UNIT I

OVERVOLTAGES
IN
ELECTRICAL POWER SYSTEMS

INTRODUCTION

- Protection of transmission lines and Power apparatus from the chief causes of over voltages is necessary
  - Lightning Overvoltages
  - Switching Overvoltages
- Lightning Overvoltages – Natural Phenomenon of charging and Discharging of clouds
- Switching Overvoltages – connection and disconnection of circuit breakers due to interruption of faults – short duration overvoltages – Temporary overvoltages

Comparison between overvoltages

- Magnitude of Lightning OVs not depends on Line design and Operating Voltages
- Magnitude of Switching OVs proportional to line design and Operating Voltages.
- Probability of Both OVs occurring together, is very small &negligible for insulation design
- From 300 kV to 765 kV, both OVs to be considered
- Above 700 kV, Switching OVs be the chief condition for design purpose

Charge Formation

- Positive & Negative charges in the clouds separated by heavy air currents with ice crystals in upper part and rain in lower part.
- Charge separation – height of clouds – 200m – 10 km with their charge centres at a distance of 300m to 2km
- Charge inside cloud 1 – 100 C
- Potentials of Clouds 10^7 – 10^8 V
- Field Gradients 100 V/cm – 10 kV/cm
- Energy 250 kWh
- Max gradient at ground level 300 V/cm
- Fair weather gradients 1 V/cm

Lightning

Simpson’s Theory

- Three regions A, B & C
- In region A, due to high velocity air, it breaks falling raindrops causing +ve charge in cloud & -ve charge in air.
- Region B –vely charged by air currents
- Region C ,only ice crystals exist due to low temperature.

Reynolds and Mason Theory

- Thunder clouds are developed at heights from 1 km to 14 km above ground level
- Temp – $0^{o}C$ @ 4 km Ht, reaches $-50^{o}C$ @ 12 km Ht
- Water droplets freeze below $-40^{o}C$
- Thundercloud consisting supercooled water droplets moving upwards and large hail stones moving downwards
- Splinters moved up by air Cts and carry +ve charge to upper region.
- Hail stones that travel downwards carry an equivalent –ve charge to the lower regions in the cloud

Mason Theory

- Water-> H^++ OH^-
- ion density α temperature
- Higher concentration of ions in lower regions
- H^+ ions are much lighter, they diffuse much faster all over the volume.
- Lower portion will have a net negative charge density, Upper portion will have a net negative charge density
- Outer shells of freezed water droplets coming into contact with hail stones acquire +ve charge

Reynolds Theory

- Based on exp results
- Hail packets get –vely charged when impinged upon by warmer ice crystals
- Charging polarity changes if temperature conditions reverses
- Rate of charge generation to disagree with practical observations relating to thunderclouds

Rate of Charging of Thunder clouds

Consider

λ – factor depends on conductivity of medium

E – Electric Field Intensity

ν – Velocity of separation of charges

ρ – Charge density in the cloud

$$\frac{dE}{dt} + \lambda E = \rho \upsilon$$

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

Contd.,

Let Q and Q_S be separated and Generated Charges respectively

ε – Permittivity of the medium

A – Cloud Area

h – Height of Charged region

$$\rho = \frac{Qg}{Ah};$$

$$E = \frac{Qs}{A\varepsilon_o}$$

$$Q_g = \frac{Q_S h}{\upsilon[1-\exp(-\lambda t)]} = \frac{M}{\upsilon[1-\exp(-\lambda t)]}$$

M-> Electric Moment of thunder storm

Values obtained…

The average values observed for thunder clouds are:

Time constant=1/λ = 20 s

Electric Moment = M = 110 C-km

Time for first lightning flash to appear, t=20 s

The velocity of separation of charges,

ν = 10 to 20 m/s

Substituting these values Qg = 1000C

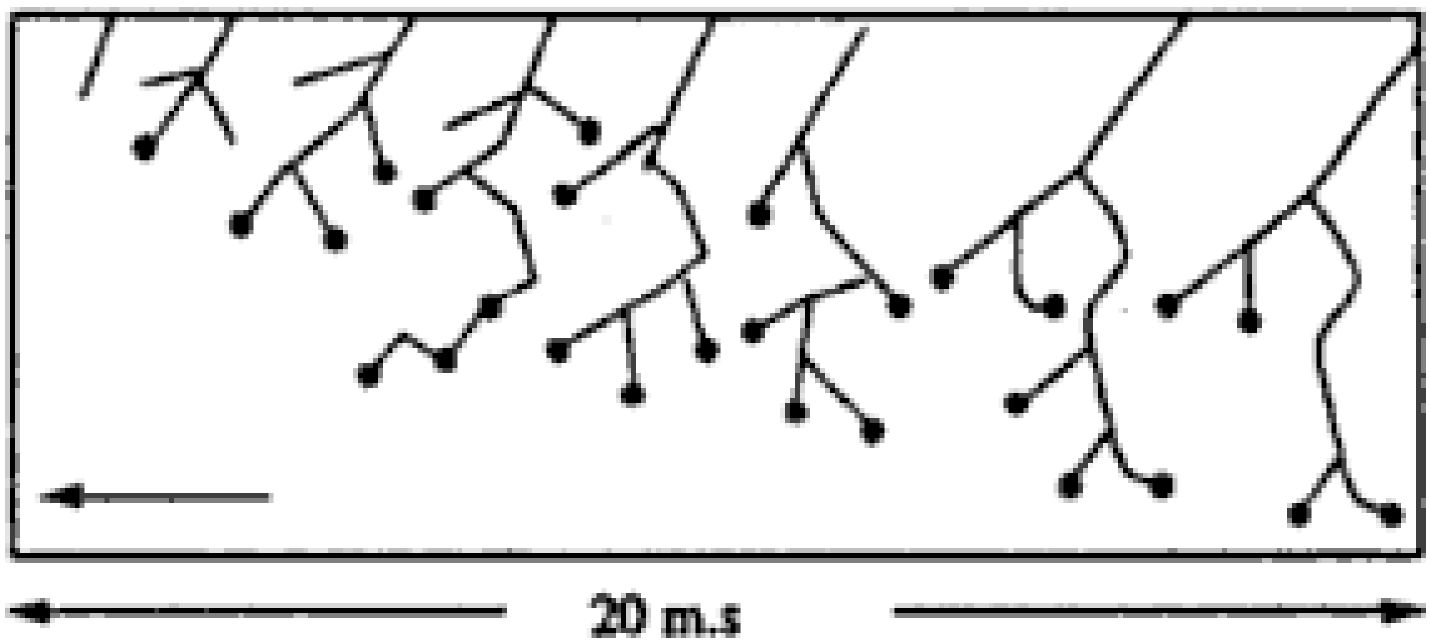
Lightning Strokes

- When EFI exceeds BD value(10kV/cm), An electric Streamer with plasma starts towards the ground velocity of 1/10th times that of the light, progress about 50m
- After 100µs, streamer starts again.
- Total time required for stepped leader to reach the ground 20 ms.
- Branches from initial leader is also formed
- Lightning consists of separate discharges starting from a leader discharge and culminates in return strokes/main discharges
- Velocity of leader stroke (first discharge) = 1.5 X 10^7 cm/s
- Succeeding strokes velocity 10^8 cm/s
- Return strokes 1.5 x 10^9 to 1.5 x 10^{10} cm/s

Return Strokes

- Currents at return strokes about 1-250 kA
- Return Strokes vanishes before it reaches to cloud
- Dia – 1-2 cm
- Corona envelop 50 cm

Propagation Of Stepped Leader Stroke From The Cloud

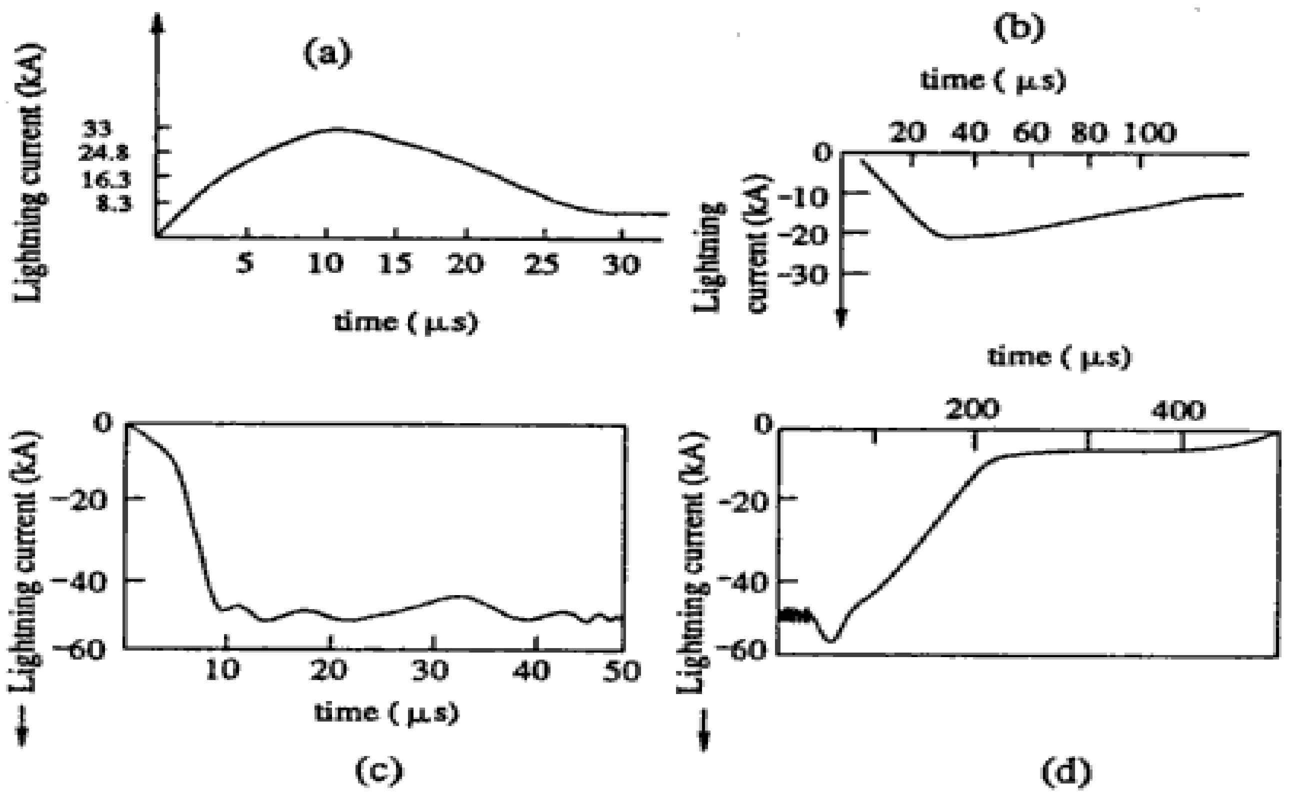


Development Of Main Or Return Stroke

Characteristics of Lightning Strokes

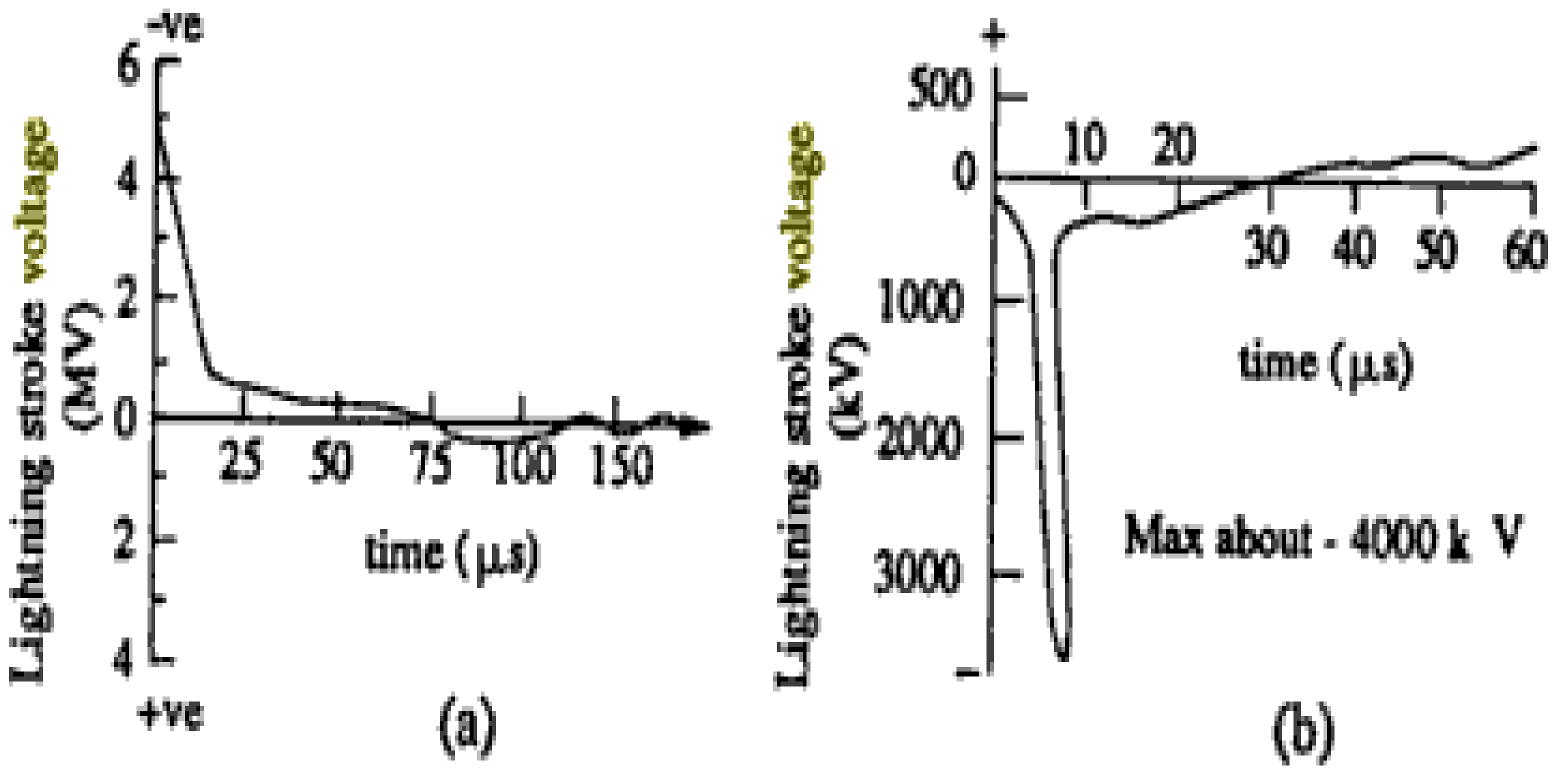
- Amplitude of currents
- Rate of rise
- Probability Distribution
- Wave shapes of lightning voltages and currents

Typical Lightning Current Oscillograms



a. Capacitive balloon (CIGRE)
b. Empire State Building (McEachron)
c. Transmission Line Tower (Berger)

Typical Lightning Stroke Voltage on a Line without ground wire



Modeling of Lightning

- During charge formation, cloud considered as a non conductor
- At charging process, local breakdown takes place within the cloud
- Dielectric – cloud – air – ground
- Lightning stroke -> Current source I_o, Source Impedance Z_o

$$V = IZ;$$

$$V = I_o \frac{ZZ_o}{Z + Z_o}$$

$$V = I_o \frac{Z}{1 + \frac{Z}{Z_o}}$$

Contd.,

- Source Imp – 1-3 k Ω
- Surge Imp - <500 Ω
  - OH lines – 300 - 500 Ω
  - Ground wires – 100 - 150 Ω
  - Towers – 10-50 Ω
- Z/Zo is neglected; $V=I_oZ$
- If lightning stroke current is 10 kA strikes a line of 400Ω surge imp, it cause over voltage of 4 MV.

Thunderstorm days

- Number of days in a year when thunder is heard or recorded in a particular direction
- This indication does not distinguish between ground strikes and C-C strikes
- Ground Flashover density

  N_g= (0.1 to 0.2) TD /strokes/km^2-year
- TD recorded
  - Britain, Europe, Pacific west of North America 5-15
  - Central, Eastern states of USA– 10-50

Traveling Waves

- OVs propagating as a traveling wave to the ends of the line.
- High frequency, reflected, transmitted, attenuated, distorted during propagating
- Characteristic Equation

$$\frac{dV}{dx} = R + L\left(\frac{di}{dt}\right)$$

$$\frac{di}{dx} = G + C\left(\frac{dV}{dt}\right)$$

- x-distance, t-time, i-current, v-voltage, R-Resistance, L-Inductance, G-Conductance, C-Capacitance.

Contd.,

- Solutions of characteristic equation

$$V = e^{\gamma x} f_1(t) + e^{-\gamma x} f_2(t)$$

$$i = -\sqrt{\frac{Y}{Z}}[e^{\gamma x} f_1(t) + e^{-\gamma x} f_2(t)]$$

where,

$$\gamma = \sqrt{(R + Ls)(G + Cs)} = \sqrt{ZY}$$

$$Y(s) = surgeadmitance = \sqrt{\frac{Y}{Z}}$$

$$Z(s) = surgeimpedance = \sqrt{\frac{Z}{Y}}$$

Classification of Transmission Lines

- Ideal lines: $R=G=0$
- Distortionless lines: $R/L=G/C=\alpha$
- Lines with small losses: R/L, G/C small
- Lines with finite and infinite length:

Ideal lines

$$V = f_1(t + x/\upsilon) + f_2(t - x/\upsilon)$$

$$i = -Y[f_2(t - x/\upsilon) - f_1(t + x/\upsilon)]$$

where,

$$\upsilon = PropagationVelocity = 1/\sqrt{LC}$$

$$Y = surgeadmitance = \sqrt{\frac{C}{L}}$$

$$Z = surgeimpedance = \sqrt{\frac{1}{Y}}$$

Distortionless lines

$$V = e^{-\alpha t}(f_3(t + x/\upsilon) + f_4(t - x/\upsilon))$$

$$i = -\frac{e^{-\alpha t}}{Z}[f_4(t - x/\upsilon) - f_3(t + x/\upsilon)]$$

$where\ ,$

$$\upsilon = Propagatio\ \ nVelocity\ \ = 1/\sqrt{LC}$$

$$\alpha = R/L = G/C$$

$$Z = surgeimped\ \ ance\ = \sqrt{\frac{L}{C}}$$

Lines with Small Losses

$$V = e^{\alpha x/\upsilon} f_1(t + x/\upsilon) + e^{-\alpha x/\upsilon} f_2(t - x/\upsilon))$$

$$i = -Y(s)[e^{-\alpha x/\upsilon} f_2(t - x/\upsilon) - e^{\alpha x/\upsilon} f_1(t + x/\upsilon)]$$

$$+V\beta[e^{\alpha x/\upsilon} \int_{-x/\upsilon}^{t} f_1(t + x/\upsilon)dt - e^{-\alpha x/\upsilon} \int_{x/\upsilon}^{t} f_2(t - x/\upsilon)dt]$$

where,

$$\upsilon = PropagationVelocity = 1/\sqrt{LC}$$

$$\alpha = \frac{1}{2} * (\frac{R}{L} + \frac{G}{C}) --- AttenuatorConstant$$

$$\beta = \frac{1}{2} * (\frac{R}{L} - \frac{G}{C}) --- WavelengthConstant$$

$$Y(s) = \sqrt{\frac{C}{L}(1 - \frac{\beta}{s})}$$

Exact solution for lines of finite and infinite length

- It is quite complex and is normally of little practical importance.
- Inferences
  - Current and voltage wave are dissimilar
  - Attenuation and Distortion due to small line resistance and leakage conductance are of little consequence
  - Surge impedance is a complex function and is not uniquely defined

Attenuation and Distortion

- Decrease in Magnitude – Attenuation
- Elongation/ change of wave shape – Distortion
- Attenuation caused by energy loss
- Distortion caused by induction and capacitance
- Energy Loss - resistance as modified by skin effect, changes in Rg, Leakage resistance and non uniform ground resistance etc.,
- Induction changes – Skin effect, proximity effect, non uniform distribution effect of current and nearness to steel structures (towers)
- Capacitance changes – in insulation near to the ground
- Corona is the another factor of attenuation and distortion

Contd.,

- For distortionless lines, Attenuation is approximated by lose function φ(V)

$$\varphi(V) = -C \quad dV^2/dt$$

i) For lines having four parameters, R, L, G & C

$$\varphi(V) = [(RC+LG)/L]V^2$$

and $dV/dt = -\alpha V$, where, $\alpha = (RC+LG)/2LC$

$$V = V_o \exp(-\alpha t)$$

Skilling and Quadratic Formula

- φV is assumed to be $\beta(V-V_c)$, V_c Critical Corona Voltage

$$dV/dt = -\beta/2c\,((V-V_c)/V)$$

$$(\beta/2c)t = (V_o-V) + V_c \ln[(V_o-V_c)/(V-V_c)]$$

- φV is assumed to vary $(V-V_c)^2$, then

$$dV/dt = (-\gamma/2c)\,[(V_o-V_c)/(V-V_c)]^2$$

Integrating the equation,

$$[(V_o-V).V_c/(V_o-V_c)(V-V_c)] + \ln[(V_o-V_c)/(V-V_c)] = \gamma t/2c$$

Foust and Manger Formula

- φV is assumed to be $\lambda V^{3,}$ then

$$dV/dt = (-\lambda/2c)V^2$$

$$V = V_O/(1+KV_O t),\ K = \lambda/2c$$

Reflection and Transmission of Waves

- For Lossless lines:

$$e_1/i_1=Z_1 \quad \text{->Incident wave}$$
$$e_1'/i_1'=-Z_1 \quad \text{->Reflected wave}$$
$$e_1''/i_1''=Z_1'' \quad \text{->Reflected wave}$$

$$i_0 = i_1 + i'_1;\ e_0 = e_1 + e'_1 = Z_0(s).i_0$$
$$e'_1=[(Z_0(s)-Z_1)/(Z_0(s)+Z_1)]e_1$$
$$i'_1=[(Z_0(s)-Z_1)/(Z_0(s)+Z_1)]i_1$$

Junction Voltage and Total Current is given by

$$e_0=[(2Z_0(s))/(Z_0(s)+Z_1)]e_1$$
$$i_0=[2e_1/(Z_0(s)+Z_1)]$$

Successive reflections and lattice diagrams

i. All waves travel downhill, i.e. into the positive time
ii. The position of the wave at any instant is given by means of the time scale at the left of the lattice diagram
iii. The total potential at any instant of time is the superposition of all the waves which arrive at the point until that instant of time, displaced in position from each other by time intervals equal to the time differences of their arrival
iv. Attenuation is included so that the amount by which a wave is reduced is taken care of and
v. The previous history of the wave, if desired can be easily traced. If the computation is to be carried out at a point where the operations cannot be directly placed on the lattice diagram, the arms can be numbered and the quantity can be tabulated and computed.

Behavior of Rectangular traveling wave:

Open ended transmission line of surge impedance Z

$e=E\,U(t)$; $Z_1=Z$ and $Z_2=\infty$

Coefficient of reflection

$$\Gamma=(Z_2-Z_1)/(Z_2+Z_1)$$

Simplifying, $\Gamma=1$

Reflected wave, $e'=\Gamma e=E\,U(t)$

Transmitted wave $e''=(1+\Gamma)e=2E\,U(t)$

The voltage at open end rises to double its value

Short Circuited Line

$e = E\,U(t)$; $Z_1 = Z$ and $Z_2 = 0$

Coefficient of reflection

$$\Gamma = -1$$

Reflected wave, $e' = \Gamma e = -E\,U(t)$

Transmitted wave $e'' = (1+\Gamma)e = 0$

Reflected Current wave $= |-e'/Z| = E\,U(t)/Z$

Total Current $i_0 = (i + I') = 2i$

Current at junction point rises to double the value

Line terminated with a resistance equal to the surge imp of the line

Z_1=Z and Z_2=R=Z

Coefficient of reflection, $\Gamma = 0$

Reflected wave, $e' = \Gamma e = 0$

Transmitted wave $e'' = (1+\Gamma)e = e$

There is no reflected wave.

Line terminated with a Capacitor

Z_1=Z and Z_2=1/sC

Coefficient of reflection, $\Gamma = (1-CZs)/(1+CZs)$

Reflected wave,

$e' = [1-2\exp(-t/CZ)]EU(t)$

Transmitted wave

$e'' = 2[1-\exp(-t/CZ)]EU(t)$

Line terminated with a Inductor

Z_1=Z and Z_2=Ls

Coefficient of reflection, Γ= (Ls-Z)/(Ls+Z)

Reflected wave,

$$e' = -[1-2\exp(-Zt/L)]EU(t)$$

Transmitted wave

$$e'' = [2\exp(-Zt/L)]EU(t)$$

Line having a series Inductor

$Z_1 = Z + Ls$ and $Z_2 = Z$

Coefficient of reflection, $\Gamma = (Ls)/(Ls+2Z)$

Reflected wave,

$e' = -\exp(-2Zt/L)EU(t)$

Transmitted wave

$e'' = [1-\exp(-2Zt/L)]EU(t)$

Line Terminated Transformer (LC Parallel Connection)

$$e = EU(t); Z_1 = Z; Z_2 = \frac{s}{C}\left(\frac{1}{s^2 + \frac{1}{LC}}\right)$$

Let

$$\alpha = \frac{1}{CZ}; \varpi_0^2 = \frac{1}{LC}; then$$

Coefficient − of − Reflection

$$\Gamma = -\frac{s^2 - \alpha s + \varpi_0^2}{s^2 + \alpha s + \varpi_0^2}$$

Reflectedwave,

$$e'(s) = -\left\{1 - \frac{2\alpha}{n-m}[e^{-mt} - e^{-nt}]\right\}EU(t) --- > if -)\varpi_0^2 < (\frac{\alpha}{2})^2$$

$$e'(s) = -EU(t)[1 - \frac{2\alpha}{\varpi_0^2 - \left(\frac{\alpha}{2}\right)^2}\exp(-\alpha t/2)\sin(t\sqrt{\varpi_0^2 - \left(\frac{\alpha}{2}\right)^2}), ---- > if -)\varpi_0^2 > (\frac{\alpha}{2})^2$$

Contd.,

- Transmitted wave,

$$e''(s) = \left\{ \frac{2\alpha}{n-m} [e^{-mt} - e^{-nt}] \right\} EU(t)$$

$$if \; --) \varpi_0^2 < (\frac{\alpha}{2})^2$$

$$e''(s) = \frac{2\alpha EU(t)}{\varpi_0^2 - \left(\frac{\alpha}{2}\right)^2} \exp(-\alpha t/2) \sin(t \sqrt{\varpi_0^2 - \left(\frac{\alpha}{2}\right)^2}),$$

$$if \; --) \varpi_0^2 > (\frac{\alpha}{2})^2$$

- m,n are the roots of $s^2 + \alpha s + \omega_0^2$

Overvoltages due to switching, faults and other abnormal conditions

Introduction

- Switching surges generated inside the system reached the same order of magnitude equivalent to lightning
- Lasts for longer durations
- Depends on Normal Voltage of the system
- Insulation Design is based upon the magnitude of these surges
- Origin is making and breaking of circuits

Characteristics

- De-energizing of transmission lines, cables shunt capacitors, banks, etc.,
- Disconnection of unloaded transformers, reactors, etc
- Energization or reclosing of lines and reactive loads
- Sudden switching off of loads
- Short circuits and fault clearances
- Resonance phenomenon like Ferro-resonance, arcing grounds, etc

Switching in EHV,UHV Systems

Situations of Overvoltages of the order of 2-3.3 pu, duration of these OVs from 1 to 10ms

- Interruption of Low Inductive Currents (Current Chopping) By High Speed CBs. It occurs when the transformers or reactors are switched off.
- Interruption of small capacitive currents, such as switching off of unloaded lines etc.
- Ferro Resonance condition. It occurs when poles of CB do not close simultaneously
- Energization of long EHV or UHV lines

Situations of lower magnitude Overvoltages

Short duration-(0.5-5ms), Mag-(2-2.5 pu)

- Single pole closing of CB
- Interruption of fault current when the LG or LL fault is cleared
- Resistance Switching used in circuit breakers
- Switching lines terminated by transformers
- Series capacitor compensated lines
- Sparking of the surge diverter located at the receiving end of the line to limit the lightning overvoltages

These overvoltages studied from

- Mathematical modelling of a system using digital computers
- Scale modeling using traqnsi3ent network analysers
- By conducting field tests to determine the expected maximum amplitude3 of the overvoltages and their duration at different points on the line.

Factors

- Effect of line parameters, series capacitors and shunt reactors on the magnitude and duration of the transients
- The damping factors needed to reduce magnitude of Overvoltages
- The effect of single pole closing, restriking and switching with series resistors or circuit breakers on the overvoltages, and
- Lightning arrestor spark over characteristics

Some of the overvoltages

Sl No	Type of Operation	Over voltage pu
1	Switching an open ended line with:	
	a) Infinite bus as source with trapped charges on line	4.1
	b) Infinite bus as source without trapped charges	2.6
	c) De-energizing an unfaulted line with a restrike in the circuit breaker	2.7
	d) De-energizing an unfaulted line with a line to ground fault	1.3

Contd.,

Sl No	Type of Operation	Over voltage pu
2	a) Switching a 500 kV line through an auto transformer, 220 kV/500 from the LV side b) Switching a transformer terminated line c) Series capacitor compensated line with 50% compensation d) Series capacitor compensated line with shunt reactor compensation	2.0 2.2 2.2 2.6
3	High speed reclosing of line after fault clearance	3.6

Power Frequency Overvoltages

- Sudden loss of loads
- Disconnection of inductive loads or connection of capacitive loads
- Ferranti Effect, Unsymmetrical faults, and
- Saturation in transformers

Sudden Load Rejection

- It causes the speeding up of generator prime movers
- Voltage rise is given by

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

- Where,
  - x_s – Reactance of the generator (sum of transient reactance of generator and transformer)
  - x_c – Capacitive reactance of the line at open end at increased frequency,
  - E' – Voltage generated before the over-speeding and load rejection
  - f – Instantaneous increased frequency
  - f_0 – Normal frequency

Contd.,

- Increase in V-> 2 pu with 400 kV lines
- Voltage at sending end is affected by line length, SC MVA at sending end bus and Reactive Power Generation of line
- Shunt reactors may reduce the voltage to 1.2 to 1.4 pu

Ferranti Effect

Long uncompensated lines exhibit voltage rise at receiving end

$$V_2 = V_1 / \cos \beta l$$

Where V_1, V_2 are the sending and receiving end voltages respectively

l=length of the line

β=Phase constant of the line

$= [(R+j\omega L)(G+j\omega C)/LC]^{1/2}$

6^0 per 100 km line at 50 Hz frequency

ω=Angular frequency

Approximated solution

- Capacitance is concentrated in middle

Solution yields

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

Ground Faults and Their Effects

- SLTG cause rise in voltage in other healthy phases
- Solid ground systems, voltage rise is less than the line to line voltage
- Effectively ground systems,

  $X_0/X_1 \leq 3.0$ and $R_0/X_1 \leq 1.0$

  rise in voltage of healthy phases does not usually exceed 1.4 pu

Saturation Effects

- When overvoltage is applied to transformers, their magnetizing currents increase rapidly, full rated current at 50% overvoltage
- These are not sinusoidal
- 3^{rd},5^{th} and 7^{th} harmonics be 65%,35%,and 25% of rated current with fundamental frequency to OV 1.2 pu

Control of Switching Overvoltages

- Energization of transmission lines in one or more steps by inserting resistance and withdrawing them afterwards,
- Phase controlled closing
- Drainage of trapped changes before reclosing
- Use of shunt reactors
- Limiting switching surges by suitable surge diverters

Lightning Protection using Ground wires

- Ground Wire conductor run parallel to the main conductor of line supported on the same tower and earthed at every equally and regularly spaced towers.
- It is run above main line
- Shielding angle $\theta_s \approx 30^0$ was considered adequate for tower heights of 30m or less.
- Number of shielding wires is depends upon the type of tower used
- Present trend in fixing the tower heights and shielding angles is by considering the “flashover rates” and failure probabilities.

Ground rods and Counter-Poise wires

- Instantaneous Potential to which tower top can rise is

$$V_T = I_0 Z_T / (1 + (Z_T / Z_S))$$

Where, Z_T, Z_S surge impedances of tower and ground wire.

- If Z_T (tower footing resistance), is reduced , surge voltage developed is also reduced.
- It can be done by ground rods and counterpoise wires at legs of the tower.

Ground Rods

- 15mm dia, 2.5-3m long driven into the ground
- 50m long for hard soils
- Made by galvanized iron or copper bearing steel
- Design specifications depends on desired tower footing resistance.
- 10 rods of 4m long and spaced 5m apart, effective resistance is reduced to 10%

Counter Poise Wires

- Wires buried in the ground at a depth of 0.5 to 1 m, running parallel to the conductors connected to legs of tower
- 50 – 100 m long
- More effective then rods and resistance is reduced to as low as 25 Ohms

Protective Devices

- Expulsion Gaps
- Protector tubes
- Rod gaps
- Surge diverters or lightning arresters