ The high voltage winding of the first unit is connected to the tank of the second unit.

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⇒ The low voltage winding of this unit is supplied from the excitation winding of the transformer

⇒ The high-voltage connection from the first transformer winding and the excitation winding terminal are taken through a bushing to the second transformer.

⇒ In similar manner, the third transformer is kept on insulators above the ground at a potential of $2V_2$ and is supplied likewise from the second transformer.

⇒ The number of stages in this type of arrangement are usually two to four, three stages are adopted to facilitate a three phase operation so that $\sqrt{3}V_2, V_2$ can be obtained between the lines.

Typical capacitance values for high capacitance test object like power tranformers, cables, etc as follows.

Power transformers	1000 pF
Power cables (solid insulation)	250 - 300 pF/m
Power cable (gas insulation	50 - 80 pF/m

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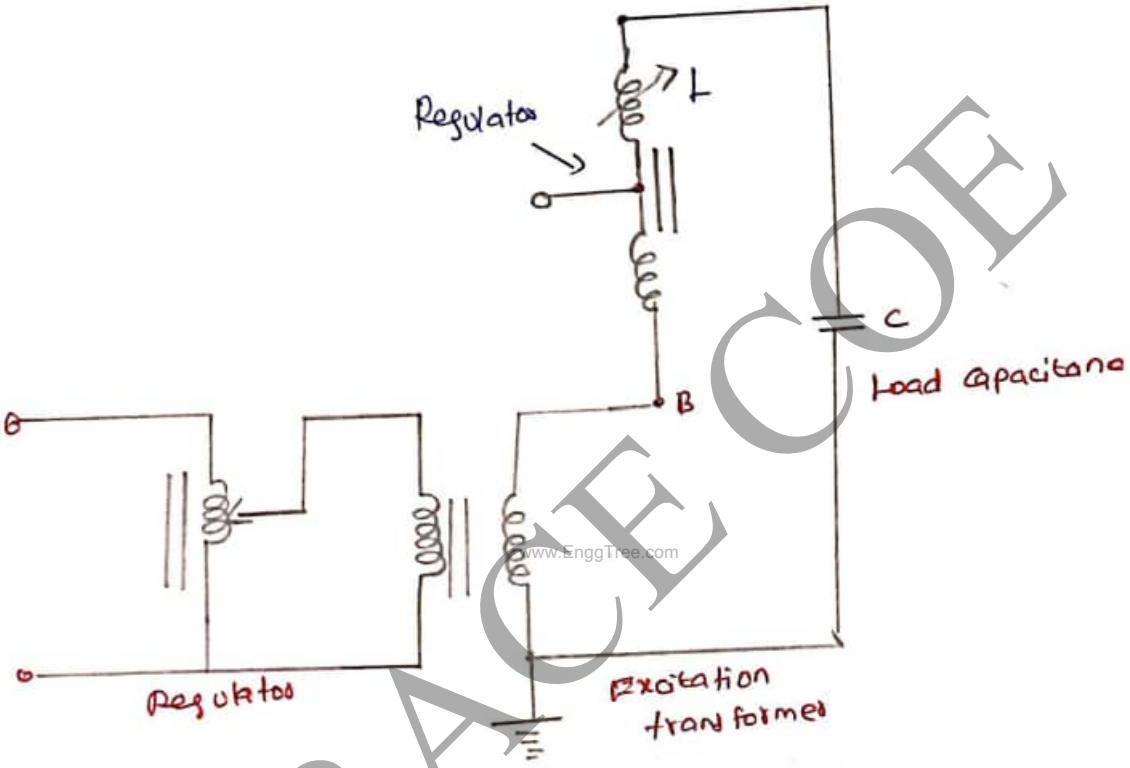
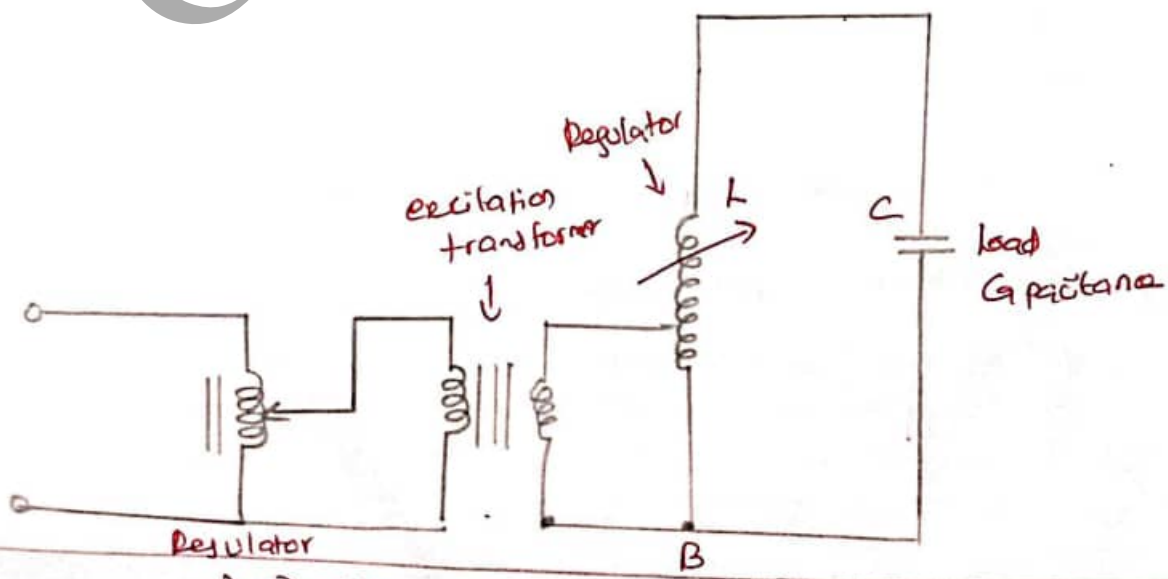
Resonant transformer.

i) series resonant AC test system

ii) Parallel resonant AC test system



a) series resonant AC test system



b) Paraller resonant AC test system

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=> A voltage regulator of auto transformer type is connected to the supply main and secondary winding of the exciter transformer is connected across the high voltage reactor L and the capacitive load C.

=> The inductance of the reactor L is varied by by varying its air gap and operating range is set in the ratio 10 : 1.

=> Capacitance C comprise of the capacitance of the test object, capacitance of measuring voltage divider, capacitance of the high-voltage bushing, etc.

=> In parallel resonant mode, the high voltage reactor is connected as an auto tranformer

=> The advantages of the parallel resonant circuits is that more stable output voltage can be obtained.

=> Single-unit resonant test systems are built for out voltage up to 500 kV, while cascaded units for outputs up to 3000 kV, 50/60 Hz are avilable.

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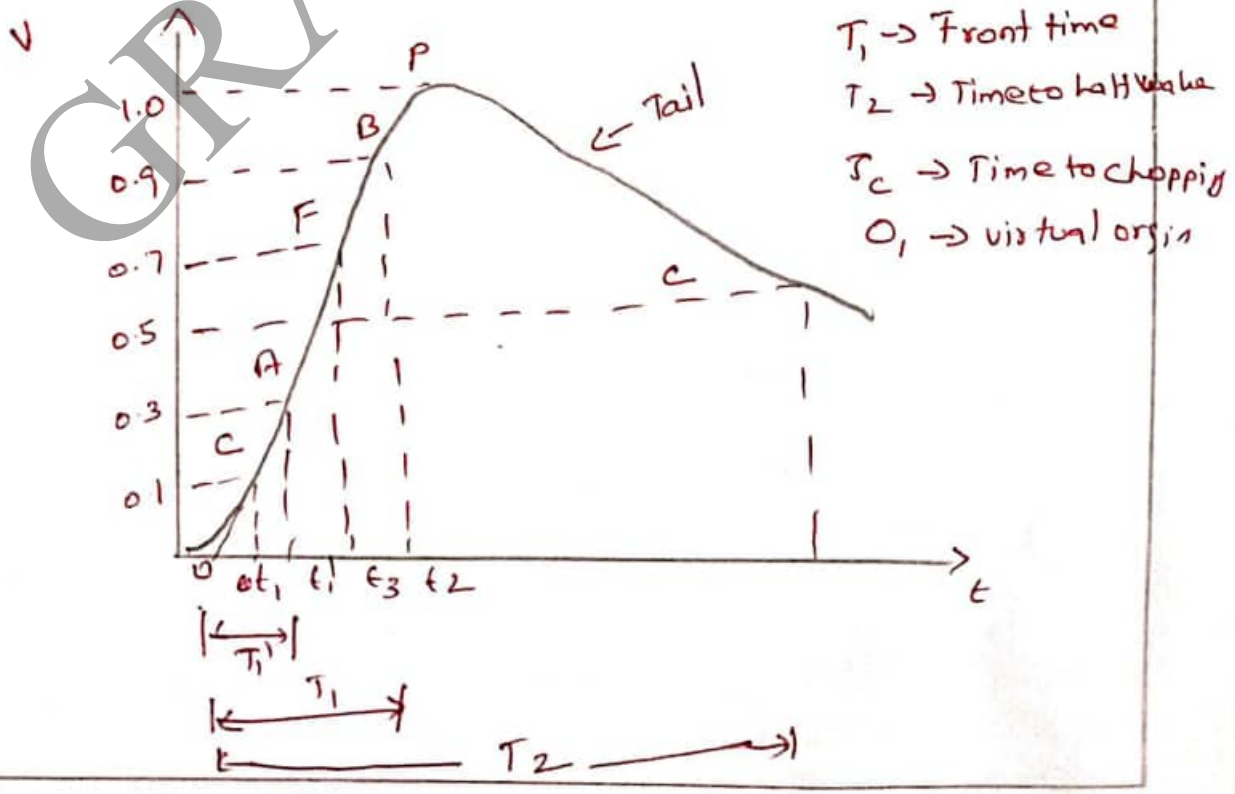
Generation of impulse voltages.

i) standard Impulse waveshapes.

⇒ The international standard lightning impulse waveform is an aperiodic voltage impulse that does not cross the zero line which reaches its peak in 1.2 μsec and then decreases slowly in 50 μsec.

⇒ The standard impulse waveform is unidirectional and has a rapid to peak and slowly falls to zero. The impulse wave chopped on the tail and the front is shown in figure.



standard Impulse waveform.

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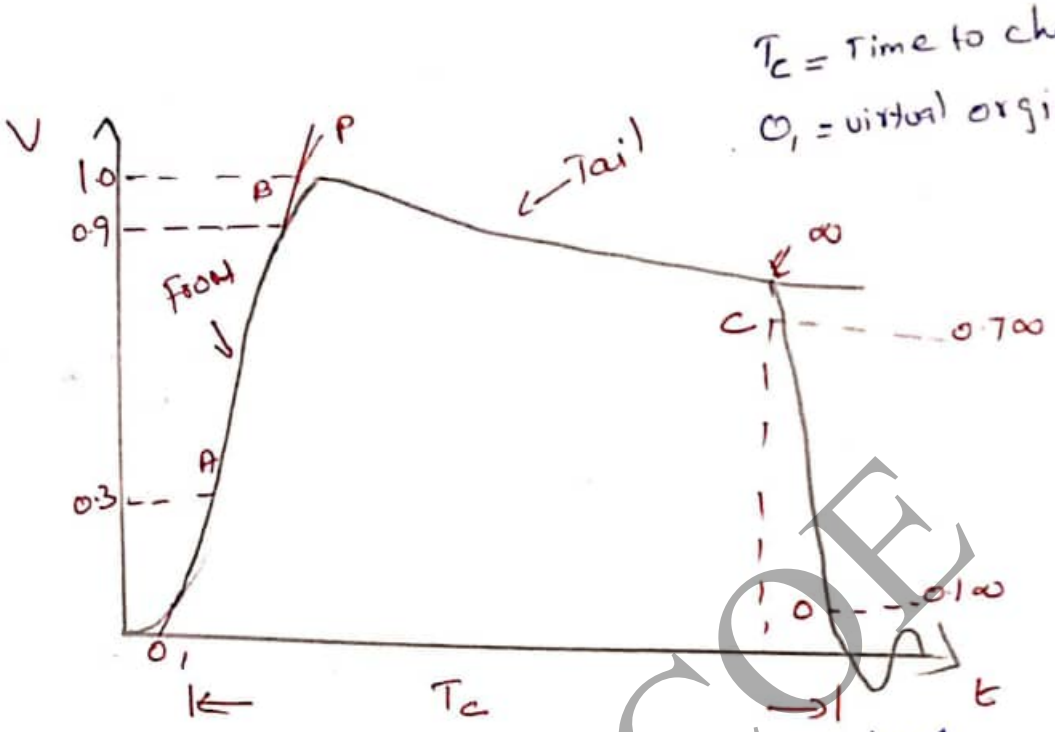
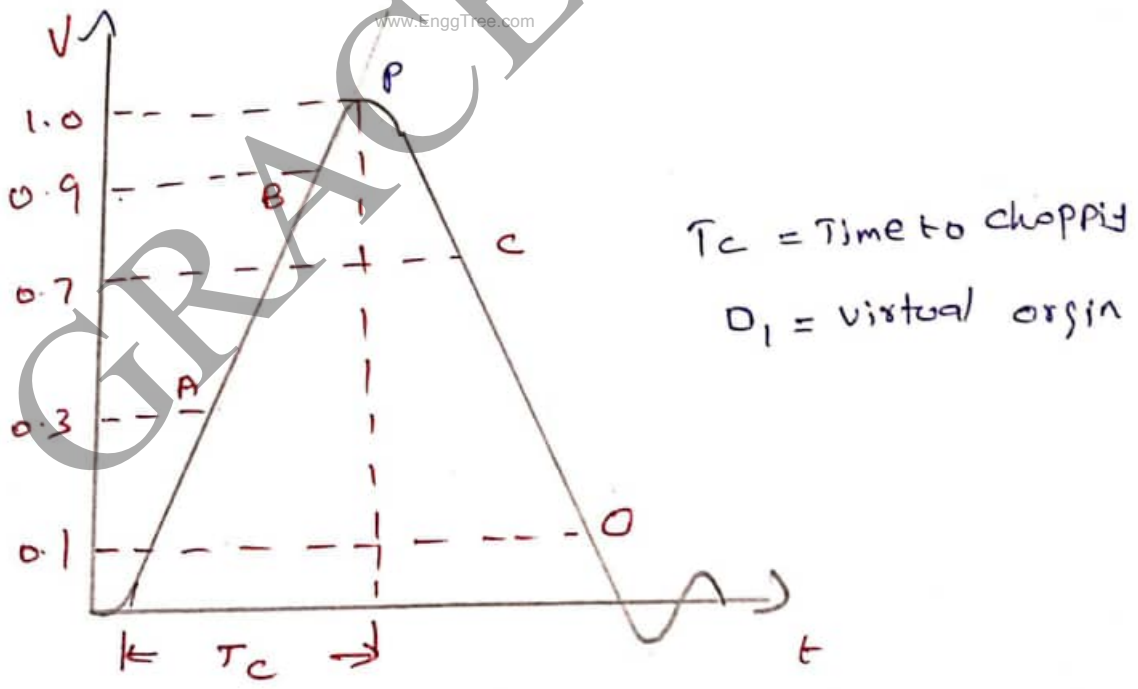


(b) impulse wave chopped on the tail



(C) impulse wave chopped on the front

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The impulse waveform can be specified by

⇒ Rise or front time

⇒ Fall or tail time to 50%. Peak value

⇒ Delay time

Rise (or) Front time

⇒ It is required for the response to raise from 10 % to 90% (or) 100% of the final value at the very first instance.

⇒ Rise time of standard impulse wave of 1.2/50 μs, 1000 kV = 1.2 μs

Fall or) Tail time

⇒ The magnitude of the oscillation present in the output time decreases. Fall time to reach 50 % peak value.

⇒ $1.2/^{50}_{\mu s}$, 100 kV = 50 % of Peak value of 50 μs.

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Peak value. ⇒ The maximum positive deviation of the output with respect to its desired value is known as peak value

Impulse wave can be defined as $V = V_0(e^{-\alpha t} - e^{-\beta t})$

where, α, β are constant in μsec

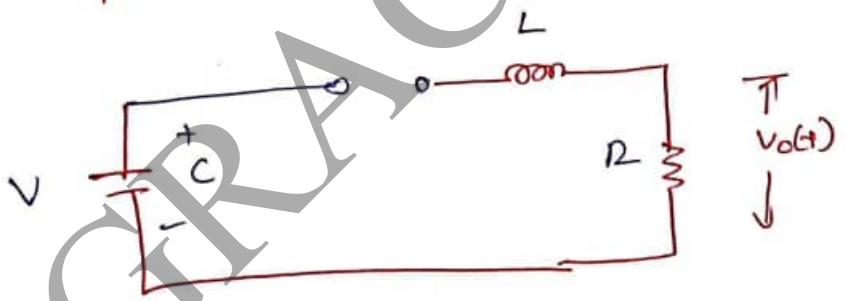
1.2/50 μs ; 1000kV = 1000k

Front time.

Lets P as be the peak value, i.e 100% value or 1.0 p.u

Front time. $= 1.25 (O_1 t_2 - O_1 t_1)$

Series RLC circuit under overdamped condition for producing Impulse wave.



⇒ Capacitance C of the generator is charged from D.C source to suitable voltage V.

For RLC series circuit,

$$V = \frac{1}{C}\int_0^t i(t)\,dt + L\frac{di}{dt} + Ri$$

At $t = 0$, $i(0) = 0$

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$$\frac{V}{s} = \frac{I(s)}{Cs} + Ls\,I(s) + R\,I(0)$$

$$= \left[\frac{1}{Cs} + Ls + R\right] I(s)$$

$$= \frac{LCs^2 + RCs + 1}{Cs}\, I(s)$$

$$V = L\left[s^2 + \frac{R}{L}s + \frac{1}{LC}\right] I(0)$$

Current through resistance R

$$I(s) = \frac{V}{L\left[s^2 + \frac{R}{L}s + \frac{1}{LC}\right]}$$

output current $V_0(s) = R \cdot I(s)$

$$= \frac{R \cdot V}{L\left[s^2 + \frac{R}{L}s + \frac{1}{LC}\right]}$$

Roots of $s^2 + \frac{R}{L}s + \frac{1}{LC}$ are

$$s = \frac{-\frac{R}{L} \pm \sqrt{\left(\frac{R}{L}\right)^2 - \frac{4}{LC}}}{2}$$

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$$s = -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

$$s_1 = \alpha = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

$$s_2 = \beta = -\frac{R}{2L} - \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

For an over damped case, $\frac{R}{2L} \geq \frac{1}{\sqrt{LC}}$

$$\frac{RV}{L(s+\alpha)(s+\beta)}$$

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Applying Partial fraction and inverse transform, we get

$$V_0(t) = \frac{RV}{2L\sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}} \left(e^{-\alpha t} - e^{-\beta t}\right)$$

⇒ wave front time or β can be determined by choosing suitable value of L.

⇒ wave tail or β & α can be determined by choosing suitable value of R.

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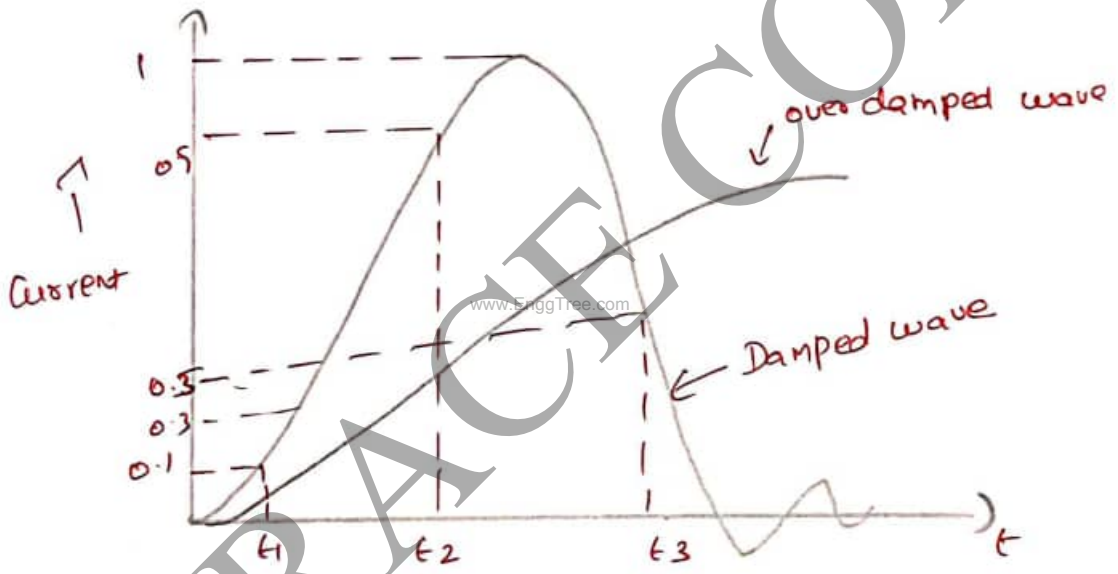
Impulse current Generation.

⇒ To test lightning arrester which discharge the lightning current safely.

Impuse current waveform.



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⇒ Standard impulse current wave used for testing lightning arrester are 8/20 μsec. Tolerance allowed is ± 10%

⇒ A Bank of capacitance connected in parallel are charged and discharged through R-L series circuit.

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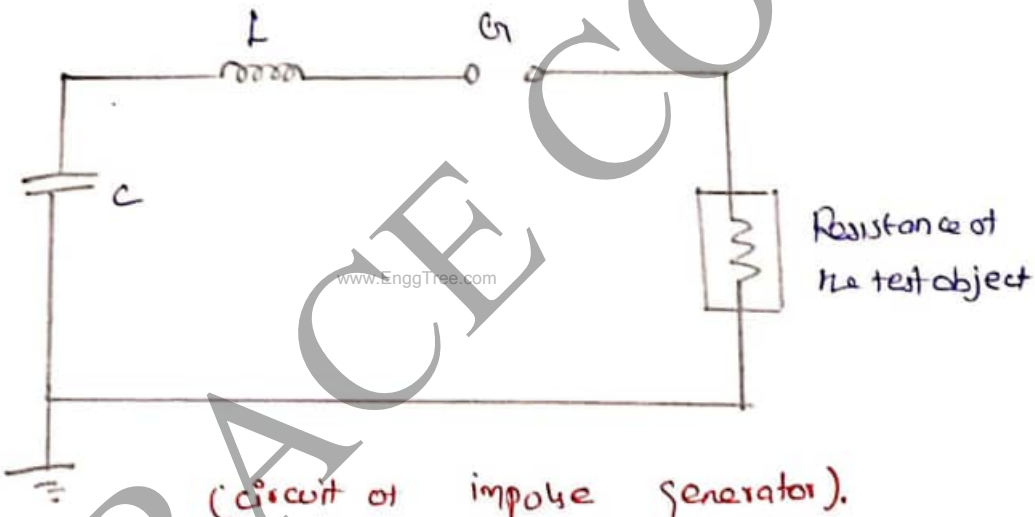
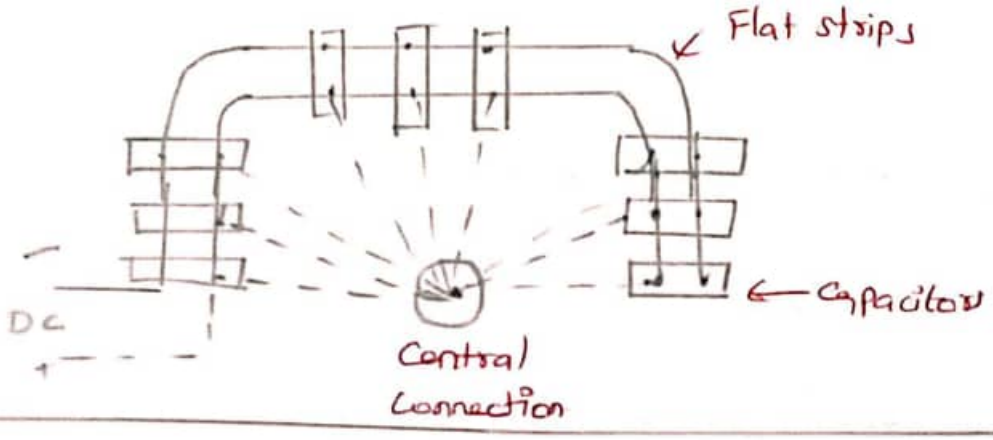
=> Effective inductance of the unit can be reduced by sub-dividing the capacitance into groups of smaller units in parallel

=> Co-axial can be used because of inherently very low inductance between capacitors



(Circuit of impulse generator).

The arrangement of capacitors for producing impulse current wave is shown in figure.



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If the capacitors is charged to a voltage V and discharged when spark gap is triggered, voltage equation is

$$V = iR + L\frac{di}{dt} + \frac{1}{C}\int i\,dt$$

Taking Laplace transform

$$\frac{V}{s} = R\,I(s) + Ls\,I(s) + \frac{1}{Cs}I(s)$$

$$I(s) = \frac{V}{s\left[R + Ls + \frac{1}{Cs}\right]} = \frac{Vc}{Lc^2 + RCs + 1}$$

$$I(s) = \frac{V}{L\left[s^2 + \frac{R}{L}s + \frac{1}{LC}\right]}$$

Roots of $s^2 + \frac{R}{L}s + \frac{1}{LC} = 0$ are

$$s = \frac{-\frac{R}{L} \pm \sqrt{\left(\frac{R}{L}\right)^2 - \frac{4}{LC}}}{2}$$

$$= -\frac{R}{2L} \pm \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}$$

$$\alpha = \frac{R}{2L} \quad | \quad \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

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Maximum current, $I_m = \frac{V}{\omega L} e^{-\alpha t}$

energy co $= \frac{1}{2} C V^2$

Triggering and Control of Impulse Generator

=> A self triggering by a fast mechanical closure of the first gap is used to avoid due to dust particle. But, this method cannot be used to synchronize the impulse voltage with other events within a short time.

=> Synchronization is necessary to initiate the time sweep of oscilloscope which is to be used to record wavefront of the transient wave.

=> The oscilloscope has to be triggered slightly before the impulse wave reaches the deflection plates so that to record the wavefront.

=> The first stage of the impulse generator is fitted a three electrode gap (top, bottom, middle.

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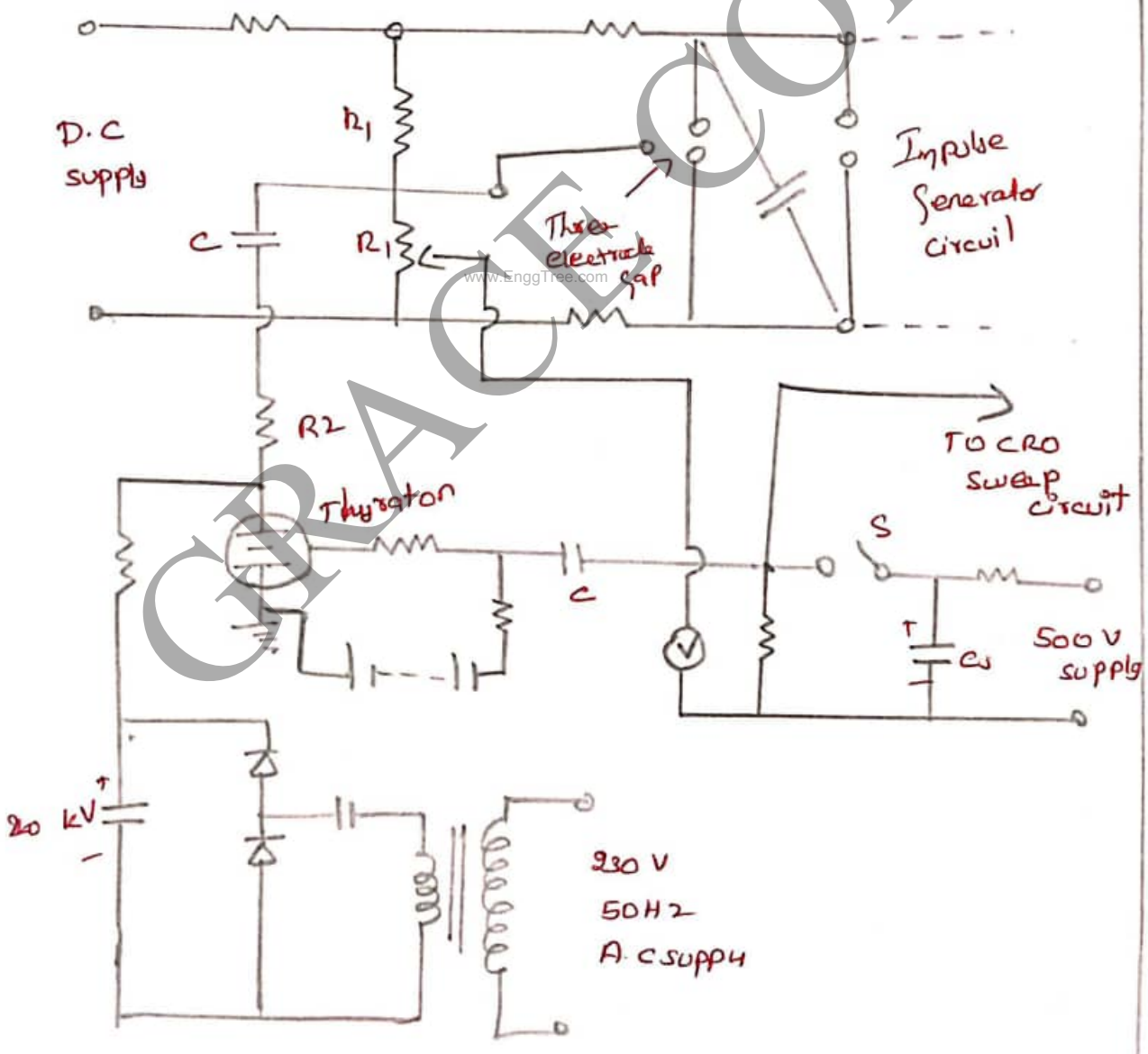
=> The top and bottom electrodes are supplied by D.C supply. The centre electrode is maintained at a potential in between that of top and bottom electrodes with resistance R_1 and R_1. This three electrodes gap is triggered by using thyratron.



Triggering of Impulse generator

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=> when closing the 's', the trigger is initiated by applying a pulse to thyratron C_1. The pulse also initiates the oscillascope time base.

=> The thyratron conducts and produces negative pulses to the central electrode of three electrode gap through capacitance C_1.

=> potential across the central and top electrode is maintained at higher than sparking potential and the gap conducts.

- The time lag required for the thyraton firing and breakdown of three electrode gap ensures that the sweep circit of oscillascope begins before the start of the impulse generator.

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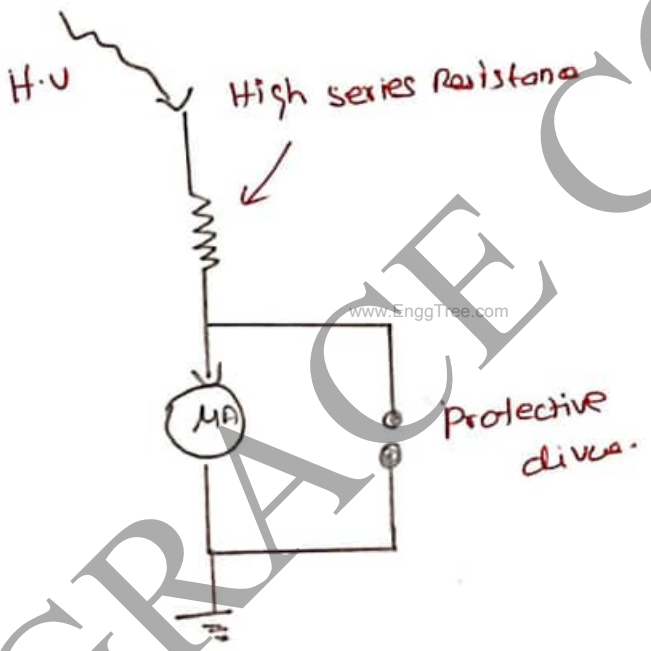
Measurement of DC voltage

i) ohmic series Resistance with Micro ammeters.

A high resistance, i.e. few hundreds of mega ohms is connected in series with a micro ammeter (μA)



=> A Protective device like paper cap, a neon glow tube or zener diode with suitable resistance is connected across the micro ammeter.

=> It is used to protect the meter against high voltage (H.V) occurs due to failure of high series resistance.

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=> A current of 1 to 10 μA is allowed for one full scale defection.

=> It consists of large number of wire wound resistor in series.

=> To provide corona free termination

=> Temperature coefficient $< 10^{-4}$ °C

=> To maintain very good temperature stability.

=> Current I flowing through resistance R is measured using microammeter

=> voltage of the source $V = IR$

=> If any over voltage occurs, the protective device will come into action to bypass the current.

=> series ristance meter can operate upto 500 KV (D.C)

Accuracy = ± 0.2%.

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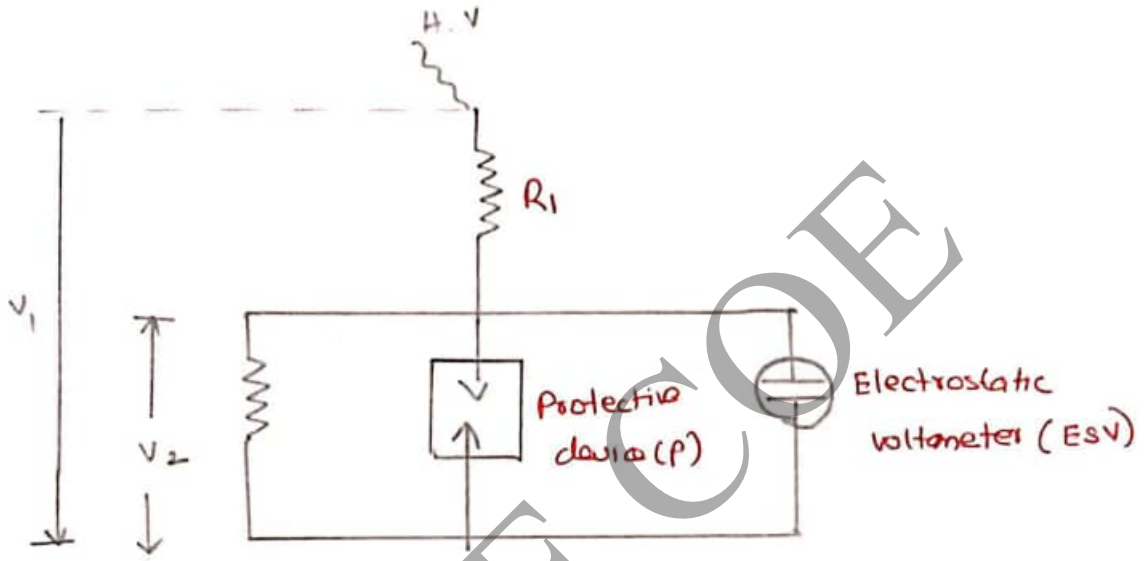
ii) Resistance Potential Dividers.

A resistance potential divider for D.C voltage measurement with an electrostatic voltmeter.



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Let V_2 be the d.c voltage across resistance (R_2) (low voltage)

$$V_2 = V_1 \times \frac{R_2}{R_1 + R_2}$$

High voltage magnitude, $V_1 = \frac{R_1 + R_2}{R_2} \cdot V_2$

⇒ Sudden voltage change occur during transient period due to

⇒ Switching operation

⇒ Flashover of test objects

⇒ Damage may occur to the diverter elements due to stray capacitance across the elements and due to ground capacitance.

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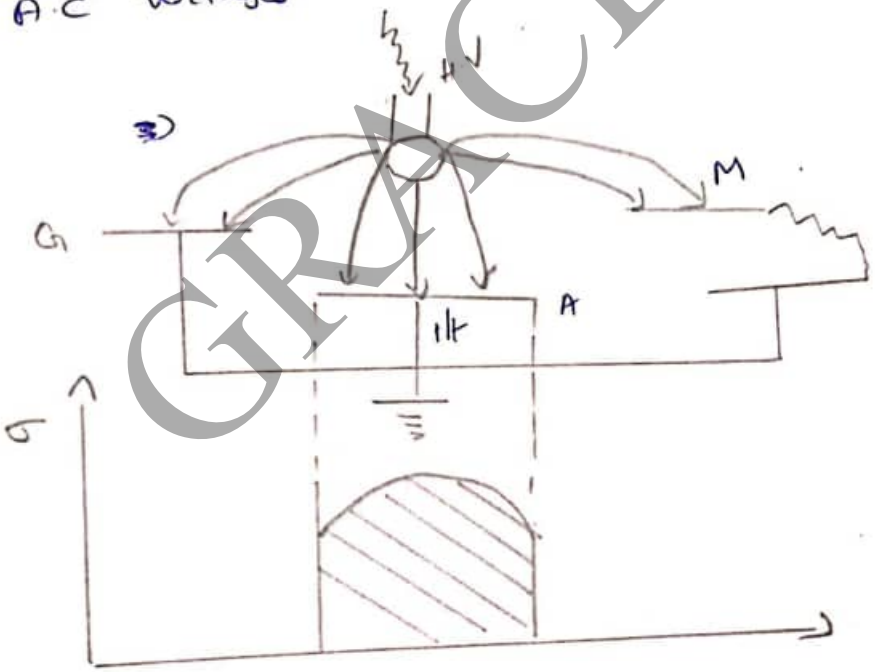
Generating voltmeter

=> High voltage D.C measurent, the generating Principle is used when source loading is not permitted.

=> A generating voltmeter is a variable capacitor electrostatic voltage generator which generate current proportional to the voltage to be measured.

=> It provides loss free measurement of D.C and A.C voltages.

3)



=> High voltage electrode excites the electrostatic field within a highly insulating medium (gas or) vaccum) and ground potential.

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UNIT IV

High voltage Testing and Insulation Co-ordination

Need of Testing for over voltage

⇒ High voltage testing of electrical apparatus is essential to ensure that the electrical equipment is capable of withstanding the over voltages

⇒ The over voltages may be either due to natural cause like lightning or) switching voltages.

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Definitions

i) Disruptive Discharge Voltage

⇒ The voltage which produces the loss of dielectric strength of an insulation.

⇒ when a discharge takes place between two electrode in gas or a liquid over solid surface in air, it is called flashover.

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=> If the discharge occurs through a solid insulation, it is called Puncture.

b) withstand Voltage

The voltage which has to be applied to a test object under specified condition in withstand test is called withstand voltage

c) Flash over Voltage

The voltage that causes a flashover at each or its application under specified conditions when applied to test object.

d) Wet and Dry Power Frequency test

The voltage specified in a specification is applied und try or wet condition for a specified period

h) Impulse voltages.

characterised by Polarity, Peak value, time to front (t_f), and time to half the peak value.

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Indian and International standard Specification

⇒ According to Indian standard Specification,

Temperature : 27°C

Pressure : 1013 millibars

Absolute humidity : 17 gm/m³

⇒ According to British standard Specification

Temperature : 20°C

Pressure : 1013 millibars

Absolute humidity : 11 gm/m³

⇒ The flashover voltage of test object

$$V_s = V_a \times h/d$$

V_a = Voltage under actual test condition

V_s = Voltage under reference atmospheric

h = Humidity correction factor

d = Air density correction factor.

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Testing of Insulators

⇒ Insulators are the elements which provide necessary insulation between line conductors and supports and thus prevent any leakage current from conductors to earth

Types of Insulators

* Pin type
* Suspension type
* Strain
* Shackle
* Stay
* Stack.

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Type tests

⇒ These tests are intended to check design features and the quality

⇒ Type tests are done on samples when new design are introduced.

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Routine test:

⇒ intended to check the quality of the individual test piece.

⇒ to ensure the reliability of the individual test

Testing of Insulators and circuit Breakers.

Isolator is a mechanical switching device which provides in open position, and isolating distance in accordance with special requirements.

i) Electrical characteristics

- the arcing voltage
- the current chopping
- the residual current
- ars space and plasma
- shunting effect

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Physical Characteristics

=) Arc extinguishing Media

=) Pressure developed at the point of interruption

=) Speed of contact travel

=) Number of breaks

=) Sizes of breaks.

circuit Characteristics

=) Applied Voltage

=) Types of faults

=) Time of interruption

=) Frequency

=) Power factor

=) Restriking voltage

=) D.C Component

=) Rate of rise.

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tests on Isolators and CB

over Voltage Test

=> CB are checked their ability to withstand over voltage at normal condition and their ability to withstand abnormal voltage during lightning

Impulse voltage test.

=> Applying standard impulse voltage of 1/50 μsec wave under dry condition.

Power Freq test

=> Phase with earth with CB open

=> Phase with breaker closed

=> Across the terminal with breaker open

Short circuit Test

* Direct test
* Synthetic test
* Composite test

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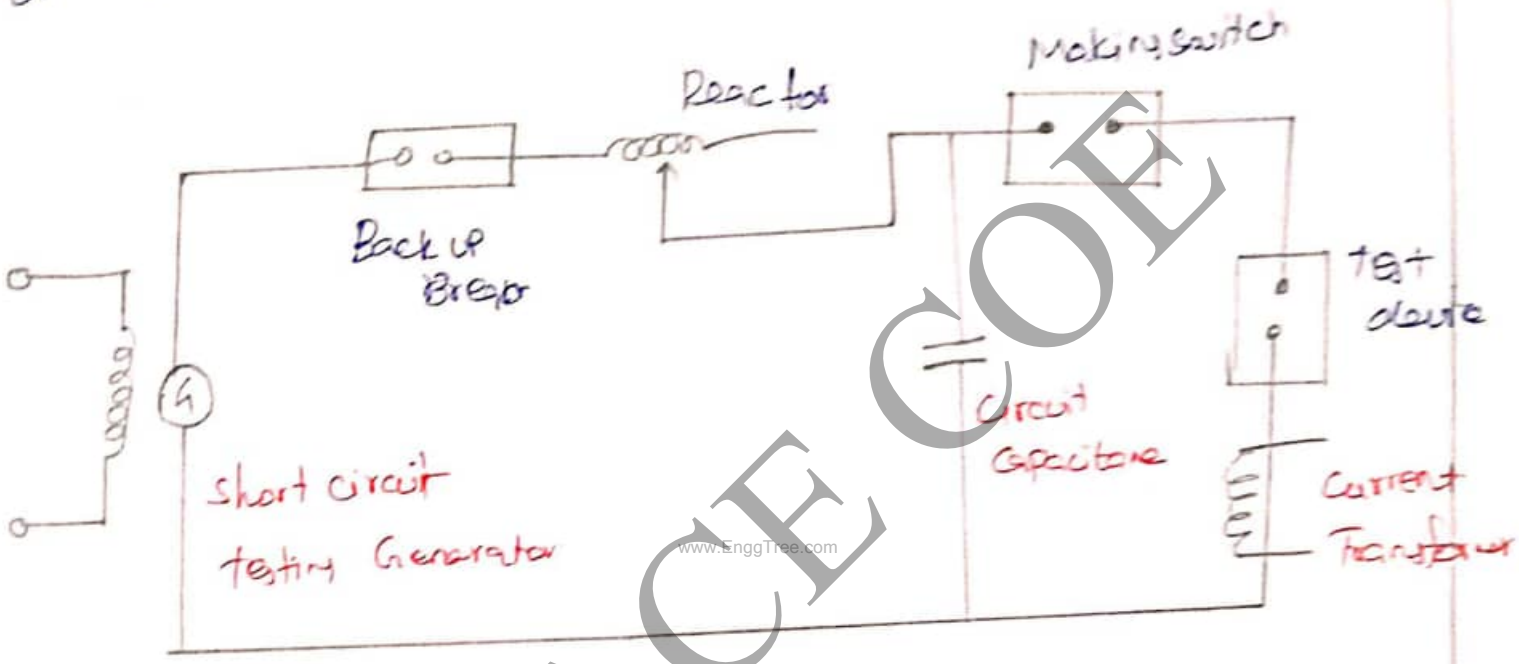
Direct testing

=> CB are tested for their ability to make or break the CB normal load conditions



=> The short circuit testing generator supplies current to the circuit. Induction motor may be used as prime movers

=> The making switch initiates the short circuit the breaker open & isolates the test device from source generator.

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Synthetic testing

⇒ A.C current source supplies the heavy at low voltage and then the recovery voltage is simulated by source of high voltage of small current capacity.

Composite testing

⇒ The CB is first tested for its rated breaking capacity at a reduced voltage and then for rated at low current.

Testing of Transformers :—

⇒ Transformer may damage due to transient over voltages of either lightning (or) Power freq. The test involves

i) Induced over voltage test

ii) Partial discharge test

iii) Impulse testing.

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i) Induced over voltage Test.

* Reduce core saturation
* Limit the charging current necessary
* Check the insulation withstand strength.

ii) Partial Discharge Test

=> The test is carried out on the winding of the transformer to assess the discharge magnitudes and the radio interference levels.

iii) Impulse test.

=> Impulse testing of transformers is used to determine the ability of insolation to withstand the transient voltages due to lightning.

=> By applying Impulse voltages, the distribution of voltages in the network is not

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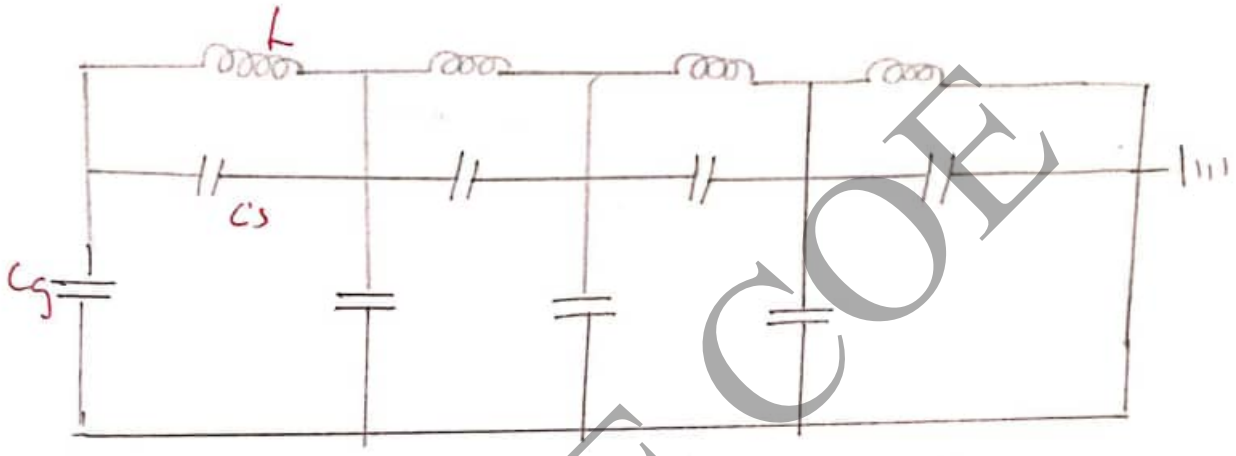
Uniform and oscillations are produced which have a magnitude higher than that of applied voltage.



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L = Inductance

Cs = self Capacitance

Cg = Ground Capacitance.

Impulse testing can be done by the following tests.

⇒ Applying impuls voltage of magnitude 75%.

⇒ one full wave voltage of 100% BIL

⇒ Two chopped waves of 100% BIL

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This test is essential to

⇒ Record the applied voltage curve

⇒ Record the current through the winding

⇒ Record the transferred voltage.

Testing of Surge Arresters :-

⇒ A surge arrester is a device used to protect the system transient voltage s due to lightning and switching surges. They can be installed to protect Distribution and transmission System

The following tests on surge arresters

⇒ Power frequency spark over test

⇒ 100 % standard Impulse spark over test

⇒ Residual Voltage test

⇒ High current impulse test

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Power frequency test :-

⇒ The arrester has to withstand at least 1.5 times the rated value of voltage. This test is repeated for 5 times. The arrester withstands means the surge arrester is said to have passed. This test done under both wet and dry conditions

Front of wave spark over test :-

⇒ This is done by applying steep fronted wave having a rate of rise of 100 kV/μs per 12kV rating.

Residual voltage test :-

Pre-rated arrester is an arrester including series gaps and non-linear resistors in the same proportion as in the complete arrester.

$$\frac{V_1}{V_2} = \frac{V_{R_1}}{V_{R_2}}$$

$$V_1 = V_2 \cdot \frac{V_{R_1}}{V_{R_2}}$$

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High Impulse test

When the impulse current wave of 4/10 μsec is applied to a pro-rated arrester in the range of 3 to 12 kV. This test is repeated two times. Allow the surge arrester to cool to the room temperature.

Testing of cables:

Different tests are conducted on cable are

i) Mechanical tests
   a) Bending test
   b) Dripping and drainage test
   c) Fire resistance test
   d) Corrosion test

ii) Thermal duty test

iii) Dielectric power factor test

iv) Power frequency test

v) Impulse withstand test

vi) Partial withstand test

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Testing of Bushings

⇒ power frequency test

⇒ Impulse voltage test

⇒ Thermal test

i) Power frequency test

Bushings are connected to the high voltage side of the line and are immersed in oil. The tank or earth is connected to the detector side of high voltage schering bridge

⇒ Fine voltage is applied in steps and then reduced. Capacitance and Power factor are recorded at each step

⇒ If the Power factor is high, efficiency is high the Bushings is high and have long life.

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Impulse voltage test

when the withstand impulse voltage of 1/50 usec wave is applied to the bushings both for positive and negative polarities.

⇒ the bushing is said to have failed if two flashover take place.

⇒ If one flash over occurs, then consecutive application of standard impulse wave and the bushing is said to have passed if no flash over takes place.

Thermal test:

⇒ some times the bushing is operated with the transformer, the temperature may increase beyond 80°c and thermal run away condition occurs. So, thermal stability test is essential.

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Insulation Co-ordination

The selection of suitable values for the insulation levels of the various components like transformers, circuit breakers, bus supports etc.

=) Choose insulation levels for components that would withstand all kind of overvoltages

=) consider Protective devices that could be installed at the sensitive points to limit overvoltages.

Necessity of insulation Co-ordination

=) To ensure reliability and continuity to the utility concerns.

=) To minimize the number of failures of line and substations due to voltages

=) To minimize the cost involved in the design, installation and operation of Protective devices.

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Insulation Problems :-

=> Determination of line insulation

=> selection of Basic Impulse Insulation Level (BIL)

=> selection of lightning arresters.

Lightning Impulse withstand Level (or) BIL

Basic ~~Concepts of~~ Impulse level is established for each system nominal voltage for different apparatus. various equipments should have their BIL value above the system protection level.

Voltage - Time characteristics.

Proper insulation co-ordination would ensure that the volt-time characteristics of the equipment.

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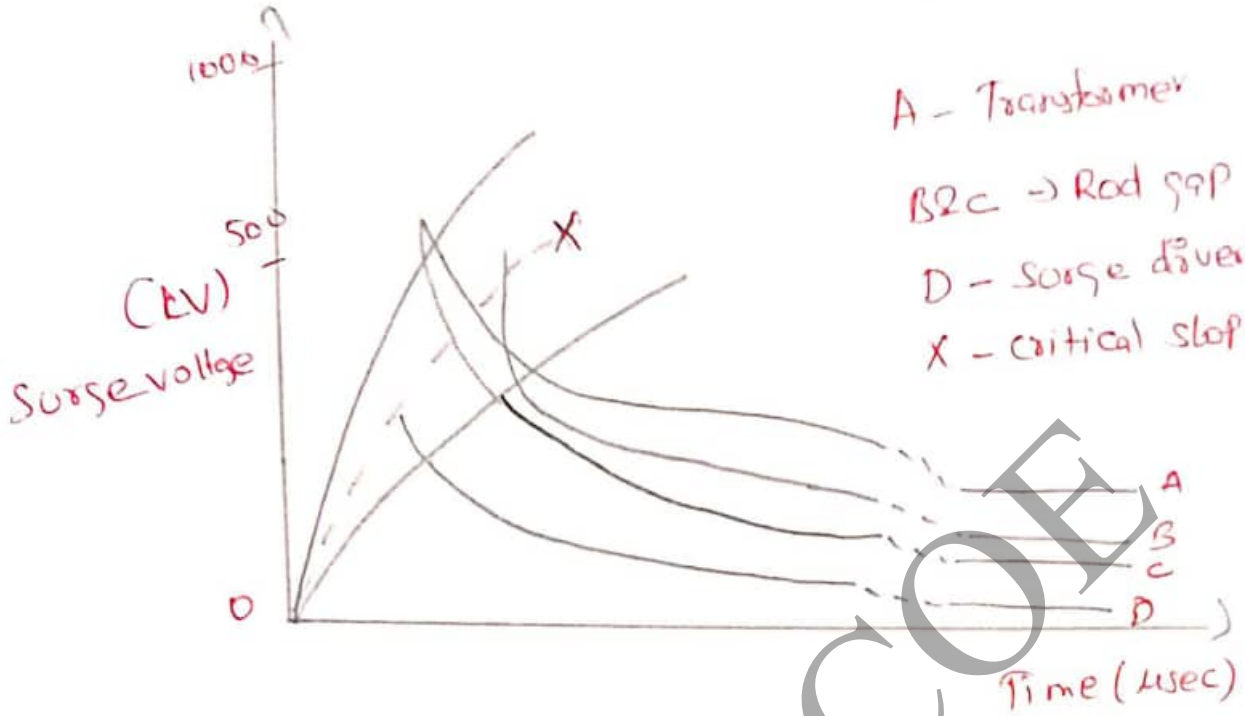

⇒ The rate of rise of voltage

⇒ Type of the system

⇒ ~~Zinc~~ operating characteristis

The selection of ~~dept~~ of surge arrester depends on the above parameters.

The following types of arresters are used for this purpose

⇒ silicon carbide arresters with spark gap

⇒ silicon carbide arresters with current limiting gap

⇒ zinc oxide.

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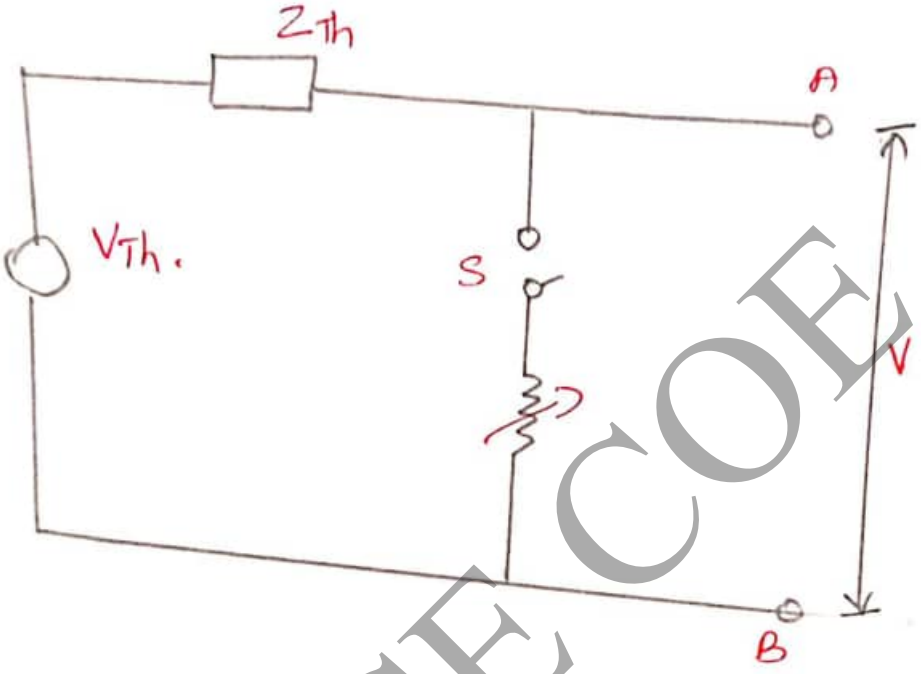
Equivalent circuit of surge arrester.



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$$V = 2(R+\gamma)(R+\gamma+Z)\,u(t)$$

where

R = Resistance of non-linear elements

γ = Ground to earth resistance

$u(t)$ = surge voltage.

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UNIT - V - Application in Industry

5.1 Introduction, Electrostatic Applications:

→ Electrostatics is currently found at the basis of many major industries related to environment preservation, communications, processing of mineral ore resources and so on.

→ In the majority of these industries, unique properties of high voltage electrostatic fields and forces are utilized to collect, direct, deposit, seperate (or) select very small (or) light weight particles.

→ the principles of application of electrostatics can be seen for selected industries like electrostatic precipitation, electrostatic seperation, electrostatic painting, electrostatic spraying of pesticides in orchards, electrostatic imaging, electrostatic printing, electret transducers, transport of light materials, paper manufacture, smoke detection, electrostatic spinning, electrostatic pumping, electrostatic propulsion, air cleaning from gaseous pollutants, ozone generation and biomedical applications

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5.2 Electrostatic Precipitation

precipitation

→ Electrostatic precipitation is the charging of dust particles in a gas and their subsequent seperation under the effect of electric field.

→ These processes may occur with a single zone (or) be distributed over 2 zones

(i) First zone is the charging zone to charge the particles

(ii) Second zone is the collecting zone to settle the particles.

→ The stream of ions charging the dust particles is produced by means of corona discharge in an inhomogeneous electric field.

entrain –

→ These ions interact with the particulates entrained in gas and impart charge to the dusts, which then experience a force towards collecting electrode where it is held by electrostatic forces until it is removed by mechanical rapping.

rapping –

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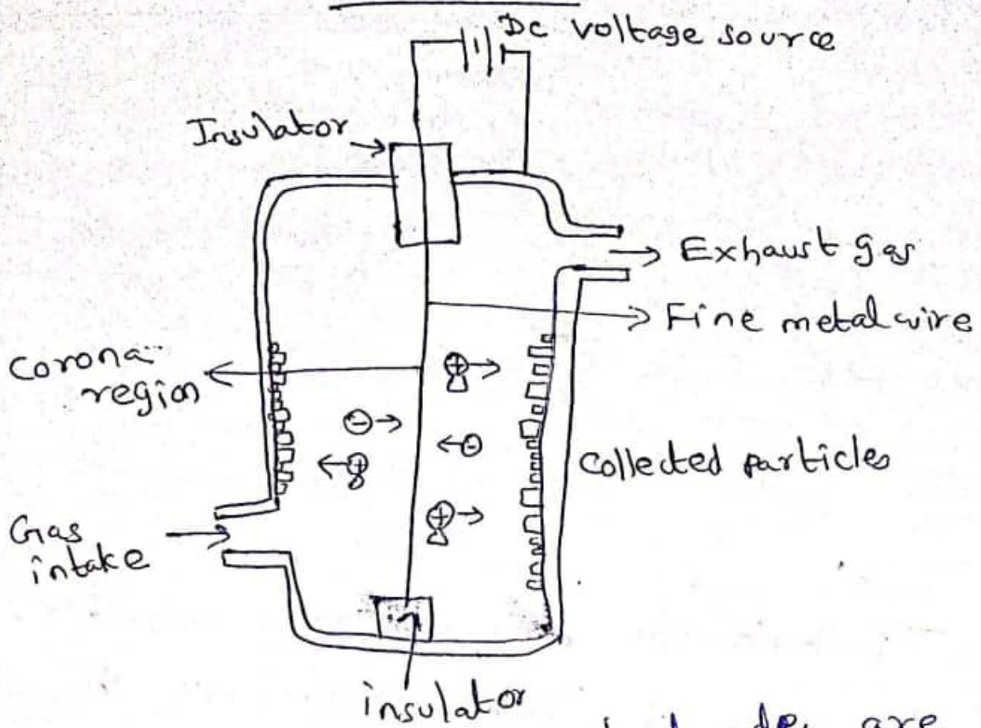
Pipe type electrostatic Precipitator



→ Two systems of electrodes are used in electrostatic precipitators to obtain an inhomogeneous electric field

(i) wire conductor enclosed in cylindrical pipe (pipe-type precipitators)

(ii) row of wire conductors located between plates (plate(or) duct type precipitators).

→ Electrodes around which a corona discharge is formed are termed as discharge electrodes, whereas the electrodes receiving charged dust particles, deposited by the action of electric field are collecting electrodes

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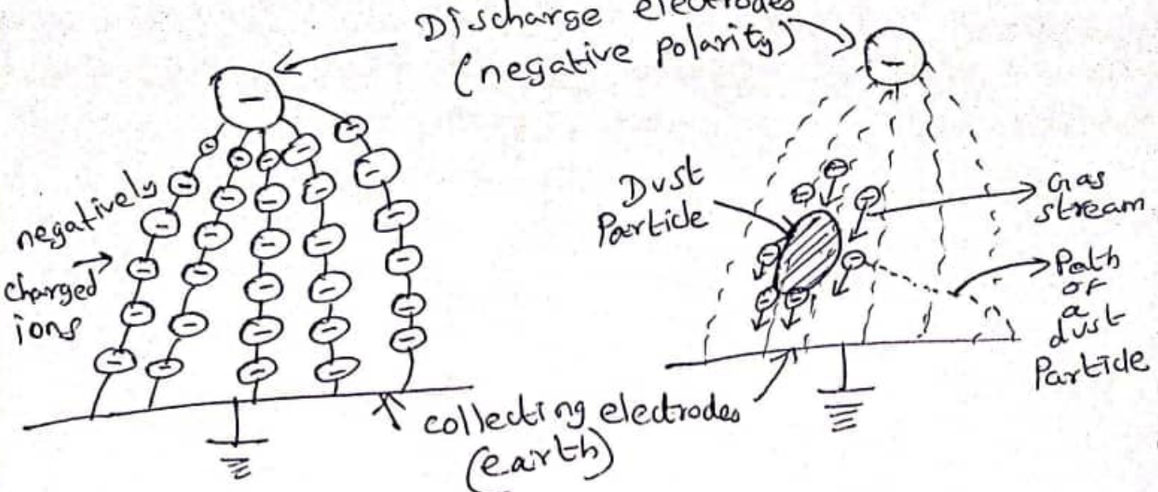
Schematic diagram of charging of dust particles in precipitator



bombardment

→ Particles are charged as a result of bombardment by ions energized in electric field, for particles larger than 1 μm and through collision with ions which participate in continuous thermal motion of molecules without the aid of an electric field for particles in sub micron range

→ Dust cake on collecting electrode has 10 - 50% dust, remaining being channels (cracks) filled with gas.

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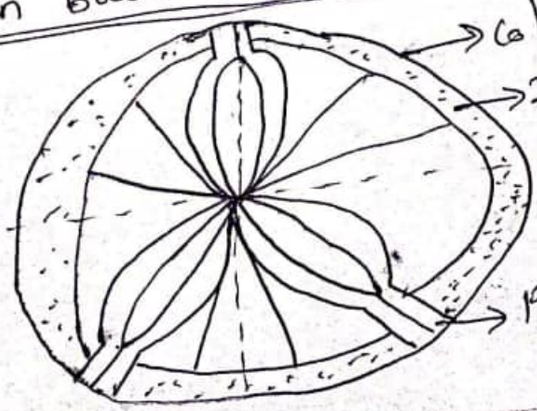
Schematic of arrangement of field lines on back corona formation



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→ Because of difference in relative permittivity of dust and gas, electric field lines concentrate inside the channels.

→ When voltage is high, electric breakdown occurs across dust cake and gas in the channels gets ionised. Outlet of each channel acts as a point discharge, on the collecting electrode. This phenomenon is termed back corona.

→ High resistivity particles cause back corona to be formed in precipitation layer and it has deleterious effects.

→ The most significant is the release of ions which gives counter current and partly neutralize charges, so that dust collection is adversely affected and current intensity increases, so that spark over voltage reduced and reduces Precipitator's performance.

deleterious

adversely

→ Pulse charging was proposed as an alternative solution to back discharge

→ A train of pulses, usually super imposed on a DC level value, provides high peak electric field for particle charging

→ Mean collector current not only depends on peak voltage but also on pulse duty cycle.

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→ In this way, voltage and current can be decoupled by changing mark/space ratio of applied pulses and high charging fields can be established without back discharge.

→ Pulse charging can produces a uniform distribution of ionic current on both discharge and collecting electrodes.

→ Disadvantage of pulse charging is ion shortage due to low current in high dust resistivity and result low charging rate

→ To overcome this, prechargers have been proposed.

→ Precharger system aims to seperate charging and collecting process into two seperate stages

→ In charging stage, different techniques are used to reduce back corona.

→ In collecting stage, it has only parallel plates and so that no back corona was formed.

→ Different types of precharger are developed and tested at various chargers.

→ precipitator efficiency can reach upto 99% by having various dimensions in gas duct and design parameters.

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5.3 (Electrostatic) Seperation:

→ Electrostatic seperation is the selective sorting of solid species by means of utilizing forces acting on these species in an electric field.

→ Main items of the seperator are

(i) charging mechanism in the charging zone
(ii) external electric field in the seperating zone
(iii) feed and product collection system.

→ Charging of 2 different species entering the seperating zone results in

a) Partides bear electric charges of opposite sign

(or)

b) only one type of particle bears an electric charge

(or)

c) Particles bear the same sign of charge, but different magnitude.

→ The common mechanisms to charge solid particles are

① Charging by contact and frictional electrification is the mechanism frequently used to charge and electrostatically seperate two species of different materials such as phosphate and quartz. The ore composed of

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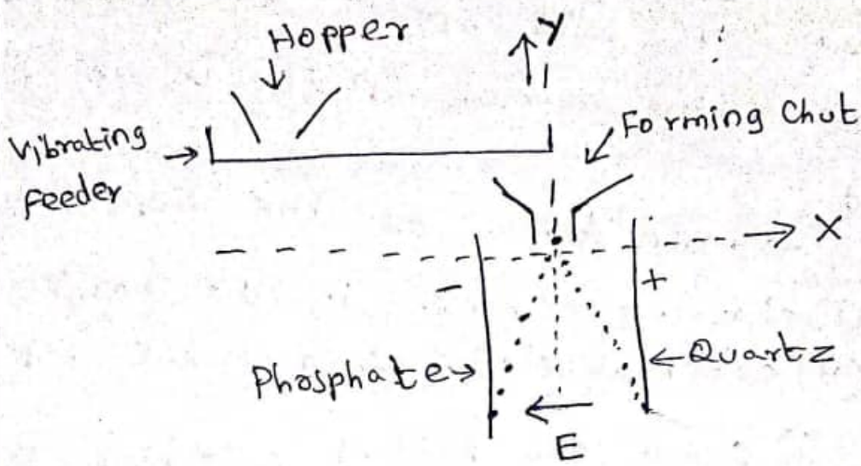
hopper - quartz and phosphate small particles is vibrated from hopper to forming chute.

chute -



→ Phosphate particles enter seperating zone with a net positive while quartz particles bear a net negative charge.

→ A coal beneficiation system have been developed on basis of electrostatic seperation where external field in seperation zone deflects coal rich and ash rich particles in opposite directions towards collecting plate compartments

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② Charging by ion (or) electron bombardment is used, in which solid particles pass through corona discharge from a fine wire (or) a series of needle points positioned parallel to a grounded rotor of seperator. Particles are charged by bombardment with corona ions. The charged particles rapidly share their charge with grounded rotor and are thrown

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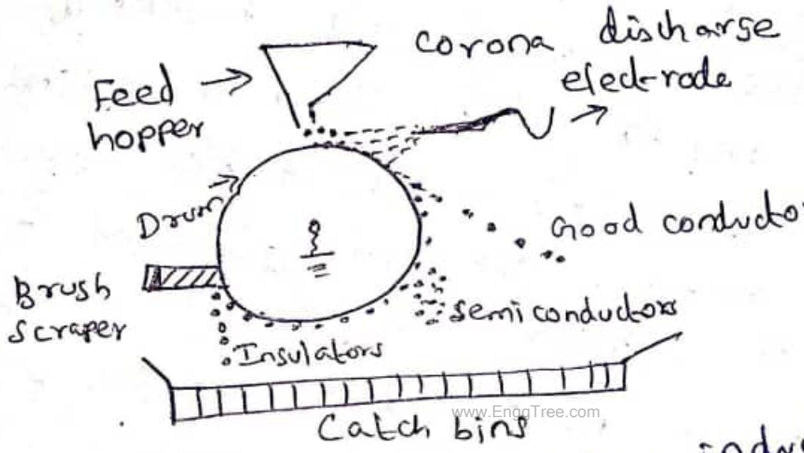
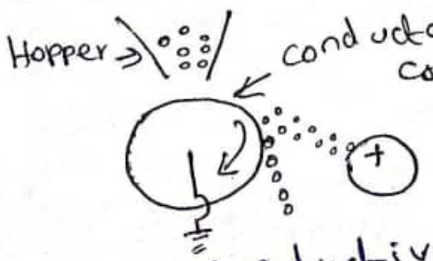
from rotor in a trajectory by centrifugal force, gravity and air resistance

→ Dielectric (or) poorly conducting particles lose their charge slowly and so held to rotor surface by image force in charge.

→ The well conducting particles are thrown free of the rotor by centrifugal force and gravity combination.



(3) Charging by conductive induction is a charging mechanism suitable for seperating well conducting particles from well insulating particles. A grounded rotor is located close to a positive drum.



→ when conductive particle coming from hopper pass over the rotor, they become negatively charged and attracted towards the positive drum. However insulating particles fall down by gravity

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5.4 (Electrostatic) Painting / coating:

→ This is a kind of electrostatic precipitation of powder (or) liquid paint on the surface of an object to be coated (or) painted.

→ In liquid paint, a liquid jet issues from reservoir and extends along the axis of a concentric charging cylinder where a potential V_p is applied between jet and cylinder.

→ Jet charges and breaks up into charged droplets while it is in cylinder.

→ The electric field plus space charge effects between jet and grounded object deposit the paint droplets on surface of object to be painted, not only on front side but also on back side of object.

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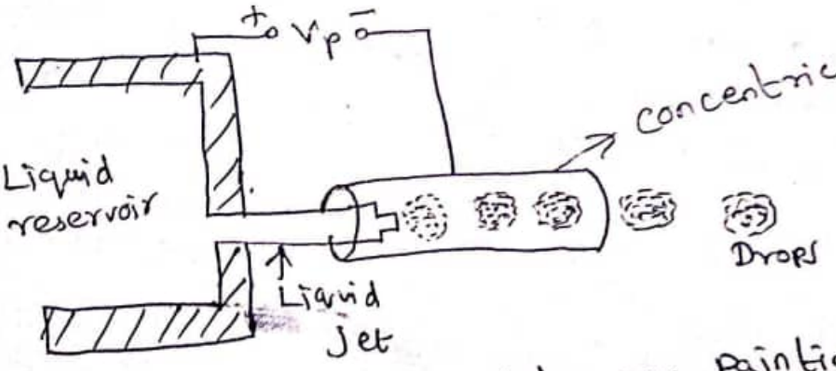

Liquid droplets for painting

→ In powder painting, paint particles are charged by bombardment with corona ions moving under influence of electric field between corona electrode and object being grounded.

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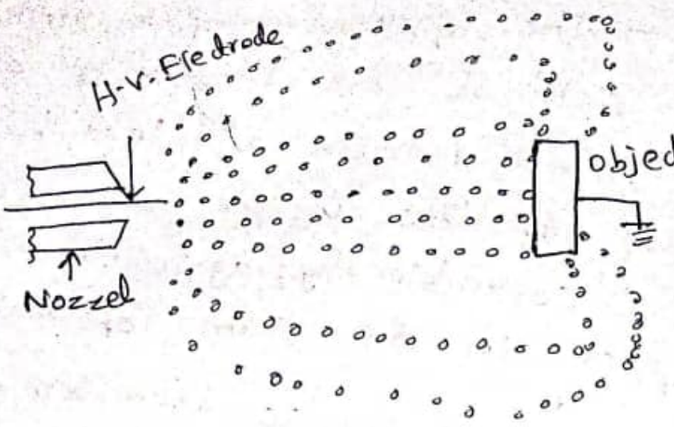
Powder Painting



craters - various

→ Paint precipitation stops at a certain thickness called "limiting thickness" because of back discharge, which results in craters that impair the qualities of finished coat.

→ The object to be coated is grounded and supported so that its surface can be approached without obstruction.

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→ Coating material, after being charged, is sprayed into space above the surface in form of finely divided particles.

→ There is an attraction of particles to the surface and as a result, they move toward and accumulate on surface to form coating.

→ Electrostatic painting is widely used in continuous coating lines of automobiles, electric appliances, furniture and so on.

→ Various electrostatic coating differ from one another by simple modifications in particles.

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5.5 (Electrostatic) Spraying

→ The application of a sufficiently high voltage field at the surface of a liquid coming from a nozzle will lead to the formation of charged droplets in the form of a spray

→ Conventionally, agricultural pesticides are applied in the form of water based sprays using hydraulic-atomizing nozzle.

→ Major problem in this method, is that a large portion of the spray is lost and target deposition efficiency is less than 25%.

→ Spray loss and accordingly the deposition efficiency can be attributed to both wind drift out of target area (exodrift) and deposition of soil during process (endodrift)

→ As with industrial coating techniques, electrostatic pesticide spraying technology offers an attractive alternative, which will increase not only the pesticide deposition efficiency but the biological efficacy as well.

→ The reason behind this is the small droplet sizes that can be achieved in electrostatics based systems (ie) in addition to being essential for increasing the

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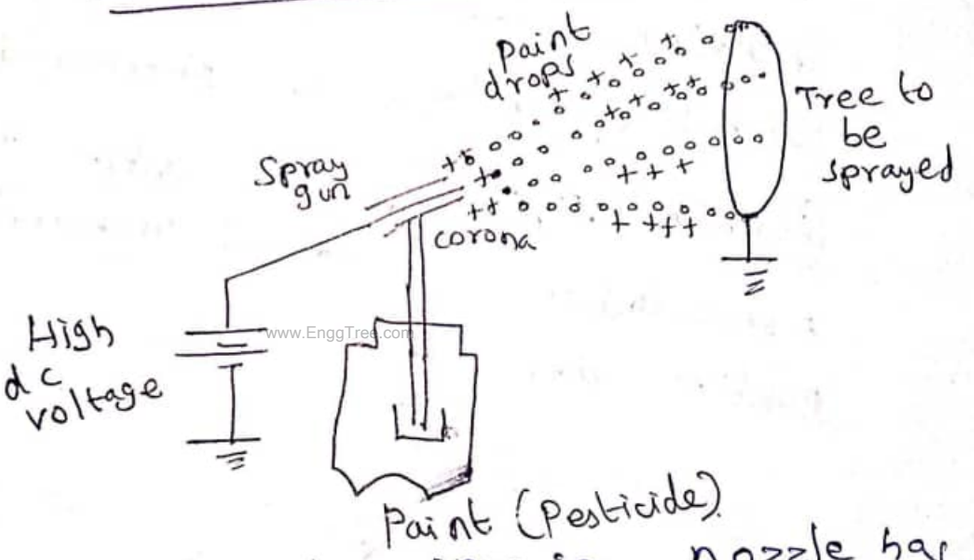
biological efficacy, the generation of small droplets will increase the droplet's charge to mass ratio.

→ This will increase coulomb force acting on droplet to a value, high enough to overcome mass dependent gravitational and inertial forces, with a subsequent increase of deposition efficiency of pesticides.

Electrostatic Spraying of trees



→ In pesticide spraying, nozzle has been developed to generate a concentrated jet which forms an electrified cloud inside the tree foilage.

→ Mutual repulsion of the particles and their coulomb attraction to the leaves ensure a superior coverage on both sides of leaves.

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5.6 (Electrostatic) Imaging

latent - hided

→ Electrostatic imaging is a process by which an ordered arrangement of electric charges is deposited on a surface as a latent electrostatic image and subsequently "developed" to convey visual information to an observer.

→ consider a system of metal plate (aluminium) covered by a very thin layer of insulating material (alumina), which in turn is covered by a layer of photo conducting material (selenium). Initially the entire surface of the photoconductor is charged uniformly by a positive charge.

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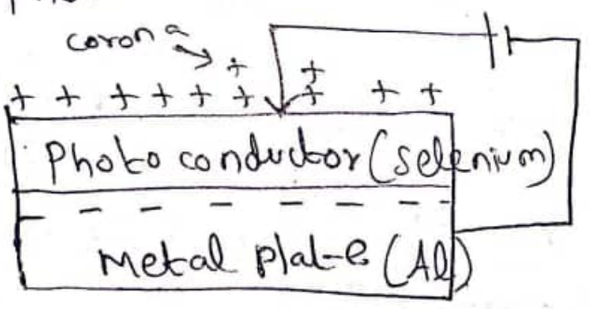
Step 1 : photo conductive plate is charged



→ Charge on top surface comes from positive ions produced by a corona discharge on a wire travelling above photo conductor.

→ negative charge on lower surface comes from metal plate below and is

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drawn by attraction to upper positive charges.

→ Since the photoconductor is an insulator in the dark, negative charges can get no farther than the bottom of the photoconductor.

→ when light from the document to be copied is focused on photo conductor, it becomes a conductor and the negative charges on the lower surface can combine with the positive polarity on upper surface to neutralize each other.

→ However, positive surface charge in dark areas is maintained on photoconductor.

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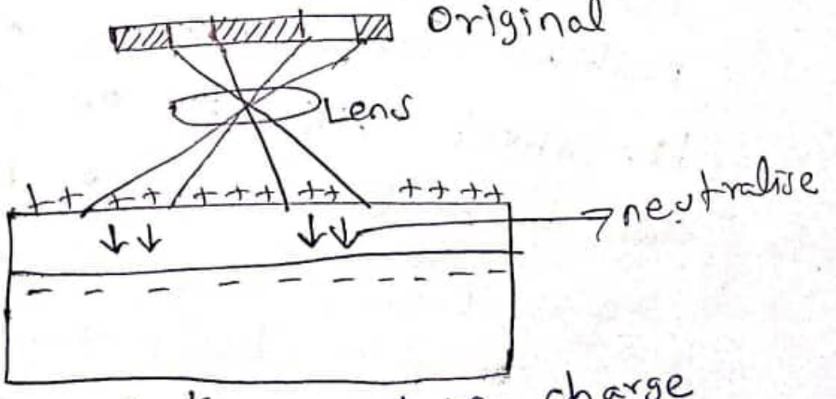
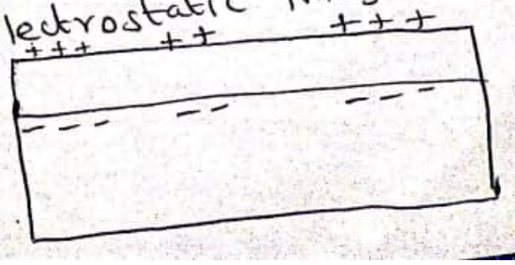
Step 2 : Photoconductive plate is exposed



→ "latent" positive charge electrostatic image is produced on the surface of photo conductor

Step 3 : Electrostatic image is formed



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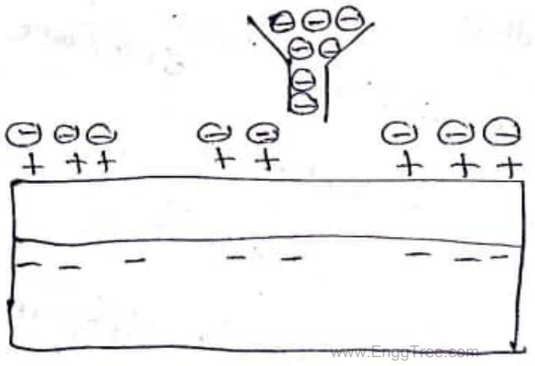
→ Development of electrostatic image is the process of supplying powder (toner) to the charged areas to provide visibility of image.

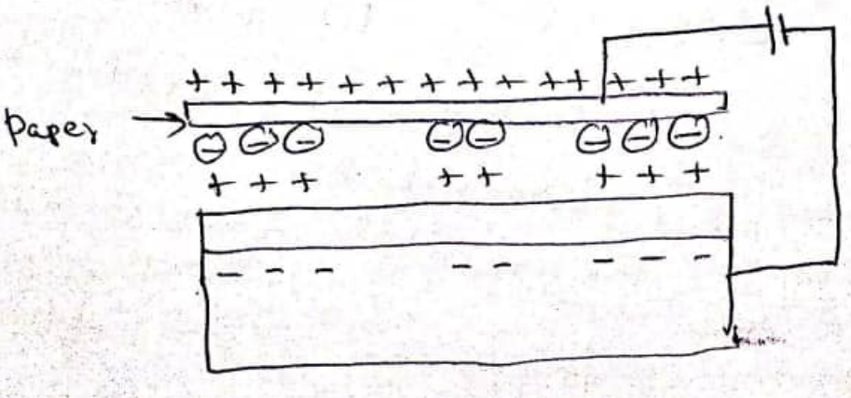
→ Toner particles are charged negatively and attracted to positive image by external electric field generated by this image.

Step 4: carbon toner particles are attracted to image charges



→ If a sheet of paper is placed over the development image and sprayed with positive charge, electric field penetrating the sheet will act on negative tone and cause it to transfer to paper.

Step 5 Carbon particles are transferred to paper



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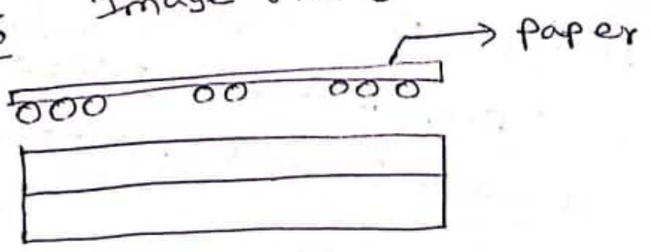
Stripped

→ when the sheet is stripped away from imaging surface, a well-toned image is still present.

→ A second sheet of paper can then be placed over the image and the transfer process is repeated.

→ Later, the toner is thermally fixed to form a permanent image.

Step 6 Image fixing



5.7 (Electrostatic) Printing:

→ Many typewriters and computer line printers use so-called impact printing (ie) characters are cast on metal type, which makes an impact on an ink ribbon to produce prints on paper.

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→ New requirements for performance and speed, exceed the capabilities of most impact printing technologies.

→ Electrostatic printing is an alternative method.

→ Electrostatic printers are classified into a) ink-jet and b) ink-spray printers

→ The printing ink is formed into

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macroscopic droplets which are imaged by electric field, external to print surface (form). The form serves only as a receptor for imaged ink droplets and upon contact, a visible image is instantly produced.

→ This technique is viable on standard forms (sheets of paper) and no image development (or) fixing is required.

→ Electrostatic printers are usually known as non impact printers.

a) Ink-Jet printing Technique:

→ It produces instantly visible images on standard forms by electrostatic deflection of charged ink droplets into electrically programmable dot matrix patterns.

→ This principle is analogous to deflection of electrons in cathode ray tube.

→ The electrically conducting ink is forced through a nozzle to form a thin jet, which then breaks up into droplets under the influence of surface tension and mechanical vibrations in the nozzle.

→ At the point, where droplets are forming, a high voltage field controlled by a computer is applied to the jet to give the

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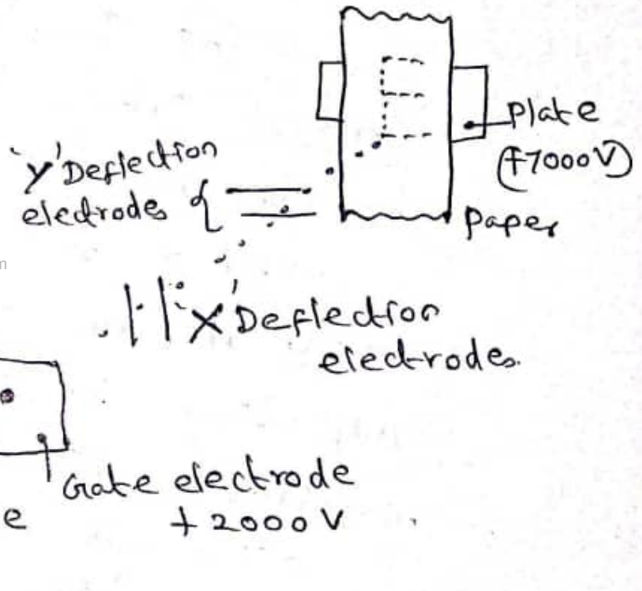
newly formed droplets an electric charge related to signal.

→ This ink-jet printer is called as charge modulation type of ink printer.

→ The drops then move into a deflection region where a steady transverse electric field deflects them by an amount depending on their acquired charge.

→ This deflection causes them to strike the print surface at different points, creating an image.

Ink Jet Printer



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b) Ink-Spray Printing Technique:

→ A reservoir containing the ink is pressurized at low level sufficient to form a convex meniscus of ink at opening of vibrating nozzle, but not high enough to cause an overflow of ink.

→ The conductive ink, maintained at ground potential, is attracted by electric field of

meniscus - drop by drop

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the gate.

→ when the electrostatic attraction force exceeds the surface tension of meniscus, droplets are produced, when potential (V) between gate electrode and meniscus is

$$V > 2D(\gamma/\varepsilon d)^{0.5}$$

where γ → ink surface tension

ε → ink permittivity

d → nozzle orifice diameter

D → distance between orifice and gate

→ The Droplets are accelerated and then imaged into desired dot-matrix format by electrostatic deflection.

→ Since the droplets are produced with a nearly uniform specific charge, programmable deflection is obtained by varying the magnitude of deflection field.

→ This is accomplished by electronically controlling the voltage applied to deflection electrodes.

→ This is why the ink spray printer is known as field modulation type of ink printer.

→ Two sets of electrodes are employed to obtain both horizontal and vertical deflection, to allow for printing on stationary forms.

→ Since the droplets are very small, they can be quickly accelerated and are

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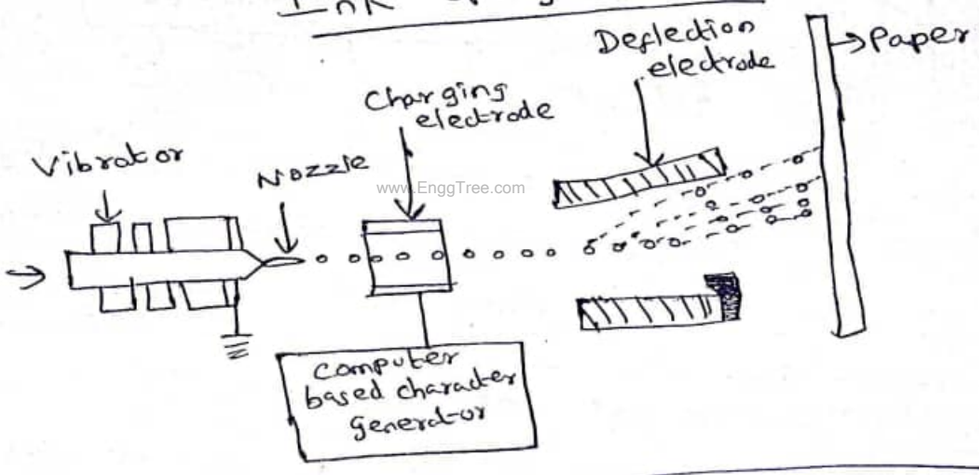
able to produce high quality hard copy much faster than electronic (impact) printers.

→ There are commercially available electrostatic printers with capabilities of printing in excess of 30000 lines/minute.

→ with the current concern for noise from impact printers, electrostatic printers have a definite advantage as the level of noise is only that generated by the hardly visible droplets of ink landing on paper.

Ink Spray printer



5.8 (Electrostatic) Transport of Light Materials:

tribo electrify - charge generated by 2 things

→ the feasibility of electrostatic transport of light materials which triboelectrify themselves on a stationary "conveyer" belt, appears very promising.

→ 3φ high voltage supply U-V-W

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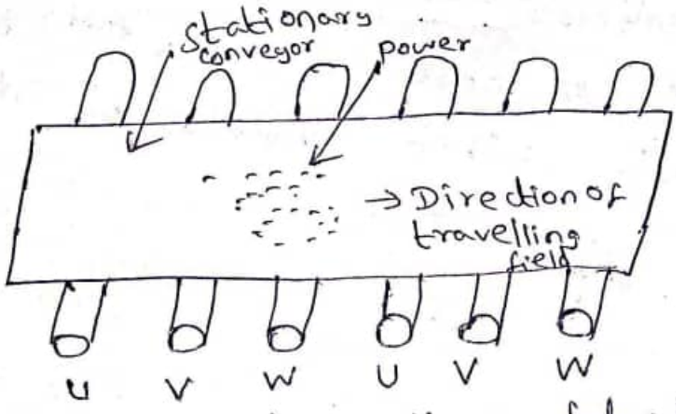
generates a traveling field at the surface of conveyor.

→ The charged particles will be transported along the field.

→ The electrostatic conveying is independent of the sign of the charge; thus both positively and negatively charged particles will transport in same direction.



3φ high voltage electrodes

Electrostatic conveying of tribo electrified materials

5-9 MANUFACTURING OF SANDPAPER.

Abrasive - Sandy

→ Electrostatics is evidenced for industry in the lining up and gluing of billions of particles in the right position with uniform distribution.

→ Abrasive particles of quartz, silicon carbide, diamond etc are poured onto a continuous conveyor (or) belt.

→ As they arrive in the strong electric field between 2 parallel electrodes

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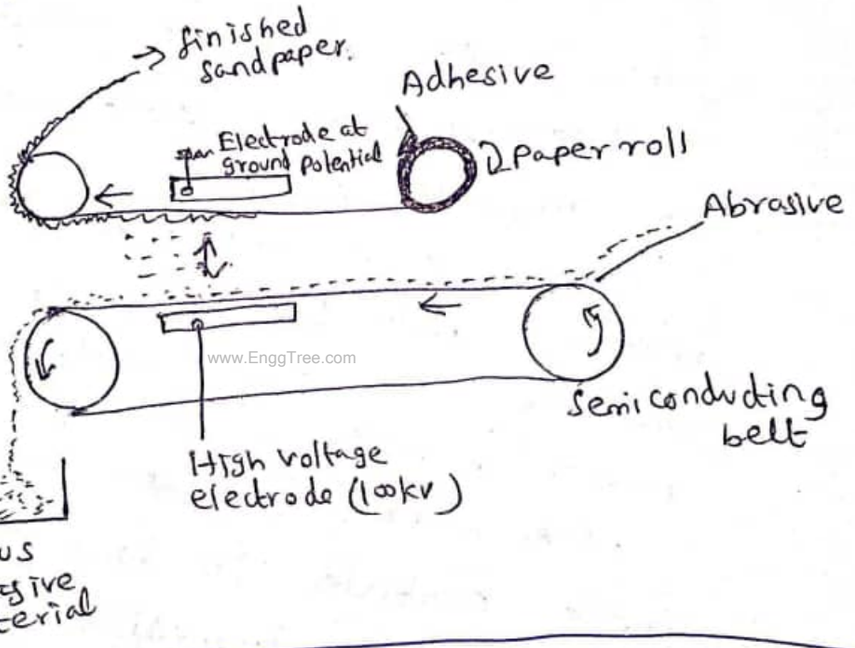
stressed by a voltage upto 100 kV, they line up along the field lines with sharp points facing the electrodes.

→ The electric charge which they acquire from semiconducting belt causes them to be propelled and implanted in adhesive.

→ Any particle which strikes an area already fully covered by other particles falls back and is recovered for reprocessing as surplus abrasive material.



5.10 Smoke Particle Detector

→ The design of smoke particle detector is based on the fact that electrically charged particles of smoke have substantially lower mobility than ions.

→ During the normal surveillance periods, 2 continuous and equal ion currents i_1 & i_2 flow through air of 2 chambers made conductive by radiation from a radioactive

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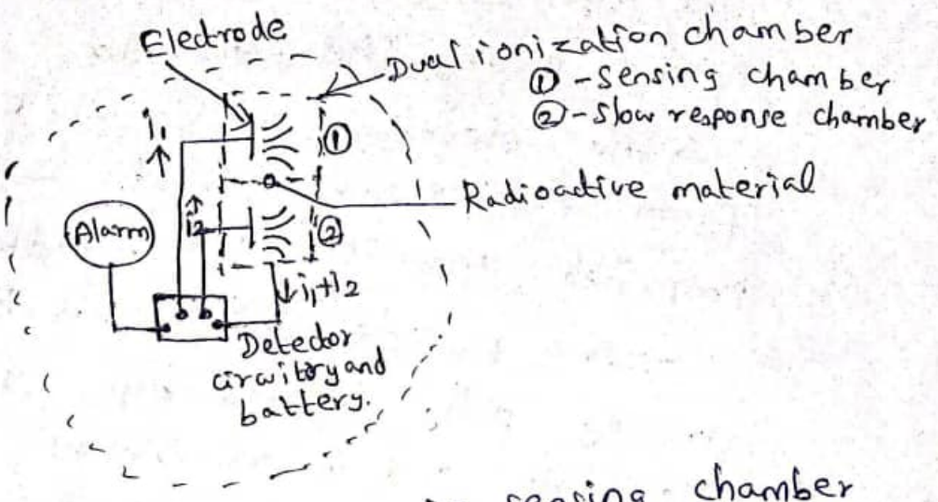
material.



→ current i_1 flows in sensing chamber whose walls have so many holes that smoke particles flow in easily, in contrast to the low response chamber.

→ In large chambers, the radio active material may be replaced by a corona source of ions for sensitive detection of smoke particles.

→ A sudden increase in number of smoke particles in the ambient will be followed by an immediate increase in particle density in the sensing chamber and by a slower increase in the corresponding particle density in the second chamber.

→ current i_1 will decrease on account of the attachment of ions to smoke particles.

→ the decrease is more than sufficient to actuate the solid state circuitry, which sounds the alarm

→ This low cost smoke warning device will save lives.

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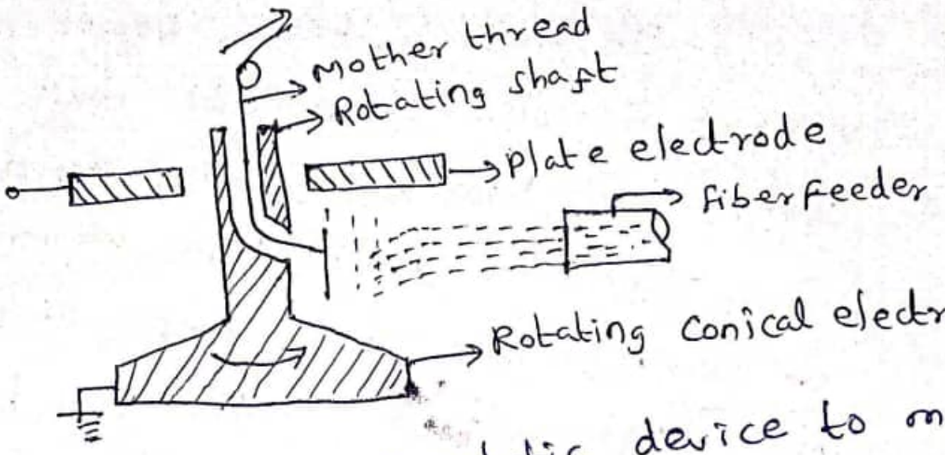
5.11 Electrostatic Spinning



→ It is an electrostatic device to make a thread from fiber with minimum use of air to avoid quality degradation due to particle contamination.

→ the air conveyed fibers are fed from a feeder into a high voltage DC field between gap plate and conical electrodes and are aligned along field lines.

→ At the same time, they are attracted towards the rotating shaft by a gradient force caused by narrowing gap.

→ A mother thread is inserted from top of rotating shaft into its hole to grasp the vertically aligned fibers.

→ when it is pulled upwards, fibers are pulled into hole to be spun continuously to produce a thread.

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5-12 (Electrostatic) Pumping:

→ In high voltage power equipment, current carrying components must be cooled to carry away the heat caused by ohmic losses.

→ Generally, the fluids are more effective in cooling when they make direct contact with high voltage conductors, but this requires that they must be electrical insulators such as oils.

→ The coolant must also circulate to carry away the heat, so some means of pumping by thermal convection (or) mechanical pumps is generally included.

→ A more effective method in coolant circulation is based on force transmitted to the cooling fluid by charges in a high voltage field.

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→ This electrohydrodynamic pumping is used in transformer and in cable.

5-13 (Electrostatic) Propulsion:

→ An ordinary rocket engine propels the rocket forward by ejecting fuel backwards.

propel – ஓட்டு

→ The propulsion force F is

$$F = \frac{d}{dt} mv = v \frac{dm}{dt}$$

where v → ejection velocity (constant), $\frac{dm}{dt}$ → rate of ejection of propellant

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→ For chemical fuel, the ejection velocity is of 10^3 m/s.

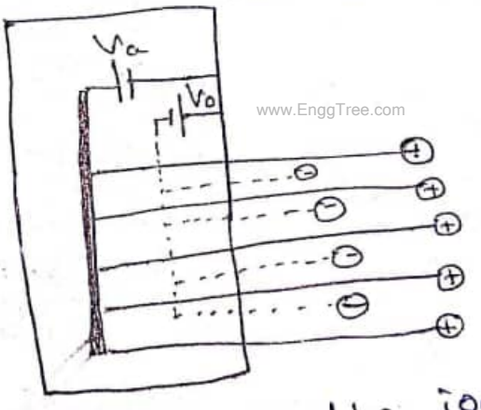
→ It is difficult to achieve much higher velocities using chemical fuels.

→ Electrostatic propulsion uses ionized particles as propellant.

→ The particles are accelerated by electrostatic force to a much higher velocity.

→ Thus, for the same propulsion force, electrostatic propulsion consumes less mass than a chemical engine does.

Electrostatic Propulsion basic operating principle



→ Propellent enters the ionization chamber, where it is ionized either by heat or by bombardment with electrons.

→ Positive ions are accelerated and ejected through the screen.

→ Electrons are absorbed by anode and must also be ejected with positive ions at same velocity; otherwise, the rocket will be increasingly negatively charged.

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→ velocity of positive ion $v_i = \sqrt{\frac{2q_i V_a}{m_i}}$

where q_i → charge on positive ion

m_i → mass

V_a → accelerating voltage for positive ions

→ velocity of electron $v_e = \sqrt{\frac{2q_e V_e}{m_e}}$

where $q_e = 1.6 \times 10^{-19}$ C

$m_e = 9.11 \times 10^{-31}$ kg.

V_e → accelerating voltage for electron

→ To neutralise the ejected ion,

$v_e = v_i$

→ voltage $\frac{V_a}{m_i} = \frac{V_e}{m_e}$

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→ ion current $I = n_i v_i q_i A = \frac{dq_i}{dt}$ — ①

A → cross section of ion beam

n_i → density of ions

→ rate of mass ejection $\frac{dm_i}{dt} = n_i v_i m_i A$

→ Propulsion force $F = v_i \frac{dm_i}{dt}$

$F = v_i \cdot n_i v_i m_i A$

from ①, $\frac{I}{q_i} = n_i v_i A$

$\therefore \boxed{F = \frac{v_i m_i I}{q_i}}$

→ Electrostatic propulsion is used on synchronous satellites to adjust their position and to adjust antenna orientations.

→ It is potentially useful for exploring deep

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space because of large propulsion force to fuel ratio as compared with chemical engines.

5-14 Ozone Generation:

→ Ozone is a virtually colourless gas with an acrid odor and very strong oxidizing properties.

acrid odor – hard smell

→ Ozone is very toxic to humans and animals, causes serious damage to plant life, and produces deterioration in many materials.

deterioration – ನಿಷ್ಕ್ರಿಯತೆ

→ Ozone is the triatomic form of oxygen that has been formed by recombining highly excited oxygen atoms (or) molecules with one another.

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→ Unlike other agents such as chlorine, oxidation with ozone leaves, no toxic residues that have to be removed and disposed of because the process yields only "oxygenated" products and oxygen.

→ In practise, ozone is completely non selective and immediately starts to oxidize everything it comes into contact with.

bactericide – ಬ್ಯಾಕ್ಟೀರಿಯಾ ನಾಶಕ

→ This property makes it a very powerful bactericide and viricide as well as strong bleaching agent.

→ Ozone molecule is only moderately stable and in the absence of oxidizable

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substances, will decay to form stable diatomic oxygen.

→ The instability of ozone has the consequence that it can be neither stored nor transported over distances requiring long periods of time.

→ This means it must be produced on site when and where it is required, which has the added environmental and safety advantages of not having to store or transport potentially dangerous chemicals in large quantities.

→ The traditional way of producing ozone is by means of dielectric barrier discharge called silent electrical discharge.

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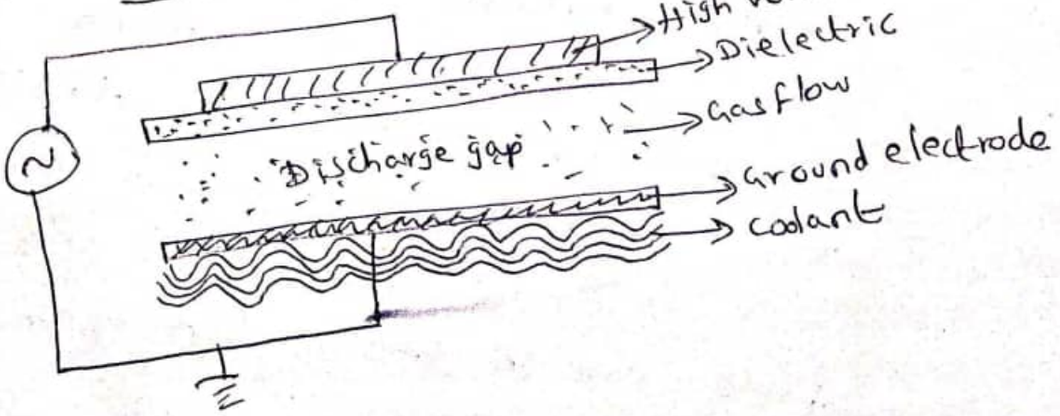
→ Dry feed gas (either oxygen or air) is passed through a narrow discharge gap.

→ one side of the gap is formed by a grounded electrode, the other by a dielectric, normally glass in contact with a high voltage electrode.

Electrode configuration of silent electrical discharge



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→ When high voltage at high frequency is applied to high voltage electrode, ozone is produced in feed gas by micro discharges taking place in discharge gap.

Applications of Ozone in Industry:

→ Industry several applications are sterilization processes and control of microbials, purification of drinking water and treatment of waste water instead of use of chlorine, control of survival rate of farmed fishes, cleaning, deodorization and making healthy indoor air, $deNO_x$ and $deSO_x$ processes by eliminating these hazardous pollutants from flue gases, ozone therapy and protection of earth's surface from dangerous ultraviolet radiation.

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5-15 Biomedical Applications:

→ There are needs in biotechnology for manipulation of small objects, such as cells, chromosomes, biological membranes and nucleic acid and protein molecules.

→ Biological cells size range are less than μm to several hundred μm and molecules are even smaller, measured in nm.

→ High voltage electrostatic forces are highly suitable for handling, characterization,

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and seperation of these fine particles.

→ With the use of electrostatic effects, these objects can be manipulated collectively or even individually.

→ In addition, because the electrostatic force is a "surface force" distributed around the surface of an object, it enables gentle manipulation without applying too much stress of the object.

→ Another aspect of electrostatic effects is associated with breakdown of membranes.

→ When a pulsed electric field of moderate magnitude is applied, a cell membrane breaks down and becomes permeable, but a reseal ing process follows due to fluidity of membrane. This process is called "reversible breakdown" and is used for bringing foreign material into cell interior.

→ In particular, when this process is conducted in a DNA solution, it can be used to inject foreign genes into cells (transfection)

→ Alternatively, when a partial breakdown occurs at contact point of 2 cells, they may fuse into one, to yield a hybrid between 2 cells (electrical cell fusion)

→ If pulse is too strong, irreversible breakdown takes place and cell is destroyed.

→ This effect can be used for sterilization.

transfection
- Bringing

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