HIGH VOLTAGE ENGINEERING

18/11/20

Generation 11KV – 30KV
↓
Transmission 66KV, 132KV, 220KV, 500KV
↓ Extra high voltage (EHV)
Distribution 11 KV
↓
utilization. 220 / 400 V

Electric field = V/m

Insulation is the isolation b/w two voltages.

Dielectric is also insulation but it is basically used with capacitance.

Copper and Aluminum are the most widely used conductors.
→ windings ↓ transmission lines.

Polymers → Rubber
→ Plastic → PVC

Higher the voltage higher the insulation.

Three types of insulations; Dielectric strength:
- Gases air, N_2, SF_6 < 1 MV/cm → full recovery
- Liquids oil < 10 MV/cm → partial recovery
- Solids paper, wood, PVC, plastics 1 – 100 MV/cm
↳ used in transformers as ↳ no recovery
- Vacuum very high maintenance costs.

SF_6 → normal insulating properties
↳ cooling (referegerant).

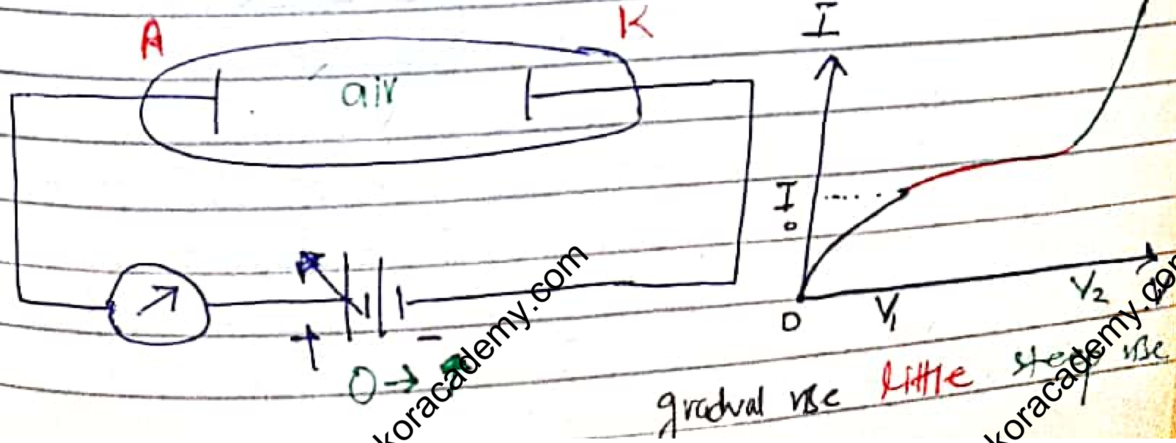
Transformer is a static machine which transforms voltage levels.

Dielectric strength is the ability to withstand a particular voltage.

Properties of Gases;
- High dielectric strength.
- It should be inert.
- Non flamable.
- Non toxic
- Environment friendly.
- Non corrosive. Corrosion → continuous eating of metals after a chemical process. Erosion → physical process.
- Should not dissociate in service.
  ↳ separate

Mechanism of Breakdown.

Tounsend (1920 - 30) was the first to study breakdown in gases. STP → 14 psi ↳ 25°c



0 to V_1 → photo ionization current
pre ionization produces (a very few) electrons
↳ Due to cosmic radiations.

$$h\nu + e'\left(\frac{1}{2}mv^2\right) \longrightarrow e(E)$$

photon — electron — energetic electron

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

atom — unstable atom

$n_1 \longrightarrow n_2$

$n_2 \longrightarrow n_1$ ⇒ $A^* \longrightarrow A + h\nu$

$e + A \longrightarrow A^*$ $\varepsilon_e < IP$
$A^* \longrightarrow A + h\nu$

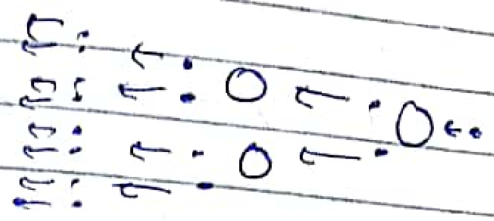
$e + A \rightarrow A^+ + e$ $\varepsilon_e > IP$

The speed of electron is greater near the anode. So the ionization process is more likely to occur near the anode.

+ve ions now will be → near the anode
↳ are bulky

V_1 to V_2 → the electrons moving from cathode to anode will be absorbed by the cluster of +ve ions in the way before reaching anode.
So a small current.

$V_2 \uparrow$. There would be a high voltage so electron will be imparted from cathode at a very high speed.



Avalanche of electrons → steep rise in current → luminous path of current.

Electron flows from cathode to anode.

Separation b/w K and A = d
consider a distance from K = x.
A strip = dx having charges dn.
No. of electrons = n.
Initiating electrons by photo ionization = n_0.

$$dn \propto n\,dx$$

$$dn = \alpha\, n\, dx$$

(primary)

$\alpha \rightarrow$ Townsent 1st coefficient of ionization.

$$\int_{n_0}^{n} \frac{dn}{n} = \int_0^d \alpha\, dx$$

$$\left| \ln(n) \right|_{n_0}^{n} = \alpha d$$

$$\ln\left(\frac{n}{n_0}\right) = \alpha d \Rightarrow \boxed{\frac{n}{n_0} = e^{\alpha d}}$$

$$n = n_o e^{\alpha d}$$

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

Say $I_o = 0.1\,mA$, $d = 1\,cm = 0.01\,m$, $\alpha = 400\,m^{-1}$

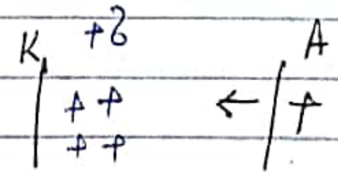
Lecture 2 — 25/11/20

Two important points were observed from Tawnsent theory;

- Role of +ve ions.
- STP — Conduction, $\frac{1}{2} m_p U_p^2$

The positive ion density will be more at the anode and will slowly drift towards the cathode

Field distortion due to space charge (+ve ions) due to which electron will not get enough energy to the point of



ϕ_K work function is the minimum amount of energy to dislodge an electron from a metal.

Electron will be ejected and absorbed directly by the +ve ion.
Slowly the +ve ions near cathode density will decrease and the field will reform.

If $\frac{1}{2} m_p v_p^2 \geq 2\phi_k$

Now two electrons will be ejected, out of which one will be absorbed and the other would be free to move towards the anode.

Control the extra electrons; by using electrodes with high work function.

Oxide coated materials posess very high work functions.

$\gamma \rightarrow$ Taunsent's 2nd (secondary) ionization constant.

$$\gamma = \frac{e'}{\text{single +ve ion}}$$

say n_0 = initiatory electrons. n_1 = no. of e' produced as a result of +ve ions impact.

n_2 = total no. of e's reaching the anode.

$$\Rightarrow n_2 = n_0 + n_1 \quad -①$$

Total no. of electrons produced by single electron;

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

$\Rightarrow$ Electrons produced by n_2 no. of electrons;

$$n_2 (e^{\alpha d} - 1)$$

$$\Rightarrow \gamma = \frac{n_1}{n_2 (e^{\alpha d} - 1)} \Rightarrow n_1 = \gamma n_2 (e^{\alpha d} - 1)$$

$$① \Rightarrow n_2 = n_0 + \gamma n_2 (e^{\alpha d} - 1)$$

$$n_2 [1 - \gamma (e^{\alpha d} - 1)] = n_0$$

$$\boxed{n_2 = \frac{n_0}{1 - \gamma (e^{\alpha d} - 1)}}$$

Similarly

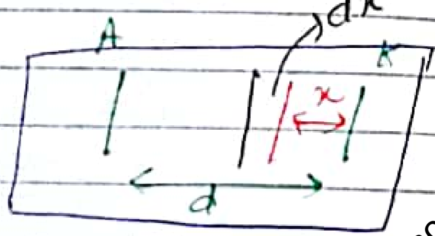
$$I = \frac{I_0}{1-\gamma(e^{\alpha d}-1)}$$

If we have an electronegative gas in the Taunsent chamber instead of air.

$$e' + B\,(EN) \longrightarrow B^- + h\nu$$

e', +ve ions (CI), −ve ions (Attachment).

CI



$$dn_i = n\alpha\,dx$$
$$dn' = -n\eta\,dx$$

$$dn = n\alpha\,dx - n\eta\,dx = n(\alpha-\eta)\,dx$$

$$n = n_0\, e^{(\alpha-\eta)x} \rightarrow (1)$$

Now $dn_g = n\eta\,dx = n_0\, e^{(\alpha-\eta)x}\,\eta\,dx$

$$n_g = \int n_0\eta\, e^{(\alpha-\eta)x}\,dx$$

$$n_g = \left(\frac{n_0\eta}{\alpha-\eta}\right) e^{(\alpha-\eta)x} + K$$

At the cathode; $x=0$, $n_g = 0$
Boundary condition

$$\Rightarrow 0 = \frac{n_0\eta}{\alpha-\eta} + K$$

$$\Rightarrow K = -\left(\frac{n_0\eta}{\alpha-\eta}\right)$$

$$n_g = \left(\frac{n_0 \eta}{\alpha - \eta}\right) e^{(\alpha-\eta)x} - \left(\frac{n_0 \eta}{\alpha - \eta}\right) \rightarrow (2)$$

$$n_T = n + n_g$$

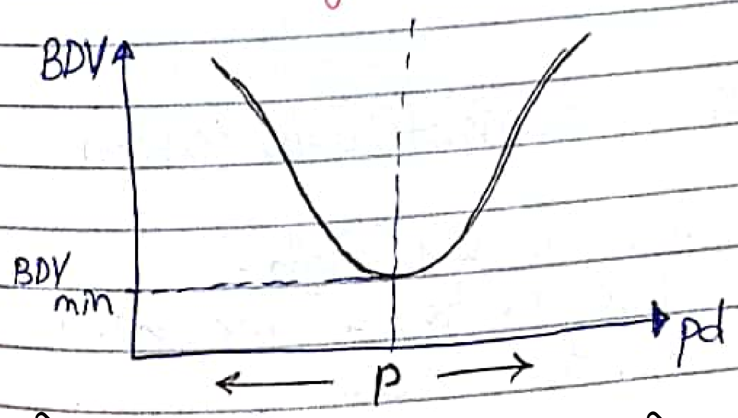
$$n_T = n_0 e^{(\alpha-\eta)x} + \left(\frac{n_0 \eta}{\alpha - \eta}\right) e^{(\alpha-\eta)x} - \left(\frac{n_0 \eta}{\alpha - \eta}\right)$$

$$n_T = \frac{n_0 (\alpha - \eta) e^{(\alpha-\eta)x} + n_0 \eta e^{(\alpha-\eta)x} - n_0 \eta}{\alpha - \eta}$$

Simplify and finally put $x = d$

Now discussing STP;
The experiments were carried out by Paschan; An alteration in transient tube = Inserted a valve to insert and take out gas.

Take out gas; $P < STP$
Insert gas; $P > STP$



Lecture 3

Liquid Dielectrics.

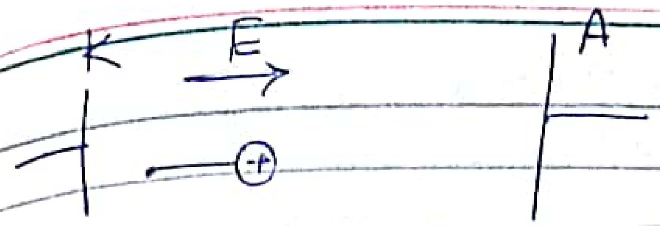
Liquids have a dielectric strength around 1MV/cm
Their dielectric properties are partially recoverable after breakdown.

Liquid DE are generally a family of crude oil.

Crude Oil
- Nephthenic
  - ↓ Generally preffered.
- Paraffinic
  - ↓ has tendency to form wax so not used mostly.
  - ↓ consists of long chains of hydrocarbons.

The mechanisms which are dominant for breakdown are;
i. Electronic.
ii. Cavitation / Bubble breakdown.
iii. Suspended particle.

1. Electronic mechanism is dominant under certain conditions ie;
When the electric field is very high.
Practically we dont have electronic mechanism such as in Xfors, capacitors etc.



$q\lambda E = ch\nu \Rightarrow \boxed{E_c = \frac{ch\nu}{q\lambda}}$

ii. How a bubble is formed?

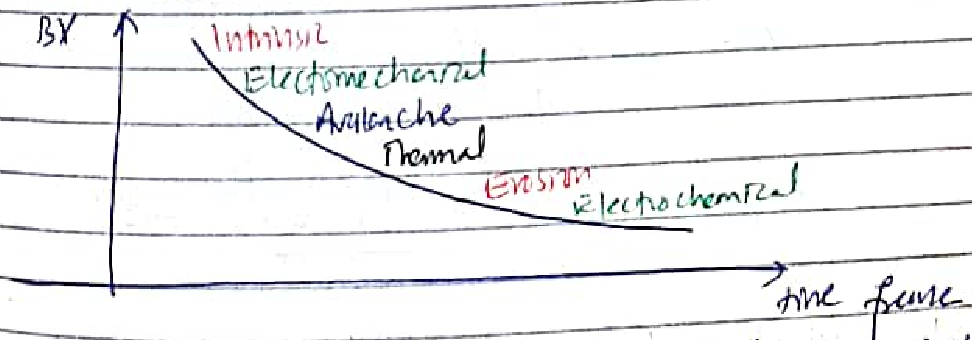
- Gas pockets at electrode surfaces.
- Thermal activity.
- Repulsion of space charge to overcome surface tension.
- Corona type discharges.

Lecture 4

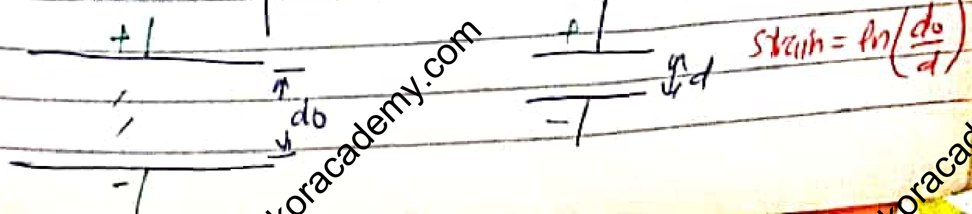
Solid Dielectrics

Have DES around 10MV/cm.
Not recoverable after breakdown.

Extensively used in machines, transformers etc.



Electromechanical breakdown is like introducing a component in the electric field.



We know that $\frac{\text{Stress}}{\text{strain}} = Y$ (young's modulus)

$$S_m \text{ ~~strain~~ } = Y \ln\left(\frac{d_0}{d}\right) \quad -① $$

Also $\frac{F}{a} = \frac{1}{2}\frac{qE}{a}$ $\quad F/a = \text{stress}$

$$S_B = \frac{1}{2}\frac{qE}{a}$$

we have $C = q/V$ or $q = CV$

$$\Rightarrow S_B = \frac{CVE}{2a}$$

As for parallel plate capacitor, $C = \frac{\varepsilon a}{d} = \frac{\varepsilon_0 \varepsilon_r a}{d}$

$$\Rightarrow S_B = \frac{\varepsilon_r \varepsilon_0 a E V}{2da}$$

$$\Rightarrow S_B = \frac{\varepsilon_r \varepsilon_0 E V}{2d}$$

As $E = V/d \Rightarrow S_e = \frac{\varepsilon_r \varepsilon_0 V^2}{2d^2} \quad -②$

Under critical condition; $S_m = S_e$

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

$\Rightarrow V^2 = \frac{2d^2 Y \ln(d_0/d)}{\varepsilon_r \varepsilon_0}$ — (3)

$\Rightarrow E = V/d$

$$\Rightarrow \boxed{E = \sqrt{\frac{2Y \ln(d_0/d)}{\varepsilon_0 \varepsilon_r}}} \quad — (4)$$

Take the derivative of (3) and equate it to 0.

$\Rightarrow \frac{d}{d(d)} = 0 \quad \Rightarrow d = 0.6 d_0$

Also $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

$$(4) \Rightarrow \boxed{E_{critical} = 3.383 \times 10^{4} \sqrt{\frac{Y}{\varepsilon_r}}}$$

Ex 1 $\quad \varepsilon_r = 3.6, \; Y = 3.2 \times 10^{7}, \; d_0 = 1cm$

Thermal breakdown is evident from the fact that we have I^2R losses when we talk about flow of current.

$$P = I^2R = \frac{V^2}{R}$$

↓

heat = absorbed + flow out

$$H_{abs} = C_V \frac{dT}{dt}$$

$C_V \rightarrow$ specific heat at constant volume.

$T \rightarrow$ temperature.

$$H_{diss} = div(K \, grad \, T)$$

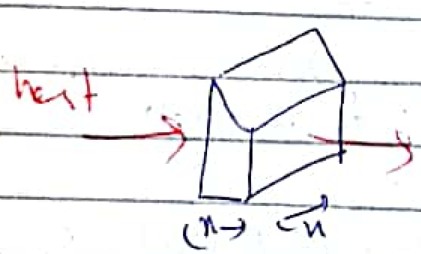
K → Thermal conductivity
T → absolute temperature

Whenever we have Temp gradient. This means that it is bound to have a heat flow. One end at higher T and the other at lower T.

Divergence involved in flow at conditions.

$$\Rightarrow H = C_v \frac{dT}{dt} + div(K \, grad \, T)$$

Now the heat produced by I^2R



$a = x^2$, vol $= x^3$

As $R = \frac{l}{\sigma a} = \frac{x}{\sigma x^2} = \frac{1}{\sigma x}$

$$\Rightarrow P = V^2 \sigma x$$

Also $E = V/d = V/x \Rightarrow V = Ex$

$$\Rightarrow P = \sigma E^2 x^3$$

$$\frac{P}{x^3} = \sigma E^2$$

→ power loss per unit volume W_L.

$$W_L = \sigma E^2$$

so under control condition.

$$\sigma E^2 = C_v \frac{dT}{dt} + \text{div}(K \text{ grad } T)$$

The breakdown process is concerned with that output of heat which is dissipated.

temp ↑ $R_{dielectric}$ ↓ I ↑ I^2R ↑

Thermal instability.

All breakdowns are ultimately thermal in characteristics.

B/c breakdown actually burns the path they ended at first.

Lecture 5

Breakdown By Partial Discharges. (PD)

PD are localized i.e they occur in a very small portion of solid dielectric.

Defects.

i. Structural defects (inherited). non homogeneous, anisotropic.

ii. Manufacturing defects (Micro cracks).

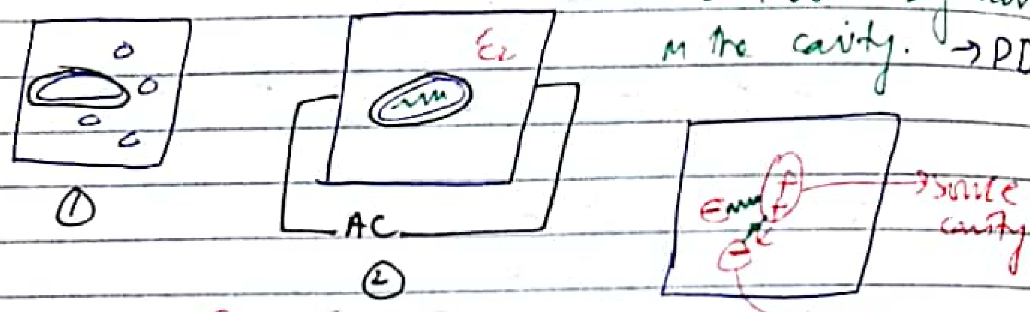
iii. Voids (cavities (contain trapped air)).

Voids → harmful → significant size to sustain PD.
Voids → harmless → insignificant size. → no PD.

Mechanism of PD.

discharge = charge transfer.

Breakdown may occur in the cavity. → PD.



$E_{air} = E_1 < E_2$

PD

- Charge transfer
  ↓
  Electron trapping in defects
  ↓
  Local BD through dielectric
  ↓
  different paths/channels
  ↓
  Nucleation
  ↓
  treeing / tracking
- Local high temperature. (2800 – 3000°K)
  ↓ hotspot
  Melting of walls of void.
  ↓
  Gradual enlargement
  ↓
  more intense PD
  ↓
  Complete breakdown.

In practice, this process (of PD) is very common.

Lecture 6

Corona

↳ refers to some sort of an ionization activity (having some audio and visual effects).

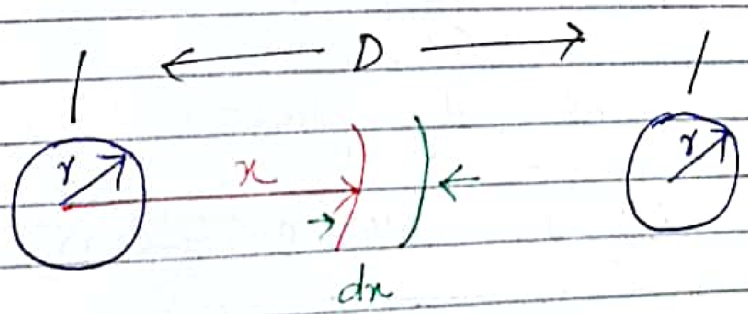
Uniform Electric field ∄ corona

→ generally depends on the distance b/w the source conductor (HV) and the ground terminal and medium present b/w the two.

Air ionizes at 21.1 kV/cm at STP. (rms value)

Presence of corona (Manifestation)

i. Audible noise (sizzling type).
ii. Visual appearance (faint purple blush or orange reddish)
iii. Smell of Ozone (pungent / irritating).



As $E = \frac{q}{2\pi \varepsilon_0 r} = \frac{q}{2\pi\varepsilon_0 x}$

charge density, $D = \frac{q}{2\pi r}$

$\Rightarrow \varepsilon_0 E = D$

$\Rightarrow E = \frac{D}{\varepsilon_0} = \frac{q}{2\pi r x \varepsilon_0}$

$$A \quad V = \int E\,dx$$

$$\Rightarrow V = \int \frac{q}{2\pi r x \varepsilon_0}\,dx = \frac{q\,x}{x\,2\pi r \varepsilon_0}\int \frac{dx}{x}$$

$$\Rightarrow V = xE\int_r^D \frac{dx}{x} = xE\ln\left(\frac{D}{r}\right)$$

$$\boxed{V = xE\ln\left(\frac{D}{r}\right)}$$

When $x = r \Rightarrow$ max electric field.

$$V_0 = rE\ln\left(\frac{D}{r}\right)$$

$$V_0 = 21.1\, r \ln\left(\frac{D}{r}\right) \quad \text{— (1)}$$

Kmission lines are not purely cylindrical.

Strands $\boxed{n \geq 37} \rightarrow m \approx 0.85 - 0.95$

$$\boxed{V_0 = 21.1\, r m \ln\left(\frac{D}{r}\right)} \quad \text{— (2)}$$

$0.7 < m \leq 1$ Take $m = 0.9$

The air Xtics keep on change.

P = cm-Hg

t → °C

Air density correction factor → $\boxed{\delta = \frac{3.92\,p}{t + 273}}$

$$\Rightarrow \boxed{V_0 = 21.1\, r m \delta \ln\left(\frac{D}{r}\right)} \quad \text{— (3) KV/ph}$$

$\delta = 1$ for STP

↳ audible corona

$$V_{visual} = k V_0$$ where $$k = \left(1 + \frac{0.3}{\sqrt{r\delta}}\right)$$

Disadvantages of corona

1. Radio interference → High frequency radiation originating from the corona site → is picked up by a radio reciever → so interferes with the normal information.

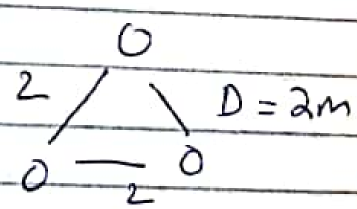
ii. Power loss (partial ionization) → leakage current.

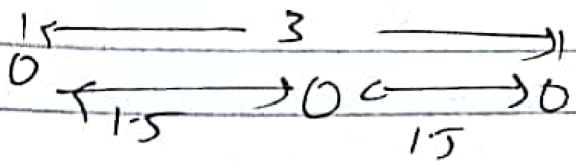
$$P_c = \frac{1.1106 \times 10^{-4} f V^2 F}{\ln(D/r)} \text{ kW/km/phase.}$$

F = corona factor = $f(V/V_0)$

$1 \leq \frac{V}{V_0} < 2$ $0.037 < F < 7$

Ex $V_L = 132$ kV, $r = 1$ cm





$D \to GMD = \sqrt[3]{1.5 \times 1.5 \times 3}$

$V_0 > V \Rightarrow$ no corona

$V_0 < V$ corona.

Lecture 7

Example ↓

Radio Interference

3 KHz — 30 MHz
500 KHz — 1.6 MHz

1 MHz AM band.
BW of 5 KHz
1ms
6ms

Final

Lecture 8

Electrostatic Discharge (ESD)

Every body is charged.

→ Accumulators < 50 pS/m → conductivity (seimen)
→ Non accumulators. > 50 pS/m
↳ no risk of static discharge.

charges at rest ⇒ static electricity.

i. Tribo electricity. → static → an object stationary for some period of time and it accumulates charge.
⊙ by rubbing two objects together
ii. Piezo electricity.
mechanical effect converted into electricity.
iii. Pyro electricity
thermal effects are converted into electricity

The time for which charge is retained by accumulator or decay time etc is given by relaxation time.

$$T = \frac{\varepsilon_0 \varepsilon_r}{\delta}$$ → conductivity

say for T/F $\varepsilon_r = 2.2$

$$\Rightarrow T = \frac{8.85 \times 10^{-12} \times 2.2}{1} = \_\_\_\_ \text{ sec}$$

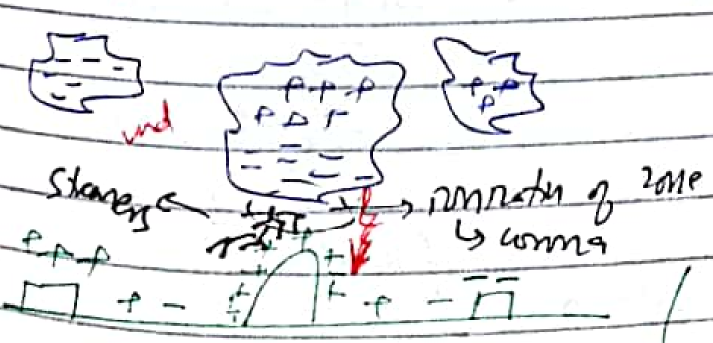
Accumulator → hazardous.

anti liquids

eg Gasoline → strong accumulator → can acquire a large amount of charge.
can catch fire

Lightning stroke mechanism is basically due to static electricity & the static charges that are accumulated.

__Cloud__ A cloud must be a Thunder cloud.
↓ contain Graupel
↵
soft mixture of ice and moisture
↳ (water droplets)



$E = V/d$

$$E = \frac{2V}{r \ln 4d/r}$$

↳ this is much much higher.

↓ leader

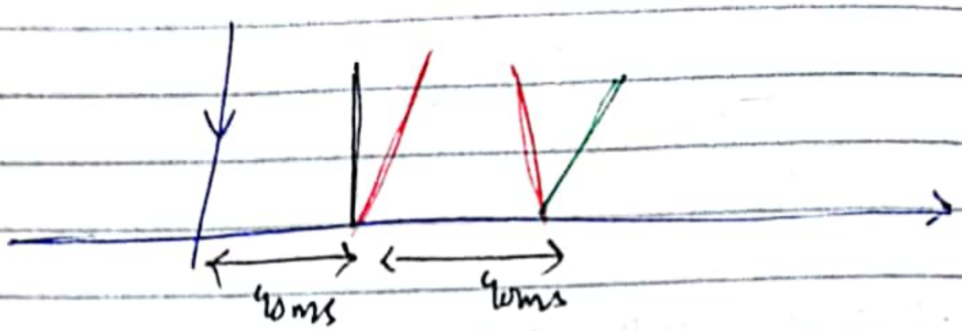
↑ return streamer

↳ short circuited by very heavy current discharge plasma.

Energy is transferred from cloud to the ground in the form of discharge → lightning discharge.

↓ Incident stroke

then we have a return stroke that is from ground to the cloud.



stroke meaning.

Lighting discharge completed; return stroke

This can follows another stroke.

i) dark leader → curve and zigzag not dominant is a single bolt, directly takes place b/w cloud and ground.

Then another stroke and so on

This process continues untill all the charges are cleared.

1 sec? 40 ms = $\frac{10^3}{40} = \frac{100}{4} = 25$ strokes in 1 second.

This could be very disastrous.

i. Current in each stroke is upto 200kA.

ii. Charges 15C – 350C

iii. Energy in single stroke is about 500MJ.

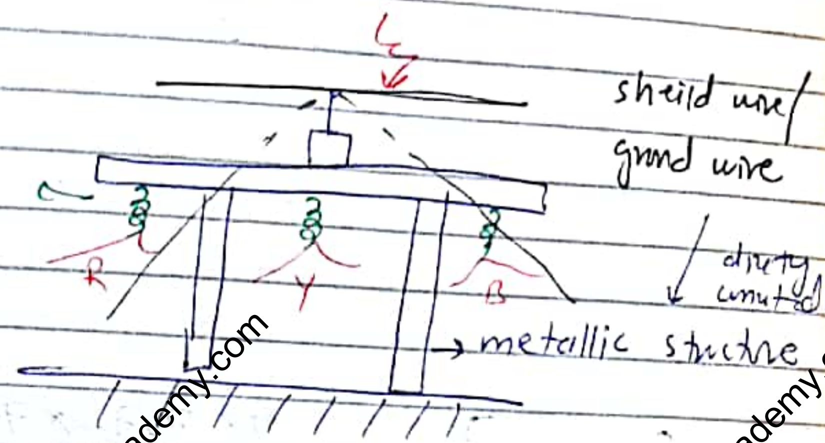
iv. Temp is 15000°F – 60000°F
about 3 times surface temp of sun.

v. Terristial Gamma ray flashes with energy of 20 MeV.

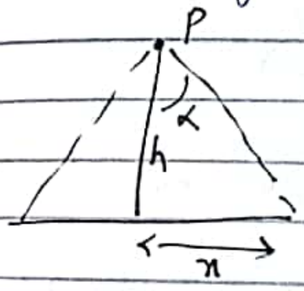
vi. Magnetic field.

vii. Shock waves.

Protection



The sheilding effect



$\alpha = 30^\circ - 60^\circ$
✓ 45°

$I_{surge} = 100\,kA$

$Z_s = 400\,\Omega$

$V_s = \frac{1}{2} I_s Z_s$

$= \frac{1}{2} \times 100 \times 10^3 \times 400 = 20\,MV$

Lightning arrester → Gap type
→ MOV type

thunderstorm days / year = Karonic level / number

Say for Peshawar $K_L = 40$.

Protection zone
$\tan \alpha = \frac{x}{h}$
$x = \tan(\alpha) h$.

$N_s = 0.04\, K_L^{1.25}$
↳ no. of lighting strikes

$2\pi h$
$A_t = 2\pi h \tan\alpha$

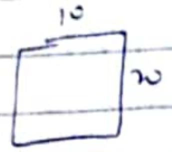
$N_K = 0.12\ K_L$

↳ no. of flashes to earth per km^2 per year

Q. $A = 10 \times 20m$.

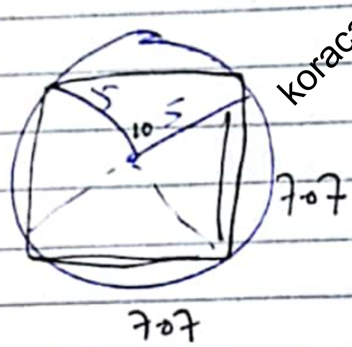
Lighting rod with $h = 5m$

Protection zone $A_z = 2\pi(5) = 10\pi = 31.4m$



Perimeter $= 20 + 40 = 60m$

$A = 200\ m^2$



$A = 7.07 \times 7.07$

$= 50m^2$

$\frac{200\ m^2}{50\ m^2} = 4$

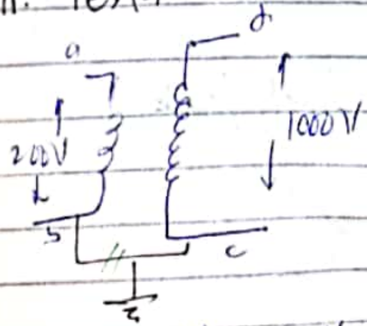
↳ we need 4 rods

Lecture 9.

Generation of High Voltage Alternating Current

i. Using cascaded transformers.

ii. Tesla coil.



$V_c = 0,\ V_d = 1000V$

$\Rightarrow V_{dc} = 1000V$

If $V_b = 100V$

then $V_a = 300V$ to main

the difference of 200V.

the grid connection has to be maintained.

$V_b = 0,\ V_a = 200V$

$\Rightarrow V_{ab} = 200V$

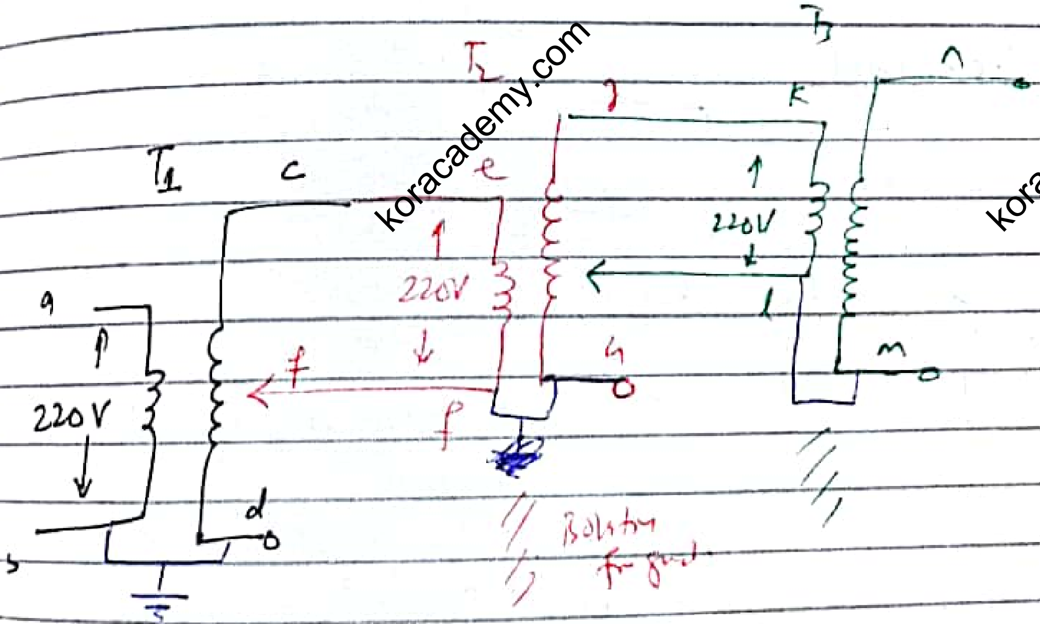
Similarly if $V_c = V_b = 100V$
$\Rightarrow V_a = 1100V$

Cascading of T/F.

↳ o/p of preceding is i/p to the following.

All T/Fs must have the same rating and the same construction.

say 220 V / 100 KV, 2 KVA, 50 Hz
3 units.



$V_a = 220V$, $V_s = 0 = V_d$, $V_c = 100 KV$
$\Rightarrow V_{cd} = 100KV$

$V_c = V_e = 100KV$, $V_{ef} = 220V = V_{ef}$
$\Rightarrow V_f = 100000 - 220 = 99.7$ KV

$V_f = V_h = 99.78$ KV

$V_{gh} = V_g - V_h \Rightarrow V_g = V_{gh} + V_h = 100KV + 99.78$
$\Rightarrow V_g = 199.78 KV$

$V_{KL} = 220V$ $\quad V_g = V_k = 199.78 kV$

$\Rightarrow V_{KL} = V_K - V_L$ $\Rightarrow V_L = V_K - V_{KL}$

$\Rightarrow V_L = 199.56\ kV$

$V_L = V_m = 199.56\ kV$

$V_{nm} = 100\ kV$ $V_m = V_L = 199.56\ kV$

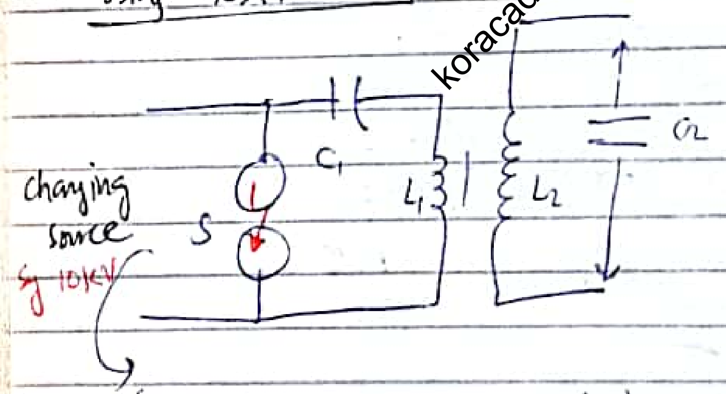
$V_{nm} = V_n - V_m$ $\Rightarrow V_n = V_{nm} + V_m$

$\Rightarrow V_n = 299.56\ kV$

Hex $n = 3$

$\Rightarrow V_0 = 3V_s$

Using Tesla Coil



C_1 and L_1 → series resonant circuit.

C_2 and L_2 → parallel " "

In either case; resonant frequency $f_s = \frac{1}{2\pi\sqrt{L_2C_2}}$

Similarly $f_p = \frac{1}{2\pi\sqrt{L_1C_1}}$

spark contains a lot of frequencies (from kHz to large MHz) (4 kHz — 300 MHz)

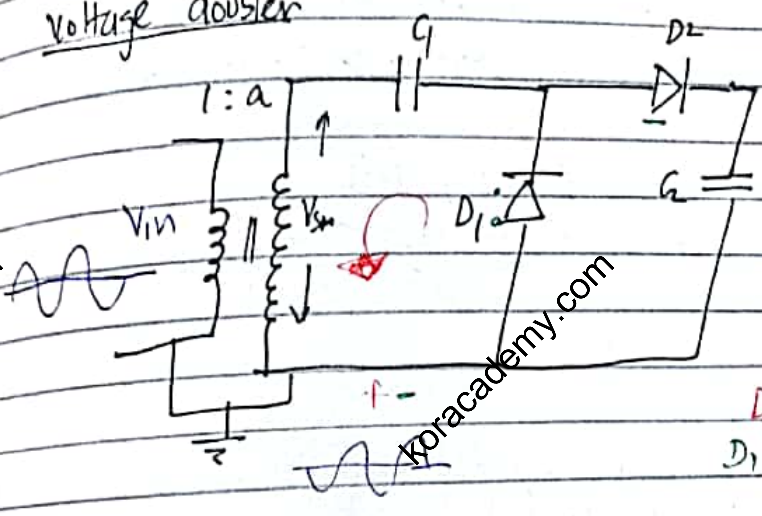
C_1 and L_1 are designed such that its resonant frequencies lie in this range →

Lecture 10

Generation of High Voltage DC

i. Rectifiers (HW / FW)
ii. Voltage doublers.
iii. cascade voltage doublers (walten cockroft generator)

voltage doubler



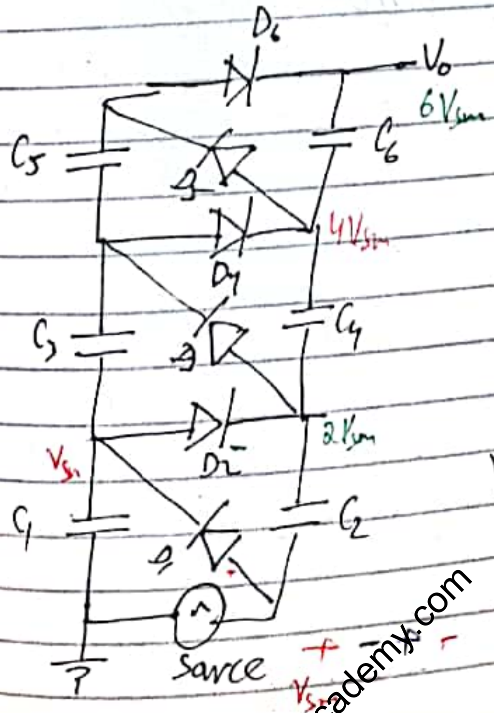
C_1 and C_2 are identical.
C_2 is the capacitor of rectified voltage test.

$2V_{sm}$ gain C_2

D_1 is FB
D_1 is RB D_2 is FB

Commonly will produce 200kV DC.

walten cockroft generator



n = 3
$2V_{sm}$

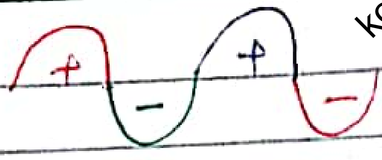
$2nV_{sm}$

$$\delta V = \frac{I_0}{fC}\left[\frac{n(n+1)}{4}\right]$$

$$V_0 = 2nV_{sm} - V_d$$

$$V_d = \frac{I_0}{6fC}(4n^3 + 3n^2 - n)$$

$$V_r = \frac{I_0}{2fC}[n(n+1)]$$



D_1 is FB, D_2 is RB
C_1 will charge through D_1 - C_2 is uncharged now.

D_1 is RB, D_2 is FB. C_2 is being charged through D_2.
C_1 also discharges through C_2 making the voltage $2V_{sm}$.

D_3 is FB, D_4 is RB, D_1 FB D_2 RB
C_1 will charge and $2V_{sm}$ will discharge through C_3.

D_4 is FB D_3 is RB.

Unless the three cycles are completed, we will not get any output. We get o/p after the third cycle is complete.
$(V_0 = 6V_{sm})$

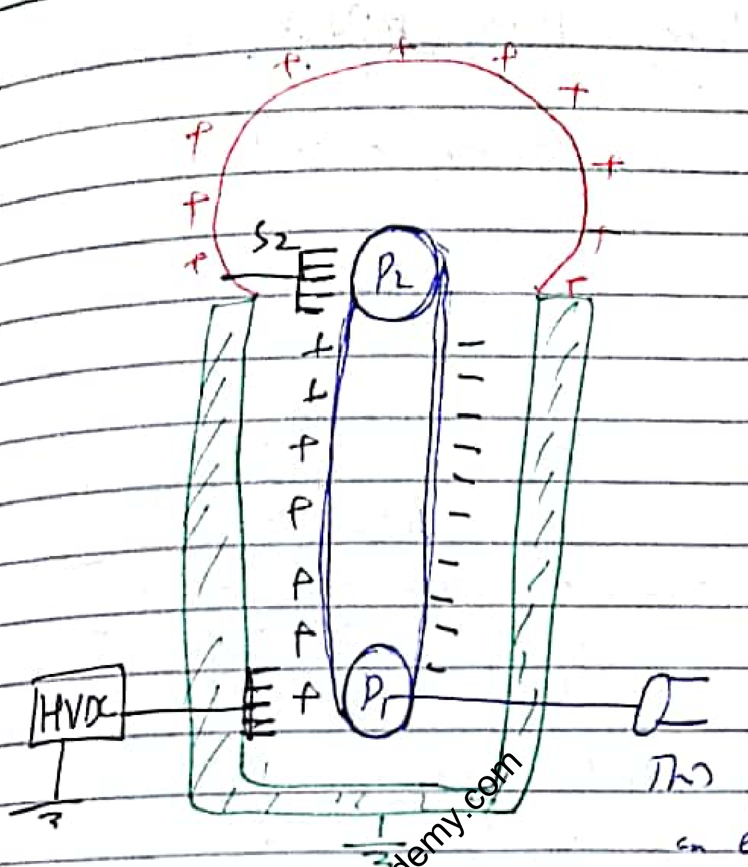
Q. T/F = 220V/100kV, 1.5kVA.
$n = 3$, $I_0 = 1mA$ $C = 10\mu F$

Each capacitor should withstand twice the peak voltage i.e. $2\sqrt{2} \times 100 kV$

$$V_d = \frac{I_0}{2fC}(4n^3 + 3n^2 - n)$$

$$V_0 = 2nV_{sm} - V_d$$ $V_{sm} = \sqrt{2} \times 100 kV$

Ripple voltage $V_r = \frac{I_0}{2fC}[n(n+1)]$



$$V = \frac{q}{4\pi\varepsilon r}$$

$$V = R_2 v_2 b_2 \sigma_2$$

$R = 10^{14}$, $v = 8\,m/s$, width $= 20\,cm$, $\sigma = 1\,\mu C/m^2$

$$I_{leakage} = \frac{V}{R}$$

voltage b/w dome shaped electrode and the ground.

$$V = 10^{14} \times 8 \times 0.2 \times 1 \times 10^{-6}$$

The charges will keep on accumulating if the process keeps on continuing.

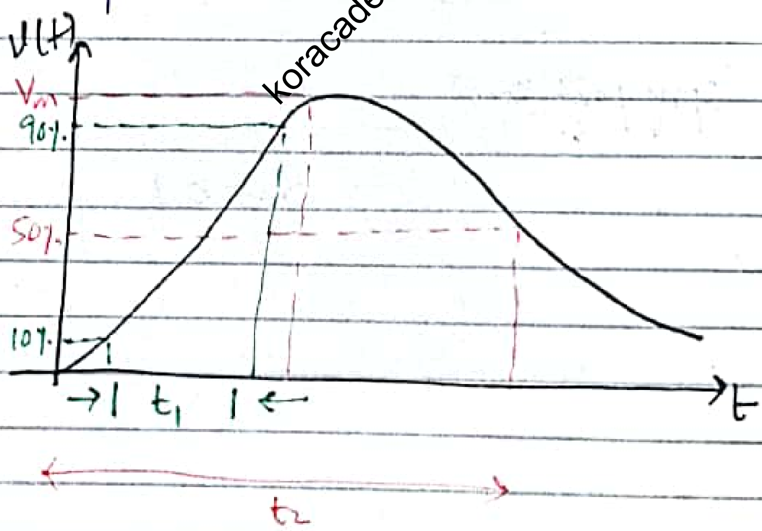
Lecture 11.

Generation of High Voltage Impulse

Three types of voltages for which an insulation must be tested;

i. HVAC
ii. HVDC
iii. Impulse
↳ generated b/c of the incident lightning strokes on the transmission lines or switching operations (closing and opening of CB and Isolator switches)

The HV impulse characteristic is as;



Rise time or wave front time = t_1 = 10% to 90%
Decay time = t_2 = from 0 to t where voltage has decayed to 50%.

we characterize the impulse by t_1/t_2 wave

British standard specification; BS = $\frac{t_1}{t_2} \Rightarrow \frac{1}{50}$ μs
American standard specification: AS = $\frac{t_1}{t_2} \Rightarrow \frac{1.5}{40}$ μs

} Tolerance: ± 50% in t_1, ± 20% in t_2

→ lightning

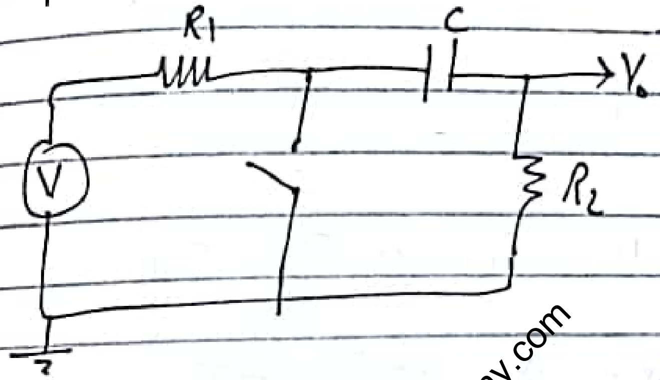
$t_1 \Rightarrow 250\ \mu s$ } $t_1 \Rightarrow \pm 20\%$

$t_2 \quad 2500$ } $t_2 \rightarrow \pm 60\%$

→ switching.

Both switching and lightning impulse waves are exponential in nature.

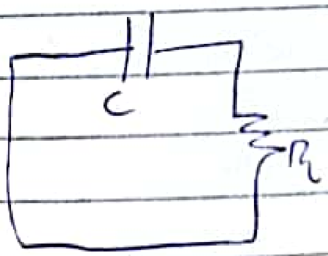
Exponential Generator.



V → charging DC voltage

When capacitor is charged it becomes open circuit and the charging current stops and the circuit remains idle.

Now we close the switch → now we don't require the charging voltage.



$$0 = V_t = \frac{1}{C}\int i\,dt + iR_2$$

no derivative

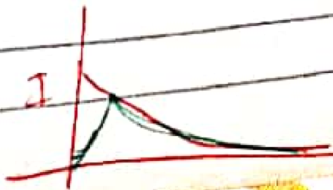
$$\frac{i}{C} + R_2\frac{di}{dt} = 0$$

$$\Rightarrow \frac{di}{dt} + i\frac{1}{R_2 C} = 0$$ First order diff equation

There is no particular solution b/c there is no forcing function. (It's a free response)

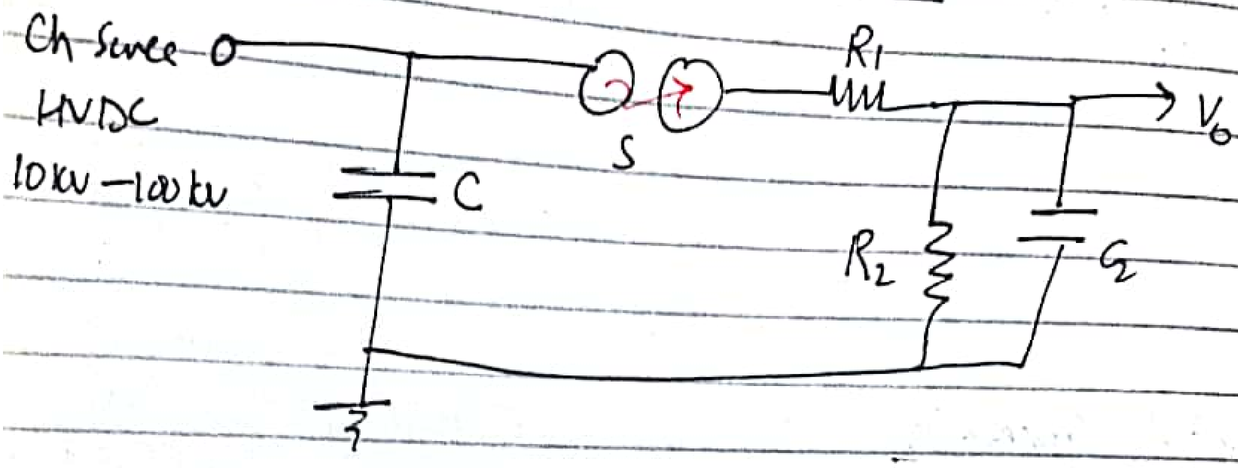
The complementary part of the solution will be:

$$i(t) = K e^{-t/R_2 C}$$



If charging source is removed and the switch is placed and closed.

Single stage Impulse Generator



S → adjustable spark gap
R_1 → wave front control resistor
R_2 → wave tail control resistor
C_0 → capacitance of test object + stray capacitance

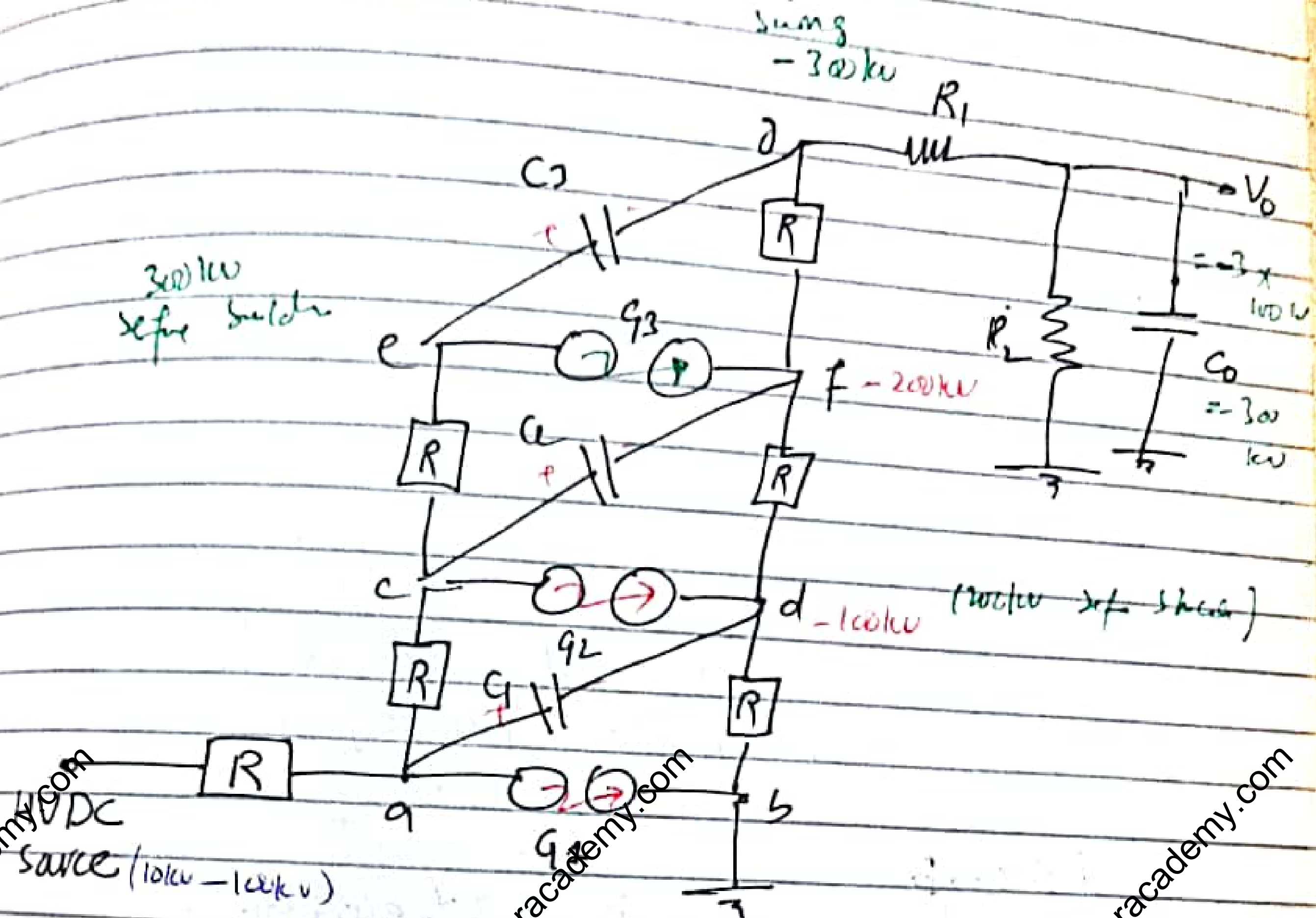
when C is charged we remove the charging source and reduce the spark gap such that a breakdown occurs and a large breakdown current flows in the circuit

the shape of the wave is controlled by values of R_1 and R_2

R_1 low resistance (10 – 100 Ohms)
R_2 kilo ohms (1 kΩ – 100 kΩ)

$$V_0 = V\left[\exp\left(\frac{-t}{R_2 C}\right) - \exp\left(\frac{-t}{R_1 C_0}\right)\right]$$

Multi stage Impulse Generator



R all same values (1 - 10 kΩ)
R_1 front R_2 tail C_0 - test object.

a, c, e are at same potential say 100 kV.
G_1, G_2, G_3 are open circuits so we are charging C_1, C_2 and C_3 through the resistances R.

Now we do not require HVDC source and we close the gaps remotely.

If we need + at the o/p we simply reverse the capacitors and supply - HVDC.

All the capacitors are charged in parallel and are discharged in series.

$V_0 = nV$

Lecture 12

Measurement of High voltages

No direct method for measurement of high voltages.

- HVAC - HVDC - HV impulse

1. Spark gaps.

Characteristics of spark gaps.

i. Uniformity of gap
(Geometry, separation, surface condition, alignment).

ii. Material and gas dielectric used (air, SF_6).

iii. Lab conditions. (temp, humidity, pressure).

$d \leq 0.5D$

{ Impulse HVAC / impulse: $d \leq 0.5D$ $\pm 3\%$ accuracy.
HVDC, $d < 0.4D$ $\pm 5\%$ accuracy

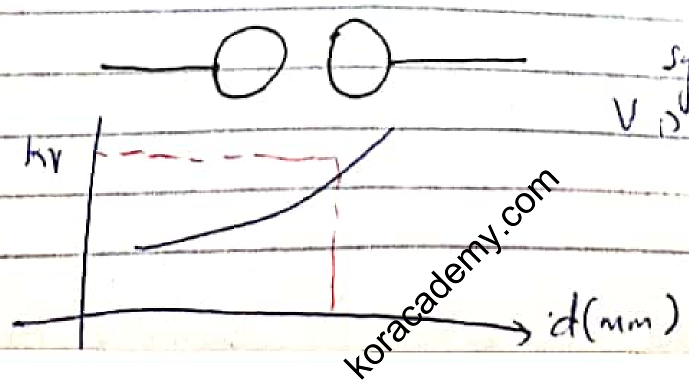
1. Sphere gaps.

2. Rogowski gap $V_{sd} = ad + b\sqrt{d}$

$$V_{sd} = a(\delta d) + b\sqrt{\delta d}$$

where

$$\delta = \frac{P}{P_0}\left(\frac{273 + t_0}{273 + t}\right)$$



Sg 1mm separation.
V is varied at 1kV/sec

Measurement:

$$V_g = k V_{g0}$$

$$k = f(\delta) \quad (\text{given})$$

Ex. $t = 35°C$, $p = 78$ cm of Hg $t_0 = 25°C$ $P^0 = 76$ cm Hg
$V_{g0} = 30$ kV

$\delta = 0.99$, $k = 0.99$

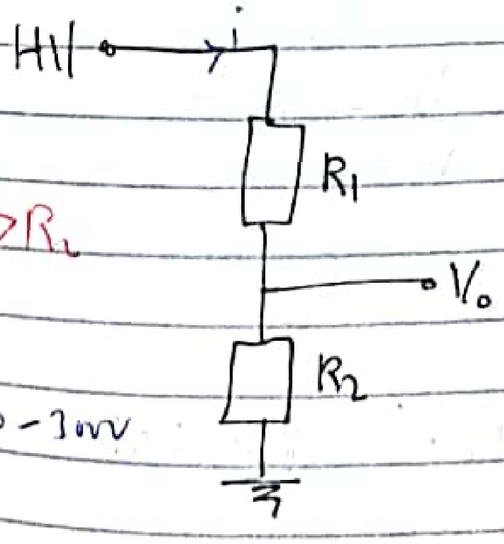
$\Rightarrow V_g = 0.99 \times 30 = 27.7$ kV

$$\text{err} = \frac{30 - 27.7}{30} = 1\%$$

2. Potential Divider

i. Resistive PD for HVAC / DC / Impulse.

ii. Capacitive PD for HVAC / Impulse.



$R_1 >> R_2$

$V_o = 0 - 300$ V

$$i = \frac{V}{R_1 + R_2}$$

$$V_o = i R_2$$

$$\Rightarrow V_o = V \left(\frac{R_2}{R_1 + R_2} \right)$$

$$V_o = V/N$$

Stray inductance depends on size of the equipment
Stray capacitance depends on clearances b/w the earth equipment and the equipment

They should both be kept very small.

Say $V_0 = 200V$

$\Rightarrow \frac{V_0}{V} = N = \frac{R_2}{R_1 + R_2}$

$\frac{200}{200 \times 10^3} = \frac{R_2}{R_1 + R_2} = 1 \times 10^{-3}$

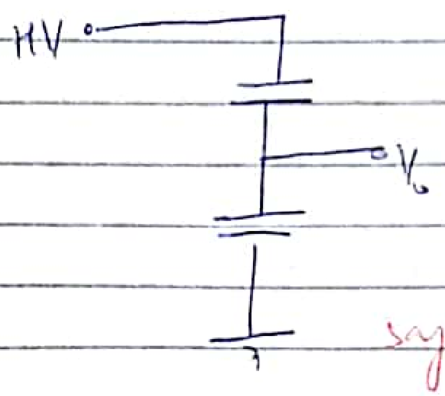
$R_1 + R_2 \simeq R_1$ $\Rightarrow \frac{R_2}{R_1} \simeq 1 \times 10^{-3}$

$R_2 = 1K - 100 K\Omega$

Say $R_2 = 1 K\Omega$ $\Rightarrow R_1 = \frac{R_2}{1 \times 10^{-3}} = 1 \times 10^{+6} = 1 M\Omega$

Similarly capacitive PD.

$X_{C1} = \frac{1}{\omega C_1}, X_{C2} = \frac{1}{\omega C_2}$



$N = \frac{V_0}{V} = \frac{C_1}{C_1 + C_2}$

say $C_2 = 1nF$.

Ex. 200KV, 0–300V 200V ✓ $C_2 = 10nF$

$\frac{V_0}{V} = \frac{C_1}{C_1 + C_2} = 1 \times 10^{-3}$

$\Rightarrow C_1 \simeq 10 \times 10^{-12} \sim 10pF$

If n = 10 units $\Rightarrow C_1' = nC_1 = 10 \times 10pF$
$= 100 pF$

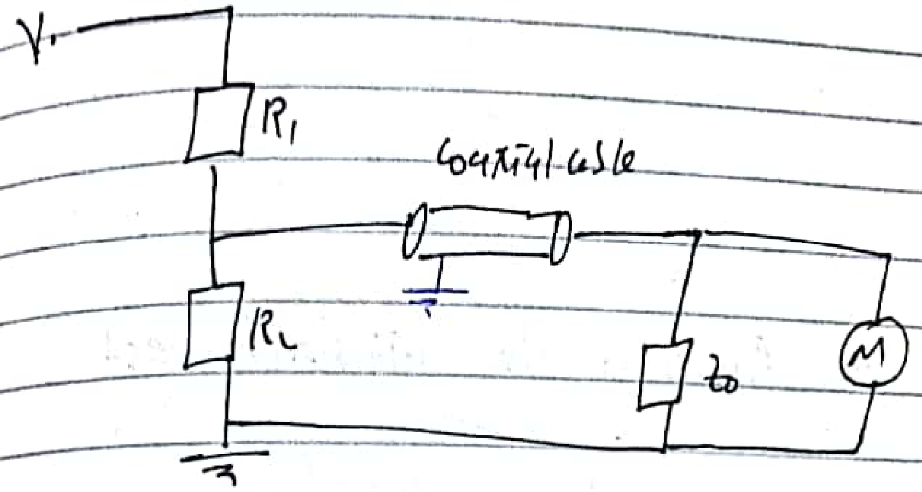
Measurement

Strain

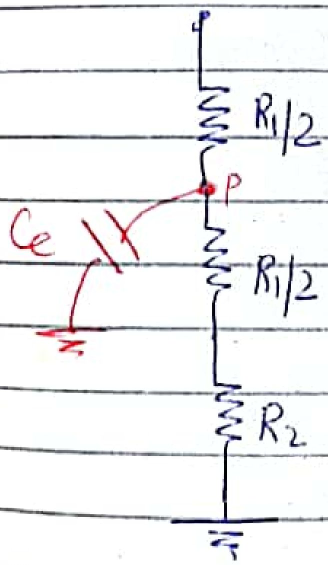
Ce

time

Measurement of Impulse voltage



Stray Capacitance



$\frac{R_1}{2} \parallel \frac{R_1}{2} = \frac{R_1}{4}$

$$C_e = \frac{2}{3} C_T$$

C_e → stray C to earth.

$15\,pF/m < C_T\ 30\,pF/m$

time constant $T = \frac{R_1}{4} C_e = \frac{R_1 C_T}{6}$

$$C_e = \frac{2\pi\varepsilon_0 h}{\ln \frac{2h}{d}\sqrt{\frac{4y+h}{4y+2h}}}$$

y is the distance from the ground, h is height of the resistive column.

$$C_e = \frac{2\pi\varepsilon_0 h}{\ln\left(\frac{1.15h}{d}\right)}, \quad y \ll h$$

Lecture 13

High Voltage Testing.

used on insulation which is used in practice.

i. Impulse test   1/50 μs   5 +5 with 10's interval.
(5 +ve, 5 −ve)

ii. High voltage power frequency dry withstand test for 1 minute at factor of safety (FOS) of 2

iii. HV power frequency wet withstand test for 1 minute at FOS of 2 with artificial rain at about 45°.

iv. HVDC test both dry and wet for 1 minute.

statistical estimation of flashover voltage.

- Normal guassian method.
- weibull distribution method.

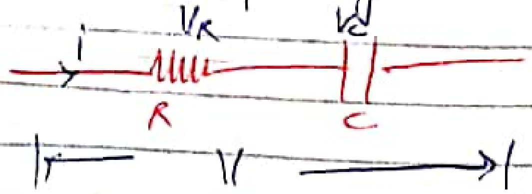
confidence interval CI → 95% or 99%

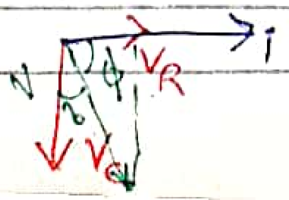
Insulation Quality.

Non destructive insulation testing.

R, C, tan δ
↳ power loss capability.

insulation model.



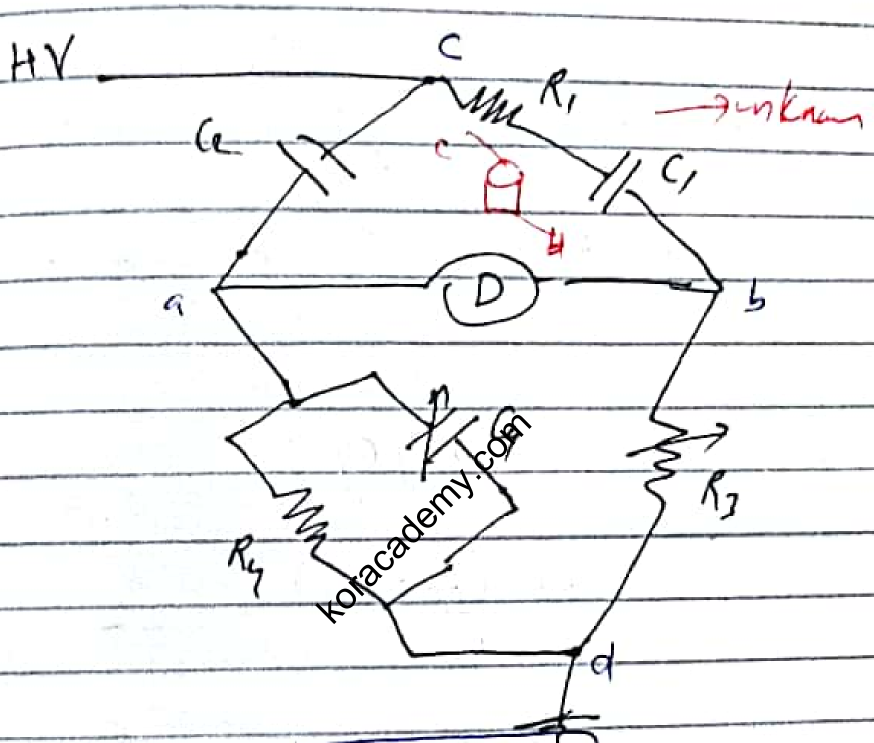


φ → power factor angle
δ → loss angle.

The best insulation is → pure capacitor. $\delta \simeq 0$

$V_R \downarrow \Rightarrow$ Quality $\uparrow$ $\quad V_R \downarrow\downarrow \quad \propto \quad \delta \downarrow$ mul cap q

Shceering bridge



Balancing condition ⇒ $\boxed{\dfrac{Z_2}{Z_4} = \dfrac{Z_1}{Z_3}}$

$$Z_1 = R_1 + j\omega C_1 = \frac{1 + j\omega R_1 C_1}{j\omega C_1}, \quad Z_2 = \frac{1}{j\omega C_2}$$

$$Z_3 = R_3, \quad Z_4 = \frac{R_4 \times 1/j\omega C_4}{R_4 + \frac{1}{j\omega C_4}} = \frac{R_4}{1 + j\omega R_4 C_4}$$

$\Rightarrow Z_2 Z_3 = Z_1 Z_4$

$$\frac{1}{j\omega C_2} \times R_3 = \frac{1 + j\omega R_1 C_1}{j\omega C_1} \times \frac{R_4}{1 + j\omega R_4 C_4}$$

$\Rightarrow j\omega R_3 C_1 (1 + j\omega R_4 C_4) = j\omega R_4 C_2 (1 + j\omega R_1 C_1)$

$\Rightarrow j\omega R_3 C_1 - \omega^2 R_4 C_4 C_1 R_3 = j\omega R_4 C_2 - \omega^2 R_4 C_2 R_1 C_1$

Comparing Imaginary: $R_3 C_1 = R_4 C_2$

$\Rightarrow C_1 = C_2 \left(\frac{R_4}{R_3}\right)$ — (1)

Real: $R_4 C_4 C_1 R_3 = R_4 C_2 R_1 C_1$

$\Rightarrow R_1 = \left(\frac{C_4}{C_2}\right) R_3$ — (2)

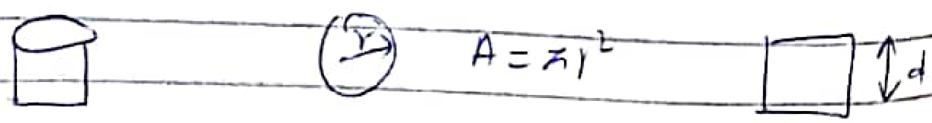
Also $\tan\delta = \frac{V_R}{V_C} = \omega R_1 C_1$

$= \omega \frac{C_4}{C_2} \times R_3 \times C_2 \times \frac{R_4}{R_3} = \omega C_4 R_4$

Dielectric constant (ε_r)

It is the measure of dielectric strength of a material.

$\varepsilon_r = 2$ means that this material has twice the capability of air ($\varepsilon_r = 1$).



$A = \pi r^2$

$$C = \frac{\varepsilon A}{d} = \frac{\varepsilon_0 \varepsilon_r \pi r^2}{d}$$

Lecture 14

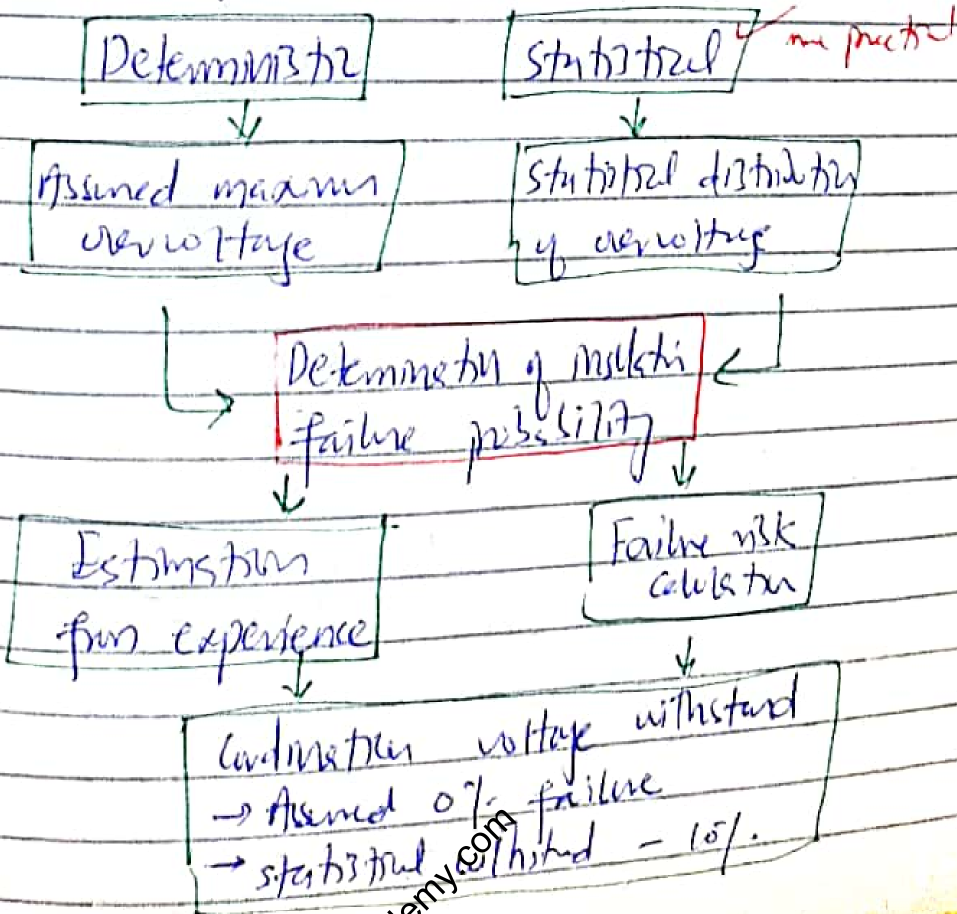
Insulation Coordination

The operating stresses of insulation.

We need to know,
1. level of possible overvoltages.
ii. Sensitive locations.
iii. Proper protective devices (surge diverters)
iv. Proper choice of insulation.

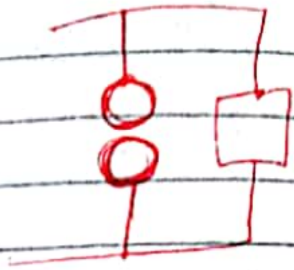
Protection level is calculated on the basis of:
i. Type of installation (generator, transformer etc).
ii. Kind of environment
iii. Equipment use.

Cost insulation, protective devices, cost of operation, failure, repairs.



Protective Gear:

Spark gap



Surge arresters

1. Gap type.
✓ ii. Metal oxide resistor (MOV) ZnO (gapless)
↓
nle voltage controlled resistor

gases → dielectric properties recover after each breakdown
liquid → partially recover
solid → completely destroyed. (most expensive)

Gases or air is generally used as insulator in power systems.

Air breakdown strength < liquids < solids
(weakest) (strongest)

Gas reliability > liquid > solid
↳ most reliable ... least reliable

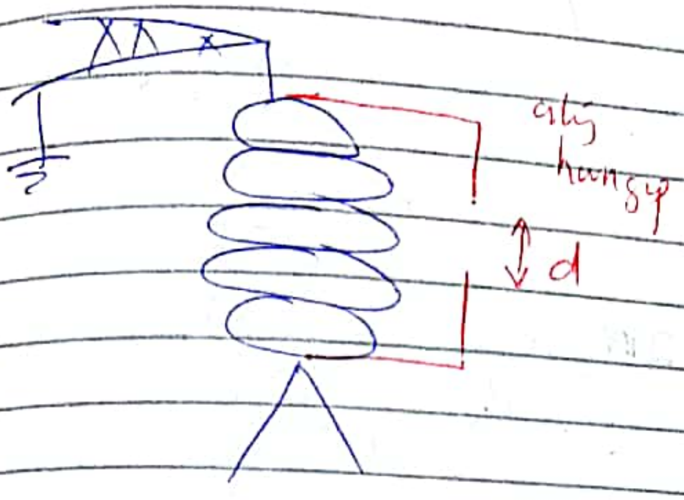
Time Lag

The time of application of voltage upto the time when breakdown occurs

$$T = T_s + T_f$$

T_s → statistical time lag → for solid assume 0
for ... ?

T_f → formative time lag → order of 10^{-7} sec



Rod gap

$V_{50} = 850(d)^{0.576}$ → power frequency voltage.

$V_{50} = 850d$ → surge voltage

d → separation b/w the two rods.

V_{50} → 50% breakdown voltage.
(what is the probability that it will have 50% breakdown)

withstand voltages must be at least twice the operating voltages. $V_w = 2V$

Overvoltages are less dangerous than surge voltages (it is due to lighting or switching effects).

$$N_s = FK_L[0.0133(h+2h_g)] + 0.1D_g$$

N_s → no of lighting strokes.

F

$0.15 \le F \le 0.2$

$K_L \rightarrow$ Keraunic level, $h \rightarrow$ height of the tower

$h_g \rightarrow$ height of ground wire from ground to that point where sag is maximum (at the midspan).

$D_g \rightarrow$ separation b/w ground and.

$$V_t = \frac{I_s}{\frac{1}{R_F} + \frac{2 n_s}{Z_g} + \frac{1}{Z_{sc}}}$$

Tower top potential.

$R_F \rightarrow$ tower footing resistance $(10 < R_F < 20)$

$Z_g \rightarrow$ surge impedance of ground wire.

$Z_L \rightarrow$ surge impedance of the lightning channel (same as the surge impedance of tower or on which the lightning strikes).

$n_g \rightarrow$ no. of ground wires.

$I_s \rightarrow$ surge current injected by the ground wire.

$$V_{st} = V_t(1-K_F) + V_{pm}$$

voltage across the entire string.

$$0.2 < K_f < 0.3$$

$$V_{pm} = \frac{(220)}{\sqrt{3}}\sqrt{2} = \_\_\_.$$

if not properly grounded (weak ground) we have arcing ground a back splash.
(b/w ground surface and → particular phase).

Lecture 15.

Grounding and shielding

↳ giving a protection.

↳ something (current (fault current)) is being conveyed to the ground.

Earth surface → infinite conductor
→ equipotential surface.

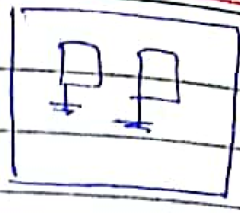
Area of earth, $A_s = 5.11 \times 10^{14} m^2$
consider a fault current, $I = 1GA = 10^9 A$

Current density $= \frac{I}{A_s} < 2.4 \frac{A}{m^2}$ negligibly small

Grounding.

i. Connection to all T/F, Gen, neutrals.
ii. Personal safety.
iii. Avoid step / transfer potential.
iv. Minimize electromagnetic interference.
v. Correct operation of protective devices.

Substation Grounding



$$S(mm^2) = \frac{I_{sc}\sqrt{t}}{k}$$

S → area of cross section of dead rod which is used for grounding. (length 6–8 ft)

I_{sc} → short circuit current

t → time required for that current to be dispersed off.

t: 1–3 sec

$138 < k < 159$

Assume I = 10 kA, dia 1–4 feet, t = 3, k = [illegible]
→ $S \sim 1.2\ cm^2$

$$R_R = \frac{\rho}{2\pi L}\left[\ln\left(\frac{8L}{d}\right) - 1\right]$$

R_R → footing resistance.

ρ → resistivity. $\rho = 1\ \Omega m$ for sea water

$\rho = 10\ \Omega m$ for moist soil. $\rho = 100\ \Omega m$ for hard rock.

L → length in metres   d = diameter in metres.

$$I_{soil} = \frac{1}{2\pi}\frac{\rho E_0}{R_{soil}}$$

I_{soil} = soil current

$E_0 = 400\ kV/m$

$$R_F = \frac{R_{soil}}{\sqrt{\left(1 + \frac{I_f}{I_{sum}}\right)}}$$

10-2052

Three types of earthing equipment are used:

i. Driven Rod. (vertically).
ii. Horizontally laid rod.
iii. Counterpoise (hemispherical mostly (square))

man made soil consists of some correct proportion of coal, rock salt, lime, clay

gravelling in ground so to keep the ground moist.