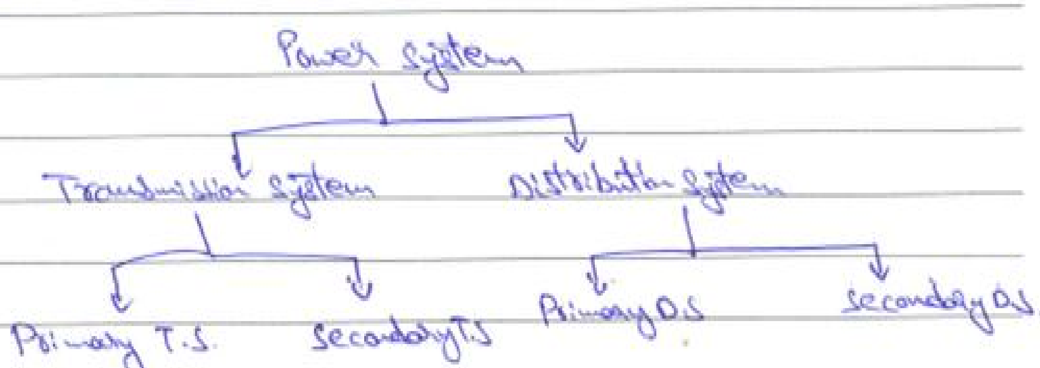
1. (a) With a neat sketch, describe a typical transmission and distribution scheme. (8M)

Typical transmission & Distribution systems scheme

The conveyance of electric power from a power station to consumers premises is known as electric supply system. It consists of three principal components, The power station, the transmission line and the distribution system.

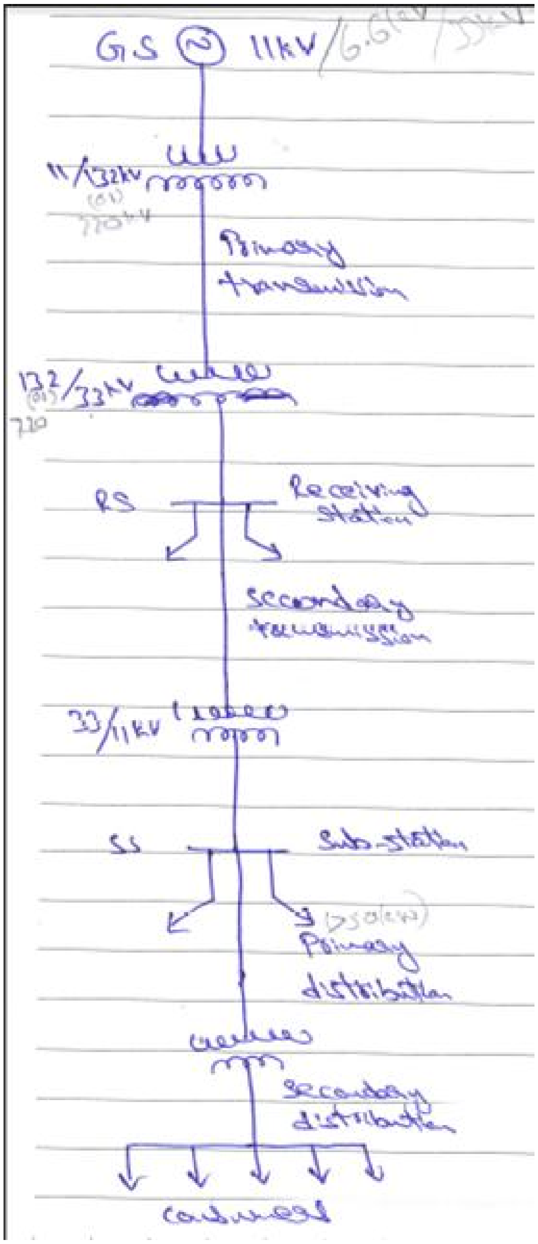
Electrical power is produced at the power stations which are located at favourable places, generally quite away from the consumers. It is then transmitted over large distances to load centres with the help of conductors known as transmission lines. Finally, it is distributed to a large number of small and big consumers through a distribution network.

General layout of power system:-



It is not necessary that all power schemes include all the stages shown in the figure.

Generating station:- Electrical power is produced by 3-phase alternators operating in parallel at 11 kV [6.6 kV (or) 33 kV], which


GS
11kV/6.6kV/33kV
11/132kV
(or)
220kV
Primary
transmission
132/33kV
(or)
220
RS
Receiving
station
secondary
transmission
33/11kV
SS
Sub-station
Primary
distribution
secondary
distribution
consumers

is stepped upto 132kV at the generating station with the help of 3-ϕ transformers.

Primary transmission:- The electric power at 132kV is transmitted by 3-phase, 3-wire overhead system to the outskirts of the city. It terminates at receiving station (RS)

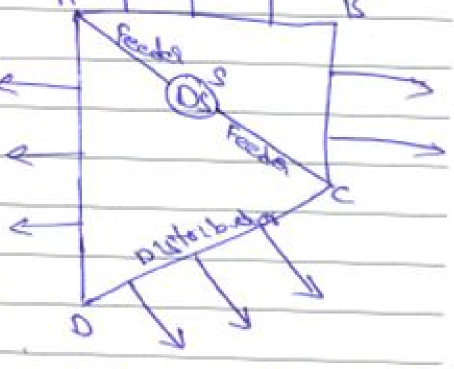
Secondary transmission:- At RS, voltage is reduced to 33kV by step-down transformers & transmitted to various sub-stations (SS) located at the strategic points in the city by 3-ph, 3-wire OH system. This forms the secondary transmission.

Primary distribution:- At the sub-station (SS), voltage is reduced from 33kV to 11kV. These 3-ϕ, 3W lines run along the important road sides of the city. This forms the Pr. distribution. Big consumers (> 50kW) are generally supplied power at 11kV for further handling with their own substations.

Secondary distribution:- The electric power from primary distribution i.e. (11kV) is delivered to distribution sub-station (DS) near consumer's localities and stepdown the voltage to 400V, 3-ph, 4-W for secondary distribution.

The voltage b/w any two phases is 400V and b/w any phase and neutral is 230V. 1-ϕ residential loads are connected b/w any one phase and neutral, whereas 3-ϕ, 400V motor load is connected across 3-ϕ lines directly.

Secondary distribution system consists of



(i) Feeders:- A conductor which connects the DSS to the area where power is to be distributed. Generally, no tappings are taken from the feeder so that current in it remains the same throughout. The main consideration in the design of a feeder is the current carrying capacity.

(ii) Distributor:- A distributor is a conductor from which tappings are taken for supply to the consumer. The current through a distributor is not constant b/c tappings are taken at various places along its length. While designing a distributor, voltage drop along its length is the main consideration since the statutory limit of voltage variations is ± 6% of rated value at the consumers terminals.
(iii) Service mains:- A small cable which connects the distributor to the consumer's terminals.

(b) What are the limitations of increasing the transmission voltage level to very high volume? (2M)

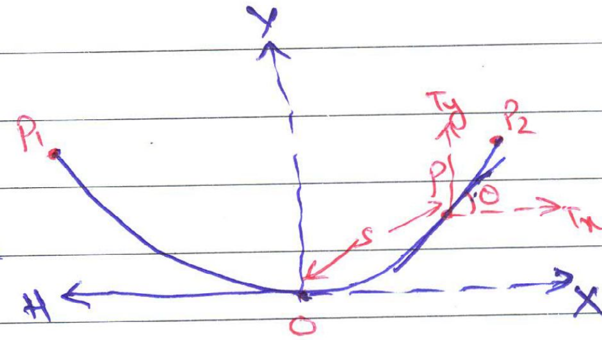
Limitations of high transmission voltage

High transmission voltage results in
(i) increased cost of insulating the conductor
(ii) increased cost of transformers, switchgear and other terminal apparatus.
∴ there is a limit to the higher transmission voltage which can be economically employed in a particular case. This limit is reached when the saving in cost of conductor material due to higher voltage is offset by the increased cost of insulation, transformer, switchgear etc. Hence the choice of proper transmission voltage is essentially a question of economics.

2. (a) What is sag in a conductor? Derive the expression for the sag when the supports are at equal heights. (8M)

Sag in overhead lines :-
While erecting an overhead line, it is very important that conductors are under safe tension. The conductor may break due to excessive tension.
In order to permit safe tension in the conductors, they are not fully stretched but are allowed to have a dip (or) sag.
The difference in level between points of supports and the lowest point on the conductor is called "Sag."

calculation of sag:-



Consider the conductor to be suspended from points P_1 & P_2 with O as the lowest point as shown in fig.

let w = weight of conductor per unit length.

let us choose the axes OX & OY through 'O'.

let P(x,y) be any point on the curve.

Tangent at 'P' makes an angle 'θ' with the horizontal.

let H = Horizontal tension in the conductor which is constant through out the conductor length.

S = length of conductor b/w O & P

The forces acting on the conductor portion 'OP' are

(i) Tension (Tangential) which can be divided in to two components T_x & T_y.

(ii) weight of the conductor ws acting vertically down.

For equilibrium, horizontal & vertical forces should balance.

$\therefore \; T_x = H \quad \& \quad T_y = ws$

& $\tan\theta = \frac{T_y}{T_x} = \frac{ws}{H}$ —— (1)

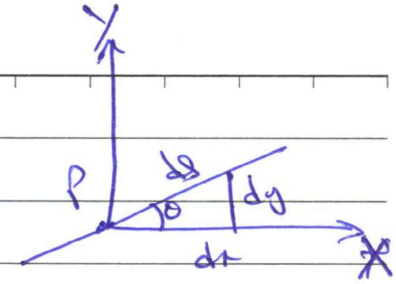


fig 2

if dx = incremental distance in x-axis
dy = " " y-axis
ds = incremental length of conductor

then $\tan\theta = \frac{dy}{dx}$ —— (2).

From eq. (1) & (2).

$\tan\theta = \frac{dy}{dx} = \frac{T_y}{T_x} = \frac{ws}{H} \Rightarrow \boxed{\frac{dy}{dx} = \frac{ws}{H}}$ —— (3).

& $\boxed{\frac{H}{w} = s\frac{dx}{dy}}$ —— (4).

From the fig (2). $(ds)^2 = (dx)^2 + (dy)^2$

$\Rightarrow \frac{ds}{dx} = \sqrt{1 + \left(\frac{dy}{dx}\right)^2} \Rightarrow dx = \frac{ds}{\sqrt{1 + \left(\frac{dy}{dx}\right)^2}}$

Sub. eq (3) in above equation

$dx = \frac{ds}{\sqrt{1 + \left(\frac{ws}{H}\right)^2}}$

integrating both the sides $\quad x = \frac{H}{w}\sinh^{-1}\left(\frac{ws}{H}\right) + A \quad$ where

A = integration constant.

Substituting the condition $x=0, s=0$
equation

$$0 = \frac{H}{w}\sinh^{-1}(0) + A \Rightarrow A = 0$$

$$\therefore \quad x = \frac{H}{w}\sinh^{-1}\left(\frac{ws}{H}\right) \quad \text{—— (4)}$$

$$\Rightarrow \quad \frac{wx}{H} = \sinh^{-1}\left(\frac{ws}{H}\right)$$

$$\Rightarrow \quad \frac{ws}{H} = \sinh\left(\frac{wx}{H}\right).$$

$$\Rightarrow \quad s = \frac{H}{w}\sinh\left(\frac{wx}{H}\right) \quad \text{—— (5)}.$$

From eq (2)

$$\frac{dy}{dx} = \frac{ws}{H} = \sinh\left(\frac{wx}{H}\right)$$

$$\Rightarrow \quad dy = dx \sinh\left(\frac{wx}{H}\right).$$

integrating both the sides.

$$y = \frac{H}{w}\cosh\left(\frac{wx}{H}\right) + B$$

Substituting the condition $x=0$ & $y=0$

$$0 = \frac{H}{w} + B \Rightarrow B = -\frac{H}{w}$$

$$\Rightarrow \quad y = \frac{H}{w}\cosh\left(\frac{wx}{H}\right) - \frac{H}{w}$$

$$\Rightarrow \boxed{y = \frac{H}{w}\left[\cosh\left(\frac{wx}{H}\right) - 1\right]} \quad \text{--- (6).}$$

This is the equation of a catenary.

So we can conclude that, The shape attained by the conductor b/w the two supporting structures is a catenary.

consider.

If l = half span length.

Tension T at the point 'p' is

$$T^2 = T_x^2 + T_y^2$$

$$= H^2 + w^2 S^2 = H^2 + H^2 \sinh^2\left(\frac{wx}{H}\right)$$

$$= H^2\left(1 + \sinh^2\left(\frac{wx}{H}\right)\right)$$

$$T^2 = H^2 \cosh^2\left(\frac{wl}{H}\right)$$

$$\Rightarrow \boxed{T = H\cosh\left(\frac{wl}{H}\right)} \quad \text{--- (7).}$$

Arc length in half span = $\boxed{S = \frac{H}{w}\sinh\left(\frac{wl}{H}\right)}$ (8) (from eq 5)

ordinate 'y' at P_1 & P_2 is the sag (D)

$\therefore$ from eq (6) $\boxed{D = \frac{H}{w}\left[\cosh\left(\frac{wl}{H}\right) - 1\right]}$ --- (9).

eq (7), (8) & (9) gives the exact values but for approximation.

From eq (7)

$$T = H\left[1 + \frac{w^2 l^2}{2H^2} + \frac{w^4 l^4}{H^4} + \cdots\right]$$

$$= H + \frac{w^2 l^2}{2H} \quad \text{[neglecting higher order terms]}$$

$$T = H\left[1 + \frac{w^2 l^2}{2H}\right]$$

$$\boxed{T \simeq H.} \quad \text{— (10)}$$

$$S = \frac{H}{w}\left[\frac{wl}{H} + \frac{w^3 l^3}{3!\,H^3} + \frac{w^5 l^5}{5!\,H^5} + \cdots\right]$$

$$= \frac{H}{w}\left[\frac{wl}{H} + \frac{w^3 l^3}{6H^3}\right]$$

$$= l + \frac{w^2 l^3}{6H^2}$$

$$\boxed{S = l\left[1 + \frac{w^2 l^2}{6T^2}\right]} \quad \text{— (11).}$$

$$D = \frac{H}{w}\left[1 + \frac{w^2 l^2}{2H^2} - 1\right]$$

$$= \frac{wl^2}{2H} \Rightarrow \boxed{D = \frac{wl^2}{2T}} \quad \text{— (12)}$$

(b) Write a short note on stringing chart. (2M)

stringing chart:-

The temperature will not be the same as that of erection time through out the lifetime of OH lines.

As the temperature changes, the sag will change and also the tension will be changed. Both sag & tension have a limit on these values, so the erection time, it should be taken care that the maximum values of sag as well as tension are within the limits.

It has already been deduced that

$T = H$, $y = \frac{wx^2}{2T}$, $D = \frac{wl^2}{2T}$ & $S = l + \frac{w^2 l^3}{6T^2}$

let w = weight per unit length

f = stress

S = Arc length in half span

D = sag

& t = temperature.

→ Suffix '1' will denote maximum weight condition (with ice & wind & low temp usually −5.5°C).

→ Suffix '2' will denote erection conditions. (No ice & wind, actual temp at the time of erection).

let a = area of c/s of conductor

α = coefficient of linear expansion

E = Young's modulus.

Then $f = \frac{T}{a} \Rightarrow T = fa$ & $S_1 = l + \frac{w_1^2 l^3}{6 f_1^2 a^2}$

consider the temperature has increased from 't_1 to t_2' then the result is increase in the length of conductors

to $(t_2-t_1)\alpha S_1$

$$\simeq (t_2-t_1)\alpha l$$

At the same time, there will be reduction in stress from f_1 to f_2, which will decrease the length to

to $\frac{(f_1-f_2)}{E} \cdot S_1$

$$\simeq \left(\frac{f_1-f_2}{E}\right) \cdot l.$$

$\therefore$ the new length $S_2 = S_1 + (t_2-t_1)\alpha l - \left(\frac{f_1-f_2}{E}\right) \cdot l$ — ①

& also $S_2 = l + \frac{\omega_2^2 l^3}{6 f_2^2 a^2}$ — ②.

equating ① & ②.

$$\cancel{l} + \frac{\omega_1^2 l^3}{6f_1^2 a^2} + (t_2-t_1)\alpha l - \left(\frac{f_1-f_2}{E}\right) \cdot l = \cancel{l} + \frac{\omega_2^2 l^3}{6 f_2^2 a^2}$$

$$\Rightarrow \frac{\omega_1^2 l^{3\,2}}{6f_1^2 a^2} + (t_2-t_1)\alpha \cancel{l} + \frac{(f_2-f_1)}{E}\cancel{l} = \frac{\omega_2^2 l^{3\,2}}{6f_2^2 a^2}$$

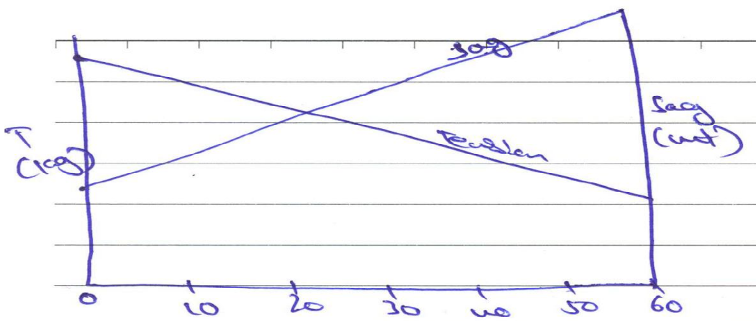
$$\Rightarrow \frac{\omega_1^2 l^2 E}{6f_1^2 a^2} + (t_2-t_1)\alpha E + (f_2-f_1) = \frac{\omega_2^2 l^2}{6f_2^2 a^2} \cdot E$$

$$\Rightarrow f_2^2 \left[f_2 - f_1 + (t_2-t_1)\alpha E + \frac{\omega_1^2 l^2 E}{6f_1^2 a^2}\right] = \frac{\omega_2^2 l^2 E}{6a^2} \quad \text{— ③.}$$

eq ③ is a cubic equation in f_2. knowing the value of f_2, D_2 can be determined as

$$D_2 = \frac{\omega_2 l^2}{2T} = \frac{\omega_2 l^2}{2f_2 a}$$

∴ A graph can be plotted b/w temp & sag.
and also b/w temp & f_2. as shown in fig.



The plot of tension vs temperature & sag vs temp is called stringing chart.

3. A 132 kV transmission line uses ACSR conductor whose data are: nominal copper are 110mm^2; size 30+7/2.79mm; weight 844kg/km; ultimate strength 7950kg. The line is subjected to a horizontal wind pressure of 40kg/m^2 of projected area and 1.25cm radial ice coating. If the maximum permissible sag is 6m, calculate the permissible span between the two supports, allowing for a factor of safety of 2.weight of ice is 915 kg/m^2 (10M)

Given Data

Diameter = 2.79mm

no. of Strands x = 30+7 = 37

let n = no. of layers

$\therefore x = 3n^2+3n+1$

$37 = 3n^2+3n+1$

$n = -4, 3$ hence $n=3$, neglecting negative value

$d_c = (2n+1)d = 7 \times 2.79 = 19.53$ mm

$w_w = P \times [d_c+2t)$ where $t = 1.25$cm, $P = 40$ kg/m^2

$= 40 \times [19.53 \times 10^{-3} + 2 \times 1.25 \times 10^{-2}] = 1.7812$ kg/m

$w = 844$ kg/km $= 0.844$ kg/m

Density of ice = 915 kg/m3

$\therefore w_i = 915 \pi t [d_c+t] = 915 \pi \times 1.25 \times 10^{-2} [19.53 \times 10^{-3} + 1.25 \times 10^{-2}]$

$= 1.1509$ kg/m

$\therefore w_t = \sqrt{(w+w_i)^2+(w_w)^2} = \sqrt{(0.844+1.1509+(1.7812)^2}$

$= 2.6743$ kg/m

$SF = \frac{\text{Ultimate Strength}}{T}$ i.e. $2 = \frac{7950}{T}$ i.e. $T = 3975$ kg

$S = \frac{w_t l^2}{2T}$ i.e. $6 = \frac{2.6743 \times l^2}{2 \times 3975}$

$\therefore L = 133.5511$ m

4. (a) Define string efficiency. (2M)

String efficiency:-

The unequal voltage distribution is undesirable.

The ratio of voltage across the whole string to the product of number of discs & the voltage across the disc nearest to the conductor is known as string efficiency ie,

$$\text{String efficiency} = \frac{\text{Voltage across the string}}{n \times \text{Voltage across disc nearest to conductor}}$$

where n = number of discs in the string.

The greater the string efficiency, the more uniform is the voltage distribution. 100 % string efficiency is an ideal case for which the voltage a/c each disc will be exactly the same.

(b) Why string efficiency should be as high as possible? Explain the use of guard ring for improving the string efficiency. (8M)

The greater the string efficiency, the more uniform is the voltage distribution. 100 % string efficiency is an ideal case for which the voltage a/c each disc will be exactly the same.

Imp Points:-

(i) The voltage impressed on a string of suspension insulators does not distribute itself uniformly a/c the individual discs due to presence of shunt capacitance.

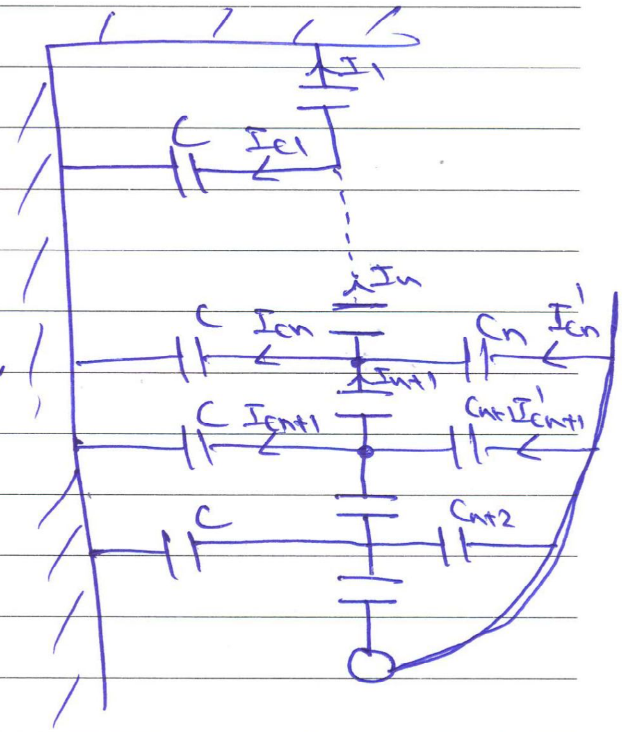
(ii) The disc nearest to the conductor has maximum voltage across it. As we move towards the cross-arm, the voltage across each disc goes on decreasing.

(iii) The unit nearest to the conductor is under maximum electrical stress and is likely to be punctured.

(iii) <u>Static shielding</u>:- The Idea is to cancel exactly the pin to tower charging currents so that the same current flows through the units of identical capacities to produce equal voltage drops across each unit.

A <u>guard ring</u> (or) <u>grading ring</u> is connected round to the power conductor such that this surrounds the bottom unit.

The design of the ring is such that this gives rise to the capacitance which will cancel exactly the charging current in that particular section, such that



$I_{n+1} = I_n$

ie $I_{cn} = I'_{cn}$

$nV_1 \omega C = (V - nV_1)\omega C_n$ — ①

where

V = operating voltage

C_n = capacitance b/w the guard ring and the pin of the n^{th} unit.

V_1 = voltage a/c each unit.

If k = total no. of units then. from eq ①.

$nV_1 \omega C = (kV_1 - nV_1) C_n \omega$

$nC = (k-n) C_n$

$\Rightarrow \quad C_n = \frac{n}{k-n} \cdot C.$

∴ In order to obtain perfect equal distribution of voltage, the capacitance of the guard ring w.r.t. the pins of the insulators can be given by the above expression.

In practice it is difficult to achieve this condition. Nevertheless this method is normally used.

Grading ring serves two purpose

(i) equalisation of voltage drop across the units

(ii) when used with arcing horn (which is fixed at the top end of the string) it protects the insulator string from flashover whenever an overvoltage appears b/w the tower structure and the power conductor.

5. (a) Write a short note on testing of insulators briefly explaining different tests. (4M)

Testing of insulators

(i) Mechanical tests:- Insulators are subjected to various types of mechanical stresses. The important mechanical tests are

→ Tensile strength
→ compression test
→ Torsional test
→ Bending minimum test
→ Mechanical vibration test.

(ii) Electrical Insulation tests:-

Insulators are subjected to normal continuous power frequency voltage, power freq. over voltage, and impulse voltage test. These voltages have different waveforms & durations.

(a) Power frequency withstand test. 2Vr

Normal power frequency voltage is continuously applied to the insulators. The effect of this voltage is to align the dust particles on the surface and cause leakage currents over the surface.

Voltage of the order of twice the rated voltage is applied for a period of a minute. There should be no flashover or puncture.

It is conducted in two categories

→ 1 minute power frequency withstand test → Dry
→ " " " → wet

wet test is applicable only to the outdoor insulators

(b) Impulse voltage withstand test

A standard impulse voltage wave is applied to the insulator. The clearance, voltage distribution, stress concentration at sharp points, smoothness of metal fittings etc are observed.

(iii) Environmental tests & Temperature cycle tests:-

Insulators are subjected to alternate temperature cycles, sudden temperature changes, pollution & other environmental stresses.

→ Sudden temperature drop test (thermal shock tests)
→ Extremely low temperature test.
→ Pollution test.

(iv) Corona & Radio interference test:-

When voltage stress at the surface of conductor increases beyond corona inspection level, corona discharge starts. While designing an insulator, the voltage distribution pattern is analysed. By providing suitable voltage grading rings & smooth surface, the possibility of corona discharge & radio interference is eliminated for certain voltage range.

other tests include

(i) Power frequency puncture test

This is a destructive test. Here, the insulator with the pin and conductor in proper position is immersed in an insulating oil and a steadily increasing power frequency voltage is applied. The voltage at which conduction starts is called puncture voltage.

(ii) Porosity test

This is also a destructive test. The specimen insulator is broken in to pieces and the pieces are immersed in a 1% solution of dye in alcohol under a pressure of 15×10^3 kN/m^2. After a specified time the pieces are removed and the penetration of dye is observed. This gives the degree of porosity.

(iii) Galvanising test

The metal parts of the insulator are galvanised & this test is conducted to assess the strength of galvanisation.

(b) In a 5 insulator disc string, capacitance of each unit and the earth is 1/6th of the mutual capacitance. Find the voltage distribution across each insulator in the string, as a percentage of voltage of conductor to earth. Find also the string efficiency. (6M)

$V = 1V$

$V_2 = 1.1666\,V$

$V_3 = 1.527\,V$

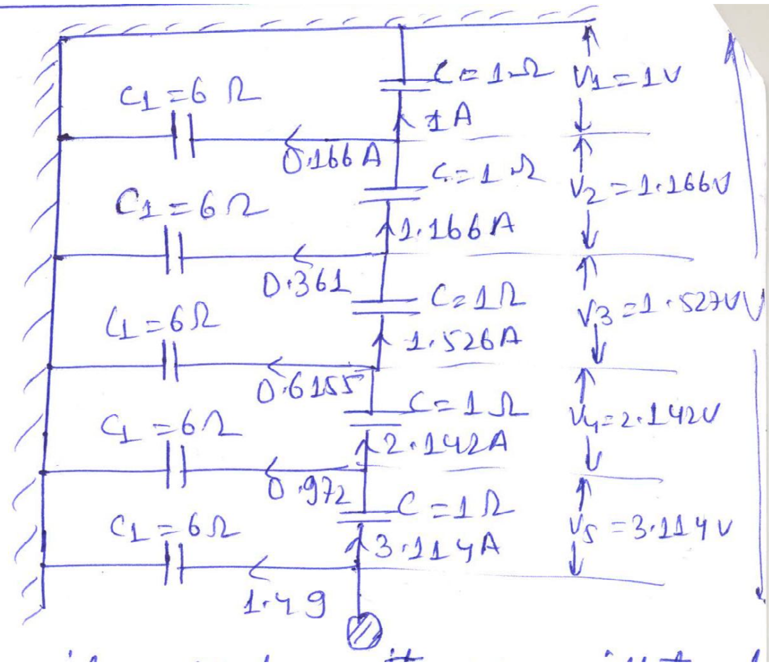
$V_4 = 2.147\,V$

$V_5 = 3.114\,V$

$$\text{string efficiency} = \frac{V}{nV_s}$$

$$= \frac{8.949}{5 \times 3.114}$$

$$= 57.47\%$$



6. Find the inductance per phase per km of line length of a 3-ϕ double circuit line shown in fig 4.1. The radius of each conductor is 0.9cm. (10M)

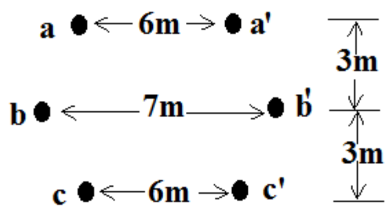


Fig. 4.1

$L_A = L_B = L_C = ?$

$r = 0.9 cm$, $r' = 0.7788 r = 0.7009 \times 10^{-2} m.$

$L_A = 0.2 \ln\left(\frac{D_m}{D_s}\right)$ -- mH/ph/km.

self GMD of phase A

$D_{SA} = \sqrt[4]{D_{aa} D_{aa'} D_{a'a} D_{a'a'}}$

$D_{SA} = \sqrt[4]{(0.7009 \times 10^{-2})^2 6^2}$

$D_{SA} = 0.2050 m.$

self GMD of phase B

$D_{SB} = \sqrt[4]{D_{bb} D_{b'b} D_{b'b} D_{b'b'}}$

$D_{SB} = \sqrt[4]{(0.7009 \times 10^{-2})^2 (7)^2}$

$D_{SB} = 0.2215 m.$

self GMD of phase C

$D_{SC} = \sqrt[4]{D_{cc} D_{c'c} D_{cc'} D_{c'c'}}$

$D_{SC} = \sqrt[4]{(0.7009 \times 10^{-2})^2 (6)^2}$

$D_{SC} = 0.2050 m.$

$$D_s = \sqrt[3]{(0.2050)^2 (0.2215)}$$

$$D_s = 0.2103\,m.$$

Mutual GMD btw phase A & phase B.

$$D_{AB} = \sqrt[4]{D_{ab} D_{a'b} D_{ab'} D_{a'b'}}$$

$$D_{AB} = \sqrt[4]{(3.041)^2 (7.1589)^2} = 4.6658\,m.$$

mutual GMD between phase B and phase C

$$D_{BC} = \sqrt[4]{D_{BC} D_{BC'} D_{B'C} D_{B'C'}}$$

$$D_{BC} = \sqrt[4]{(3.041)^2 (7.1589)^2}$$

$$D_{BC} = 4.6658\,m.$$

Mutual GMD between phase C and phase A

$$D_{CA} = \sqrt[4]{D_{ac} D_{ac'} D_{a'c} D_{a'c'}}$$

$$= \sqrt[4]{(6)^2 (8.485)^2}$$

$$D_{CA} = 7.135\,m.$$

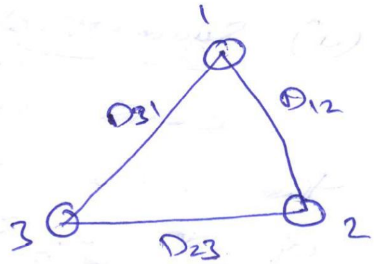
$$D_m = \sqrt[3]{D_{AB} D_{BC} D_{CA}}$$

$$D_m = 5.375\,m$$

$$L_A = L_B = L_C = 0.2 \ln \left(\frac{5.375}{0.2103} \right)$$

$$L_A = L_B = L_C = 0.6481 \text{ mH/ph/km}.$$

7. Derive an expression for the inductance per phase for a 3-phase overhead transmission line when conductors are asymmetrically placed but the line is completely transposed (clearly explaining transposition). (10M)

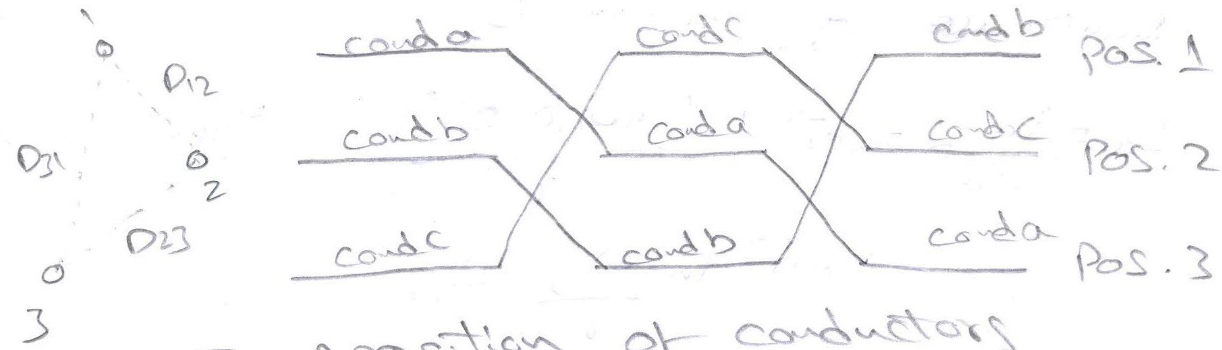


In practice the conductors of 3-φ line are not at the corners of an equilateral triangle.

∴ the flux linkages & inductance of each phase are not same. A different inductance in each phase results in an unbalanced ckt.

In long lines, to make the inductance of each phase equal, the lines are transposed. ie, the phase conductors have their positions interchanged at special transposition towers, so that the conductor of each phase occupies positions 1, 2 & 3 for about one third of its length as shown in fig. This interchange is also made at switching stations.

The average inductance of a conductor of a transposed line is found by calculating the flux linkages for each position occupied by conductor & then finding avg. flux linkages.



Transposition of conductors

→ Flux linkages of cond a when cond a in Pos 1, cond b in Pos. 2 & cond c in Pos 3 is

$$\psi_{a1} = 2\times10^{-7}\left[I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{12}} + I_c \ln\frac{1}{D_{13}}\right] \text{wb-T/m}$$

→ Flux linkages of cond a when cond a in Pos 2, cond b in pos 3 & cond c in pos 1 is

$$\psi_{a2} = 2\times10^{-7}\left[I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{23}} + I_c \ln\frac{1}{D_{12}}\right] \text{wb-T/m}$$

→ Flux linkages of cond a when cond a is in pos 3, cond b in pos 1 & cond c in pos 2 is

$$\psi_{a3} = 2\times10^{-7}\left[I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{13}} + I_c \ln\frac{1}{D_{23}}\right] \text{wb-T/m}$$

avg. flux linkages of cond. 'a' are

$$\psi_a = \frac{\psi_{a1} + \psi_{a2} + \psi_{a3}}{3} = \frac{2\times10^{-7}}{3}\left[3 I_a \ln\frac{1}{r'} + \right.$$

$$= \frac{2\times10^{-7}}{3}\left[3 I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{12}D_{23}D_{13}} + I_c \ln\frac{1}{D_{13}D_{12}D_{23}}\right]$$

but $I_a = -(I_b + I_c)$

$$\Rightarrow \psi_a = \frac{2\times10^{-7}}{3}\left[3 I_a \ln\frac{1}{r'} - I_a \ln\frac{1}{D_{12}D_{23}D_{13}}\right]$$

$$= 2\times10^{-7} I_a \ln\left(\frac{\sqrt[3]{D_{12}D_{23}D_{13}}}{r'}\right) \text{ wb-T/m}$$

inductance of phase a is

$$L_a = \frac{\psi_a}{I_a} = 2\times10^{-7} \ln\left(\frac{\sqrt[3]{D_{12}D_{23}D_{31}}}{r'}\right) \text{ H/m}$$

$$= 2\times10^{-7} \ln\frac{D_{eq}}{r'} \text{ H/m}$$

where D_{eq} = equivalent spacing.

= geometric mean of 3 distances of the line.