MALLA REDDY EGNGINEERING COLLEGE (AUTONOMOUS)

Maisammaguda, Dhulapally (Post Via. Kompally), Secunderabad – 500100,
Telangana State, India.

DEPARTMENT OF
ELECTRICAL & ELECTRONICS ENGINEERING

Course Material
for
POWER TRANSMISSION SYSTEMS

For
B.Tech (EEE)

2015–16

Malla Reddy Engineering College (Autonomous)

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Course Code:50211 **Credits: 3**

B.Tech. – V – Semester

POWER TRANSMISSION SYSTEMS

Objective:

This course is an extension of Generation of Electric Power course. It deals with basic theory oftransmission lines modeling and their performance analysis. Also this course gives emphasis onmechanical design of transmission lines, cables and insulators.

Module I: TRANSMISSION LINE PARAMETERS [12 Periods]

Types of Conductors – ACSR, Bundled and Standard Conductors- Resistance For Solid Conductors –Skin Effect- Calculation of Inductance for Single Phase and Three Phase, Single and Double Circuit Lines, Concept of GMR & GMD, Symmetrical and Asymmetrical Conductor Configuration with and without Transposition, Numerical Problems, Capacitance Calculations for Symmetrical and Asymmetrical Single and Three Phase, Single and Double Circuit Lines, Effect of Ground on Capacitance, Numerical Problems.

ModuleII: PERFORMANCE OF TRANSMISSION LINES: [12 Periods]

Classification of Transmission Lines - Short, Medium and Long Line and Their Exact Equivalent Ciruits- Nominal-T, Nominal-Pie. Mathematical Solutions to Estimate Regulation and Efficiency of All Types of Lines. Long Transmission Line-Rigorous Solution, Evaluation of A,B,C,D Constants, Interpretation of the Long Line Equations – Surge Impedance and Surge Impedance Loading - Wavelengths and Velocity of Propagation – Ferranti Effect , Charging Current-Numerical Problems.

Module III: MECHANICAL DESIGN OF TRANSMISSION LINES [12 Periods]

Overhead Line Insulators: Types of Insulators, String Efficiency and Methods for Improvement, Capacitance Grading and Static Shielding.

Corona: Corona Phenomenon, Factors Affecting Corona, Critical Voltages and Power Loss, Radio Interference.

Sag and Tension Calculations: Sag and Tension Calculations with Equal and Unequal Heights of Towers, Effect of Wind and Ice on Weight of Conductor, Stringing Chart and Sag Template and Its Applications, Numerical Problems.

Module IV: POWER SYSTEM TRANSIENTS & TRAVELLING WAVES [10 Periods]

Types of System Transients - Travelling or Propagation of Surges - Attenuation, Distortion, Reflection and Refraction Coefficients - Termination of Lines with Different Types of Conditions - Open Circuited Line, Short Circuited Line, T-Junction, Lumped Reactive Junctions (Numerical Problems). Bewley‘s Lattice Diagrams (for all the cases mentioned with numerical examples).

ModuleV: CABLES [12 Periods]

Types of Cables, Construction, Types of Insulating Materials, Calculations of Insulation Resistance and Stress in Insulation, Numerical Problems. Capacitance of Single and 3-Core Belted Cables, Numerical Problems. Grading of Cables - Capacitance Grading, Numerical Problems, Description of Inter-Sheath Grading.

Text Books:

1. C.L.Wadhwa, **"Electrical power systems"**, New Age International (P) Limited, Publishers,4th Edition, 2005.
2. John J Grainger, William D Stevenson, **"Power system Analysis"**, TMC Companies, 4th edition, 1994.

References:

1. B.R.Gupta**, "Power System Analysis and Design",** S. Chand & Co, 6th Revised Edition, 2010.
2. I.J.Nagrath and D.P.Kothari , **"Modern Power System Analysis",** Tata McGraw Hill, 3rd Edition,2008.
3. Turan Gonen, **"Electric Power Transmission System Engineering: Analysis and Design",** 2nd Edition, CRC Press, 2009.
4. S. A. Nasar, **"Electric Power Systems",** Schaum"s Outline Series, TMH, 3rd Edition, 2008.
5. M.L.Soni, P.V.Gupta, U.S.Bhatnagar, A.Chakrabarti, **"A Text Book on Power System Engineering"**, Dhanpat Rai & Co Pvt. Ltd., 2003.

Outcomes:

After going through this course the student will be able to

1. Derive L and C expressions for various configurations and analyze different types of Transmission lines.
2. Model the transmission line and analyze their performance.
3. Describe Traveling wave theory and derive expressions for reflection and refraction coefficients with various terminations of the lines.
4. Derive expressions for sag with equal and unequal height towers and describe various types of Insulators and also explain various string efficiency methods.
5. Illustrate different types of cables and derive capacitance expressions and describe grading of cables.

CONTENTS

Module-I

Transmission Line Parameters

Conductor: Conductor is a physical medium to carry electrical energy form one place to other. It is an important component of overhead and underground electrical transmission and distribution systems. The choice of conductor depends on the cost and efficiency. An ideal conductor has following features.

1. It has maximum conductivity
2. It has high tensile strength
3. It has least specific gravity i.e. weight / unit volume
4. It has least cost without sacrificing other factors.

1.Types of Conductors:

In the early days conductor used on transmission lines were usually Copper, but Aluminum Conductors have Completely replaced Copper because of the much lower cost and lighter weight of Aluminum conductor compared with a Copper conductor of the same resistance. The fact that Aluminum conductor has a larger diameter than a Copper conductor of the same resistance is also an advantage. With a larger diameter the lines of electric flux originating on the conductor will be farther apart at the conductor surface for the same voltage. This means a lower voltage gradient at the conductor surface and less tendency to ionise the air around the conductor. Ionization produces the undesirable effect called **corona.**

The symbols identifying different types of Aluminium conductors are as follows:-

AAC: AllAluminiumconductors.

AAAC: AllAluminiumAlloyconductors

ACSR: Aluminiumconductors,Steel-Reinforced

ACAR : Aluminum conductor, Alloy-Reinforced

Aluminium alloy conductors have higher tensile strength than the conductor of EC grade Aluminium or AAC, ACSR consists of a central core of steel strands surrounded by layers of Aluminium strands. ACAR has a central core of higher strength Aluminium Alloy surrounded by layer of Electrical-Conductor-Grade Aluminium.

ACSR (Aluminum Conductor Steel Reinforced)

- Aluminum Conductor Steel Reinforced (ACSR) is concentrically stranded conductor with one or more layers of hard drawn 1350-H19 aluminum wire on galvanized steel wire core.
- The core can be single wire or stranded depending on the size.
- Steel wire core is available in Class A ,B or Class C galvanization for corrosion protection.
- Additional corrosion protection is available through the application of grease to the core or infusion of the complete cable with grease.
- The proportion of steel and aluminum in an ACSR conductor can be selected based on

the mechanical strength and current carrying capacity demanded by each application.

- ACSR conductors are recognized for their record of economy, dependability and favorable strength / weight ratio. ACSR conductors combine the light weight and good conductivity of aluminum with the high tensile strength and ruggedness of steel.
- In line design, this can provide higher tensions, less sag, and longer span lengths than obtainable with most other types of overhead conductors.
- The steel strands are added as mechanical reinforcements.
- ACSR conductors are recognized for their record of economy, dependability and favorable strength / weight ratio.
- ACSR conductors combine the light weight and good conductivity of aluminum with the high tensile strength and ruggedness of steel.
- In line design, this can provide higher tensions, less sag, and longer span lengths than obtainable with most other types of overhead conductors.
- The steel strands are added as mechanical reinforcements.
- The cross sections above illustrate some common stranding.
- The steel core wires are protected from corrosion by galvanizing.
- The standard Class A zinc coating is usually adequate for ordinary environments.
- For greater protection, Class B and C galvanized coatings may be specified.
- The product is available with conductor corrosion resistant inhibitor treatment applied to the central steel component.
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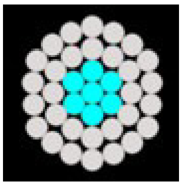


Features

- High Tensile strength
- Better sag properties
- Economic design
  - Suitable for remote applications involving long spans
  - Good Ampacity
  - Good Thermal Characteristics
  - High Strength to Weight Ratio
  - Low sag
  - High Tensile Strength

Typical Application

- Commonly used for both transmission and distribution circuits.
- Compact Aluminum Conductors, Steel Reinforced (ACSR) are used for overhead distribution and transmission lines.

BUNDLED CONDUCTORS:

Bundle conductors are widely use for transmission line and has its own advantages and disadvantages.

Bundle conductor is a conductor which consist several conductor cable which connected. Bundle conductors also will help to increase the current carried in the transmission line. The main disadvantage of Transmission line is its having high wind load compare to other conductors.

(Or)

The combination of more than one conductor per phase in parallel suitably spaced from each other used in overhead Transmission Line is defined as conductor bundle. The individual conductor in a bundle is defined as Sub-conductor.

At Extra High Voltage (EHV), i.e. voltage above 220 KV corona with its resultant power loss and particularly its interference with communication is excessive if the circuit has only one conductor per phase. The High-Voltage Gradient at the conductor in the EHV range is reduced considerably by having two or more conductors per phase in close proximity compared with the spacing between conductor-bundle spaced 450 mm is used in India

The three conductor bundle usually has the conductors at the vertices of an equilateral triangle and four conductors bundle usually has its conductors at the corners of a square.

The current will not divide exactly between the conductor of the bundle unless there is a transposition of the conductors within the bundle, but the difference is of no practical importance.

Reduced reactance is the other equally important advantage of bundling. Increasing the number of conductor in a bundle reduces the effects of **corona** and reduces the reactance. The reduction of reactance results from the increased Geometric Mean Radius (GMR) of the bundle.

2. TRANSMISSION LINES:

The electric parameters of transmission lines (i.e. resistance, inductance, and capacitance) can be determined from the specifications for the conductors, and from the geometric arrangements of the conductors.

2.1 Transmission Line Resistance

Resistance to d.c. current is given by

$$R_{dc} = \rho \frac{\ell}{A}$$

where ρ is the resistivity at 20° C

ℓ is the length of the conductor

A is the cross sectional area of the conductor

Because of skin effect, the d.c. resistance is different from ac resistance. The ac resistance is referred to as effective resistance, and is found from power loss in the conductor

$$R = \frac{\text{power loss}}{I^2}$$

The variation of resistance with temperature is linear over the normal temperature range

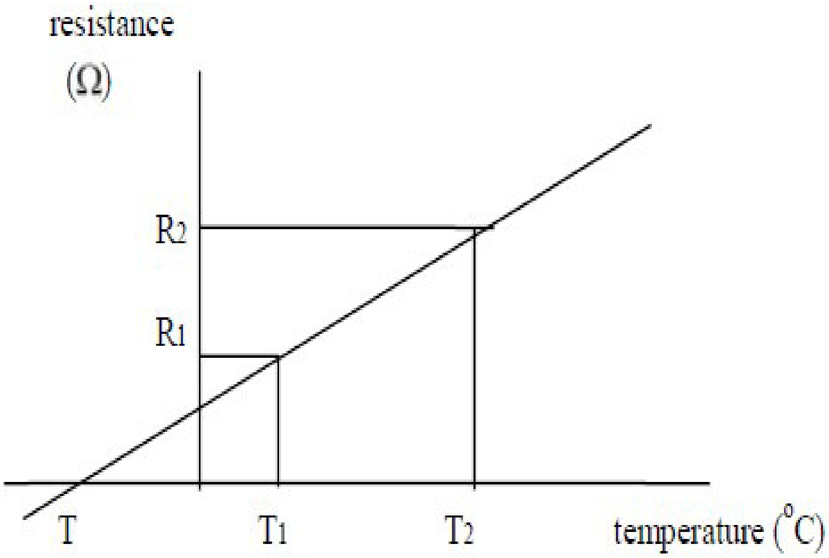


Figure 9 Graph of Resistance vs Temperature

$$R_2 = \frac{T_2 - T}{T_1 - T} R_1$$

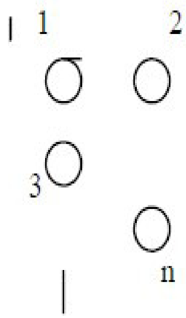
2.2 Transmission Line Inductive Reactance

Inductance of transmission lines is calculated per phase. It consists of self inductance of the phase conductor and mutual inductance between the conductors. It is given by:

$$L = 2 \times 10^{-7} \ln \frac{GMD}{GMR} \qquad [H/m]$$

where GMR is the geometric mean radius (available from manufacturer's tables)
GMD is the geometric mean distance (must be calculated for each line configuration)

Geometric Mean Radius: There are magnetic flux lines not only outside of the conductor, but also inside. GMR is a hypothetical radius that replaces the actual conductor with a hollow conductor of radius equal to GMR such that the self inductance of the inductor remains the same. If each phase consists of several conductors, the GMR is given by

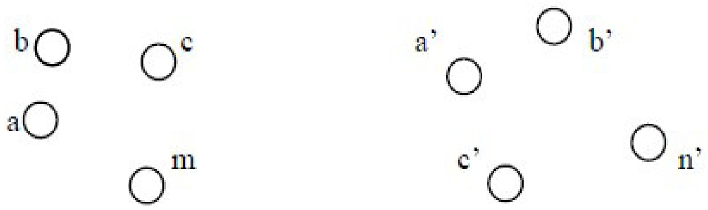


$$GMR = \sqrt[n^2]{(d_{11}d_{12}d_{13}\ldots d_{1n}).(d_{21}.d_{22}\ldots d_{2n})\ldots\ldots(d_{n1}.d_{n2}\ldots\ldots d_{nn})}$$

where $d_{11}=GMR_1$
$d_{22}=GMR_2$
.
.
.
$d_{nn}=GMR_n$

Note: for a solid conductor, $GMR = r.e^{-1/4}$, where r is the radius of the conductor.

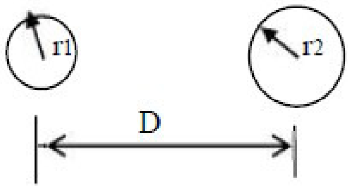
Geometric Mean Distance replaces the actual arrangement of conductors by a hypothetical mean distance such that the mutual inductance of the arrangement remains the same



$$GMD = \sqrt[mn']{(D_{aa'}D_{ab'}\ldots D_{an'}).(D_{ba'}D_{bb'}\ldots D_{bn'})\ldots\ldots(D_{ma'}D_{mb'}\ldots\ldots D_{mn'})}$$

where $D_{aa'}$ is the distance between conductors "a" and "a'" etc.

Inductance Between Two Single Phase Conductors



$$L_1 = 2\times10^{-7}\times\ln\frac{D}{r_1'} \qquad L_2 = 2\times10^{-7}\times\ln\frac{D}{r_2'}$$

where r_1' is GMR of conductor 1
r_2' is GMR of conductor 2
D is the GMD between the conductors

The total inductance of the line is then

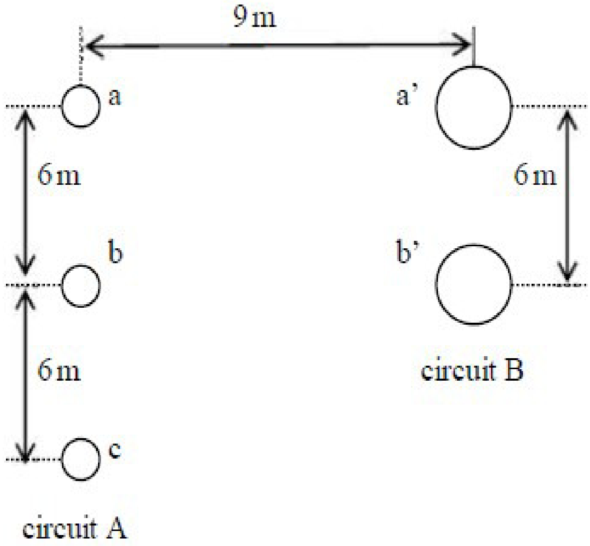
$$L_T = L_1 + L_2 = 2\times10^{-7}\times\left[\ln\frac{D}{r_1'}+\ln\frac{D}{r_2'}\right] = 2\times10^{-7}\times\ln\frac{D^2}{r_1'r_2'} = 2\times10^{-7}\times2\times\frac{1}{2}\times\ln\frac{D^2}{r_1'r_2'}$$

$$L_T = 4\times10^{-7}\times\ln\left[\frac{D^2}{r_1'r_2'}\right]^{1/2} = 4\times10^{-7}\times\ln\frac{D}{\sqrt{r_1'r_2'}}$$

If $r_1 = r_2$, then

$$L_T = 4\times10^{-7}\times\ln\frac{D}{r_1'}$$

Example: Find GMD, GMR for each circuit, inductance for each circuit, and total inductance per meter for two circuits that run parallel to each other. One circuit consists of three 0.25 cm radius conductors. The second circuit consists of two 0.5 cm radius conductor



Solution:

$m = 3,\ n' = 2,\ \therefore m{\cdot}n' = 6$

$$GMD = \sqrt[6]{(D_{aa'}D_{ab'})(D_{ba'}B_{bb'})(D_{ca'}D_{cb'})}$$

where

$$D_{aa'} = D_{bb'} = 9\ m$$

$$D_{ab'} = D_{ba'} = D_{cb'} = \sqrt{6^2 + 9^2} = \sqrt{117}\ m$$

$$D_{ca'} = \sqrt{12^2 + 9^2} = 15\ m$$

$\therefore$ GMD = 10.743 m

Geometric Mean Radius for Circuit A:

$$GMR_A = \sqrt[3^2]{D_{aa}D_{ab}D_{ac}D_{ba}D_{bb}D_{bc}D_{ca}D_{cb}D_{cc}} = \sqrt[9]{\left(0.25\times10^{-2}\times e^{-1/4}\right)^3\times6^4\times12^2} = 0.481m$$

Geometric Mean Radius for Circuit B:

$$GMR_B = \sqrt[2^2]{D_{a'a'}D_{a'b'}D_{b'b'}D_{b'a'}} = \sqrt[4]{\left(0.5\times10^{-2}\times e^{-1/4}\right)^2\times6^2} = 0.153m$$

Inductance of circuit A

$$L_A = 2\times10^{-7}\ln\frac{GMD}{GMR_A} = 2\times10^{-7}\ln\frac{10.743}{0.481} = 6.212\times10^{-7} \qquad H/m$$

Inductance of circuit B

$$L_B = 2\times10^{-7}\ln\frac{GMD}{GMR_B} = 2\times10^{-7}\ln\frac{10.743}{0.153} = 8.503\times10^{-7} \qquad H/m$$

The total inductance is then

$$L_T = L_A + L_B = 14.715\times10^{-7} \qquad H/m$$

The Use of Tables

Since the cables for power transmission lines are usually supplied by U.S. manufacturers, the tables of cable characteristics are in American Standard System of units and the inductive reactance is given in Ω/mile.

$$X_L = 2\pi fL = 2\pi f\times2\times10^{-7}\ln\frac{GMD}{GMR} \qquad \Omega/m$$

$$X_L = 4\pi f\times10^{-7}\ln\frac{GMD}{GMR} \qquad \Omega/m$$

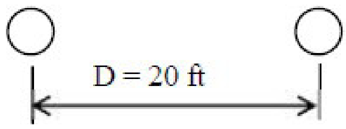
$$X_L = 4\pi f\times10^{-7}\times1609\times\ln\frac{GMD}{GMR} \qquad \Omega/\text{mile}$$

$$X_L = 2.022\times10^{-3}\times f\times\ln\frac{GMD}{GMR} \qquad \Omega/\text{mile}$$

$$X_L = \underbrace{2.022\times10^{-3}\times f\times\ln\frac{1}{GMR}}_{X_a} + \underbrace{2.022\times10^{-3}\times f\times\ln GMD}_{X_d} \qquad \Omega/\text{mile}$$

If both, GMR and GMD are in feet, then X_a represents the inductive reactance at 1 ft spacing, and X_d is called the inductive reactance spacing factor.

Example: Find the inductive reactance per mile of a single phase line operating at 60 Hz. The conductor used is Partridge, with 20 ft spacings between the conductor centers.



Solution: From the Tables, for Partridge conductor, GMR = 0.0217 ft and inductive reactance at 1 ft spacing X_a= 0.465 Ω/mile. The spacing factor for 20 ft spacing is X_d = 0.3635 Ω/mile. The inductance of the line is then

$$X_L = X_a + X_d = 0.465 + 0.3635 = 0.8285 \;\Omega/\text{mile}$$

Inductance of Balanced Three Phase Line

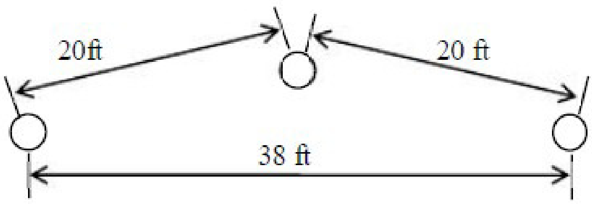
Average inductance per phase is given by:

$$L = 2 \times 10^{-7} \ln \frac{D_{eq}}{GMR}$$

where D_{eq} is the geometric mean of the three spacings of the three phase line.

$$D_{eq} = \sqrt[3]{D_{ab} D_{ac} D_{bc}}$$

Example: A three phase line operated at 60 Hz is arranged as shown. The conductors are ACSR Drake. Find the inductive reactance per mile.



Solution:

For ACSR Drake conductor, GMR = 0.0373 ft

$$D_{eq} = \sqrt[3]{20 \times 20 \times 38} = 24.8 \quad \text{ft}$$

$$L = 2 \times 10^{-7} \ln \frac{24.8}{\quad} = \quad \times \quad ^{-} \qquad H/m$$

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$$X_L = 2\pi \times 60 \times 1609 \times 13 \times 10^{-9} = 0.788 \quad \Omega/\text{mile}$$

OR

from the tables $X_a = 0.399 \;\Omega/\text{mile}$

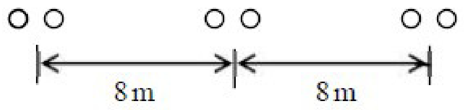
The spacing factor is calculated for spacing equal the geometric mean distance between the conductors, that is, $X_d = 2.022 \times 10^{-3} \times 60 \ln 24.8 = 0.389 \quad \Omega/\text{mile}$

Then the line inductance is $X_{line} = X_a + X_d = 0.788 \quad \Omega / \text{mile} \quad$ per phase

Example: Each conductor of the bundled conductor line shown in the figure is 1272 MCM Pheasant. Find:

a) the inductive reactance in Ω/km and Ω/mile per phase for d = 45 cm

b) the p.u. series reactance if the length of the line is 160 km and the base is 100 MVA, 345 kV.



Solution:

a) The distances in ft are

$$d = \frac{0.45}{0.3048} = 1476 \quad \text{ft}$$

$$D = \frac{8}{0.3048} = 26.25 \quad \text{ft}$$

For Pheasant conductors, GMR = 0.0466 ft.

GMR_b for a bundle of conductors is

$$GMR_b = \sqrt{GMR \times d} = \sqrt{0.0466 \times 1476} = 0.2623 \quad \text{ft}$$

The geometric mean of the phase conductor spacing is

$$D_{eq} = \sqrt[3]{26.25 \times 26.25 \times 52.49} = 3307 \quad \text{ft}$$

The inductance of the line is then

$$L = 2 \times 10^{-7} \ln \frac{D_{eq}}{GMR_b} = 2 \times 10^{-7} \ln \frac{33.07}{0.2623} = 9.674 \times 10^{-7} \quad \text{H / m}$$

The inductive reactance is

$$X_L = 2\pi f L = 2\pi \times 60 \times 9.674 \times 10^{-7} = 3.647 \times 10^{4} \quad \Omega / \text{m} = 0.3647 \quad \Omega / \text{km} = 0.5868 \quad \Omega / \text{mile}$$

b) Base impedance $Z_b = \frac{V_b^2}{S_b} = \frac{345^2}{100} = 1190 \quad \Omega$

Total impedance of the 160 km line is

Reactive power to charge the line is

$$Q_C = \sqrt{3}V_{LL}I_C = \sqrt{3} \times 220k \times 119 = 45.45 \quad MVAr$$

2.5 Transmission Line Losses and Thermal Limits

The power losses of a transmission line are proportional to the value of resistance of the line. The value of the resistance is determined by the type and length of the conductor. The current in the line is given by the power being delivered by the transmission line.

$$P_R = E_R I_{equiv} \cos\Phi_R \qquad \therefore \qquad I_{equiv} = \frac{P_R}{E_R \cos\Phi_R}$$

From that,

$$P_{loss} = I_{equiv}^2 R = \left(\frac{P_R}{E_R \cos\Phi_R}\right)^2 R$$

Power utilities usually strive to maintain the receiving end voltage constant. The power delivered by the transmission line is determined by the load connected to the line and cannot be changed without changing the load. The only term in the above equation that can be regulated is the power factor. If the power factor can be adjusted to be equal to 1, the power losses will be minimum.

Efficiency of the transmission line is given by

$$\eta_{\%} = \frac{P_R}{P_S} \cdot 100\%$$

Thermal Limits on equipment and conductors depend on the material of the insulation of conductors. The I^2R losses are converted into heat. The heat increases the temperature of the conductors and the insulation surrounding it. Some equipment can be cooled by introducing circulation of cooling media, other must depend on natural cooling. If the temperature exceeds the rated value, the insulation will deteriorate faster and at higher temperatures more immediate damage will occur.

The power losses increase with the load. It follows that the rated load is given by the temperature limits. The consequence of exceeding the rated load for short periods of time or by small amounts is a raised temperature that does not destroy the equipment but shortens its service life. Many utilities routinely allow short time overloads on their equipment - for example transformers are often overloaded by up to 15% during peak periods that may last only 15 or 30 minutes.

Module-II

Performance of Transmission Lines

SHORT TRANSMISSION LINES

The transmission lines are categorized as three types

1) Short transmission line – the line length is up to 80 km

2) Medium transmission line – the line length is between 80km to 160 km

3) Long transmission line – the line length is more than 160 km

Whatever may be the category of transmission line, the main aim is to transmit power from one end to another. Like other electrical system, the transmission network also will have some power loss and voltage drop during transmitting power from sending end to receiving end. Hence, performance of transmission line can be determined by its efficiency and voltage regulation.

$$\text{Efficiency of transmission line} = \frac{\text{power delivered at receiving end}}{\text{power sent from sending end}} \times 100\ \%$$

power sent from sending end – line losses = power delivered at receiving end

Voltage regulation of transmission line is measure of change of receiving end voltage from no-load to full load condition.

$$\%\ \text{regulation} = \frac{\text{no load receiving end voltage} - \text{full load receiving end voltage}}{\text{full load voltage}} \times 100\ \%$$

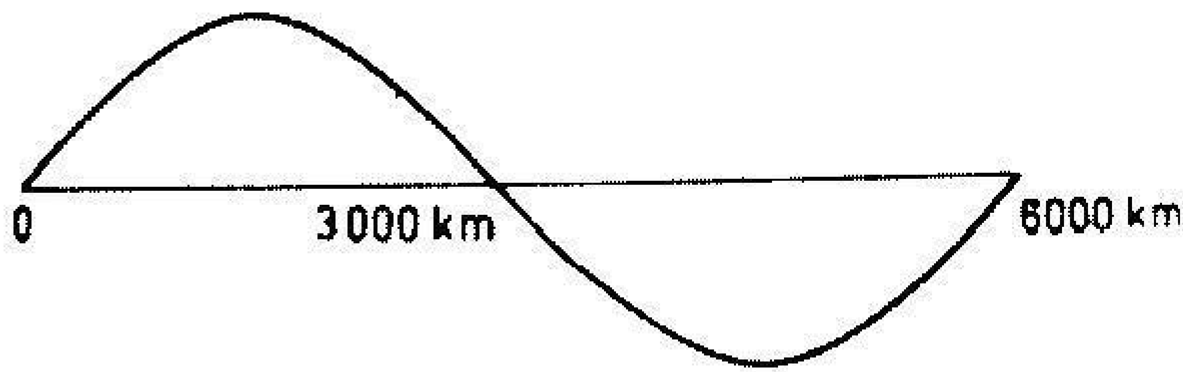
Every transmission line will have three basic electrical parameters. The conductors of the line will have resistance, inductance, and capacitance. As the transmission line is a set of conductors being run from one place to another supported by transmission towers, the parameters are distributed uniformly along the line.

The electrical power is transmitted over a transmission line with a speed of light that is $3X10^8$ m / sec. Frequency of the power is 50Hz. The wave length of the voltage and current of the power can be determined by the equation given below, f.λ = v where f is power frequency, &labda is wave length and v is the speed of light.

$$\text{Therefore, } \lambda = \frac{v}{f}$$

$$\lambda = \frac{3X10^8}{50} = 6X10^6 \text{ meters} = 6000 \text{ km.}$$

Hence the wave length of the transmitting power is quite long compared to the generally used line length of transmission line.



Voltage distribution of 50 Hz supply

For this reason, the transmission line, with length less than 160 km, the parameters are assumed to be lumped and not distributed. Such lines are known as electrically short transmission line. This electrically short transmission lines are again categorized as short transmission line (length up to 80 km) and medium transmission line(length between 80 and 160 km). The capacitive parameter of short transmission line is ignored whereas in case of medium length line the capacitance is assumed to be lumped at the middle of the line or half of the capacitance may be considered to be lumped at each ends of the transmission line. Lines with length more than 160 km, the parameters are considered to be distributed over the line. This is called long transmission line.

ABCD PARAMETERS

A major section of power system engineering deals in the transmission of electrical power from one particular place (eg. Generating station) to another like substations or distribution units with maximum efficiency. So its of substantial importance for power system engineers to be thorough with its mathematical modeling. Thus the entire transmission system can be simplified to a **two port network** for the sake of easier calculations.

The circuit of a 2 port network is shown in the diagram below. As the name suggests, a 2 port network consists of an input port PQ and an output port RS. Each port has 2 terminals to connect itself to the external circuit. Thus it is essentially a 2 port or a 4 terminal circuit, having

Supply end voltage = VS

and Supply end current = IS

Given to the input port P Q.

And there is the Receiving end Voltage = VR

and Receiving end current = IR

Given to the output port R S.

As shown in the diagram below.

Now the **ABCD parameters** or the transmission line parameters provide the link between the supply and receiving end voltages and currents, considering the circuit elements to be linear in nature.

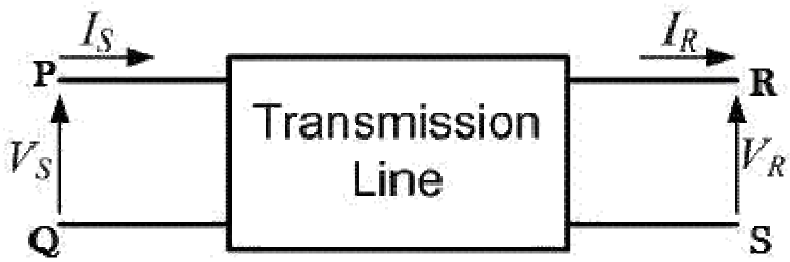
Thus the relation between the sending and receiving end specifications are given using **ABCD parameters** by the equations below.

VS = A VR + B IR ———————-(1)

IS = C VR + D IR ———————-(2)

Now in order to determine the ABCD parameters of transmission line let us impose the required circuit conditions in different cases.

ABCD parameters, when receiving end is open circuited



The receiving end is open circuited meaning receiving end current IR = 0.

Applying this condition to equation (1) we get.

$$V_S = A\,V_R + B\,0 \Rightarrow V_S = A\,V_R + 0$$
$$A = \left.\frac{V_S}{V_R}\right|_{I_R = 0}$$

Thus its implies that on applying open circuit condition to ABCD parameters, we get parameter A as the ratio of sending end voltage to the open circuit receiving end voltage. Since dimension wise A is a ratio of voltage to voltage, A is a dimension less parameter.

Applying the same open circuit condition i.e IR = 0 to equation (2)

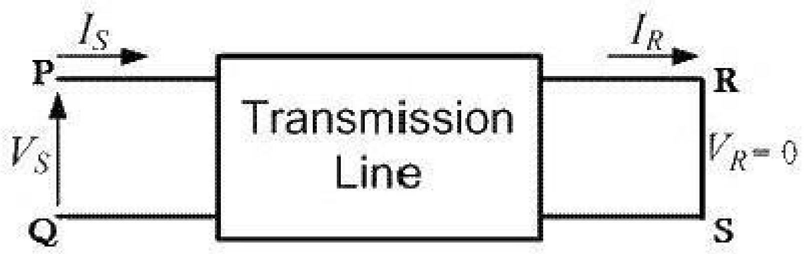
$$I_S = C V_R + D\,0 \Rightarrow I_S = C V_R + 0$$

$$C = \left.\frac{I_S}{V_R}\right| I_R = 0$$

Thus its implies that on applying open circuit condition to ABCD parameters of transmission line, we get parameter C as the ratio of sending end current to the open circuit receiving end voltage. Since dimension wise C is a ratio of current to voltage, its unit is mho.

Thus C is the open circuit conductance and is given by C = IS ⁄ VR mho.

ABCD parameters when receiving end is short circuited



Receiving end is short circuited meaning receiving end voltage VR = 0

Applying this condition to equation (1) we get

$$V_S = A\,0 + B I_R \Rightarrow V_S = 0 + B I_R$$

$$B = \left.\frac{V_S}{I_R}\right| V_R = 0$$

Thus its implies that on applying short circuit condition to ABCD parameters, we get parameter B as the ratio of sending end voltage to the short circuit receiving end current. Since dimension wise B is a ratio of voltage to current, its unit is Ω. Thus B is the short circuit resistance and is given by

B = VS ⁄ IR Ω.

Applying the same short circuit condition i.e VR = 0 to equation (2) we get

$$I_S = C\,0 + D I_R \Rightarrow I_S = 0 + D I_R$$

$$D = \left.\frac{I_S}{I_R}\right| V_R = 0$$

Thus its implies that on applying short circuit condition to ABCD parameters, we get parameter D as the ratio of sending end current to the short circuit receiving end current. Since dimension wise D is a ratio of current to current, it's a dimension less parameter. ∴ the ABCD parameters of transmission line can be tabulated as:-

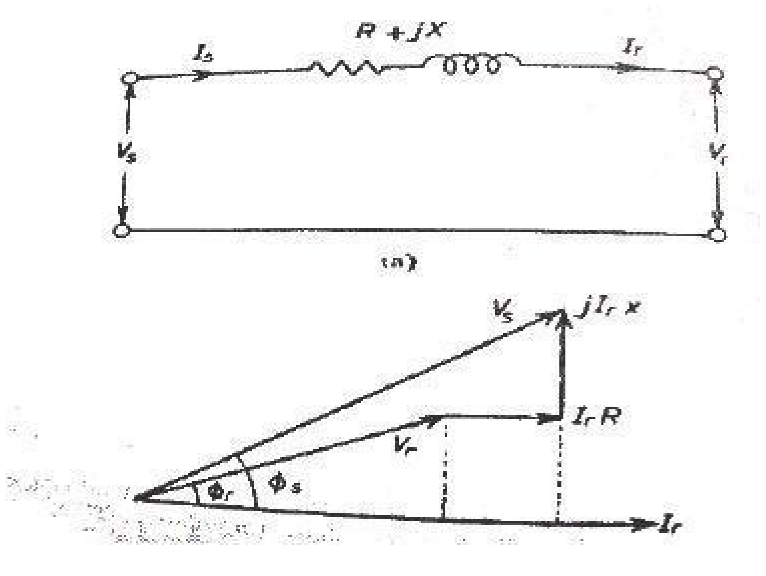
Parameter	Specification	Unit
A = VS / VR	Voltage ratio	Unit less
B = VS / IR	Short circuit resistance	Ω
C = IS / VR	Open circuit conductance	mho
D = IS / IR	Current ratio	Unit less

SHORT TRANSMISSION LINE

The transmission lines which have length less than 80 km are generally referred as **short transmission lines**.

For short length, the shunt capacitance of this type of line is neglected and other parameters like resistance and inductance of these short lines are lumped, hence the equivalent circuit is represented as given below,

Let's draw the vector diagram for this equivalent circuit, taking receiving end current Ir as reference. The sending end and receiving end voltages make angle with that reference receiving end current, of φs and φr, respectively.



As the shunt capacitance of the line is neglected, hence sending end current and receiving end current is same, i.e.

Is = Ir.

Now if we observe the vector diagram carefully, we will
get, Vs is approximately equal to

Vr + Ir.R.cosφr + Ir.X.sinφr

That means,

Vs ≅ Vr + Ir.R.cosφr + Ir.X.sinφr as the it is assumed that φs ≅ φr

As there is no capacitance, during no load condition the current through the line is considered as zero, hence at no load condition, receiving end voltage is the same as sending end voltage

As per dentition of voltage regulation,

$$\% \text{ regulation} = \frac{V_s - V_r}{V_r} \times 100\ \%$$

$$= \frac{I_r.R.\cos\varphi_r + I_r.X.\sin\varphi_r}{V_r} \times 100\ \%$$

$$\text{per unit regulation} = \frac{I_r.R}{V_r}\cos\varphi_r + \frac{I_r.X}{V_r}\sin\varphi_r = v_r\cos\varphi_r + v_x\sin\varphi_r$$

$$A = \left.\frac{V_s}{V_r}\right|_{I_r = 0}$$

Here, vr and vx are the per unit resistance and reactance of the short transmission line.

Any electrical network generally has two input terminals and two output terminals. If we consider any complex electrical network in a black box, it will have two input terminals and output terminals. This network is called two – port network. Two port model of a network simplifies the network solving technique. Mathematically a two port network can be solved by 2 by 2 matrixes.

A transmission as it is also an electrical network; line can be represented as two port network. Hence two port network of transmission line can be represented as 2 by 2 matrixes. Here the concept of ABCD parameters comes. Voltage and currents of the network can represented as ,

Vs= AVr + BIr… ....(1)

Is= CVr + DIr…........... (2)

Where A, B, C and D are different constant of the network.

If we put Ir = 0 at equation (1), we get

Hence, A is the voltage impressed at the sending end per volt at the receiving end when receiving end is open. It is dimension less.

If we put Vr = 0 at equation (1), we get

$$B = \left.\frac{V_s}{I_r}\right|_{V_r = 0}$$

That indicates it is impedance of the transmission line when the receiving terminals are short circuited. This parameter is referred as transfer impedance.

$$C = \left.\frac{I_s}{V_r}\right| I_r = 0$$

C is the current in amperes into the sending end per volt on open circuited receiving end. It has the dimension of admittance.

$$D = \left.\frac{I_s}{I_r}\right| V_r = 0$$

D is the current in amperes into the sending end per amp on short circuited receiving end. It is dimensionless.

Now from equivalent circuit, it is found that,

Vs = Vr + IrZ and Is = Ir

Comparing these equations with equation 1 and 2 we get,

A = 1, B = Z, C = 0 and D = 1. As we know that the constant A, B, C and D are related for passive network as

Here, A = 1, B = Z, C = 0 and D = 1

AD − BC = 1.

⇒ 1.1 − Z.0 = 1

So the values calculated are correct for short transmission line.

From above equation (1),

Vs = AVr + BIr

When Ir = 0 that means receiving end terminals is open circuited and then from the equation 1, we get receiving end voltage at no load

$$V_r' = \frac{V_s}{A}$$

and as per definition of voltage regulation,

$$\%\ \text{voltage regulation} = \frac{V_s / A - V_r}{V_r} X100\ \%$$

Efficiency of Short Transmission Line

The efficiency of short line as simple as efficiency equation of any other electrical equipment, that means

$$\% \text{ efficiency } (\mu) = \frac{\text{Power received at receiving end}}{\text{Power delivered at sending end}} \times 100\ \%$$

$$\% \mu = \frac{\text{Power received at receiving end}}{\text{Power received at receiving end} + 3I_r^2.R} \times 100\ \%$$

MEDIUM TRANSMISSION LINE

The transmission line having its effective length more than 80 km but less than 250 km, is generally referred to as a **medium transmission line**. Due to the line length being considerably high, admittance Y of the network does play a role in calculating the effective circuit parameters, unlike in the case of short transmission lines. For this reason the modelling of a **medium length transmission line** is done using lumped shunt admittance along with the lumped impedance in series to the circuit.

These lumped parameters of a medium length transmission line can be represented using two different models, namely.

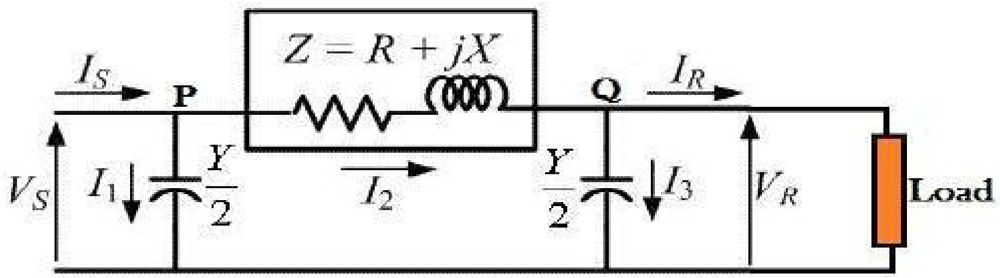
1) Nominal **Π** representation.

2) Nominal **T** representation.

Let's now go into the detailed discussion of these above mentioned models.

Nominal Π representation of a medium transmission line

In case of a nominal **Π** representation, the lumped series impedance is placed at the middle of the circuit where as the shunt admittances are at the ends. As we can see from the diagram of the Π network below, the total lumped shunt admittance is divided into 2 equal halves, and each half with value $Y/2$ is placed at both the sending and the receiving end while the entire circuit impedance is between the two. The shape of the circuit so formed resembles that of a symbol **Π**, and for this reason it is known as the nominal Π representation of a medium transmission line. It is mainly used for determining the general circuit parameters and performing load flow analysis.



Nominal π network of medium transmission line.

As we can see here, VS and VR is the supply and receiving end voltages respectively, and Is is the current flowing through the supply end.

IR is the current flowing through the receiving end of the circuit.

I1 and I3 are the values of currents flowing through the admittances.

And I2 is the current through the impedance Z.

Now applying KCL, at node P, we

get. IS = I1 + I2 ——————(1)

Similarly applying KCL, to node

Q. I2 = I3 + IR ——————(2)

Now substituting equation (2) to equation

(1) IS = I1 + I3 + IR

$$= \frac{Y}{2}V_S + \frac{Y}{2}V_R + I_R \text{---------(3)}$$

Now by applying KVL to the circuit,

VS = VR + Z I2

$$= V_R + Z(V_R\frac{Y}{2} + I_R)$$

$$= (Z\frac{Y}{2} + 1)\,V_R + ZI_R \text{---------(4)}$$

Now substituting equation (4) to equation (3), we get.

$$I_s = \frac{Y}{2}[(\frac{Y}{2}Z + 1)V_R + ZI_R] + \frac{Y}{2}V_R + I_R$$

$$= Y(\frac{Y}{4}Z + 1)V_R + (\frac{Y}{2}Z + 1)I_R \text{-----------(5)}$$

Comparing equation (4) and (5) with the standard ABCD parameter equations

VS = A VR + B IR

IS = C VR + D IR

We derive the parameters of a medium transmission line as:

$$A = (\frac{Y}{2}Z + 1)$$

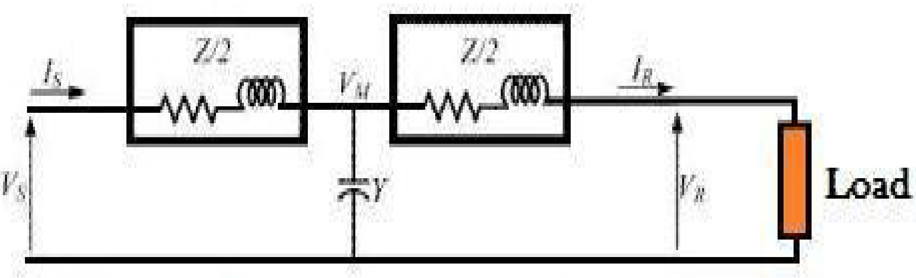
$$B = Z\ \Omega$$

$$C = Y(\frac{Y}{4}Z + 1)$$

$$D = (\frac{Y}{2}Z + 1)$$

Nominal T representation of a medium transmission line

In the **nominal T** model of a medium transmission line the lumped shunt admittance is placed in the middle, while the net series impedance is divided into two equal halves and and placed on either side of the shunt admittance. The circuit so formed resembles the symbol of a capital **T**, and hence is known as the nominal T network of a medium length transmission line and is shown in the diagram below.



Nominal T representation of a medium transmission line.

Here also Vs and Vr is the supply and receiving end voltages respectively, and

Is is the current flowing through the supply end. Ir is the current flowing through the receiving end of the circuit. Let M be a node at the midpoint of the circuit, and the drop at M, be given by

Vm. Applying KVL to the above network we get

$$\frac{V_S - V_M}{Z/2} = Y\,V_M + \frac{V_m - V_R}{Z/2}$$

$$\text{Or } V_M = \frac{2(V_S + V_R)}{YZ + 4} \text{ ----------------(6)}$$

And the receiving end current

$$\text{Or } I_R = \frac{2(V_M - V_R)}{Z/2} \text{ ------------------(7)}$$

Now substituting V_M from equation (6) to (7) we get,

$$\text{Or } I_R = \frac{[(2V_S + V_R)/YZ+4] - V_R}{Z/2}$$

Rearranging the above equation:

$$V_S = (\frac{Y}{2}Z + 1)V_R + Z(\frac{Y}{4}Z + 1)I_R \text{ ----------------(8)}$$

Now the sending end current is

Is = Y VM + IR ——————(9)

Substituting the value of VM to equation (9) we get,

$$\text{Or } I_S = Y\,V_R + (\frac{Y}{2}Z + 1)I_R \text{ ----------------(10)}$$

Again comparing Comparing equation (8) and (10) with the standard ABCD parameter equations

VS = A VR + B IR

IS = C VR + D IR

The parameters of the **T** network of a medium transmission line are

$$A = (\frac{Y}{2}Z + 1)$$

$$B = Z(\frac{Y}{4}Z + 1)\ \Omega$$

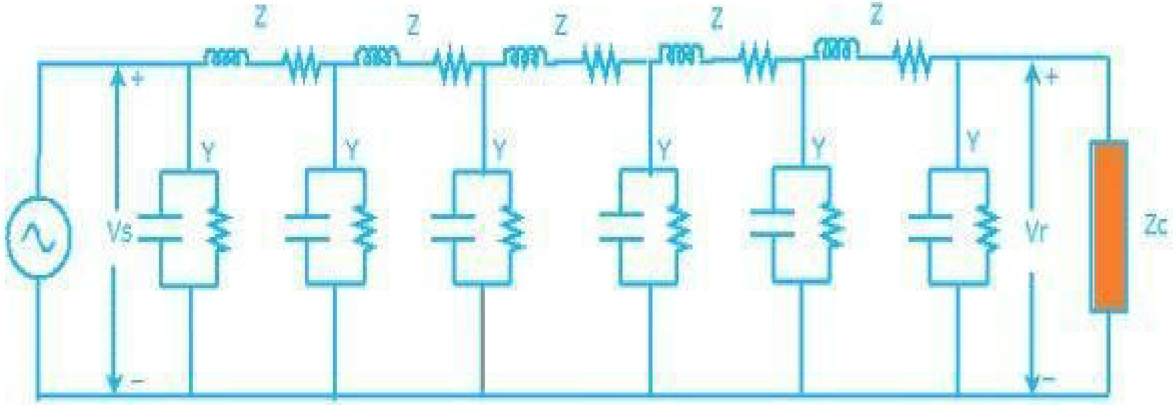
$$C = Y \text{ mho}$$

$$D = (\frac{Y}{2}Z + 1)$$

Performance of Long Transmission Lines

LONG TRANSMISSION LINE

A power transmission line with its effective length of around 250 Kms or above is referred to as a **long transmission line**. Calculations related to circuit parameters (ABCD parameters) of such a power transmission is not that simple, as was the case for a short or medium transmission line. The reason being that, the effective circuit length in this case is much higher than what it was for the former models(long and medium line) and, thus ruling out the approximations considered there like.

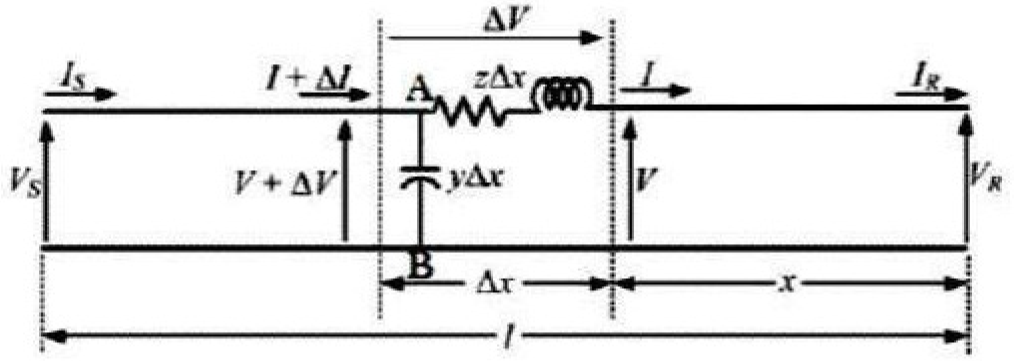


Long Transmission Line model

a) Ignoring the shunt admittance of the network, like in a small transmission line model.
b) Considering the circuit impedance and admittance to be lumped and concentrated at a point as was the case for the medium line model.

Rather, for all practical reasons we should consider the circuit impedance and admittance to be distributed over the entire circuit length as shown in the figure below.

The calculations of circuit parameters for this reason is going to be slightly more rigorous as we will see here. For accurate modeling to determine circuit parameters let us consider the circuit of the **long transmission line** as shown in the diagram below.



Long Transmission Line.

Here a line of length l > 250km is supplied with a sending end voltage and current of VS and IS respectively, where as the VR and IR are the values of voltage and current obtained from the receiving end. Lets us now consider an element of infinitely small length Δx at a distance x from the receiving end as shown in the figure where.

V = value of voltage just before entering the element Δx.

I = value of current just before entering the element Δx.

V+ΔV = voltage leaving the element Δx.

I+ΔI = current leaving the element Δx.

ΔV = voltage drop across element Δx.

zΔx = series impedence of element Δx

yΔx = shunt admittance of element Δx

Where Z = z l and Y = y l are the values of total impedance and admittance of the long transmission line.

∴ the voltage drop across the infinitely small element Δx is given by

$\Delta V = I z \Delta x$

Or $I z = \Delta V / \Delta x$

Or $I z = dV / dx$ ——————————(1)

Now to determine the current ΔI, we apply KCL to node A.

$\Delta I = (V+\Delta V)y\Delta x = V y\Delta x + \Delta V y\Delta x$

Since the term ΔV yΔx is the product of 2 infinitely small values, we can ignore it for the sake of easier calculation.

∴ we can write $dI / dx = V y$ ————————(2)

Now derevating both sides of eq (1) w.r.t x,

$d^2 V / d x^2 = z\, dI / dx$

Now substituting $dI/dx = V\,y$ from equation (2)

$d^2 V/d x^2 = zyV$

or $d^2 V/d x^2 - zyV = 0$ ————(3)

The solution of the above second order differential equation is given by.

$V = A1\, e^{x\sqrt{yz}} + A2\, e^{-x\sqrt{yz}}$ —————(4)

Derivating equation (4) w.r.to x.

$dV/dx = \sqrt{(yz)}\, A1\, e^{x\sqrt{yz}} - \sqrt{(yz)} A2\, e^{-x\sqrt{yz}}$ ————

(5) Now comparing equation (1) with equation (5)

$$I = \frac{dV}{dx} = \frac{zA_1 e^{x\sqrt{(yz)}}}{\sqrt{(z/y)}} - \frac{zA_1 e^{-x\sqrt{(yz)}}}{\sqrt{(z/y)}} \text{----------------(6)}$$

Now to go further let us define the characteristic impedance Zc and propagation constant δ of a long transmission line as

$Zc = \sqrt{(z/y)}$

$\Omega\ \delta = \sqrt{(yz)}$

Then the voltage and current equation can be expressed in terms of characteristic impedance and propagation constant as

$V = A1\, e^{\delta x} + A2\, e^{-\delta x}$ ————(7)

$I = A1/Zc\, e^{\delta x} + A2/Zc\, e^{-\delta x}$ —————(8)

Now at x=0, V= VR and I= Ir. Substituting these conditions to equation (7) and (8) respectively. $VR = A1 + A2$ —————(9)

$IR = A1/Zc + A2/Zc$ —————(10)

Solving equation (9) and (10), We get values of A1 and A2 as,

$A1 = (VR + ZCIR)/2$

And $A1 = (VR - ZCIR)$

Now applying another extreme condition at x=l, we have V = VS and I = IS.

Now to determine VS and IS we substitute x by l and put the values of A1 and A2 in equation (7) and (8) we get

$VS = (VR + ZC\ IR)e^{\delta l}/2 + (VR - ZC\ IR)e^{-\delta l}/2$ —————(11)

$IS = (VR/ZC + IR)e^{\delta l}/2 - (VR/ZC - IR)e^{-\delta l}/2$————— (12

By trigonometric and exponential operators we know

$\sinh \delta l = (e^{\delta l} - e^{-\delta l})/2$

And $\cosh \delta l = (e^{\delta l} + e^{-\delta l})/2$

∴ equation(11) and (12) can be re-written as

$VS = VR\cosh \delta l + ZC\ IR \sinh \delta l$

$IS = (VR \sinh \delta l)/ZC + IR\cosh \delta l$

Thus comparing with the general circuit parameters equation, we get the ABCD parameters of a long transmission line as,

$C = \sinh \delta l / ZC$ $A = \cosh \delta l$ $D = \cosh \delta l$ $B = ZC \sinh \delta l$

Surge Impedance: The **characteristic impedance** or **surge impedance** (usually written Z_0) of a uniform transmission line is the ratio of the amplitudes of voltage and current of a single wave propagating along the line; that is, a wave travelling in one direction in the absence of reflections in the other direction. Characteristic impedance is determined by the geometry and materials of the transmission line and, for a uniform line, is not dependent on its length. The SI unit of characteristic impedance is the ohm.

The characteristic impedance of a lossless transmission line is purely real, with no reactive component. Energy supplied by a source at one end of such a line is transmitted through the line without being dissipated in the line itself. A transmission line of finite length (lossless or lossy) that is terminated at one end with an impedance equal to the characteristic impedance appears to the source like an infinitely long transmission line and produces no reflections.

The surge impedance loading:

The surge impedance loading (SIL) of a line is the power load at which the net reactive power is zero. So, if your transmission line wants to "absorb" reactive power, the SIL is the amount of reactive power you would have to produce to balance it out to zero. You can calculate it by dividing the square of the line-to-line voltage by the line's characteristic impedance. Transmission lines can be considered as, a small inductance in series and a small capacitance to earth, - a very large number of this combinations, in series. Whatever voltage drop occurs

due to inductance gets compensated by capacitance. If this compensation is exact, you have surge impedance loading and no voltage drop occurs for an infinite length or, a finite length terminated by impedance of this value (SIL load). (Loss-less line assumed!). Impedance of this line (Zs) can be proved to be sqrt (L/C). If capacitive compensation is more than required, which may happen on an unloaded EHV line, then you have voltage rise at the other end, the ferranti effect. Although given in many books, it continues to remain an interesting discussion always.

The capacitive reactive power associated with a transmission line increases directly as the square of the voltage and is proportional to line capacitance and length.

Capacitance has two effects:

1 Ferranti effect

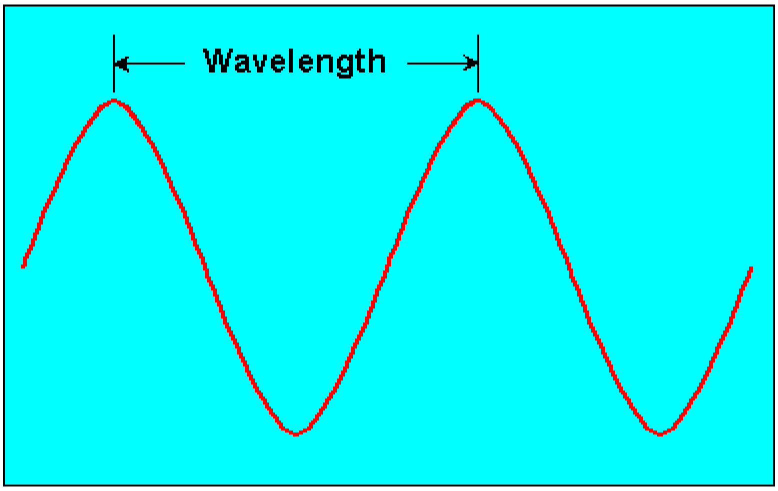
2 rise in the voltage resulting from capacitive current of the line flowing through the source impedances at the terminations of the line.

SIL is Surge Impedance Loading and is calculated as (KV x KV) / Zs their units are megawatts.

Where Zs is the surge impedance....be aware...one thing is the surge impedance and other very different is the surge impedance loading.

Wavelength:

Wavelength is the distance between identical points in the adjacent cycles of a waveform signal propagated in space or along a wire, as shown in the illustration. In wireless systems, this length is usually specified in meters, centimeters, or millimeters. Inthe case of infrared, visible light, ultraviolet, and gamma radiation, the wavelength ismore often specified in nanometers (units of 10^{-9}meter) or Angstrom units(units of 10^{-10} meter).



Wavelength is inversely related to frequency. The higher the frequency of the signal, the shorter the wavelength. If*f* is the frequency of the signal as measured in megahertz, and *w* isthe wavelength as measuredin meters, then

$w = 300/f$ and conversely

$f = 300/w$

Wavelength is sometimes represented by the Greek letter lambda.

Velocity of Propagation:

Velocity of propagation is a measure of how fast a signal travels over time, or the speed of the transmitted signal as compared to the speed of light.

In computer technology, the velocity of propagation of an electrical or electromagnetic signal is the speed of transmission through a physical medium such as a coaxial cable or optical fiber.

There is also a direct relation between velocity of propagation and wavelength. Velocity of propagation is often stated either as a percentage of the speed of light or as time-to distance.

FERRANTI EFFECT

In general practice we know, that for all electrical systems current flows from the region of higher potential to the region of lower potential, to compensate for the potential difference that exists in the system. In all practical cases the sending end voltage is higher than the receiving end, so current flows from the source or the supply end to the load. But Sir S.Z. Ferranti, in the year 1890, came up with an astonishing theory about medium or long distance transmission lines suggesting that in case of light loading or no load operation of transmission system, the receiving end voltage often increases beyond the sending end voltage, leading to a phenomena known as **Ferranti effect in power system**.

Why Ferranti effect occurs in a transmission line?

A long transmission line can be considered to composed a considerably high amount of capacitance and inductance distributed across the entire length of the line. Ferranti Effect occurs when current drawn by the distributed capacitance of the line itself is greater than the current associated with the load at the receiving end of the line(during light or no load). This capacitor charging current leads to voltage drop across the line inductance of the transmission system which is in phase with the sending end voltages. This voltage drop keeps on increasing additively as we move towards the load end of the line and subsequently the receiving end voltage tends to get larger than applied voltage leading to the phenomena called Ferranti effect in power system. It is illustrated with the help of a phasor diagram below.

Thus both the capacitance and inductance effect of transmission line are equally responsible for this particular phenomena to occur, and hence Ferranti effect is negligible in case of a short transmission lines as the inductance of such a line is practically considered to be nearing zero. In general for a 300 Km line operating at a frequency of 50 Hz, the no load receiving end voltage has been found to be 5% higher than the sending end voltage.

Now for analysis of Ferranti effect let us consider the phasor diagrame shown above.

Here Vr is considered to be the reference phasor, represented by OA.

Thus $V_r = V_r (1 + j0)$

Capacitance current, $I_c = j\omega C V_r$

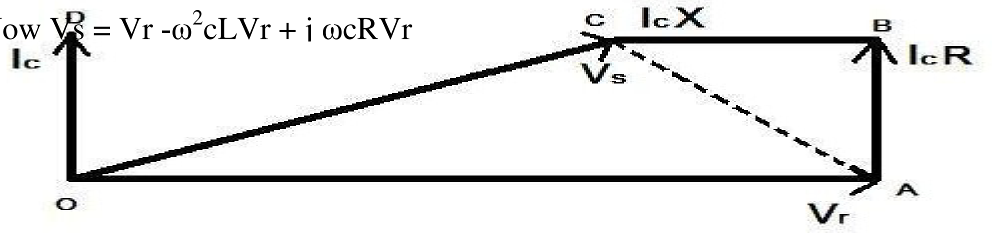
Now sending end voltage $V_s = V_r$ + resistive drop + reactive drop.

$= Vr + IcR + jIcX$

$= Vr + Ic (R + jX)$

$= Vr + j\omega cVr (R + j\omega L)$ [since $X = \omega L$]

Now $Vs = Vr - \omega^2 cLVr + j\, \omega cRVr$



Ferranti effect in transmission lines.

This is represented by the phasor OC.

Now in case of a long transmission line, it has been practically observed that the line resistance is negligibly small compared to the line reactance, hence we can assume the length of the phasor Ic R = 0, we can consider the rise in the voltage is only due to OA – OC = reactive drop in the line.

Now if we consider c0 and L0 are the values of capacitance and inductance per km of the transmission line, where l is the length of the line.

Thus capacitive reactance $Xc = 1/(\omega\, l\, c0)$

Since, in case of a long transmission line the capacitance is distributed throughout its length, the average current flowing is,

$Ic = {}^1/2\ Vr/Xc = {}^1/2\ Vr\omega\, l\, c0$

Now the inductive reactance of the line $= \omega\, L0\, l$

Thus the rise in voltage due to line inductance is given by,

$IcX = {}^1/2 Vr\omega\, l\, c0 \ X\ \omega\, L0\, l$

Voltage rise $= {}^1/2\ Vr\omega^2\, l^2\, c0L0$

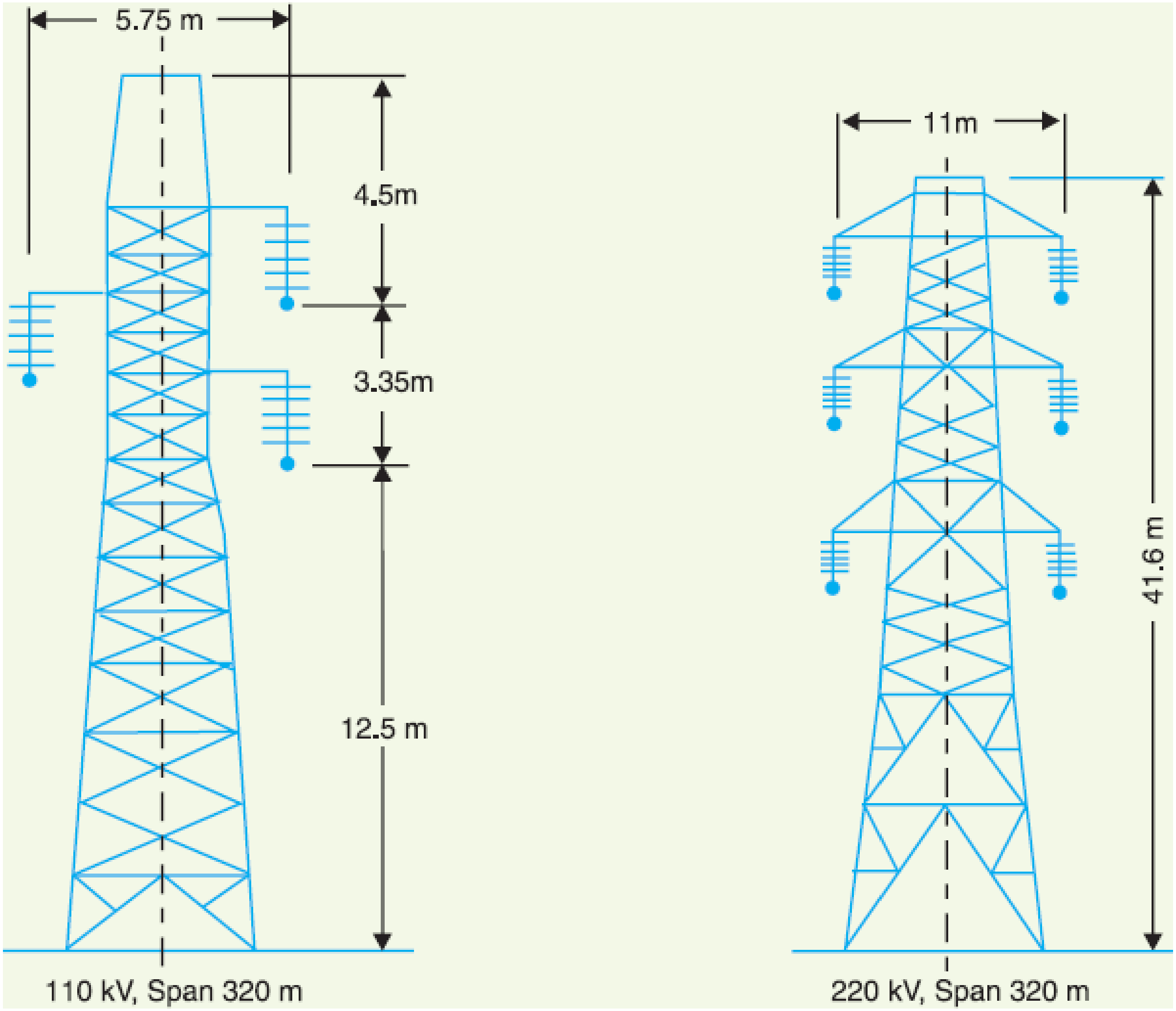
From the above equation it is absolutely evident, that the rise in voltage at the receiving end is directly proportional to the square of the line length, and hence in case of a long transmission line it keeps increasing with length and even goes beyond the applied sending end voltage at times, leading to the phenomena called Ferranti effect in power system.

Module-III

MECHANICAL DESIGN OF TRANSMISSION LINES

Insulators

The overhead line conductors should be supported on the poles or towers in such a way that currents from conductors do not flow to earth through supports *i.e.*, line conductors must be properly insulated from supports. This is achieved by securing line conductors to supports with the help of *insulators*. The insulators provide necessary insulation between line conductors and supports and thus prevent any leakage current from conductors to earth. In general, the insulators should have the following desirable properties :



(i) High mechanical strength in order to withstand conductor load, wind load etc.

(ii) High electrical resistance of insulator material in order to avoid leakage currents to earth.

(iii) High relative permittivity of insulator material in order that dielectric strength is high.

(iv) The insulator material should be non-porous, free from impurities and cracks otherwise the permittivity will be lowered.

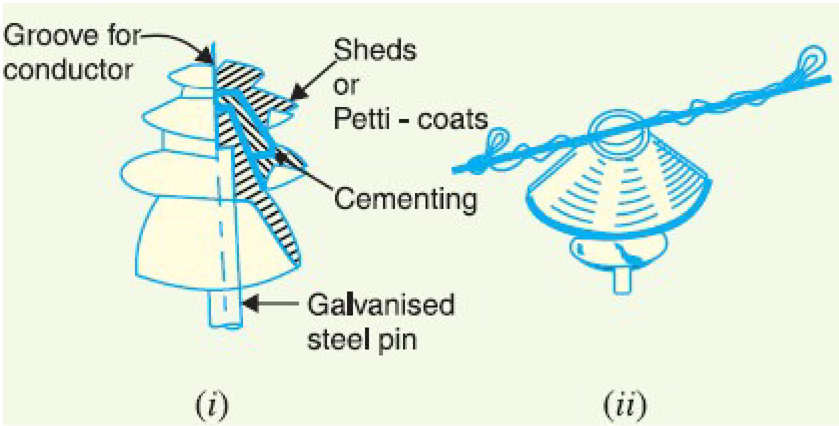
(v) High ratio of puncture strength to flashover.

The most commonly used material for insulators of overhead line is *porcelain* but glass, steatite and special composition materials are also used to a limited extent. Porcelain is produced by firing at a high temperature a mixture of kaolin, feldspar and quartz. It is stronger mechanically than glass, gives less trouble from leakage and is less effected by changes of temperature.

Types of Insulators

The successful operation of an overhead line depends to a considerable extent upon the proper selection of insulators. There are several types of insulators but the most commonly used are pin type, suspension type, strain insulator and shackle insulator.

1. Pin type insulators. The part section of a pin type insulator is shown in Fig. As the name suggests, the pin type insulator is secured to the cross-arm on the pole. There is a groove on the upper end of the insulator for housing the conductor. The conductor passes through this groove and is bound by the annealed wire of the same material as the conductor Pin type insulators are used for transmission and distribution of electric power at voltages upto 33 kV. Beyond operating voltage of 33 kV, the pin type insulators become too bulky and hence uneconomical.



Causes of insulator failure. Insulators are required to withstand both mechanical and electrical stresses. The latter type is pirmarily due to line voltage and may cause the breakdown of the insulator. The electrical breakdown of the insulator can occur either by *flash-over* or *puncture.* In flashover, an arc occurs between the line conductor and insulator pin (*i.e*., earth) and the discharge jumps across the *air gaps, following shortest distance.

Fig. shows the arcing distance (*i.e.* $a + b + c$) for the insulator. In case of flash-over, the insulator will continue to act in its proper capacity unless extreme heat produced by the arc destroys the insulator. In case of puncture, the discharge occurs from conductor to pin through the body of the insulator. When such breakdown is involved, the insulator is permanently destroyed due to excessive heat. In practice, sufficient thickness of porcelain is provided in the insulator to avoid puncture by the line voltage. The ratio of puncture strength to flashover voltage is known as safety factor *i.e.,*

$$\text{Safety factor of insulator} = \frac{\text{Puncture strength}}{\text{Flash-over voltage}}$$

It is desirable that the value of safety factor is high so that flash-over takes place before the insulator gets punctured. For pin type insulators, the value of safety factor is about 10.

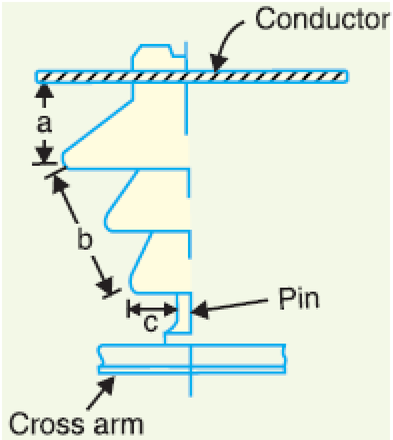
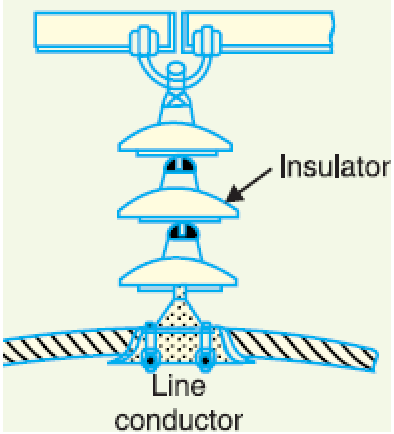


Fig. 8.6



2 Suspension type insulators. The cost of pin type insulator increases rapidly as the working voltage is increased. Therefore, this type of insulator is not economical beyond 33 kV. For high voltages (>33 kV), it is a usual practice to use suspension type insulators shown in Fig. . They consist of a number of porcelain discs connected in series by metal links in the form of a string. The conductor is suspended at the bottom end of this string while the other end of the string is secured to the cross-arm of the tower. Each unit or disc is designed for low voltage, say 11 kV. The number of discs in series would obviously depend upon the working voltage. For instance, if the working voltage is 66 kV, then six discs in series will be provided on the string.

Advantages

(i) Suspension type insulators are cheaper than pin type insulators for voltages beyond 33 kV.

(ii) Each unit or disc of suspension type insulator is designed for low voltage,usually 11 kV.

Depending upon the working voltage, the desired number of discs can be connected in series.

(iii) If any one disc is damaged, the whole string does not become useless because the damaged disc can be replaced by the sound one.

(iv) The suspension arrangement provides greater flexibility to the line. The connection at the cross arm is such that insulator string is free to swing in any direction and can take up the position where mechanical stresses are minimum.

(v) In case of increased demand on the transmission line, it is found more satisfactory to supply the greater demand by raising the line voltage than to provide another set of conductors. The additional insulation required for the raised voltage can be easily obtained in the suspension

arrangement by adding the desired number of discs.

(vi) The suspension type insulators are generally used with steel towers. As the conductors run below the earthed cross-arm of the tower, therefore, this arrangement provides partial protection from lightning.

3. Strain insulators. When there is a dead end of the line or there is corner or sharp curve, the line is subjected to greater tension. In order to relieve the line of excessive tension, strain insulators are used. For low voltage lines (< 11 kV), shackle insulators are used as strain insulators. However,

for high voltage transmission lines, strain insulator consists of an assembly of suspension insulators as shown in Fig. The discs of strain insulators are used in the vertical plane. When the tension in lines is exceedingly high, as at long river spans, two or more strings are used in parallel.

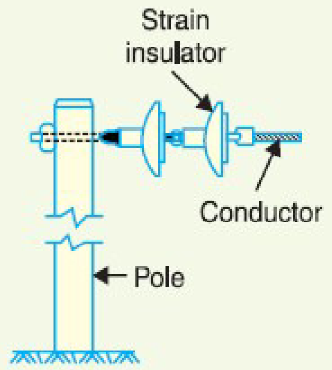


Fig. 8.8. Strain insulator.

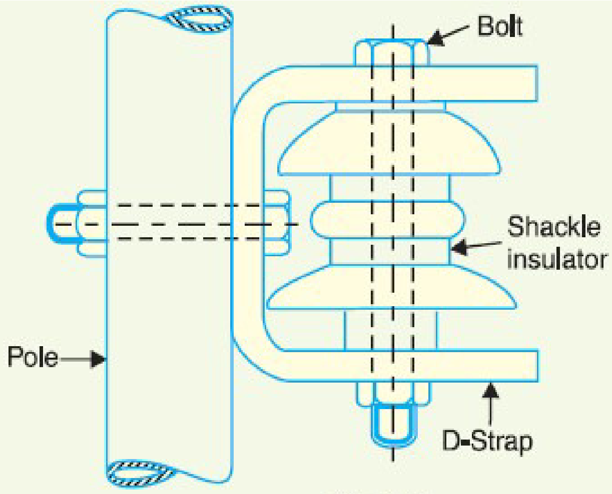


Fig. 8.9

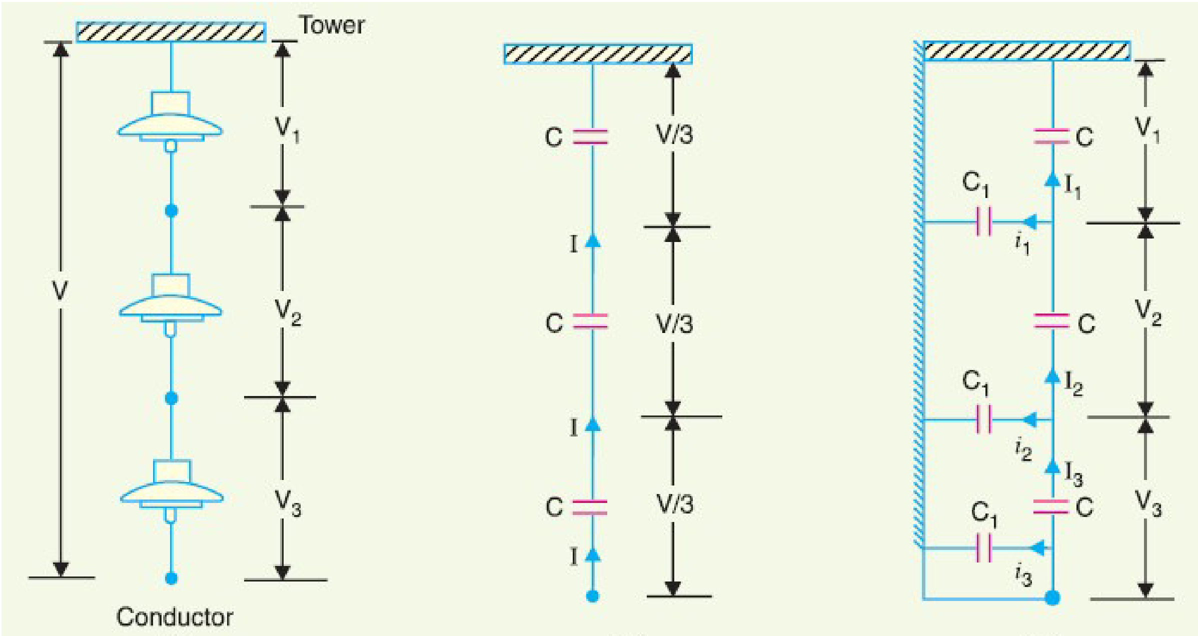
4. Shackle insulators. In early days, the shackle insulators were used as strain insulators. But now a days, they are frequently used for low voltage distribution lines. Such insulators can be used either in a horizontal position or in a vertical position. They can be directly fixed to the pole with a bolt or to the cross arm. Fig. shows a shackle insulator fixed to the pole. The conductor in the groove is fixed with a soft binding wire.

Potential Distribution over Suspension Insulator String

A string of suspension insulators consists of a number of porcelain discs connected in series through metallic links. Fig. (*i*) shows 3-disc string of suspension insulators. The porcelain portion of each disc is inbetween two metal links. Therefore, each disc forms acapacitor *C* as shown in Fig. (*ii*). This is known as *mutual capacitance* or *self-capacitance*.

If there were mutual capacitance alone, then charging current would have been the same through all the discs and consequently voltage across each unit would have been the same *i.e.,* $V/3$ as shown in Fig. (*ii*). However, in actual practice, capacitance also exists between metal fitting of each disc and tower or earth. This is known as *shunt capacitance* $C1$. Due to shunt capacitance, charging current is not the same through all the discs of the string [See Fig. (*iii*)].

Therefore, voltage across each disc will be different. Obviously, the disc nearest to the line conductor will have the maximum voltage. Thus referring to Fig.(*iii*), $V3$ will be much more than $V2$or$V1$.



(*i*) (*ii*) (*iii*)

The following points may be noted regarding the potential distribution over a string of suspension insulators :

(i) The voltage impressed on a string of suspension insulators does not distribute itself uniformly across the individual discs due to the 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. Therefore, means must be provided to equalise the potential across each unit. This is fully discussed in Art. 8.8.

(iv) If the voltage impressed across the string were d.c., then voltage across each unit would be the same. It is because insulator capacitances are ineffective for d.c.

String Efficiency

As stated above, the voltage applied across the string of suspension insulators is not uniformly distributed across various units or discs. The disc nearest to the conductor has much higher potential than the other discs. This unequal potential distribution is undesirable and is usually expressed in terms of string efficiency.

The ratio of voltage across the whole string to the product of number of discs and the voltage across the disc nearest to the conductor is known as **string efficiency** *i.e.,*

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

where n = number of discs in the string.

String efficiency is an important consideration since it decides the potential distribution along the string. The greater the string efficiency, the more uniform is the voltage distribution. Thus 100% string efficiency is an ideal case for which the volatge across each disc will be exactly the same. Although it is impossible to achieve 100% string efficiency, yet efforts should be made to improve it as close to this value as possible.

Mathematical expression. Fig. 8.11 shows the equivalent circuit for a 3-disc string. Let us suppose that self capacitance of each disc is C. Let us further assume that shunt capacitance C_1 is some fraction K of self-capacitance *i.e.*, $C_1 = KC$. Starting from the cross-arm or tower, the voltage across each unit is V_1, V_2 and V_3 respectively as shown.

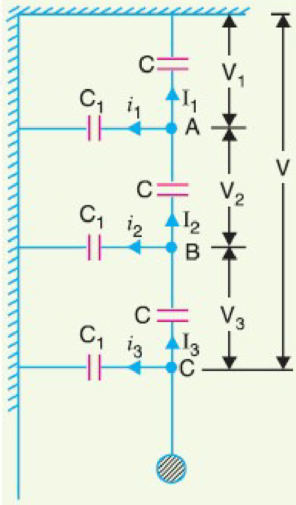


Fig. 8.11

Applying Kirchhoff's current law to node A, we get,

$$I_2 = I_1 + i_1$$

or $$V_2 \omega C^* = V_1 \omega C + V_1 \omega C_1$$

or $$V_2 \omega C = V_1 \omega C + V_1 \omega K C$$

$\therefore$ $$V_2 = V_1 (1 + K) \quad ...(i)$$

Applying Kirchhoff's current law to node B, we get,

$$I_3 = I_2 + i_2$$

or $$V_3 \omega C = V_2 \omega C + (V_1 + V_2) \omega C_1 \dagger$$

or $$V_3 \omega C = V_2 \omega C + (V_1 + V_2) \omega K C$$

or $$V_3 = V_2 + (V_1 + V_2) K$$

$$= KV_1 + V_2 (1 + K)$$

$$= KV_1 + V_1 (1 + K)^2 \quad [\because V_2 = V_1 (1 + K)]$$

$$= V_1 [K + (1 + K)^2]$$

$\therefore$ $$V_3 = V_1 [1 + 3K + K^2] \quad ...(ii)$$

Voltage between conductor and earth (*i.e.*, tower) is

$$V = V_1 + V_2 + V_3$$

$$= V_1 + V_1 (1 + K) + V_1 (1 + 3K + K^2)$$

$$= V_1 (3 + 4K + K^2)$$

$\therefore$ $$V = V_1 (1 + K)(3 + K) \quad ...(iii)$$

From expressions (*i*), (*ii*) and (*iii*), we get,

$$\frac{V_1}{1} = \frac{V_2}{1 + K} = \frac{V_3}{1 + 3K + K^2} = \frac{V}{(1 + K)(3 + K)} \quad ...(iv)$$

$\therefore$ Voltage across top unit, $$V_1 = \frac{V}{(1 + K)(3 + K)}$$

Voltage across second unit from top, $V_2 = V_1 (1 + K)$

Voltage across third unit from top, $V_3 = V_1 (1 + 3K + K^2)$

$$\text{\%age String efficiency} = \frac{\text{Voltage across string}}{n \times \text{Voltage across disc nearest to conductor}} \times 100$$

$$= \frac{V}{3 \times V_3} \times 100$$

The following points may be noted from the above mathematical analysis :

(i) If $K = 0{\cdot}2$ (Say), then from exp. (*iv*), we get, $V2 = 1{\cdot}2\ V1$ and $V3 = 1{\cdot}64\ V1$. This clearly shows that disc nearest to the conductor has maximum voltage across it; the voltage across other discs decreasing progressively as the cross-arm in approached.

(ii) The greater the value of K (= $C1/C$), the more non-uniform is the potential across the discs and lesser is the string efficiency.

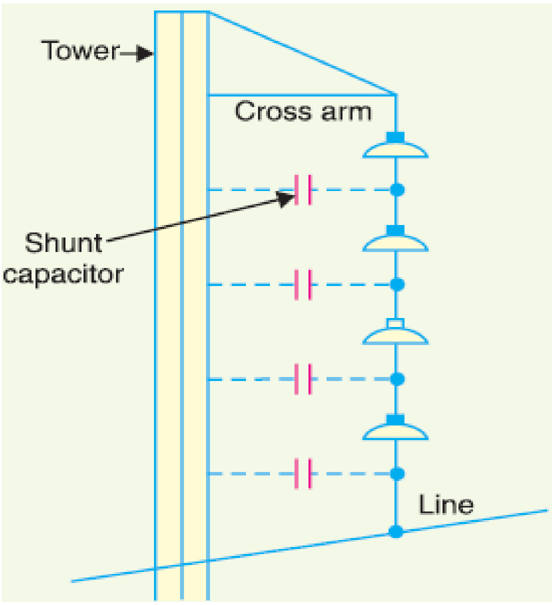
(iii) The inequality in voltage distribution increases with the increase of number of discs in the string. Therefore, shorter string has more efficiency than the larger one.

Methods of Improving String Efficiency

It has been seen above that potential distribution in a string of suspension insulators is not uniform. The maximum voltage appears across the insulator nearest to the line conductor and decreases progressively as the cross arm is approached. If the insulation of the highest stressed insulator (*i.e.* nearest to conductor) breaks down or flash over takes place, the breakdown of other units will take place in succession. This necessitates to equalise the potential across the various units of the string *i.e.* to improve the string efficiency. The various methods for this purpose are :

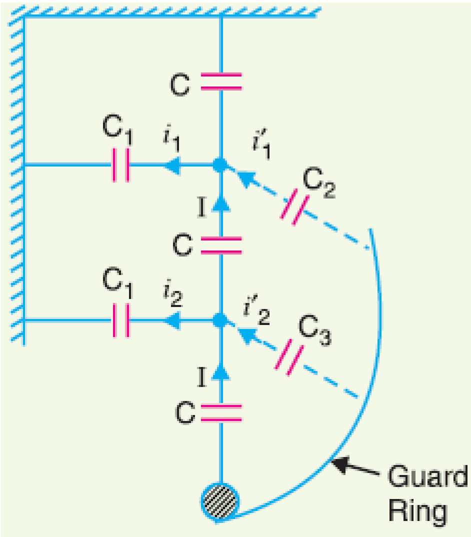
(i) ***By using longer cross-arms*****. The value of string efficiency**

depends upon the value of *K i.e.*, ratio of shunt capacitance to mutual capacitance. The lesser the value of *K*, the greater is the string efficiency and more uniform is the voltage distribution. The value of *K* can be decreased by reducing the shunt capacitance. In order to reduce shunt capacitance, the distance of conductor from tower must be increased *i.e.,* longer cross-arms should be used. However, limitations of cost and strength of tower do not allow the use of very long cross-arms. In practice, $K = 0{\cdot}1$ is the limit that can be achieved by this method.



(ii) ***By grading the insulators***. In this method, insulators of different dimensions are so chosen that each has a different capacitance. The insulators are capacitance graded *i.e.* they are assembled in the string in such a way that the top unit has the minimum capacitance, increasing progressively as the bottom unit (*i.e.,* nearest to conductor) is reached. Since voltage is inversely proportional to capacitance, this method tends to equalise the potential distribution across the units in the string. This method has the disadvantage that a large number of different-sized insulators are required. However, good results can be obtained by using standard insulators for most of the string and larger units for that near to the line conductor.

(iii) *By using a guard ring*. The potential across each unit in a string can be equalised by using a guard ring which is a metal ring electrically connected to the conductor and surrounding the bottom insulator as shown in the Fig. The guard ring introduces capacitance between metal fittings and the line conductor. The guard ring is contoured in such a way that shunt capacitance currents $i1$, $i2$ etc. are equal to metal fitting line capacitance currents $i21$, $i22$ etc. The result is that same charging current I flows through each unit of string. Consequently, there will be uniform potential distribution across the units.



Important Points

While solving problems relating to string efficiency, the following points must be kept in mind:

(i) The maximum voltage appears across the disc nearest to the conductror (*i.e.,* line conductor).

(ii) The voltage across the string is equal to phase voltage *i.e.,* Voltage across string = Voltage between line and earth = Phase Voltage

(iii) Line Voltage = 3 √ Voltage across string

CORONA

Electric-power transmission practically deals in the bulk transfer of electrical energy, from generating stations situated many kilometers away from the main consumption centers or the cities. For this reason the long distance transmission cables are of utmost necessity for effective power transfer, which in-evidently results in huge losses across the system. Minimizing those has been a major challenge for power engineers of late and to do that one should have a clear understanding of the type and nature of losses. One of them being the **corona effect in power system**, which has a predominant role in reducing the efficiency of EHV(extra high voltage lines) which we are going to concentrate on, in this article.

What is corona effect in power system and why it occurs?

For corona effect to occur effectively, two factors here are of prime importance as mentioned below:-

1) Alternating potential difference must be supplied across the line.

2) The spacing of the conductors, must be large enough compared to the line diameter.

Corona Effect in Transmission Line

When an alternating current is made to flow across two conductors of the transmission line whose spacing is large compared to their diameters, then air surrounding the conductors (composed of ions) is subjected to di-electric stress. At low values of supply end voltage, nothing really occurs as the stress is too less to ionize the air outside. But when the potential difference is made to increase beyond some threshold value of around 30 kV known as the critical disruptive voltage, then the field strength increases and then the air surrounding it experiences stress high enough to be dissociated into ions making the atmosphere conducting. This results in electric discharge around the conductors due to the flow of these ions, giving rise to a faint luminescent glow, along with the hissing sound accompanied by the liberation of ozone, which is readily identified due to its characteristic odor. This phenomena of electrical discharge occurring in transmission line for high values of voltage is known as the **corona effect in power system**. If the voltage across the lines is still increased the glow becomes more and more intense along with hissing noise, inducing very high power loss into the system which must be accounted for.

Factors Affecting Corona

The phenomenon of corona is affected by the physical state of the atmosphere as well as by the conditions of the line. The following are the factors upon which corona depends :

(i) ***Atmosphere***. As corona is formed due to ionsiation of air surrounding the conductors, therefore, it is affected by the physical state of atmosphere. In the stormy weather, the number of ions is more than normal and as such corona occurs at much less voltage as compared with fair weather.

(ii) ***Conductor size.*** The corona effect depends upon the shape and conditions of the conductors. The rough and irregular surface will give rise to more corona because unevenness ofthe surface decreases the value of breakdown voltage. Thus a stranded conductor has irregular surface and hence gives rise to more corona that a solid conductor.

(iii) ***Spacing between conductors.*** If the spacing between the conductors is made very large as compared to their diameters, there may not be any corona effect. It is because larger distance between conductors reduces the electro-static stresses at the conductor surface, thus avoiding corona formation.

(iv) ***Line voltage***. The line voltage greatly affects corona. If it is low, there is no change in the condition of air surrounding the conductors and hence no corona is formed. However, if the line voltage has such a value that electrostatic stresses developed at the conductor surface make the air around the conductor conducting, then corona is formed.

Important Terms

The phenomenon of corona plays an important role in the design of an overhead transmission line. Therefore, it is profitable to consider the following terms much used in the analysis of corona effects:

(*i*) Critical disruptive voltage. *It is the minimum phase-neutral voltage at which corona occurs.* Consider two conductors of radii *r* cm and spaced *d* cm apart. If *V* is the phase-neutral potential, then potential gradient at the conductor surface is given by:

$$g = \frac{V}{r \log_e \frac{d}{r}} \text{ volts / cm}$$

In order that corona is formed, the value of *g* must be made equal to the breakdown strength of air. The breakdown strength of air at 76 cm pressure and temperature of 25ºC is 30 kV/cm (*max*) or 21·2 kV/cm (*r.m.s.*) and is denoted by *go*. If *Vc* is the phase-neutral potential required under these conditions, then,

$$g_o = \frac{V_c}{r \log_e \frac{d}{r}}$$

where g_o = breakdown strength of air at 76 cm of mercury and 25°C = 30 kV/cm (*max*) or 21·2 kV/cm (*r.m.s.*)

$$\therefore \text{ Critical disruptive voltage, } V_c = g_o \, r \log_e \frac{d}{r}$$

The above expression for disruptive voltage is under standard conditions *i.e.,* at 76 cm of Hg and 25ºC. However, if these conditions vary, the air density also changes, thus altering the value of *go*. The value of *go* is directly proportional to air density. Thus the breakdown strength of air at a barometric pressure of *b* cm of mercury and temperature of *t*ºC becomes *go* where

$$\delta = \text{air density factor} = \frac{3 \cdot 92b}{273 + t}$$

Under standard conditions, the value of $\delta = 1$.

$$\therefore \quad \text{Critical disruptive voltage}, \quad V_c = g_o \, \delta \, r \log_e \frac{d}{r}$$

Correction must also be made for the surface condition of the conductor. This is accounted for by multiplying the above expression by irregularity factor m_o.

$$\therefore \text{Critical disruptive voltage,} \quad V_c = m_o g_o \, \delta \, r \log_e \frac{d}{r} \text{ kV/phase}$$

where m_o = 1 for polished conductors
= 0·98 to 0·92 for dirty conductors
= 0·87 to 0·8 for stranded conductors

(*ii*) Visual critical voltage. *It is the minimum phase-neutral voltage at which corona glow appears all along the line conductors.*

It has been seen that in case of parallel conductors, the corona glow does not begin at the disruptive voltage V_c but at a higher voltage V_v, called *visual critical voltage.* The phase-neutral effective value of visual critical voltage is given by the following empirical formula :

$$V_v = m_v g_o \, \delta \, r \left(1 + \frac{0 \cdot 3}{\sqrt{\delta \, r}}\right) \log_e \frac{d}{r} \text{ kV/phase}$$

where m_v is another irregularity factor having a value of 1·0 for polished conductors and 0·72 to 0·82 for rough conductors.

(*iii*) Power loss due to corona. Formation of corona is always accompanied by energy loss which is dissipated in the form of light, heat, sound and chemical action. When disruptive voltage is exceeded, the power loss due to corona is given by :

$$P = 242 \cdot 2 \left(\frac{f + 25}{\delta}\right) \sqrt{\frac{r}{d}} \, (V - V_c)^2 \times 10^{-5} \text{ kW / km / phase}$$

where f = supply frequency in Hz
V = phase-neutral voltage (*r.m.s.*)
V_c = disruptive voltage (*r.m.s.*) per phase

Advantages and Disadvantages of Corona

Corona has many advantages and disadvantages. In the correct design of a high voltage overhead line, a balance should be struck between the advantages and disadvantages.

Advantages

(i) Due to corona formation, the air surrounding the conductor becomes conducting and hence virtual diameter of the conductor is increased. The increased diameter reduces the electrostatic stresses between the conductors.

(ii) Corona reduces the effects of transients produced by surges.

Disadvantages

(i) Corona is accompanied by a loss of energy. This affects the transmission efficiency of the line.

(ii) Ozone is produced by corona and may cause corrosion of the conductor due to chemical action.

(iii) The current drawn by the line due to corona is non-sinusoidal and hence non-sinusoidal voltage drop occurs in the line. This may cause inductive interference with neighbouring communication lines.

Methods of Reducing Corona Effect

It has been seen that intense corona effects are observed at a working voltage of 33 kV or above. Therefore, careful design should be made to avoid corona on the sub-stations or bus-bars rated for 33 kV and higher voltages otherwise highly ionised air may cause flash-over in the insulators or between the phases, causing considerable damage to the equipment. The corona effects can be reduced by the following methods :

(i) *By increasing conductor size.* By increasing conductor size, the voltage at which corona occurs is raised and hence corona effects are considerably reduced. This is one of the reasons that *ACSR* conductors which have a larger cross-sectional area are used in transmission lines.

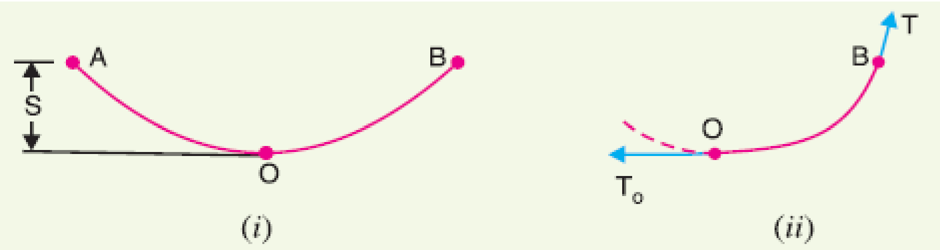
(ii) *By increasing conductor spacing.* By increasing the spacing between conductors, the voltage at which corona occurs is raised and hence corona effects can be eliminated. However, spacing cannot be increased too much otherwise the cost of supporting structure (*e.g.,* bigger cross arms and supports) may increase to a considerable extent.

Sag in Overhead Lines:

While erecting an overhead line, it is very important that conductors are under safe tension. If the conductors are too much stretched between supports in a bid to save conductor material, the stress in the conductor may reach unsafe value and in certain cases 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.**

Fig. shows a conductor suspended between two equilevel supports *A* and *B*. The conductoris not fully stretched but is allowed to have a dip. The lowest point on the conductor is *O* and the sag is *S*. The following points may be noted :



(i) When the conductor is suspended between two supports at the same level, it takes the shape of catenary. However, if the sag is very small compared with the span, then sag-span curve is like a parabola.

(ii) The tension at any point on the conductor acts tangentially. Thus tension *TO* at the lowest point *O* acts horizontally as shown in Fig.(*ii*).

(iii) The horizontal component of tension is constant throughout the length of the wire.

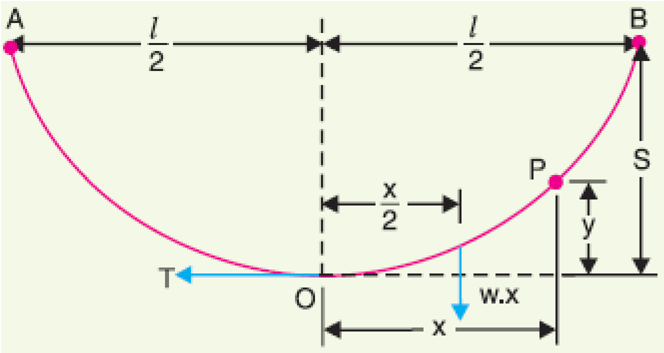
(iv) The tension at supports is approximately equal to the horizontal tension acting at any point on the wire. Thus if *T* is the tension at the support *B*, then *T* = *TO*.

Conductor sag and tension. This is an important consideration in the mechanical design of overhead lines. The conductor sag should be kept to a minimum in order to reduce the conductor material required and to avoid extra pole height for sufficient clearance above ground level. It is also desirable that tension in the conductor should be low to avoid the mechanical failure of conductor and to permit the use of less strong supports. However, low conductor tension and minimum sag are not possible. It is because low sag means a tight wire and high tension, whereas a low tension means a loose wire and increased sag. Therefore, in actual practice, a compromise in made between the two.

8.16 Calculation of Sag

In an overhead line, the sag should be so adjusted that tension in the conductors is within safe limits. The tension is governed by conductor weight, effects of wind, ice loading and temperature variations. It is a standard practice to keep conductor tension less than 50% of its ultimate tensile strength *i.e.,* minimum factor of safety in respect of conductor tension should be 2. We shall now calculate sag and tension of a conductor when (*i*) supports are at equal levels and (*ii*) supports are at unequal levels.

(i) When supports are at equal levels. Consider a conductor between two equilevel supports *A* and *B* with *O* as the lowest point as shown in Fig. It can be proved that lowest point will be at the mid-span.



Let

l = Length of span

w = Weight per unit length of conductor

T = Tension in the conductor.

Consider a point P on the conductor. Taking the lowest point O as the origin, let the co-ordinates of point P be x and y. Assuming that the curvature is so small that curved length is equal to its horizontal projection (*i.e.*, $OP = x$), the two forces acting on the portion OP of the conductor are :

(a) The weight wx of conductor acting at a distance $x/2$ from o

(b) The tension T acting at O.

Equating the moments of above two forces about point O, we get,

$$Ty = wx \times \frac{x}{2}$$

or $$y = \frac{wx^2}{2T}$$

The maximum dip (sag) is represented by the value of y at either of the supports A and B.

At support A, $x = l/2$ and $y = S$

$$\therefore \quad \text{Sag, } S = \frac{w(l/2)^2}{2T} = \frac{wl^2}{8T}$$

(ii) When supports are at unequal levels. In hilly areas, we generally come across conductors suspended between supports at unequal levels. Fig. shows a conductor suspended between two supports A and B which are at different levels. The lowest point on the conductor is O.

Let

l = Span length

h = Difference in levels between two supports

$x1$ = Distance of support at lower level (*i.e.*, A) from O

$x2$ = Distance of support at higher level (*i.e.* B) from O

T = Tension in the conductor

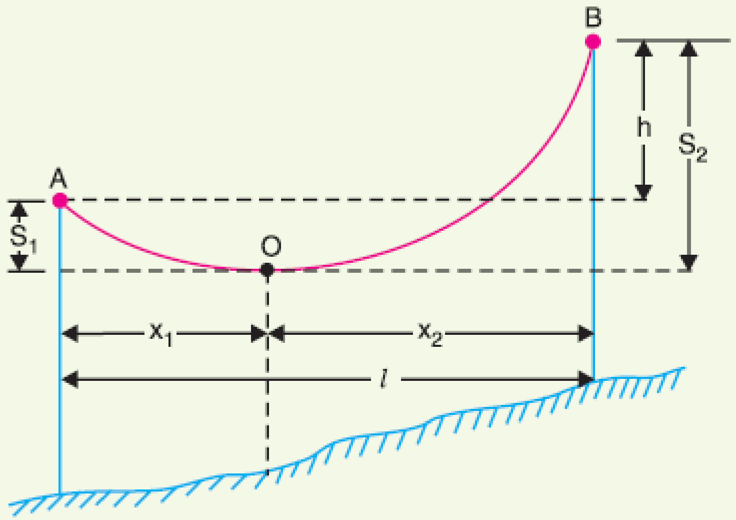


Fig. 8.25

If w is the weight per unit length of the conductor, then,

$$\text{Sag } S_1 = \frac{w\, x_1^{2*}}{2T}$$

and $$\text{Sag } S_2 = \frac{w\, x_2^{2}}{2T}$$

Also $$x_1 + x_2 = l$$

Now $$S_2 - S_1 = \frac{w}{2T}[x_2^2 - x_1^2] = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

$$\therefore \quad S_2 - S_1 = \frac{w\,l}{2T}(x_2 - x_1) \qquad [\because x_1 + x_2 = l]$$

But $$S_2 - S_1 = h$$

$$\therefore \quad h = \frac{w\,l}{2T}(x_2 - x_1)$$

or $$x_2 - x_1 = \frac{2\,Th}{w\,l} \qquad ...(ii)$$

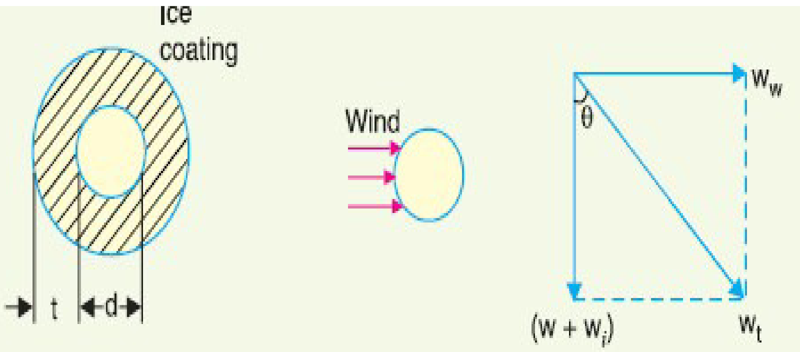
Solving exps. (*i*) and (*ii*), we get,

$$x_1 = \frac{l}{2} - \frac{T\,h}{w\,l}$$

$$x_2 = \frac{l}{2} + \frac{T\,h}{w\,l}$$

Having found $x1$ and $x2$, values of $S1$ and $S2$ can be easily calculated.

Effect of wind and ice loading. The above formulae for sag are true only in still air and at normal temperature when the conductor is acted by its weight only. However, in actual practice, a conductor may have ice coating and simultaneously subjected to wind pressure. The weight of ice acts vertically downwards *i.e.*, in the same direction as the weight of conductor. The force due to the wind is assumed to act horizontally *i.e.*, at right angle to the projected surface of the conductor. Hence, the total force on the conductor is the vector sum of horizontal and vertical forces as shown in Fig. (*iii*).



(i) (ii) (iii)

Fig. 8.26

Total weight of conductor per unit length is

$$w_t = \sqrt{(w + w_i)^2 + (w_w)^2}$$

where w = weight of conductor per unit length

= conductor material density × volume per unit length

w_i = weight of ice per unit length

= density of ice × volume of ice per unit length

$= \text{density of ice} \times \frac{\pi}{4}[(d+2t)^2 - d^2] \times 1$

$= \text{density of ice} \times \pi\, t\,(d+t)$*

w_w = wind force per unit length

= wind pressure per unit area × projected area per unit length

$= \text{wind pressure} \times [(d+2t) \times 1]$

When the conductor has wind and ice loading also, the following points may be noted :

(i) The conductor sets itself in a plane at an angle θ to the vertical where

$$\tan\theta = \frac{w_w}{w + w_i}$$

(ii) The sag in the conductor is given by :

$$S = \frac{w_t\, l^2}{2T}$$

Hence S represents the slant sag in a direction making an angle θ to the vertical. *If no specific mention is made in the problem, then slant slag is calculated by using the above formula.*

(iii) The vertical sag $= S\cos\theta$

Example 8.18. *A transmission line has a span of 150 m between level supports. The conductor has a cross-sectional area of 2 cm². The tension in the conductor is 2000 kg. If the specific gravity of the conductor material is 9·9 gm/cm³ and wind pressure is 1·5 kg/m length, calculate the sag. What is the vertical sag?*

Solution.

Span length, $l = 150$ m; Working tension, $T = 2000$ kg

Wind force/m length of conductor, $w_w = 1{\cdot}5$ kg

Wt. of conductor/m length, w = Sp. Gravity × Volume of 1 m conductor

$= 9{\cdot}9 \times 2 \times 100 = 1980$ gm $= 1{\cdot}98$ kg

Total weight of 1 m length of conductor is

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1\cdot 98)^2 + (1\cdot 5)^2} = 2{\cdot}48 \text{ kg}$$

$$\therefore \quad \text{Sag,} \quad S = \frac{w_t l^2}{8T} = \frac{2\cdot 48 \times (150)^2}{8 \times 2000} = 3{\cdot}48 \text{ m}$$

This is the value of slant sag in a direction making an angle θ with the vertical. Referring to Fig. 8.27, the value of θ is given by ;

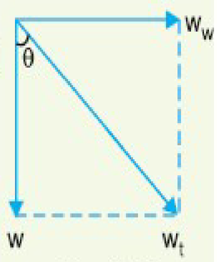


Fig. 8.27

$$\tan\theta = w_w/w = 1{\cdot}5/1{\cdot}98 = 0{\cdot}76$$

$$\therefore \quad \theta = \tan^{-1} 0{\cdot}76 = 37{\cdot}23°$$

$$\therefore \quad \text{Vertical sag} = S\cos\theta$$

$$= 3{\cdot}48 \times \cos 37{\cdot}23° = 2{\cdot}77 \text{ m}$$

Example 8.19. *A transmission line has a span of 200 metres between level supports. The conductor has a cross-sectional area of 1·29 cm², weighs 1170 kg/km and has a breaking stress of 4218 kg/cm². Calculate the sag for a safety factor of 5, allowing a wind pressure of 122 kg per square metre of projected area. What is the vertical sag?*

Solution.

Span length, $l = 200$ m

Wt. of conductor/m length, $w = 1170/1000 = 1{\cdot}17$ kg

Working tension, $^*T = 4218 \times 1{\cdot}29/5 = 1088$ kg

Diameter of conductor, $d = \sqrt{\dfrac{4 \times \text{area}}{\pi}} = \sqrt{\dfrac{4 \times 1\cdot 29}{\pi}} = 1{\cdot}28$ cm

Wind force/m length, w_w = Pressure × projected area in m²

$= (122) \times (1{\cdot}28 \times 10^{-2} \times 1) = 1{\cdot}56$ kg

Total weight of conductor per metre length is

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1\cdot 17)^2 + (1\cdot 56)^2} = 1{\cdot}95 \text{ kg}$$

$\therefore$ Slant sag, $S = \frac{w_t l^2}{8T} = \frac{1 \cdot 95 \times (200)^2}{8 \times 1088} = $ **8·96 m**

The slant sag makes an angle θ with the vertical where value of θ is given by :

$$\theta = \tan^{-1} (w_w/w) = \tan^{-1} (1 \cdot 56/1 \cdot 17) = 53 \cdot 13°$$

$\therefore$ Vertical sag $= S \cos \theta = 8 \cdot 96 \times \cos 53 \cdot 13° =$ **5·37 m**

Example 8.20. *A transmission line has a span of 275 m between level supports. The conductor has an effective diameter of 1·96 cm and weighs 0·865 kg/m. Its ultimate strength is 8060 kg. If the conductor has ice coating of radial thickness 1·27 cm and is subjected to a wind pressure of 3·9 gm/cm² of projected area, calculate sag for a safety factor of 2. Weight of 1 c.c. of ice is 0·91 gm.*

Solution.

Span length, $l = 275$ m ; Wt. of conductor/m length, $w = 0 \cdot 865$ kg

Conductor diameter, $d = 1 \cdot 96$ cm ; Ice coating thickness, $t = 1 \cdot 27$ cm

Working tension, $T = 8060/2 = 4030$ kg

Volume of ice per metre (*i.e.*, 100 cm) length of conductor

$$= \pi\, t\, (d + t) \times 100 \text{ cm}^3$$

$$= \pi \times 1 \cdot 27 \times (1 \cdot 96 + 1 \cdot 27) \times 100 = 1288 \text{ cm}^3$$

Weight of ice per metre length of conductor is

$$w_i = 0 \cdot 91 \times 1288 = 1172 \text{ gm} = 1 \cdot 172 \text{ kg}$$

Wind force/m length of conductor is

$$w_w = [\text{Pressure}] \times [(d + 2t) \times 100]$$

$$= [3 \cdot 9] \times (1 \cdot 96 + 2 \times 1 \cdot 27) \times 100 \text{ gm} = 1755 \text{ gm} = 1 \cdot 755 \text{ kg}$$

Total weight of conductor per metre length of conductor is

$$w_t = \sqrt{(w + w_i)^2 + (w_w)^2}$$

$$= \sqrt{(0 \cdot 865 + 1 \cdot 172)^2 + (1 \cdot 755)^2} = 2 \cdot 688 \text{ kg}$$

$\therefore$ Sag $= \frac{w_t l^2}{8T} = \frac{2 \cdot 688 \times (275)^2}{8 \times 4030} =$ **6·3 m**

Example 8.21. *A transmission line has a span of 214 metres between level supports. The conductors have a cross-sectional area of 3·225 cm². Calculate the factor of safety under the following conditions :*

Vertical sag = 2·35 m ; *Wind pressure = 1·5 kg/m run*

Breaking stress = 2540 kg/cm² ; *Wt. of conductor = 1·125 kg/m run*

Solution.

Here, $l = 214$ m ; $w = 1 \cdot 125$ kg ; $w_w = 1 \cdot 5$ kg

Total weight of one metre length of conductor is

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1 \cdot 125)^2 + (1 \cdot 5)^2} = 1 \cdot 875 \text{ kg}$$

If f is the factor of safety, then,

$$\text{Working tension, } T = \frac{\text{Breaking stress} \times \text{conductor area}}{\text{safety factor}} = 2540 \times 3 \cdot 225/f = 8191/f \text{ kg}$$

$$\text{Slant Sag, } S = \frac{\text{Vertical sag}}{{}^{*}\cos \theta} = \frac{2 \cdot 35 \times 1 \cdot 875}{1 \cdot 125} = 3 \cdot 92 \text{ m}$$

Now $S = \frac{w_t l^2}{8T}$

or $T = \frac{w_t l^2}{8S}$

$\therefore \quad \frac{8191}{f} = \frac{1 \cdot 875 \times (214)^2}{8 \times 3 \cdot 92}$

or Safety factor, $f = \frac{8191 \times 8 \times 3 \cdot 92}{1 \cdot 875 \times (214)^2} = \mathbf{3}$

Example 8.22. *An overhead line has a span of 150 m between level supports. The conductor has a cross-sectional area of 2 cm^2. The ultimate strength is 5000 kg/cm^2 and safety factor is 5. The specific gravity of the material is 8·9 gm/cc. The wind pressure is 1·5 kg/m. Calculate the height of the conductor above the ground level at which it should be supported if a minimum clearance of 7 m is to be left between the ground and the conductor.*

Solution.

Span length, $l = 150$ m ; Wind force/m run, $w_w = 1 \cdot 5$ kg

Wt. of conductor/m run, w = conductor area × 100 cm × sp. gravity

$= 2 \times 100 \times 8 \cdot 9 = 1780$ gm $= 1 \cdot 78$ kg

Working tension, $T = 5000 \times 2/5 = 2000$ kg

Total weight of one metre length of conductor is

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1 \cdot 78)^2 + (1 \cdot 5)^2} = 2 \cdot 33 \text{ kg}$$

$$\text{Slant sag, } S = \frac{w_t l^2}{8T} = \frac{2 \cdot 33 \times (150)^2}{8 \times 2000} = 3 \cdot 28 \text{ m}$$

$$\text{Vertical sag} = S \cos \theta = 3 \cdot 28 \times w/w_t = 3 \cdot 28 \times 1 \cdot 78/2 \cdot 33 = 2 \cdot 5 \text{ m}$$

Conductor should be supported at a height of 7 + 2·5 = **9·5 m**

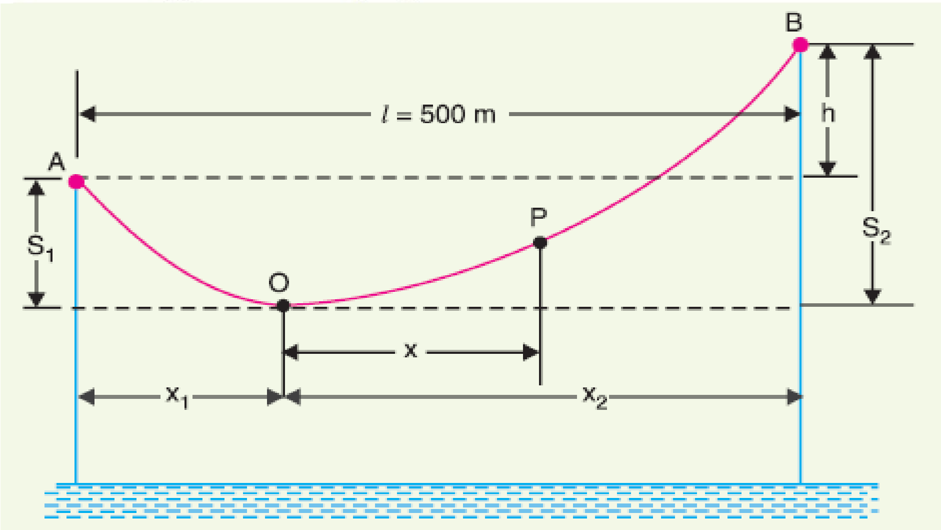
Example 8.23. *The towers of height 30 m and 90 m respectively support a transmission line conductor at water crossing. The horizontal distance betwen the towers is 500 m. If the tension in the conductor is 1600 kg, find the minimum clearance of the conductor and water and clearance mid-way between the supports. Weight of conductor is 1·5 kg/m. Bases of the towers can be considered to be at water level.*

Solution. Fig. 8.28 shows the conductor suspended between two supports *A* and *B* at different levels with *O* as the lowest point on the conductor.

Here, $l = 500$ m ; $w = 1 \cdot 5$ kg ; $T = 1600$ kg.

Difference in levels between supports, $h = 90 - 30 = 60$ m. Let the lowest point *O* of the conductor be at a distance x_1 from the support at lower level (*i.e.*, support *A*) and at a distance x_2 from the support at higher level (*i.e.*, support *B*).

Obviously, $x_1 + x_2 = 500$ m ...(*i*)



Now Sag $S_1 = \dfrac{w\,x_1^2}{2T}$ and Sag $S_2 = \dfrac{w\,x_2^2}{2T}$

$$\therefore \quad h = S_2 - S_1 = \frac{w\,x_2^2}{2T} - \frac{w\,x_1^2}{2T}$$

or

$$60 = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

$$\therefore \quad x_2 - x_1 = \frac{60 \times 2 \times 1600}{1 \cdot 5 \times 500} = 256 \text{ m} \qquad ...(ii)$$

Solving exps. (*i*) and (*ii*), we get, $x_1 = 122$ m; $x_2 = 378$ m

Now,

$$S_1 = \frac{w\,x_1^2}{2T} = \frac{1 \cdot 5 \times (122)^2}{2 \times 1600} = 7 \text{ m}$$

Clearance of the lowest point O from water level

$$= 30 - 7 = \mathbf{23\ m}$$

Let the mid-point P be at a distance x from the lowest point O.

Clearly, $x = 250 - x_1 = 250 - 122 = 128$ m

Sag at mid-point P,

$$S_{mid} = \frac{w\,x^2}{2T} = \frac{1 \cdot 5 \times (128)^2}{2 \times 1600} = 7 \cdot 68 \text{ m}$$

Clearance of mid-point P from water level

$$= 23 + 7 \cdot 68 = \mathbf{30 \cdot 68\ m}$$

Example 8.24. *An overhead transmission line conductor having a parabolic configuration weighs 1·925 kg per metre of length. The area of X-section of the conductor is 2·2 cm² and the ultimate strength is 8000 kg/cm². The supports are 600 m apart having 15 m difference of levels. Calculate the sag from the taller of the two supports which must be allowed so that the factor of safety shall be 5. Assume that ice load is 1 kg per metre run and there is no wind pressure.*

Solution. Fig. 8.29. shows the conductor suspended between two supports at A and B at different levels with O as the lowest point on the conductor.

Here, $l = 600$ m ; $w_i = 1$ kg ; $h = 15$m

$w = 1 \cdot 925$ kg ; $T = 8000 \times 2 \cdot 2/5 = 3520$ kg

Total weight of 1 m length of conductor is

$$w_t = w + w_i = 1 \cdot 925 + 1 = 2 \cdot 925 \text{ kg}$$

Let the lowest point O of the conductor be at a distance x_1 from the support at lower level (*i.e., A*) and at a distance x_2 from the support at higher level (*i.e., B*).

Clearly,

$$x_1 + x_2 = 600 \text{ m} \qquad ...(i)$$

Now,

$$h = S_2 - S_1 = \frac{w_t\,x_2^2}{2T} - \frac{w_t\,x_1^2}{2T}$$

or

$$15 = \frac{w_t}{2T}(x_2 + x_1)(x_2 - x_1)$$

$$\therefore \quad x_2 - x_1 = \frac{2 \times 15 \times 3520}{2 \cdot 925 \times 600} = 60 \text{ m} \qquad ...(ii)$$

Solving exps. (*i*) and (*ii*), we have, $x_1 = 270$ m and $x_2 = 330$ m

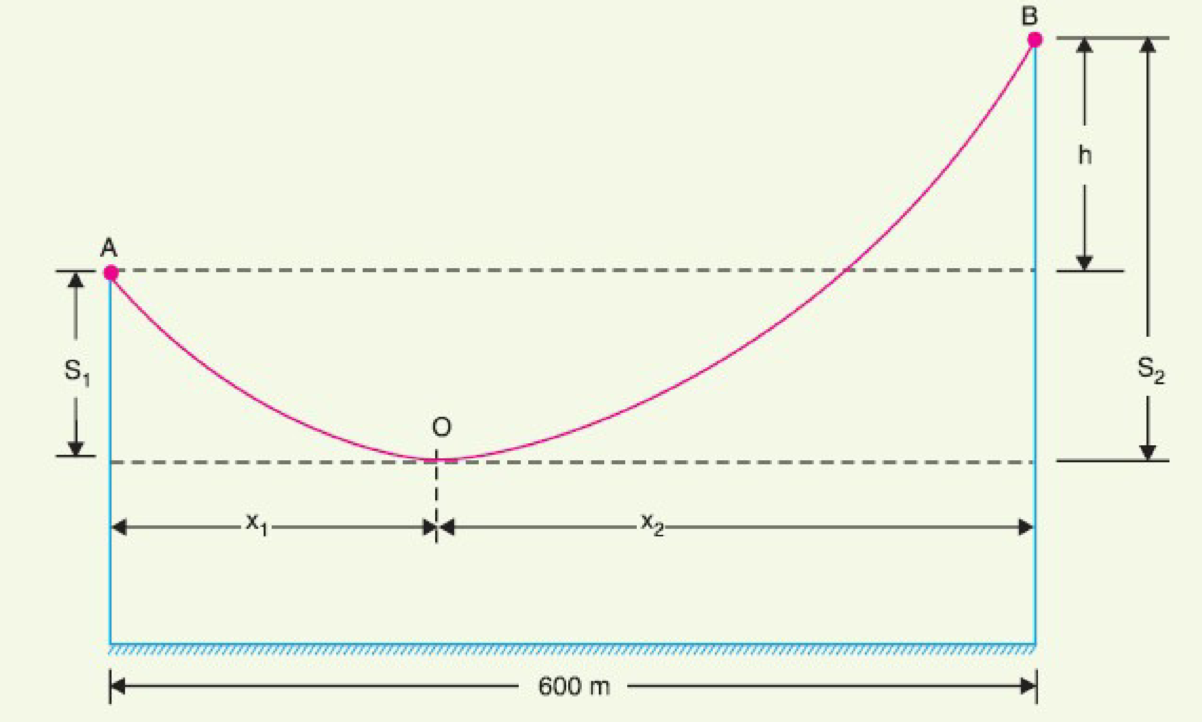


Fig. 8.29

Sag from the taller of the two towers is

$$S_2 = \frac{w_t\, x_2^2}{2T} = \frac{2 \cdot 925 \times (330)^2}{2 \times 3520} = \mathbf{45 \cdot 24\ m}$$

Example 8.25. *An overhead transmission line at a river crossing is supported from two towers at heights of 40 m and 90 m above water level, the horizontal distance between the towers being 400 m. If the maximum allowable tension is 2000 kg, find the clearance between the conductor and water at a point mid-way between the towers. Weight of conductor is 1 kg/m.*

Solution. Fig. 8.30 shows the whole arrangement.

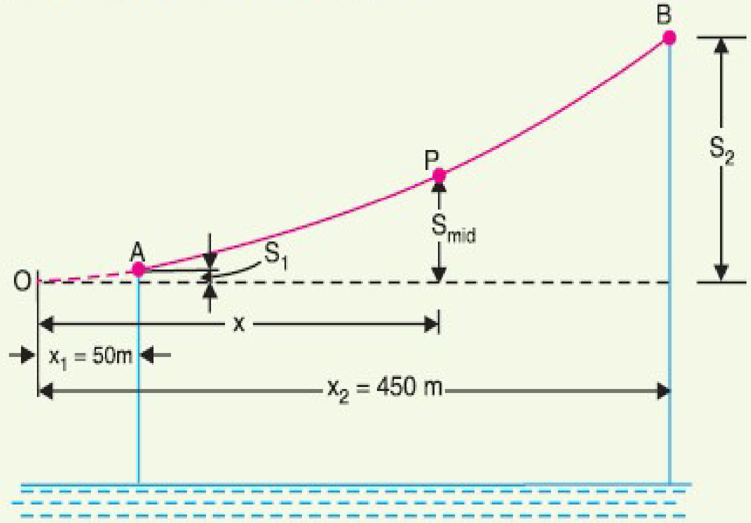


Fig. 8.30

Here, $h = 90 - 40 = 50$ m; $l = 400$ m

$T = 2000$ kg; $w = 1$ kg/m

Obviously, $x_1 + x_2 = 400$ m ...(*i*)

Now $$h = S_2 - S_1 = \frac{wx_2^2}{2T} - \frac{wx_1^2}{2T}$$

or $$50 = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

∴ $$x_2 - x_1 = \frac{50 \times 2 \times 2000}{400} = 500 \text{ m} \quad ...(ii)$$

Solving exps. (*i*) and (*ii*), we get, $x_2 = 450$ m and $x_1 = -50$ m

Now x_2 is the distance of higher support *B* from the lowest point *O* on the conductor, whereas x_1 is that of lower support *A*. As the span is 400 m, therefore, point *A* lies on the same side of *O* as *B* (see Fig. 8.30).

Horizontal distance of mid-point *P* from lowest point *O* is

$$x = \text{Distance of } A \text{ from } O + 400/2 = 50 + 200 = 250 \text{ m}$$

∴ Sag at point *P*, $$S_{mid} = \frac{w\,x^2}{2T} = \frac{1 \times (250)^2}{2 \times 2000} = 15{\cdot}6 \text{ m}$$

Now Sag $$S_2 = \frac{w\,x_2^2}{2T} = \frac{1 \times (450)^2}{2 \times 2000} = 50{\cdot}6 \text{ m}$$

Height of point *B* above mid-point *P*

$$= S_2 - S_{mid} = 50{\cdot}6 - 15{\cdot}6 = 35 \text{ m}$$

∴ Clearance of mid-point *P* above water level

$$= 90 - 35 = \textbf{55 m}$$

Example 8.26. *A transmission line over a hillside where the gradient is 1 : 20, is supported by two 22 m high towers with a distance of 300 m between them. The lowest conductor is fixed 2 m below the top of each tower. Find the clearance of the conductor from the ground. Given that conductor weighs 1 kg/m and the allowable tension is 1500 kg.*

Solution. The conductors are supported between towers *AD* and *BE* over a hillside having gradient of 1 : 20 as shown in Fig. 8.31. The lowest point on the conductor is *O* and $\sin\theta = 1/20$.

Effective height of each tower (*AD* or *BE*)

$$= 22 - 2 = 20 \text{ m}$$

Vertical distance between towers is

$$h = EC = DE \sin\theta = 300 \times 1/20 = 15 \text{ m}$$

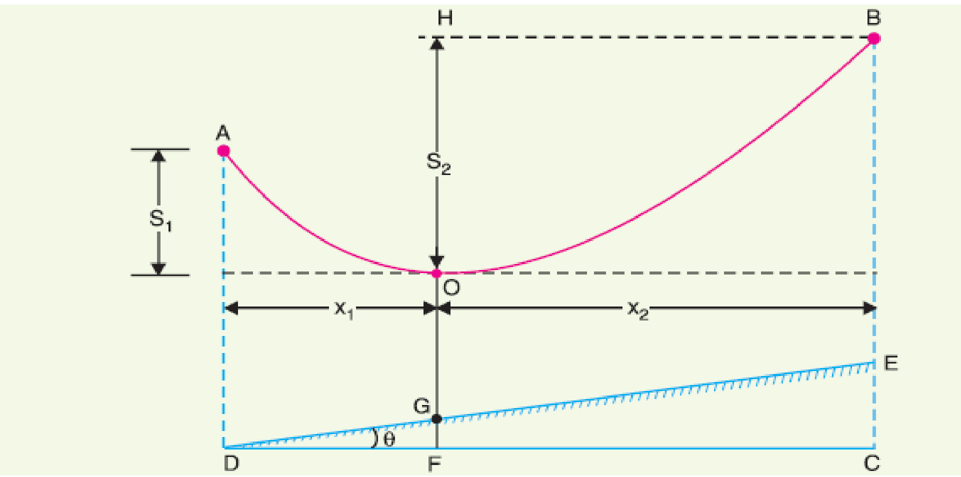
Horizontal distance between two towers is

$$DC = \sqrt{DE^2 - EC^2} = \sqrt{(300)^2 - (15)^2} \simeq 300 \text{ m}$$

or $$x_1 + x_2 = 300 \text{ m} \quad ...(i)$$

Now $$h = \frac{w\,x_2^2}{2T} - \frac{w\,x_1^2}{2T} = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

or $$x_2 - x_1 = \frac{2T\,h}{w\,(x_2 + x_1)} = \frac{2 \times 1500 \times 15}{1 \times 300} = 150 \text{ m} \quad ...(ii)$$



Solving exps. (*i*) and (*ii*), we have, $x_1 = 75$ m and $x_2 = 225$ m

$$\text{Sag } S_2 = \frac{w x_2^2}{2T} = \frac{1 \times (225)^2}{2 \times 1500} = 16{\cdot}87 \text{ m}$$

Now $$BC = BE + EC = 20 + 15 = 35 \text{ m}$$

Clearance of the lowest point *O* from the ground is

$$OG = HF - S_2 - GF$$
$$= BC - S_2 - GF \qquad (\because BC = HF)$$
$$[\text{Now } GF = x_1 \tan\theta = 75 \times 0{\cdot}05 = 3{\cdot}75 \text{ m}]$$
$$= 35 - 16{\cdot}87 - 3{\cdot}75 = \mathbf{14{\cdot}38 \text{ m}}$$

Example 8.27. *A transmission tower on a level ground gives a minimum clearance of 8 metres for its lowest conductor with a sag of 10 m for a span of 300 m. If the same tower is to be used over a slope of 1 in 15, find the minimum ground clearance obtained for the same span, same conductor and same weather conditions.*

Solution. On level ground

$$\text{Sag, } S = \frac{w l^2}{8T}$$

$$\therefore \quad \frac{w}{T} = \frac{8S}{l^2} = \frac{8 \times 10}{(300)^2} = \frac{8}{9 \times 10^3}$$

Height of tower = Sag + Clearance = 10 + 8 = 18 m

On sloping ground. The conductors are supported between towers *AD* and *BE* over a sloping ground having a gradient 1 in 15 as shown in Fig. 8.32. The height of each tower (*AD* or *BE*) is 18 m.

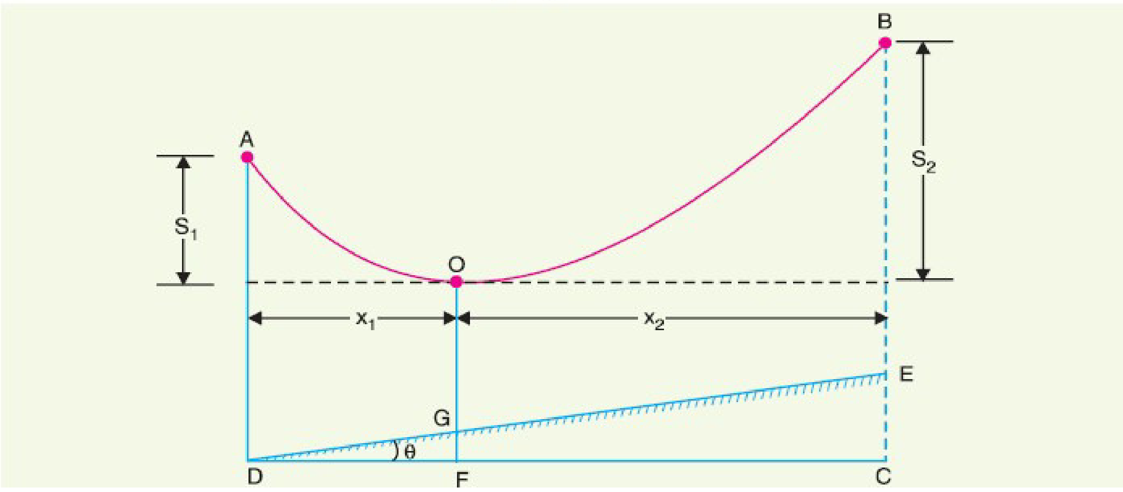
Vertical distance between the two towers is

$$h = EC = {}^*DE \sin\theta = 300 \times 1/15 = 20 \text{ m}$$

Now $$x_1 + x_2 = 300 \text{ m} \qquad ...(i)$$

Also $$h = \frac{w x_2^2}{2T} - \frac{w x_1^2}{2T} = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

$$\therefore \quad x_2 - x_1 = \frac{2\,T\,h}{w(x_2 + x_1)} = \frac{2 \times 9 \times 10^3 \times 20}{8 \times 300} = 150 \text{ m} \qquad ...(ii)$$



Solving exps. (*i*) and (*ii*), we have, $x_1 = 75$ m and $x_2 = 225$ m

Now
$$S_1 = \frac{w\,x_1^2}{2T} = \frac{8 \times (75)^2}{2 \times 9 \times 10^3} = 2{\cdot}5 \text{ m}$$

$$S_2 = \frac{w\,x_2^2}{2T} = \frac{8 \times (225)^2}{2 \times 9 \times 10^3} = 22{\cdot}5 \text{ m}$$

Clearance of point O from the ground is

$$OG = BC - S_2 - GF = 38 - 22{\cdot}5 - 5 = 10{\cdot}5 \text{ m}$$

$[\because\ GF = x_1 \tan\theta = 75 \times 1/15 = 5\text{m}]$

Since O is the origin, the equation of slope of ground is given by :

$$y = m\,x + A$$

Here
$$m = 1/15 \text{ and } A = OG = -10{\cdot}5 \text{ m}$$

$\therefore$
$$y = \frac{x}{15} - 10{\cdot}5$$

$\therefore$ Clearance C from the ground at any point x is

$$C = \text{Equation of conductor curve} - y = \left(\frac{w\,x^2}{2T}\right) - \left(\frac{x}{15} - 10\cdot5\right)$$

$$= \frac{8x^2}{2 \times 9 \times 10^3} - \left(\frac{x}{15} - 10\cdot5\right)$$

$\therefore$
$$C = \frac{x^2}{2250} - \frac{x}{15} + 10\cdot5$$

Clearance will be minimum when $dC/dx = 0$ *i.e.,*

$$\frac{d}{dx}\left[\frac{x^2}{2250} - \frac{x}{15} + 10\cdot5\right] = 0$$

or
$$\frac{2x}{2250} - \frac{1}{15} = 0$$

or
$$x = \frac{1}{15} \times \frac{2250}{2} = \mathbf{75\ m}$$

i.e., minimum clearance will be at a point 75 m from O.

$$\text{Minimum clearance} = \frac{x^2}{2250} - \frac{x}{15} + 10\cdot5 = (75)^2/2250 - 75/15 + 10{\cdot}5$$

$$= 2{\cdot}5 - 5 + 10{\cdot}5 = \mathbf{8\ m}$$

Module -IV

POWER SYSTEM TRANSIENTS & TRAVELLING WAVES

Transmission Line Transient Over voltages (Travelling Waves on Power Systems)

The establishment of a potential difference between the conductors of an overhead transmission line is accompanied by the production of an electrostatic flux, whilst the flow of current along the conductor results in the creation of a magnetic field. The electrostatic fields are due, in effect, to a series of shunt capacitors whilst the inductances are in series with the line.

Consider the section of the line adjacent to the generator in Figure 1.

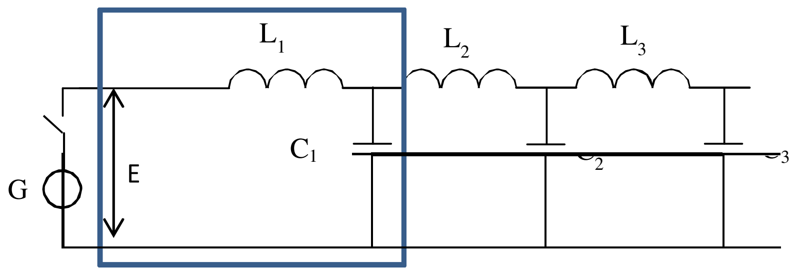


Figure 1.

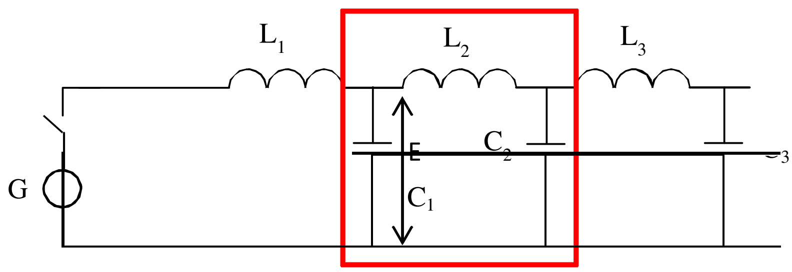


Figure 2.

Let the voltage E suddenly applied to the circuit by closing the switch. Under these conditions, the capacitance C_1 takes a large initial charging current the whole of the voltage will at first be used in driving a charging current through the circuit consisting of L_1 and C_1 in series. As the charge on C1 builds up its voltage will increase and this voltage will begin to charge C2 by driving a current through the inductance L2 (Figure 2), and so on, showing that the greater the distance from the generator, the greater will be the time elapsed from the closing the switch to the establishment of the full line voltage E. It is also clear that voltage and current are intimately associated and that any voltage phenomenon is associated with an attendant current phenomenon.

The gradual establishment of the line voltage can be regarded as due to a voltage wave travelling from the generator towards the far end and the progressing charging of the line capacitances will account for the associated current wave.

Effect of the 60 Hz Alternating Voltage

In the above treatment, the voltage E has been assumed constant and in practice such an assumption is usually adequate owing to the very high velocity of propagation. So far as most lines are concerned, the impulse would have completely traversed the whole length before sufficient time had elapsed for an appreciable change in the 60 Hz voltage to occur. Assuming that v is equal 3×10^8 m/sec in an actual case, the first impulse will have travelled a distance of $(3 \times 10^8)/60$ i.e. 5×10^6 meters by the end of the first cycle which means that the line would have to be 5000 km long to carry the whole of the voltage distribution corresponding to one cycle. A line of such a length is impossible.

The Open-Circuited Line

Let a source of constant voltage E be switched suddenly on a line open-circuited at the far end. Then neglecting the effect of line resistance and possible conductance to earth, a rectangular voltage wave of amplitude E and its associated current wave of amplitude $I = E/Z_c$ will travel with velocity v towards the open end. Figure 3.a shows the conditions at the instant when the waves have reached the open end, the whole line being at the voltage E and carrying a current I.

Figure 3.a

At the open end, the current must of necessity fall to zero, and consequently the energy stored in the magnetic field must be dissipated in some way. In the case under consideration, since resistance and conductance have been neglected, this energy can only be used in the production of an equal amount of electrostatic field. If this is done, the voltage at the point will be increased by an amount e such that the energy lost by the electromagnetic field ($0.5\ LI^2$) is equal to the energy gained by the electrostatic field ($0.5Cv^2$), or:

$$\frac{1}{2} LI^2 = \frac{1}{2} Cv^2$$

Whence,

$$e = \sqrt{\frac{L}{C}}\, I = Z_c I = E$$

Hence, the total voltage at the open end becomes 2E. The open end of the line can thus be regarded as the origin of a second voltage wave of amplitude E, this second wave travelling back to the source with the same velocity v. At some time subsequent to arrival of the initial wave at the open end, i.e. the condition shown in Figure 3.a, the state affairs on the line will be as in Figure 3.b in which the incoming and reflected voltage waves are superposed, resulting in a step in the voltage wave which will travel back towards the source with a velocity v. The doubling of the voltage at the open end must be associated with the disappearance of the current since none can flow beyond the open circuit. This is equivalent to the establishment of a reflected current

Wave of negative sign as shown in Figure 3.b.

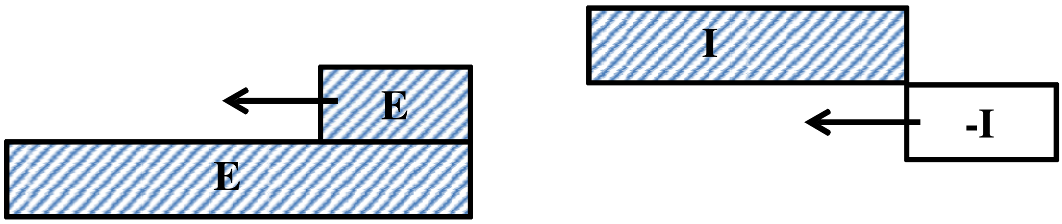


Figure 3.b

At the instant the reflected waves reach the end G, the distribution along the whole line will be a voltage of 2E and a current of zero as in Figure 3.c.

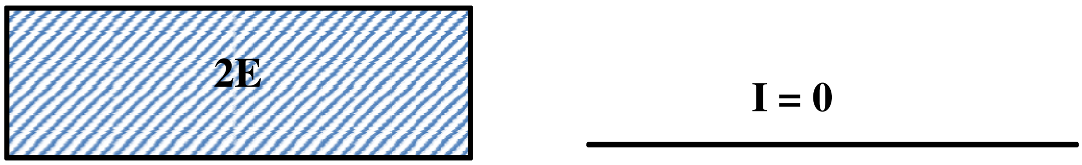


Figure 3.c

At G, the voltage is held by the source to the value E, it follows that there must be a reflected voltage of –E and associated with it there will be a current wave of –I. After these have travelled a little way along the line, the conditions will be as shown in Figure 3.d.

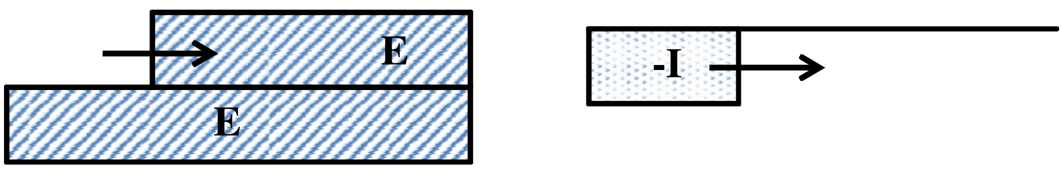
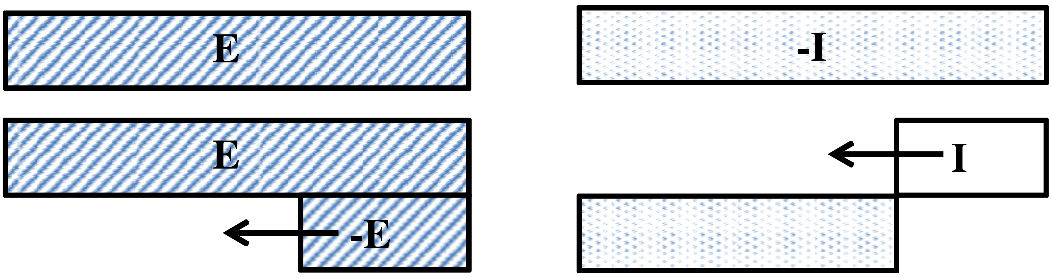


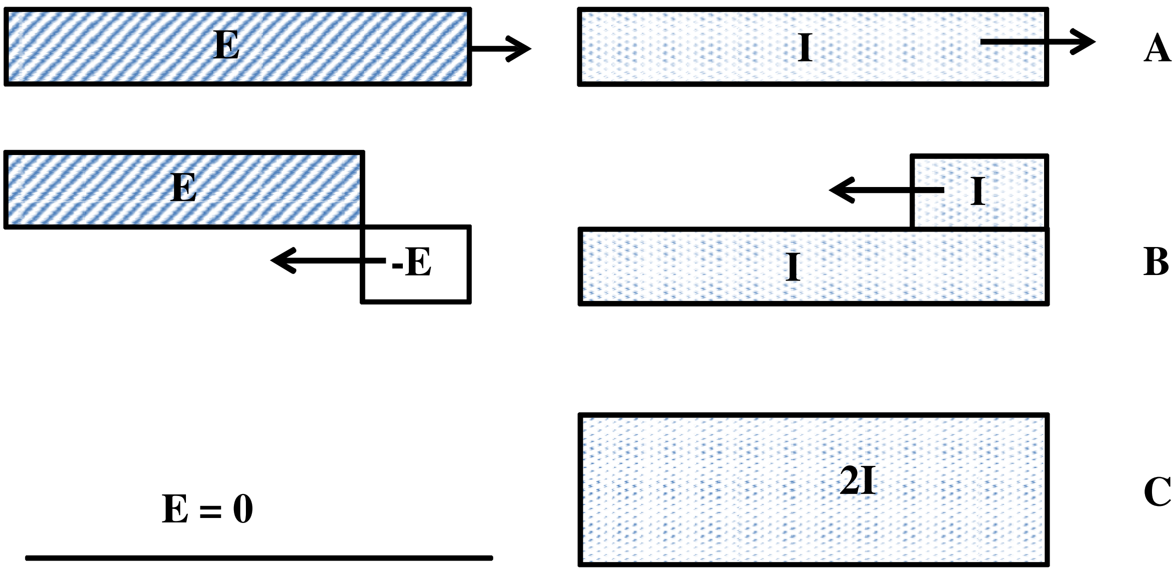
Figure 3.d

When these reach the open end the conditions along the line will be voltage E and current –I. The reflected waves due to these will be –E and +I and when these have travelled to the end G they will have wiped out both voltage and current distributions, leaving the line for an instant in its original state. The above cycle is then repeated.



The Short-Circuited Line

In this case, the voltage at the far end of the line must of necessity be zero, so that as each element of the voltage wave arrives at the end there is a conversion of electrostatic energy into electromagnetic energy. Hence, the voltage is reflected with reversal sign while the current is reflected without any change of sign: thus on the first reflection, the current builds up to 2I. Successive stages of the phenomenon are represented in Figure 4.



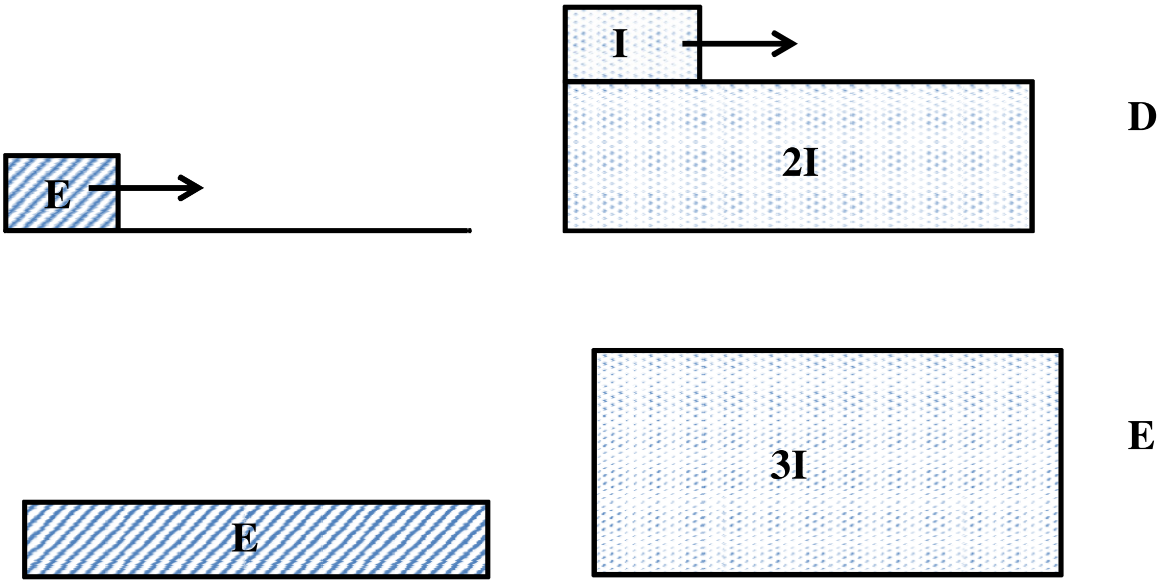


Figure 4

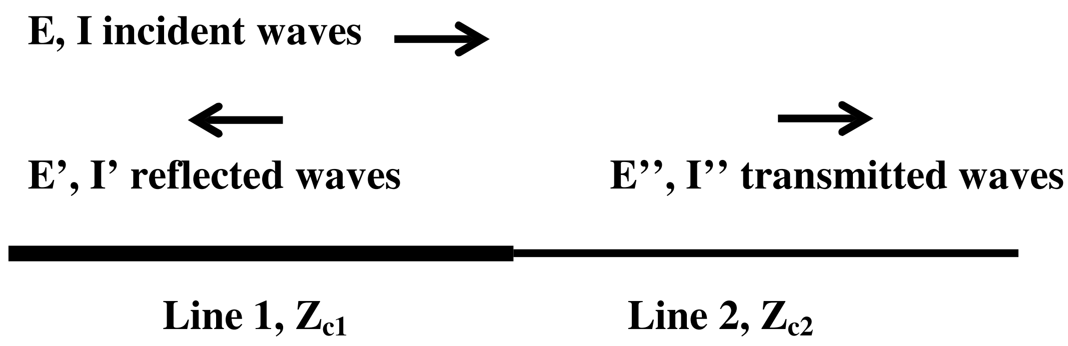
A. Original current and voltage waves just prior to the first reflection.
B. Distributions just after the first reflection.
C. Distributions at the instant the first reflection waves have reached the generator. Note that the whole of the line is at zero voltage.
D. Distributions after the first reflection at the generator end.
E. Distributions at the instant the first reflected waves from the generator reach the far end.

It will be seen that the line voltage is periodically reduced to zero, but that at each reflection at either end the current is built up by the additional amount $I = E/Z_c$. Thus, theoretically, the current will eventually become infinite as is to be expected in the case of a lossless line. In practice, the resistance of the line produces attenuation so that the amplitude of each wave-front gradually diminishes as it travels along the line and the ultimate effect of an infinite number of reflections is to give the steady Ohm's law of current E/R.

Junction of Lines of Different Characteristic Impedance

If a second line is connected to the termination of the first, the voltage of the reflected wave ***at the junction*** will depend on the magnitude of Z_{c1} and Z_{c2}.

With $Z_{c2} = \infty$, we have the case of the open-circuited line. With $Z_{c2} = 0$, the case of the short-circuited line. If $Z_{c2} = Z_{c1}$, the second line can be regarded as a natural continuation of the first and the current and voltage waves pass into Z_{c2} without any change. For any value of Z_{c2} different from the above special cases, there will be partial reflection of the current and voltage waves.



$$\frac{E}{I} = Z_{c1}$$

Since the reflection is accompanied by a change in sign of either voltage or current but not both:

$$\frac{E'}{I'} = -Z_{c1}$$

The voltage entering the second line at any instant will be the algebraic sum of the incident and reflected voltages in the first line.

$$\therefore E'' = E + E'$$

The difference between the incident current I and the current I'' transmitted into the second circuit is the reflected current I' or

$I' = I'' - I$ where I' carries the appropriate sign

Also $\frac{E''}{I''} = Z_{c2}$

$$I'' Z_{c2} = E'' = E + E' = Z_{c1} I - Z_{c1} I' = Z_{c1} I - Z_{c1}(I'' - I)$$

Giving $I'' = \frac{2IZ_{c1}}{(Z_{c1}+Z_{c2})} = \frac{2E}{(Z_{c1}+Z_{c2})}$

And $I' = I'' - I = \frac{2IZ_{c1}}{(Z_{c1}+Z_{c2})} - I = \frac{E}{Z_{c1}} \frac{(Z_{c1}-Z_{c2})}{(Z_{c1}+Z_{c2})}$

Also $E'' = I'' Z_{c2} = \frac{2EZ_{c2}}{(Z_{c1}+Z_{c2})}$

And $E' = -Z_{c1} I' = -E \frac{(Z_{c1}-Z_{c2})}{(Z_{c1}+Z_{c2})}$

$$E^{u} = E\frac{(Z_{c2}-Z_{c1})}{(Z_{c1}+Z_{c2})}$$

$$E^{u} = E\,\frac{(Z_{c2}-Z_{c1})}{(Z_{c1}+Z_{c2})} = TE \qquad \textbf{(1)}$$

$$E^{uu} = \frac{2EZ_{c2}}{(Z_{c1}+Z_{c2})} \qquad \textbf{(2)}$$

The Bewley Lattice Diagram

This is a diagram which shows at a glance the position and direction of motion of every incident, reflected and transmitted wave on the system at every instant of time. Providing that the system of lines is not too complex the difficulty of keeping track of the multiplicity of successive reflections is simplified. As a first example, consider the case of an open-circuited line having the following parameters:

$$R = 0.5\ \Omega \text{ per KN};\ G = 10\ \times 10^{-7}\text{S per KN};\ l = 400 \text{ KN}$$

Assume also that RC = GL; this condition (Heaviside condition) results in a distortionless line and the voltage and current waves remain of similar shape in spite of attenuation. In such a line, it can be shown that if a wave of amplitude A at any point of the line, the amplitude A_x at some point distant x from the original point is

$$A_s = Ae^{-\alpha s}$$

For the distortionless line, the attenuation constant is given by $\alpha = \sqrt{RG}$

$$\alpha = \sqrt{RG} = \sqrt{0.5 \times 10 \times 10^{-7}} = 0.000707$$

When x = l = 400 km, $e^{-0.2828} = 0.7536$

Source impedance = 0

E, I incident waves with respect to the source

$$\Gamma = \frac{(0 - Z_{c1})}{(Z_{c1} + 0)} = -1$$

At the receiving end, the line is open-circuited and $\Gamma = +1$.

Let us denote the initial value of the voltage at the sending (generating) end by 1 p.u., then, we will have the following sequence of events as far as the reflected wave is concerned. Let t' be the time taken to make one tour of the line, i.e. $400/3\times10^5 = 0.0013$ sec in the present case.

At zero time, a wave of amplitude 1 starts from G. At time t', a wave of amplitude 0.7536 reaches the open end and a reflected wave of amplitude 0.7536 commences the return journey. At time 2t', this reflected wave is attenuated to 0.5679 and has reached G. Here it is reflected to -0.5679 and after a time 3t' it reaches the open end attenuated to -0.428.

It is then reflected and reaches G after a time 4t' with an amplitude of -0.3225. It is then reflected with change of sign thus starting with an amplitude of 0.3225 and so on. The Bewley lattice diagram is a space-time diagram with space measured horizontally and time vertically and the lattice of the aboveexample is shown in Figure 5. The final voltage at the receiving end is the sum to infinity of all such increments.

Thus, in the above example, it is:

$2(0.7536 - 0.428 + \cdots \ldots)$

It is simpler to express the series generally in terms of α, thus

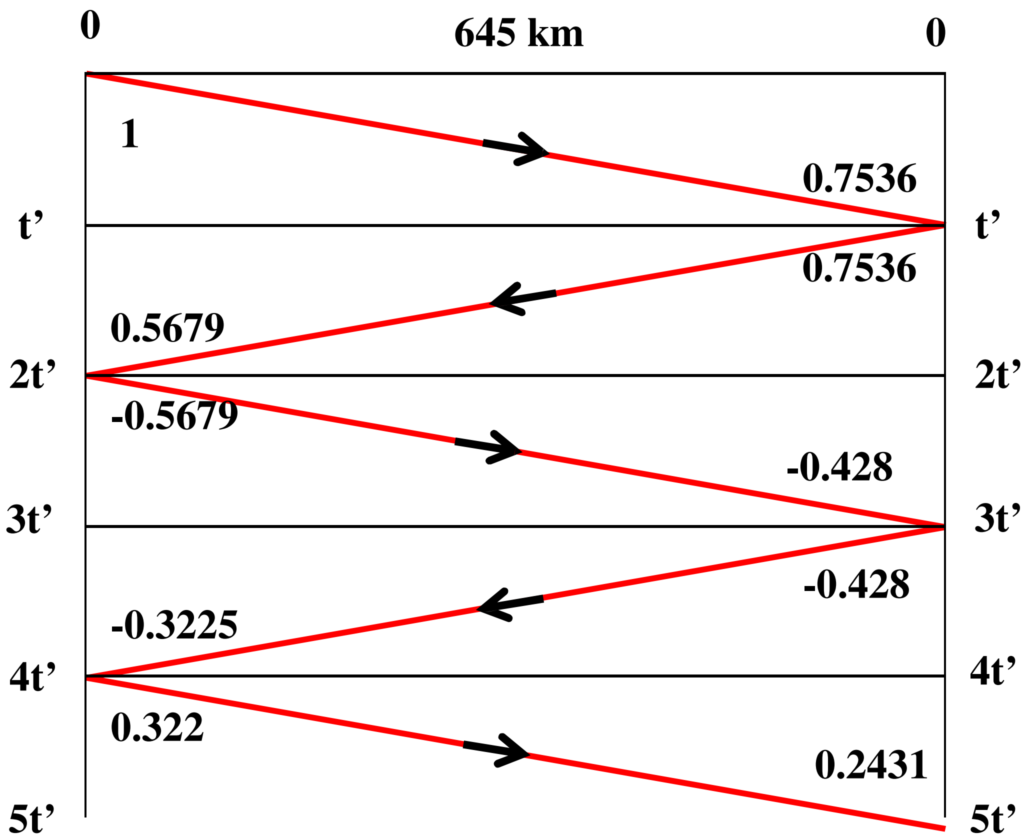
$= 2(\alpha - \alpha^3 + \alpha^5 - \alpha^7 + \cdots \ldots)$

$= 2[(\alpha + \alpha^5 + \alpha^9 + \cdots \ldots) - (\alpha^3 + \alpha^7 + \alpha^{11} + \cdots \ldots)]$

$$= \frac{2\alpha}{(1 + \alpha^2)}$$

When the given values are substituted in the above expression its value is 0.9613.

Thus, even when open-circuited, such a line gives a far end voltage less than the sending end voltage, the reason being that the shunt conductance current produces a drop in the series resistance.



Sending end
Reflection operator = -1

Receiving end
Reflection operator = +1

Example 1:

Line terminated in a

resistance R Assume

that R = 3 Z_c

The reflection operator at the receiving end

$$\Gamma = \frac{(Z_{c2} - Z_{c1})}{(Z_{c1} + Z_{c2})} = \frac{(3Z_c - Z_c)}{(4Z_c)} = 0.5$$

At the sending end □ = -1 (the source impedance is zero i.e. a short-circuit)

Source impedance = 0

$$\Gamma = \frac{(0 - Z_{c1})}{(Z_{c1} + 0)} = -1$$

E, I incident waves with respect to the source

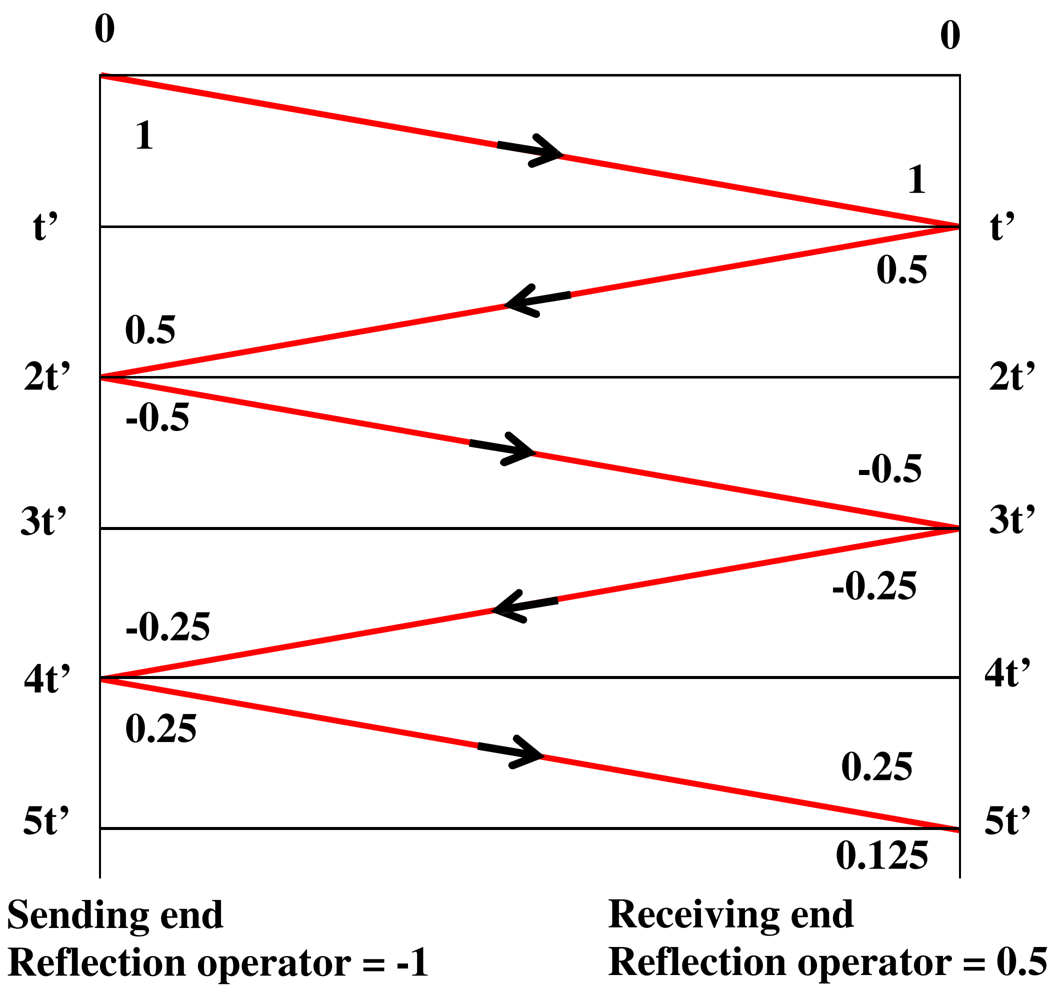


Figure 5: Lattice diagram for line terminated in a resistance

At the receiving end, the increment of voltage is the sum of the incident and reflected waves at each reflection, so that the ultimate voltage at this point is the sum to infinity of the series:

$$(1+\Gamma)-(\Gamma+\Gamma^2)+(\Gamma^2+\Gamma^3)-(\Gamma^3+\Gamma^4)+\cdots$$
$$=(1+\Gamma)(1-\Gamma+\Gamma^2-\Gamma^3+\cdots)$$
$$=(1+\Gamma)\{(1+\Gamma^2+\Gamma^4+\cdots)-(\Gamma+\Gamma^3+\Gamma^5+\cdots)\}$$
$$=(1+\Gamma)\left\{\frac{1}{1-\Gamma^2}-\frac{\Gamma}{1-\Gamma^2}\right\}=1$$

Thus the voltage at the receiving end finally settles down to that at the receiving end and consequently the current settles down to the simple Ohm's law value of E/R. The increments of current are obviously proportional to the increments of voltage at the receiving end and, therefore, the voltage-time and current-time curves for this end for $\Gamma = 0.5$ are shown in Figure 6. The tabulated values are shown and it can be seen that the voltage and current oscillate around the value 1 and finally settle down to this value.

Time	Increment of voltage or current	Sum of increments
0	0	0
t'	1.5	1.5
3t'	-0.75	0.75
5t'	0.375	1.125
7t'	-0.188	0.937
9t'	0.094	1.031

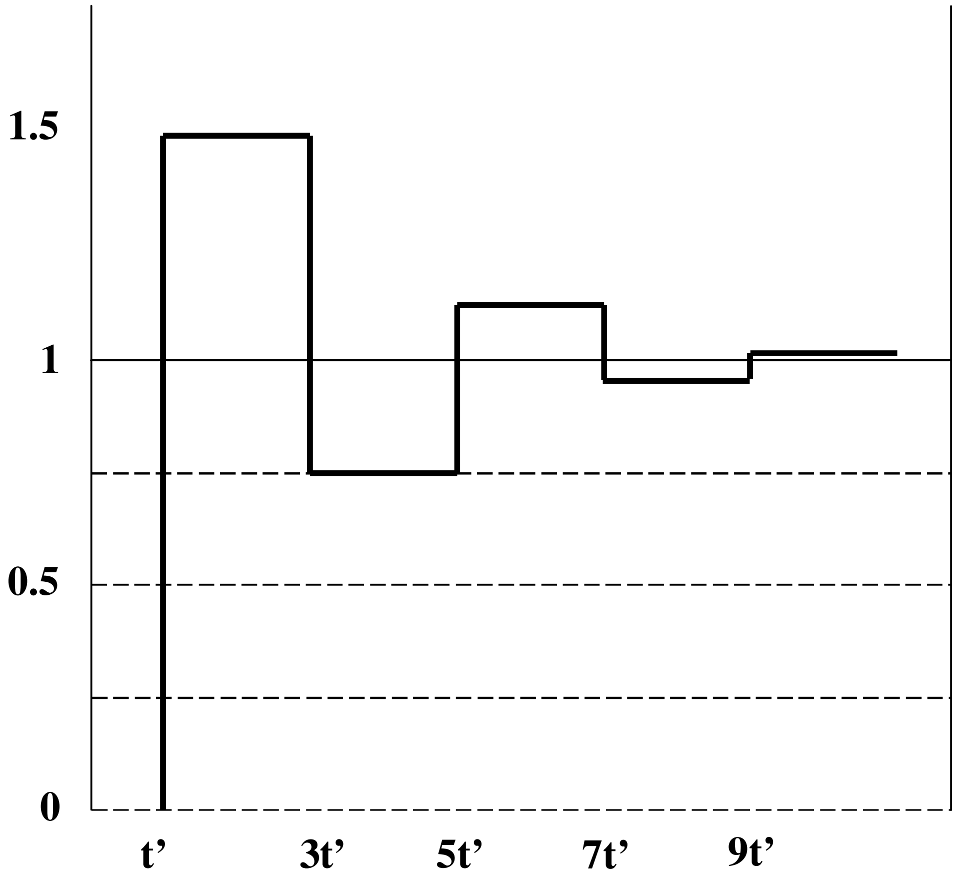


Figure 6: Building up of current and voltage in a line terminated in a resistance.

Junction of a Cable and an Overhead Line

Example:

A long overhead line is joined to a ***short*** length of cable which is open-circuited at its far end. The ratio of the characteristic impedance of the line to that of the cable is 10. Draw a Bewley lattice diagram for this case if the wave originates in the line.

1. From line to cable

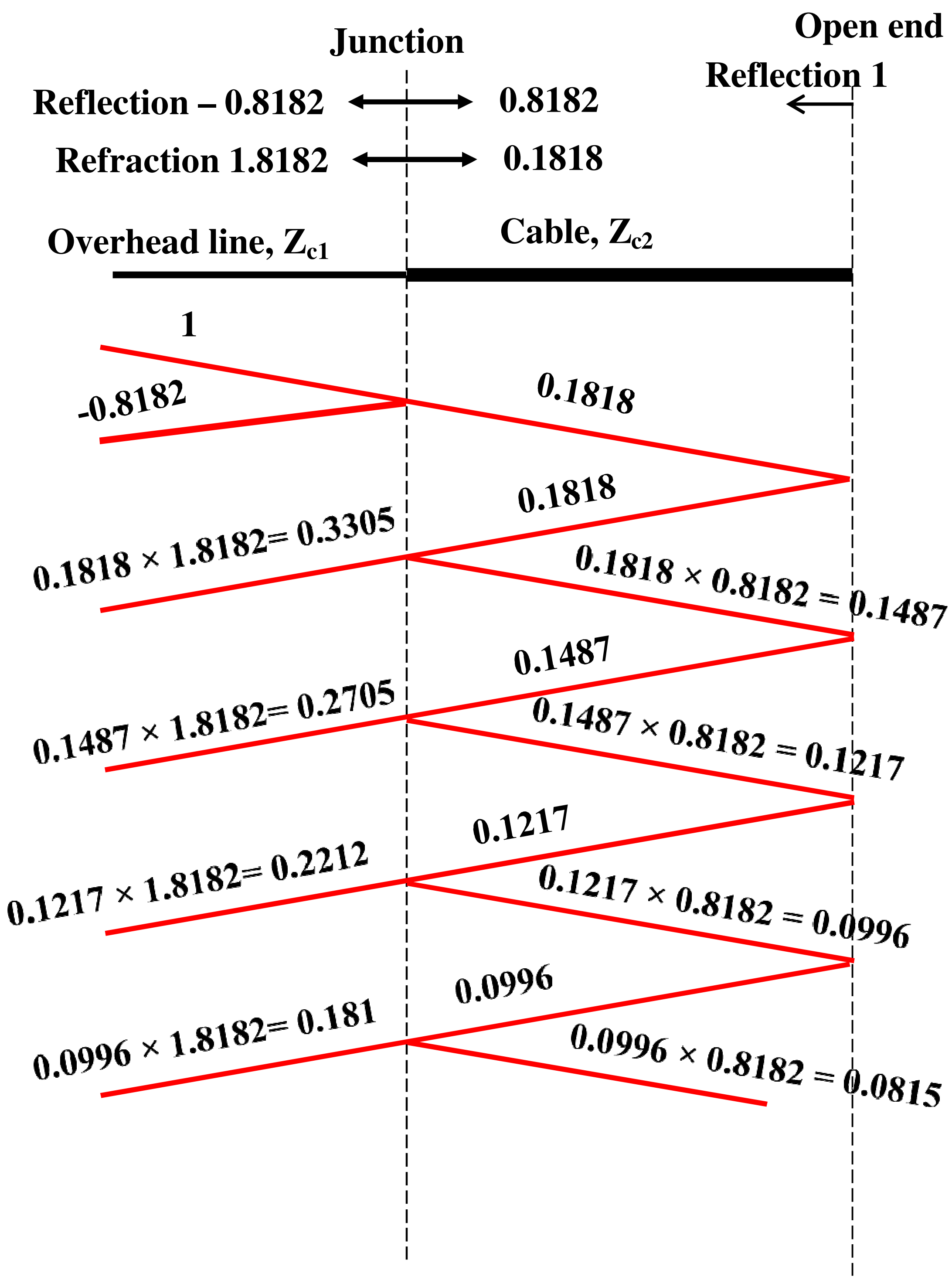
Reflection operator: $\Gamma = \frac{(Zc2-Zc1)}{(Z_{c1}+Z_{c2})} = \frac{(1-10)}{(1+10)} = -0.8182$

Transmission operator $T = \frac{2Zc2}{(Z_{c1}+Z_{c2})} = \frac{2\times1}{(1+10)} = 0.1818$

2. From cable to line

Reflection operator: $\Gamma = \frac{(Zc2-Zc1)}{(Z_{c1}+Z_{c2})} = \frac{(10-1)}{(1+10)} = 0.8182$

Transmission operator $T = \frac{2Zc2}{(Z_{c1}+Z_{c2})} = \frac{2\times10}{(1+10)} = 1.8182$



Lattice diagram for a line consisting of two sections with different constants.

Since the characteristic impedance of an (Extra High Voltage) EHV cable is about 30 to 50 Ω whereas that for a line is frequently about 250 to 350 Ω, the voltage transmitted from a line into a cable is of the order 40/(40+300), i.e. about 0.125 of the surge voltage travelling along the line. For this reason, a transmission line is sometimes connected to a substation by a cable of perhaps less than 2 km length so that lightning or switching surges travelling along the line are much attenuated by the cable and are less likely to flashover or damage apparatus in the substation.

Example:

An overhead line for which L = 1.5 mH/km and C = 0.015 μF/km is connected to a cable for which L = 0.25 mH/km and C = 0.45 μF/km. If a surge of 10 kV originates in the line and enters the cable, calculate the voltage and current in the cable.

$$Z_{c1} = \sqrt{\frac{1.5 \times 10^{-3}}{0.015 \times 10^{-6}}} = 316.2278\ \Omega$$

$$Z_{c2} = \sqrt{\frac{0.25 \times 10^{-3}}{0.45 \times 10^{-6}}} = 23.5702\ \Omega$$

Original current in the overhead line

$$I = \frac{E}{Z_{c1}} = 31.6228\ \text{A}$$

Voltage in cable

$$E^{uu} = \frac{2Z_{c2}E}{(Z_{c1}+Z_{c2})} = \frac{2\times 23.5702\times 10000}{316.2278+23.5702} = 1387.3066\ \text{V}$$

Current in cable

$$I^{uu} = \frac{1387.3066}{23.5702} = 58.8585\ \text{A}$$

Example:

The ends of two long transmission lines A and B are connected by a cable C 1.5 km long. The lines have capacitance of 10 pF/m and inductance 1.6×10^{-6} H/m and the cable has capacitance 89 pF/m and inductance 5×10^{-7} H/m. A rectangular voltage wave of magnitude 10 kV and of long duration travels along line A towards the cable. Find the magnitude of the second voltage step occurring at the junction of the cable and line B. What will be the voltage at the junction of line A and the cable 20 μsec after the initial surge reaches this point?

$$Z_{cL} = J\frac{1.6\times10^{-6}}{10\times10^{-12}} = 400\ \Omega$$

$$Z_{cc} = J\frac{5\times10^{-7}}{89\times10^{-12}} = 75\ \Omega$$

From line A to cable

Transmission operator $T = \frac{2Zc2}{(Z_{c1}+Z_{c2})} = \frac{2\times75}{(400+75)} = 0.3158$

From cable to lines A and B

Reflection operator: $\Gamma = \frac{(Zc2-Zc1)}{(Z_{c1}+Z_{c2})} = \frac{(400-75)}{(400+75)} = 0.6842$

From line A to cable

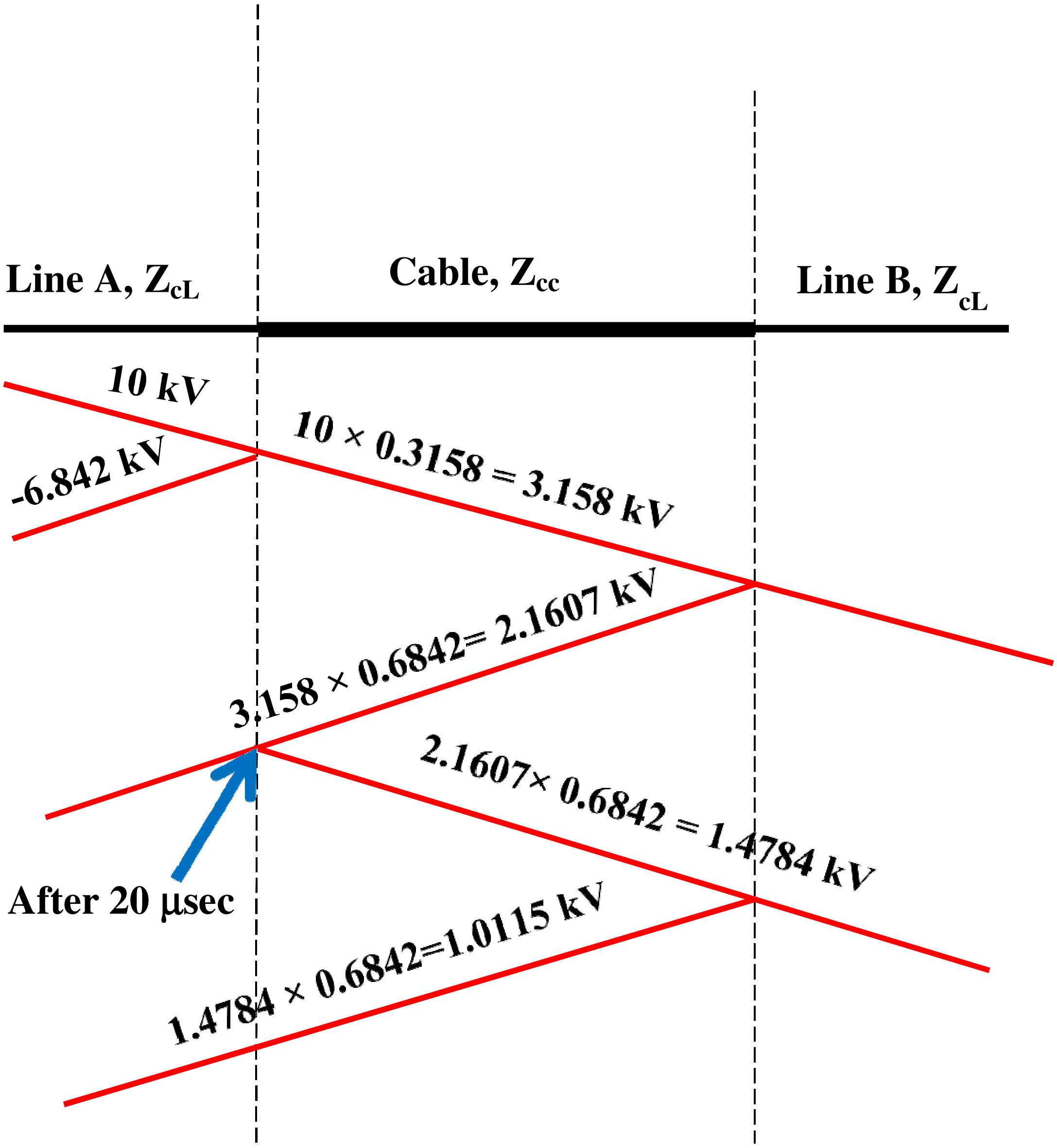
Reflection operator: $\Gamma = \frac{(Zc2-Zc1)}{(Z_{c1}+Z_{c2})} = \frac{(75-400)}{(400+75)} = -0.6842$

Surge velocity in the cable

$$v = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{5\times10^{-7}\times89\times10^{-12}}}$$
$$= 149906.3378\ \text{KN/sec}$$

Time of travelling through the cable

$$t = \frac{1.5}{149906.3378} = 10\ \mu\text{sec}$$



Answer = 3.158 + 2.1607 + 1.4784 + 1.0115 = 7.8086 kV

After 20 μsec
Answer = 10 – 6.842 + 2.1607 + 1.4784 = 6.7971 kV

`

Example:

A 500 kV surge on a long overhead line of characteristic impedance 400 Ω, arrives at a point where the line continues into a cable AB of length 1 km having a total inductance of 264 μH and a total capacitance of 0.165 μF. At the far end of the cable, connection is made to a transformer of characteristic impedance 1000 Ω. The surge has negligible rise-time and its amplitude may be considered to remain constant at 500 kV for a time-longer than the transient times involved here.

Draw the Bewley lattice diagram at the junction A of the cable for 26.4 μsec after the arrival at this junction of the original surge.

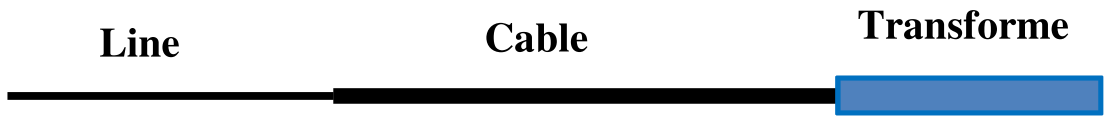
$$Z_{cc} = \sqrt{\frac{264 \times 10^{-6}}{0.165 \times 10^{-6}}} = 40\ \Omega$$

Velocity of the surge through the cable:

$$v = \frac{1}{\sqrt{264 \times 10^{-9} \times 0.165 \times 10^{-9}}} = 151515.2\ \text{KN/sec}$$

Time for the surge to travel through the cable:

$$t = \frac{1}{151.5152} = 6.6\ \mu\text{sec}$$



From Line to cable:

$$\text{Transmission operator } T = \frac{2Zc2}{(Z_{c1}+Z_{c2})} = \frac{2\times 40}{(400+40)} = 0.1818$$

$$\text{Reflection operator: } \Gamma = \frac{(Zc2-Zc1)}{(Z_{c1}+Z_{c2})} = \frac{(40-400)}{(400+40)} = -0.8182$$

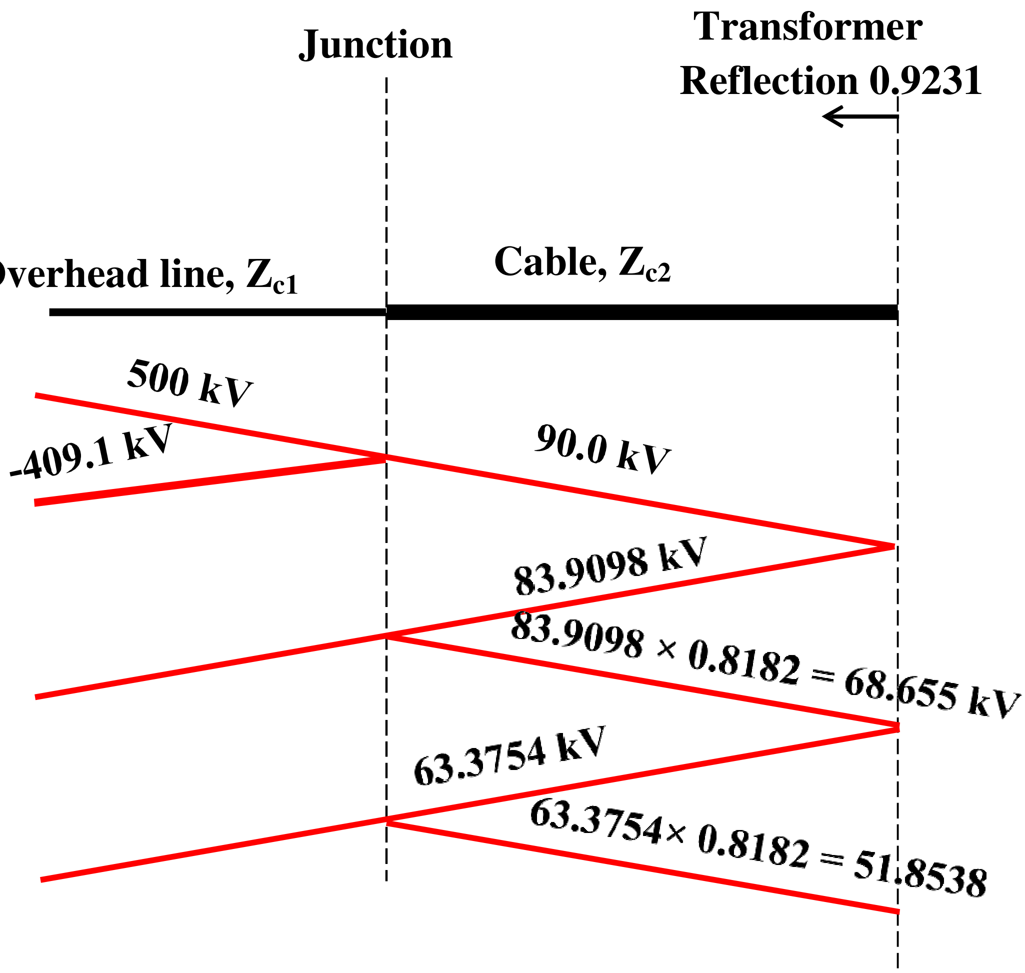
From Cable to Line:

$$\text{Reflection operator: } \Gamma = \frac{(Zc2-Zc1)}{(Z_{c1}+Z_{c2})} = \frac{(400-40)}{(400+40)} = 0.8182$$

Transmission operator $T = \frac{2Zc2}{(Z_{c1}+Z_{c2})} = \frac{2\times400}{(400+40)} = 1.8182$

From cable to transformer

Reflection operator: $\Gamma = \frac{(Zc2-Zc1)}{(Z_{c1}+Z_{c2})} = \frac{(1000-40)}{(1000+40)} = 0.9231$

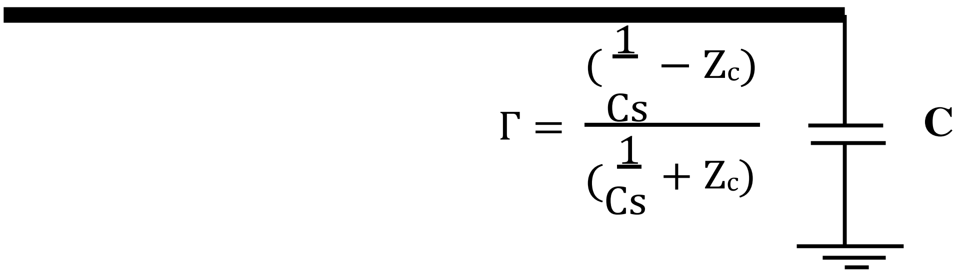


90.9 kV up to 13.2 µsec, 243.46 kV from 13.2 to 26.4 µsec, rising to 358.69 kV at 26.4 µsec.

Reactive Termination

When a loss-free line is terminated by an impedance which contains inductive or capacitive elements, the resulting voltages can be obtained by Laplace transformation. In simple cases, of say a single capacitance or inductor, the impedance of these elements may be written as 1/Cs and Ls respectively (s is the Laplace operator) and the voltage and current will vary exponentially.

If a unit function surge of voltage V is switched on to a line which is terminated by an initially uncharged shunt capacitor of C farads, then the Laplace transform of the voltage reflected is:



$$\Gamma = \frac{\left(\frac{1}{Cs} - Z_c\right)}{\left(\frac{1}{Cs} + Z_c\right)}$$

$$V_{refSected}(s) = \frac{\left(\frac{1}{Cs} - Z_c\right)}{\left(\frac{1}{Cs} + Z_c\right)} \frac{V}{s} = \Gamma(s)\frac{V}{s} = \left[\frac{1 - Z_c Cs}{1 + Z_c Cs}\right]\frac{V}{s}$$

$$V_{refSected}(s) = \frac{V}{Z_c C}\left[\frac{1 - Z_c Cs}{s + \frac{1}{Z_c C}}\right]\frac{1}{s} = \frac{V}{Z_c C}\left[\frac{A}{s} + \frac{B}{s + \frac{1}{Z_c C}}\right]$$

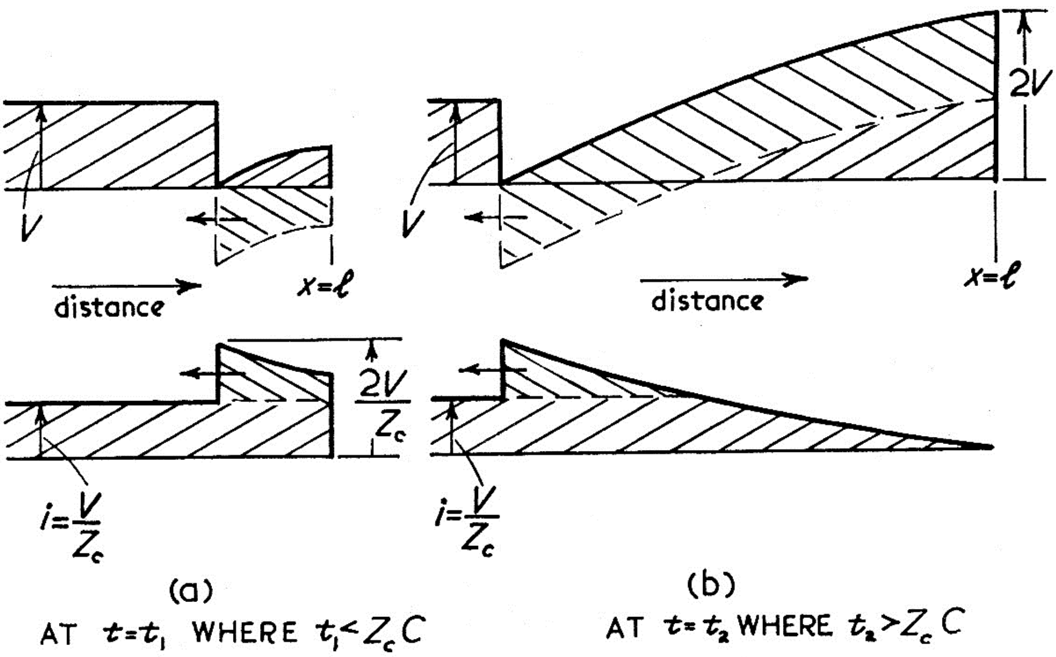
$A = Z_c C$ and $B = -2Z_c C$

$$V_{refSected}(s) = \frac{V}{Z_c C}\left[\frac{Z_c C}{s} + \frac{-2Z_c C}{s + \frac{1}{Z_c C}}\right]$$

$$v_{refSected}(t) = V\left(1 - 2\,e^{-\frac{t}{Z_c C}}\right) \qquad (3)$$

It should be noted that t is here measured from the time the surge reaches the capacitor.

The voltages and currents are illustrated in the figure below. The currents follow from $I = V/Z_c$, $\frac{E_F}{I_F} = -Z_c$ and the above $v_{reflected}$ equation. The distributions of voltages and current shown in this figure and the time variations of voltage given by Equation (3) might have been deduced from the fact that the applied surge is assumed to be of infinitely steep wavefront so that it contains a range of frequencies extending to infinity. The capacitor, therefore, acts initially as a short-circuit so that the reflected wave is negative and brings the voltage at that point to zero. The capacitor then charges up with a time constant of CZ_c until, when completely charges, it constitutes an open circuit and the voltage is then 2V.



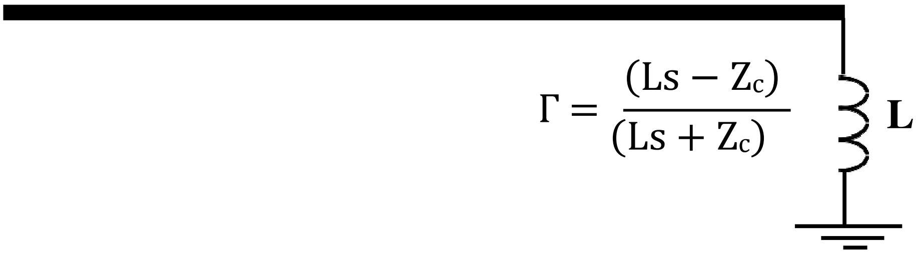
Voltages and currents at a capacitor line termination.

The corresponding case of a shunt inductor of L Henrys gives the transform reflected voltage as

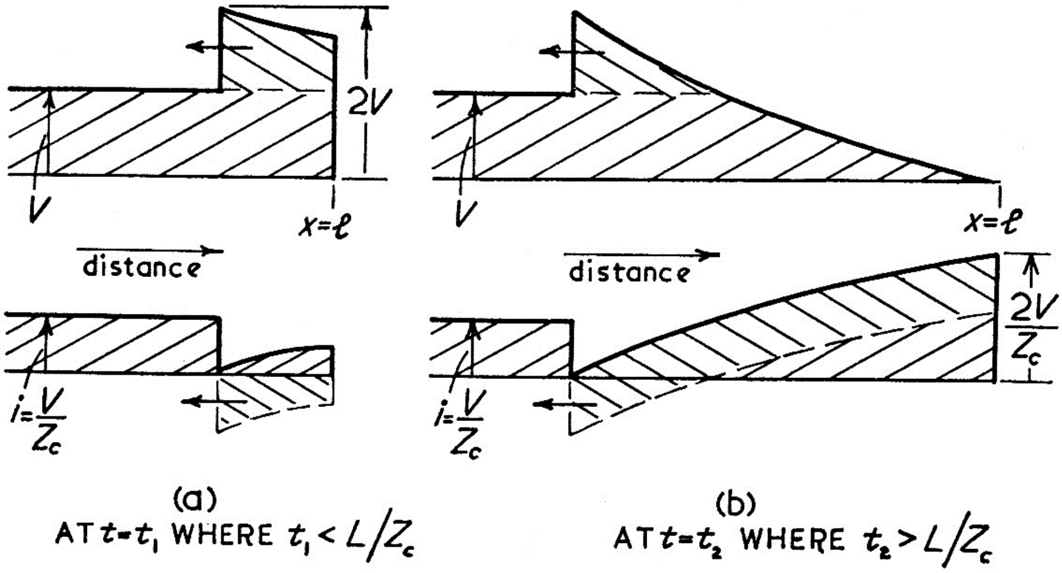
$$\mathcal{L}[v_{refSected}] = \frac{(Ls - Z_c)\,V}{(Ls + Z_c)\,s} = \left[1 - \frac{2\left(\frac{Z_c}{L}\right)}{s + \frac{Z_c}{L}}\right]\frac{V}{s}$$

$$v_{refSected}(t) = V\left(-1 + 2e^{-\frac{Z_c t}{L}}\right) \qquad (4)$$

The voltage and current distributions are shown in the figure below. The voltages and current for this case are the duals of those for the capacitor termination. At the instant the surge arrives the inductor appears as an open circuit so that the voltage doubles. The current increases exponentially from zero in L until finally it corresponds to a short-circuit if the resistance of the inductor is negligible.



$$\Gamma = \frac{(Ls - Z_c)}{(Ls + Z_c)}$$



Voltages and currents at an inductive line termination.

Example:

A rectangular surge of 100 kV and 20 µsec duration travels along a line of surge impedance 500 Ω and 100 km long with a velocity of 3×10^{8} m/sec, towards the end of the line which is terminated with a 0.02 µF capacitor. Calculate the maximum voltage appearing across the capacitor.

$$CZ_c = 0.02 \times 10^{-6} \times 500 = 1 \times 10^{-5}$$

$$v_{refSected}(t) = 100\left(1 - 2\,e^{-\frac{20\times10^{-6}}{1\times10^{-5}}}\right) = 72.9329\,\text{kV}$$

Maximum voltage = 100 + 72.9329 = 172.9329 kV

Reflection and Refraction at a Bifurcation

Let a line of natural impedance Z_1 bifurcate into two branches of natural impedances Z_2 and Z_3, then, as far as the voltage wave is concerned, the transmitted wave will be the same for both branches, since they are in parallel. On the other hand, the transmitted currents will be different in the general case of $Z_3 \neq Z_2$. A short time after reflection the condition will be as shown in Figure B-1 in which it is assumed that the voltage is reflected with reversal of sign.

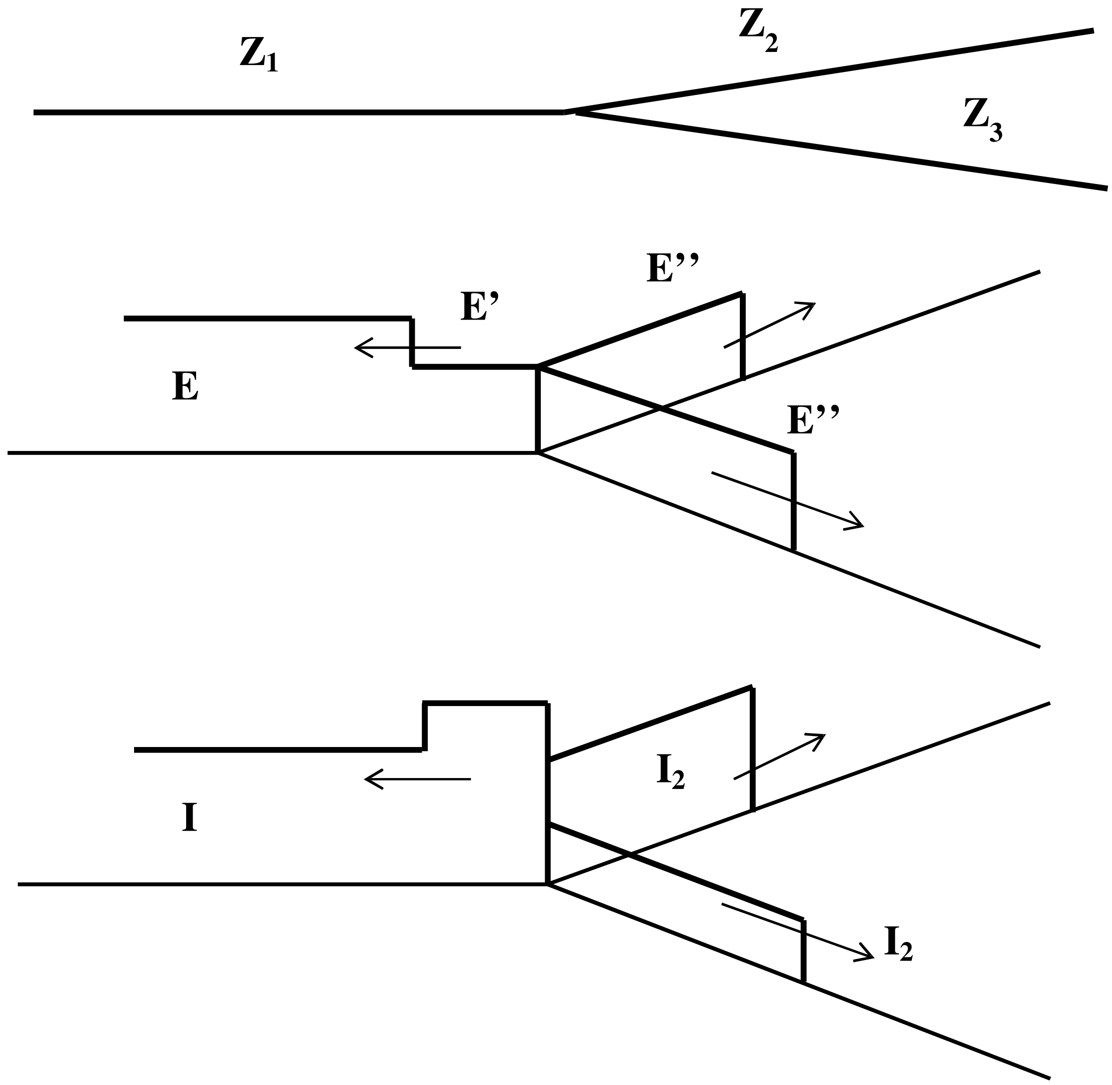


Figure B.1: Effect of a bifurcation on the travelling waves.

Let E_1, I_1 be the incident voltage and current

E’, I’ be the reflected voltage and current

E’’, I_2 be the transmitted voltage and current along Z_2

E’’, I_3 be the transmitted voltage and current along Z_3

Then $I_2 = \frac{Euu}{Z_2}$ and $I_3 = \frac{Euu}{Z_3}$

Also $\frac{E_1}{Z_1} - \left(\frac{E^{FF} - E_1}{Z_1}\right) = \frac{E^{FF}}{Z_2} + \frac{Euu}{Z_3}$

The solution of which is

$$E^{uu} = \frac{\frac{2E_1}{Z_1}}{\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3}}$$

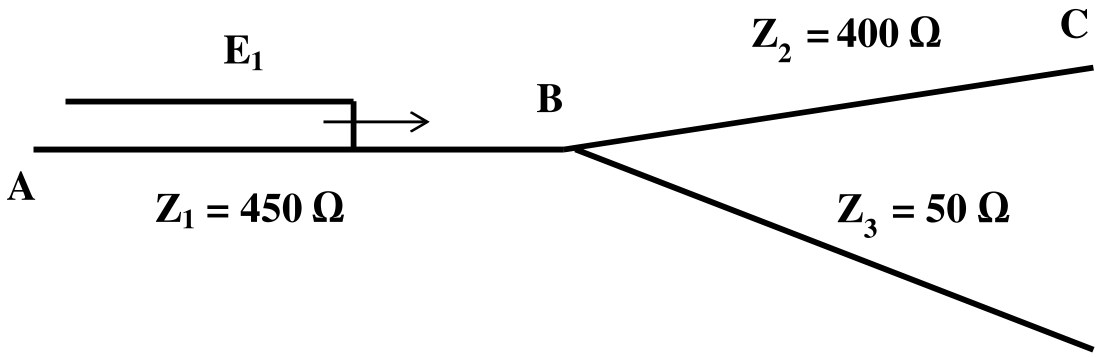
Knowing E_1, all the other quantities can be calculated. If we put $Z_3 = \infty$ in the above expression, we have

$$E^{uu} = \frac{2E_1Z_2}{Z_1 + Z_2}$$

The case becoming that of a simple junction of two lines having different characteristics.

Example

An overhead transmission line having a surge impedance of 450 ohms runs between two substations A and B; at B it branches into two lines C and D, of surge impedances 400 and 50 ohms respectively. If a travelling wave of vertical front and magnitude 25 kV travels along the line AB, calculate the magnitude of the voltage and current waves which enter the branches at C and D.



Incident voltage = E_1 =25000 V

Incident current = $I_1 = E_1/Z_1$ = 25000/450 = 55.6 A

Transmitted voltage along BC and BD

$$E^{uu} = \frac{\frac{2E_1}{Z_1}}{\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3}}$$

$$E^{uu} = \frac{\frac{2 \times 25}{450}}{\frac{1}{450} + \frac{1}{400} + \frac{1}{50}} = 4.5\ kV$$

Transmitted current along BC:

$I_2 = E''/Z_2$ = 4500/400 = 11.25 A

Transmitted current along BD:

$I_3 = E''/Z_3$ = 4500/50 = 90 A

Thus, the current reflected back into line AB = 90 + 11.25 – 55.6 = 45.65 A

Module V

CABLES

Underground Cables

An **underground cable** *essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover.* Although several types of cables are available, the type of cable to be used will depend upon the Working voltage and service requirements. In general, a cable must fulfil the following necessary requirements :

(i) The conductor used in cables should be tinned stranded copper or aluminium of high conductivity. Stranding is done so that conductor may become flexible and carry more current.

(ii) The conductor size should be such that the cable carries the desired load current without overheating and causes voltage drop within permissible limits.

(iii) The cable must have proper thickness of insulation in order to give high degree of safety and reliability at the voltage for which it is designed.

(iv) The cable must be provided with suitable mechanical protection so that it may withstand the rough use in laying it.

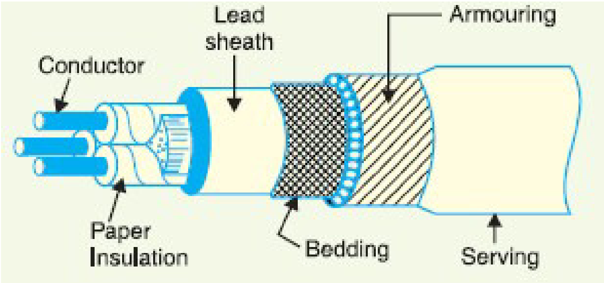
(v) The materials used in the manufacture of cables should be such that there is complete chemical and physical stability throughout.

Construction of Cables

Fig. shows the general construction of a 3-conductor cable. The various parts are : **(*i*)** *Cores or Conductors.* A cable may have one or more than one core (conductor) depending upon the type of service for which it is intended. For instance, the 3-conductor cable shown in Fig. is used for 3-phase service. The conductors are made of tinned copper or aluminium and are usually stranded in order to provide flexibility to the cable.

(ii) *Insulatian.* Each core or conductor is provided with a suitable thickness of insulation, the thickness of layer depending upon the voltage to be withstood by the cable. The commonly used materials for insulation are impregnated paper, varnished cambric or rubber mineral compound.

(iii) *Metallic sheath.* In order to protect the cable from moisture, gases or other damaging liquids (acids or alkalies) in the soil and atmosphere, a metallic sheath of lead or aluminium is provided over the insulation as shown in Fig.



(iv) *Bedding.* Over the metallic sheath is applied a layer of bedding which consists of a fibrous material like jute or hessian tape. The purpose of bedding is to protect the metallic sheath against corrosion and from mechanical injury due to armouring.

(v) *Armouring.* Over the bedding, armouring is provided which consists of one or two layers of galvanised steel wire or steel tape. Its purpose is to protect the cable from mechanical injury while laying it and during the course of handling. Armouring may not be done in the case of some cables.

(vi) *Serving.* In order to protect armouring from atmospheric conditions, a layer of fibrous material (like jute) similar to bedding is provided over the armouring. This is known as *serving.* It may not be out of place to mention here that bedding, armouring and serving are only applied to the cables for the protection of conductor insulation and to protect the metallic sheath from mechanical injury.

Insulating Materials for Cables

The satisfactory operation of a cable depends to a great extent upon the characteristics of insulation used. Therefore, the proper choice of insulating material for cables is of considerable importance. In general, the insulating materials used in cables should have the following properties :

(i) High insulation resistance to avoid leakage current.

(ii) High dielectric strength to avoid electrical breakdown of the cable.

(iii) High mechanical strength to withstand the mechanical handling of cables.

(iv) Non-hygroscopic *i.e.,* it should not absorb moisture from air or soil. The moisture tends to decrease the insulation resistance and hastens the breakdown of the cable. In case the insulating material is hygroscopic, it must be enclosed in a waterproof covering like lead sheath.

(v) Non-inflammable.

(vi) Low cost so as to make the underground system a viable proposition.

(vii) Unaffected by acids and alkalies to avoid any chemical action. No one insulating material possesses all the above mentioned properties. Therefore, the type of insulating material to be used depends upon the purpose for which the cable is required and the quality of insulation to be aimed at. The principal insulating materials used in cables are rubber, vulcanised India rubber, impregnated paper, varnished cambric and polyvinyl chloride.

1. Rubber. Rubber may be obtained from milky sap of tropical trees or it may be produced from oil products. It has relative permittivity varying between 2 and 3, dielectric strength is about 30 kV/mm and resistivity of insulation is 1017□ cm. Although pure rubber has reasonably high insulating properties, it suffers form some major drawbacks *viz.,* readily absorbs moisture, maximum safe temperature is low (about 38ºC), soft and liable to damage due to rough handling and ages when exposed to light. Therefore, pure rubber cannot be used as an insulating material.

2. Vulcanised India Rubber (*V.I.R.*). It is prepared by mixing pure rubber with mineral matter such as zine oxide, red lead etc., and 3 to 5% of sulphur. The compound so formed is rolled into thin sheets and cut into strips. The rubber compound is then applied to the conductor and is heated to a temperature of about 150ºC. The whole process is called *vulcanisation* and the product obtained is known as vulcanised India rubber. Vulcanised India rubber has greater mechanical strength, durability and wear resistant property than pure rubber. Its main drawback is that sulphur reacts very quickly with copper and for this reason, cables using *VIR* insulation have tinned copper conductor. The *VIR* insulation is generally used for low and moderate voltage cables.

3. Impregnated paper. It consists of chemically pulped paper made from wood chippings and impregnated with some compound such as paraffinic or napthenic material. This type of insulation has almost superseded the rubber insulation. It is because it has the advantages of low cost, low capacitance, high dielectric strength and high insulation resistance. The only disadvantage is that paper is hygroscopic and even if it is impregnated with suitable compound, it absorbs moisture and thus lowers the insulation resistance of the cable. For this reason, paper insulated cables are always provided with some protective covering and are never left unsealed. If it is required to be left unused on the site during laying, its ends are temporarily covered with wax or tar. Since the paper insulated cables have the tendency to absorb moisture, they are used where the cable route has a *few joints. For instance, they can be profitably used for distribution at low voltages in congested areas where the joints are generally provided only at the terminal apparatus. However, for smaller installations, where the lenghts are small and joints are required at a number of places, *VIR* cables will be cheaper and durable than paper insulated cables.

4. **Varnished cambric.** It is a cotton cloth impregnated and coated with varnish. This type of insulation is also known as *empire tape.* The cambric is lapped on to the conductor in the form of a tape and its surfaces are coated with petroleum jelly compound to allow for the sliding of one turn over another as the cable is bent. As the varnished cambric is hygroscopic, therefore, such cables are always provided with metallic sheath. Its dielectric strength is about 4 kV/mm and permittivity is 2.5 to 3.8.

5. **Polyvinyl chloride (*PVC*).** This insulating material is a synthetic compound. It is obtained from the polymerisation of acetylene and is in the form of white powder. For obtaining this material as a cable insulation, it is compounded with certain materials known as plasticizers which are liquids with high boiling point. The plasticizer forms a gell and renders the material plastic over the desired range of temperature. Polyvinyl chloride has high insulation resistance, good dielectric strength and mechanical toughness over a wide range of temperatures. It is inert to oxygen and almost inert to many alkalies and acids. Therefore, this type of insulation is preferred over *VIR* in extreme enviormental conditions such as in cement factory or chemical factory. As the mechanical properties (*i.e.,* elasticity etc.) of *PVC* are not so good as those of rubber, therefore, *PVC* insulated cables are generally used for low and medium domestic lights and power installations.

Classification of Cables

Cables for underground service may be classified in two ways according to (*i*) the type of insulating material used in their manufacture (*ii*) the voltage for which they are manufactured. However, the latter method of classification is generally preferred, according to which cables can be divided into the following groups :

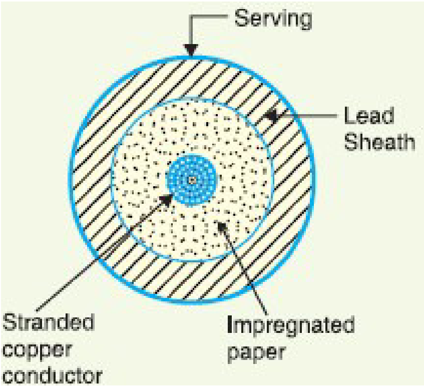
(i) Low-tension (L.T.) cables — upto 1000 V

(ii) High-tension (H.T.) cables — upto 11,000 V

(iii) Super-tension (S.T.) cables — from 22 kV to 33 kV

(iv) Extra high-tension (E.H.T.) cables — from 33 kV to 66 kV

(v) Extra super voltage cables — beyond 132 Kv



A cable may have one or more than one core depending upon the type of service for which it is intended. It may be (*i*) single-core (*ii*) two-core (*iii*) three-core (*iv*) four-core etc. For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand. Fig. shows the constructional details of a single-core low tension cable. The cable has ordinary construction because the stresses developed in the cable for low voltages (upto 6600 V) are generally small. It consists of one circular core of tinned stranded copper (or aluminium) insulated by layers of impregnated paper. The insulation is surrounded by a lead sheath which prevents the entry of moisture into the inner parts. In order to protect the lead sheath from corrosion, an overall serving of compounded fibrous material (jute etc.) is provided. Single-core cables are not usually armoured in order to avoid excessive sheath losses. The principal advantages of single-core cables are simple construction and availability of larger copper section.

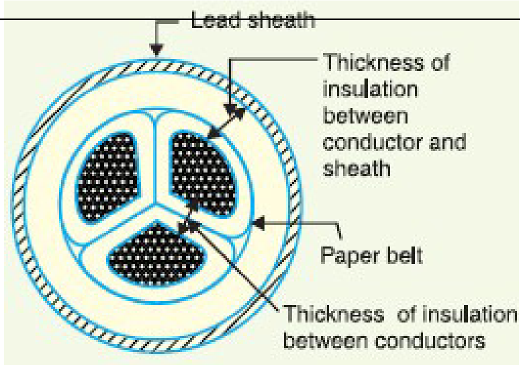
Cables for 3-Phase Service

In practice, underground cables are generally required to deliver 3-phase power. For the purpose, either three core cable or *three single core cables may be used. For voltages upto 66 kV, 3-core cable (*i.e.,* multi-core construction) is preferred due to economic reasons. However, for voltages beyond 66 kV, 3-core-cables become too large and unwieldy and, therefore, single-core cables are used. The following types of cables are generally used for 3-phase service :

1. Belted cables — upto 11 kV

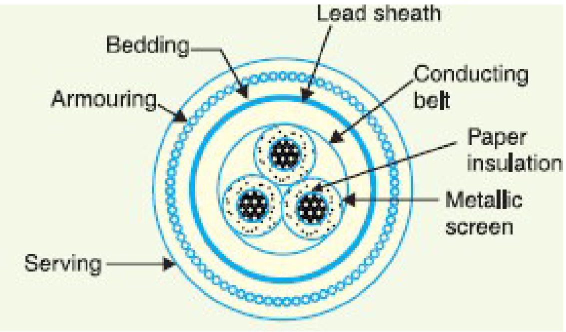
2. Screened cables — from 22 kV to 66 kV

3. Pressure cables — beyond 66 kV.



1. Belted cables. These cables are used for voltages upto 11kV but in extraordinary cases, their use may be extended upto 22kV. Fig shows the constructional details of a 3-core belted cable. The cores are insulated from each other by layer of impregnated paper. Another layer of impregnated paper tape, called *paper belt* is wound round the grouped insulated cores. The gap between the insulated cores is filled with fibrous insulating material (jute etc.) so as to give circular cross-section to the cable. The cores are generally stranded and may be of noncircular shape to make better use of available space. The belt is covered with lead sheath to protect the cable against ingress of moisture and mechanical injury. The lead sheath is covered with one or more layers of armouring with an outer serving (not shown in the figure0). The belted type construction is suitable only for low and medium voltages as the electrostatic stresses developed in the cables for these voltages are more or less radial *i.e.,* across the insulation. However, for high voltages (beyond 22 kV), the tangential stresses also become important. These stresses act along the layers of paper insulation. As the insulation resistance of paper is quite small along the layers, therefore, tangential stresses set up leakage current along the layers of paper insulation. The leakage current causes local heating, resulting in the risk of breakdown of insulation at any moment. In order to overcome this difficulty, *screened cables* are used where leakage currents are conducted to earth through metallic screens.

1. **Screened cables.** These cables are meant for use upto 33 kV, but in particular cases their use may be extended to operating voltages upto 66 kV. Two principal types of screened cables are Htype cables and S.L. type cables.



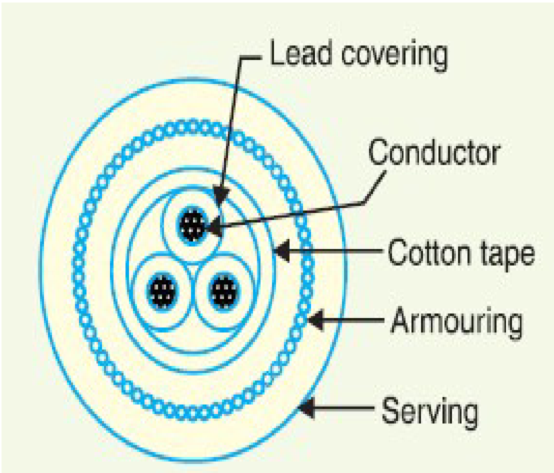
(i) *H-type cables.* This type of cable was first designed by H. Hochstadter and hence the name. Fig.shows the constructional details of a typical 3-core, *H*-type cable. Each core is insulated by layers of impregnated paper. The insulation on each core is covered with a metallic screen which usually consists of a perforated aluminium foil. The cores are laid in such a way that metallic screens make contact with one another. An additional conducting belt (copper woven fabric tape) is wrapped round the three cores. The cable has no insulating belt but lead sheath, bedding, armouring and serving follow as usual. It is easy to see that each core screen is in electrical contact with the conducting belt and the lead sheath. As all the four screens (3 core screens and one conducting belt) and the lead sheath are at †earth potential, therefore, the electrical stresses are purely radial and consequently dielectric losses are reduced.

(ii)

Two principal advantages are claimed for *H*-type cables. Firstly, the perforations in the metallic screens assist in the complete impregnation of the cable with the compound and thus the possibility of air pockets or voids (vacuous spaces) in the dielectric is eliminated. The voids if present tend to reduce the breakdown strength of the cable and may cause considerable damage to the paper insulation. Secondly, the metallic screens increase the heat dissipating power of the cable.

(iii) *S.L. type cables.* Fig. shows the constructional details of a 3-core *S.L. (separate lead) type cable. It is basically *H*-type cable but the screen round each core insulation is covered by its own lead sheath. There is no overall lead sheath but only armouring and serving are provided. The S.L. type cables have two main advantages over *H*-type cables. Firstly, the separate sheaths minimise the possibility of core-to-core breakdown. Secondly, bending of cables becomes easy due to the elimination of overall lead sheath. However, the disadvantage is that the three lead sheaths of S.L.

cable are much thinner than the single sheath of *H*-cable and, therefore, call for greater care in manufacture



2. Pressure cables For voltages beyond 66 kV, solid type cables are unreliable because there is a danger of breakdown of insulation due to the presence of voids. When the operating voltages are greater than 66 kV, *pressure cables* are used. In such cables, voids are eliminated by increasing the pressure of compound and for this reason they are called pressure cables. Two types of pressure cables *viz* oil-filled cables and gas pressure cables are commonly used.

Insulation Resistance of a Single-Core Cable

The cable conductor is provided with a suitable thickness of insulating material in order to prevent leakage current. The path for leakage current is radial through the insulation. The opposition offered by insulation to leakage current is known as insulation resistance of the cable. For satisfactory operation, the insulation resistance of the cable should be very high. Consider a single-core cable of conductor radius $r1$ and internal sheath radius $r2$ as shown in Fig. Let l be the length of the cable and be the resistivity of the insulation.

Consider a very small layer of insulation of thickness dx at a radius x. The length through which leakage current tends to flow is dx and the area of X-section offered to this flow is $2\pi x\ l$.

∴ Insulation resistance of considered layer

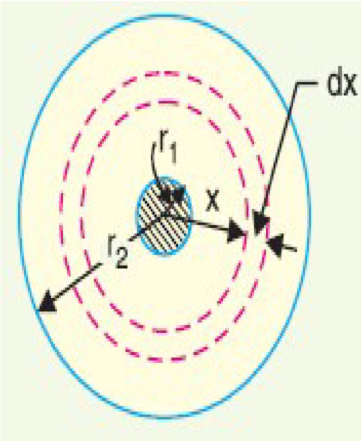
$$= \rho \frac{dx}{2\pi x l}$$

Insulation resistance of the whole cable is

$$R = \int_{r_1}^{r_2} \rho \frac{dx}{2\pi x l} = \frac{\rho}{2\pi l} \int_{r_1}^{r_2} \frac{1}{x} dx$$

$$\therefore \quad R = \frac{\rho}{2\pi l} \log_e \frac{r_2}{r_1}$$

This shows that insulation resistance of a cable is inversely proportional to its length. In other words, if the cable length increases, its insulation resistance decreases and *vice-versa*.



Example 11.1. *A single-core cable has a conductor diameter of 1cm and insulation thickness of 0·4 cm. If the specific resistance of insulation is 5 × 10^14 Ω-cm, calculate the insulation resistance for a 2 km length of the cable.*

Solution

Conductor radius, $r_1 = 1/2 = 0{\cdot}5$ cm

Length of cable, $l = 2$ km $= 2000$ m

Resistivity of insulation, $\rho = 5 \times 10^{14}\ \Omega\text{-cm} = 5 \times 10^{12}\ \Omega\text{-m}$

Internal sheath radius, $r_2 = 0{\cdot}5 + 0{\cdot}4 = 0{\cdot}9$ cm

∴ Insulation resistance of cable is

$$R = \frac{\rho}{2\pi l}\log_e\frac{r_2}{r_1} = \frac{5\times10^{12}}{2\pi\times2000}\log_e\frac{0\cdot9}{0\cdot5}$$

$$= 0{\cdot}234\times10^9\ \Omega = \mathbf{234\ M\ \Omega}$$

Example 11.2. *The insulation resistance of a single-core cable is 495 MΩ per km. If the core diameter is 2·5 cm and resistivity of insulation is 4·5 × 10^{14} Ω-cm, find the insulation thickness.*

Solution.

Length of cable, $l = 1\text{ km} = 1000\text{ m}$

Cable insulation resistance, $R = 495\text{ M}\Omega = 495\times10^6\Omega$

Conductor radius, $r_1 = 2{\cdot}5/2 = 1{\cdot}25\text{ cm}$

Resistivity of insulation, $\rho = 4{\cdot}5\times10^{14}\ \Omega\text{-cm} = 4{\cdot}5\times10^{12}\Omega\text{m}$

Let r_2 cm be the internal sheath radius.

Now, $$R = \frac{\rho}{2\pi l}\log_e\frac{r_2}{r_1}$$

or $$\log_e\frac{r_2}{r_1} = \frac{2\pi l R}{\rho} = \frac{2\pi\times1000\times495\times10^6}{4\cdot5\times10^{12}} = 0{\cdot}69$$

or $$2{\cdot}3\log_{10} r_2/r_1 = 0{\cdot}69$$

or $$r_2/r_1 = \text{Antilog } 0{\cdot}69/2{\cdot}3 = 2$$

or $$r_2 = 2\,r_1 = 2\times1{\cdot}25 = 2{\cdot}5\text{ cm}$$

∴ Insulation thickness $= r_2 - r_1 = 2{\cdot}5 - 1{\cdot}25 = \mathbf{1{\cdot}25\ cm}$

Example 11.3. *A single core cable 5 km long has an insulation resistance of 0·4 MΩ. The core diameter is 20 mm and the diameter of the cable over the insulation is 50 mm. Calculate the resistivity of the insulating material.*

Solution.

Length of cable, $l = 5\text{ km} = 5000\text{ m}$

Cable insulation resistance, $R = 0{\cdot}4\text{ M}\Omega = 0{\cdot}4\times10^6\Omega$

Conductor radius, $r_1 = 20/2 = 10\text{ mm}$

Internal sheath radius, $r_2 = 50/2 = 25\text{ mm}$

∴ Insulation resistance of the cables is

$$R = \frac{\rho}{2\pi l}\log_e\frac{r_2}{r_1}$$

or $$0{\cdot}4\times10^6 = \frac{\rho}{2\pi\times5000}\times\log_e\frac{25}{10}$$

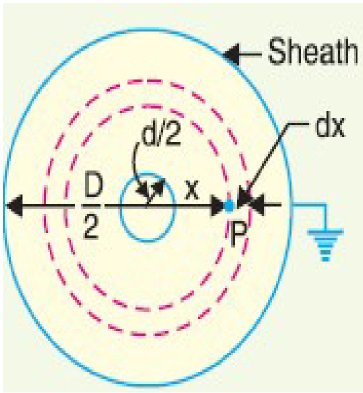
∴ $$\rho = \mathbf{13.72\times10^9\ \Omega m}$$

Capacitance of a Single-Core Cable

A single-core cable can be considered to be equivalent to two long co-axial cylinders. The conductor (or core) of the cable is the inner cylinder while the outer cylinder is represented by lead sheath which is at earth potential. Consider a single core cable with conductor diameter *d* and inner sheath diameter *D*. Let the charge per metre axial length of the cable be *Q* coulombs and be the permittivity of the insulation material between core and lead sheath. Obviously * = 0 *r* where *r* is the relative permittivity of the insulation.

Consider a cylinder of radius *x* metres and axial length 1 metre. The surface area of this cylinder is

= 2π*x* × 1 = 2 π *x* m2



∴ Electric flux density at any point *P* on the considered cylinder is

$$D_x = \frac{Q}{2\pi x} \text{ C/m}^2$$

Electric intensity at point *P*, $E_x = \frac{D_x}{\varepsilon} = \frac{Q}{2\pi x \varepsilon} = \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r}$ volts/m

The work done in moving a unit positive charge from point *P* through a distance *dx* in the direction of electric field is *Ex dx*. Hence, the work done in moving a unit positive charge from conductor to sheath, which is the potential difference *V* between conductor and sheath, is given by :

Here $\varepsilon_r = 4$; $l = 1000$ m

$D = 1{\cdot}8$ cm ; $d = 1$ cm

Substituting these values in the above expression, we get,

$$C = \frac{4 \times 1000}{41 \cdot 4 \log_{10}(1 \cdot 8 / 1)} \times 10^{-9} \text{ F} = 0{\cdot}378 \times 10^{-6} \text{ F} = \mathbf{0{\cdot}378\ \mu F}$$

Example 11.5. *Calculate the capacitance and charging current of a single core cable used on a 3-phase, 66 kV system. The cable is 1 km long having a core diameter of 10 cm and an impregnated paper insulation of thickness 7 cm. The relative permittivity of the insulation may be taken as 4 and the supply at 50 Hz.*

Solution.

Capacitance of cable, $$C = \frac{\varepsilon_r\ l}{41 \cdot 4 \log_{10}(D/d)} \times 10^{-9} \text{ F}$$

Here, $\varepsilon_r = 4$; $l = 1000$ m

$d = 10$ cm; $D = 10 + 2 \times 7 = 24$ cm

Substituting these values in the above expression,

$$C = \frac{4 \times 1000}{41 \cdot 4 \times \log_{10}(24/10)} \times 10^{-9} \text{ F} = 0{\cdot}254 \times 10^{-6} \text{ F} = \mathbf{0{\cdot}254\ \mu F}$$

Voltage between core and sheath is

$$V_{ph} = 66/\sqrt{3} = 38{\cdot}1 \text{ kV} = 38{\cdot}1 \times 10^3 \text{ V}$$

Charging current $= V_{ph}/X_C = 2\pi f C V_{ph}$

$= 2\pi \times 50 \times 0{\cdot}254 \times 10^{-6} \times 38{\cdot}1 \times 10^3 \text{A} = \mathbf{3.04\ A}$

$\log_e(D/d)$

$$= \frac{2\pi \times 8 \cdot 854 \times 10^{-12} \times \varepsilon_r}{2 \cdot 303 \log_{10}(D/d)} \text{ F/m}$$

If the cable has a length of l metres, then capacitance of the cable is

$$C = \frac{\varepsilon_r\ l}{41 \cdot 4 \log_{10} \frac{D}{d}} \times 10^{-9} \text{ F}$$

Example 11.4. *A single core cable has a conductor diameter of 1 cm and internal sheath diameter of 1·8 cm. If impregnated paper of relative permittivity 4 is used as the insulation, calculate the capacitance for 1 km length of the cable.*

Solution.

Capacitance of cable, $$C = \frac{\varepsilon_r\ l}{41 \cdot 4 \log_{10}(D/d)} \times 10^{-9} \text{ F}$$

Example 11.6. *A 33 kV, 50 Hz, 3-phase underground cable, 4 km long uses three single core cables. Each of the conductor has a diameter of 2·5 cm and the radial thickness of insulation is 0·5 cm. Determine (i) capacitance of the cable/phase (ii) charging current/phase (iii) total charging kVAR. The relative permittivity of insulation is 3.*

Solution.

(*i*) Capacitance of cable/phase, $C = \dfrac{\varepsilon_r\, l}{41 \cdot 4 \log_{10}(D/d)} \times 10^{-9}$ F

Here $\varepsilon_r = 3$; $l = 4$ km $= 4000$ m

$d = 2 \cdot 5$ cm ; $D = 2.5 + 2 \times 0.5 = 3.5$ cm

Putting these values in the above expression, we get,

$$C = \frac{3 \times 4000 \times 10^{-9}}{41 \cdot 4 \times \log_{10}(3 \cdot 5 / 2 \cdot 5)} = \mathbf{1984 \times 10^{-9}\ F}$$

(*ii*) Voltage/phase, $V_{ph} = \dfrac{33 \times 10^3}{\sqrt{3}} = 19 \cdot 05 \times 10^3$ V

Charging current/phase, $I_C = \dfrac{V_{ph}}{X_C} = 2\pi f C V_{ph}$

$$= 2\pi \times 50 \times 1984 \times 10^{-9} \times 19 \cdot 05 \times 10^3 = \mathbf{11 \cdot 87\ A}$$

(*iii*) Total charging kVAR $= 3 V_{ph} I_C = 3 \times 19 \cdot 05 \times 10^3 \times 11 \cdot 87 = \mathbf{678 \cdot 5 \times 10^3\ kVAR}$

Dielectric stress in a single core cable:

Under operating conditions, the insulation of a cable is subjected to electrostatic forces. This is known as dielectric stress. The dielectric stress at any point in a cable is infact the potential gradient (or *electric intensity) at that point.

Consider a single core cable with core diameter d and internal sheath diameter D. As proved in Art 11.8, the electric intensity at a point x metres from the centre of the cable is

$$E_x = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r x} \text{ volts/m}$$

By definition, electric intensity is equal to potential gradient. Therefore, potential gradient g at a point x metres from the centre of cable is

$$g = E_x$$

or $$g = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r x} \text{ volts/m} \quad ...(i)$$

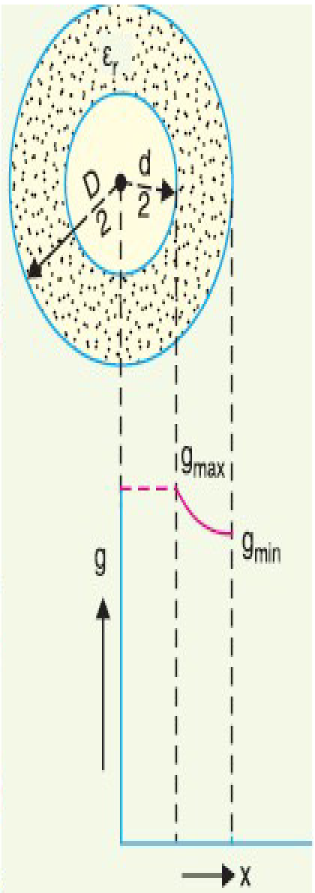


Fig. 11.14

As proved in Art. 11.8, potential difference V between conductor and sheath is

$$V = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \log_e \frac{D}{d} \text{ volts}$$

or $$Q = \frac{2\pi \varepsilon_0 \varepsilon_r V}{\log_e \frac{D}{d}} \quad ...(ii)$$

Substituting the value of Q from exp. (ii) in exp. (i), we get,

$$g = \frac{\dfrac{2\pi \varepsilon_0 \varepsilon_r V}{\log_e D/d}}{2\pi \varepsilon_0 \varepsilon_r x} = \frac{V}{x \log_e \frac{D}{d}} \text{ volts/m} \quad ...(iii)$$

$$\therefore \quad \frac{g_{max}}{g_{min}} = \frac{\dfrac{2V}{d \log_e D/d}}{\dfrac{2V}{D \log_e D/d}} = \frac{D}{d}$$

The variation of stress in the dielectric is shown in Fig. 11.14. It is clear that dielectric stress is maximum at the conductor surface and its value goes on decreasing as we move away from the conductor. It may be noted that maximum stress is an important consideration in the design of a cable. For instance, if a cable is to be operated at such a voltage that *maximum stress is 5 kV/mm, then the insulation used must have a dielectric strength of atleast 5 kV/mm, otherwise breakdown of the cable will become inevitable.

It is clear from exp. (*iii*) that potential gradient varies inversely as the distance x. Therefore, potential gradient will be maximum when x is minimum *i.e.,* when $x = d/2$ or at the surface of the conductor. On the other hand, potential gradient will be minimum at $x = D/2$ or at sheath surface.

∴ Maximum potential gradient is

$$g_{max} = \frac{2V}{d \log_e \frac{D}{d}} \text{ volts/m} \qquad [\text{Putting } x = d/2 \text{ in exp. } (iii)]$$

Minimum potential gradient is

$$g_{min} = \frac{2V}{D \log_e \frac{D}{d}} \text{ volts/m} \qquad [\text{Putting } x = D/2 \text{ in exp. } (iii)]$$

Grading of Cables

The process of achieving uniform electrostatic stress in the dielectric of cables is known as **grading of cables.**

It has already been shown that electrostatic stress in a single core cable has a maximum value (*gmax*) at the conductor surface and goes on decreasing as we move towards the sheath. The maximum voltage that can be safely applied to a cable depends upon *gmax i.e.,* electrostatic stress at the conductor surface. For safe working of a cable having homogeneous dielectric, the strength of di- electric must be more than *gmax* . If a dielectric of high strength is used for a cable, it is useful only near the conductor where stress is maximum. But as we move away from the conductor, the electrostatic stress decreases, so the dielectric will be unnecessarily overstrong. The unequal stress distribution in a cable is undesirable for two reasons.

Firstly, insulation of greater thickness is required which increases the cable size. Secondly, it may lead to the breakdown of insulation. In order to overcome above disadvantages, it is necessary to have a uniform stress distribution in cables. This can be achieved by distributing the stress in such a way that its value is increased in the outer layers of dielectric. This is known as grading of cables.

The following are the two main methods of grading of cables :

1. Capacitance Grading
2. Intersheath Grading

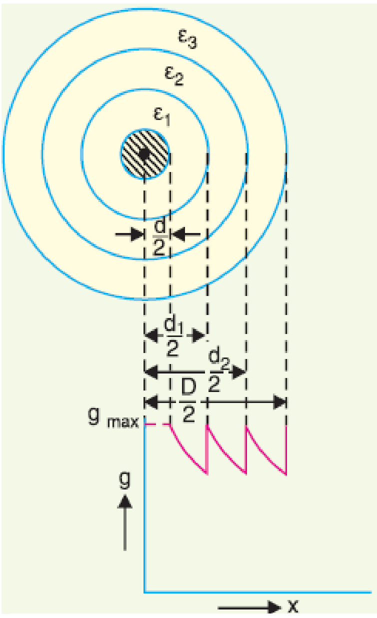
Capacitance Grading

The process of achieving uniformity in the dielectric stress by using layers of different dielectrics is known as **capacitance grading.**

In capacitance grading, the homogeneous dielectric is replaced by a composite dielectric. The composite dielectric consists of various layers of different dielectrics in such a manner that relative permittivity ε_r of any layer is inversely proportional to its distance from the centre. Under such conditions, the value of potential gradient at any point in the dielectric is constant and is independent of N its distance from the centre. In other words, the dielectric stress in the cable is same everywhere and the grading is ideal one.

However, ideal grading requires the use of an infinite number of dielectrics which is an impossible task. In practice, two or three dielectrics are used in the decreasing order of permittivity; the dielectric of highest permittivity being used near the core.

The capacitance grading can be explained beautifully by referring to Fig. There are three dielectrics of outer diameter *d*1, *d*2 and *D* and of relative permittivity E1, E2 and E3 respectively.



If the permittivities are such that $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$ and the three dielectrics are worked at the same maximum stress, then,

$$\frac{1}{\varepsilon_1 d} = \frac{1}{\varepsilon_2 d_1} = \frac{1}{\varepsilon_3 d_2}$$

or $$\varepsilon_1 d = \varepsilon_2 d_1 = \varepsilon_3 d_2$$

Potential difference across the inner layer is

$$V_1 = \int_{d/2}^{d_1/2} g\,dx = \int_{d/2}^{d_1/2} \frac{Q}{2\pi\varepsilon_0\varepsilon_1 x}\,dx$$

$$= \frac{Q}{2\pi\varepsilon_0\varepsilon_1}\log_e\frac{d_1}{d} = \frac{g_{max}}{2}\,d\log_e\frac{d_1}{d}\left[\because \frac{Q}{2\pi\varepsilon_0\varepsilon_1} = ^{*}\frac{g_{max}}{2}d\right]$$

Similarly, potential across second layer (V_2) and third layer (V_3) is given by ;

$$V_2 = \frac{g_{max}}{2}\,d_1\log_e\frac{d_2}{d_1}$$

$$V_3 = \frac{g_{max}}{2}\,d_2\log_e\frac{D}{d_2}$$

Total p.d. between core and earthed sheath is

$$V = V_1 + V_2 + V_3$$

$$= \frac{g_{max}}{2}\left[d\log_e\frac{d_1}{d} + d_1\log_e\frac{d_2}{d_1} + d_2\log_e\frac{D}{d_2}\right]$$

If the cable had homogeneous dielectric, then, for the same values of d, D and g_{max}, the permissible potential difference between core and earthed sheath would have been

$$V' = \frac{g_{max}}{2}\,d\log_e\frac{D}{d}$$

Obviously, $V > V'$ *i.e.,* for given dimensions of the cable, a graded cable can be worked at a greater potential than non-graded cable. Alternatively, for the same safe potential, the size of graded cable will be less than that of non-graded cable. The following points may be noted :

(*i*) As the permissible values of g_{max} are peak values, therefore, all the voltages in above expressions should be taken as peak values and not the r.m.s. values.

(*ii*) If the maximum stress in the three dielectrics is not the same, then,

$$V = \frac{g_{1max}}{2}\,d\log_e\frac{d_1}{d} + \frac{g_{2max}}{2}\,d_1\log_e\frac{d_2}{d_1} + \frac{g_{3max}}{2}\,d_2\log_e\frac{D}{d_2}$$

The principal disadvantage of this method is that there are a few high grade dielectrics of reasonable cost whose permittivities vary over the required range.

Intersheath Grading

In this method of cable grading, a homogeneous dielectric is used, but it is divided into various layers by placing metallic inter sheaths between the core and lead sheath. The inter sheaths are held at suitable potentials which are in between the core potential and earth potential. This arrangement im-proves voltage distribution in the dielectric of the cable and consequently more uniform potential gradient is obtained.

Consider a cable of core diameter *d* and outer lead sheath of diameter *D*. Suppose that two inter sheaths of diameters *d*1 and *d*2 are inserted into the homogeneous dielectric and maintained at some fixed potentials. Let *V*1,
*V*2 and *V*3 respectively be the voltage between core and inter sheath 1, between inter sheath 1 and 2 and between Inter sheath 2 and outer lead sheath. As there is a definite potential difference between the inner and outer layers of each inter sheath, therefore, each sheath can be treated like a homogeneous single core cable. As proved in Maximum stress between core and inter sheath 1 is

$$g_{1max} = \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}}$$

Similarly,

$$g_{2max} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}}$$

$$g_{3max} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

Since the dielectric is homogeneous, the maximum stress in each layer is the same *i.e.,*

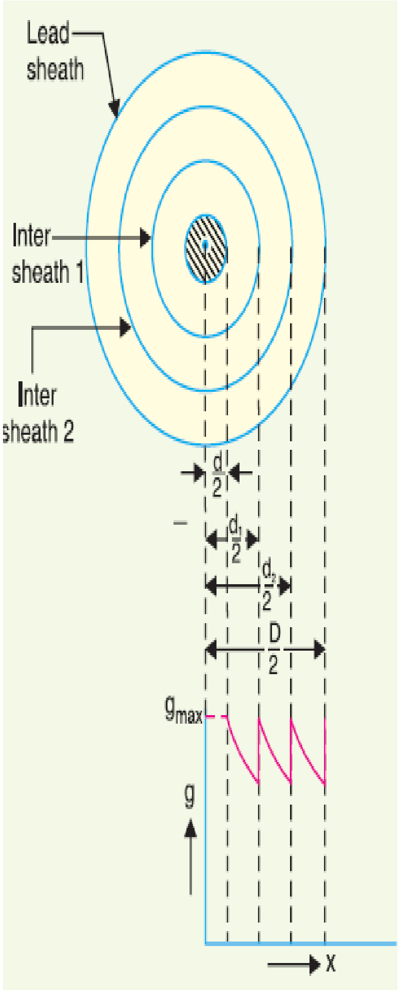
$$g_{1max} = g_{2max} = g_{3max} = g_{max} \text{ (say)}$$

$$\therefore \quad \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

As the cable behaves like three capacitors in series, therefore, all the potentials are in phase *i.e.* Voltage between conductor and earthed lead sheath is

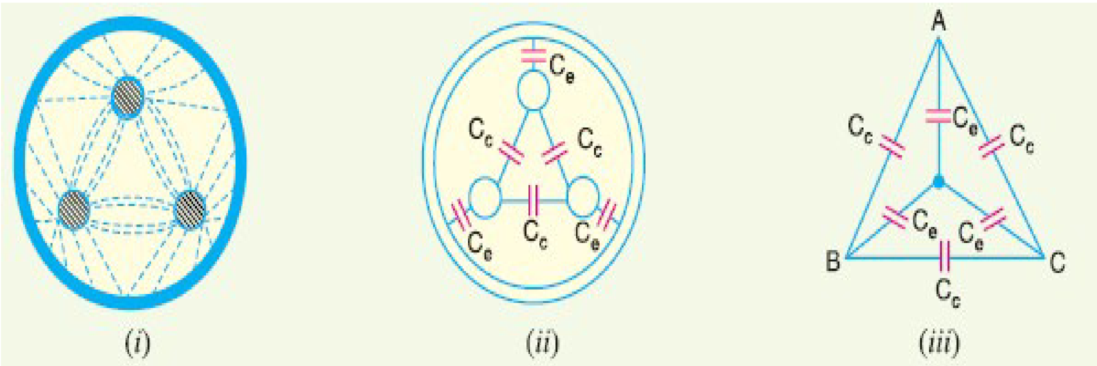
$$V = V_1 + V_2 + V_3$$

Intersheath grading has three principal disadvantages. Firstly, there are complications in fixing the sheath potentials. Secondly, the intersheaths are likely to be damaged during transportation and installation which might result in local concentrations of potential gradient. Thirdly, there are considerable losses in the intersheaths due to charging currents. For these reasons, intersheath grading is rarely used.

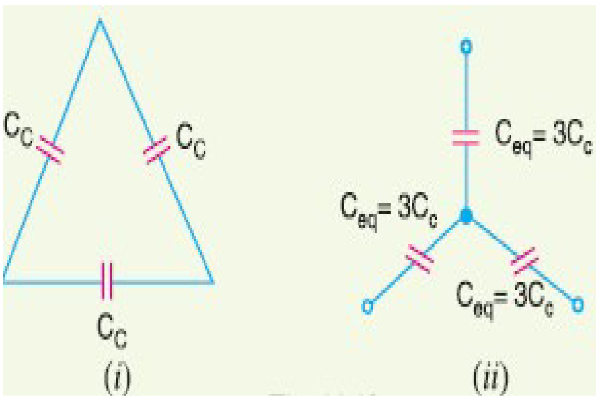


Capacitance of 3-Core Cables

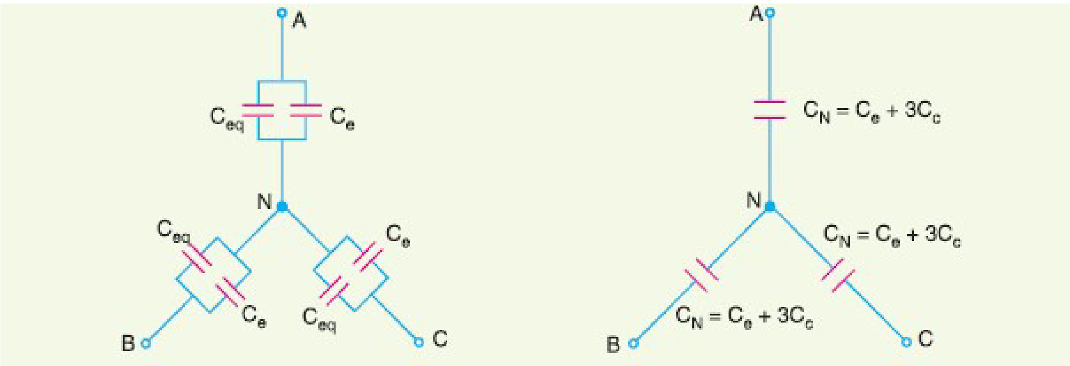
The capacitance of a cable system is much more important than that of overhead line because in cables (*i*) conductors are nearer to each other and to the earthed sheath (*ii*) they are separated by a dielectric of permittivity much greater than that of air. Fig. shows a system of capacitances in a 3-core belted cable used for 3 phase system. Since potential difference exists between pairs of conductors and between each conductor and the sheath, electrostatic fields are set up in the cable as shown in Fig.(*i*). These electrostatic fields give rise to core-core capacitances *Cc* and conductor- earth capacitances *Ce* as shown in Fig. (*ii*). The three *Cc* are delta connected whereas the three *Ce* are star connected, the sheath forming the star point



They lay of a belted cable makes it reasonable to assume equality of each *Cc* and each *Ce*. The three delta connected capacitances *Cc* [See Fig.(*i*)] can be converted into equivalent star connected capacitances as shown in Fig.(*ii*). It can be easily *shown that equivalent star capacitance *Ceq* is equal to three times the delta capacitance *Cc i.e.* $C_{eq} = 3C_c$.



The system of capacitances shown in Fig.(*iii*) reduces to the equivalent circuit shown in Fig. (*i*). Therefore, the whole cable is equivalent to three star-connected capacitors each of capacitance



(*i*) (*ii*)

$$C_N = C_e + C_{eq}$$
$$= C_e + 3C_c$$

If V_{ph} is the phase voltage, then charging current I_C is given by ;

$$I_C = \frac{V_{ph}}{\text{Capacitive reactance per phase}}$$
$$= 2\pi f V_{ph} C_N$$
$$= 2\pi f V_{ph} (C_e + 3C_c)$$

Measurements of Ce and Cc

Although core-core capacitance *Cc* and core-earth capacitance *Ce* can be obtained from the empirical formulas for belted cables, their values can also be determined by measurements. For this purpose, the following two measurements are required :

(i) In the first measurement, the three cores are bunched together (*i.e.* commoned) and the capacitance is measured between the bunched cores and the sheath. The bunching eliminates all the three capacitors *Cc*, leaving the three capacitors *Ce* in parallel. Therefore, if *C*1 is the

$$C_1 = 3\,C_e$$

or $$C_e = \frac{C_1}{3}$$

measured capacitance, this test yields :

Knowing the value of *C*1, the value of *Ce* can be determined.

(ii) In the second measurement, two cores are bunched with the sheath and capacitance is measured between them and the third core. This test yields $2C_c + C_e$. If C_2 is the measured capacitance, then, $C_2 = 2C_c + C_e$

As the value of C_e is known from first test and C_2 is found experminentally, therefore, value of C_c can be determined. It may be noted here that if value of C_N (= $C_e + 3C_c$) is desired, it can be found directly by another test. In this test, the capacitance between two cores or lines is measured with the third core free or connected to the sheath. This eliminates one of the capacitors C_e so that

$$
\begin{aligned}
C_3 &= C_c + \frac{C_c}{2} + \frac{C_e}{2} \\
&= \frac{1}{2}\,(C_e + 3C_c) \\
&= \frac{1}{2}\,C_N
\end{aligned}
$$

OBJECTIVE QUESTIONS

PART-A

1	Length of the cable is doubled, its capacitance C will be	C
	A. One-fourth.	
	B. One-half.	
	C. Doubled.	
	D. Unchanged.	
2	What should be the minimum depth (in metre)of cable trench to dug for laying of 1.1 kV?	A
	A. 0.75.	
	B. 0.90.	
	C. 1.05.	
	D. 1.20.	
3	Galvanised steel is generally used as	D
	A. Stray wire.	
	B. Earth wire.	
	C. Structural components.	
	D. All of the above.	
4	Objectives of electrical power transmission is/are	D
	A. Transmission system must be more efficient with minimum line losses	
	B. Voltage regulation of the transmission line must be zero or minimum	
	C. both 1 and 2	
	D. neither 1 nor 2	
5	Advantages of higher transmission voltage is/are	D
	A. Power transfer capability of the transmission line is increased	
	B. Transmission line losses are reduced	
	C. Area of cross section and volume of the conductor is reduced	
	D. all of the above	
6	Which of the following statement is true	A
	A. At higher voltage, cost of transmission is reduced	
	B. At higher voltage, cost of transmission is increased	
	C. efficiency decreased	
	D. all of the above	
7	Maximum power transfer capability of transmission line can be increased by	D
	A. Parallel transmission lines	
	B. Using series capacitance	
	C. Using bundled conductors	
	D. all of the above	
8	For flat voltage profile system, voltage regulation is	A
	A. 0%	
	B. 100%	
	C. 50%	
	D. any of the above	

9	Maximum power transfer in a transmission line can be obtained by	C
	A. increasing voltage level	
	B. reducing reactance	
	C. either 1 or 2	
	D. none of the above	
10	Ferranti effect will not occur in which of the following transmission lines	B
	A. long transmission lines	
	B. short transmission lines	
	C. medium transmission lines	
	D. all of the above	
11	Find the number of strands of ACSR conductor for 4 layer transmission line?	C
	A. 1	
	B. 7	
	C. 37	
	D. 29	
12	A 3 layer and diameter of each strand is d, then find the total diameter of ACSR conductor?	D
	A. d	
	B. 2d	
	C. 3d	
	D. 5d	
13	Find the number of strands of ACSR conductor for 3 layer transmission line?	C
	A. 1	
	B. 7	
	C. 19	
	D. 29	
14	The total number of strands in a ACSR conductor are 7, then find the layer number?	A
	A. 2	
	B. 3	
	C. 5	
	D. 7	
15	An ACSR conductor has a diameter of 2 cm has internal inductance of 0.05 mH/Km. If this ACSR is replaced with another having a diameter of 4 cm then its internal inductance is	C
	A. 0.1 mH/Km	
	B. 0.025 mH/Km	
	C. 0.05 mH/Km	
	D. 0 mH/Km	
16	An ACSR conductor has internal inductance 0.05 mH/Km for $\mu_r = 1$. If this ACSR is replaced with another having $\mu_r = 2$, then find the internal inductance?	A
	A. 0.1 mH/Km	
	B. 0.025 mH/Km	
	C. 0.05 mH/Km	
	D. 0 mH/Km	
17	Telecommunication lines are transposed to reduce the	B

	A. efficiency	
	B. radio interference in communication lines	
	C. voltage level	
	D. all of the above	
18	Which of the following produces the radio interference in communication lines?	C
	A. electro magnetic induction	
	B. electro static induction	
	C. both 1 and 2	
	D. none of the above	
19	To reduce the radio interference which line is/are transposed?	C
	A. Power line	
	B. Both power and telecommunication lines	
	C. either 1 or 2	
	D. none of the above	
20.	In which of the following configuration power transferability is higher?	A
	A. triangular configuration	
	B. horizontal configuration	
	C. same in both configuration	
	D. none of the above	
21	A 3 layer, total diameter of an ACSR conductor is 5 cm. Find the diameter of each strand?	A
	1 cm	
	A. 1.5 cm	
	B. 5 cm	
	C. 15 cm	
22	The total number of strands(N) is concentrically stranded cable with total annular space filled with strands of uniform diameter is given by (if x is number of layers)	B
	A. $N = 3x^2+3x+1$	
	B. $N = 3x^2-3x+1$	
	C. $N = 3x^2-6x+1$	
	D. $N = 3x^2-2x+1$	
23	Bundled conductors in EHV transmission lines	C
	A. increase inductance	
	B. increase capacitance	
	C. decrease inductance	
	D. decrease capacitance	
24	The internal flux linkage due to internal flux of a conductor is	A
	A. $I/2*10^{-7}$ wb-T/m	
	B. $I/4*10^{-7}$ wb-T/m	
	C. $I/6*10^{-7}$ wb-T/m	
	D. all of the above	
25	The skin effect shows that	D
	A. the distribution of AC current is uniform through the cross section of the conductor	
	B. current density is more at the centre of the conductor	

	C. current density is lower at the surface of the conductor	
	D. current density is more at the surface of the conductor	
26	Skin effect depends on	D
	A. frequency	
	B. conductivity	
	C. relative permeability	
	D. all of the above	
27	If the frequency is increased, then skin effect will	A
	A. increases	
	B. decreases	
	C. remains unaffected	
	D. any of the above	
28	If skin depth is more, then skin effect is	B
	A. more	
	B. less	
	C. either 1 or 2	
	D. none of the above	
29	Proximity effect is more in case of	A
	A. power cables	
	B. over head lines	
	C. same in both cases	
	D. none of the above	
30	Proximity effect depends on	D
	A. frequency	
	B. distance between the conductors	
	C. relative permeability	
	D. all of the above	
31	Skin effect is more in case of	A
	A. communication lines	
	B. power lines	
	C. same in both cases	
	D. none of the above	
32	Apart from the skin effect the non uniformity of the current distribution is also caused by	C
	A. bundled conductors	
	B. ferranti effect	
	C. proximity effect	
	D. all of the above	
33	Transmission lines are transposed to reduce	D
	A. ferranti effect	
	B. skin effect	
	C. proximity effect	
	D. interference with neighbouring communication lines	
34	In transmission lines distribution constants are	D
	A. resistance	

	B. inductance and capacitance	
	C. inductance and resistance	
	D. both 1 and 2	
35	Aluminium is now most commonly employed conductor material in transmission lines than copper because	D
	A. it is more conductive	
	B. its tensile strength is more	
	C. costlier	
	D. it is cheaper and lighter	
36	The skin effect of conductor will increase when	B
	A. diameter decrease	
	B. resistivity decrease	
	C. frequency decrease	
	D. all of the above	
37	ACSR means	B
	A. Aluminium conductor steel reinforced	
	B. Aluminium core steel reinforced	
	C. Aluminium copper steel reinforced	
	D. all conductor steel reinforced	
38	The inductance of single phase two wire line is given by	A
	A. $4\times10^{-7}\times \ln(d/r')$ H/m	
	B. $4\times10^{-7}\times \ln(r'/d)$ H/m	
	C. $0.4\times10^{-7}\times \ln(d/r')$ H/m	
	D. $0.4\times10^{-7}\times \ln(r'/d)$ H/m	
39	If the diameter of the conductor is increased	B
	A. the inductance is increased	
	B. the inductance is decreased	
	C. the resistance is increased	
	D. no change in inductance and resistance	
40	Due to proximity effect, the increase in conductor resistance is not negligible in	A
	A. underground cable	
	B. overhead transmission lines	
	C. communication lines	
	D. all of the above	
41	The fact that current density is higher at the surface when compared to centre is known as	C
	A. corona	
	B. proximity effect	
	C. skin effect	
	D. all of the above	
42	The presence of earth in case of overhead lines	B
	A. increase inductance	
	B. increase capacitance	
	C. decrease inductance	
	D. decrease capacitance	

43	The term self GMD is used to calculate	B
	A. capacitance	
	B. inductance	
	C. resistance	
	D. both 1 and 2	
44	Inductance of transmission line will decrease when	D
	A. both GMD and GMR increase	
	B. both GMD and GMR decrease	
	C. GMD increase and GMR decrease	
	D. GMD decrease and GMR increase	
45	If we increase the spacing between the phase conductors, the line capacitance	B
	A. increases	
	B. decreases	
	C. remains unaffected	
	D. none of the above	
46	If we increase the length of the transmission line, the charging current	B
	A. increases	
	B. decreases	
	C. remains unaffected	
	D. none of the above	
47	In triangular configuration, inductance and capacitance values are ------ and ------ respectively	C
	A. less, less	
	B. higher, higher	
	C. less, higher	
	D. higher, less	
48	If we increase the spacing between the phase conductors, the value of line inductance	B
	A. decrease	
	B. increase	
	C. remains unaffected	
	D. none of the above	
49	Transmission line parameters of the short transmission line are	B
	A. 1,Z,Y,1	
	B. 1,Z,0,1	
	C. 1,0,Y,1	
	D. Z,0,Y,1	
50	The ABCD constants of a 3-phase transmission line are A = D = 0.8∠1°, B = 170∠85° Ω , C = 0.002∠90.4° â„§. The sending end voltage is 400 kV. The receiving end voltage under no load condition is	B
	A. 400 kV	
	B. 500 kV	
	C. 600 kV	
	D. 350 kV	
51	The bundling of conductors is done primarily to	A
	A. reduce reactance	

	B. increase reactance	
	C. increase ratio interference	
	D. reduce radio interference.	
52	The characteristic impedance of a transmission line depends upon	D
	A. shape of the conductor	
	B. surface treatment of the conductors	
	C. conductivity of the material	
	D. geometrical configuration. of the conductors.	
53	For a distortion-less transmission line (G = shunt conductance between two wires)	A
	A. R/L = G/C	
	B. RL=GC	
	C. RG=LC	
	D. RLGC=0	
54	Guard ring transmission line	B
	A. improves power factor	
	B. reduces earth capacitance of the lowest unit	
	C. reduces transmission losses	
	D. improves regulation	
55	When the power is to be transmitted over a distance of 500 km, the transmission voltage should be in the range	D
	A. 33 kV - 66 kV	
	B. 66 kV - 100 kV	
	C. 110 kV - 150 kV	
	D. 150kV - 220kV	
56	A relay used on long transmission lines is	A
	A. mho's relay	
	B. reactance relay	
	C. impedance relay	
	D. no relay is used	
57	Total load transmitted through a 3 phase transmission line is 10,000 kW at 0.8 power factor lagging. The I^2R losses are 900 kW. The efficiency of transmission line is	B
	A. 60%	
	B. 90%	
	C. 95%	
	D. 99%.	
58	The power transmitted will be maximum when	A
	A. Sending end voltage is more	
	B. Receiving end voltage is more	
	C. Reactance is high	
	D. Corona losses are least	
59	Neglecting losses in a transmission system, if the voltage is doubled, for the same power transmission, the weight of conductor material required will be	D
	A. four times	
	B. double	

	C. half	
	D. one fourth	
60	In a transmission line having negligible resistance the surge impedance is	D
	A. $(L+C)^{1/2}$	
	B. $(C/L)^{1/2}$	
	C. $(1/LC)^{1/2}$	
	D. $(L/C)^{1/2}$	
61	A relay used on short transmission lines is	A
	A. Reactance relay	
	B. Mho's relay	
	C. Impedance relay	
	D. None of the above.	
62	In case the characteristic impedance of the line is equal to the load impedance	D
	A. all the energy will pass to the earth	
	B. all the energy will be lost in transmission losses	
	C. the system will resonate badly	
	D. all the energy sent will be absorbed by the load.	
63	For a properly terminated line	D
	A. ZR=ZO	
	B. Z/R > ZO	
	C. ZR < ZO	
	D. ZR =Z0 = 0	
64	The dielectric strength of air at 25^0C and 76 cm/Hg is	D
	A. 1 kV/cm	
	B. 1 kV/mm	
	C. 3 kV/cm	
	D. 30 kV/cm.	
65	Transmission lines link	D
	A. service points to consumer premises	
	B. distribution transformer to consumer premises	
	C. receiving end station to distribution transformer	
	D. generating station to receiving end station	
66	In case of open circuit transmission lines the reflection coefficient is	D
	A. 1	
	B. 0.5	
	C. -1	
	D. Zero.	
67	Impedance relay is used on	B
	A. Short transmission lines	
	B. Medium transmission lines	
	C. Long transmission line	
	D. All the transmission lines.	
68	Which type of insulators are used on 132 kV transmission lines ?	B
	A. Pin type	

	B. Disc type	
	C. Shackle type	
	D. Pin and shackle type	
69	String efficiency can be improved by	D
	A. using Longer cross arm	
	B. grading the insulator	
	C. using a guard ring	
	D. any of the above.	
70.	Minimum horizontal clearance of a low voltage transmission line from residential buildings must be	C
	A. 11/2 feet	
	B. 3 feet	
	C. 4 feet	
	D. 8 feet	
71	Alternating current power is transmitted at high voltage	B
	A. to safeguard against pilferage	
	B. to minimize transmission losses	
	C. to reduce cost of generation	
	D. to make the system reliable	
72	Stranded conductors arc used for transmitting, power at high voltages because of	C
	A. increased tensile strength	
	B. better wind resistance	
	C. ease-in handling	
	D. low cost	
73	For the same resistance of line the ratio, weight of copper conductor/ weight of aluminium conductor , is	D
	A. 0.50	
	B. 0.75	
	C. 1.50	
	D. 2.0.	
74	In high voltage transmission lines the top most conductor is	D
	A. R-phase conductor	
	B. Y- phase conductor	
	C. B-phase conductor	
	D. Earth conductor	
75	If 3000 kW power is to be transmitted over a distance of 30 km, the desirable transmission voltage will be	B
	A. 11 kV	
	B. 33 kV	
	C. 66 kV	
	D. 132 kV.	
76	The permissible voltage variation in transmission and distribution system is	C
	A. ± 0.1%	
	B. ± 1%	

	C. ±10%	
	D. ± 25%.	
77	The voltage of transmission can be regulated by	D
	A. use of tap changing transformers	
	B. switching in shunt capacitors at the receiving end during heavy loads	
	C. use of series capacitors to neutralize the effect of series reactance	
	D. any of the above methods	
78	The most economic voltage for transmitting given power over a known distance by overhead transmission line is approximately	A
	A. 3.6 kV/km	
	B. 1.6 kV/km	
	C. 2.6 kV/km	
	D. 3.6 kVkm.	
79	In case the height of transmission tower is increased	D
	A. the line capacitance and inductance will not change	
	B. the line capacitance will decrease but line inductance will decrease	
	C. the line capacitance will decrease and line inductance will increase	
	D. the line capacitance will decrease but line inductance will remain unaltered.	
80	In a transmission line if booster transformer are to be used, preferred location will be	C
	A. at the receiving end	
	B. at the sending end	
	C. at the intermediate point	
	D. any where in the line	
81	Under no load conditions the current in a transmission line is due to	B
	A. corona effects	
	B. capacitance of the line	
	C. back flow from earth	
	D. spinning reserve	
82	For high voltage transmission lines, why are conductors suspended from towers?	A
	A. Increase the clearance from ground.	
	B. Reduce clearance from ground.	
	C. Take care of increase in length.	
	D. Reduce the environmental effects.	
83	The maximum tension in a section of overhead line conductor between two supports of unequal height occurs at	A
	A. The higher support	
	B. The lower support	
	C. Midpoint of the conductors	
	D. None of these	
84	Galloping in transmission line conductors arises due to	A
	A. Asymmetrical layers of ice formation.	
	B. Vortex phenomenon in light winds.	
	C. Heavy weight of the line conductors	
	D. Adoption of horizontal conductor configuration.	
85	What is the minimum clearance of HV lines from ground across the streets?	B

	A. 3 m.	
	B. 6 m.	
	C. 5 m.	
	D. 8 m.	
86	What is the minimum clearance provided for the 132 kV line from the ground?	B
	A. 3.2 m.	
	B. 6.4 m.	
	C. 7.5 m.	
	D. 10.5 m.	
87	What is the horizontal spacing between phase conductors of 132 kV line?	A
	A. 8 m.	
	B. 11 m.	
	C. 14 m.	
	D. 17 m.	
88	Which type of insulator is used on 132 kV transmission lines?	B
	A. Pin type	
	B. Disc type	
	C. Shackle type	
	D. Pin and shackle type	
89	What are the line constants in a transmission line?	D
	A. Resistance and series conductance only	
	B. Series and shunt conductance	
	C. Resistance, inductance and capacitance	
	D. Resistance, inductance, capacitance and shunt conductance	
90	Proximity effect	D
	A. Is more in large conductors, high frequency	
	B. Increases the resistance of the conductor	
	C. Reduces the self reactance	
	D. All of these	
91	The inductance of a power transmission line increases with	C
	A. Decrease in line length	
	B. Increase in diameter of conductor	
	C. Increasing in spacing between the phase conductors	
	D. Increase in load current carried by the conductors	
92	Why is the transmission lines transposed?	C
	A. Reduce corona loss	
	B. Reduce skin effect	
	C. Prevent interference with the neighbouring telephone lines	
	D. Prevent short circuit between any two lines	
93	A three phase transmission line has its conductors at the corners of an equilateral triangle with sides 3m. The diameter of each conductor is 1.63 cm. What is the inductance of the line per phase?	A
	A. 1.232 mH	
	B. 1.184 mH	
	C. 2.236 mH	

	D. 2.68 mH	
94.	Why is high voltage transmission lines transposed?	
	A. Corona losses can be minimised	
	B. Computation of inductance becomes easier	
	C. Voltage drops in the lines can be minimised	
	D. Phase voltage imbalances can be minimised	
95.	When is the transposition of conductors in a transmission line done?	A
	A. When the conductors are not equally spaced	
	B. When the conductors are spaced equilaterally	
	C. When a telephone line runs parallel to the power line	
	D. None of these	
96	How many cores are used in a cable for the transmission of voltages upto 66 kV?	C
	A. Single core	
	B. Two core	
	C. Three core	
	D. All of the above	
97	The cable best suited for the transmission of voltages from 33 kV to 66 kV is________________.	B
	A. Belted cables	
	B. Screened cables	
	C. Pressure cables	
	D. None of these	
98	In transmission system, the weight of copper used is proportional to	C
	A. Square of voltage	
	B. Voltage	
	C. 1 / (square of voltage)	
	D. 1 / voltage	
99	What is the main reason for using the high voltage for the long distance power transmission?	A
	A. Reduction in the transmission losses	
	B. Reduction in the time of transmission	
	C. Increase in system reliability	
	D. None of these	
100	Which type of system is generally adopted for the generation and transmission of electrical power?	C
	A. 3 phase 4 wire	
	B. 2 phase 3 wire	
	C. 3 phase 3 wire	
	D. None of these	
101	Where is the strain type of insulators used?	D
	A. Low voltage overhead lines.	
	B. Dead ends	
	C. Change in direction of the transmission lines.	
	D. Both end .	
102	These insulators are provided on which type of plane?	A

	A. Vertical plane	
	B. Horizontal plane.	
	C. On the surface.	
	D. All of these.	
103	Which insulator is also called as spool type of insulators?	B
	A. Pin type.	
	B. Shackle type.	
	C. Suspension type.	
	D. Stay insulators.	
104	Assembly of which type of insulators are used as strain type of insulators?	C
	A. Pin type.	
	B. Shackle type.	
	C. Suspension type.	
	D. None of these.	
105	Which type of insulators is mainly used for low voltage overhead lines?	B
	A. Pin type.	
	B. Shackle type.	
	C. Suspension type.	
	D. None of these.	
106	The stay type of insulators is insulated at a height of not less than __________ m.	C
	A. 5	
	B. 6	
	C. 3	
	D. 4	
107	Post type insulators are generally used in lines operating	C
	A. Above 100 kV.	
	B. Below 33 kV.	
	C. At any voltage level.	
	D. None of these.	
108	Which type of insulators is used in guy wires?	A
	A. Stay insulators.	
	B. Shackle insulators.	
	C. Pin type.	
	D. Strain type.	
109	Which type of insulator is used on 132 kV transmission lines?	B
	A. Pin type.	
	B. Disc type.	
	C. Shackle type.	
	D. Pin and shackle type.	
110	Where is the strain type insulators used?	D
	A. At dead ends.	
	B. At any intermediate anchor tower.	
	C. On straight runs.	
	D. Either or .	
111	Porcelain is produced by firing at high temperature of which all mixtures?	D

	A. Kaolin	
	B. Feldspar	
	C. Quartz	
	D. All of these.	
112	What is the dielectric strength of porcelain?	B
	A. 55 kV/cm.	
	B. 60 kV/cm.	
	C. 75 kV/cm.	
	D. 80 kV/cm.	
113	Why is the wavy structure of pin insulators used?	C
	A. Increases mechanical strength.	
	B. Increases puncture strength.	
	C. Increases flash over voltage.	
	D. Increases thermal strength.	
114	The number of discs in a string of insulators for 400 kV ac over head transmission line lies in the range of	B
	A. 32 – 33	
	B. 22 – 23	
	C. 15 – 16	
	D. 9 – 10	
115	What is the purpose of guard ring?	A
	A. Reduce the earth capacitance of the lowest unit.	
	B. Increase the earth capacitance of the lowest unit.	
	C. Reduce the transmission line losses.	
	D. None of these.	
116	Which shielding is called the static shielding of the string?	A
	A. Using the guard rings.	
	B. Grading the insulators.	
	C. Increasing the length of cross arms.	
	D. None of this.	
117	Higher the frequency, ______________.	B
	A. Lower the corona loss.	
	B. Higher is the corona loss.	
	C. Does not effect.	
	D. Depends on the physical conditions.	
118	Which harmonics are generated during the corona, which leads to the increase in corona losses?	A
	A. Third harmonics.	
	B. Fifth harmonics.	
	C. Seventh harmonics.	
	D. None of these.	
119	What is the use of bundled conductors?	A
	A. Reduces surface electric stress of conductor.	
	B. (B0Increases the line reactance.	
	C. Decreases the line capacitance.	

	D. None of these.	
120.	On which factor is the corona loss dependent on?	B
	A. Material of the conductor.	
	B. Diameter of the conductor.	
	C. Height of the conductor.	
	D. None of these.	
121	In which climate does the chances of occurrence of corona is maximum	D
	A. Dry	
	B. Hot summer.	
	C. Winter.	
	D. Humid.	
122	What is the effect on corona, if the spacing between the conductors is increased?	B
	A. Corona increases.	
	B. Corona is absent.	
	C. Corona decreases.	
	D. None of these.	
123	Why are the hollow conductors used?	C
	A. Reduce the weight of copper.	
	B. Improve stability.	
	C. Reduce corona	
	D. Increase power transmission capacity.	
124	Which of these given statements is wrong in consideration with bundled conductors?	D
	A. Control of voltage gradient.	
	B. Reduction in corona loss.	
	C. Reduction in the radio interference.	
	D. Increase in interference with communication lines.	
125	Why are bundled conductors employed?	D
	A. Appearance of the transmission line is improved.	
	B. Mechanical stability of the line is improved.	
	C. Improves current carrying capacity	
	D. Improves the corona performance of the line.	

SUBJECTIVE QUESTIONS

Module-I

1. Write short notes about ACSR, Bundled conductors and write the advantages and disadvantages of both.
2. a) Define Inductance and derive the inductance of a 1-Φ 2 wire conductor line.

   b) The three conductors of a 3-phase line are arranged at the corners of a triangle of sides 2 m, 2·5 m and 4·5 m. Calculate the inductance per km of the line when the conductors are regularly transposed. The diameter of each conductor is 1·24 cm.
3. Derive the equation for the inductance of 3-Φ transmission if the corners of the transmission Line forms like an equilateral triangle.
4. Derive the equation for the inductance of 3-Φ transmission line for unsymmetrical spacing but Transposed
5. Derive the equation of a capacitance of 3- Φ double circuit with unsymmetrical but transposed.
6. a) Derive the capacitance of a 1-Φ 2 wire line.

   b) A single-phase transmission line has two parallel conductors 3 meters apart, radius of each Conductor being 1 cm. Calculate the capacitance of the line per km. Given that $\varepsilon_0 = 8{\cdot}854 \times 10{-}12$ F/m.
7. Clearly explain what do you understand by GMR and GMD of a transmission line?
8. Develop an expression for the inductance of a single phase two-wire transmission line taking into account the internal flux linkages. Assume conductors are solid.
9. What are the bundled conductors? How they are reduce the inductive reactance of the line.
10. What are the different types of line conductors? Explain them.

Module –II

1. Explain about Surge Impedance and Surge Impedance Loading in power transmission lines
2. Explain how medium transmission line can be represented as nominal –π using relevant equations.
3. Classify the Overhead Transmission lines with their exact equivalent circuits
4. A 3-Φ 50HZ transmission line has resistance, inductance and capacitance per phase of 10Ω, 0.1H and 0.9μF and delivers a load of 45MW at 132KV and 0.8 pf lag. Determine the efficiency and regulation of the line using nominal-T method.
5. Evaluate the A,B,C,D constants of long Transmission line.
6. Define the following terms

   a) Efficiency of transmission line b) Voltage regulation c) Charging current d) Ferranti Effect
7. Define A, B, C, and D constants of a transmission line? What are their values in short lines?
8. Define regulation of a short 3-phase transmission system and develop an expression for approximate voltage regulation.
9. Explain the physical significance of the generalized circuit constants A, B, C and D of a transmission line? Find the values of A, B, C and D in the nominal-π method in terms of Z and Y.
10. Explain the effect of power factor on regulation and efficiency.

Module -III

1. Define String Efficiency and explain any one Method for Improvement of it
2. Classify and Explain the overhead transmission line Insulators
3. Define Corona Phenomenon and explain factors affecting Corona
4. Define string efficiency. What is the necessity in having high string efficiency? Explain how it can be achieved?
5. What is Corona? What are the factors which affect Corona? Write the methods to reduce corona.
6. Each line of a 3 phase system is suspended by a string of 3 similar insulators. If the voltage across the line unit is 17.5KV, calculate the line voltage. Assume that the shunt capacitance between each insulator and earth is 1/8th of the capacitance of the insulator itself. Also find the string efficiency.
7. Explain how the effect of ice and wind can be included in sag calculation of transmission lines.
8. Define sag? Explain how can calculate sag and tension when the supports are at equal level with neat derivation.
9. Derive equations for termination of lines with different types of conditions?
10. A transmission line has a span of 214m between level supports. The conductors have a cross sectional are of $25cm^2$. Calculate the factor of safety under the following conditions.

    Vertical Sag =2.35m Wind Pressure=1.5kg/m run

    Breaking stress=2540 kg/cm^2 Weight of conductor=1.125kg/m run

Module -IV

1. Explain about travelling waves with relevant equations?

2. a) Define terms

   (i) Incident wave (ii) Reflected wave (iii) Refracted wave

3. Write short notes on line terminated with short circuited end.

4. When the transmission line is terminated with the capacitive load, hoe do you find out the expressions of reflected voltage and current wave.

5. Starting from the principles show that surges behave as traveling waves. Find expressions for surge impedance and wave velocity.

6. A step wave of 110 kV travels through a line having a surge impedance of 350Ω. The line is terminated by an inductance of 5000 μH. find the voltage across the inductance and reflected voltage wave.

7. A 400 m long loss less transmission line has a 100Ω characteristics resistance and terminates in a 60Ω resistance. A 400v dc source having an internal resistance of 300Ω is connected to the line at t=0. Calculate the sending end and receiving end voltage and current reflection coefficients of the line.

8. What is use of Bewley's lattice diagram?

9. A 400 m long loss less transmission line has a 100Ω characteristics resistance and terminates in a 60Ω resistance. A 400v dc source having an internal resistance of 300Ω is connected to the line at t=0. Calculate steady state current & voltage at receiving end of the line.

10. Derive reflection and refraction coefficients for Line terminated with resistive load

Module -V

1. What are the advantages of used cables for transmission of electrical power as compared to overhead lines ?
2. A single core 11KV, 50Hz, 5km long cable has a core diameter of 1.5cm and diameter of under sheath 3.0cm. The relative permittivity of the insulating material is 2.5. The power factor on open circuit is 0.04. Determine
   i) The capacitance of the cable
   ii) Charging current per conductor
   iii) Dielectric loss
   iv) The equivalent insulation resistance.
3. a) Derive formula for capacitance of single core cable.
   b) A Single core cable has a conductor diameter of 1cm and internal sheath diameter of 1.8cm. If impregnated paper of relative permittivity 4 is used as the insulation, calculate the capacitance for 1km length of the line.
4. Discuss about the different types of cables?
5. Explain about capacitance grading and intersheath grading?
6. What are the insulating materials used in underground cable?
7. Determine the maximum and minimum stress in the insulation of a 33 KV single core cable which has a core diameter of 1.5 cm and sheath of inside diameter 5 cm.
8. Derive the formula for calculating the current rating of a cable?
9. Single core, lead covered cable is to be designed for 66 KV to earth. Its conductor radius is 10 mm and its three insulating materials A, B and C have relative permittivity of 6, 5, and 4 respectively and the corresponding maximum permissible stress of 4.0, 3.0, and 2.0 KV / mm respectively. Find the maximum diameter of the lead sheath.
10. Show that in a three core belted cable the neutral capacitance to each conductor C_u is equal to $C_s + 3C_c$ where C_s and C_c are capacitance of each conductor to sheath and to each other respectively.

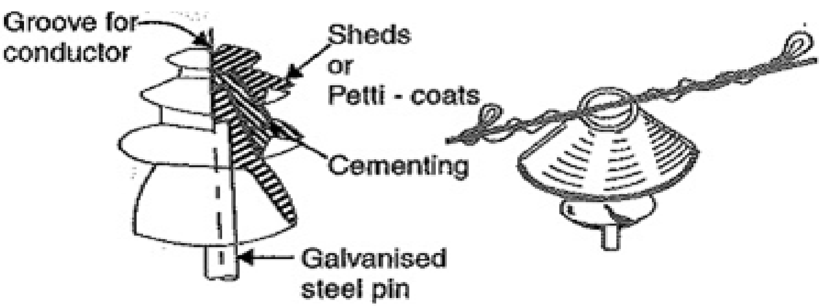
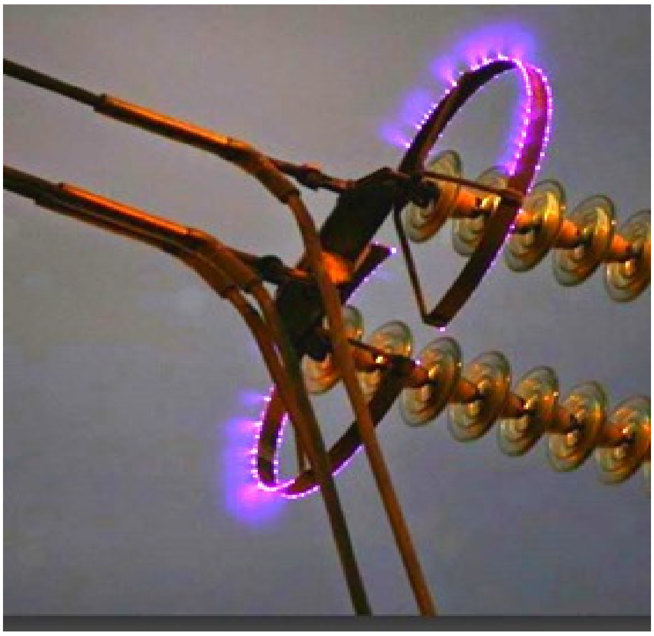
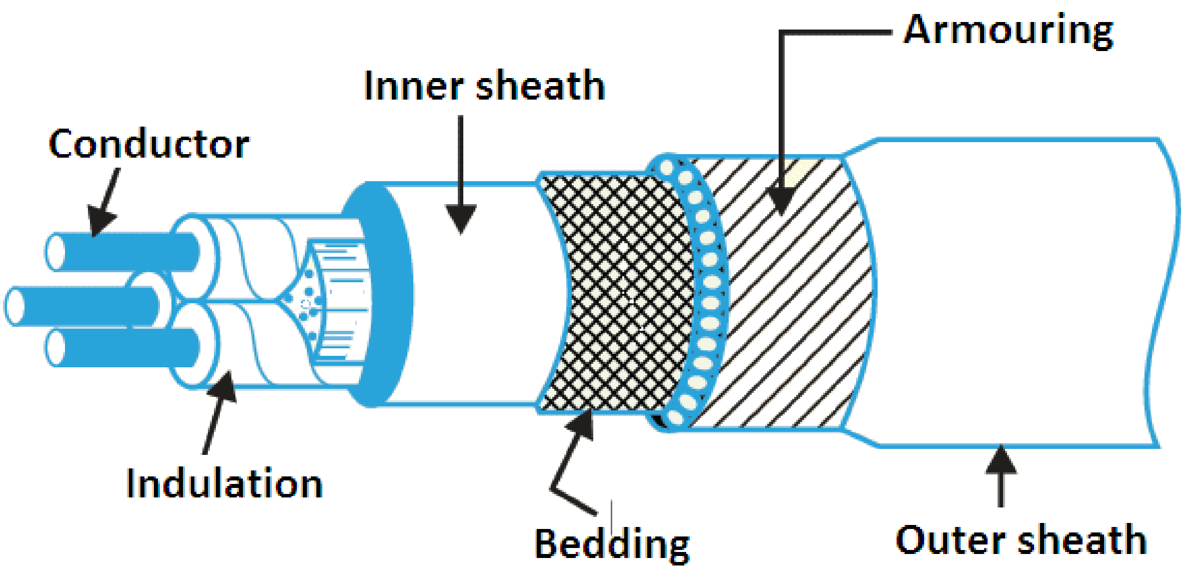


Fig. Pin-type insulator

Pin Insulator



Corona Effect in Transmission Line Visible at Night



Construction of a cable