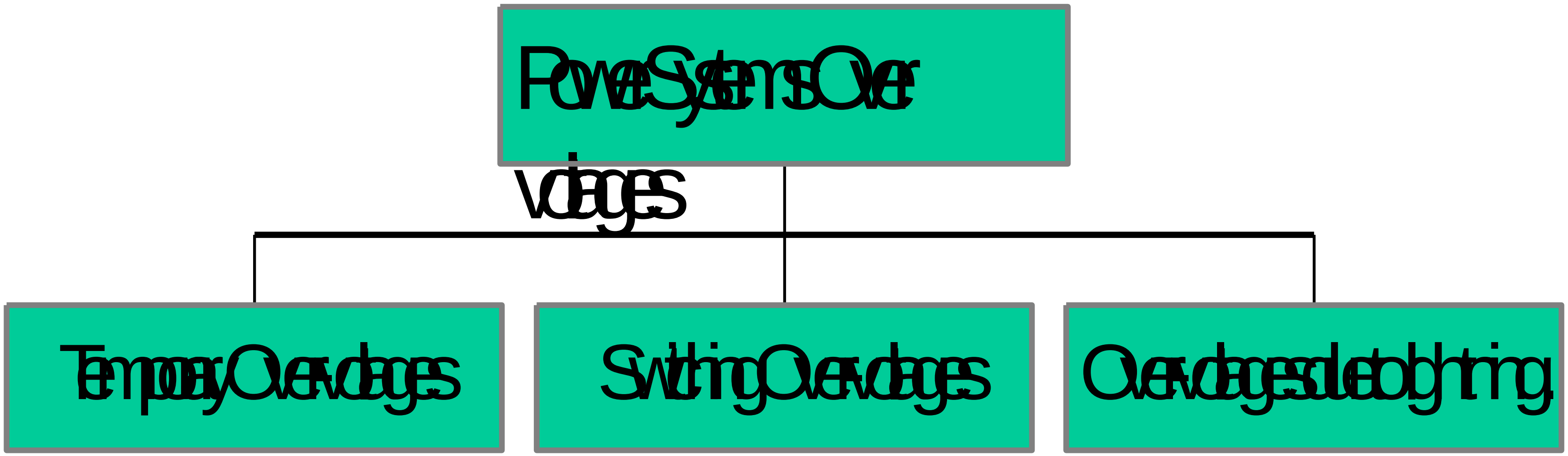
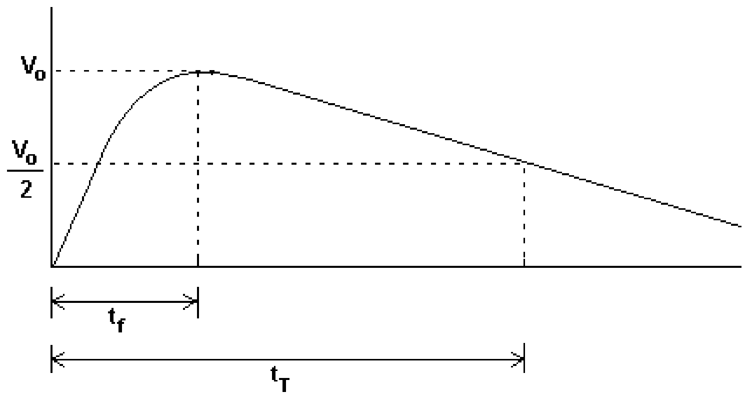
Power System Overvoltages Surge Arresters & Insulation Coordination

G.Sridhar
Associate professor,
Jyothishmathi Institute of technology and Science


Power Systems Over voltages
Temporary Overvoltages
Switching Overvoltages
Overvoltages due to lightning.

Temporary Over-Voltages

- Typically due to faults
- $\leq$ 1.2 pu
- ms to tens of second or even minutes
- Not dangerous to insulation
- Decides arrester selection.



Switching Over-Voltages

- **Due to system switching operations**
- **1.5 pu – 5 pu depends on system voltage**
- **mostly damped asymmetric sinusoids**
- **front time of first peak – tens of μs to a few ms.**
- **decides external insulation in EHV/UHV systems**
- **decides arrester duty by way of ‘long duration class’**

Over-Voltages due to Lightning

- **Due to 'direct' or 'indirect' lightning strokes.**
- **known to contribute to ≅ 50% of system outages in EHV & UHV systems**
- **few hundred kV to several tens of MV.**
- **Few kA to 200 kA**
- **very short duration : times to front : 1 to few tens of μs**
- **times to tail : few tens to hundreds of μs.**
- **Decides line insulation (BIL)**
- **Severely influences Transformer insulation.**

Basics of Switching Surges

Electrical Elements

1) **L :-** $W_B = \frac{1}{2} L i^2 = \frac{1}{2\mu 0} \int_{allspace} B^2 . dv$ $V_i = L. \frac{di}{dt} \rightarrow \infty$

as (dt → 0)

2) **C :-** $W_E = \frac{1}{2} C V^2 = \frac{\in_0}{2} \int_{space} E^2 . dv$

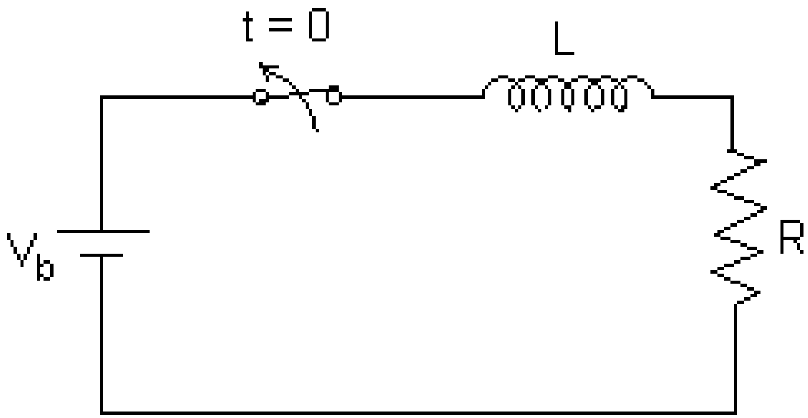
$Q = C V$ $i = C. \frac{dv}{dt} \rightarrow \infty$

as (dt → 0)

3) **R (?) :- dissipative element .**

Transducer (?)

$V = i . R$ $W = i^2 . R$



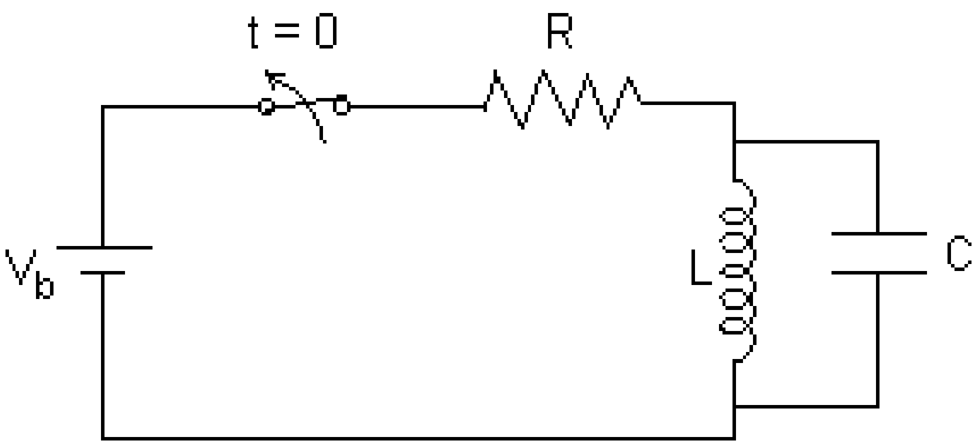
$$i\,(t = 0^-) = \frac{V_b}{R}$$

opening at t = 0

opening transient $\rightarrow V_{s.s} = L\,\dfrac{di}{dt}$

$\rightarrow \infty$

at dt $\rightarrow 0$

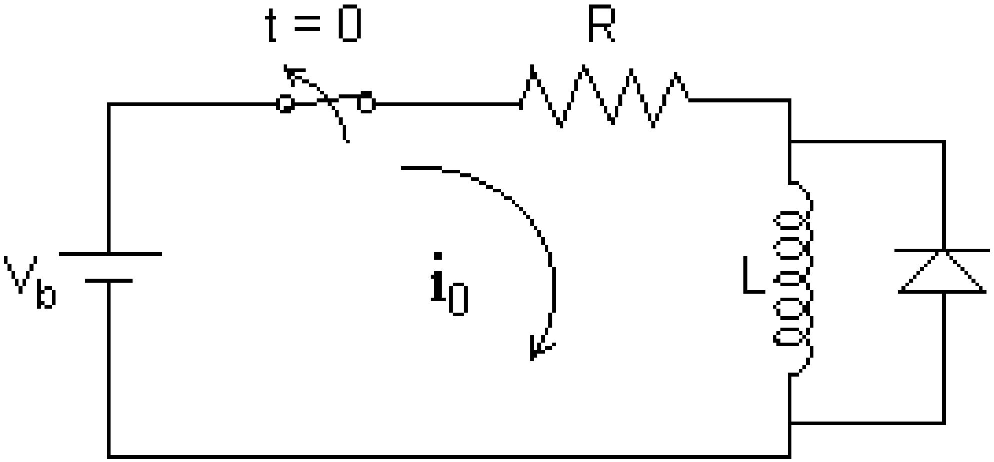


- **Vacuum circuit breakers**
- **SF_6 circuit breakers**

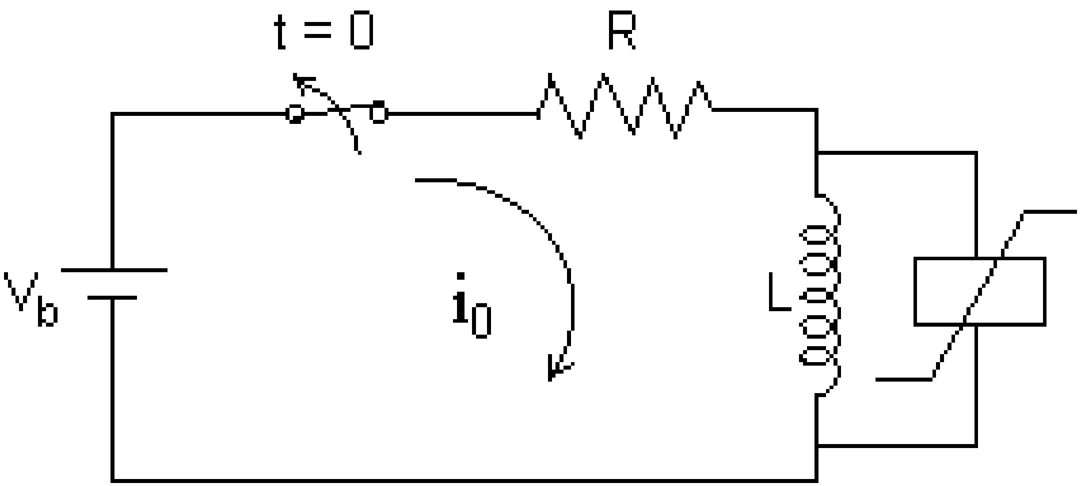
$$\frac{1}{2} L\, i^2 = \frac{1}{2} C\, V_{s.s}^2$$

$$V_{s.s} = i\,\sqrt{\frac{L}{C}}$$

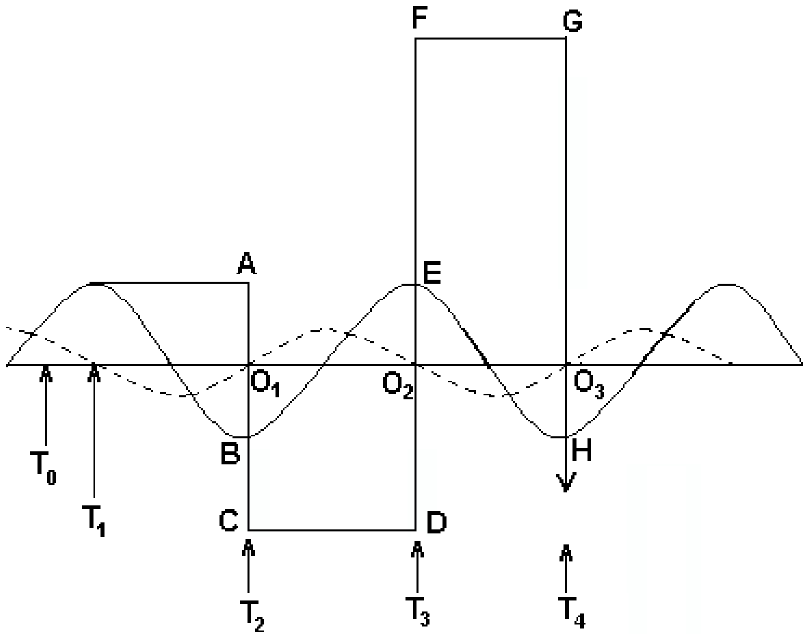
Characteristic Resistance



Reverse connected diode



Varistor
(Non linear resistor)



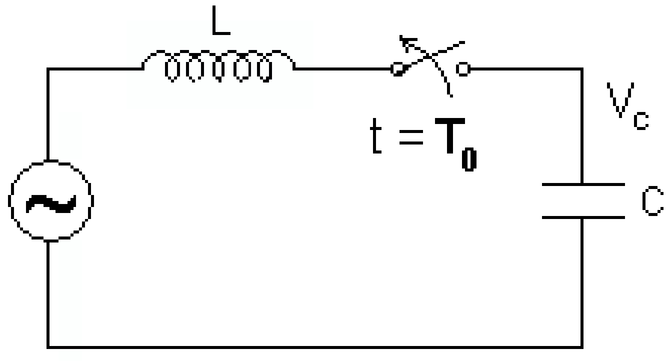


Fig: **Switching Over voltages due to breaking inductive-capacitive circuit**

Circuit breaker opens mechanically at t= T_o

Circuit breaker opens electrically at t= T_1

- **At t= T_o, V_c = O_1 A = V_p (peak voltage of system) = 1 pu**
- **At t=T_2, voltage across circuit breaker (V_{CB}) = 2 V_p (from A to B)**
- **At t=T_2 CB restrike**

V_c lends to B but due to energy in L it overshoots to C such that AB = BC

Over voltage due to this = 3V_p (O_1 to C)

Importance of Switching Surges

1. **Can cause flashover/outage of exposed insulation.**

   Clearances required :

   L_g = Gap distance in m,
   V = Switching overvoltage in MV

   $L_g = 4.V$ m for $V \leq 1$ MV

   $L_g = 4.V^2$ m for $V > 1$ MV

Energy (W_{SS}) in Switching overvoltage is enormous.

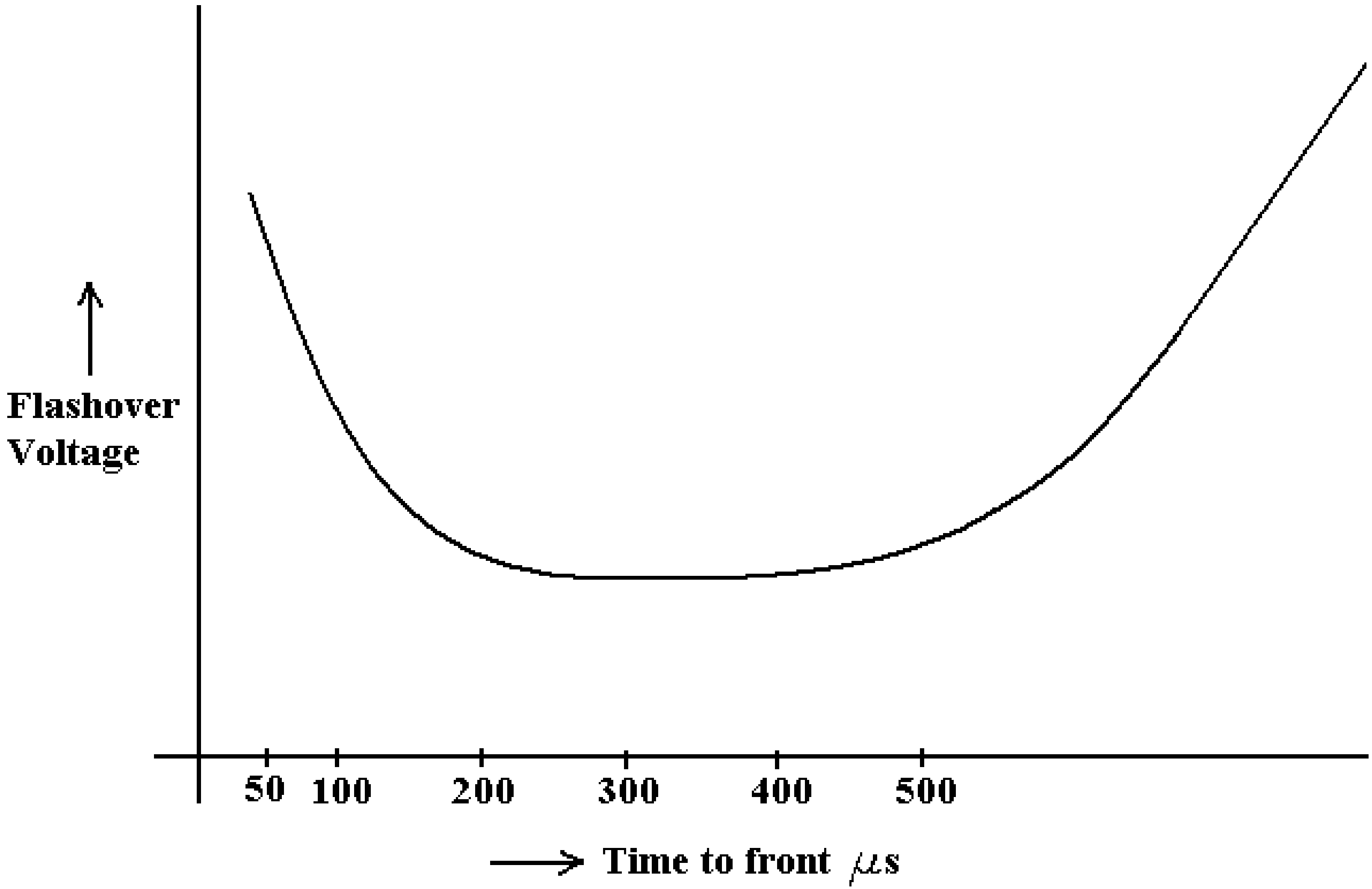
$$W_{SS} = \frac{1}{2} C_{SS} . (V_{SS})^2$$

C_{SS} = Capacitance involved in generation of switching surges.

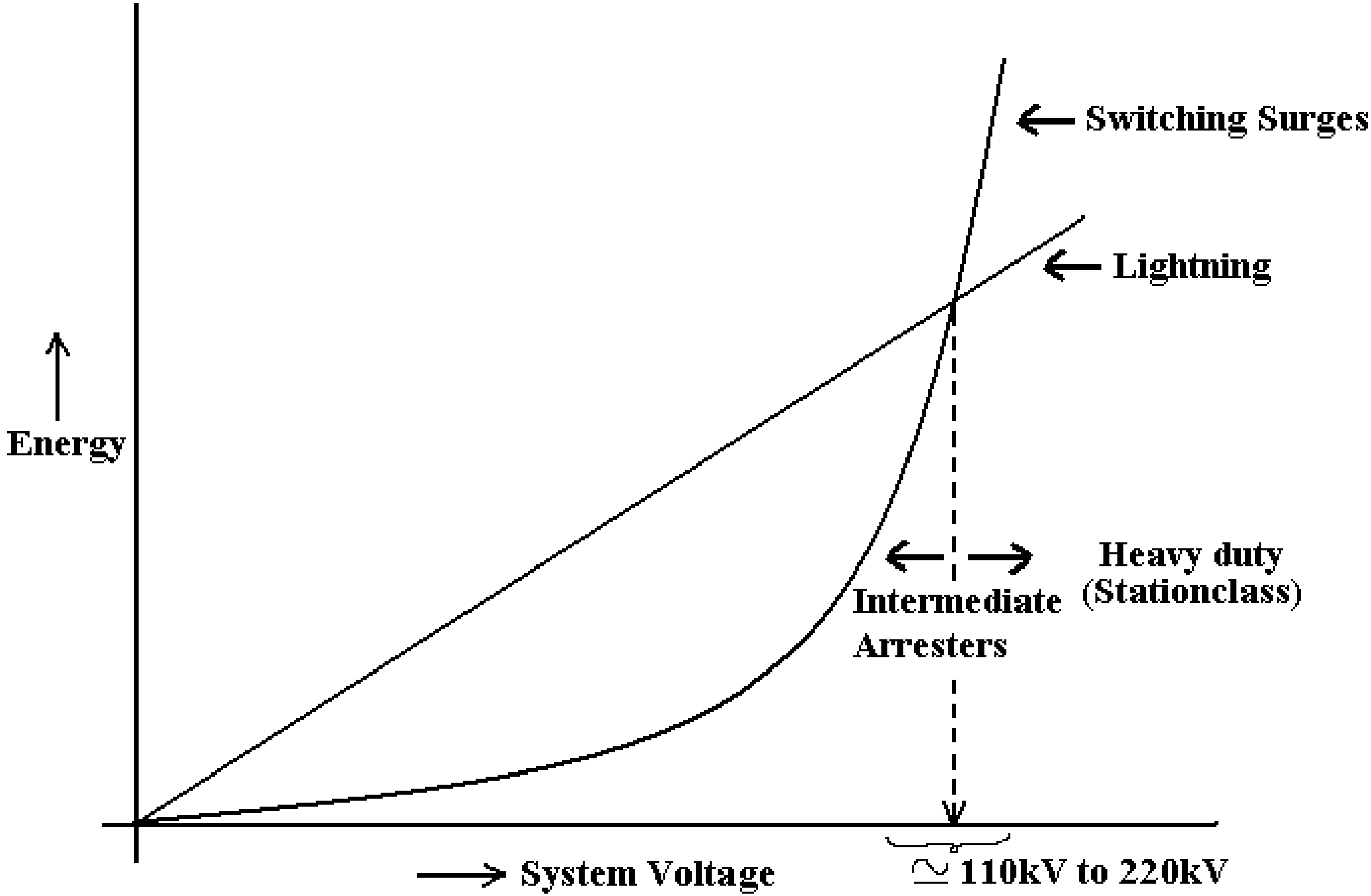
$$C_{SS} \propto \text{Length of Line} \propto \text{System voltage}$$

$$V_{SS} \propto \text{System voltage}$$

$$\therefore W_{SS} \propto (\text{System Voltage})^3$$



Behaviour of Rod-gaps



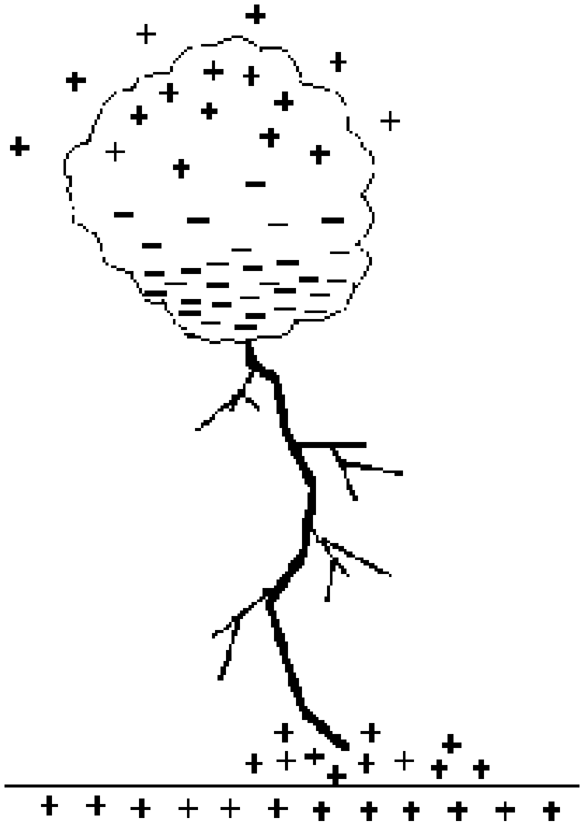
Switching Surges
Lightning
Energy
Heavy duty
(Stationclass)
Intermediate
Arresters
System Voltage
≃ 110kV to 220kV

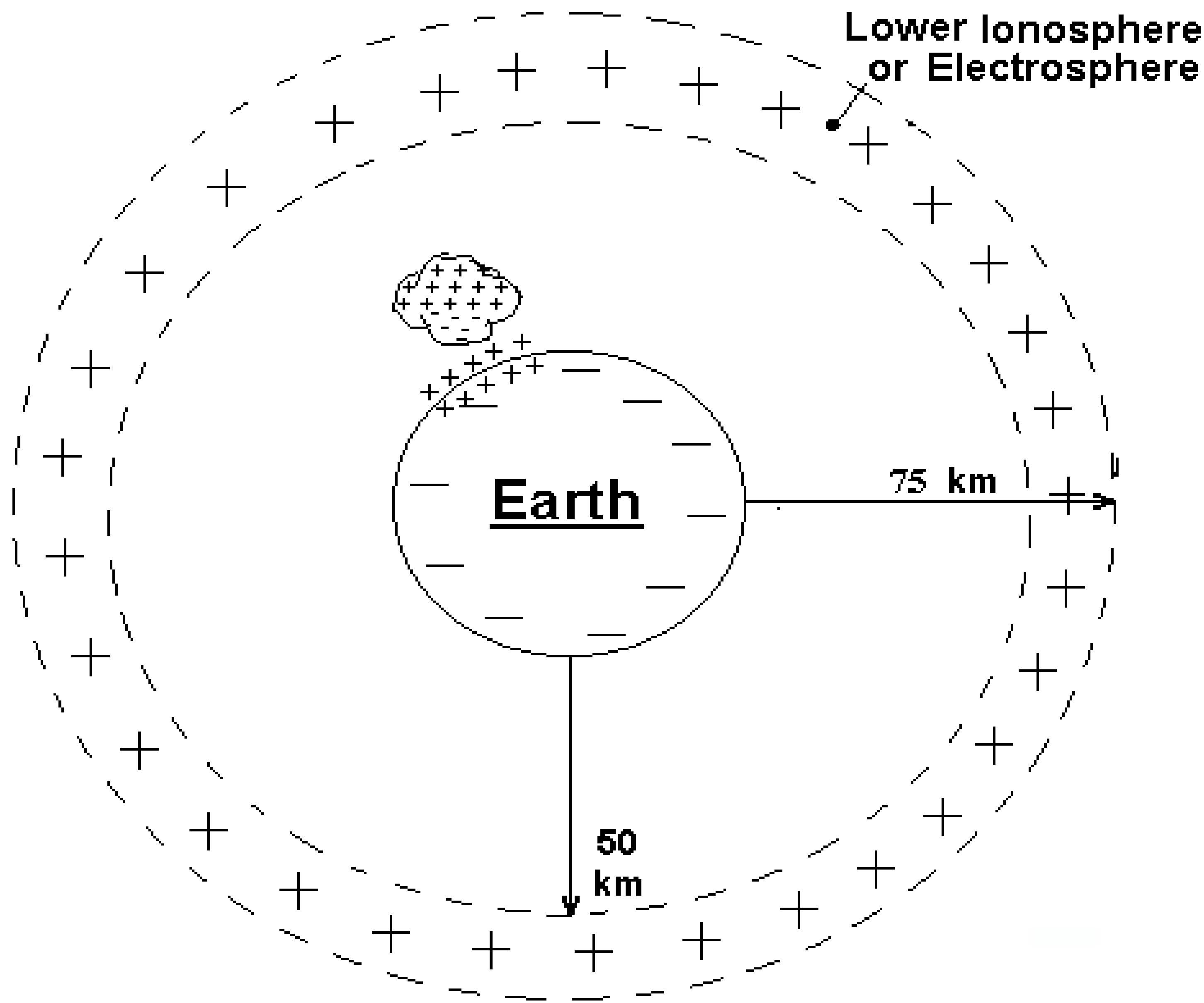
Basics of Lightning

LIGHTNING

Lightning

- **Frequent, spectacular, natural phenomena**
- **Has considerable destructive potential**
- **Electrical discharge from a charged cloud (thundercloud) to another cloud or to ground**
- **Discharges within a cloud also occur**

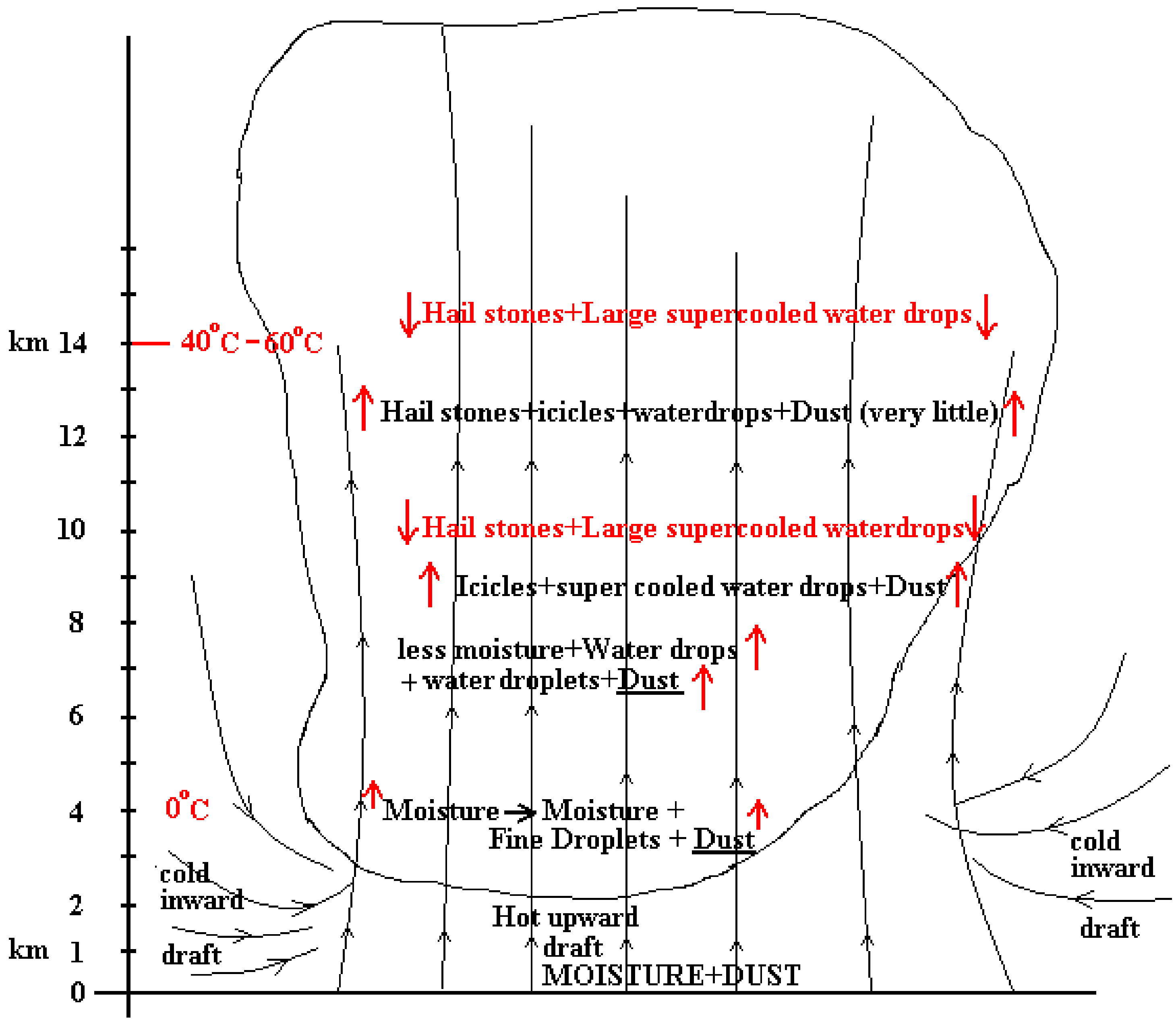



Lower Ionosphere
or Electrosphere
Earth
75 km
50
km

Global Capacitor

- **Lower Ionosphere : + 300 kV near constant voltage with respect to Earth**
- **Earth : Negative Electrode.**
- **Average leakage current from earth ~ 3 x 10^{-12} A/m²**
- **Average charge density on earth's surface ~ 1.1 x 10^{-9} C/m²**
- **Total leakage current ~ 2000A to 3000A from Lower Ionosphere to earth.**
- **Normal electric field at earth's surface ~ 3V/cm**
- **Electric field on the earth's surface under approaching stepped leader ~ 500 V/cm to 600 V/cm**
- **Effective leakage resistance of atmosphere~ 100Ω to 150Ω**
- **Average equivalent current per stroke = 2A**
- **Number of 'average current level' lightning ~ 1000 to 1500 strokes per second**
- **Estimated total number of lightning strokes per ~ 3000 to 5000 per second (global)**

Formation of Thundercloud



Mechanisms of Charge Generation

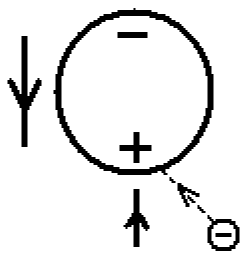
1. Simpson's Theory
2. Wilson's Theory
3. Mason's Theory

Tribo Electricity - Friction → Charge seperation

Solar Radiation → 7 to 10 electron – ion pairs per cm^3.

Electrons & ions	}	**attachment to water drop** **Dust particles**

Positive charge on Lower Ionosphere



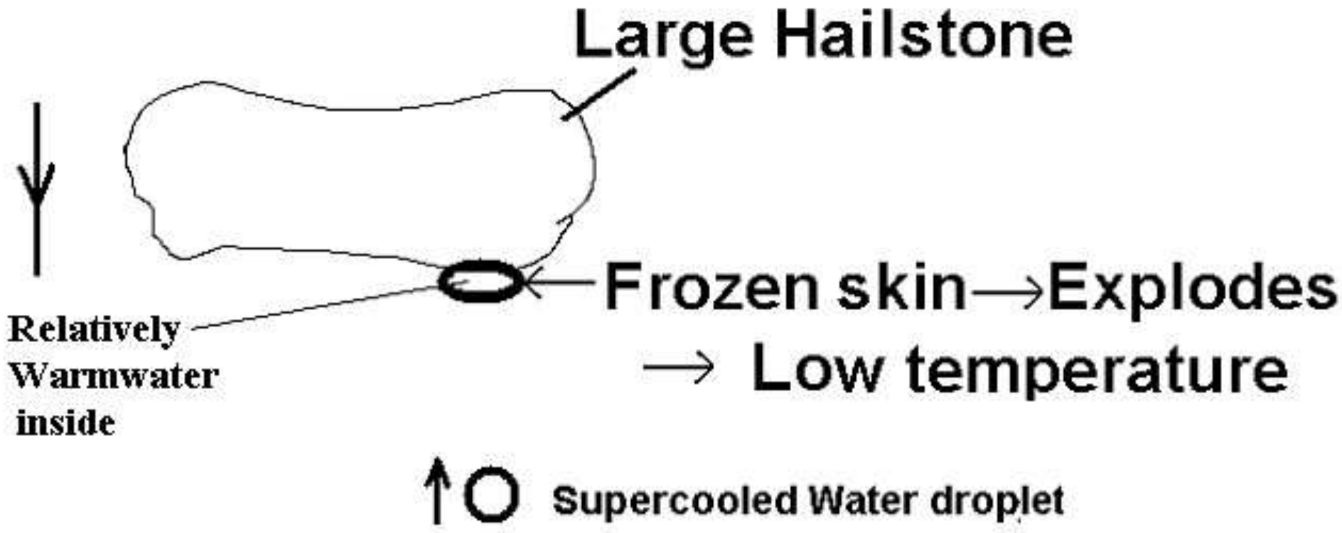
attracted – neutralisation of positive charge

electron/negative ion /negatively charged dust particle or fine droplet

- ve charge on earth

<u>Simpson’s Mechanism</u>

Mason's Theory



Lower temperature → excess + ve charges

Higher temperature → excess - ve charges

Lightning Stroke

* **Stepped Leader – develops in steps (a few m to tens of m) towards earth. (Multiple branches at nodes).**
* **When stepped leader comes sufficiently close to earth (or earthed object – tower, tall tree, water tank etc;) positive streamers start from earthed object.**
* **Stepped leader meets positive streamer – typically 10m to 200m above earth - completion of <u>Forward stroke.</u>**

<u>Forward stroke</u> - 1 kA to 2 -3 kA
- Very slow
- Not visible

Return stroke (First)

- Huge current develops in conducting channel of Forward stroke (invisible)
- Extremely rapid development
- Minimum $\simeq$ 5 kA
- Maximum $\simeq$ 200 kA
- Rise time $\simeq$ 5μs - 15μs
- Channel core temperature $\simeq$ 30000^0 C
- Velocity $\simeq$ (0.5 . velocity of light)
- Extremely Bright
- Thunder (Acoustic effect of channel heating extremely rapidly).

*** Dart Leader**

*** Second return stroke, etc;**

Lightning Flash

Minimum – one stroke

Average – 3 to 5 strokes

Maximum – upto 40 strokes.

Current magnitude – reduces progressively.

Some Basic Characteristics

- **Cloud potentials – very small to ≈ 100 MV**
- **Charge in a cloud – very small to > 300C**
- **Lightning Flash**
  - **Has many strokes – upto 40**
  - **Typically 4 to 5 strokes/Flash**
  - **Peak current reduces from that of first stroke**
- **Currents in Lightning discharges to ground**
  - **Upto ≈ 200kA (negative)**
  - **Upto ≈ 360kA (positive)**
- **Rate of rise – Max.:10^{11}A/s (100kA/μs)**
- **More than 70% of strokes – Negative**
- **Number of strokes/second – 2000 to 5000**

All over the world

Probable Lightning Flash Density =

$$N_E = (0.1 + 0.35\ \mathrm{Sin}\lambda)(0.4 \pm 0.20)$$

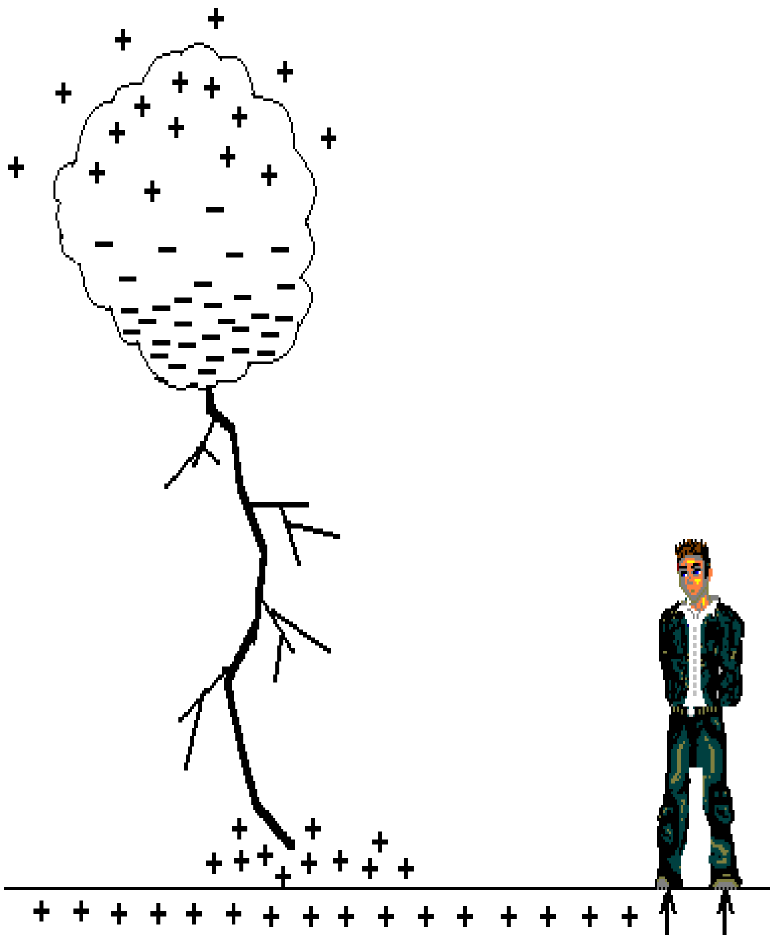
λ = Latitude.

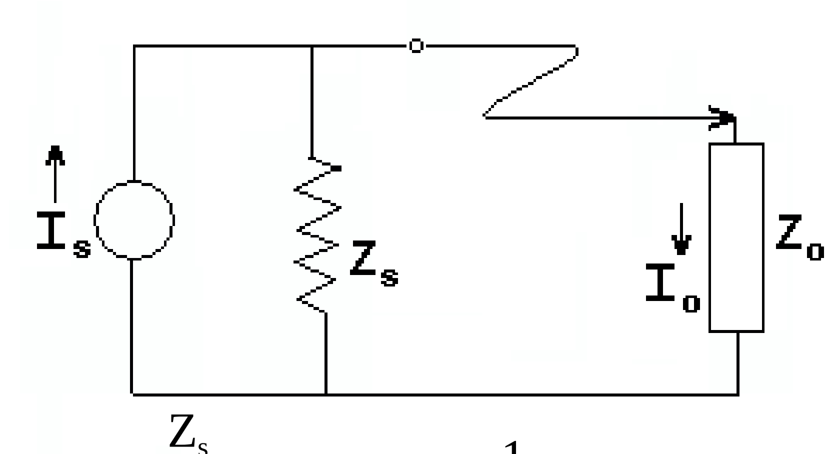
No. of strokes/km²/Thunderstorm day

$$N_G = 0.04\,(T_d)^{1.25}$$

Lightning Overvoltage Magnitudes

Equivalent Circuit for Lightning S





$$I_0 = \frac{Z_s}{Z_0 + Z_s} \cdot I_s = \frac{1}{\frac{Z_0}{Z_s} + 1} \cdot I_s$$

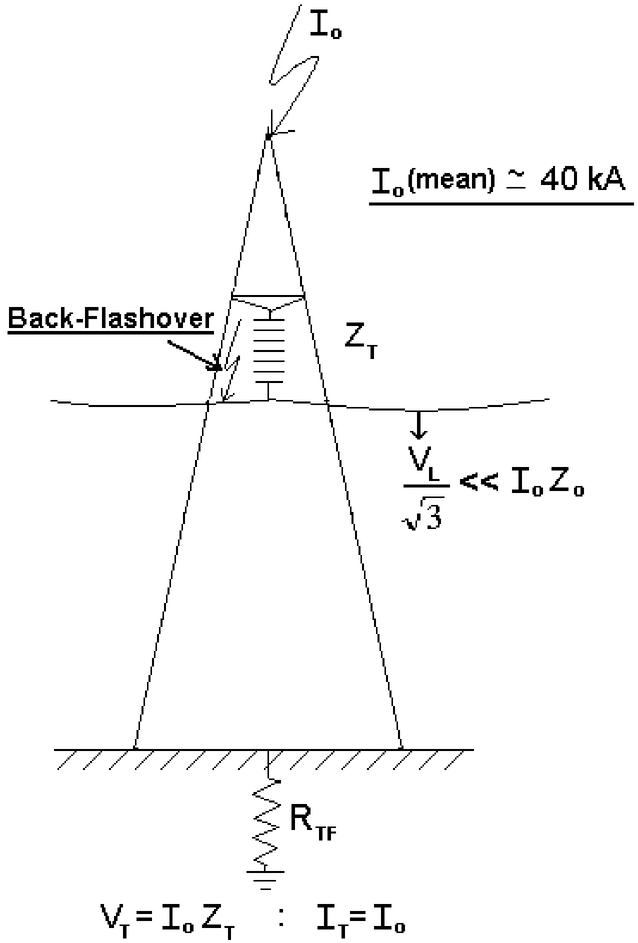
$$\simeq I_s \quad \text{if} \quad \frac{Z_0}{Z_s} << 1$$

	$Z_s \approx 3000\ \Omega$
Object	**Z_0**
Tower	**100 Ω - 150 Ω**
OHGW	**≈ 400 Ω**
Ph Condr	**≈ 330 Ω - 400 Ω**

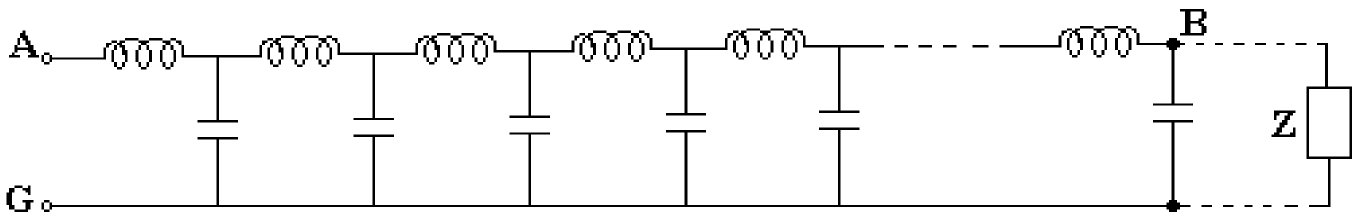
↓ **UHV lines** ↓ **LT lines (single condr/phase)**

Lightning Over Voltages

1. **Strokes to tower** – **without OHG Wire**



Travelling Waves



L = Inductance per unit length
C = capacitance per unit length

$$\sqrt{\frac{L}{C}} = Z_0 \longrightarrow \text{Surge impedance}$$

$$\Gamma_r = \frac{Z - Z_0}{Z + Z_0}$$

$\longrightarrow 1$, for $Z \longrightarrow \infty$ (open circuit)

$\longrightarrow -1$, for $Z \longrightarrow 0$ (short circuit)

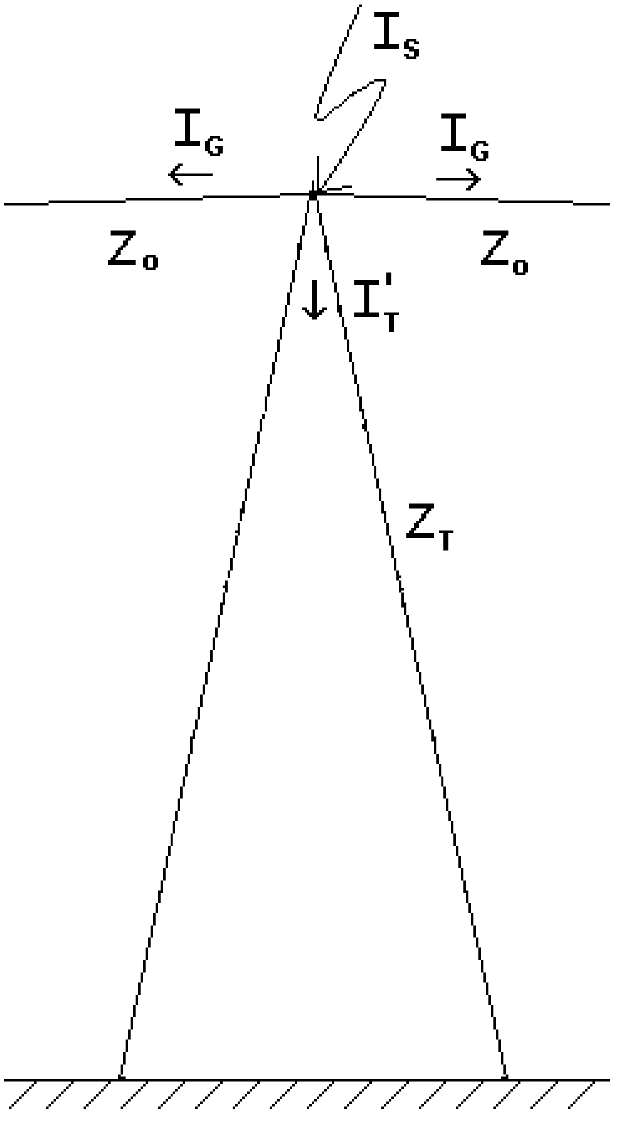
$$V = V_i + V_r$$

$$V = V_i + \underbrace{\Gamma_r \cdot V_r}$$

$2V_i$ for $\Gamma_r = 1$ $\longrightarrow$ open circuit

0 for $\Gamma_r = -1$ $\longrightarrow$ short circuit

Reduction of Tower Top potential by Overhead Ground Wire

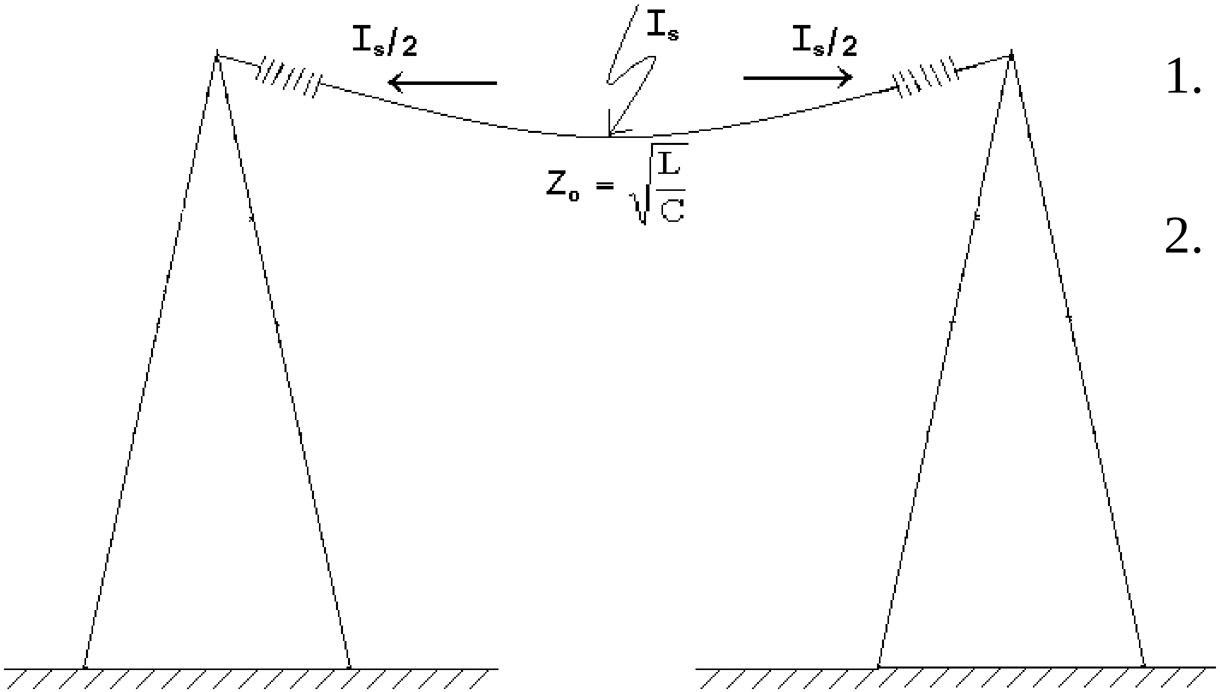


$$I_T' = \frac{Z_o/2}{(Z_o/2) + Z}.I_s$$

$$\left[\frac{400/2}{400/2+100} = 0.67\right]$$

$$V_{TT}' = I_T'(0.67)Z_T$$

Over Voltages & Currents due to Lightning



1. Lightning currents : a few to 200 kA
2. Direct stroke to transmission line-

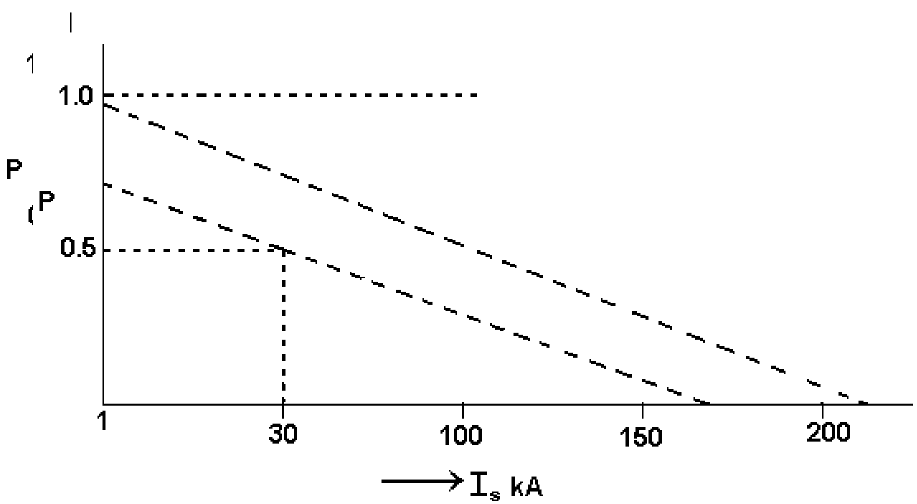
   Voltage at point of

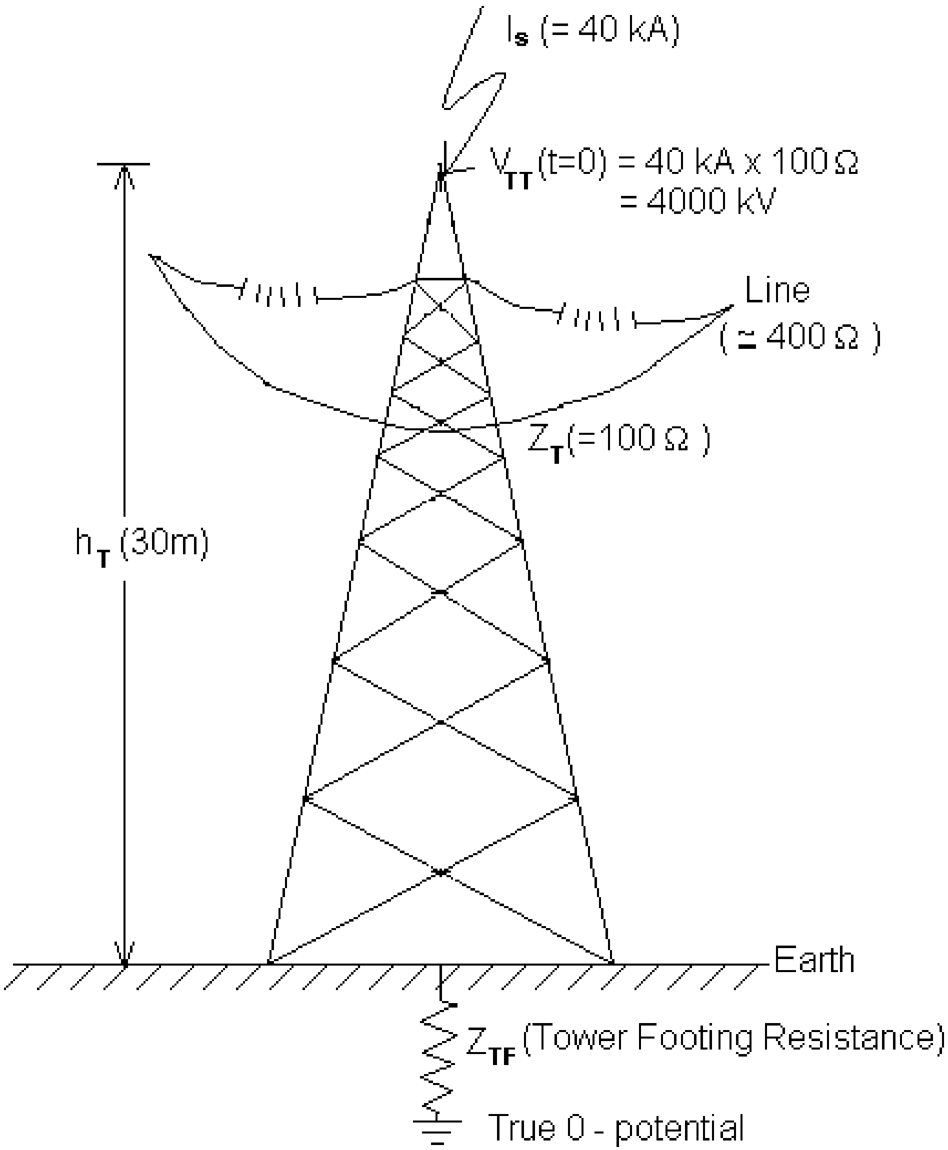
   strike : $\frac{I_S}{2} \times Z_o$

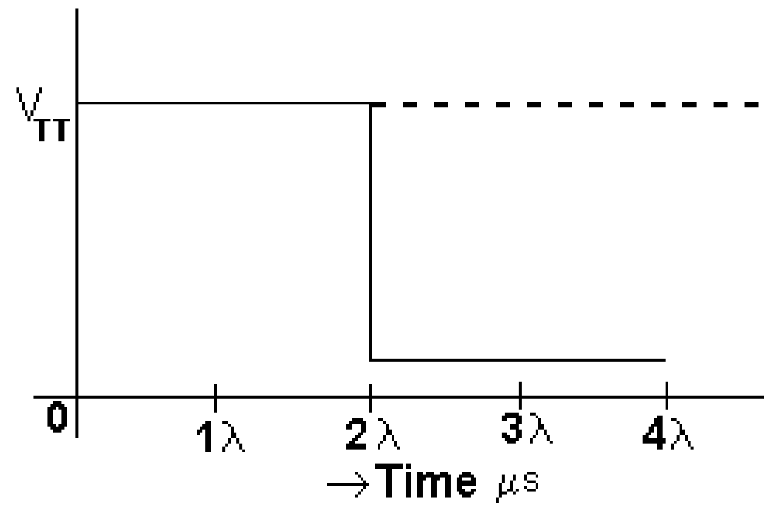
Z_o = surge impedance of transmission line

$\approx 400\Omega$ for single conductor

$\approx 350\Omega$ for twin & multiconductor bundles





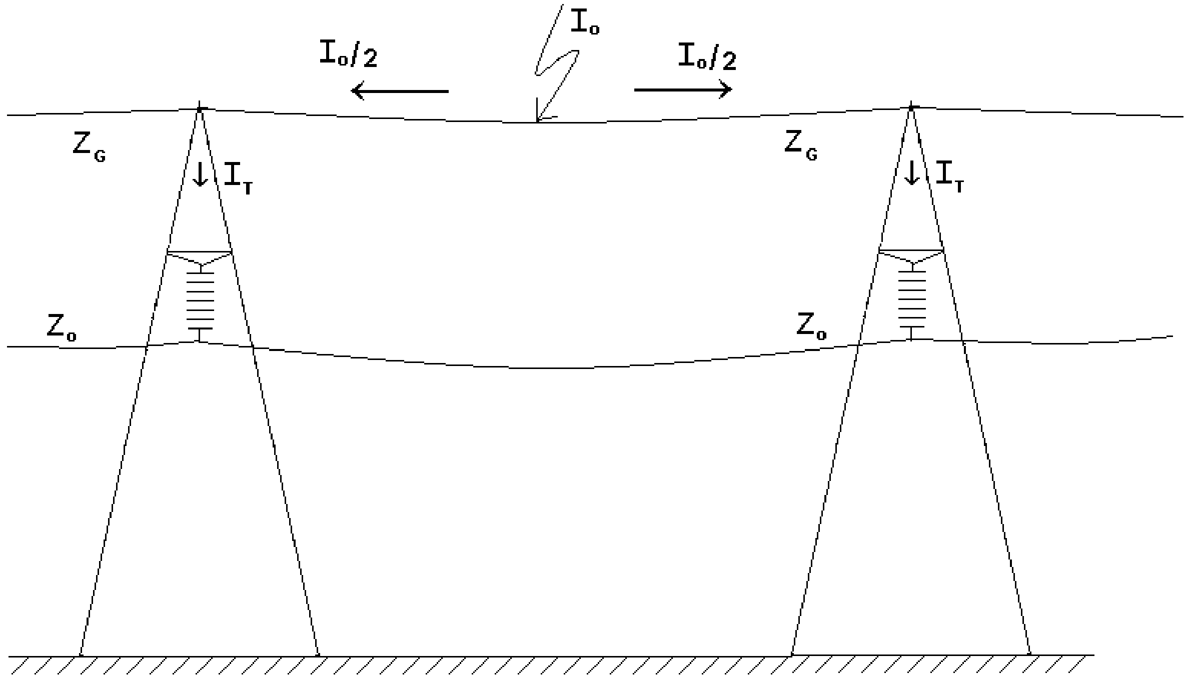


Potential at Tower Top at instant of Strike

= Tower Surge Impedance X Stroke Current

Fig : <u>Stroke to Tower Top</u>

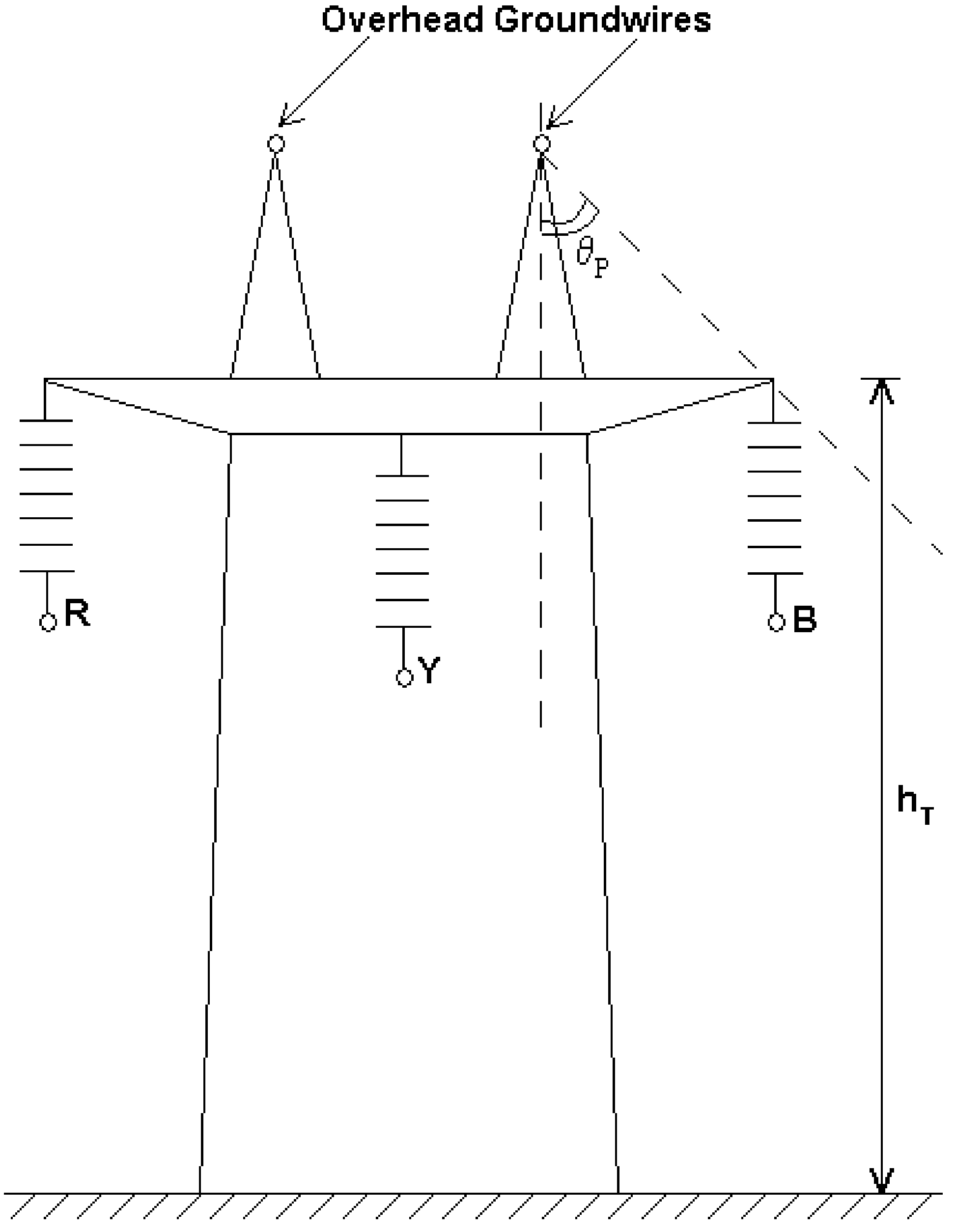
Strokes to OH GW - midspan



$$I_T = \frac{Z_G}{Z_T + Z_G} \, {}^{I_o}\!/_{2}$$

$$V_T = I_T \, . Z_T \quad = \frac{Z_G}{Z_G + Z_T} \, . \frac{I_o}{2} . Z_T$$

Protection by Overhead Ground Wires

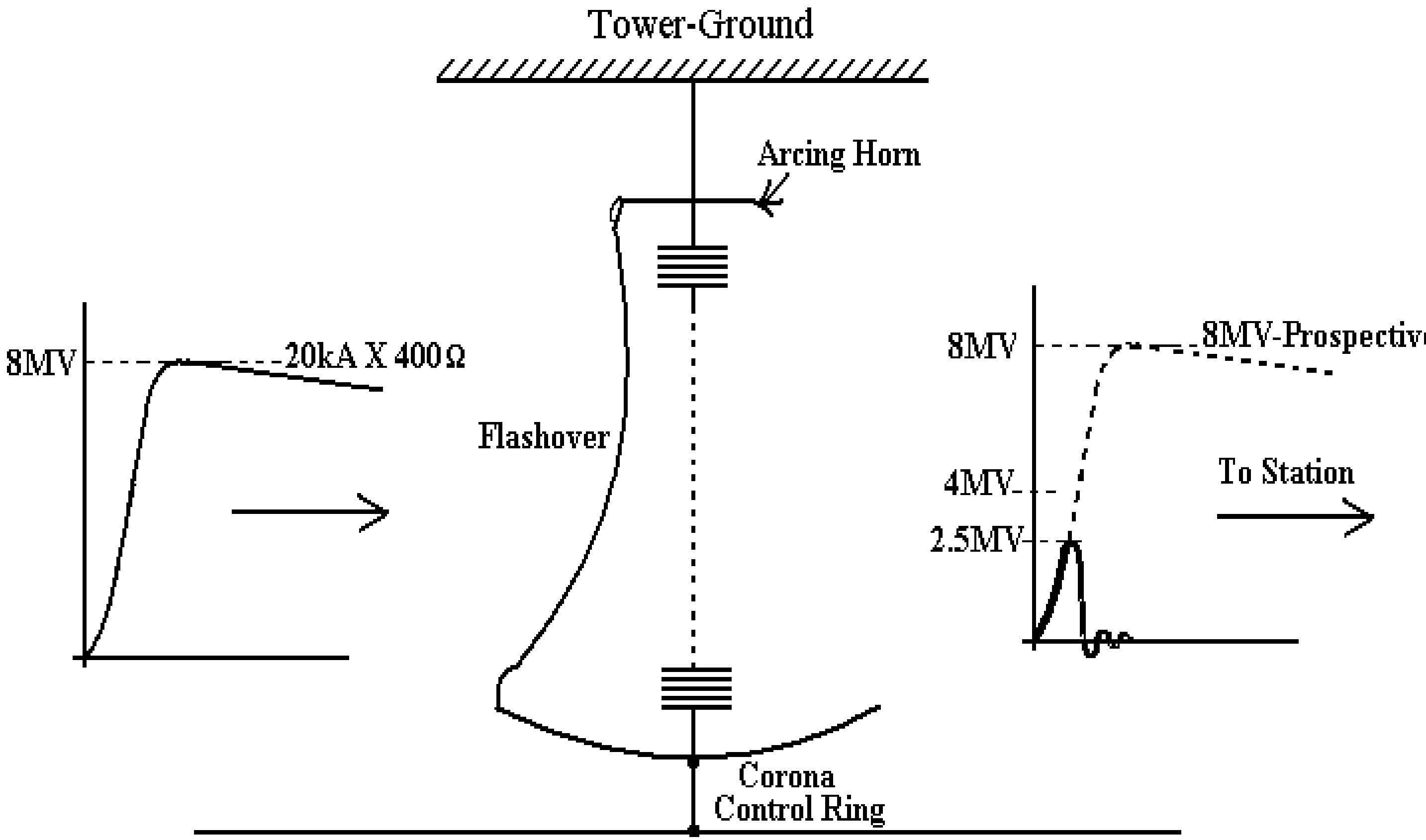


$\theta_P \leq 30^o$ for $h_T < 30$ m

$\theta_P \approx 20^o$ for $h_T \geq 30$

Electro-geometric model

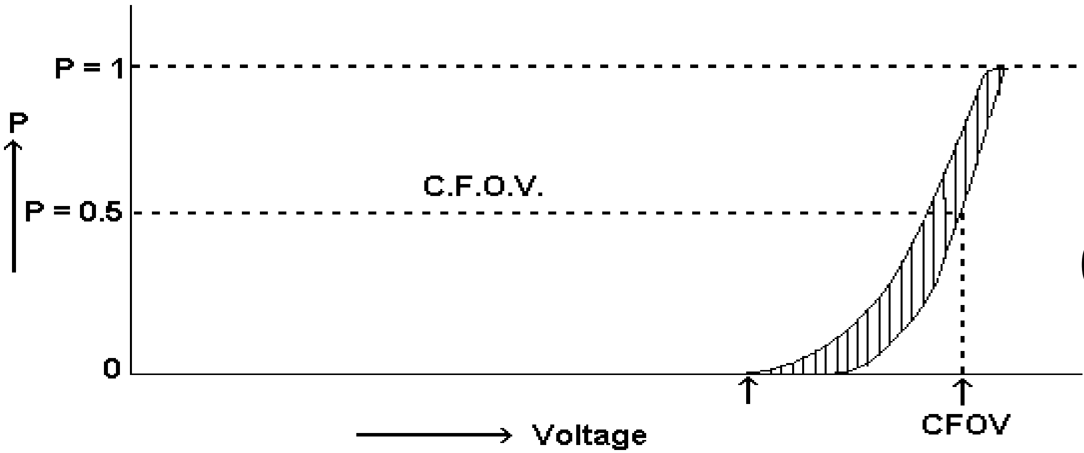
– white head – for $h_T \geq 30$



Tower-Ground
Arcing Horn
8MV
20kA X 400Ω
Flashover
8MV
8MV-Prospective
4MV
2.5MV
To Station
Corona
Control Ring

$(P_W)_n = (P_{W-1})^n$ - **n strings in Parallel**

for any given voltage



For n=4 & for V_{CFO}:

$$(P_W)_4 = (P_{W1})^4 = (0.5)^4 = 0.0625$$

Probability of flashover = 0.9375

Therefore maximum voltage entering station ≈ V_{CFOV}

Too high to be taken as Design level for Transformer Insulation

Hence compulsive need for over voltage Protection of Power-Transformers ← most critical & expensive equipment

Lightning Overvoltages at Arrester Terminal

Statistical behaviour of breakdown (of Line insulation)

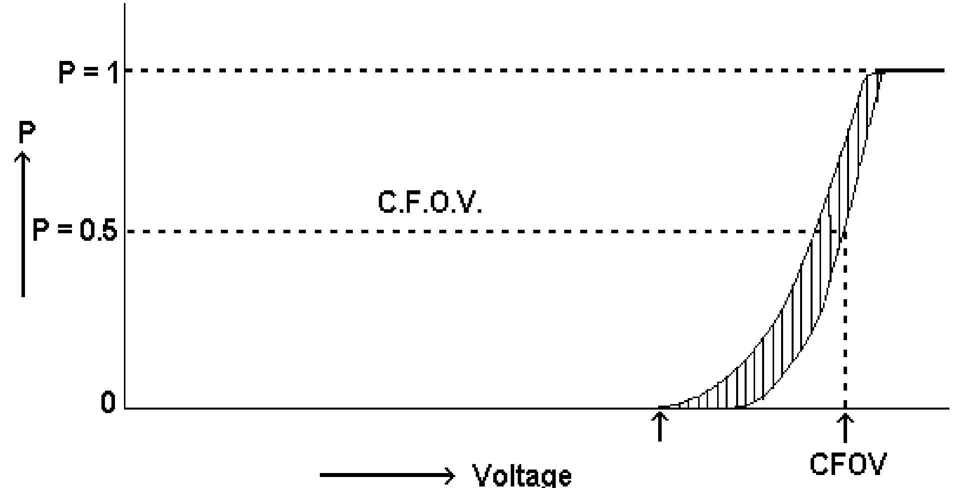
I_s, 50% probability ≈ 40kA

40kA X 400Ω = 8MV → too high

2

– flashover of line insulation

– Probabilistic



Probability of flashover = (P_F) ≤ 1 for one insulator string $(P_w)_1^n$

Probability of withstand = P_w ≤ 1

Probability of w/s of n strings in parallel = $(P_w)_n$ = $(P_w)_1^n$

Probability of Flashover = 1 - $(P_w)_1^n$

For V_{CFO}, $(P_F)_1 = (P_w)_1 = 0.5$

For 1km long line, n ≥ 4; ∴ $(P_w)_4$ = = $0.5^4 = 0.0625$

Thus, typically, max voltage inside a station protected by OHGL for atleast 1 km = V_{CFO}

Surge Arresters

Brief History of Development of Lightning Arresters (Surge Diverters) - <u>Surge Arresters</u>

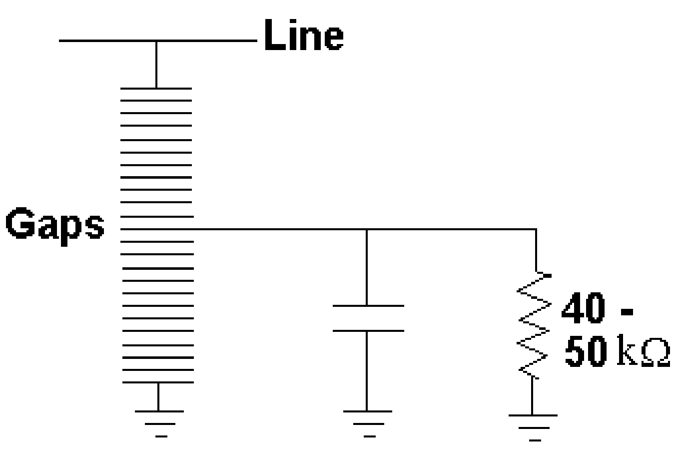
Various types of Gaps

1880 A.D.: a)'Horn Gap'

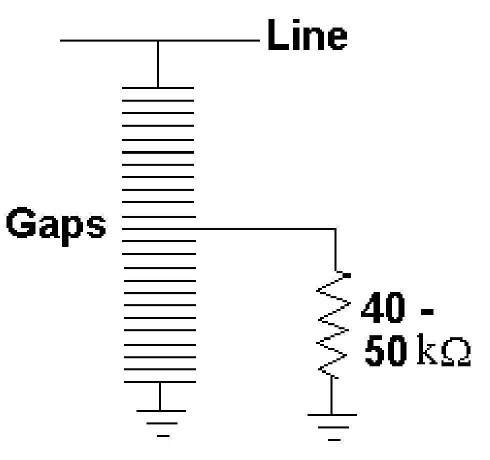
Rarely used : Waterjets to leak charges on Transmission Lines.

b)'Modified Gaps'

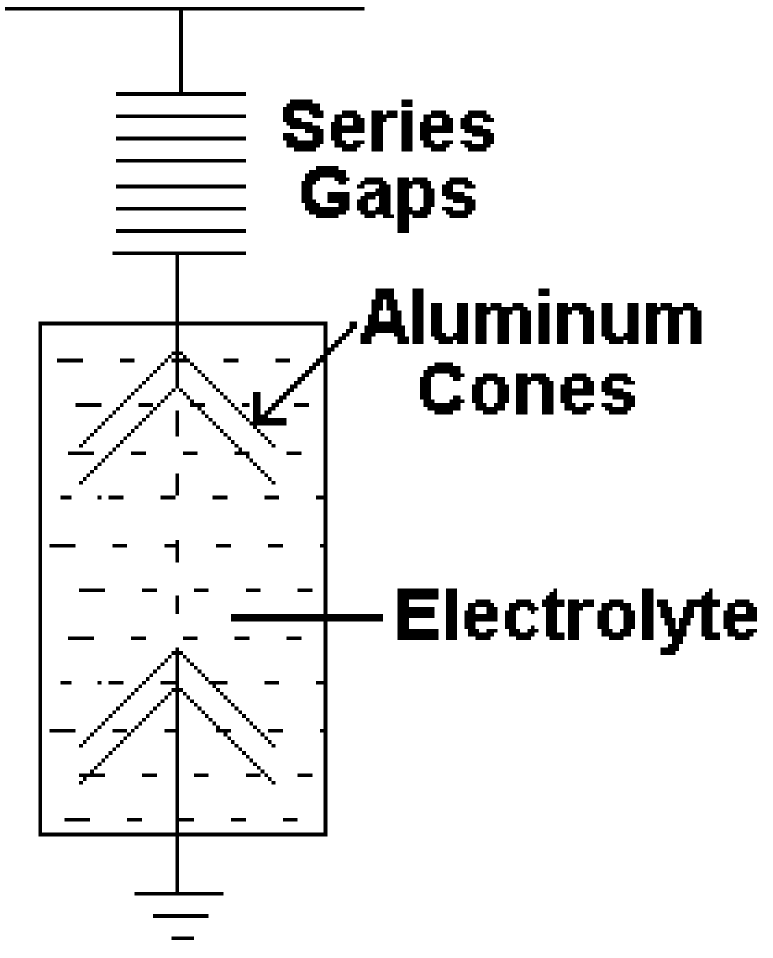
Discriminating Lightning Arrester



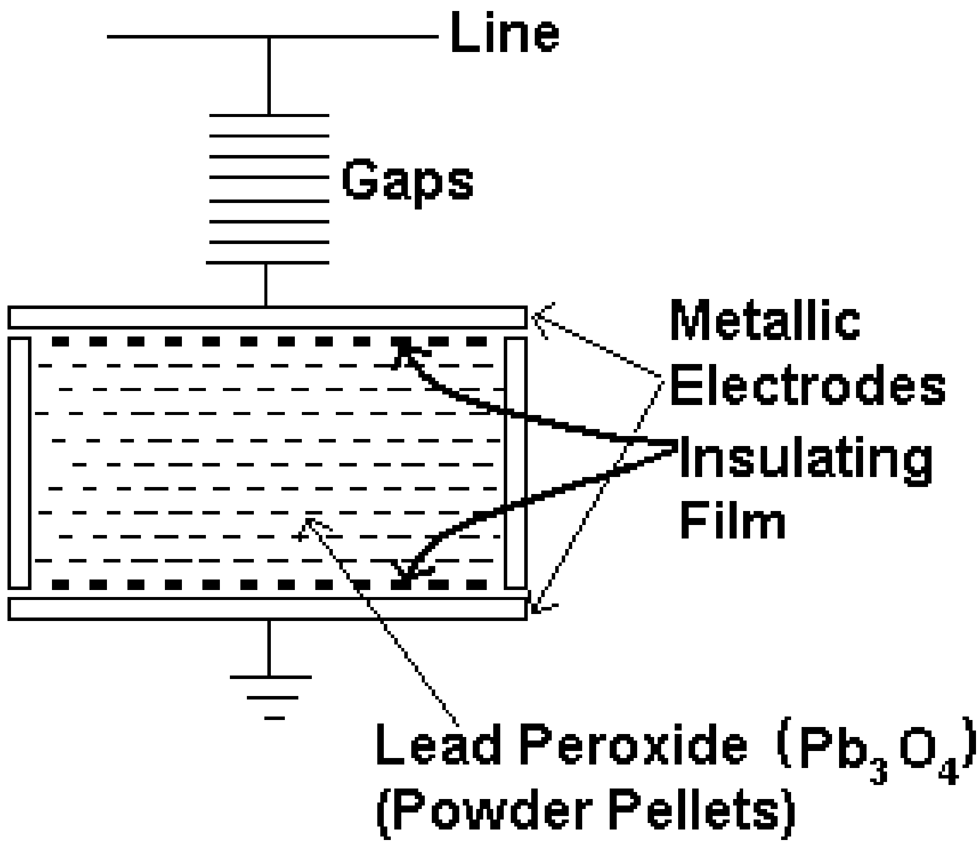
Low Equivalent Lightning Arrester



3. 'Aluminum Cell' LA

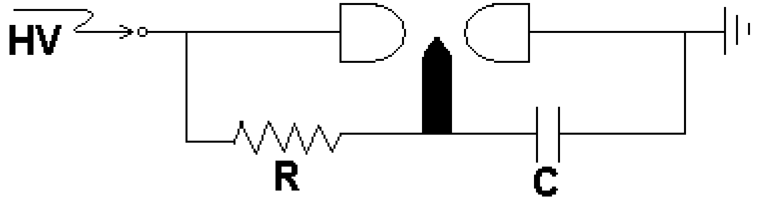


4. Oxide – Film Arrester → Pellet Arrester
Crosby Field & Christopher Lougee

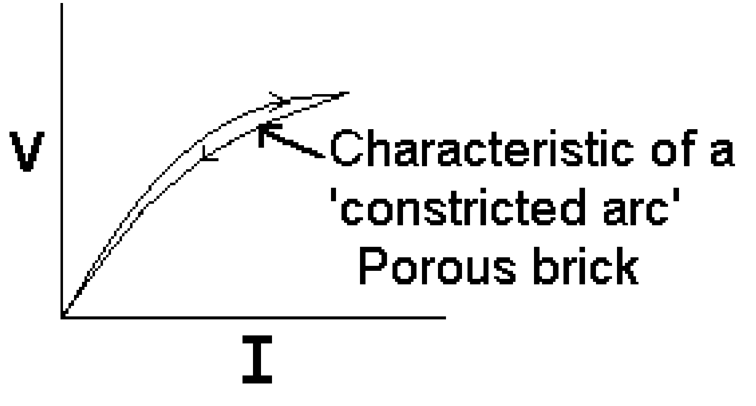


$$\underset{\text{(Conducting)}}{Pb_2O_5} \xrightarrow{150^o} \text{Red Lead } Pb_3O_4 \rightarrow \underset{\substack{\text{(Litharge)}\\ \text{Insulating}}}{PbO}$$

5. Impulse Gaps – Chester Allcut

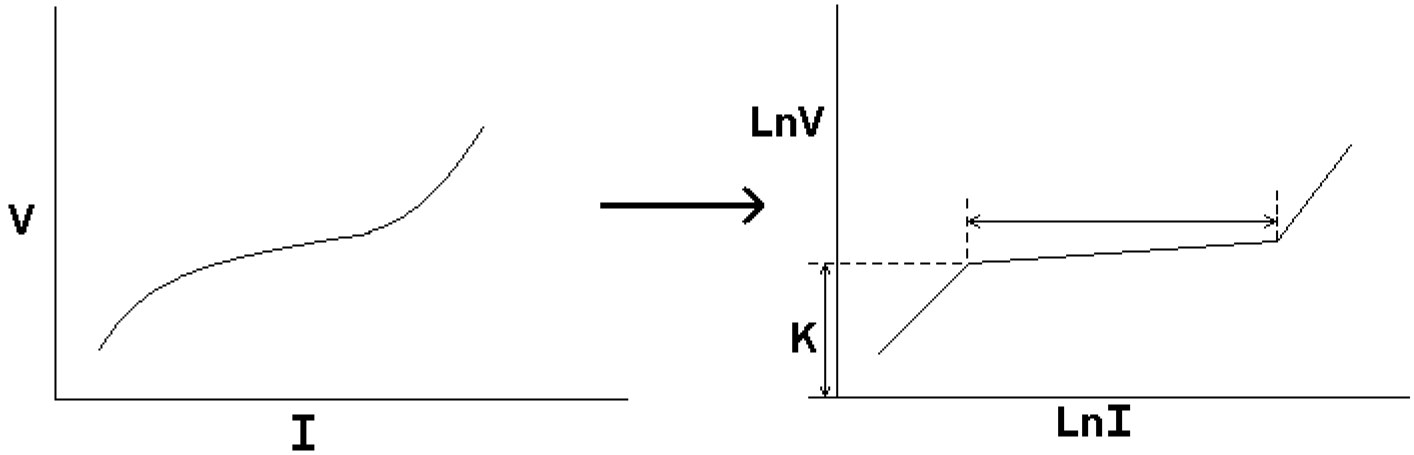


6. 'Auto Valve Arrester' – Westinghouse Stephen etal



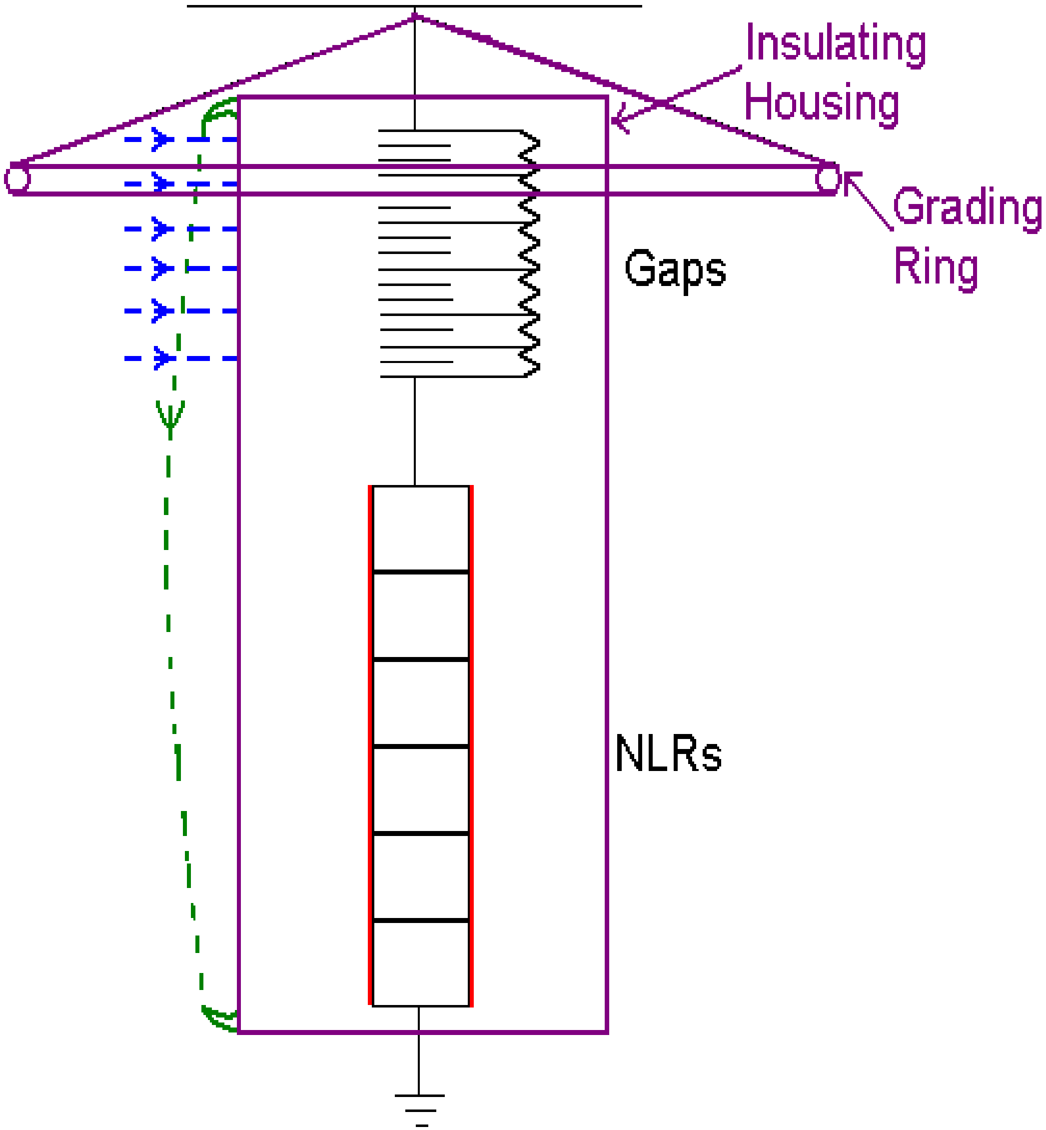
7. 'Thyrite' – McEachron – General Electric (1932)

$V = K\,I^{\beta}$ $\beta \approx 0.3$ to 0.4



$\mathrm{Ln}V = \mathrm{Ln}K + \beta\,\mathrm{Ln}I$

8. „Modern" Surge Arrester



Series Gaps

+ Magnetic Action

+ Grading Resistors

+ Non Linear Resistors

+ Insulating Coating

+ Pressure Relief

Nonlinear Resistors

- Silicon Carbide based

  Sic ≈ 80%

  Clay

  Feldspar

  MnO_2

  CuO

  (Sodium Silicate ?) ---

  $\beta \rightarrow 0.3$ to 0.45

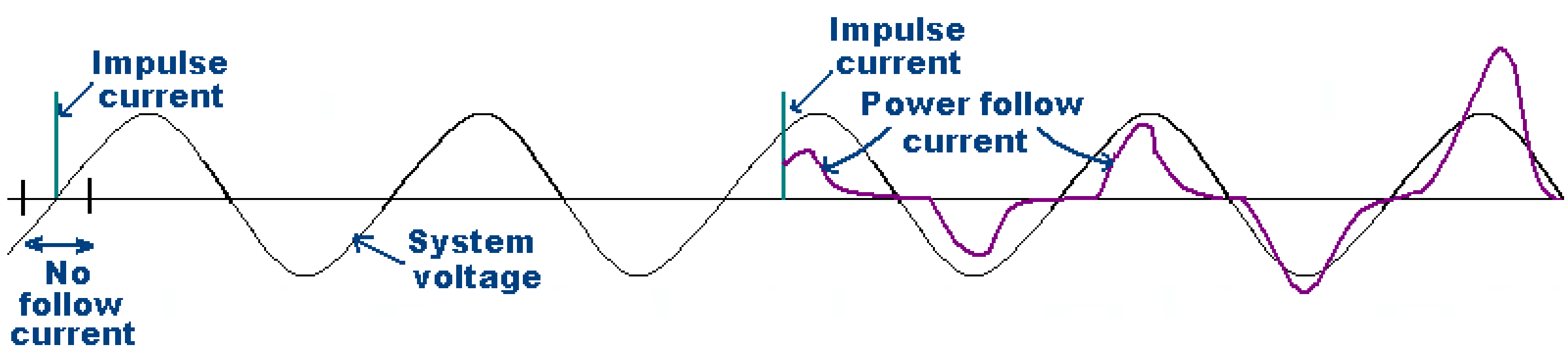
Surge Arrester

Series Gaps

1. Should be insulating under healthy voltage conditions
2. Should sparkover whenever a dangerous overvoltage arises.
3. Should quench power follow current at the earliest

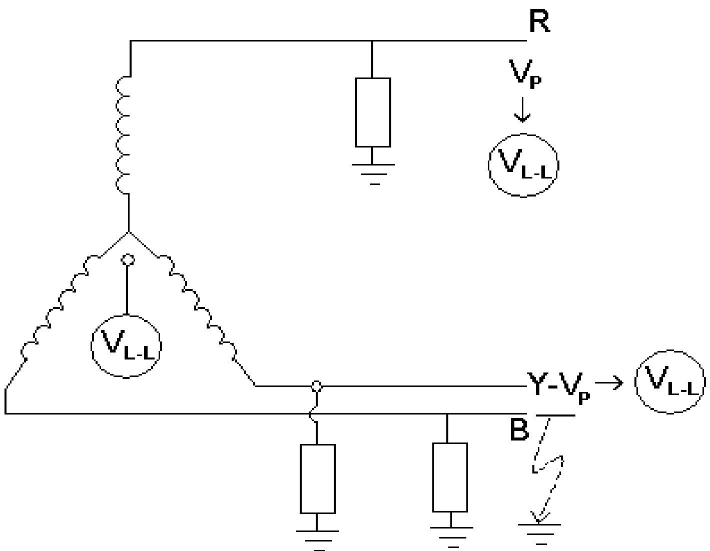
Non Linear Resistors

1. The voltage developed during flow of impulse currents should be below withstand capability of insulation under protection.
2. Should limit the power follow current to a value that can be safely interrupted by series gaps.



Power Frequency Voltage Rating of Arresters

The max voltage across arrester/s on the healthy phases under fault-conditions (single line-ground fault is almost invariably the worst) should not cause operation of arresters.



Isolated neutral

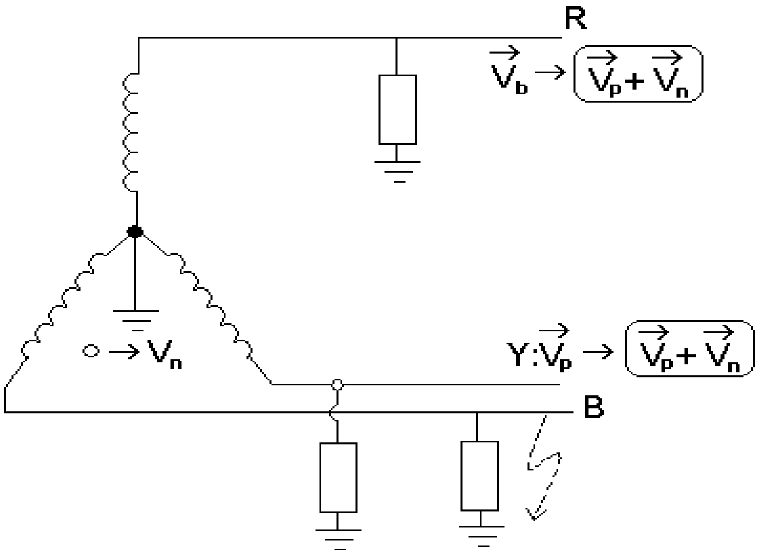
V_A= Max arrester voltage = $V_{L-L(max)}$

at power freqency

K_g =1

↑

$V_A = K_g \cdot V_{L-L(max)}$



Ideally grounded neutral

$V_n \rightarrow$ remains at 0 even when fault current flows

$V_A = V_{P(max)}$ $\quad$ $Kg = 1/\sqrt{3} \approx 0.6$

Solidly grounded(Effectively grounded system)

$V_A = 0.8\ V_{L-L(max)} \rightarrow$ Nearest higher standard rating slected

↑

80% arrester

Lightning Currents through Arresters

$V_{CFO} \rightarrow$ on impact on a Transformer winding (open circuit), doubles at the most

$\rightarrow 2\,V_{CFO}$

Assume SA sparks over at $2\,V_{CFO}$, current through S.A. = $I_{SA} = \dfrac{2\,V_{CFO}}{Z_0 + Z_A}$

Z_A ↓ negligible

Ex.: 220kV line: BIL = 1050 Kv

V_{CFO} typically 1500kV $\quad I_{SA} = \dfrac{2\,V_{CFO}}{Z_0} = \dfrac{2 \times 1500\text{kV}}{400\Omega} = 7.5\text{kA}$

Not possible to have SAs of many ratings

System Voltage	Impulse Current rating	
500 V (LT)	1.5 kA 2.5 kA	LT arresters
3.3 kV – 33kV (Distribution)	5 kA	Distribution class arresters
> 33 kV $\quad \leq$ 132 kV	10 kA	Intermediate Station class
220 kV	10 KA	Heavy duty Station class
$\geq$ 400 kV	10 kA 20 kA	Heavy duty Station class

High current ratings (4 X 10μs)

– 10 times Impulse Current rating for 1.5kA, 2.5kA & 10kA class

– 13 times Impulse Current rating for 5kA class(!)

Switching Surge Energy Handling Capability

Energy stored in a line of capacitance C_L at a switching surge voltage of V_{SS} is

$$W_S = \frac{1}{2} C_L V_{SS}^2 : W_S \, \alpha \left(V_{SYSTEM}\right)^3$$

increases linearly with line length & voltage

V_{SS} : increases with system

hence system voltage

upto & including 132 kV : Lightning surges are more important

At & above 220kV, W_s becomes very important

– decides long duration class of arresters

Energy capability per kV rating of arrester kJ/kV

Estimation of Power Follow Currents

Distribution class, 3kV/rms ,

K→ 1200 to 1500

β→ 0.43 at low currents

< 0.3 at high currents

(>10A)

Station class , 3kV/rms ,

K→ 600 to 900

β→ 0.43 at low currents

(≈1A)

→ 0.25 at high currents

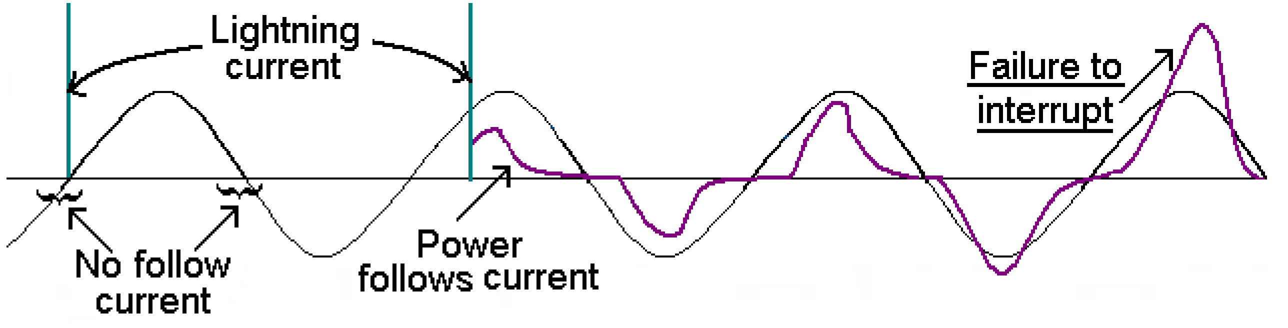
(>100A)

$$V = K.I^{\beta} \rightarrow I = 1A \rightarrow V = K = \text{voltage required to derive 1A}$$

Distribution class $K = 1200, \beta = 0.3,\ 2^{1/\beta} \approx 10$		Station class $K = 600,\ \beta = 0.2,\ 2^{1/\beta} \approx 16$	
V	I	V	I
V=K=1200 V	1 A	V=K=600 V	1 A
2400 V	10 A	1200 V	16 A
$3000\sqrt{2} = 4200$ V→ 66 A I_{PF}		2400 V	256 A
4800 V	100 A	$3000\sqrt{2} = 4200$ V → A I_{PF}	
9600 V	1000 A	4800 V	4096 A
RDV→15000 V→5000 A (I_L)		RDV→6000 V→10000 A (I_L)	
19200 V	10000 A	9600 V	65536 A
38400 V	100000 A	19200 V	*
		38400 V	*

Series Gaps

1. For temporary overvoltages, Gaps should not sparkover. Therefore, the sparkover voltage of the gaps under power frequency voltage should be more than about 1.2pu.
2. After passage of lightning currents, the power system drives a current – power follow current = which must be safely interrupted.



3. By experience, it is found that the follow current gets quenched if the power frequency sparkover voltage is greater than or at least equal to (1.5 X Voltage rating) of the arrester.

$V_A = k_g \cdot V_{L\text{-}L\text{-}max}$ (k_g = 30% for effectively grounded systems)

50Hz 5.0V $\geq 1.5\ V_A$

a) For distribution class, 2 to 3 V_A

b) For H.V. arresters – 1.5 to 1.8 V_A

Types of Gaps

$I_F < 100A$(peak)

→ Plane-Parallel Gaps

"Quench Gaps"

$I_F \geq 100A \leq 300A$

→ „Rotating Arc"

↑

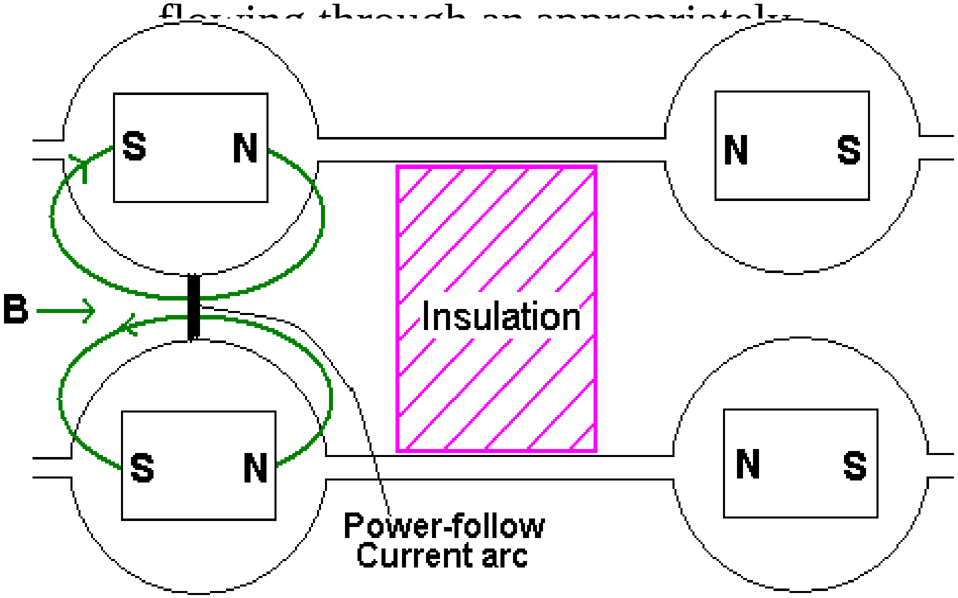
Magnetic Field

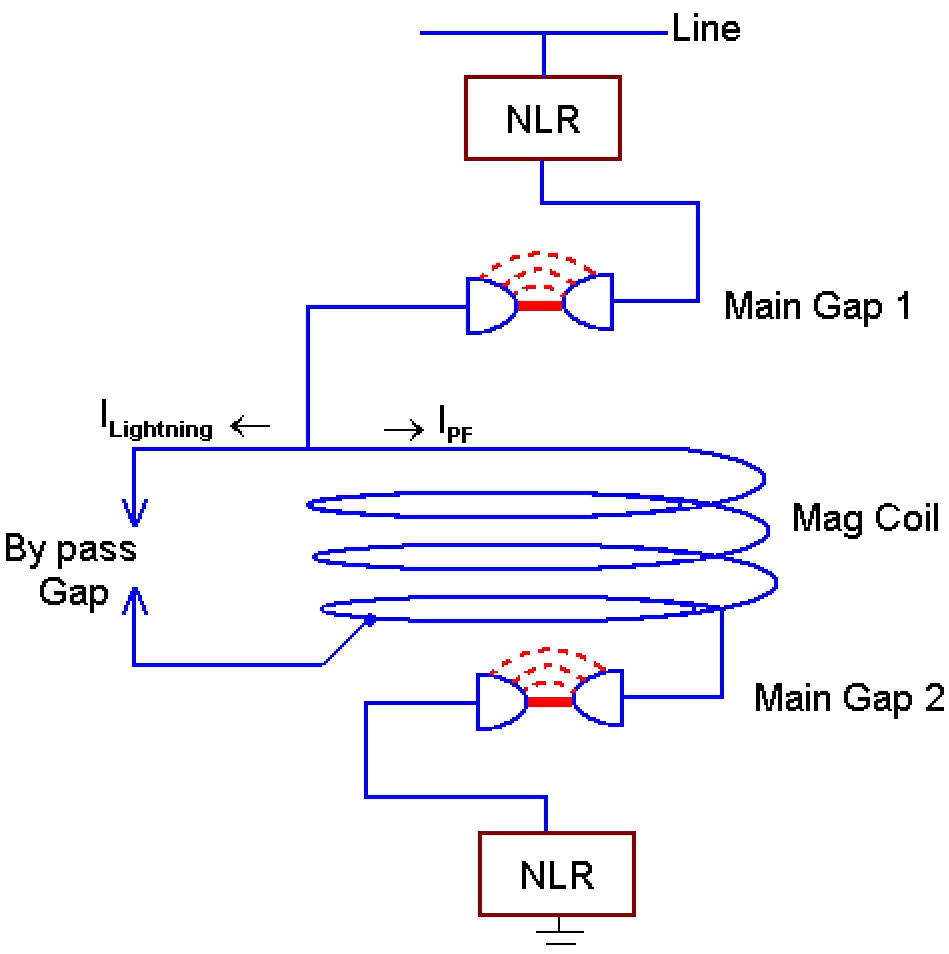
1. Permanent magnet
2. Produced by follow current

flowing through an appropriately

$I_F \geq 300A \leq 500A$ – Light duty magnetic blow out

$I_F > 500A$ → Heavy duty magnetic blow





9. ‘Most Modern‘ Surge Arrester

Metallic Oxides – ZnO ≈ 85% to 90%

$$\left.\begin{matrix} Sb_2O_3 \\ Bi_2O_3 \\ CO_2O_3 \\ Zr_2O_3 \\ Al_2O_3 + \ldots \end{matrix}\right\} \text{balance}$$

V= KI$^{\beta}$

SiC NLRs …. β ≈ 0.25 to 0.4

n = 1/β → 4 to 0.25

MOV NLRs … β ≈ 1/40 – 1/50

$$\left(\frac{V_2}{V_1}\right) = \left(\frac{I_2}{I_1}\right)^{\beta} \Rightarrow \left(\frac{I_2}{I_1}\right) = \left(\frac{V_2}{V_1}\right)^{1/\beta}$$

$$\text{If } \left(\frac{V_2}{V_1}\right) = 2, \left(\frac{I_2}{I_1}\right) = 2^4 \text{ to } 2^{2.5}$$

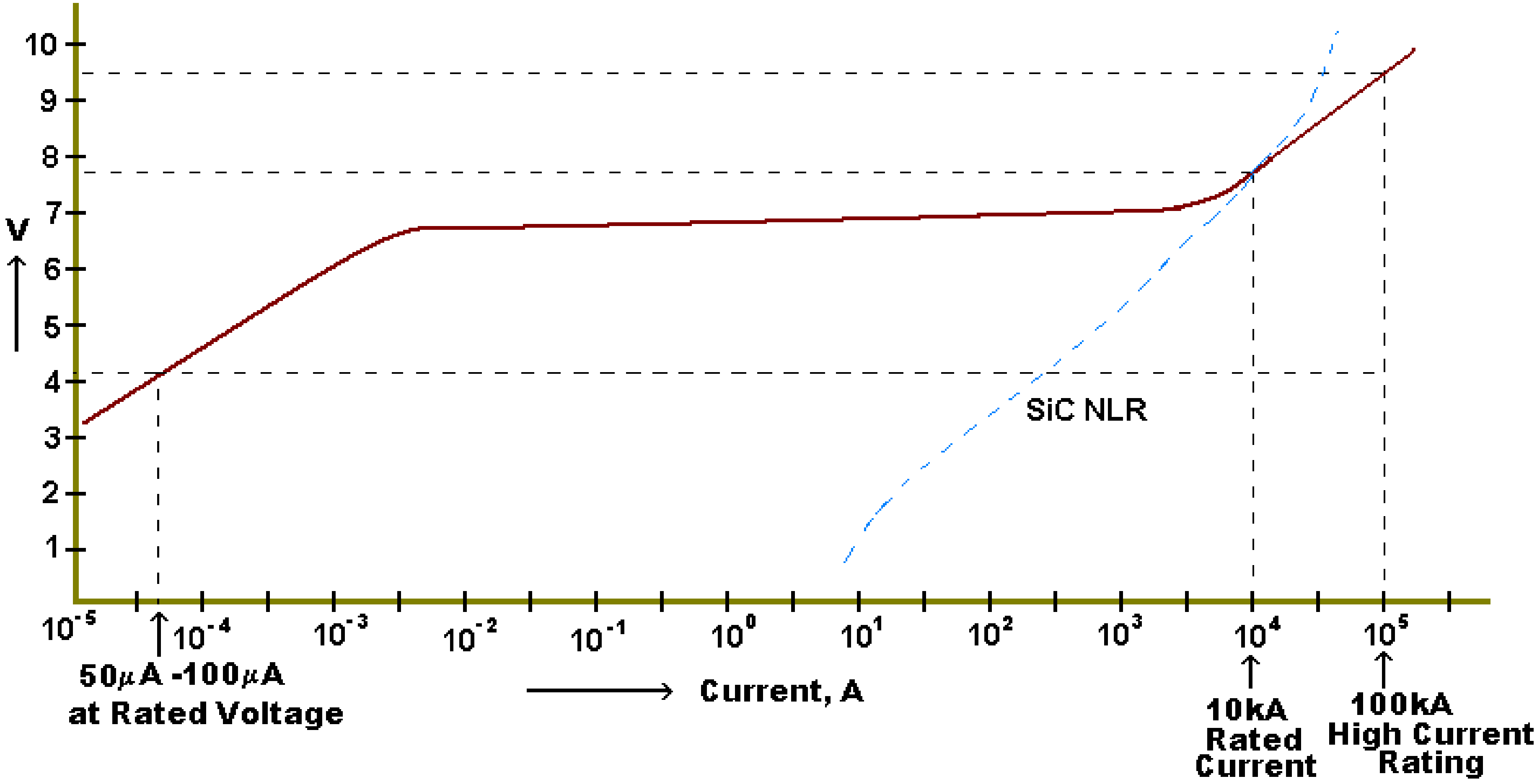
for SiC NLRs

$$= 2^{40} \text{ to } 2^{50}$$

for MOV

n = 1/β = 40 to 50

Zinc-Oxide (Metal Oxide) Gapless Surge Arresters



Advantages of MOV

Max Cont Operating Voltage – MCOV (current - 50-100μA)

Reference Voltage (current - 10 to 20 mA)

Residual Voltage (current – 10kA)

1. **Absence of Gaps – Continuous protective action**

   Temp 50Hz Overvoltage Vs Permissible time

2. **Steep Current : 1μs front Time**
3. **Significantly higher thermal capacity:**

   upto 800 J/cm^3 $\rightarrow$ 23kJ/kV

   reaches melting point of Bi_2O_3

4. **Ageing – Arrehenius Law**
5. **Parallel operation possible with nominal effort**
6. **Response time – 50ns**

   - can act for very steep impulses

   (GIS transients & Vac-C.B transients)

Other advantages of MOV Arresters

1. Very high energy handling capability
2. High yield with „Excellent Consistency" of characteristics permitting parallel operation
3. Absence of Gaps – „Continuous" protective action

   – Instantaneous action (< 40 to 50 ns)

Life – Arrehius Law

$$R = R_o . e^{-\frac{\phi_B}{KT}}$$ = Rate of reaction

ϕ_B = Barrier height

K = Boltzmann Constant

T = Temperature, °K

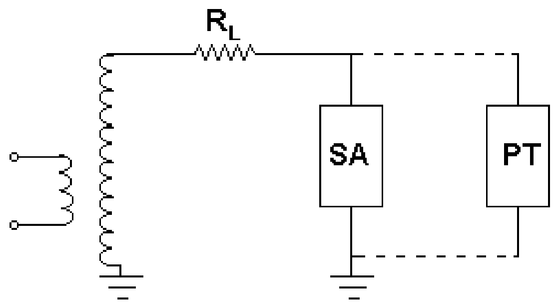
R_0 = Constant

Tests on

Surge Arresters

Tests

1) Power frequency 50 V test – **<u>Routine Test</u>**



50 Hz 5.0 V ≥ 1.5 V_A

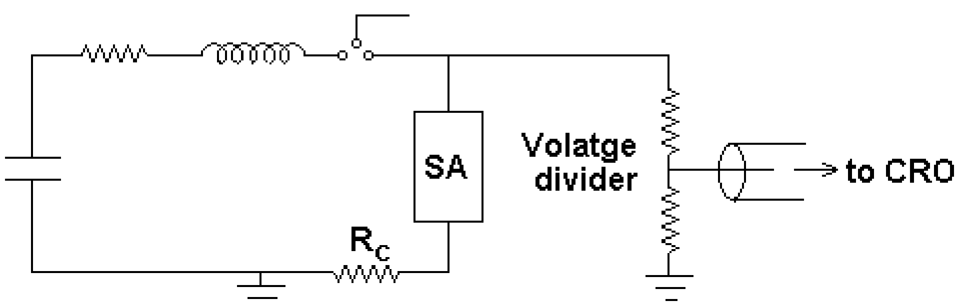
R_L should limit the current to 1A (rms) at rated voltage

2) Impulse 50V test : 1.2/50µs std wave

Apply specified voltage : 10 + and 10 – pulses at 30s intervals

<u>Should</u> sparkover on <u>each apply</u> showing that it <u>protects without fail</u>

3) Residual voltage test: <u>Measured Residual Voltage must be</u> ≤ <u>specified limit</u>



Impulse current generator

– **set to give 8 x 20µs waves**

4) High Current Test: use impulse current generator

– **set to give 4 x 10μs waves**

(a) Discs should not show signs of distress

(b) 50% S0V should not have changed by more than ± 10% showing it can survive without prejudice to protection

5) Long duration test – severity depends on duty class

6) Operating Duty Test

– Impulses superimposed at 30° (from zero) on 50 Hz → (5 pulses x 4 groups) =20 applications

Residual voltage & 50Hz S0V should not change more than ± 10%

Life of Surge Arresters

Gapped Arresters

1. a) Operating duty test → 20 applications of rated impulse current superposed.

   b) Long duration test → 20 applications

   c) Variation in SOV & Residual voltage : $\leq$ 10%
2. Gapless arresters → More Complex but similar
3. Life → 20 full blooded operations ?

   ↑

   Extremely rare

4. In real life, → Failure almost always due to ingress of moisture

   a) Condensation on electrodes of gap

   b) Condensation on surface of Non linear resistors.

Condition Monitoring & Residual Life

1. **Condition of Gaps :**

   Sparkover voltage of Full Arrester –

   a) 50 Hz - testing transformer

   b) Impulse – more appropriate but more difficult (Impulse Voltage Generator)

2. **Condition of Non Linear Resistors →**

   <u>Residual voltage level</u>

   a) Gapped arresters → Not practical

   b) **Gapped arresters → possible but in Laboratories with Impulse Voltage Generator of reasonable energy rating.**

3. Surge counter – appropriately calibrated

4. Leakage current

- **Gapped arresters – current through Grading resistor**
- **Gapless arresters – Total current (I_C + I_R) ?**
  - **I_R only → <u>best</u>**

Principles of

Insulation Coordination

Insulation Coordination

Coordination between:

- **Characteristics of line insulation**

  Feature : $V_{CFO} \rightarrow$ decided

  from point of view of acceptably low outrage rate

- **Transformer Insulation level against transients**

  (Transient insulation level –TIL)

  Decided based on surge arrester characteristics and suitable factor of safety

- **Max voltage across surge arrester under any condition**

1. Surge Arrester $V_A = k_g . V_{s(max)}$

- 100% Impulse Sparkover Voltage (in case of gapped arresters)
- Residual voltage at rated current
- Steep fronted current – residual voltage (in case of gaplers arresters)
- Front of wave sparkover voltage (in case of gapped arresters)

– Let maximum of above = V_{a-m}

(arrester – maximum voltage)

– (maximum assured & tested value)

2. Factor of safety on V_{a-m} - K_s

- To consider reduction in voltage withstand-level of transformer insulation level due to-ageing ≈ 15% minimum

$$K_{s-min} = 1.3$$

- To consider additional voltage due to voltage-drop in leads ≈ 15%

3. Line-Insulation

V_{CFO} of line insulation > 1.3 $V_{a\text{-}max}$

$V_{CFO} \rightarrow$ should be high enough to keep line voltage to acceptable levels. Otherwise

- **too many outrages**
- **electrical & mechanical stresses on power transformer due to too many faults.**

If V_{CFO} too high – outrages reduce but higher voltages appear across arresters, higher arrester currents, higher residual voltage, higher insulation level.

$\rightarrow$ choose TIL as nearest higher level-compared to 1.3 $V_{a\text{-}max}$ – from table of TILs

Max voltage (during flow of impulse currents) across apparatus protected

= Residual voltage + drop in HV & LV leads

↓

≈15 to 20 %

very close spacing **slightly farther away**

Insulation w/s level = Factor of safety × Max Impulse voltage across apparatus

W/s level of new insulation > W/s level of aged insulation

Factor of safety should include : possible rare overvoltage events & ageing insulation

Typically: ≈ 1.3 at UHV & EHV level

≈ 2 at distribution level

This gives upper limit for Residual voltage of NLRs (at rated current) as well as Impulse sparkover voltage of gaps

Example

- **400 kV nominal system voltage**
- **420 kV max system voltage – $V_{s\text{-}m}$**
- **Arrester power frequency voltage rating = $k_g \cdot V_{s\text{-}m} = V_A$**

Estimated value of grounding coefficient : 0.70

Use $k_g = 0.70 + 0.05$

safety factor to consider unusual conditions

$V_A = 420 \times 0.75 = 315$ kV (rms) (If this is not a standard rating, choose <u>nearest higher rating</u>)

Impulse current rating : <u>20kA</u>

- **From technical bids for arresters:**

Gapped arresters:

Assured max Imp 50V: 720 kV (p)

Assured max residual voltage : 860 kV (p)

Gaplers arresters:

Assured max residual voltage : 750 kV (p)

Choose: gaplers arresters : $V_{a\text{-}m}$ = 750 kV (p)

Transformer Insulation level-minimum

= <u>1.3</u> x 750 = 975 kV (< <u>1050 kV BIL of 220 kV</u>!)

→<u>1.5 x 750 = 1125 kV</u> (BIL = 1550 kV for 400 kV system)

THANK YOU