

Power System-I

Prepared by :

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Basic Course Information

Course Title	Power System-I
Course Code	EEE 427
Credit	03
Marks	150

SYNOPSIS/RATIONALE

This course is essential for learning the concepts, principles, and recent trends of the power system. Through this course, students will learn and be able to determine the various essential parameters of the power system as well as learn about mechanical design, selection of cable and current, voltage relation of a transmission line.

OBJECTIVE

The objectives of the course are:

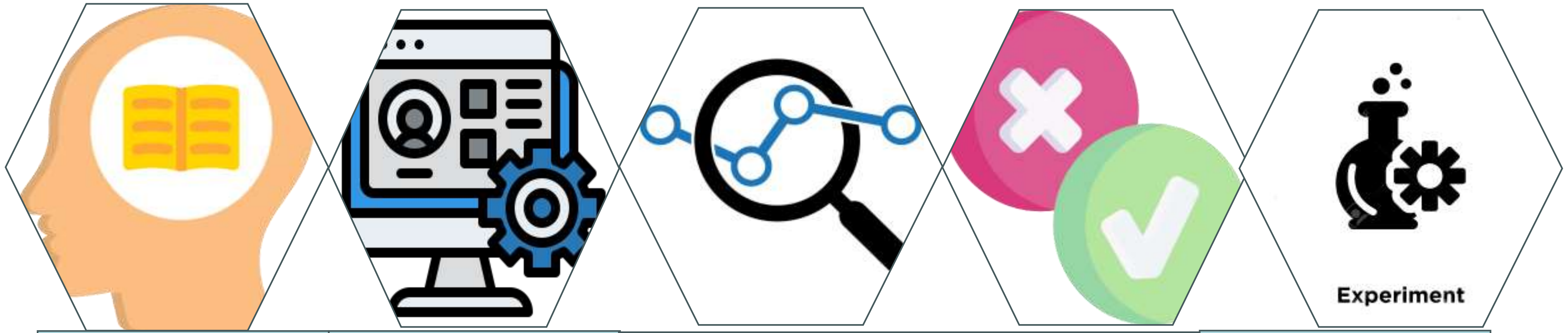
🎯To know about the recent trends in power systems, distribution systems, the

🎯parameters of the transmission line, their properties, and their effect on performance.

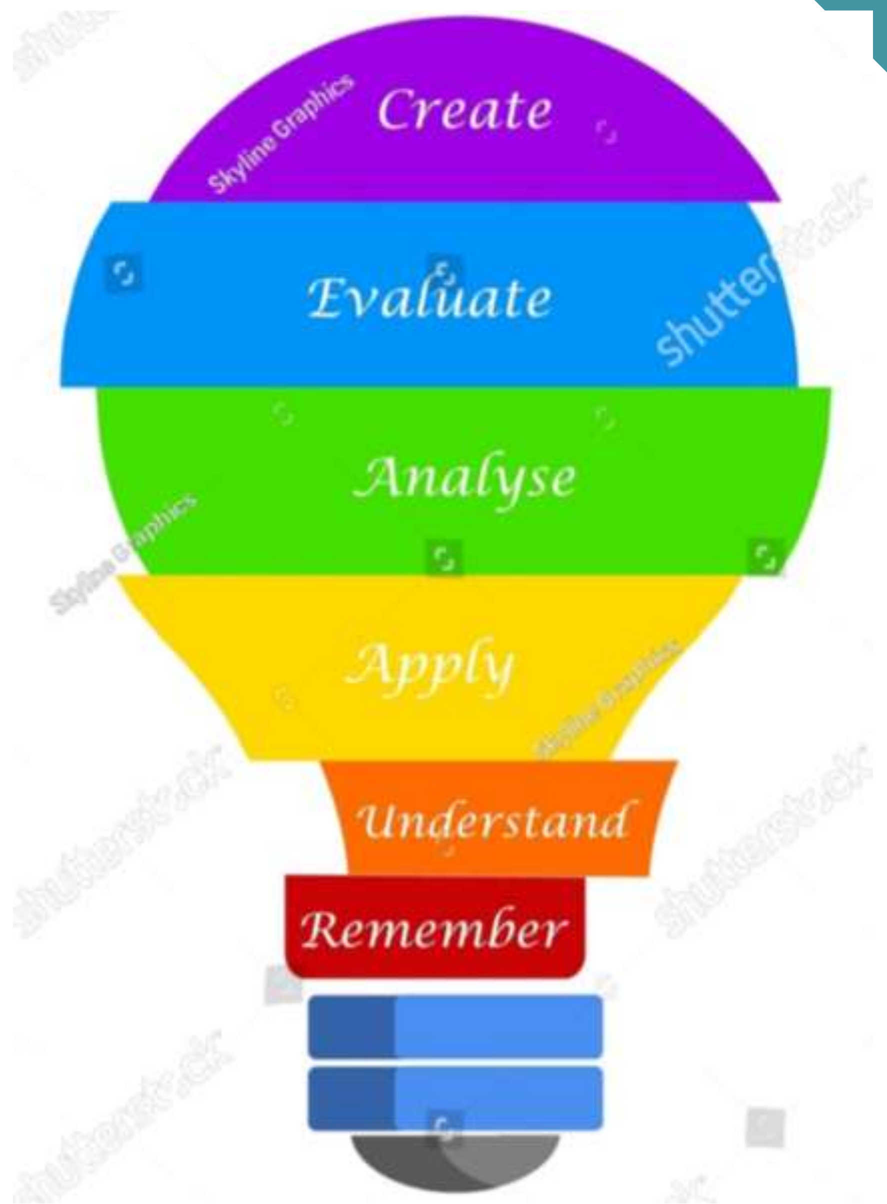
🎯To be familiarized with current, voltage relation in different types of transmission line and properties of cable with their specifications.

🎯To become skilled at the mechanical design of the overhead cable.

Course Learning Outcome (CLO)



CLO-1: Explain the aspects of network representation, transmission line and stability in power system	**CLO-2:** Apply numerical & analytical methods to solve load flow problems of a power System	**CLO-3:** Analyze symmetrical and asymmetrical faults in power system.	**CLO-4:** Design a tool for analyzing a power system, subject to specific requirements and/or constraints	**CLO-5:** Conduct experiment for analysis of electric power system behavior



Course Schedule

Week	Course Content	Teaching-Learning Strategy	Sources	Assessment Strategy	Aligned CLOs
1	Introduction to electromagnetic fields and waves, power distribution concepts	Lectures, discussions, visual aids	Slides, textbooks	Quiz, participation, short exercises	CLO1, CLO2
2	AC and DC distribution systems, classification of power distribution	Demonstrations, problem-solving	Slides, practical examples	Hands-on activities, worksheet	CLO1, CLO2
3	Underground cables: types, construction, and advantages	Case studies, visual aids	Slides, textbooks	Quiz, group discussions	CLO2, CLO3
4	Overhead vs. underground systems, fault handling, and maintenance	Interactive problem-solving	Textbooks, slides	Worksheet, participation	CLO1, CLO3
5	Mechanical design of overhead lines: sag and tension calculations	Problem-solving exercises	Slides, textbooks	Problem-solving exercises	CLO2, CLO4

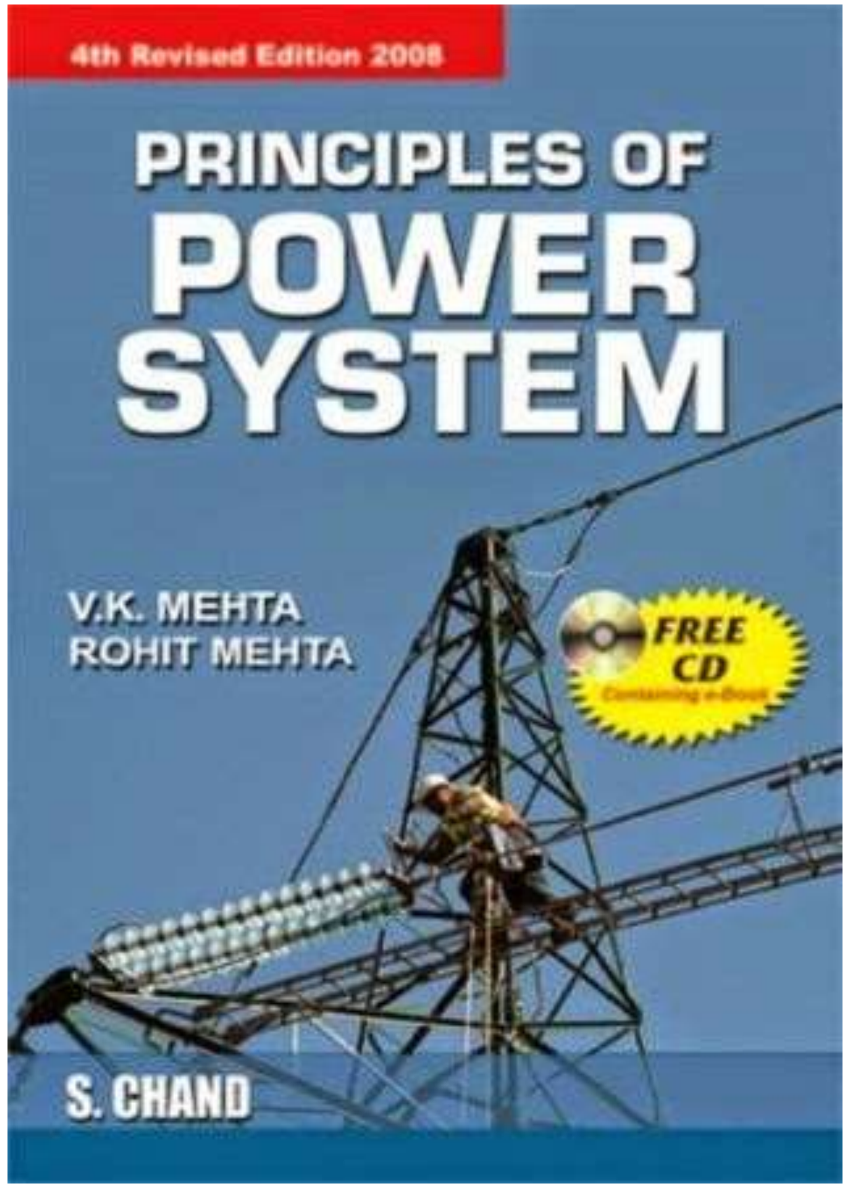
Course Schedule

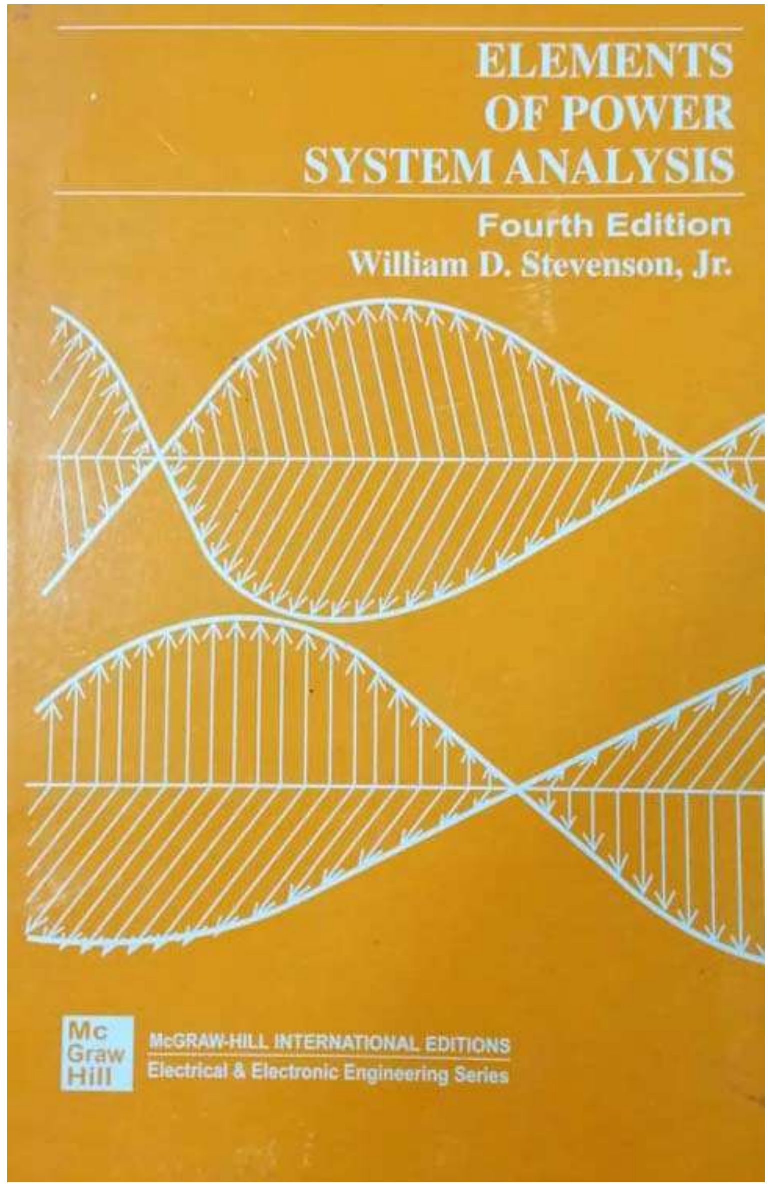
6	Transmission line parameters: resistance, inductance, and capacitance	Lectures, group activities	Textbooks, slides	Quiz, participation	CLO2, CLO3
7	Corona effect in transmission lines: causes, advantages, and disadvantages	Experiments, discussions	Reference books, slides	Case study analysis	CLO1, CLO4
8	Insulators: types, materials, and applications	Interactive discussions, hands-on	Slides, textbooks	Group presentation	CLO2, CLO4
9	Potential distribution in suspension insulators and methods to improve string efficiency	Debates, research-based learning	Slides, textbooks	Essay, participation	CLO1, CLO3
10	Busbars and substations: design considerations, site selection	Lectures, problem-solving exercises	Textbooks, slides	Problem-solving exercises	CLO2, CLO3
11	Protective devices: surge arresters, circuit breakers, and relays	Discussions, practical activities	Slides, textbooks	Lab report, short presentation	CLO1, CLO2
12	Design of transmission lines: electrical and mechanical aspects	Case studies, visual aids	Textbooks, slides	Worksheet, participation	CLO1, CLO4

Course Schedule

13	Skin effect and proximity effect in transmission lines	Lectures, interactive sessions	Slides, textbooks	Participation, problem-solving	CLO2, CLO4
14	Power factor improvement techniques and voltage regulation	Interactive problem-solving	Slides, textbooks	Group presentation	CLO1, CLO3
15	Case studies on power system failures and solutions	Summary lectures, brainstorming	Slides, textbooks	Comprehensive test	CLO1, CLO2, CLO3, CLO4
16	Advances in power systems: smart grids and renewable integration	Capstone project, discussions	All previous materials	Final project evaluation	CLO2, CLO3, CLO4
17	Course review and final assessment	Summary lectures, Q&A	All previous materials	Comprehensive assessment	CLO1, CLO2, CLO3, CLO4

Reference Books





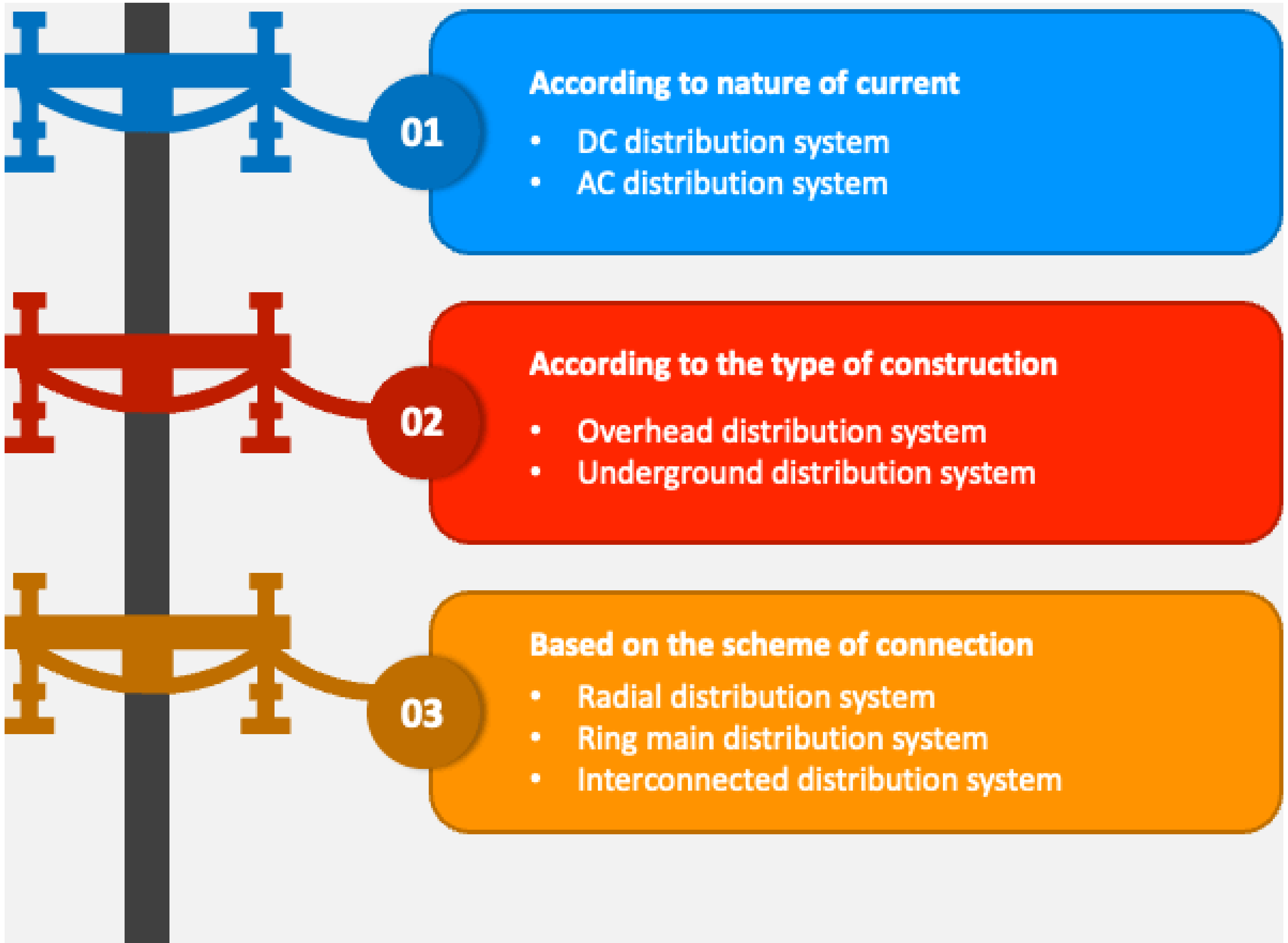

Week-01
Page: 11-20

AC DISTRIBUTION & CABLES

Electric power distribution is the final stage of the electricity delivery process, where electricity is transported from the transmission system to the end consumer. The distribution system's main purpose is to supply electricity to consumers with the required voltage, frequency, and current in a safe, reliable, and efficient manner.

ELECTRIC POWER DISTRIBUTION

Classification of Power Distribution Systems

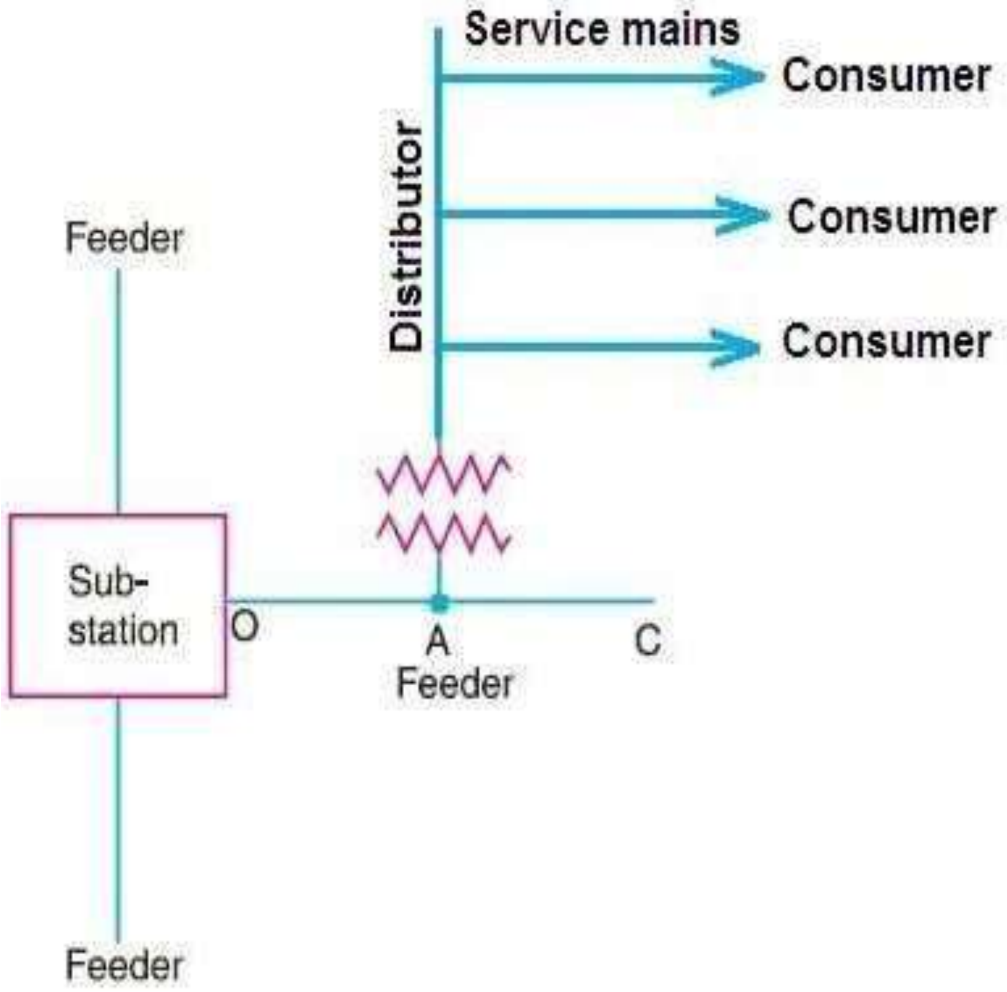


Bus Bar

The conducting material or a conductor used to collect power from the input terminals of an electrical system and distribute it to various output circuits is known as an electrical bus bar or bus system. It acts as a junction, where the incoming power and outgoing power meets. It is used to collect all the electrical power in one place. It is available in the form of rectangular strips, round tubes, round bars, and square bars made up of aluminium, copper, and brass.

Distribution System

The part of the power system that distributes electric power for local use is known as the distribution system. The distribution system generally consists of feeders, distributors and the service mains.



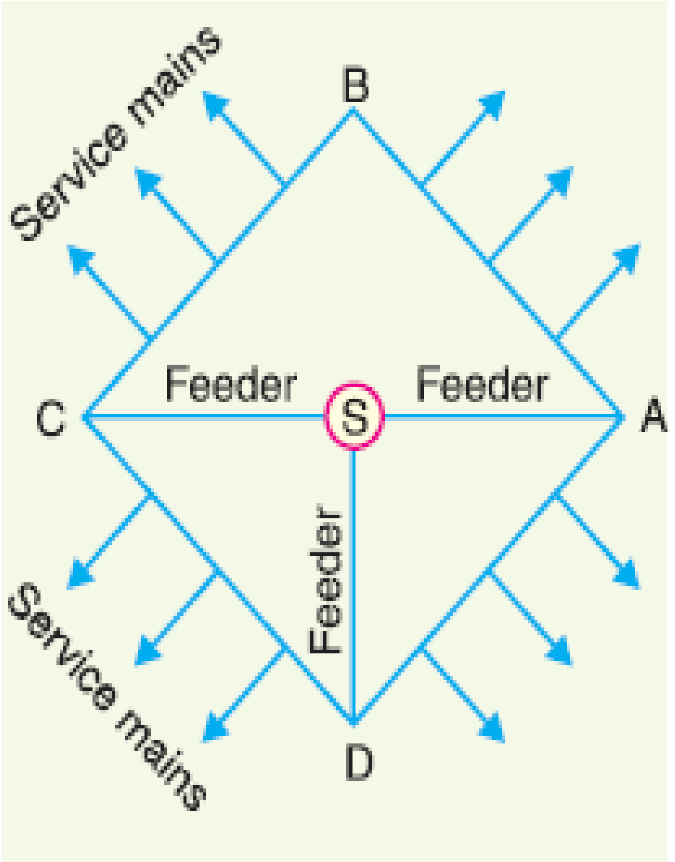


Fig shows the single line diagram of a typical low tension distribution system.

Feeders. A feeder is a conductor that connects the sub-station (or localized generating station) to the area where power is to be distributed. Generally, no tapings are taken from the feeder so that the current in it remains the same throughout. The main consideration in the design of a feeder is the current carrying capacity.

Distributor. A distributor is a conductor from which toppings are taken for supply to the consumers. In Fig. AB, BC, CD and DA are the distributors. The current through a distributor is not constant because toppings are taken at various places along its length.
While designing a distributor, voltage drop along its length is the main consideration since the statutory limit of voltage variations is ± 6% of the rated value at the consumers' terminals.

Service mains. A service mains is generally a small cable which connects the distributor to the consumers' terminals.

Classification of Distribution Systems

(i)Nature of current. According to nature of current, distribution system may be classified as

a. **DC distribution system**
b. **AC distribution system.**

Now-a-days, a.c. system is universa **l**y adopted for distribution of electric power as it is simpler and more economical than direct current method.

Type of construction. According to the type of construction, a distribution system may be classified as an **overhead system and an underground system.**

The overhead system is generally employed for distribution as it is 5 to 10 times cheaper than the equivalent underground system. In general, the underground system is used at places where overhead construction is impracticable or prohibited by local laws.

Classification of Distribution Systems

Scheme of connection. According to scheme of connection, the distribution system be classified as

(a)Radial system

(b) Ring the main system

(c) inter-connected system.

Each scheme has its own advantages and disadvantages.

A.C. distribution calculations differ from those of d.c. distribution in the following respects :

(i) In case of d.c. system, the voltage drop is due to resistance alone. However, in a.c. system, the voltage drops are due to the combined effects of resistance, inductance and capacitance.

(ii)In a d.c. system, additions and subtractions of currents or voltages are done arithmetically but in case of a.c. system, these operations are done vectorially.

(iii)In an a.c. system, power factor (p.f.) has to be taken into account. Loads tapped off form the distributor are generally at different power factors. There are two ways of referring power factor viz

(a)It may be referred to supply or receiving end voltage which is regarded as the reference vector.

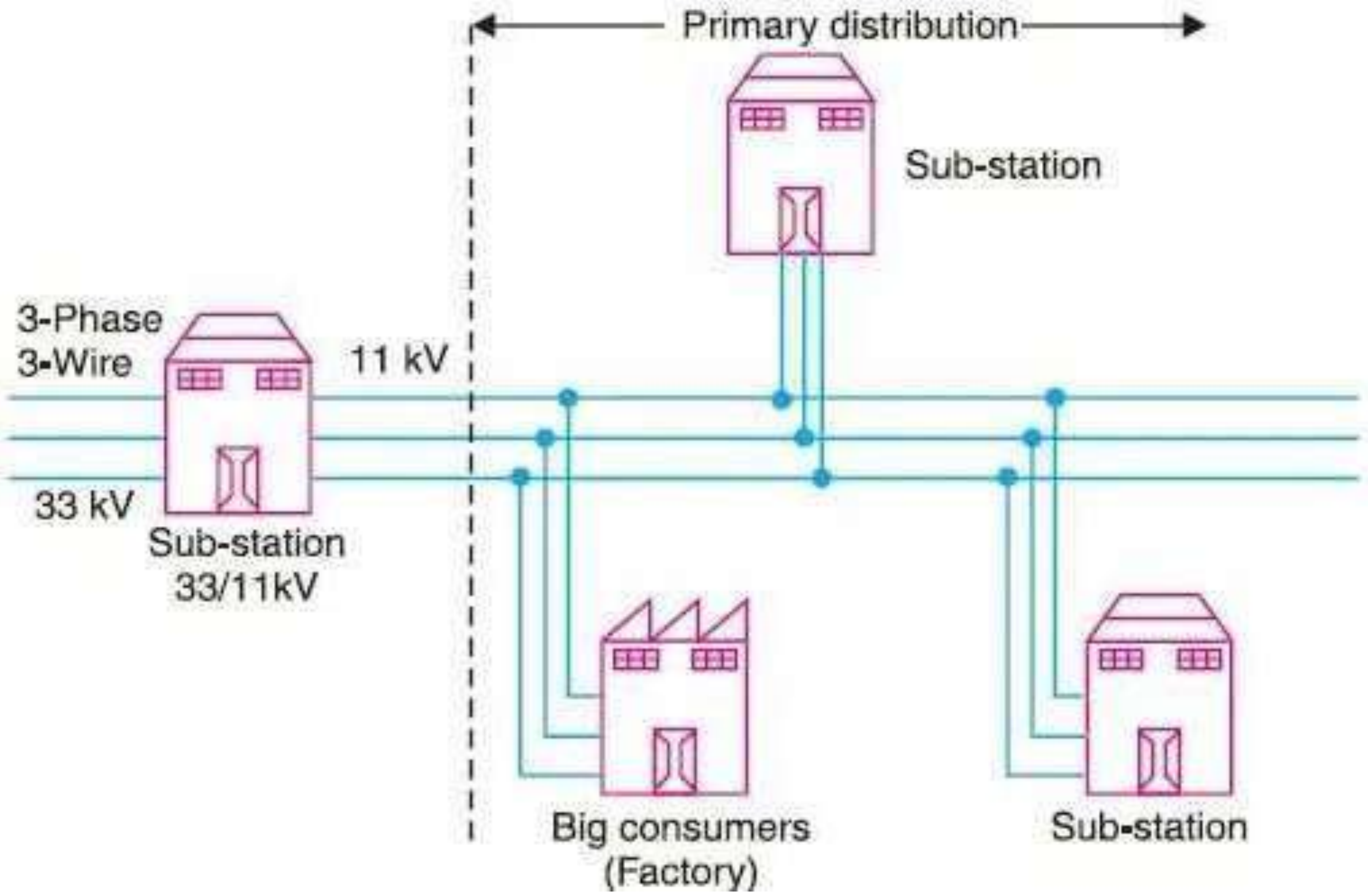
(b)It may be referred to the voltage at the load point itself.

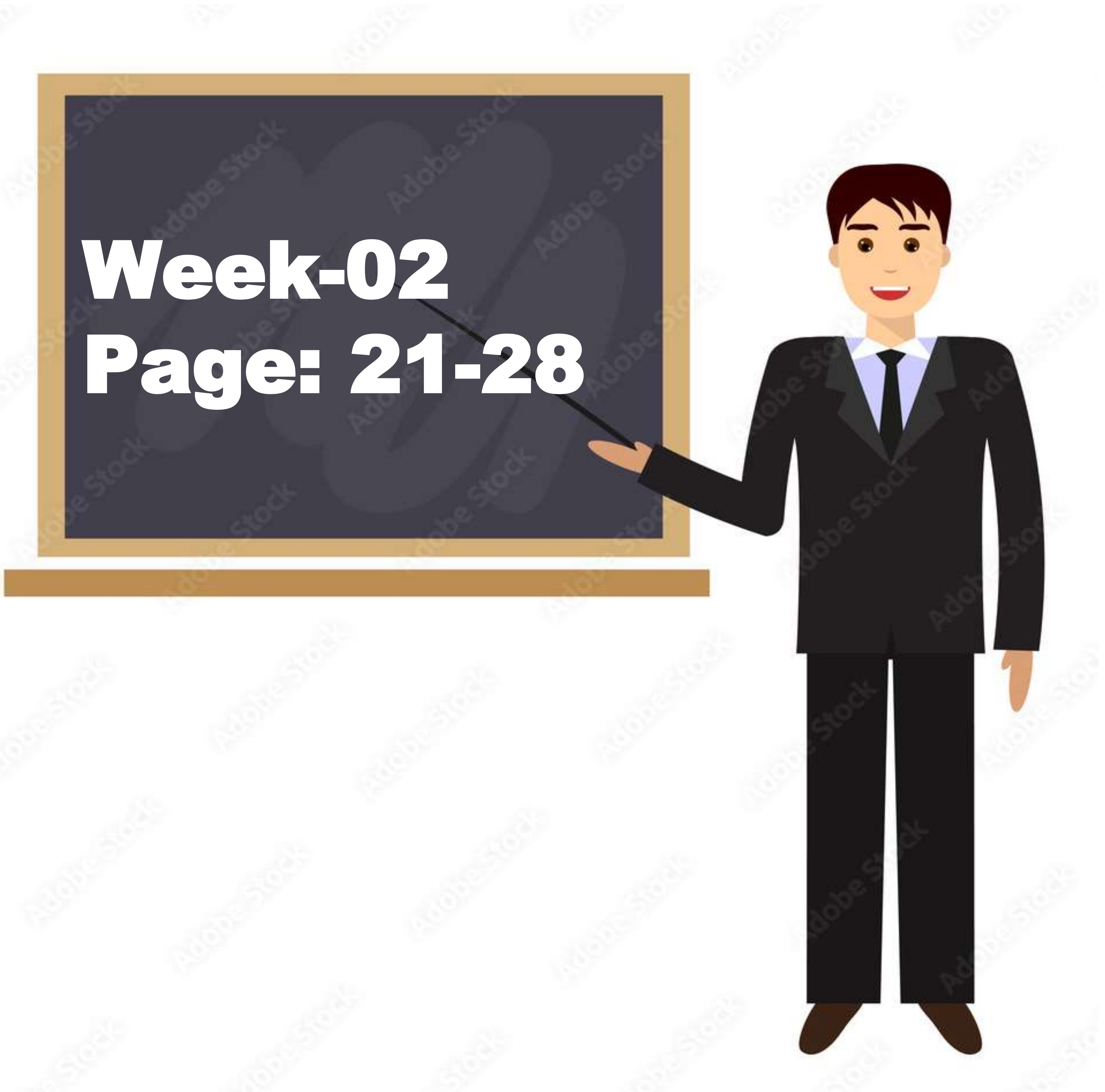
A.C. Distribution

The a.c. distribution system is classified into
(i) primary distribution system and (ii) secondary distribution system

Primary distribution system: It is that part of a.c. distribution system which operates at voltages somewhat higher than general utilisation and handles large blocks of electrical energy than the average low-voltage consumer uses. The voltage used for primary distribution depends upon the amount of power to be conveyed and the distance of the substation required to be fed. The most commonly used primary distribution voltages are 11 kV, 6·6 kV and 3·3 kV. Due to economic considerations, primary distribution is carried out by 3- phase, 3-wire system.

Fig. shows a typical primary distribution system. Electric power from the generating station is transmitted at high voltage to the substation located in or near the city. At this substation, voltage is stepped down to 11 kV with the help of step-down transformer. Power is supplied to various substations for distribution or to big consumers at this voltage. This forms the high voltage distribution or primary distribution.

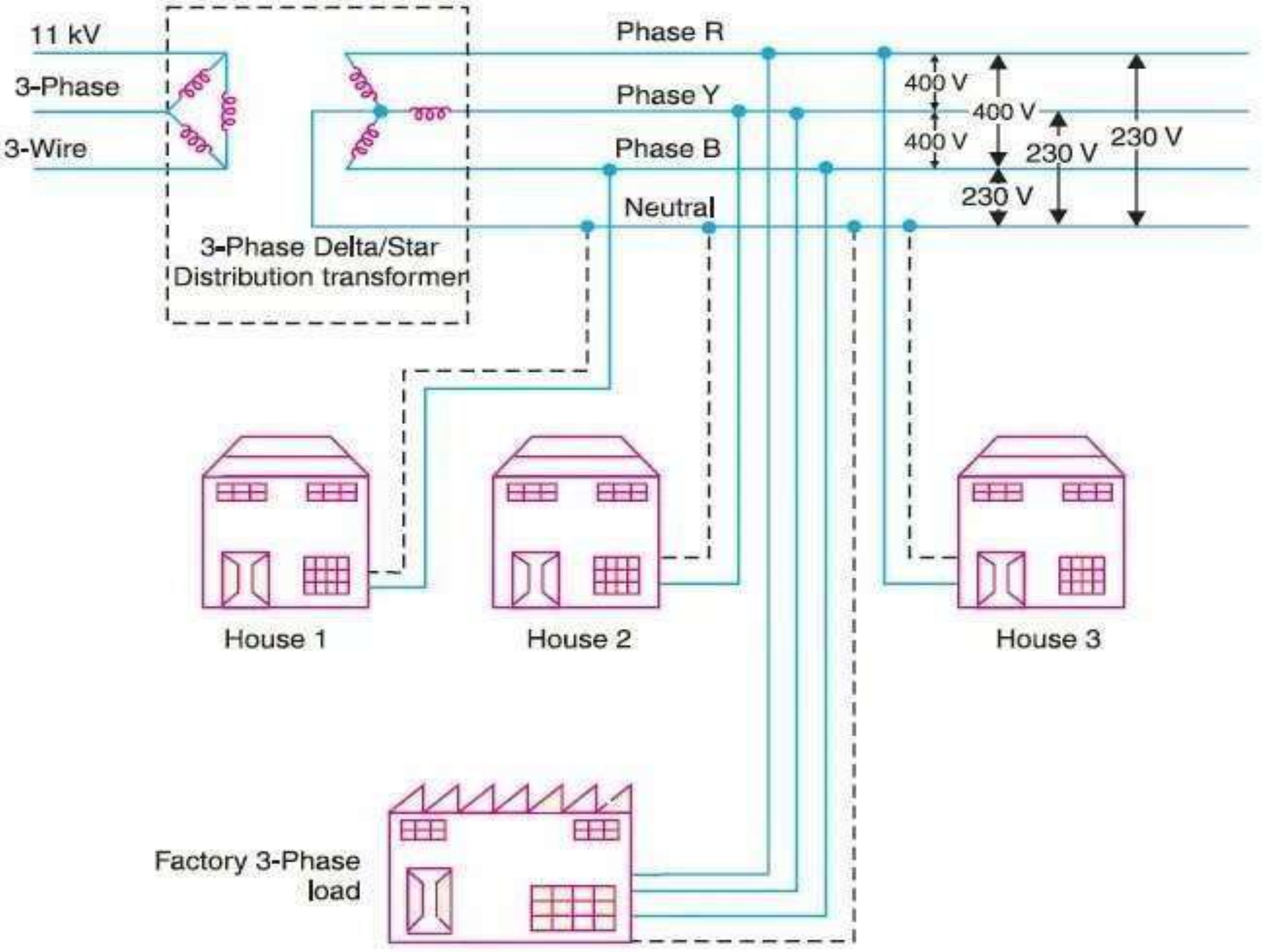



Week-02
Page: 21-28

Secondary distribution system.

It is that part of a.c. distribution system which includes the range of voltages at which the ultimate consumer utilises the electrical energy delivered to him. The secondary distribution employs 400/230 V, 3-phase, 4-wire system.

Fig. shows a typical secondary distribution system. The primary distribution circuit delivers power to various substations, called distribution substations. The substations are situated near the consumers' localities and contain stepdown transformers. At each distribution substation, the voltage is stepped down to 400V and power is delivered by 3-phase,4-wire a.c. system. The voltage between any two phases is 400 V and between any phase and neutral is 230V. The single-phase domestic loads are connected between any one phase and the neutral, whereas 3-phase 400 V motor loads are connected across 3-phase lines directly.



Overhead Versus Underground System

Public safety. The underground system is more safe than overhead system because all distribution wiring is placed underground and there are little chances of any hazard.

Initial cost. The underground system is more expensive due to the high cost of trenching, conduits, cables, manholes, and other special equipment. The initial cost of an underground system may be five to ten times than that of an overhead system.

Flexibility. The overhead system is much more flexible than the underground system. In the latter case, manholes, duct lines etc., are permanently placed once installed and the load expansion can only be met by laying new lines. However, on an overhead system, poles, wires, transformers, etc., can be easily shifted to meet the changes in load conditions.

Overhead Versus Underground System

Faults. The chances of faults in the underground system are very rare as the cables are laid underground and are generally provided with better insulation.

Appearance. The general appearance of an underground system is better as all the distribution lines are invisible. This factor is exerting considerable public pressure on electric supply companies to switch over to underground system.

Fault location and repairs. In general, there are little chances of faults in an underground system.
However, if a fault does occur, it is difficult to locate and repair on this system. On an overhead system, the conductors are visible and easily accessible so that fault locations and repairs can be easily made

Requirements of a Distribution System

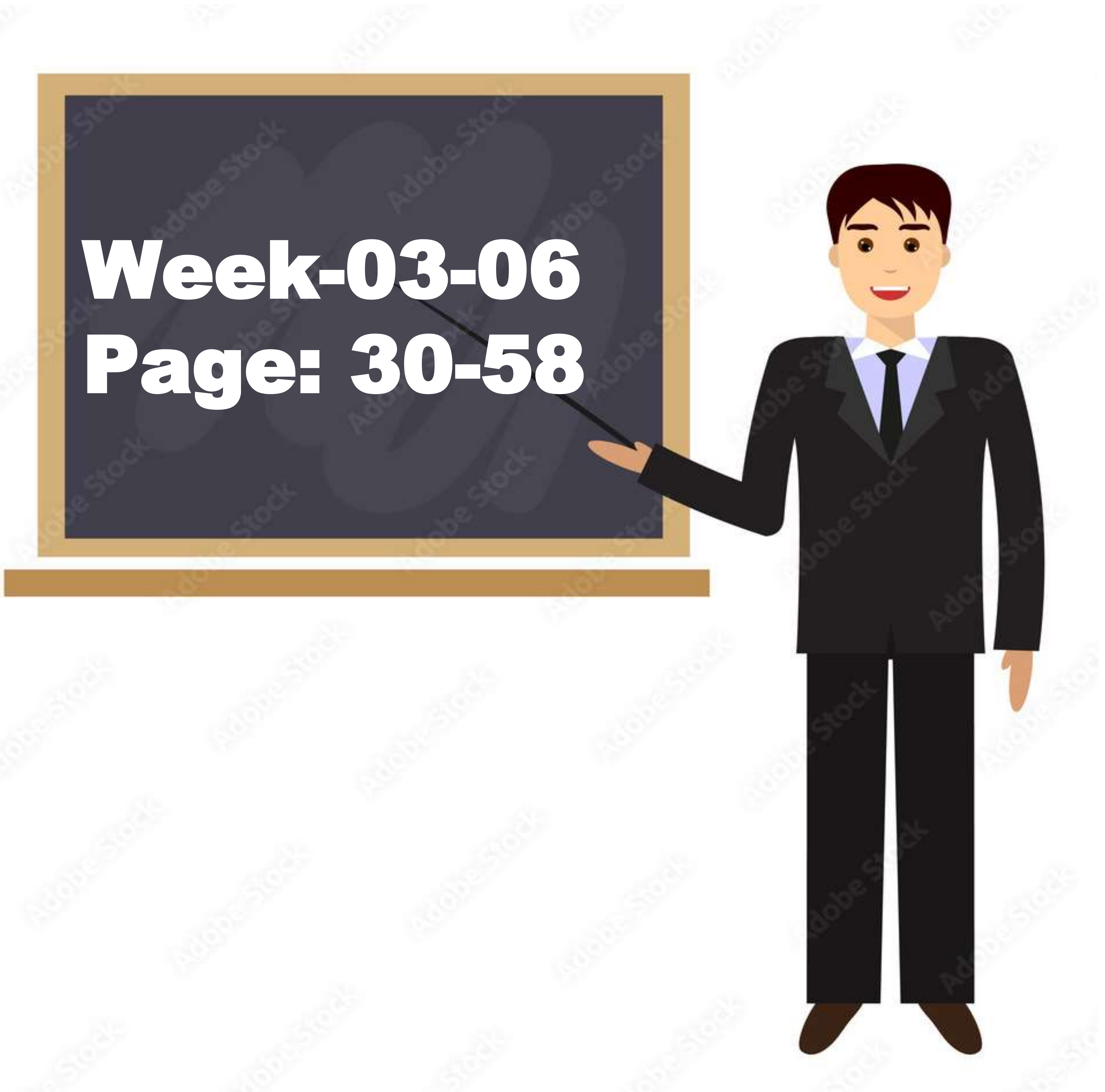
Proper voltage. One important requirement of a distribution system is that voltage variations at consumer's terminals should be as low as possible. The changes in voltage are generally caused due to the variation of load on the system. Low voltage causes loss of revenue, inefficient lighting and possible burning out of motors. High voltage causes lamps to burn out permanently and may cause failure of other appliances. Therefore, a good distribution system should ensure that the voltage variations at consumers terminals are within permissible limits. The statutory limit of voltage variations is ± 6% of the rated value at the consumer's terminals. Thus, if the declared voltage is 230 V, then the highest voltage of the consumer should not exceed 244 V while the lowest voltage of the consumer should not be less than 216 V.

Requirements of a Distribution System

Availability of power on demand. Power must be available to the consumers in any amount that they may require from time to time. For example, motors may be started or shut down, lights may be turned on or off, without advance warning to the electric supply company. As electrical energy cannot be stored, therefore, the distribution system must be capable of supplying load demands of the consumers. This necessitates that operating staff must continuously study load patterns to predict in advance those major load changes that follow the known schedules. (

Requirements of a Distribution System

Reliability. Modern industry is almost dependent on electric power for its operation. Homes and office buildings are lighted, heated, cooled and ventilated by electric power. This ca ls for reliable service. Unfortunately, electric power, like everything else that is man-made, can never be absolutely reliable. However, the reliability can be improved to a considerable extent by (a) interconnected system (b) reliable automatic control system (c) providing additional reserve facilities.


Week-03-06
Page: 30-58

Design Considerations in Distribution System

Good voltage regulation of a distribution network is probably the most important factor responsible for delivering good service to the consumers. For this purpose, design of feeders and distributors requires careful consideration.

(i)Feeders. A feeder is designed from the point of view of its current carrying capacity while the voltage drop consideration is relatively unimportant. It is because voltage drop in a feeder can be compensated by means of voltage regulating equipment at the substation.

(ii)Distributors. A distributor is designed from the point of view of the voltage drop in it. It is because a distributor supplies power to the consumers and there is a statutory limit of voltage variations at the consumer's terminals (± 6% of rated value). The size and length of the distributor should be such that voltage at the consumer's terminals is within the permissible limits.

Connection Schemes of Distribution System

All distribution of electrical energy is done by constant voltage system

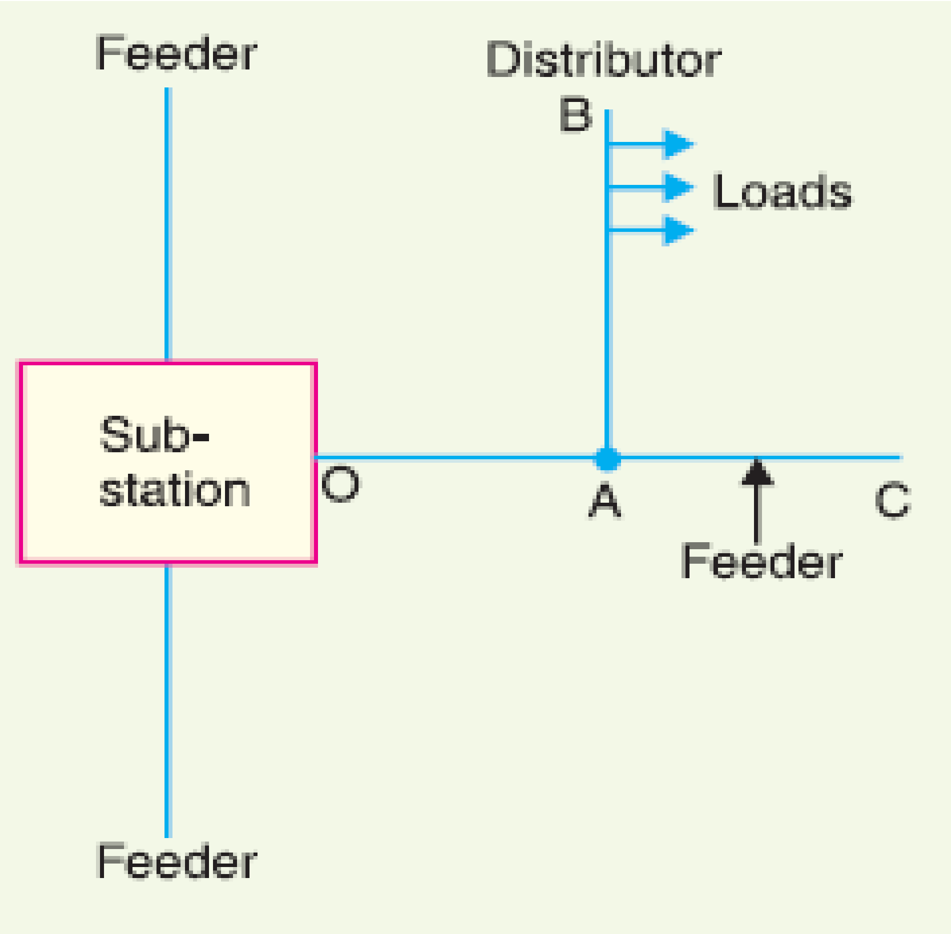
(i) Radial System. In this system, separate feeders radiate from a single substation and feed the distributors at one end only. Fig.1 shows a single line diagram of a radial system for d.c. distribution where a feeder OC supplies a distributor AB at point A. Obviously, the distributor is fed at one end only i.e., point A is this case. Fig.2 shows a single line diagram of radial system for a.c. distribution. The radial system is employed only when power is generated at low voltage and the substation is located at the centre of the load. This is the simplest distribution circuit and has the lowest initial cost.

However, it suffers from the following drawbacks :

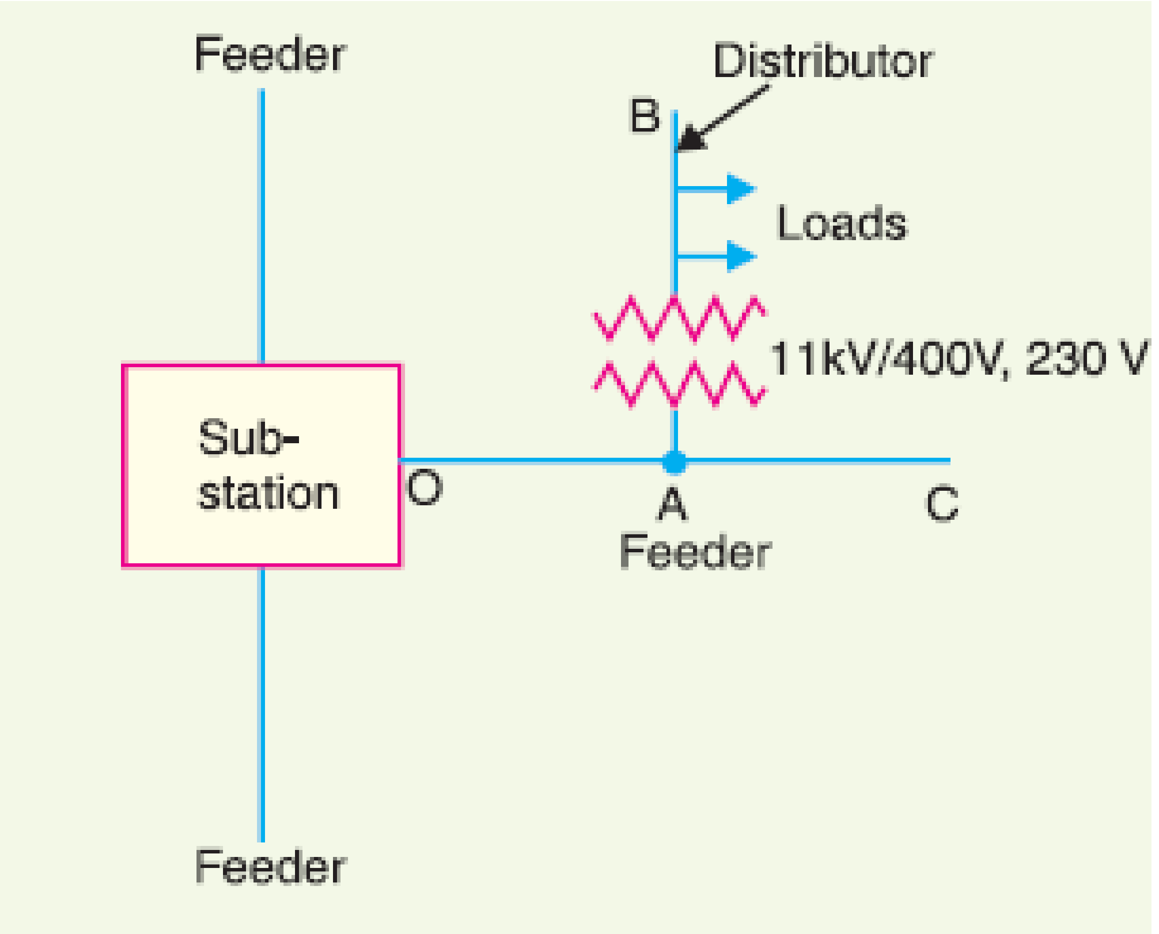
(a) The end of the distributor nearest to the feeding point will be heavily loaded.

(b) The consumers are dependent on a single feeder and single distributor. Therefore, any fault on the feeder or distributor cuts off supply to the fault away from theconsumers who are on the side of the substation.

(c)Theconsumersat the distant end of the distributor would be subjected to serious voltage fluctuations when the load on the distributor changes. Due to these limitations,this system is **used for short distances only**.



(i)



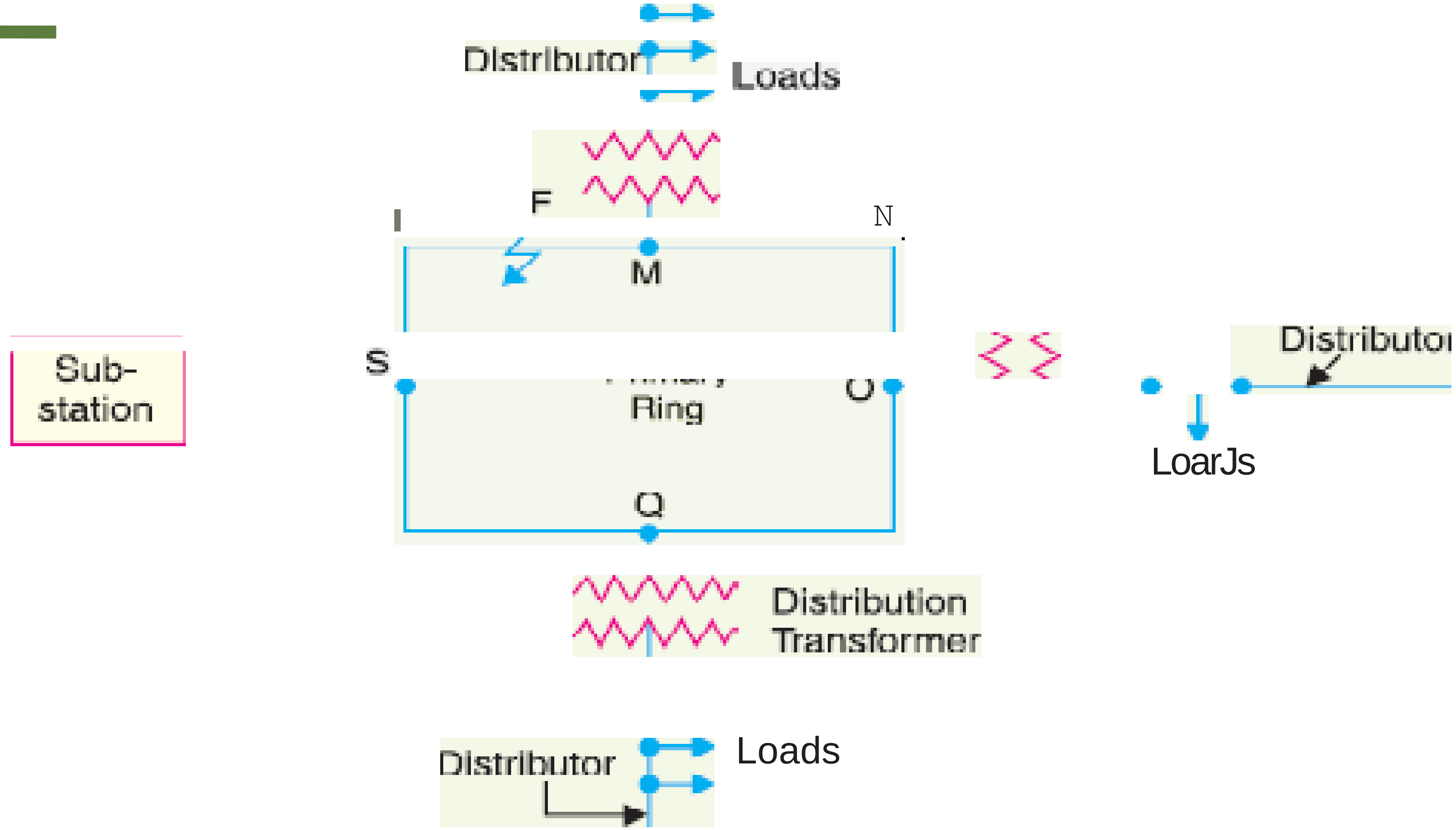
(ii)

(ii) Ring main system. In this system, the primaries of distribution transformers form a loop. The loop circuit starts from the substation bus-bars, makes a loop through the area to be served, and returns to the substation. Fig. shows the single line diagram of ring main system for a.c. distribution where substation supplies to the closed feeder LMNOPQRS.

The distributors are tapped from different points M, O and Q of the feeder through distribution transformers. The ring main system has the following advantages :

(a) There are less voltage fluctuations at consumer's terminals.

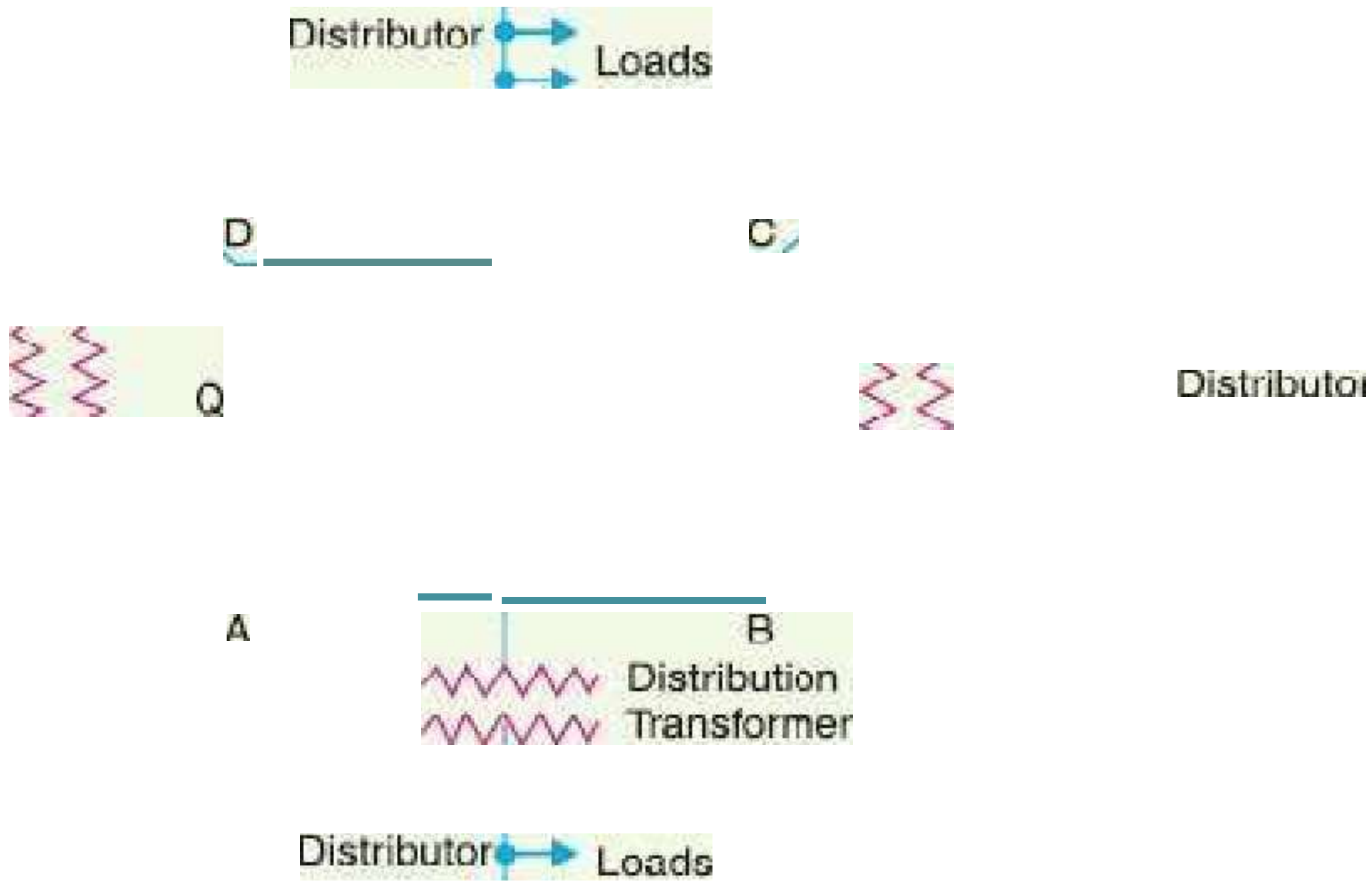
(b) The system is very reliable as each distributor is fed via two feeders. In the event of fault on any section of the feeder, the continuity of supply is maintained. For example, suppose that fault occurs at any point F of section SLM of the feeder. Then section SLM of the feeder can be isolated for repairs and at the same time continuity of supply is maintained to all the consumers via the feeder SRQPONM.


Distributor
Loads
F
N
M
Sub-
station
S
Ring
O
Distributor
LoarJs
Q
Distribution
Transformer
Distributor
Loads

(iii) Interconnected system. When the feeder ring is energised by two or more than two generating stations or substations, it is called inter-connected system. Fig. shows the single line diagram of interconnected system where the closed feeder ring ABCD is supplied by two substations S1 and S2 at points D and C respectively. Distributors are connected to points O, P, Q and R of the feeder ring through distribution transformers. The interconnected system has the following advantages :

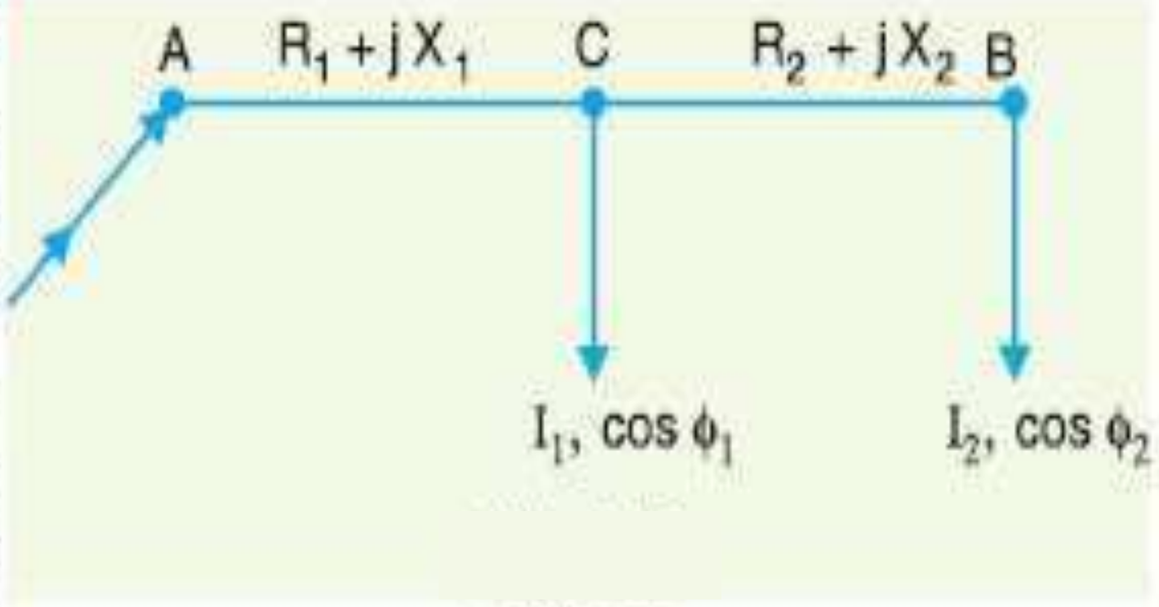
(a) It increases the service reliability

(b) Any area fed from one generating station during peak load hours can be fed from the other generating station. This reduces reserve power capacity and increases efficiency of the system.


Distributor
Loads
D
C
Q
Distributor
A
B
Distribution
Transformer
Distributor
Loads

Power factors referred to receiving end voltage

(*i*) **Power factors referred to receiving end voltage.** Consider an a.c. distributor AB with concentrated loads of I_1 and I_2 tapped off at points C and B as shown in Fig. Taking the receiving end voltage V_B as the reference vector, let lagging power factors at C and B be $\cos \phi_1$ and $\cos \phi_2$ *w.r.t.* V_B. Let R_1, X_1 and R_2, X_2 be the resistance and reactance of sections AC and CB of the distributor.



Impedance of section AC, $\quad \vec{Z_{AC}} = R_1 + j X_1$

Impedance of section CB, $\quad \vec{Z_{CB}} = R_2 + j X_2$

Load current at point C, $\quad \vec{I_1} = I_1 (\cos \phi_1 - j \sin \phi_1)$

Load current at point B, $\quad \vec{I_2} = I_2 (\cos \phi_2 - j \sin \phi_2)$

Current in section CB, $\overrightarrow{I_{CB}} = \overrightarrow{I_2} = I_2 (\cos \phi_2 - j \sin \phi_2)$

Current in section AC, $\overrightarrow{I_{AC}} = \overrightarrow{I_1} + \overrightarrow{I_2}$

$= I_1 (\cos \phi_1 - j \sin \phi_1) + I_2 (\cos \phi_2 - j \sin \phi_2)$

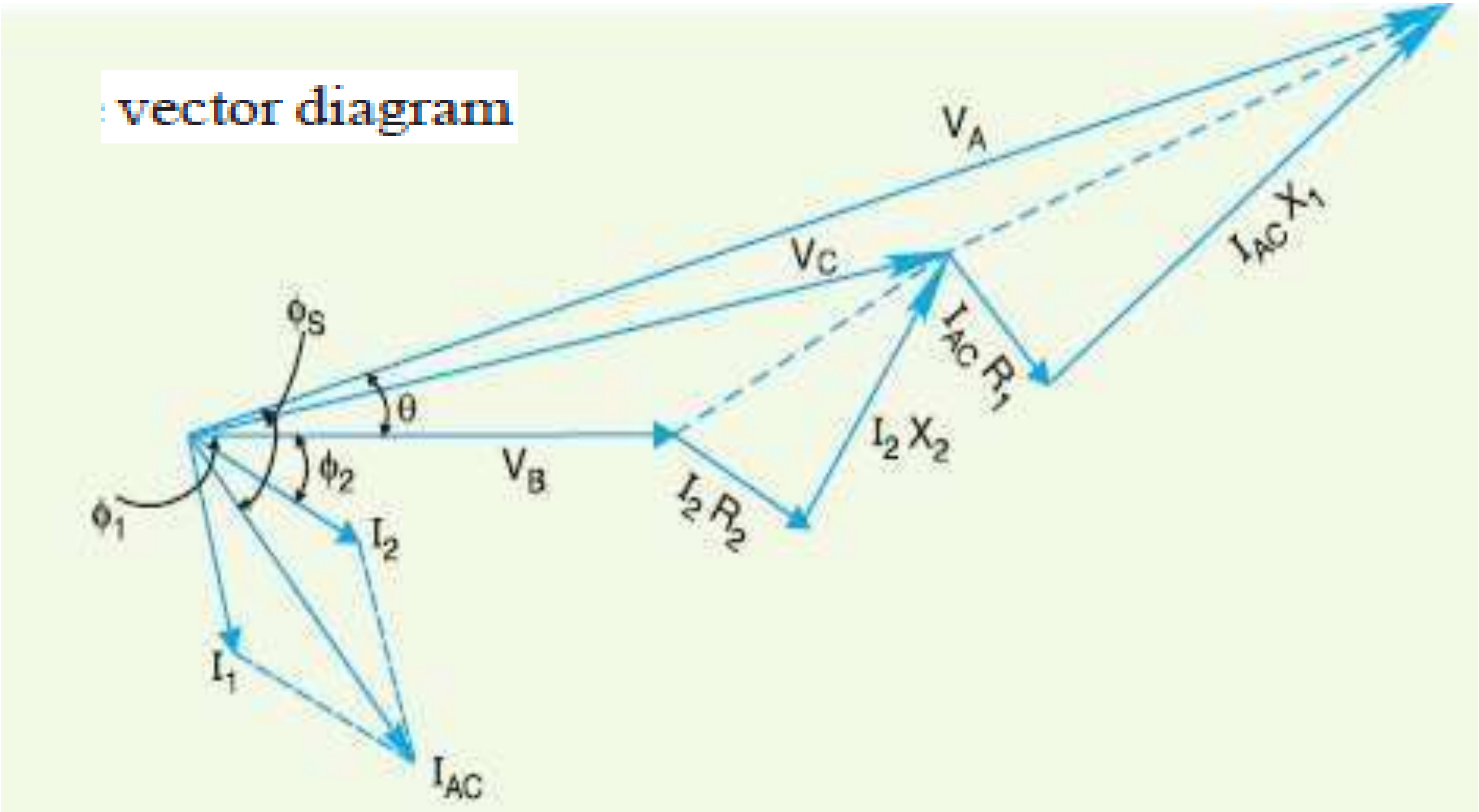
Voltage drop in section CB, $\overrightarrow{V_{CB}} = \overrightarrow{I_{CB}}\, \overrightarrow{Z_{CB}} = I_2 (\cos \phi_2 - j \sin \phi_2) (R_2 + j X_2)$

Voltage drop in section AC, $\overrightarrow{V_{AC}} = \overrightarrow{I_{AC}}\, \overrightarrow{Z_{AC}} = \left(\overrightarrow{I_1} + \overrightarrow{I_2}\right) Z_{AC}$

$= [I_1(\cos \phi_1 - j \sin \phi_1) + I_2 (\cos \phi_2 - j \sin \phi_2)] [R_1 + jX_1]$

Sending end voltage, $\overrightarrow{V_A} = \overrightarrow{V_B} + \overrightarrow{V_{CB}} + \overrightarrow{V_{AC}}$

Sending end current, $\overrightarrow{I_A} = \overrightarrow{I_1} + \overrightarrow{I_2}$


vector diagram
V_A
V_C
$I_{AC} X_1$
$I_{AC} R_1$
$I_2 X_2$
$I_2 R_2$
V_B
ϕ_S
θ
ϕ_2
ϕ_1
I_2
I_1
I_{AC}

(*ii*) **Power factors referred to respective load voltages.** Suppose the power factors of loads in the previous Fig. 14.1 are referred to their respective load voltages. Then ϕ_1 is the phase angle between V_C and I_1 and ϕ_2 is the phase angle between V_B and I_2. The vector diagram under these conditions is shown in Fig. 14.3.

Voltage drop in section CB $= \vec{I_2}\,\overrightarrow{Z_{CB}} = I_2(\cos\phi_2 - j\sin\phi_2)(R_2 + jX_2)$

Voltage at point C $= \vec{V_B}$ + Drop in section $CB = V_C \angle \alpha$ (say)

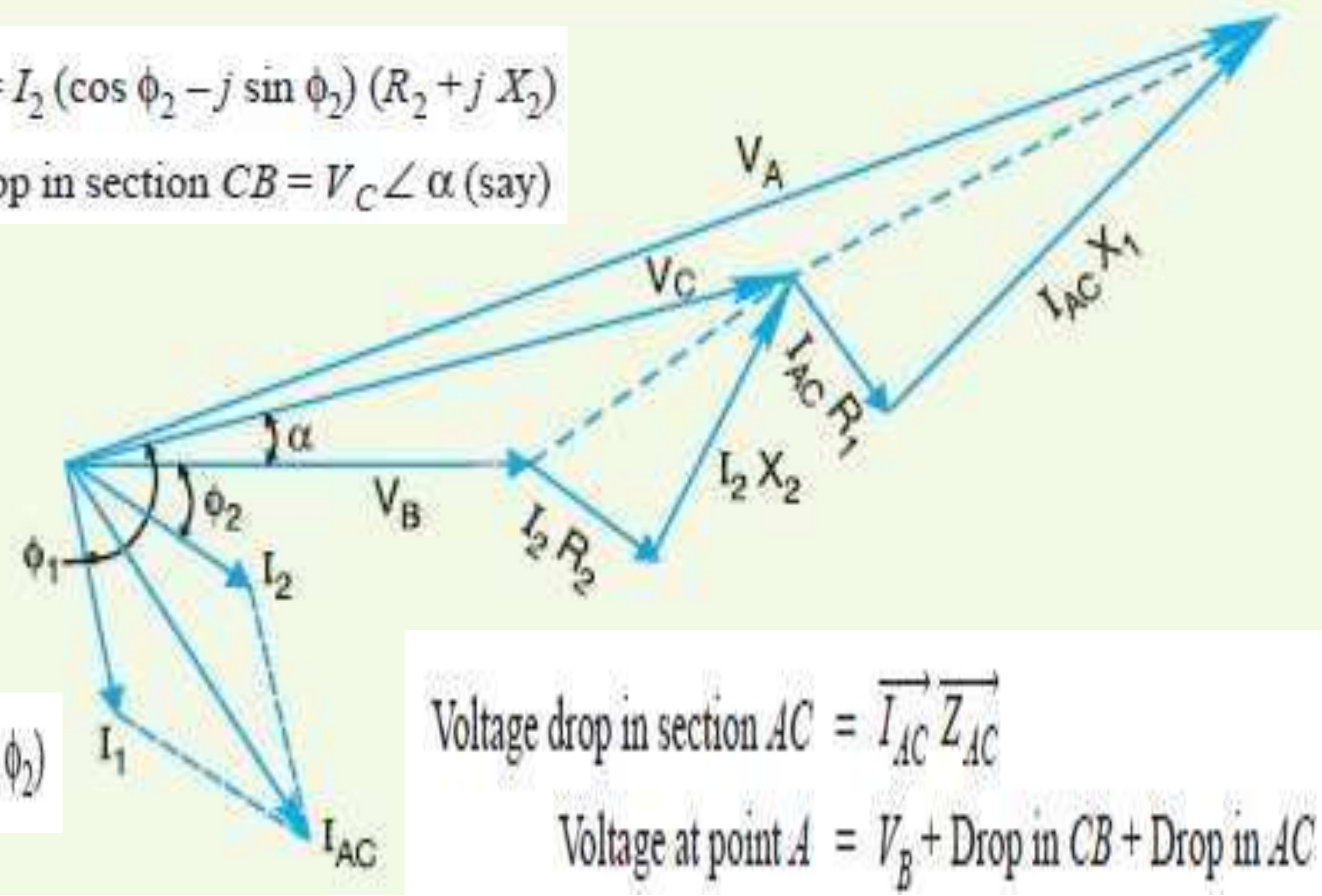
$\vec{I_1} = I_1 \angle -\phi_1$ *w.r.t.* voltage V_C

$\vec{I_1} = I_1 \angle -(\phi_1 - \alpha)$ *w.r.t.* voltage V_B

$\vec{I_1} = I_1[\cos(\phi_1 - \alpha) - j\sin(\phi_1 - \alpha)]$

$\overrightarrow{I_{AC}} = \vec{I_1} + \vec{I_2}$

$= I_1[\cos(\phi_1 - \alpha) - j\sin(\phi_1 - \alpha)] + I_2(\cos\phi_2 - j\sin\phi_2)$



Voltage drop in section AC $= \overrightarrow{I_{AC}}\,\overrightarrow{Z_{AC}}$

Voltage at point A $= V_B$ + Drop in CB + Drop in AC

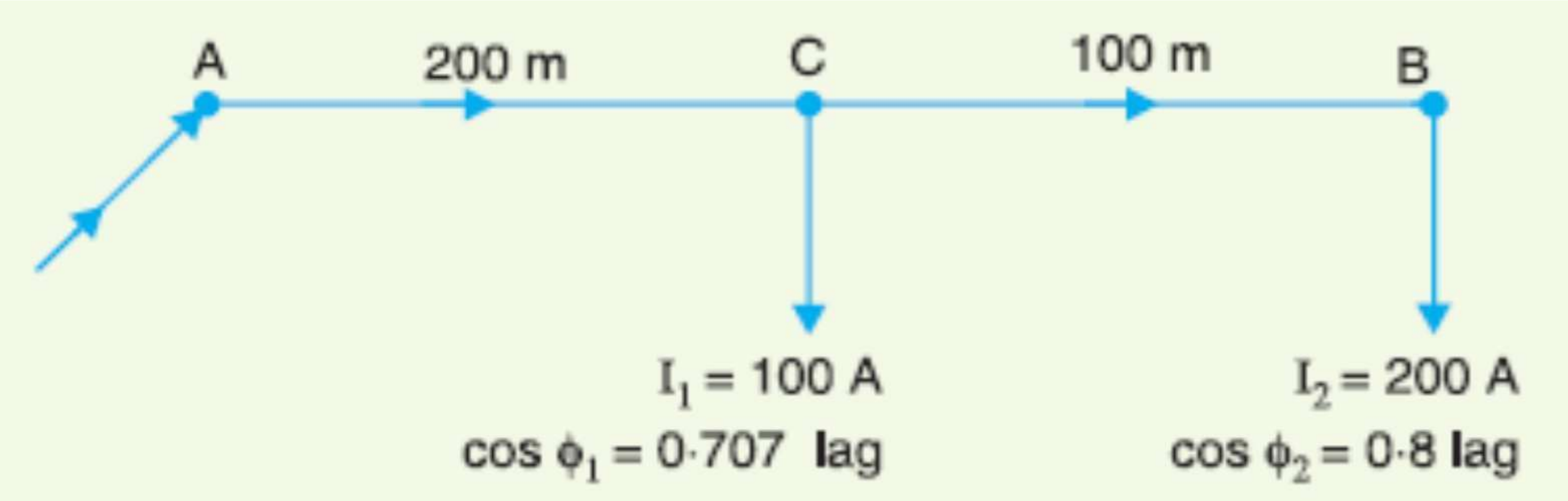
Example . *A single phase a.c. distributor AB 300 metres long is fed from end A and is loaded as under :*

(i) *100 A at 0·707 p.f. lagging 200 m from point A*

(ii) *200 A at 0·8 p.f. lagging 300 m from point A*

The load resistance and reactance of the distributor is 0·2 Ω and 0·1 Ω per kilometre. Calculate the total voltage drop in the distributor. The load power factors refer to the voltage at the far end.

Solution.



Impedance of distributor/km $= (0\cdot2 + j\,0\cdot1)\ \Omega$

Impedance of section AC, $\overrightarrow{Z_{AC}} = (0\cdot2 + j\,0\cdot1) \times 200/1000 = (0\cdot04 + j\,0\cdot02)\ \Omega$

Impedance of section CB, $\overrightarrow{Z_{CB}} = (0\cdot2 + j\,0\cdot1) \times 100/1000 = (0\cdot02 + j\,0\cdot01)\ \Omega$

Taking voltage at the far end B as the reference vector, we have,

Load current at point B, $\overrightarrow{I_2} = I_2(\cos\phi_2 - j\sin\phi_2) = 200\,(0\cdot8 - j\,0\cdot6)$

$= (160 - j\,120)\ \text{A}$

Load current at point C, $\overrightarrow{I_1} = I_1(\cos\phi_1 - j\sin\phi_1) = 100\,(0\cdot707 - j\,0\cdot707)$

$= (70\cdot7 - j\,70\cdot7)\ \text{A}$

Current in section CB, $\overrightarrow{I_{CB}} = \overrightarrow{I_2} = (160 - j\,120)\ \text{A}$

Current in section AC, $\overrightarrow{I_{AC}} = \overrightarrow{I_1} + \overrightarrow{I_2} = (70 \cdot 7 - j\, 70 \cdot 7) + (160 - j\, 120)$

$= (230 \cdot 7 - j\, 190 \cdot 7)$ A

Voltage drop in section CB, $\overrightarrow{V_{CB}} = \overrightarrow{I_{CB}}\, \overrightarrow{Z_{CB}} = (160 - j\, 120)\,(0 \cdot 02 + j\, 0 \cdot 01)$

$= (4 \cdot 4 - j\, 0 \cdot 8)$ volts

Voltage drop in section AC, $\overrightarrow{V_{AC}} = \overrightarrow{I_{AC}}\, \overrightarrow{Z_{AC}} = (230 \cdot 7 - j\, 190 \cdot 7)\,(0 \cdot 04 + j\, 0 \cdot 02)$

$= (13 \cdot 04 - j\, 3 \cdot 01)$ volts

Voltage drop in the distributor $= \overrightarrow{V_{AC}} + \overrightarrow{V_{CB}} = (13 \cdot 04 - j\, 3 \cdot 01) + (4 \cdot 4 - j\, 0 \cdot 8)$

$= (17 \cdot 44 - j\, 3 \cdot 81)$ volts

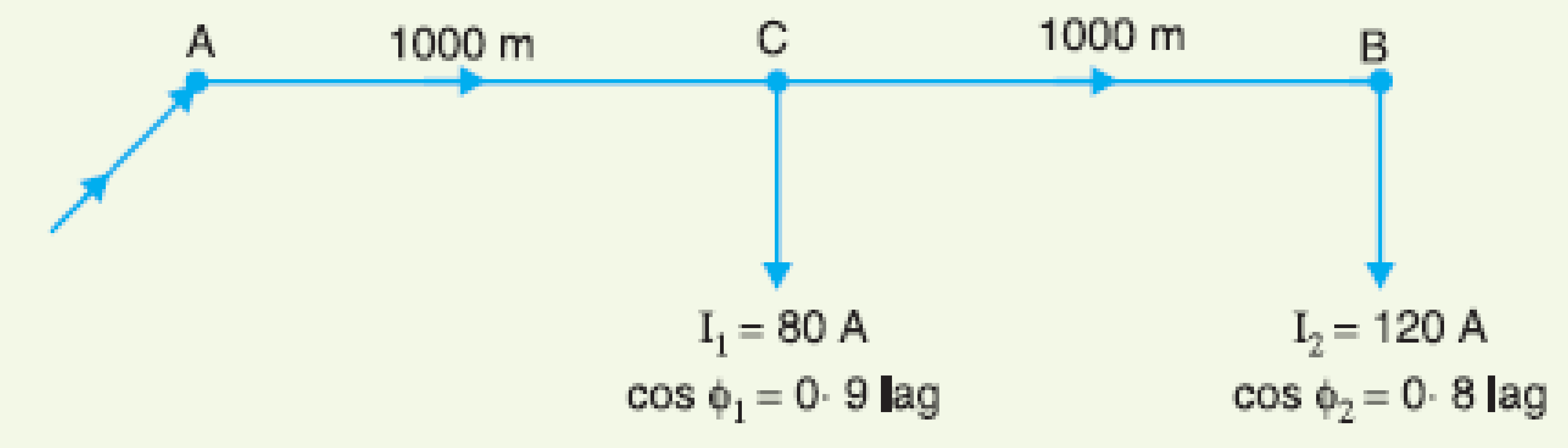
Magnitude of drop $= \sqrt{(17 \cdot 44)^2 + (3 \cdot 81)^2} = 17 \cdot 85$ V

Example *A single phase distributor 2 kilometres long supplies a load of 120 A at 0·8 p.f. lagging at its far end and a load of 80 A at 0·9 p.f. lagging at its mid-point. Both power factors are referred to the voltage at the far end. The resistance and reactance per km (go and return) are 0·05 Ω and 0·1 Ω respectively. If the voltage at the far end is maintained at 230 V, calculate :*

(i) *voltage at the sending end*

(ii) *phase angle between voltages at the two ends.*

Solution. the distributor *AB* with *C* as the mid-point



Impedance of distributor/km $= (0{\cdot}05 + j\,0{\cdot}1)\ \Omega$

Impedance of section AC, $\vec{Z}_{AC} = (0{\cdot}05 + j\,0{\cdot}1) \times 1000/1000 = (0{\cdot}05 + j\,0{\cdot}1)\ \Omega$

Impedance of section CB, $\vec{Z}_{CB} = (0{\cdot}05 + j\,0{\cdot}1) \times 1000/1000 = (0{\cdot}05 + j\,0{\cdot}1)\ \Omega$

Let the voltage V_B at point B be taken as the reference vector.

Then, $\vec{V_B} = 230 + j\,0$

(*i*) Load current at point B, $\vec{I_2} = 120\,(0{\cdot}8 - j\,0{\cdot}6) = 96 - j\,72$

Load current at point C, $\vec{I_1} = 80\,(0{\cdot}9 - j\,0{\cdot}436) = 72 - j\,34{\cdot}88$

Current in section CB, $\overrightarrow{I_{CB}} = \vec{I_2} = 96 - j\,72$

Current in section AC, $\overrightarrow{I_{AC}} = \vec{I_1} + \vec{I_2} = (72 - j\,34{\cdot}88) + (96 - j\,72)$

$= 168 - j\,106{\cdot}88$

Drop in section CB, $\overrightarrow{V_{CB}} = \overrightarrow{I_{CB}}\ \overrightarrow{Z_{CB}} = (96 - j\,72)\,(0{\cdot}05 + j\,0{\cdot}1)$

$= 12 + j\,6$

Drop in section AC, $\overrightarrow{V_{AC}} = \overrightarrow{I_{AC}}\,\overrightarrow{Z_{AC}} = (168 - j\,106{\cdot}88)\,(0{\cdot}05 + j\,0{\cdot}1)$

$= 19{\cdot}08 + j\,11{\cdot}45$

$\therefore$ Sending end voltage, $\overrightarrow{V_A} = \overrightarrow{V_B} + \overrightarrow{V_{CB}} + \overrightarrow{V_{AC}}$

$= (230 + j\,0) + (12 + j\,6) + (19.08 + j\,11.45)$

$= 261.08 + j\,17.45$

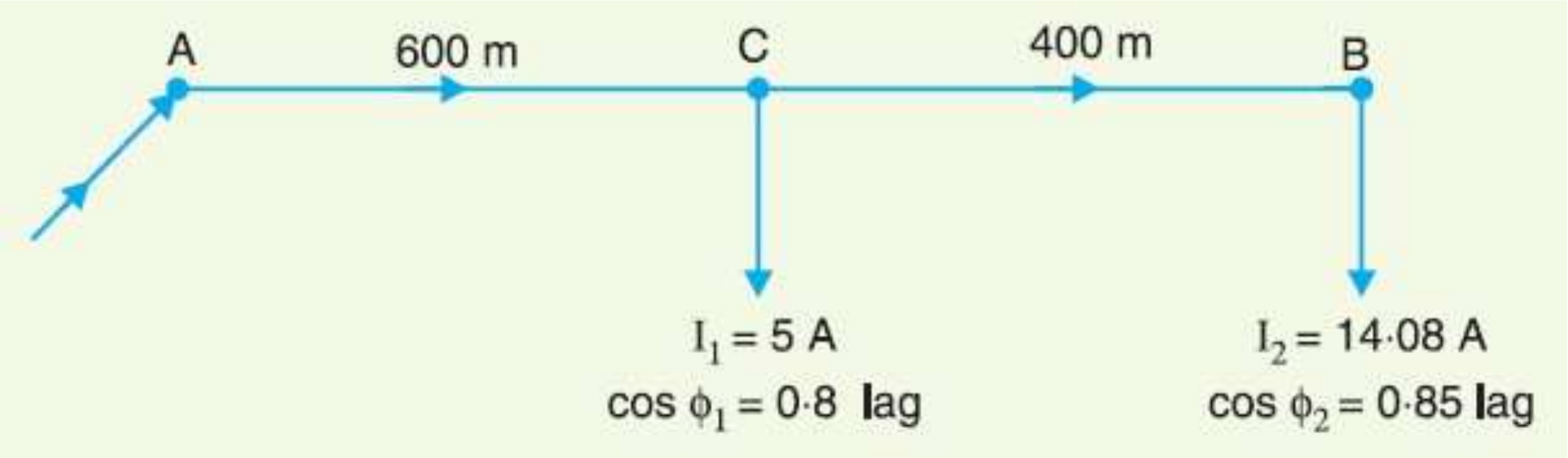
Its magnitude is $= \sqrt{(261{\cdot}08)^2 + (17{\cdot}45)^2} = $ **261·67 V**

(ii) The phase difference θ between V_A and V_B is given by :

$$\tan\theta = \frac{17{\cdot}45}{261{\cdot}08} = 0{\cdot}0668$$

$$\therefore \quad \theta = \tan^{-1} 0{\cdot}0668 = \mathbf{3{\cdot}82^\circ}$$

Example: A 3-phase, 400V distributor AB is loaded as shown in Fig.14.8. The 3-phase load at point C takes 5A per phase at a p.f. of 0·8 lagging. At point B, a 3-phase, 400 V induction motor is connected which has an output of 10 H.P. with an efficiency of 90% and p.f. 0·85 lagging. If voltage at point B is to be maintained at 400 V, what should be the voltage at point A ? The resistance and reactance of the line are 1Ω and 0·5Ωper phase per kilometre respectively



Impedance of section AC, $\overrightarrow{Z_{AC}} = (1 + j\,0{\cdot}5) \times 600/1000 = (0{\cdot}6 + j\,0{\cdot}3)\ \Omega$

Impedance of section CB, $\overrightarrow{Z_{CB}} = (1 + j\,0{\cdot}5) \times 400/1000 = (0{\cdot}4 + j\,0{\cdot}2)\ \Omega$

Phase voltage at point B, $\quad V_B = 400/\sqrt{3} = 231$ V

Let the voltage V_B at point B be taken as the reference vector.

Then, $\quad \vec{V_B} = 231 + j\,0$

Line current at B $$= \frac{\text{H.P.} \times 746}{\sqrt{3} \times \text{line voltage} \times \text{p.f.} \times \text{efficiency}}$$

$$= \frac{10 \times 746}{\sqrt{3} \times 400 \times 0{\cdot}85 \times 0{\cdot}9} = 14{\cdot}08 \text{ A}$$

$\therefore$ *Current/phase at B, $\quad I_2 = 14{\cdot}08$ A

Load current at B, $\quad \vec{I_2} = 14{\cdot}08\,(0{\cdot}85 - j\,0{\cdot}527) = 12 - j\,7{\cdot}4$

Load current at C, $\quad \vec{I_1} = 5\,(0{\cdot}8 - j\,0{\cdot}6) = 4 - j\,3$

Current in section AC, $\quad \vec{I_{AC}} = \vec{I_1} + \vec{I_2} = (4 - j\,3) + (12 - j\,7{\cdot}4)$

$= 16 - j\,10{\cdot}4$

Current in section CB, $\quad \vec{I_{CB}} = \vec{I_2} = 12 - j\,7{\cdot}4$

Voltage drop in CB, $\quad \vec{V}_{CB} = \vec{I}_{CB}\vec{Z}_{CB} = (12 - j\,7{\cdot}4)\,(0{\cdot}4 + j\,0{\cdot}2)$

$= 6{\cdot}28 - j\,0{\cdot}56$

Voltage drop in AC, $\quad \vec{V}_{AC} = \vec{I}_{AC}\vec{Z}_{AC} = (16 - j\,10{\cdot}4)\,(0{\cdot}6 + j\,0{\cdot}3)$

$= 12{\cdot}72 - j\,1{\cdot}44$

Voltage at A per phase, $\quad \vec{V}_A = \vec{V}_B + \vec{V}_{CB} + \vec{V}_{AC}$

$= (231 + j\,0) + (6{\cdot}28 - j\,0{\cdot}56) + (12{\cdot}72 - j\,1{\cdot}44)$

$= 250 - j\,2$

Magnitude of V_A/phase $= \sqrt{(250)^2 + (2)^2} = 250\text{ V}$

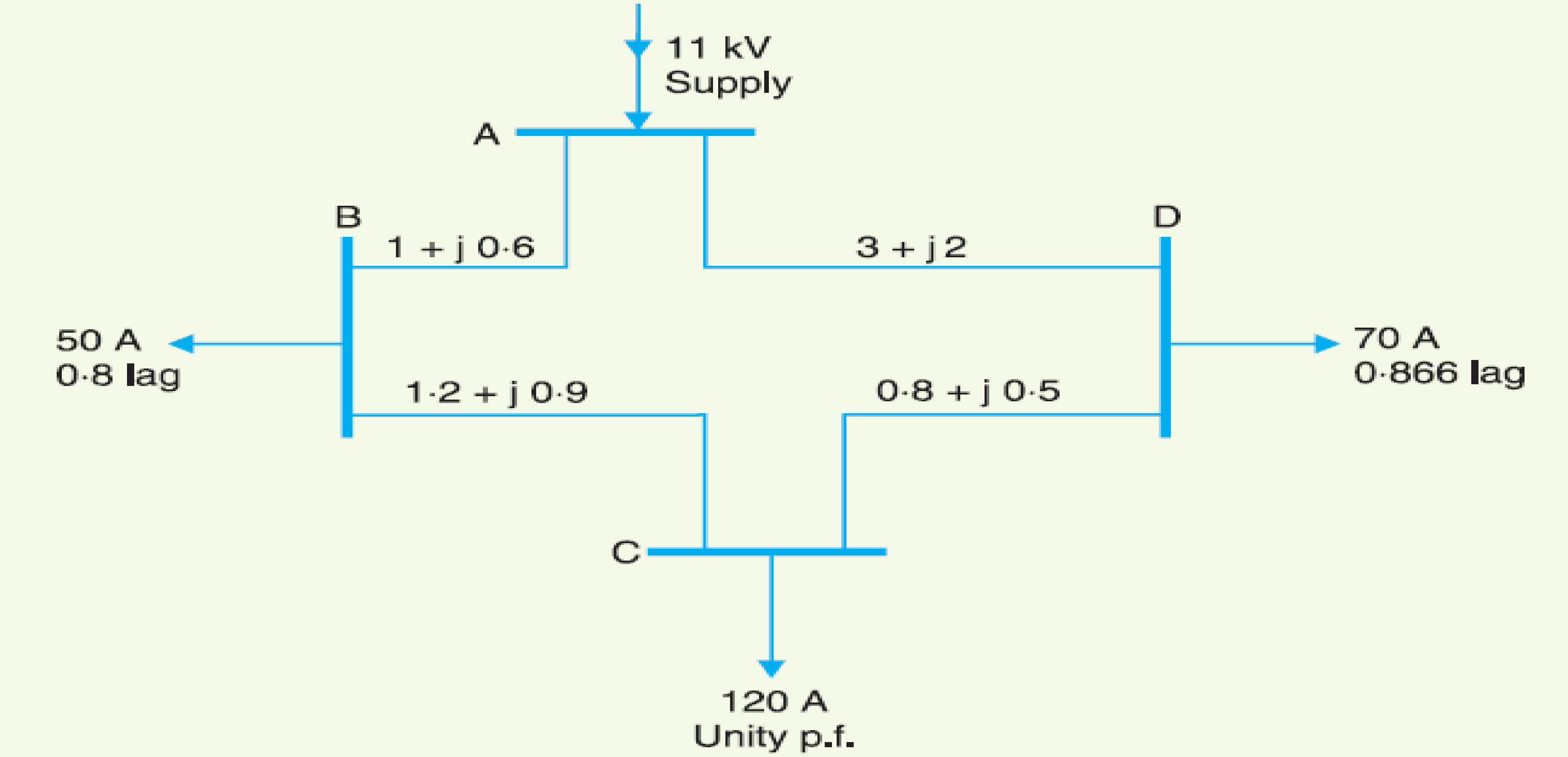
$\therefore$ Line voltage at A $= \sqrt{3} \times 250 =$ **433 V**

Example 14.6. *A 3-phase ring main ABCD fed at A at 11 kV supplies balanced loads of 50 A at 0.8 p.f. lagging at B, 120 A at unity p.f. at C and 70 A at 0·866 lagging at D, the load currents being referred to the supply voltage at A. The impedances of the various sections are :*

Section AB = $(1 + j\,0{\cdot}6)\ \Omega$; *Section BC* = $(1{\cdot}2 + j\,0{\cdot}9)\ \Omega$

Section CD = $(0{\cdot}8 + j\,0{\cdot}5)\ \Omega$; *Section DA* = $(3 + j\,2)\ \Omega$

Calculate the currents in various sections and station bus-bar voltages at B, C and D.



The problem will be solved by Kirchhoff's laws. Let current in section AB be $(x + j\,y)$.

$\therefore$ Current in section BC, $\overrightarrow{I_{BC}} = (x + j\,y) - 50\,(0{\cdot}8 - j\,0{\cdot}6) = (x - 40) + j\,(y + 30)$

Current in section CD, $\overrightarrow{I_{CD}} = [(x - 40) + j\,(y + 30)] - [120 + j\,0]$

$= (x - 160) + j\,(y + 30)$

Current in section DA, $\overrightarrow{I_{DA}} = [(x - 160) + j\,(y + 30)] - [70\,(0{\cdot}866 - j\,0{\cdot}5)]$

$= (x - 220{\cdot}6) + j\,(y + 65)$

Drop in section AB $= \overrightarrow{I_{AB}}\,\overrightarrow{Z_{AB}} = (x + jy)\,(1 + j0{\cdot}6)$

$= (x - 0{\cdot}6y) + j\,(0{\cdot}6x + y)$

Drop in section BC $= \overrightarrow{I_{BC}}\,\overrightarrow{Z_{BC}}$

$= [(x - 40) + j\,(y + 30)]\,[(1{\cdot}2 + j\,0{\cdot}9)]$

$= (1{\cdot}2x - 0{\cdot}9\,y - 75) + j\,(0{\cdot}9x + 1{\cdot}2\,y)$

$$\text{Drop in section } CD = \overrightarrow{I_{CD}}\,\overrightarrow{Z_{CD}}$$
$$= [(x - 160) + j\,(y + 30)]\,[(0{\cdot}8 + j\,0{\cdot}5)]$$
$$= (0{\cdot}8x - 0{\cdot}5y - 143) + j\,(0{\cdot}5x + 0{\cdot}8y - 56)$$

$$\text{Drop in section } DA = \overrightarrow{I_{DA}}\,\overrightarrow{Z_{DA}}$$
$$= [(x - 220{\cdot}6) + j\,(y + 65)]\,[(3 + j\,2)]$$
$$= (3x - 2y - 791{\cdot}8) + j\,(2x + 3y - 246{\cdot}2)$$

Applying Kirchhoff's voltage law to mesh *ABCDA*, we have,

Drop in *AB* + Drop in *BC* + Drop in *CD* + Drop in *DA* = 0

or
$$[(x - 0{\cdot}6y) + j\,(0{\cdot}6x + y)] + [(1{\cdot}2x - 0{\cdot}9y - 75) + j\,(0{\cdot}9x + 1{\cdot}2y)]$$
$$+ [(0{\cdot}8x - 0{\cdot}5y - 143) + j\,(0{\cdot}5x + 0{\cdot}8y - 56)]$$
$$+ [(3x - 2y - 791{\cdot}8) + j\,(2x + 3y - 246{\cdot}2)] = 0$$

or
$$(6x - 4y - 1009{\cdot}8) + j\,(4x + 6y - 302{\cdot}2) = 0$$

As the real (or active) and imaginary (or reactive) parts have to be separately zero,

$$\therefore \quad 6x - 4y - 1009 \cdot 8 = 0$$

and

$$4x + 6y - 302 \cdot 2 = 0$$

Solving for x and y, we have,

$$x = 139 \cdot 7 \text{ A} \quad ; \quad y = -42 \cdot 8 \text{ A}$$

Current in section AB $= \mathbf{(139 \cdot 7 - j\, 42 \cdot 8)\ A}$

Current in section BC $= (x - 40) + j\,(y + 30)$

$= (139 \cdot 7 - 40) + j\,(-42 \cdot 8 + 30) = \mathbf{(99 \cdot 7 - j\, 12 \cdot 8)\ A}$

Current in section CD $= (x - 160) + j\,(y + 30)$

$= (139 \cdot 7 - 160) + j\,(-42 \cdot 8 + 30)$

$= \mathbf{(-20 \cdot 3 - j\, 12 \cdot 8)\ A}$

Current in section DA $= (x - 220 \cdot 6) + j\,(y + 65)$

$= (139 \cdot 7 - 220 \cdot 6) + j\,(-42 \cdot 8 + 65)$

$= \mathbf{(-80 \cdot 9 + j\, 22 \cdot 2)\ A}$

Voltage at supply end A, $\quad V_A = 11000/\sqrt{3} = 6351$ V/phase

$\therefore$ Voltage at station B,

$$\vec{V_B} = \vec{V_A} - \overrightarrow{I_{AB}}\,\overrightarrow{Z_{AB}}$$

$$= (6351 + j\,0) - (139{\cdot}7 - j\,42{\cdot}8)\,(1 + j\,0{\cdot}6)$$

$$= \mathbf{(6185{\cdot}62 - j\,41{\cdot}02)\ volts/phase}$$

Voltage at station C,

$$\vec{V_C} = \vec{V_B} - \overrightarrow{I_{BC}}\,\overrightarrow{Z_{BC}}$$

$$= (6185{\cdot}62 - j\,41{\cdot}02) - (99{\cdot}7 - j\,12{\cdot}8)\,(1{\cdot}2 + j\,0{\cdot}9)$$

$$= \mathbf{(6054{\cdot}46 - j\,115{\cdot}39)\ volts/phase}$$

Voltage at station D,

$$\vec{V_D} = \vec{V}_C - \overrightarrow{I_{CD}}\,\overrightarrow{Z_{CD}}$$

$$= (6054{\cdot}46 - j\,115{\cdot}39) - (-20{\cdot}3 - j\,12{\cdot}8) \times (0{\cdot}8 + j\,0{\cdot}5)$$

$$= \mathbf{(6064{\cdot}3 - j\,95)\ volts/phase}$$

Example 14.3. *A single phase distributor one km long has resistance and reactance per conductor of 0·1 Ω and 0·15 Ω respectively. At the far end, the voltage V_B = 200 V and the current is 100 A at a p.f. of 0·8 lagging. At the mid-point M of the distributor, a current of 100 A is tapped at a p.f. of 0·6 lagging with reference to the voltage V_M at the mid-point. Calculate :*

(*i*) *voltage at mid-point*

(*ii*) *sending end voltage V_A*

(*iii*) *phase angle between V_A and V_B*

Total impedance of distributor $= 2(0{\cdot}1 + j\,0{\cdot}15) = (0{\cdot}2 + j\,0{\cdot}3)\ \Omega$

Impedance of section AM, $\overrightarrow{Z_{AM}} = (0{\cdot}1 + j\,0{\cdot}15)\ \Omega$

Impedance of section MB, $\overrightarrow{Z_{MB}} = (0{\cdot}1 + j\,0{\cdot}15)\ \Omega$

Let the voltage V_B at point B be taken as the reference vector.

Then, $\overrightarrow{V_B} = 200 + j\,0$

(*i*) Load current at point B, $\overrightarrow{I_2} = 100\,(0{\cdot}8 - j\,0{\cdot}6) = 80 - j\,60$

Current in section MB, $\overrightarrow{I_{MB}} = \overrightarrow{I_2} = 80 - j\,60$

Drop in section MB, $\overrightarrow{V_{MB}} = \overrightarrow{I_{MB}}\,\overrightarrow{Z_{MB}}$

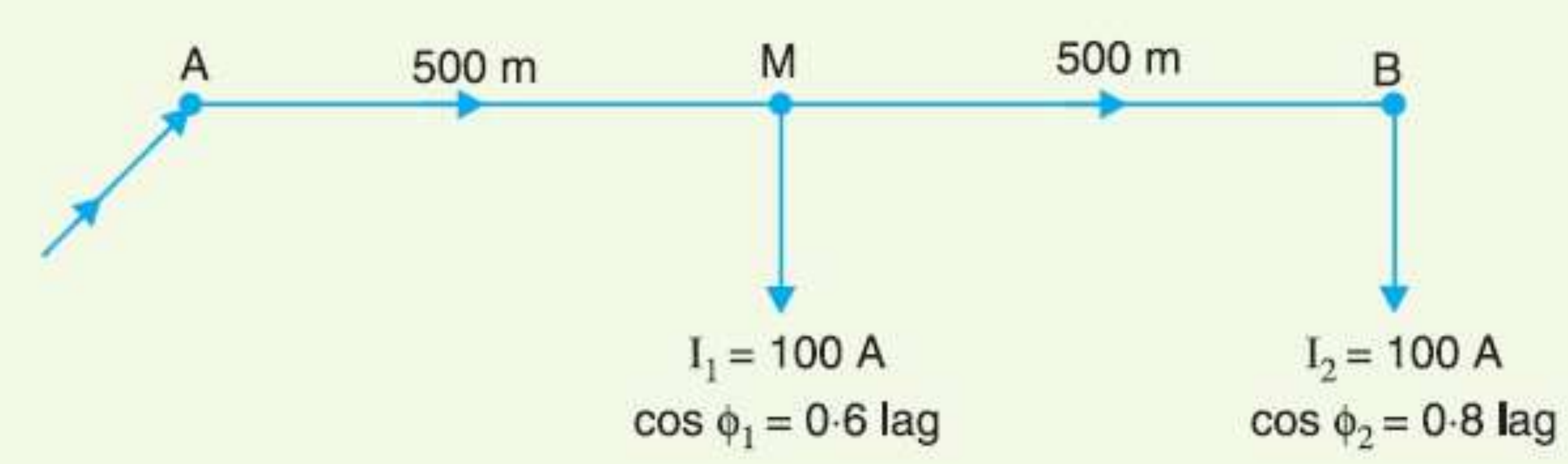
$= (80 - j\,60)\,(0{\cdot}1 + j\,0{\cdot}15) = 17 + j\,6$

$\therefore$ Voltage at point M, $\overrightarrow{V_M} = \overrightarrow{V_B} + \overrightarrow{V_{MB}} = (200 + j\,0) + (17 + j\,6)$

$= 217 + j\,6$

Its magnitude is $= \sqrt{(217)^2 + (6)^2} =$ **217·1 V**

Phase angle between V_M and V_B, $\alpha = \tan^{-1} 6/217 = \tan^{-1} 0{\cdot}0276 = 1{\cdot}58°$



(*ii*) The load current I_1 has a lagging p.f. of 0·6 *w.r.t.* V_M. It lags behind V_M by an angle $\phi_1 = \cos^{-1} 0{\cdot}6 = 53{\cdot}13^\circ$

$$\text{Phase angle between } I_1 \text{ and } V_B,\ \phi'_1 = \phi_1 - \alpha = 53{\cdot}13^\circ - 1{\cdot}58 = 51{\cdot}55^\circ$$

$$\text{Load current at } M,\quad \vec{I_1} = I_1 (\cos \phi_1' - j \sin \phi_1') = 100 (\cos 51{\cdot}55^\circ - j \sin 51{\cdot}55^\circ)$$

$$= 62{\cdot}2 - j\,78{\cdot}3$$

$$\text{Current in section } AM,\quad \overrightarrow{I_{AM}} = \vec{I_1} + \vec{I_2} = (62{\cdot}2 - j\,78{\cdot}3) + (80 - j\,60)$$

$$= 142{\cdot}2 - j\,138{\cdot}3$$

$$\text{Drop in section } AM,\quad \overrightarrow{V_{AM}} = \overrightarrow{I_{AM}}\,\overrightarrow{Z_{AM}} = (142{\cdot}2 - j\,138{\cdot}3)\,(0{\cdot}1 + j\,0{\cdot}15)$$

$$= 34{\cdot}96 + j\,7{\cdot}5$$

$$\text{Sending end voltage},\quad \vec{V_A} = \vec{V_M} + \overrightarrow{V_{AM}} = (217 + j\,6) + (34{\cdot}96 + j\,7{\cdot}5)$$

$$= 251{\cdot}96 + j\,13{\cdot}5$$

Its magnitude is $= \sqrt{(251 \cdot 96)^2 + (13 \cdot 5)^2} =$ **252·32 V**

(iii) The phase difference θ between V_A and V_B is given by :

$$\tan\theta = 13{\cdot}5/251{\cdot}96 = 0{\cdot}05358$$

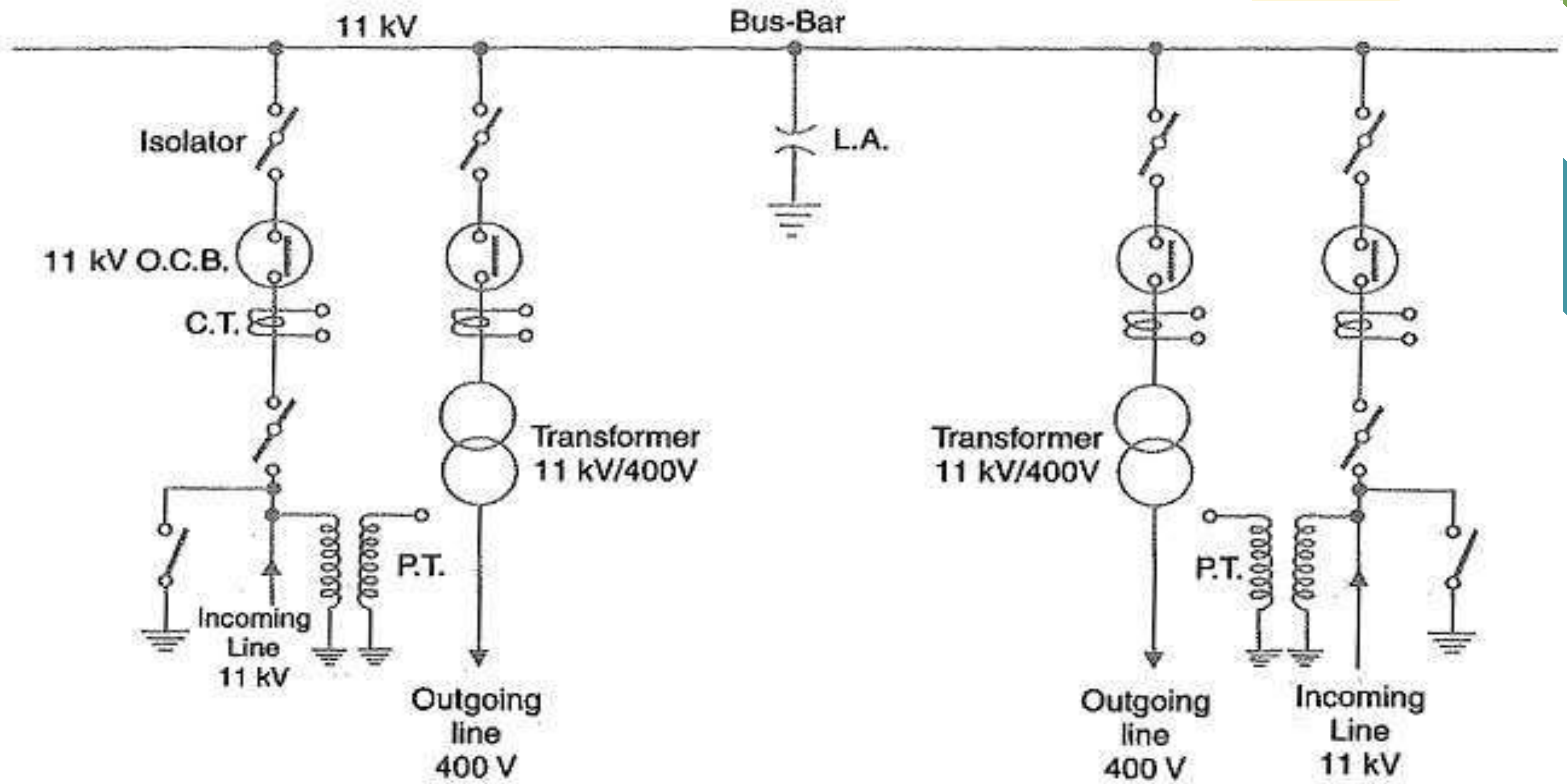
$$\therefore \quad \theta = \tan^{-1} 0{\cdot}05358 = \mathbf{3{\cdot}07^\circ}$$

Hence supply voltage is 252·32 V and leads V_B by 3·07°.

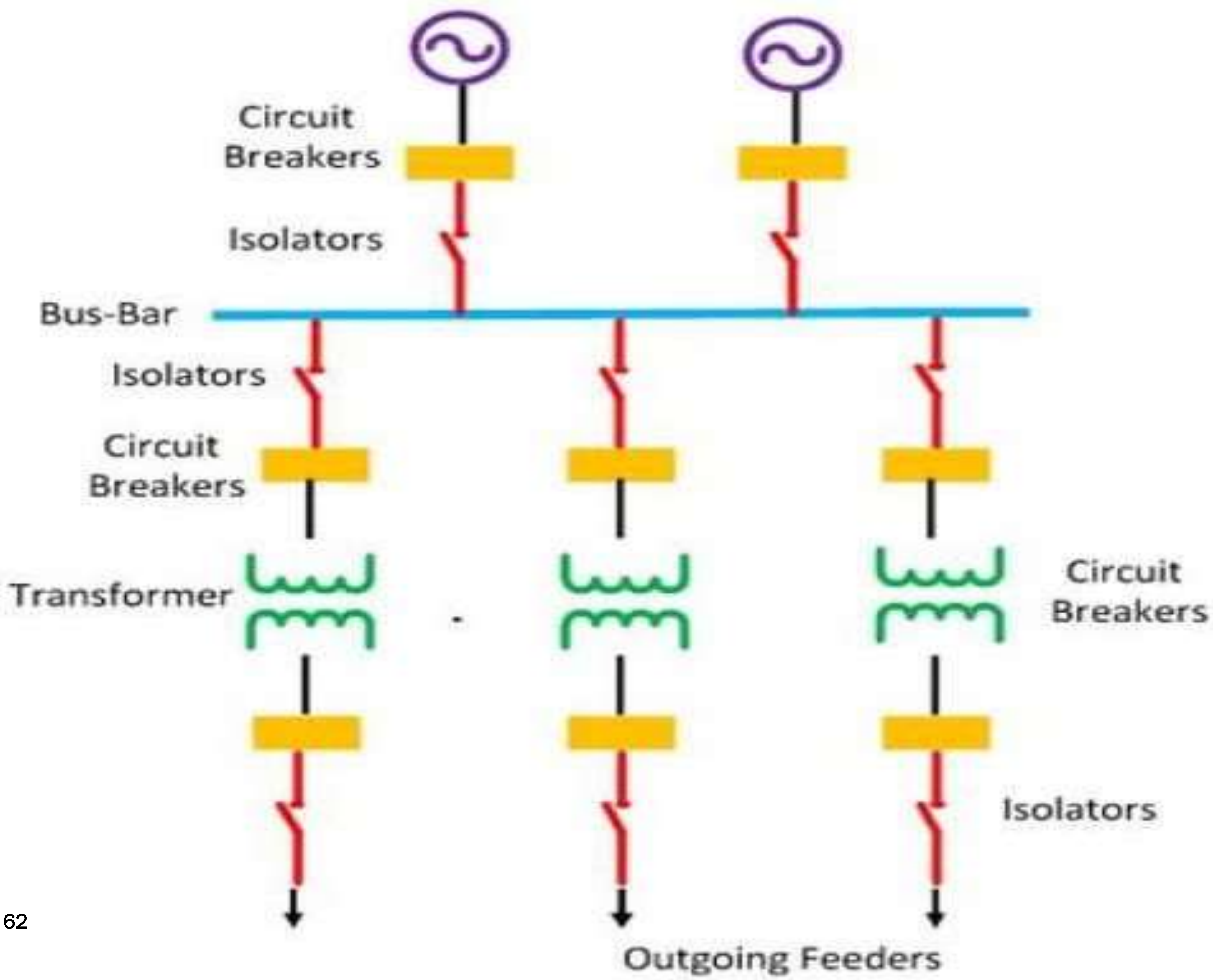

Week-07
Page: 59-70

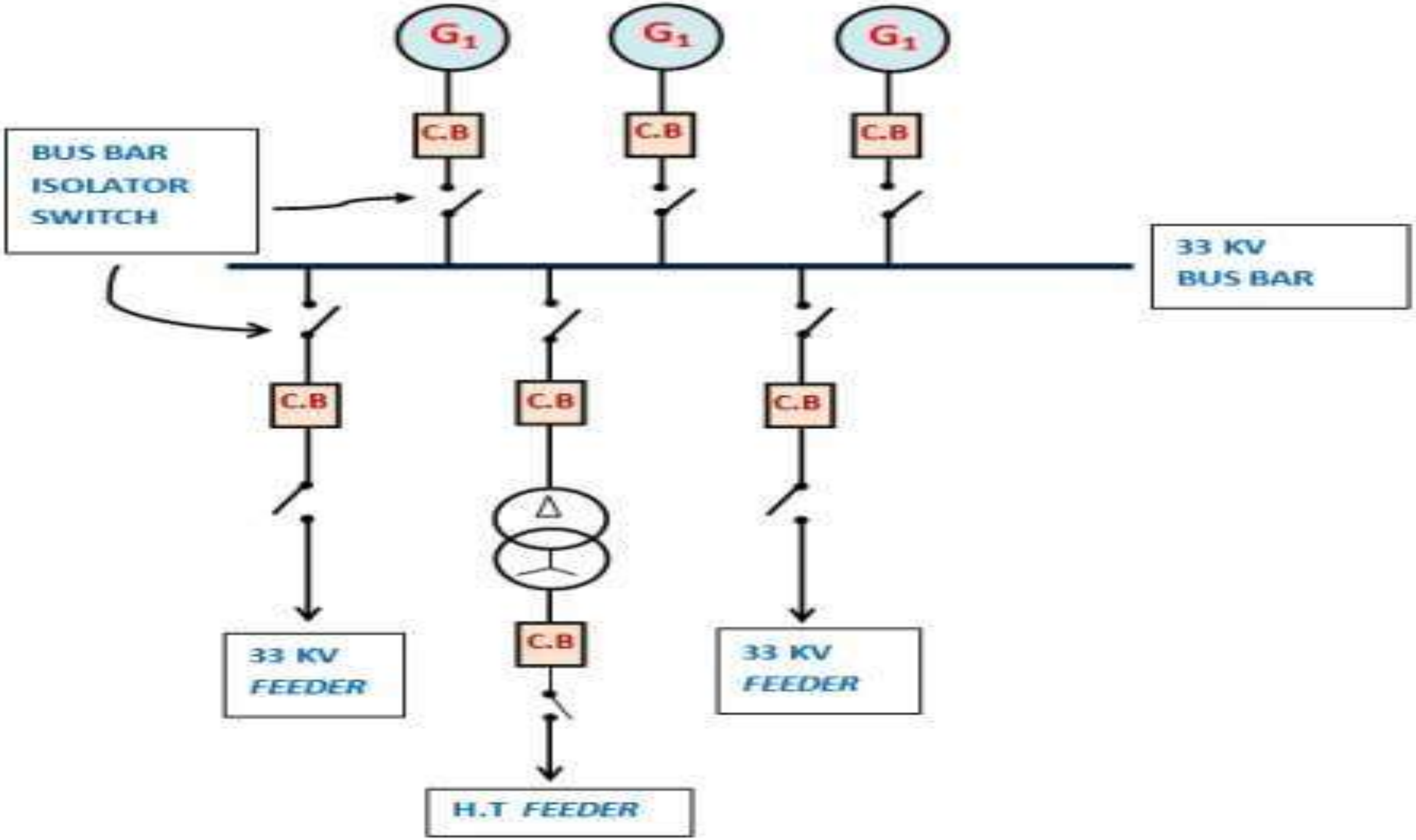
Bus Bar Arrangements

- During the distribution of electrical power to various output circuits, two or more wires are connected to a single wire.
- The improper electrical connection gets opened and the insulation of the wire may get damaged due to heat generation in the wires.
- This condition may lead to an open circuit, which is too dangerous for the distribution of power.
- In such cases, to avoid open-circuit conditions, the multiple wires are connected properly using an electric bus system.
- The bus bar is an electrical component used in electrical distribution systems to collect current from the input terminals of an electrical system and distributes it to various output circuits.
- It is used as a junction between the input power and output power.
- It distributes the power to various output circuits with more flexibility.



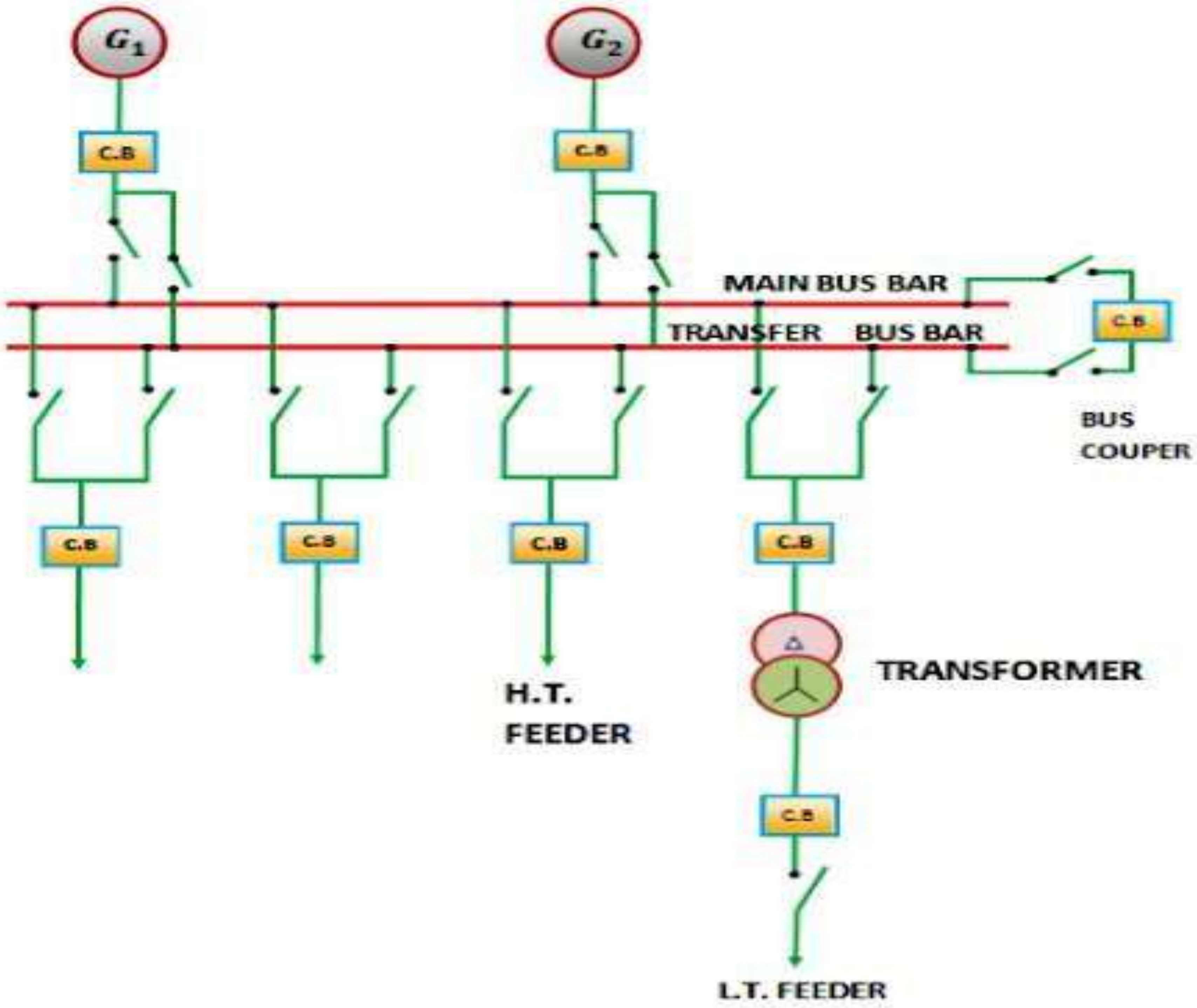
Busbar Arrangements in Substations

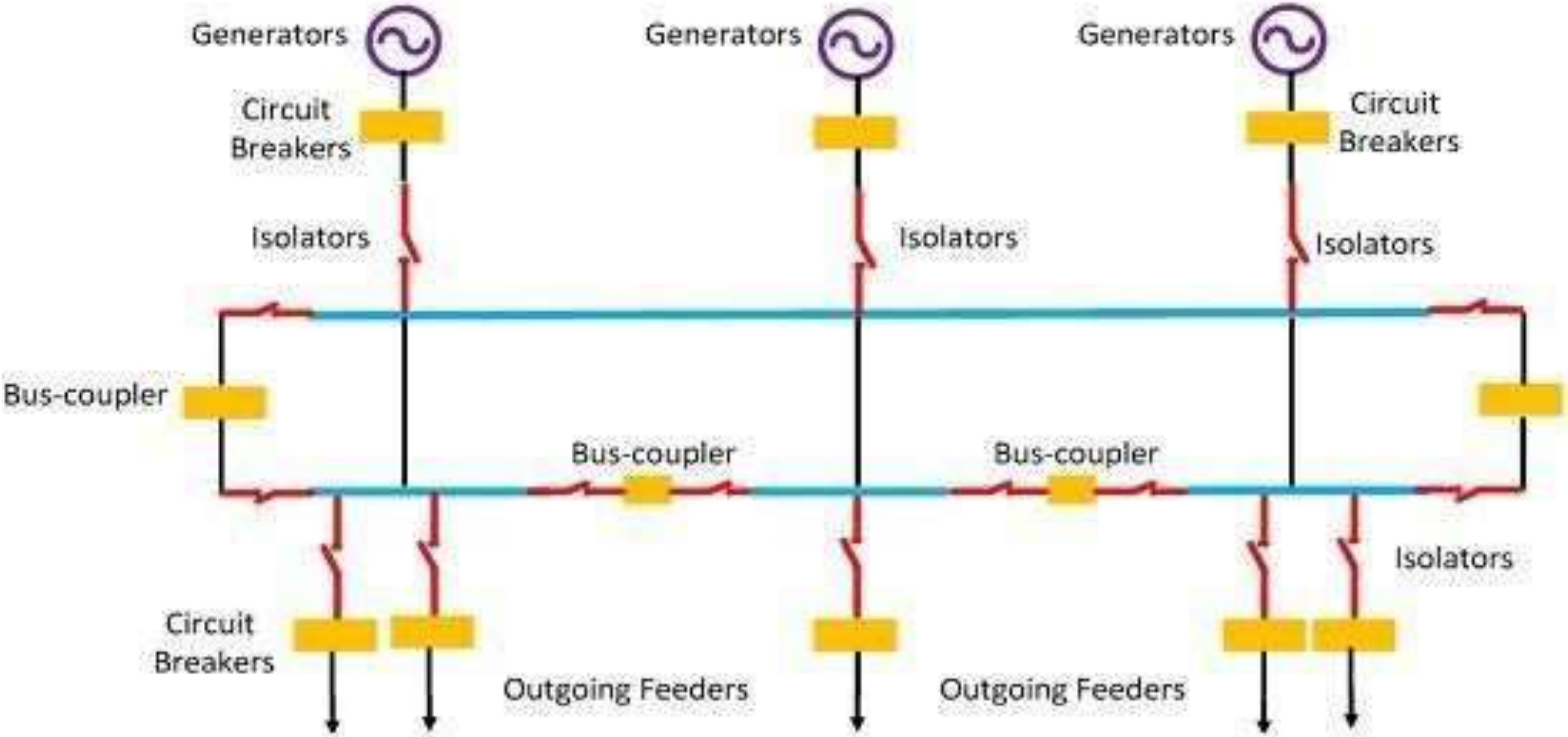

Circuit Breakers
Isolators
Bus-Bar
Isolators
Circuit Breakers
Transformer
Circuit Breakers
Isolators
Outgoing Feeders



Single bus bar arrangement

Main and Transfer Busbar Arrangement





Ring Main Arrangement

Selection and location of site for substation

Selection and location of site for substation

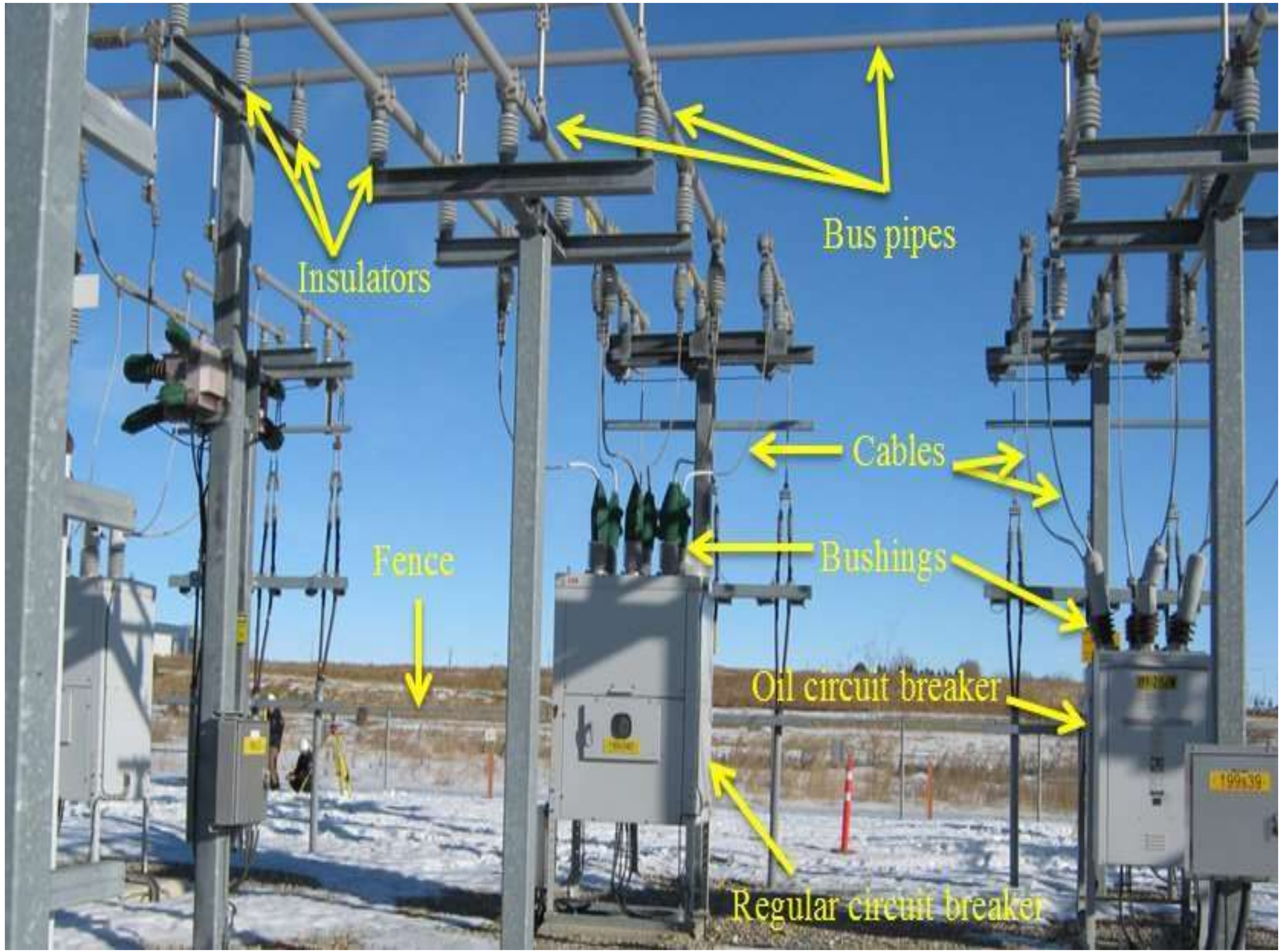
1. It should be located nearer or at the center of the gravity of load.
2. It should provide safe and reliable arrangement
3. Maintenance of regulation clearances (deals with political issues)
4. Facilities for carrying out repairs and maintenance.
5. Immediate facilities against abnormalities such as possibility of explosion or fire etc.
6. Good design and construction
7. Provision of suitable switchgear and protective gear etc.
8. Land cost
9. Number of incoming and out

Selection and location of site for substation

10. Transfer of power
11. Short-circuit levels
12. Types of substation (objective/function)
13. It should be away from airport and terrorist zones Physical amenities should be available for engineers such as communication services, transportation, schools, houses, hospitals, availability of drinking water etc.
15. Drainage facility for rainwater
16. Should be easily operated and maintained
17. Should involve minimum capital cost
18. Provision for future expansion

Selection and rating of S/s equipment

- Surge arrester
- CT
- PT
- Isolator
- Circuit breaker
- Transformer
- Busbar
- Shunt capacitor
- Earth switch
- Relays
- Auxiliaries



List of equipment in substation

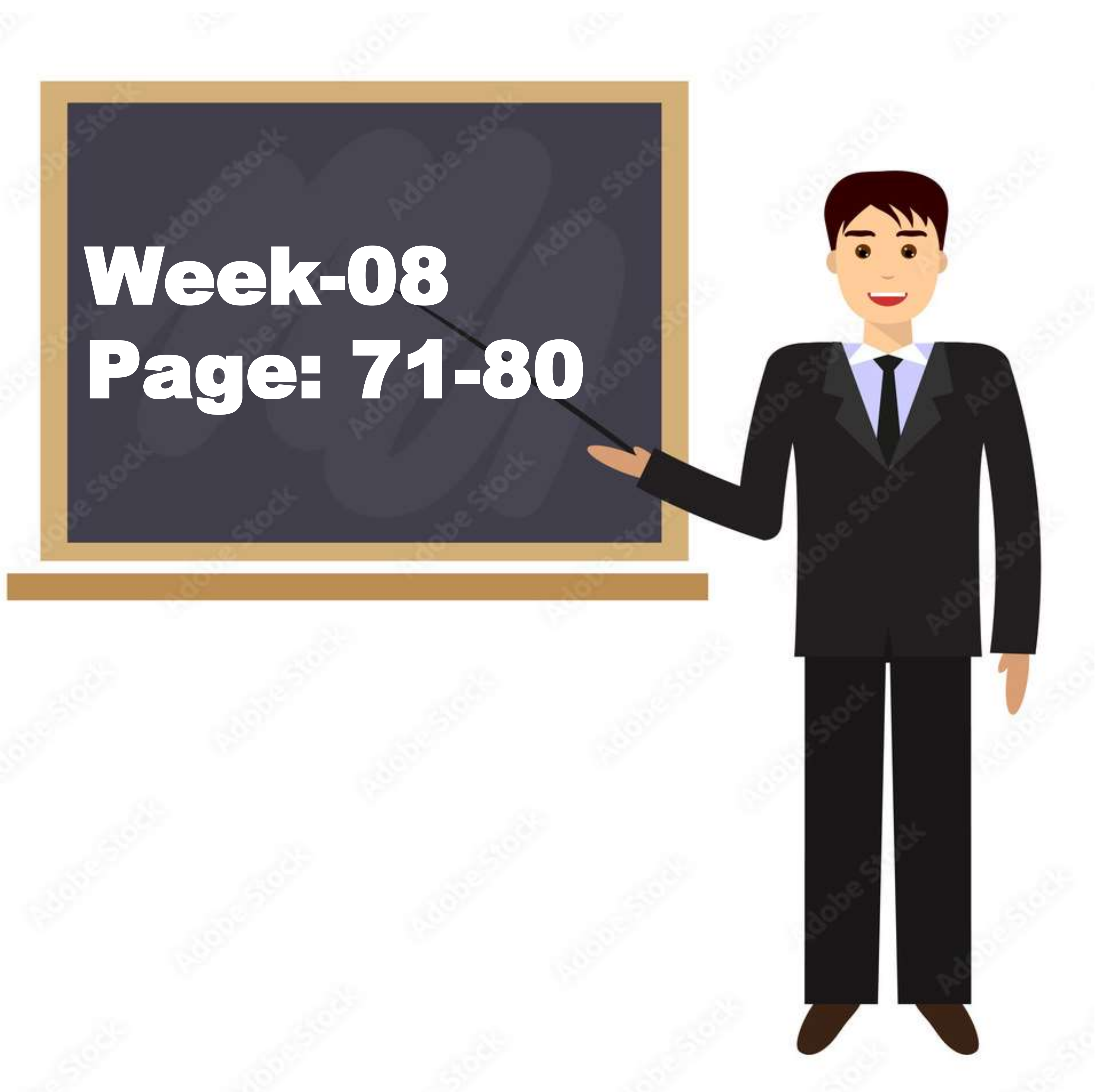
- Lightning Arrester
- Power Transformer
- Instrument Transformer
- Current Transformer
- Potential Transformer
- Busbar
- Wave Trap
- Isolator
- Circuit Breaker
- Batteries
- Capacitor Bank
- Switchyard
- Indicating and metering Instruments
- Carrier-current Equipment
- Relay
- Insulator
- Fuses
- Shunt Capacitor and Reactor
- Earthing Switch
- Distribution Transformer
- Earthing








Incoming Subtransmission Lines
Electric power path through substation
34 KV in
Lightning Arresters
Air-break Switches
Outgoing Distribution Lines
Step-down Transformer
Distribution Bus
7.2 KV out
Cutout
Switches
Oil Circuit Breakers
Voltage Regulators
Metal-clad
Switchgear
Control House


Week-08
Page: 71-80

UNIT-III UNDERGROUND CABLES

Underground Cable:

Consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover.

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.

Advantages & Disadvantages

Advantages

1. Better general appearance
2. Less liable to damage through storms or lighting
3. Low maintenance cost
4. Less chances of faults
5. Small voltage drops

Disadvantages

1. Greater installation cost
2. Insulation problems at high voltages compared with equivalent overhead system

Requirements of the insulating materials

1. High insulation resistance.
2. High dielectric strength.
3. Good mechanical properties i.e., tenacity and elasticity.
4. It should not be affected by chemicals around it.
5. It should be non-hygroscopic because the dielectric strength of any material goes very much down with moisture content

Vulcanized rubber insulated cables are used for wiring of houses, buildings and factories for low power work.

There are two main groups of synthetic rubber material :

(i)general purpose synthetics which have rubber-like properties

(ii)special purpose synthetics which have better properties than the rubber e.g. fire resisting and oil resisting properties.

The four main types are:

(i) butyl rubber, (ii) silicon rubber, (iii) neoprene, and (iv) styrene rubber.

Polyvinyl Chloride (PVC)

PVC material has many grades.

General Purpose Type: It is used both for sheathing and as an insulating material. In this compound monomeric plasticizers are used. It is to be noted that a V.R. insulated PVC sheathed cable is not good for use.

Hard Grade PVC: These are manufactured with less amount of plasticizer as compared with general purpose type. Hard grade PVC are used for higher temperatures for short duration of time like in soldering and are better than the general purpose type. Hard grade cannot be used for low continuous temperatures.

Heat Resisting PVC: Because of the use of monomeric plasticizer which volatilizes at temperature 80°C–100°C, general purpose type compounds become stiff. By using polymeric plasticizers it is possible to operate the cables continuously around 100°C.

PVC compounds are normally costlier than the rubber compounds and the polymeric plasticized compounds are more expensive than the monomeric plasticized ones. PVC is inert to oxygen, oils, alkalis and acids and, therefore, if the environmental conditions are such that these things are present in the atmosphere, PVC is more useful than rubber.

Polythene

This material can be used for high frequency cables. This has been used to a limited extent for power cables also. The thermal dissipation properties are better than those of impregnated paper and the impulse strength compares favorably with an impregnated paper- insulated cable. The maximum operating temperature of this cable under short circuits is 100°C.

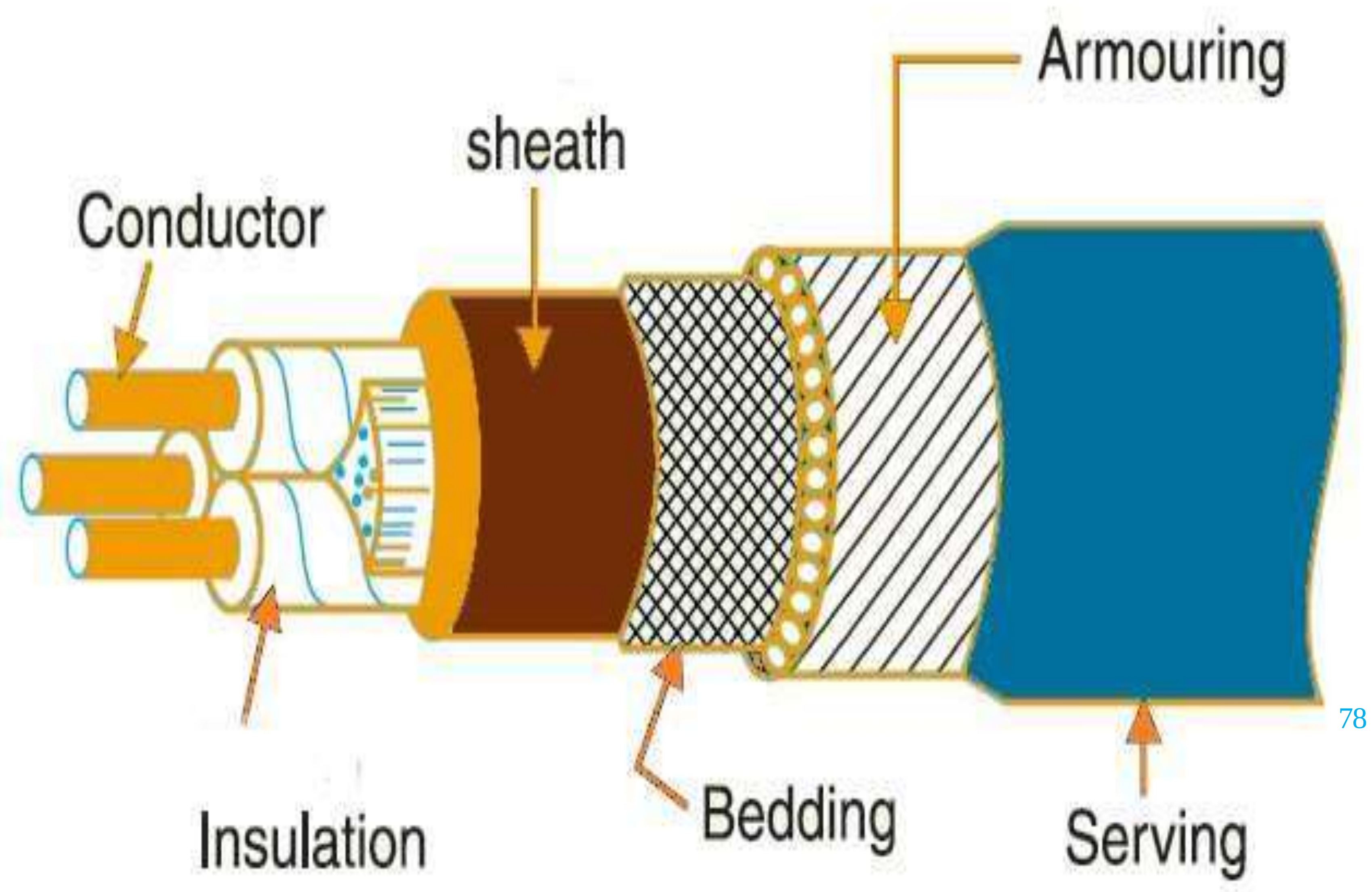
Impregnated Paper

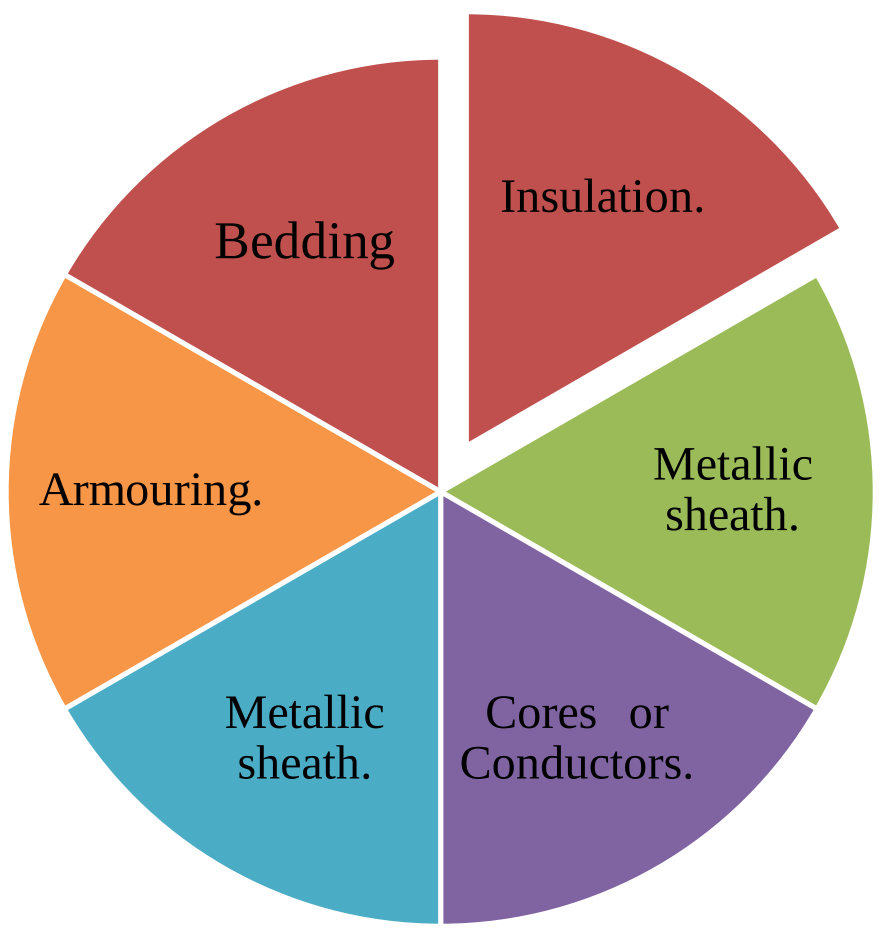
A suitable layer of the paper is lapped on the conductor depending upon the operating voltage. It is then dried by the combined application of heat and vacuum. This is carried out in a hermetically sealed steam heated chamber. The temperature is 120°–130°C before vacuum is created.

Protective Coverings

A cotton braid is applied over the insulated conductor and is then impregnated with a compound, which is water and weather proof. The rubber insulated cables are covered with a lead alloy sheath and is used for fixed installation inside or outside buildings in place of braided and compound finished cable in conduit.

Construction





1. 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. The conductors are made of tinned copper or aluminium and are usually stranded in order to provide flexibility to the cable.

2. Insulation. 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.

3. 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.

4. 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.

5. 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.

6. 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.


Week-09-11
Page: 82-108

Types of Cables

Classified in two ways according to

(i) Type of insulating material used in their manufacture

(ii)Voltage for which they are manufactured. Latter method of classification is :

(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. Fora 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand

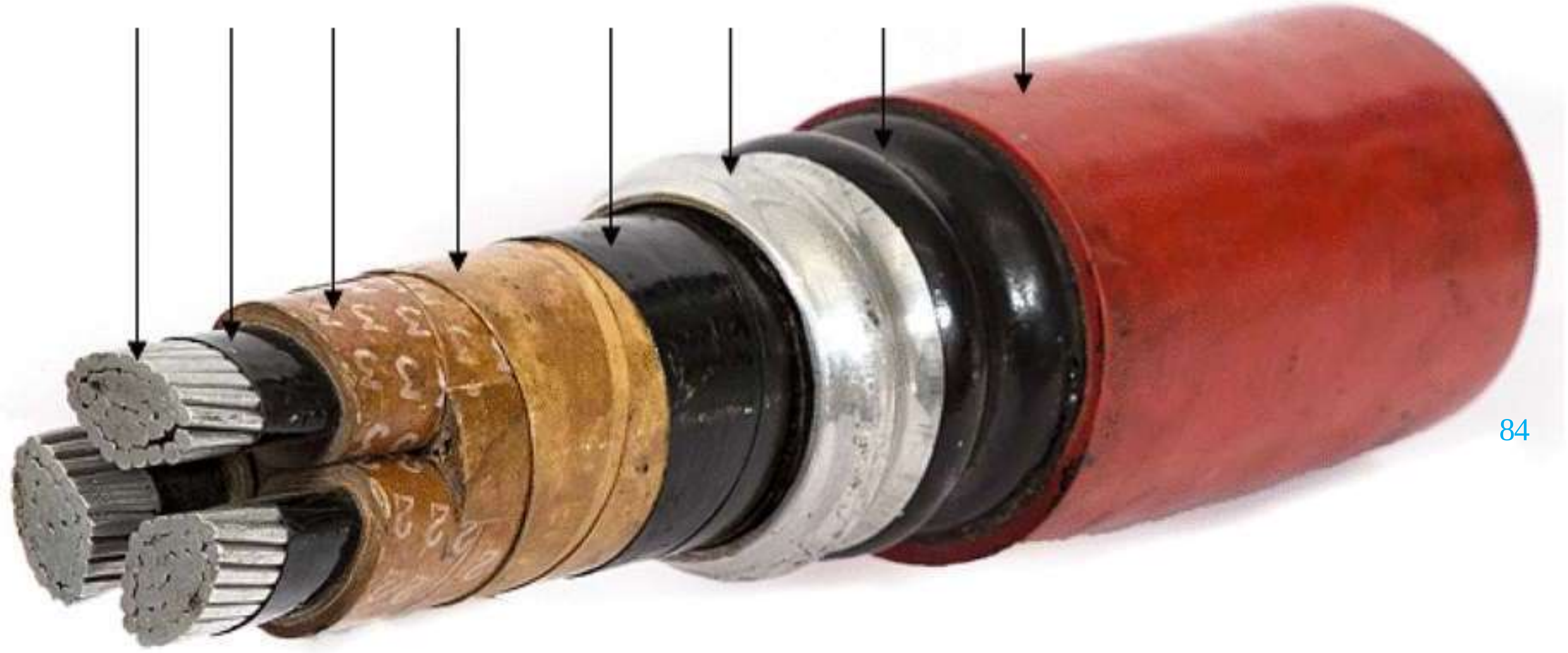
Cables for 3-Phase Service

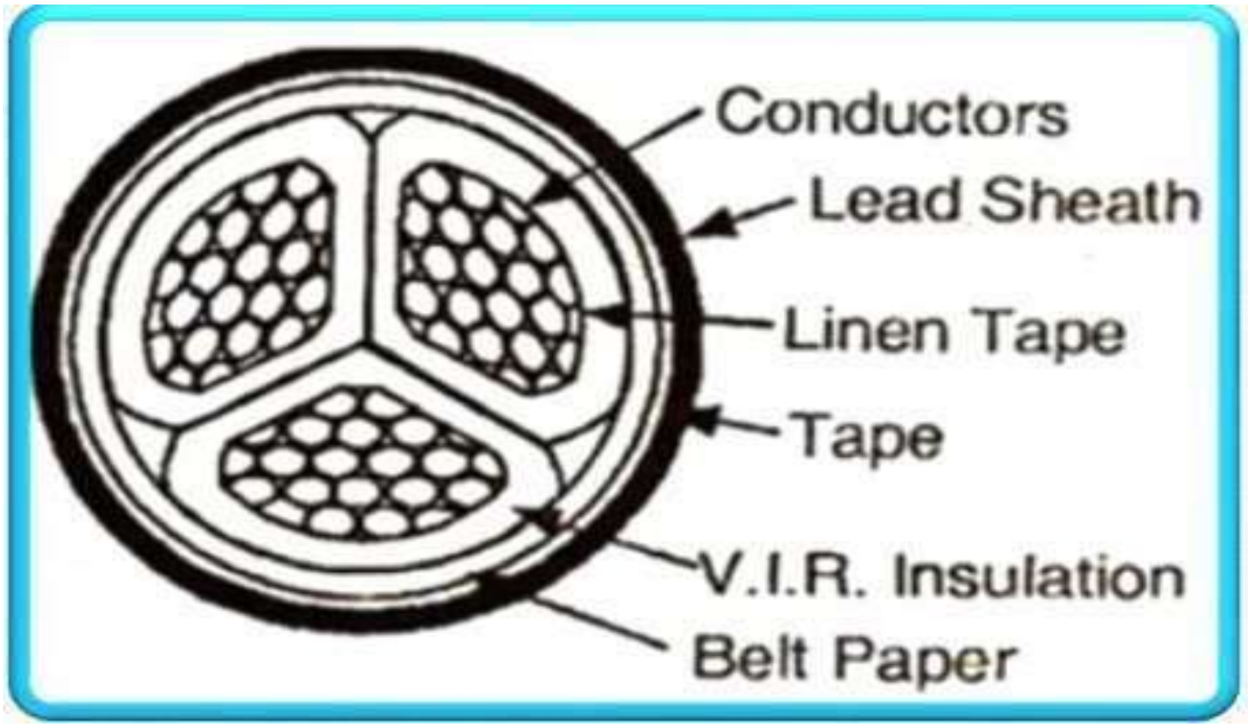
1. Belted cables — upto 11 kV

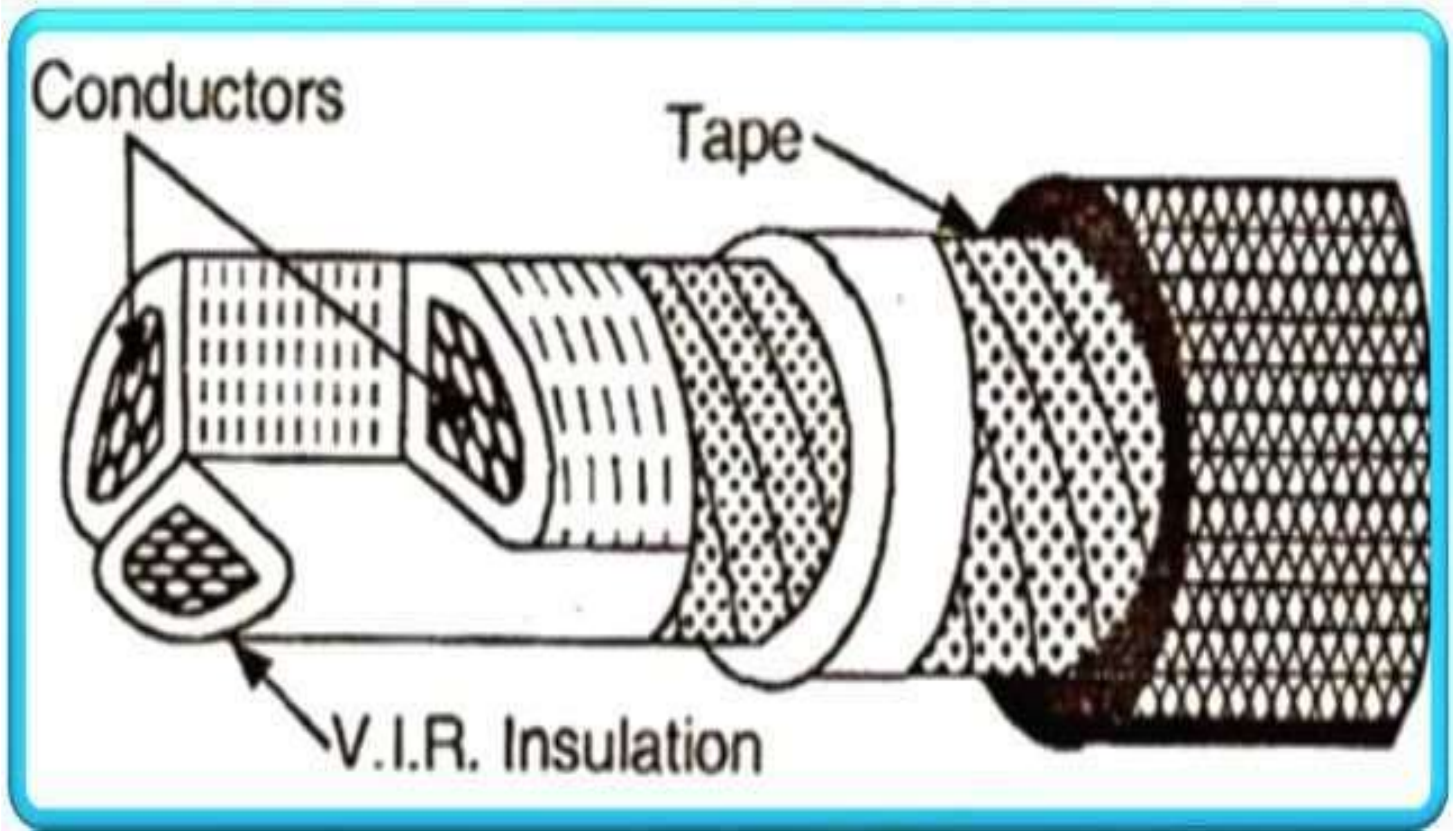
2. Screened cables — from 22 kV to 66 kV

3. Pressure cables — beyond 66 kV

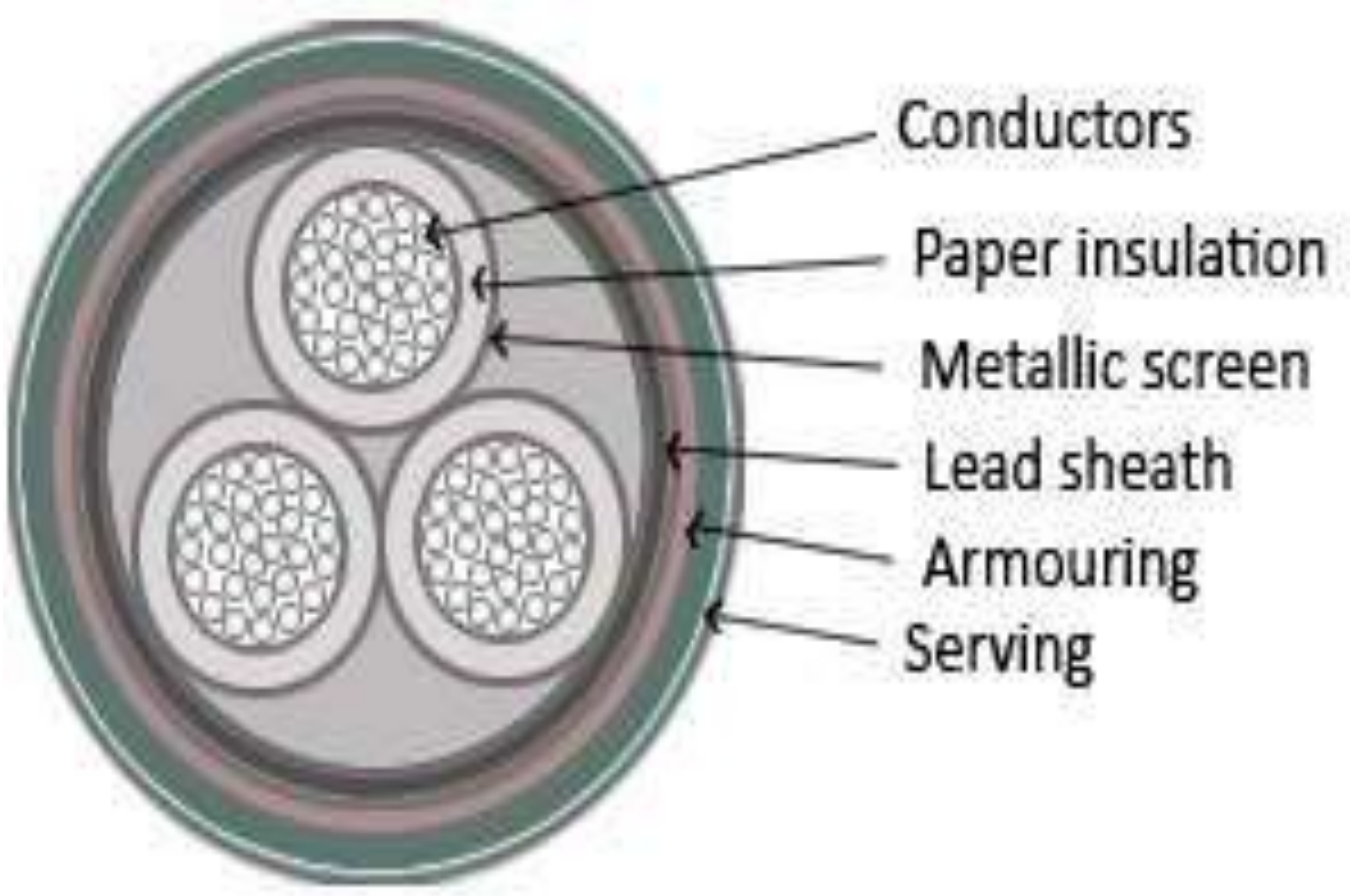
Belted cables



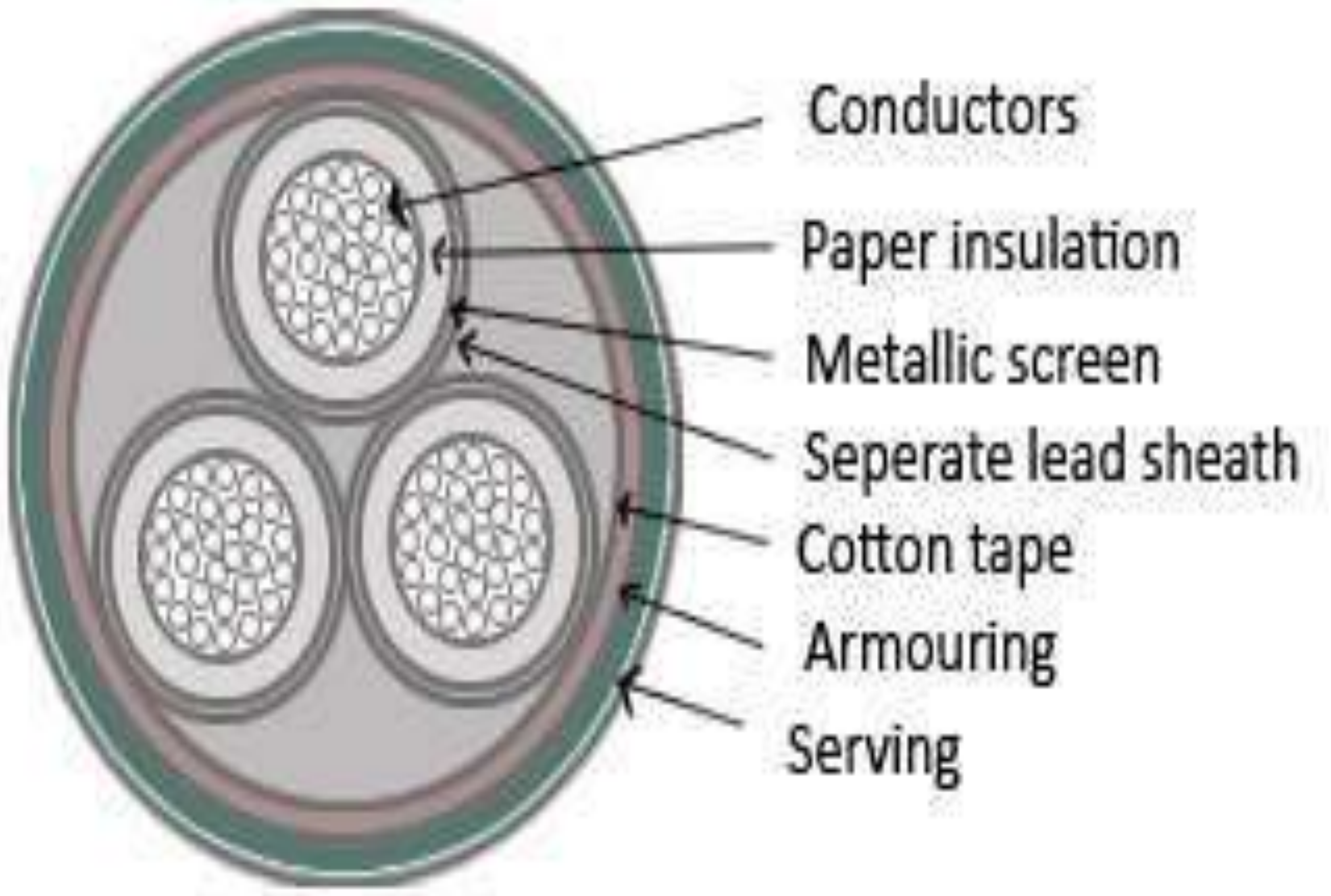




Screened cables

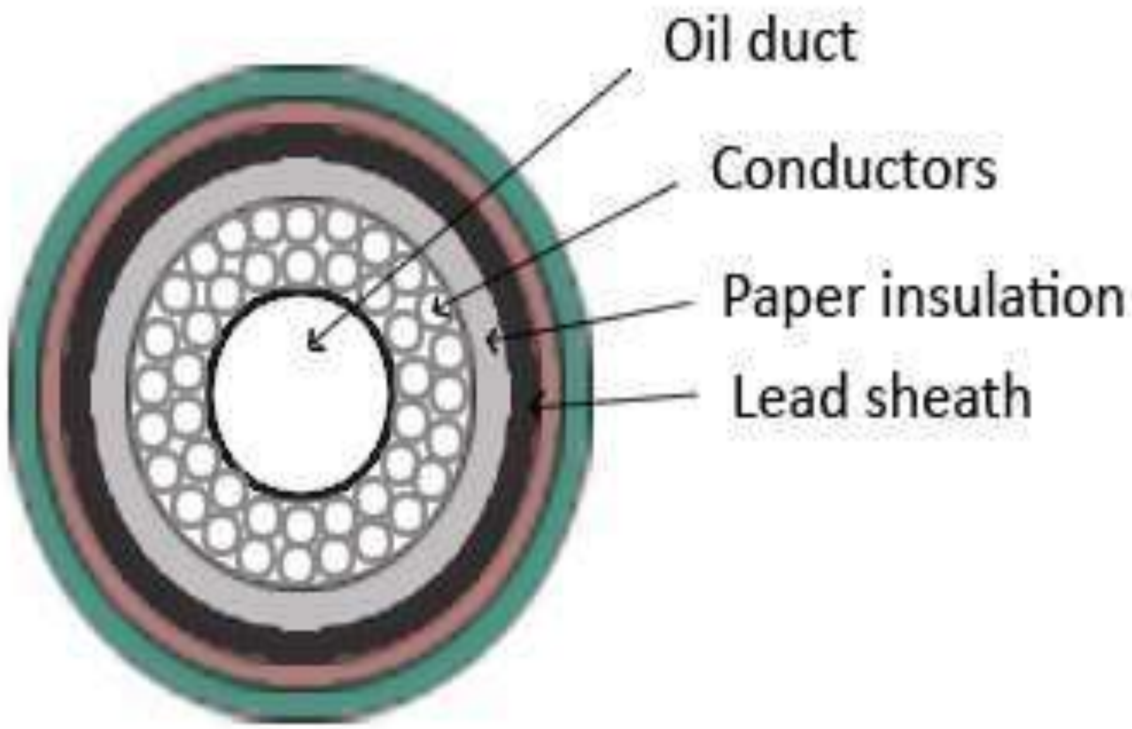


H-type cable

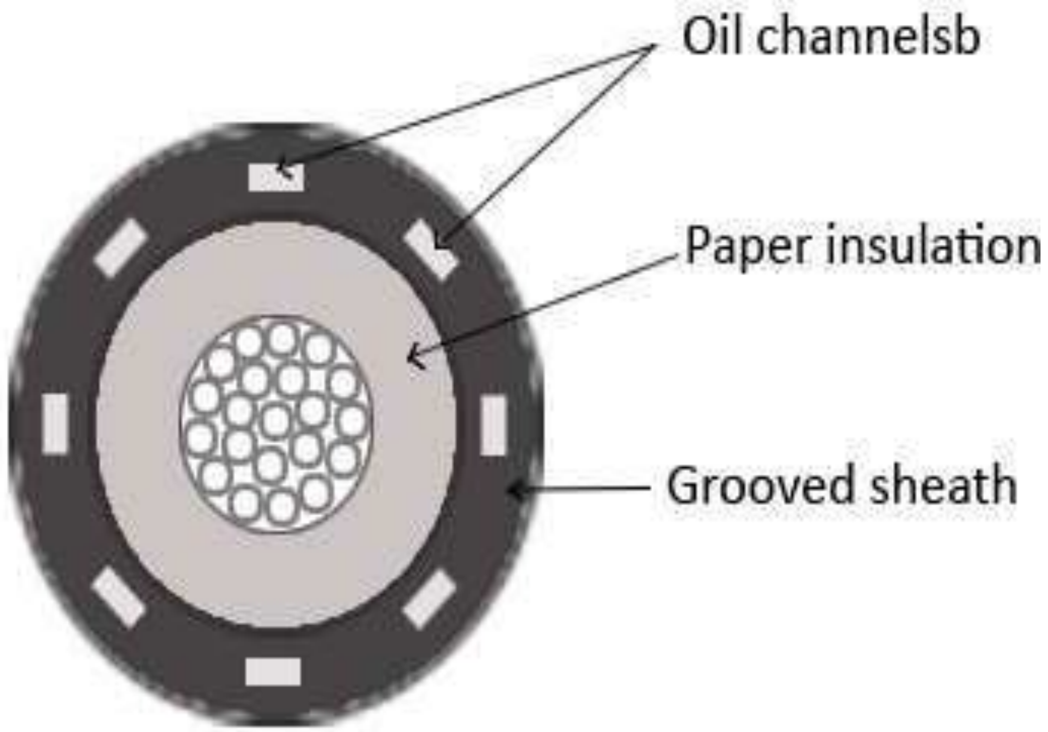


S.L. type cable

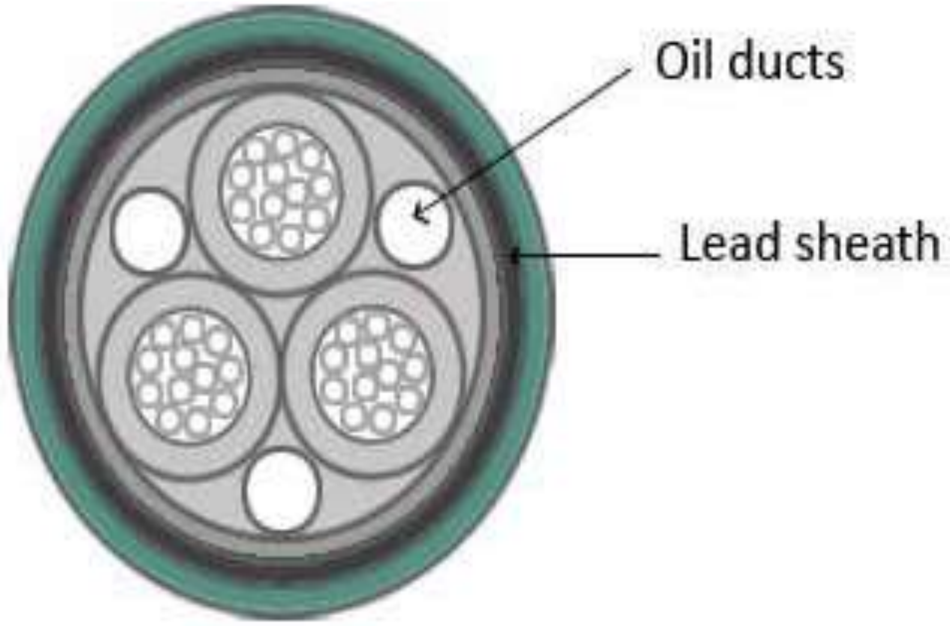
Pressure cables



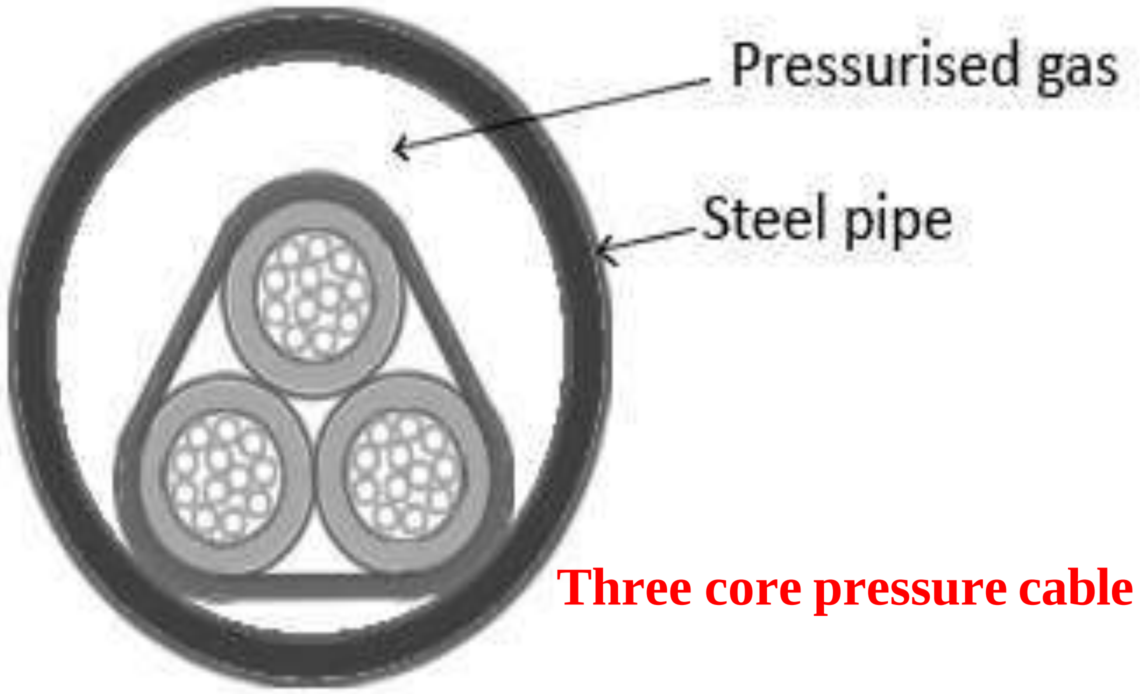
Single core conductor channel oil filled cable



Single core sheath channel oil filled cable

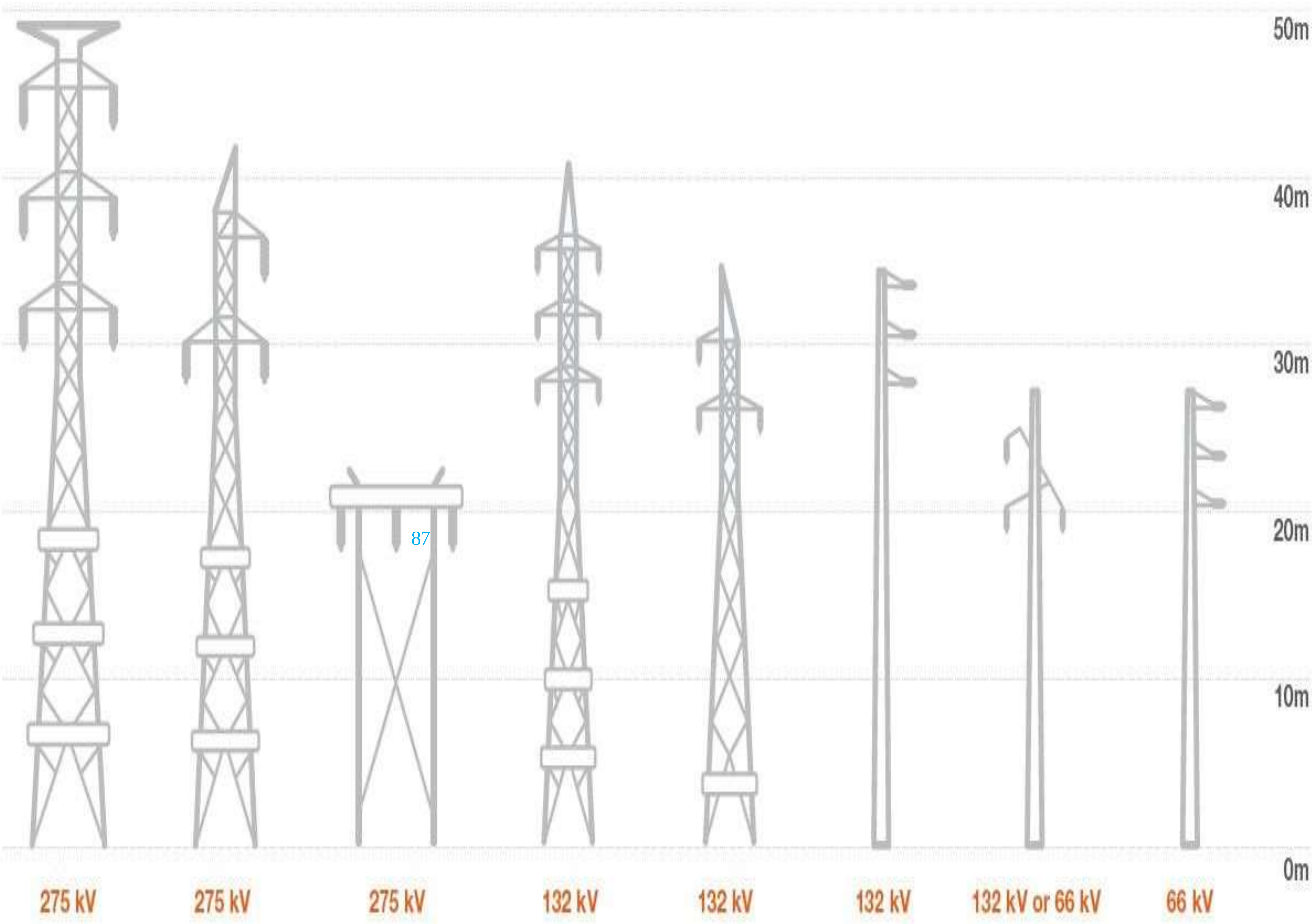


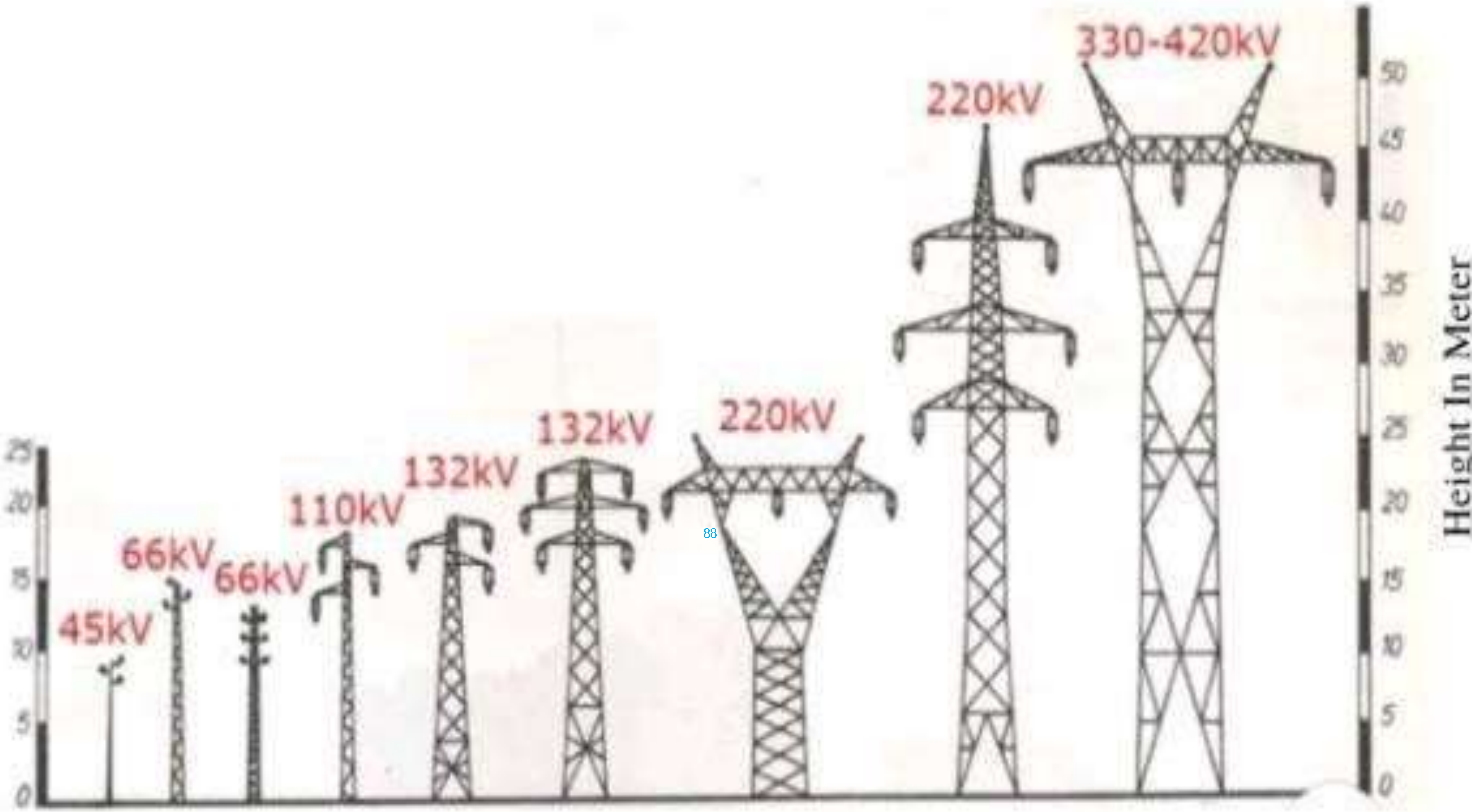
Three core oil filled cable

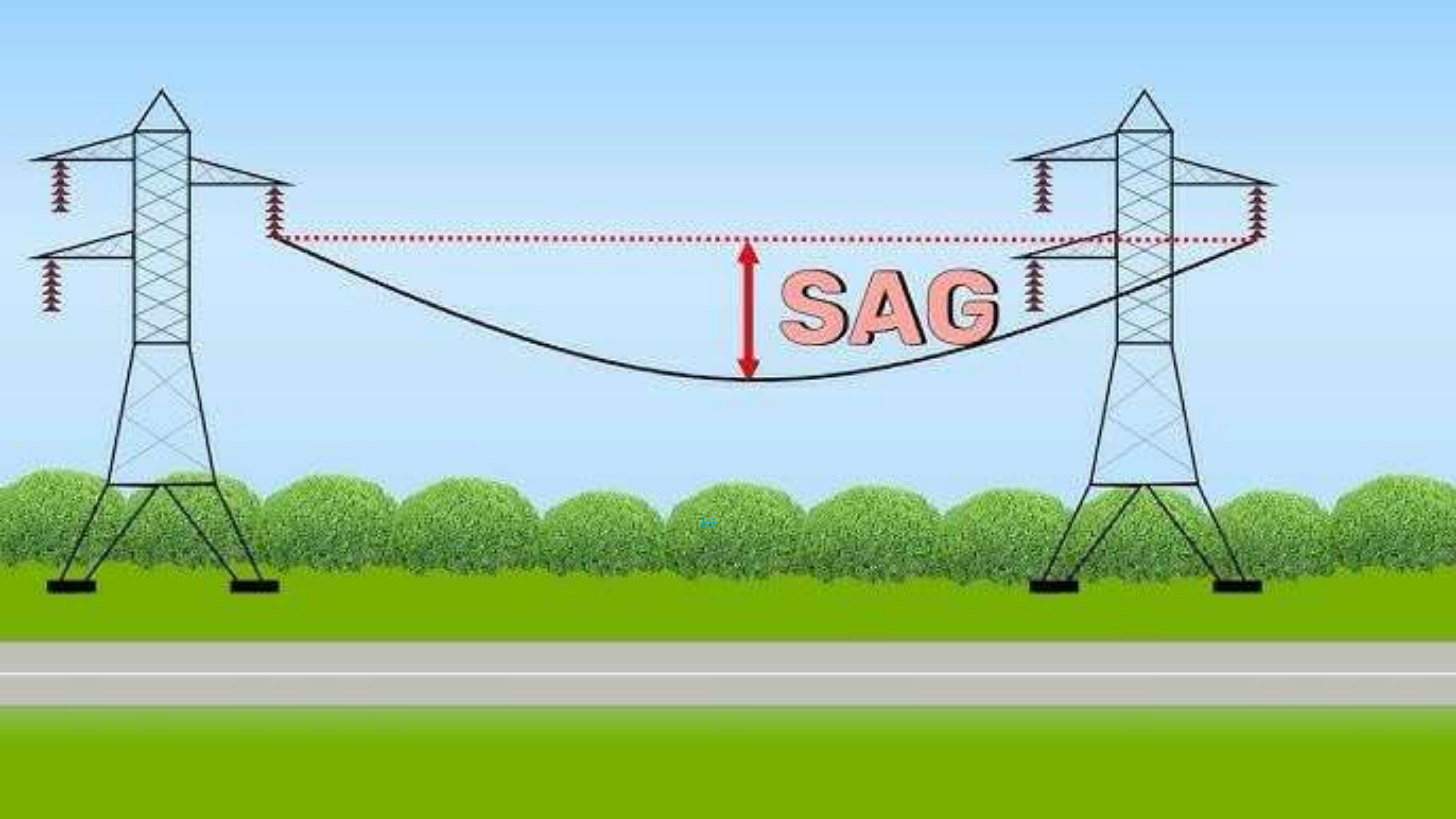


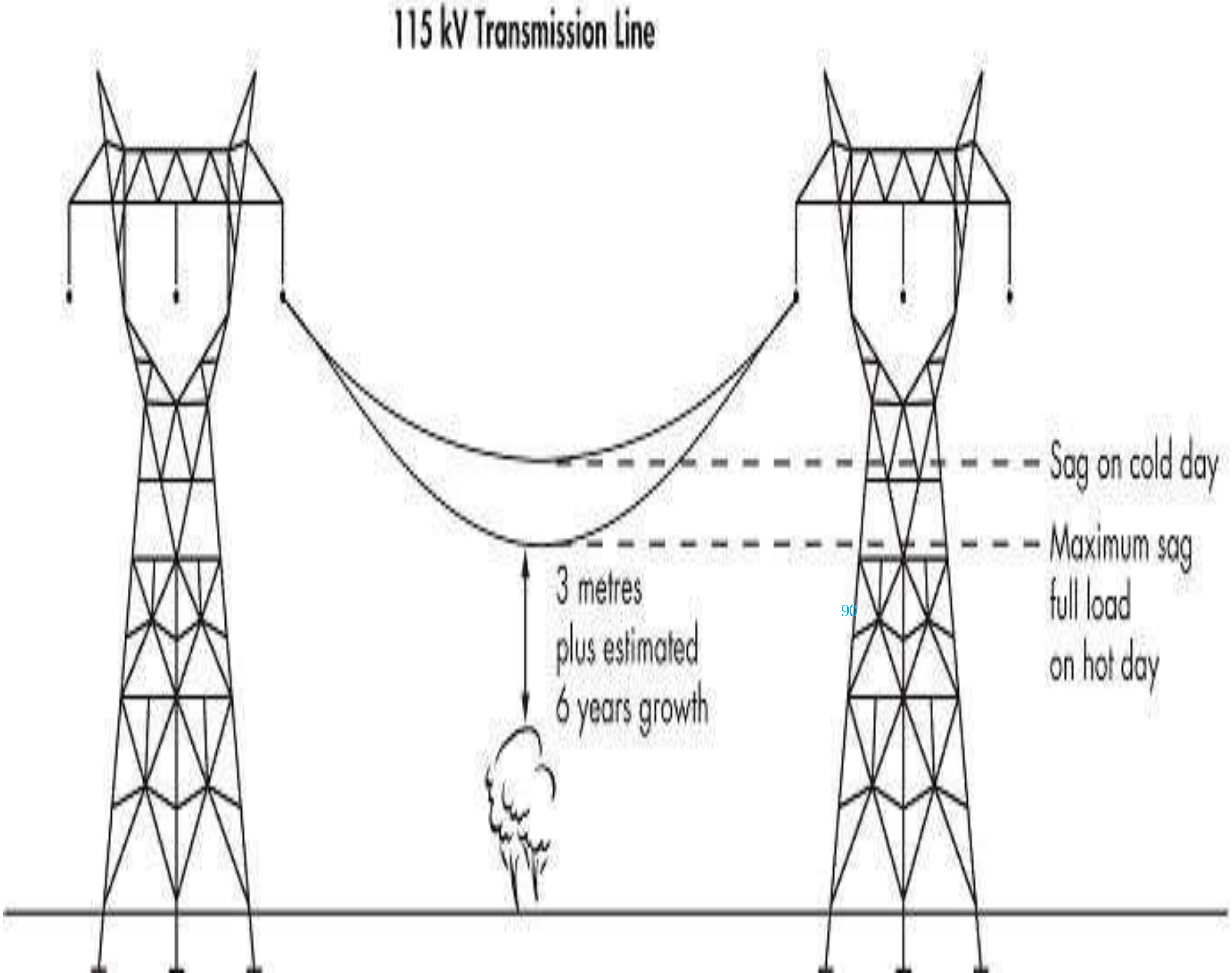
Three core pressure cable

Structure Types and Voltages



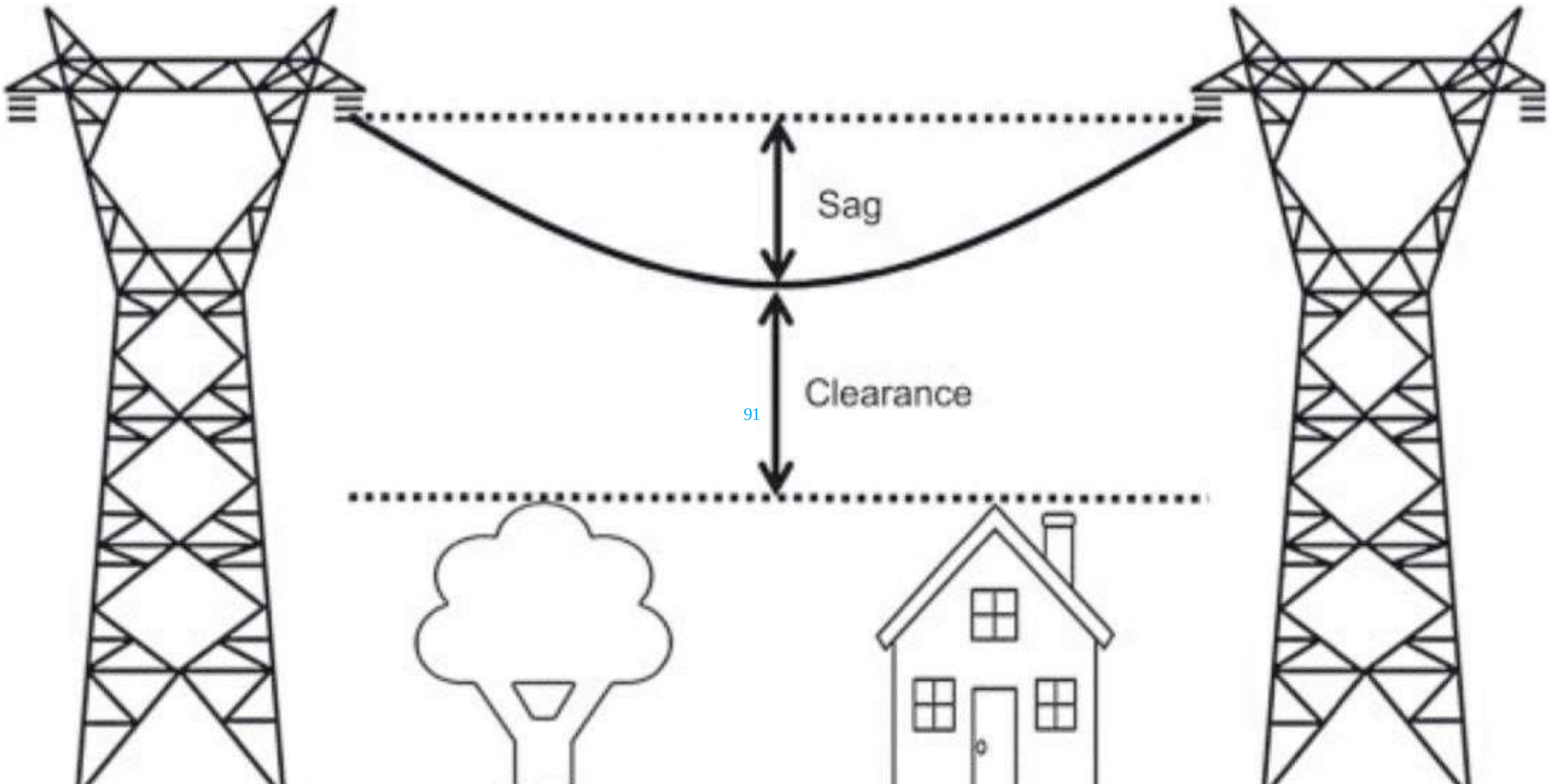

45kV
66kV
66kV
110kV
132kV
132kV
220kV
220kV
330-420kV
Height In Meter
0
5
10
15
20
25
30
35
40
45
50

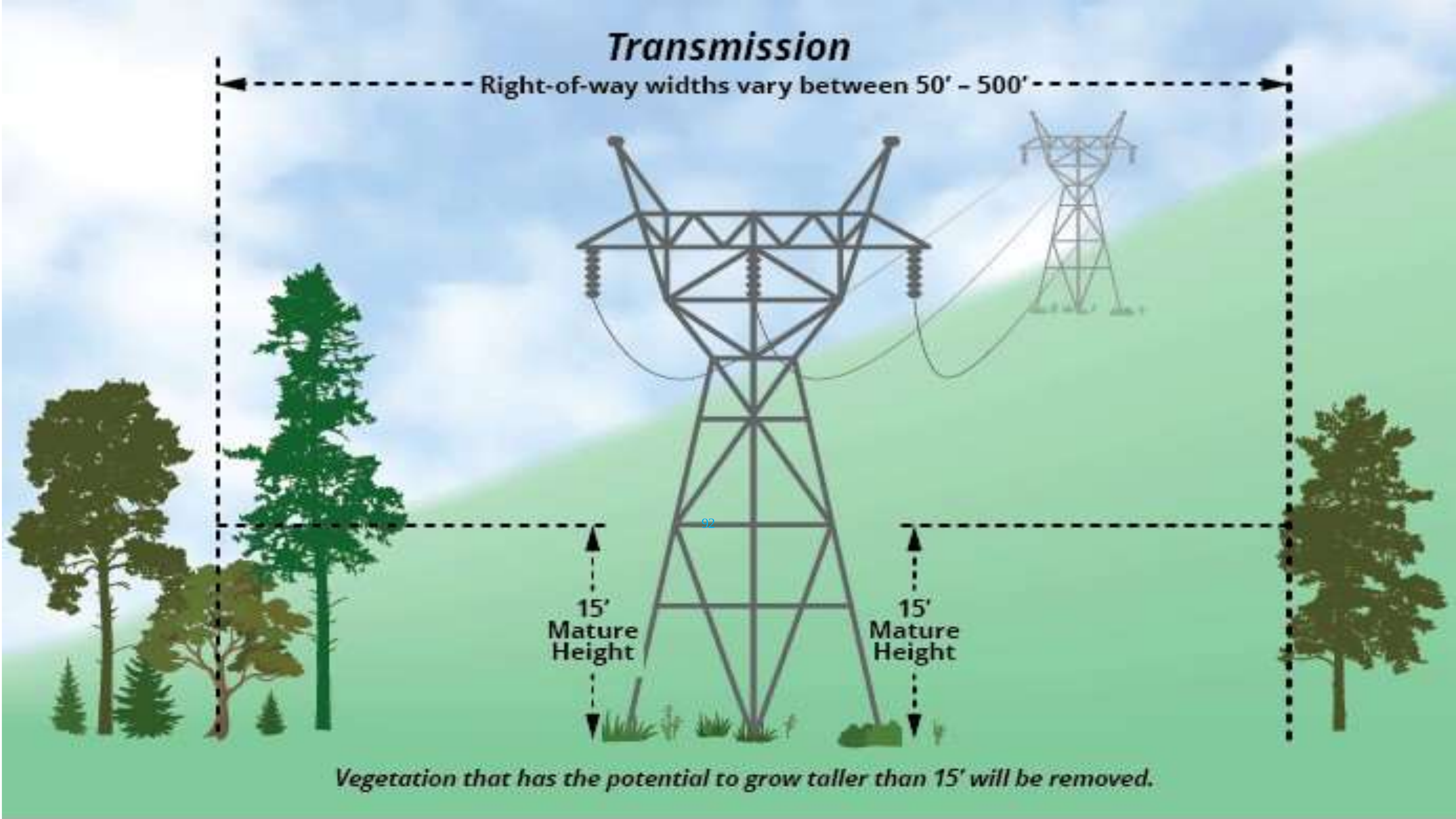

SAG



- **The difference in level between points of supports and the lowest point on the conductor is called sag.**

Sag in Overhead Transmission Line and

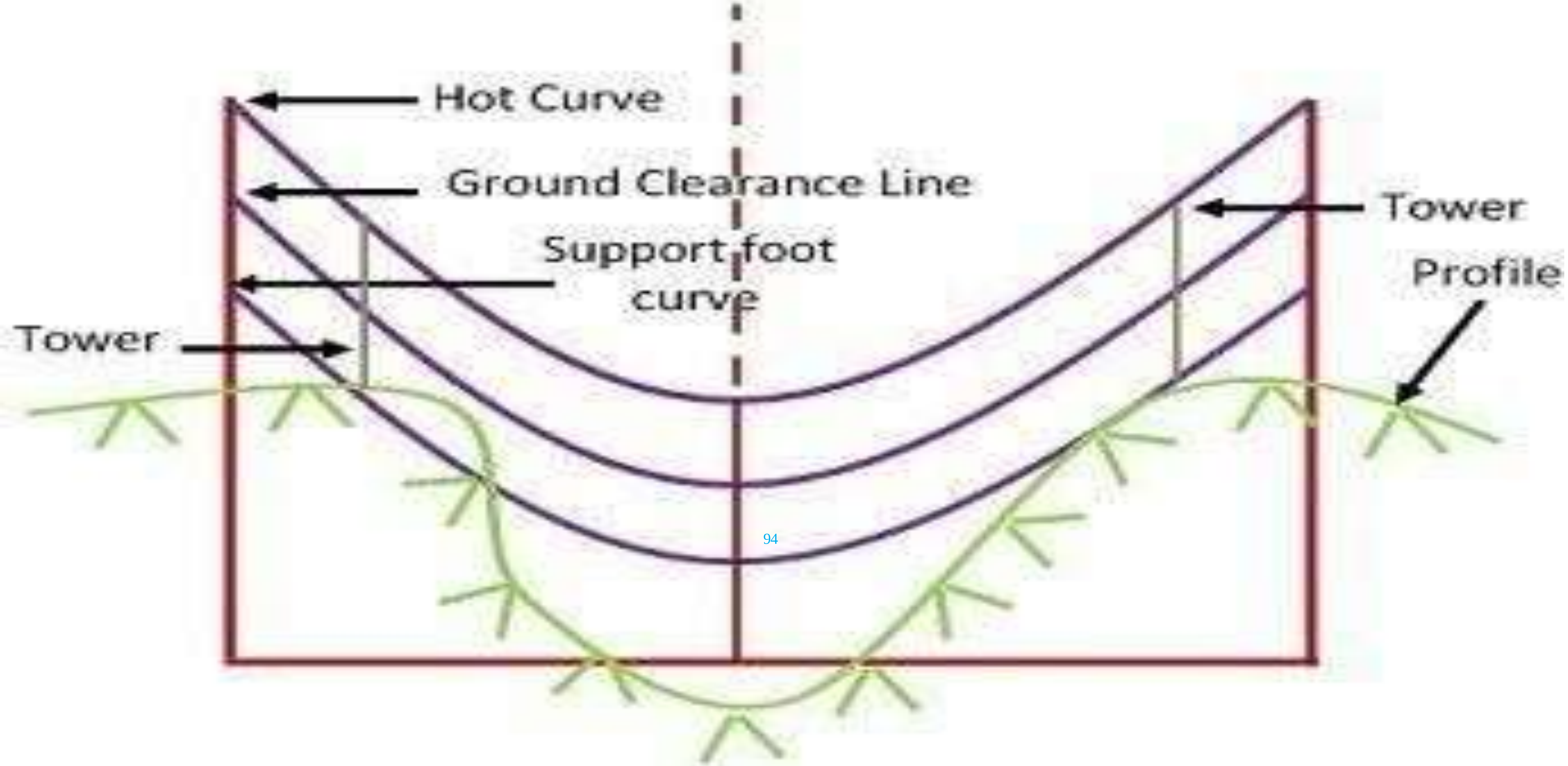



Transmission
Right-of-way widths vary between 50′ – 500′
15′
Mature
Height
15′
Mature
Height
Vegetation that has the potential to grow taller than 15′ will be removed.

Sag Template

The sag template is used for allocating the position and height of the supports correctly on the profile. The sag template decided the limitations of vertical and wind load. It also limits the minimum clearance angle between the sag and the ground for safety purpose. The sag template is usually made up of transparent celluloid, perplex, or sometimes cardboard. The following curves are marked on it.

1. Hot Template Curve or Hot Curve
2. Ground Clearance Curve
3. Support Foot or Tower Curve
4. Cold Curve or Uplift Curve



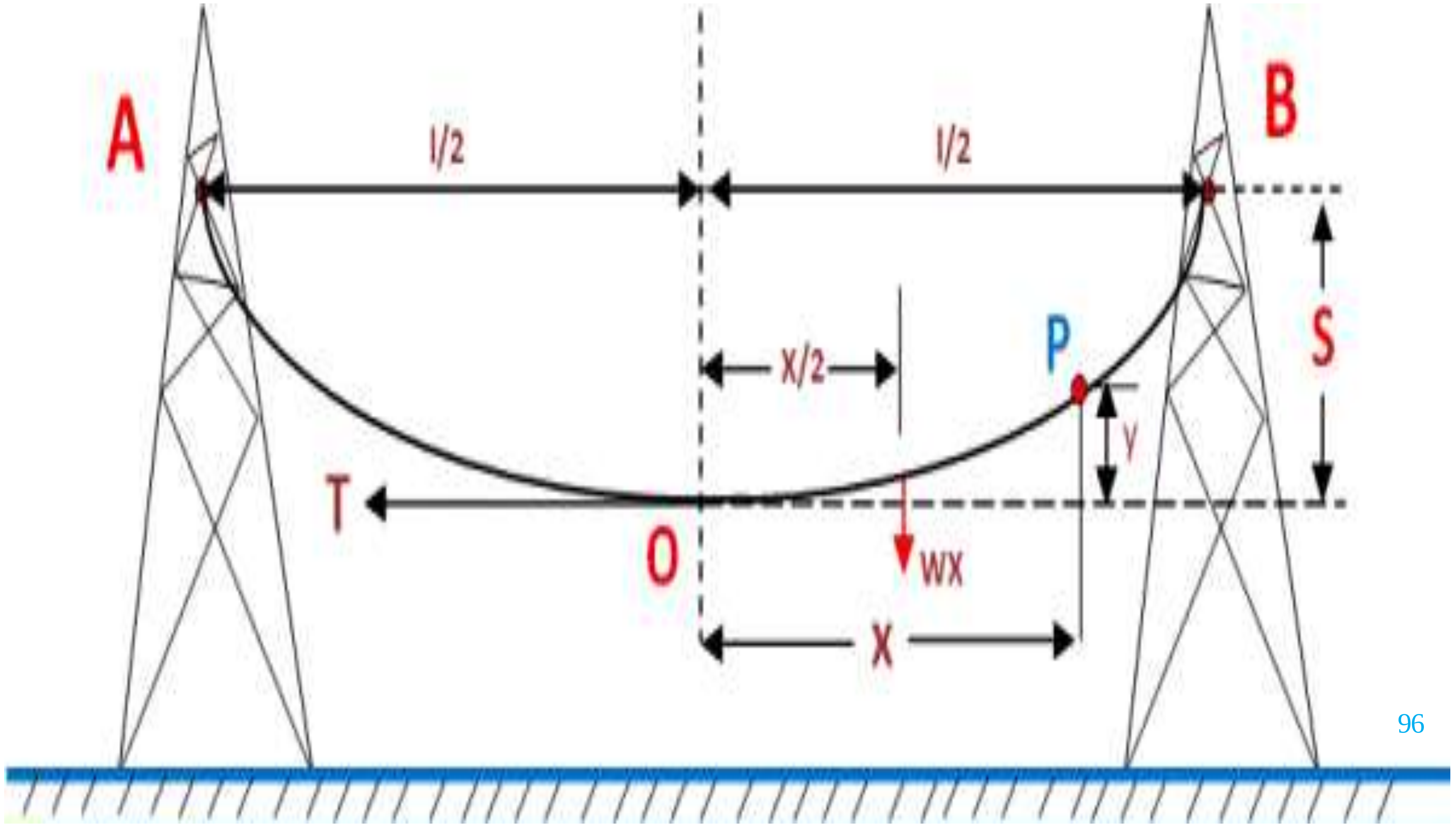
Sag Template

Hot Curve – The hot curve is obtained by plotting the sag at maximum temperature against span length. It shows where the supports must be located to maintain the prescribed ground clearance.

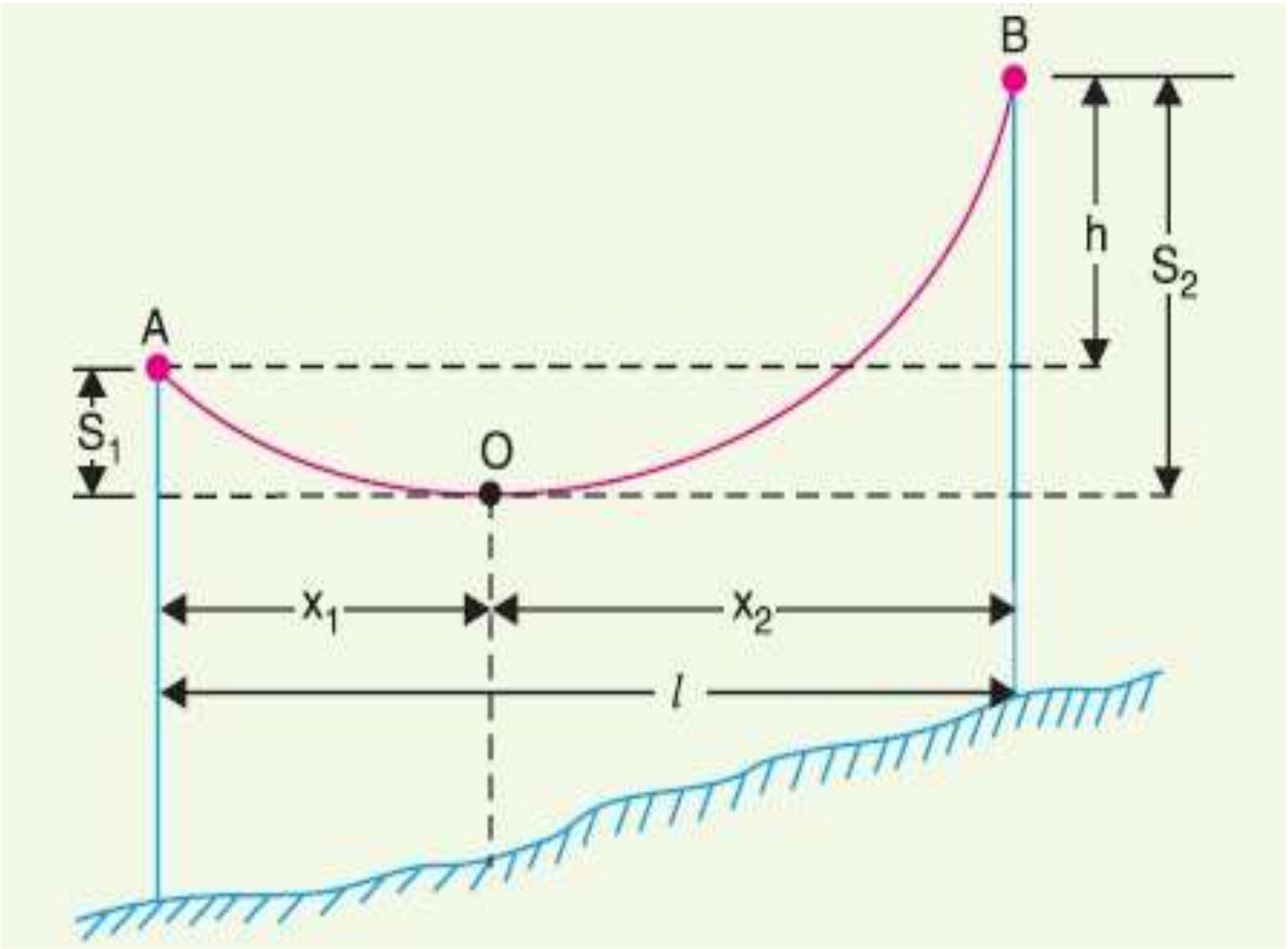
Ground Clearance Curve – The clearance curve is below the hot curve. It is drawn parallel to the hot curve and at a vertical distance equal to the ground clearance as prescribed by the regulation for the given line.

Support Foot Curve – This curve is drawn for locating the position of the supports for tower lines. It shows the height from the base of the standard support to the point of attachment of the lower conductor. For wood or concrete line, pole line this curve is not required to be drawn since they can be put in any convenient position.

Cold Curve or Uplift Curve – Uplift curve is obtained by plotting the sag at a minimum temperature without wind price against span length. This curve is drawn to determine whether uplift of conductor occurs on any support. The uplift conductor may occur at low temperature when one support is much lower than either of the adjoining ones



supports are at equal levels



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.

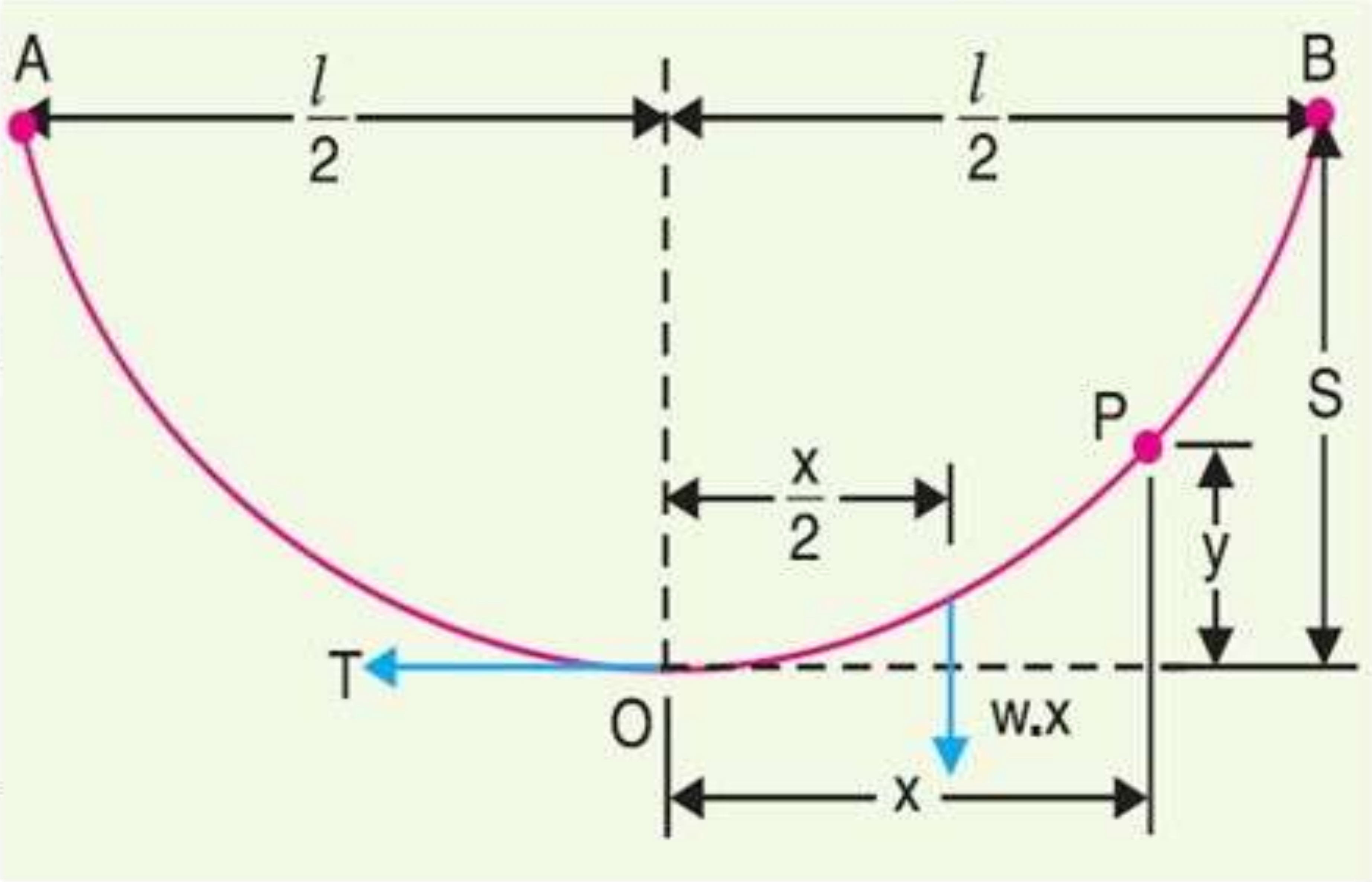
It can be proved that lowest point will be at the mid-span.

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,

$$T y = w x \times \frac{x}{2}$$

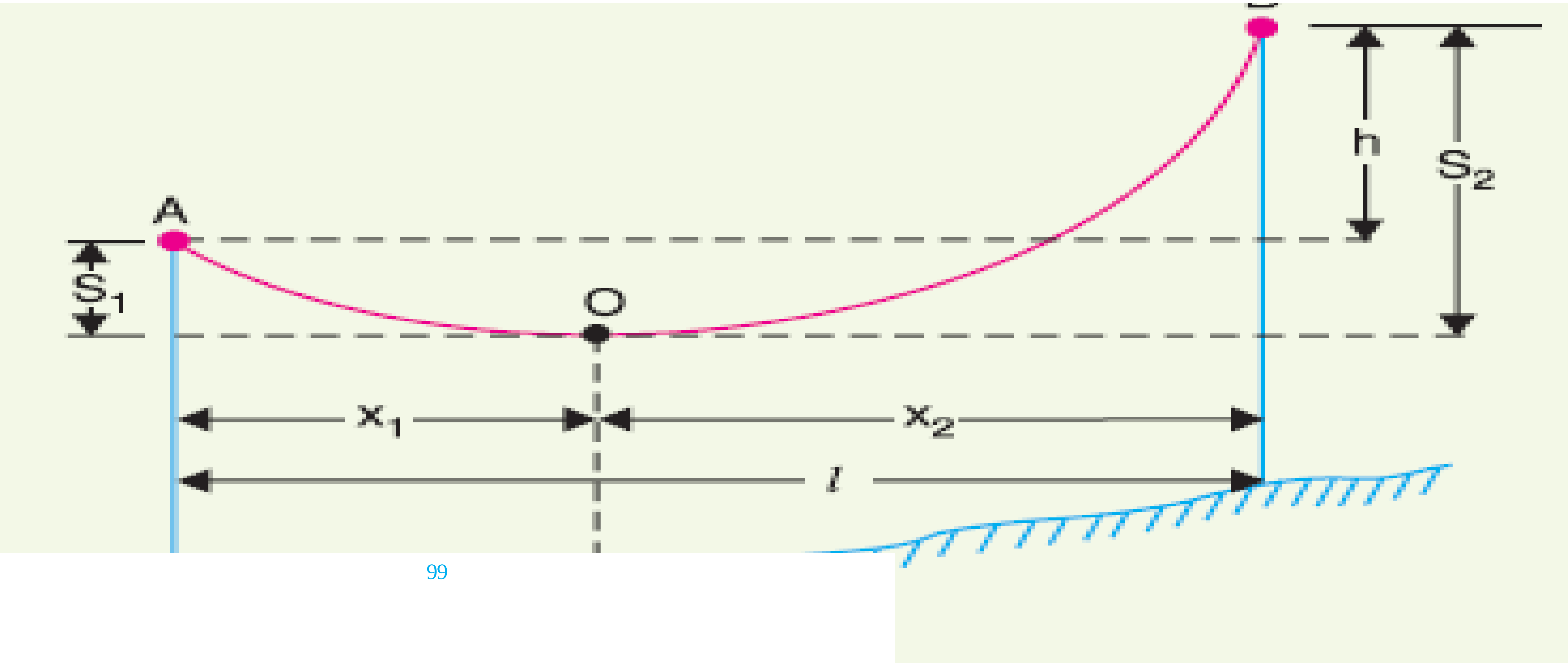
or
$$y = \frac{w x^2}{2 T}$$

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 $y = S$

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

(*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

x_1 = Distance of support at lower level (*i.e.*, *A*) from *O*

x_2 = Distance of support at higher level (*i.e.* *B*) from *O*

T = Tension in the conductor

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

$$x_1 + x_2 = l \qquad \ldots (i)$$

Now

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

$\therefore$

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

But

$$S_2 - S_1 = h$$

$\therefore$

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

or

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

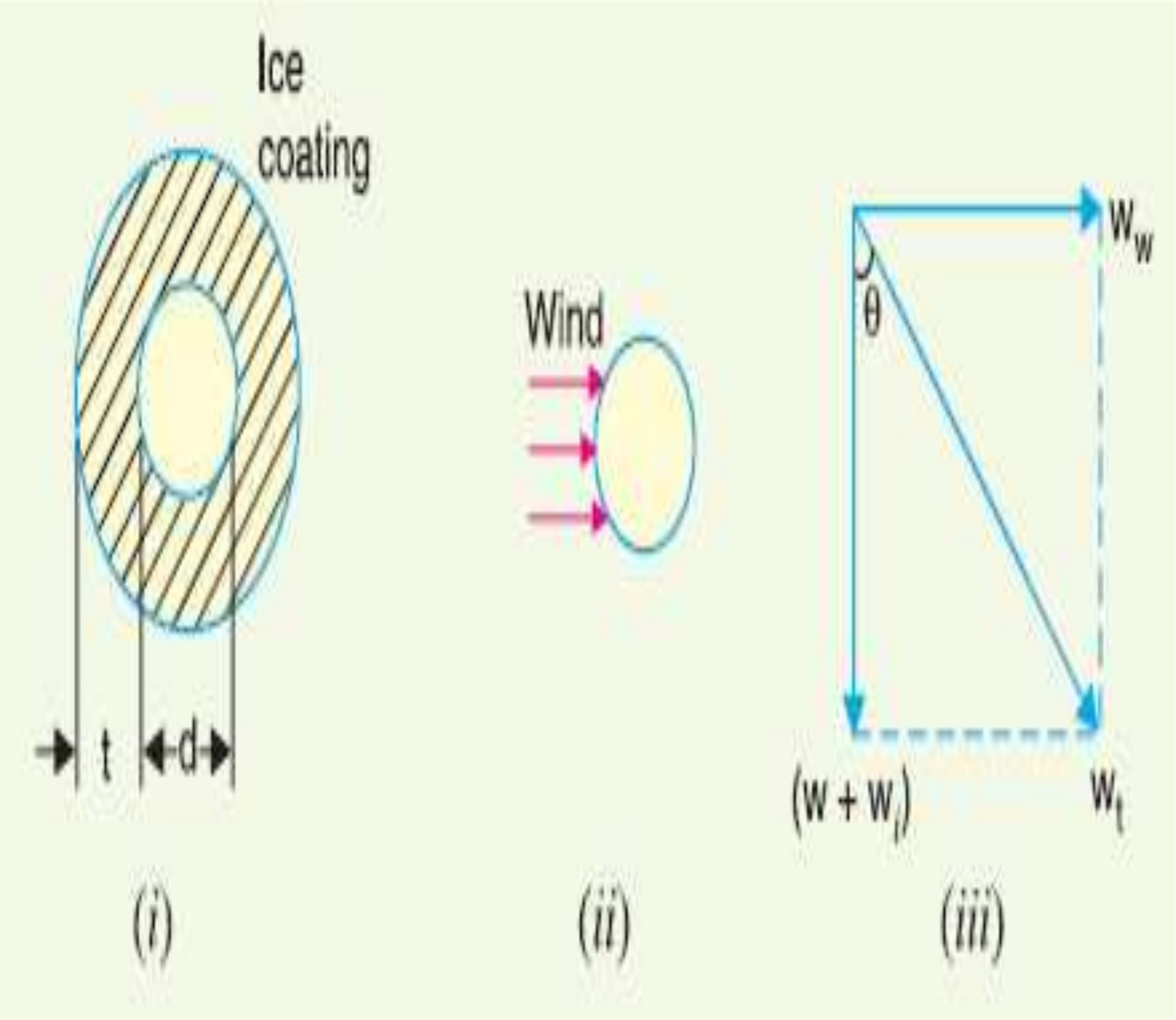
Solving exps. (*i*) and (*ii*), we get,

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

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

Having found x_1 and x_2, values of S_1 and S_2 can be easily calculated.

Effect of wind and ice loading.



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 $= S\cos\theta$

P1: 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?

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

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

Total weight of 1 m length of conductor is

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

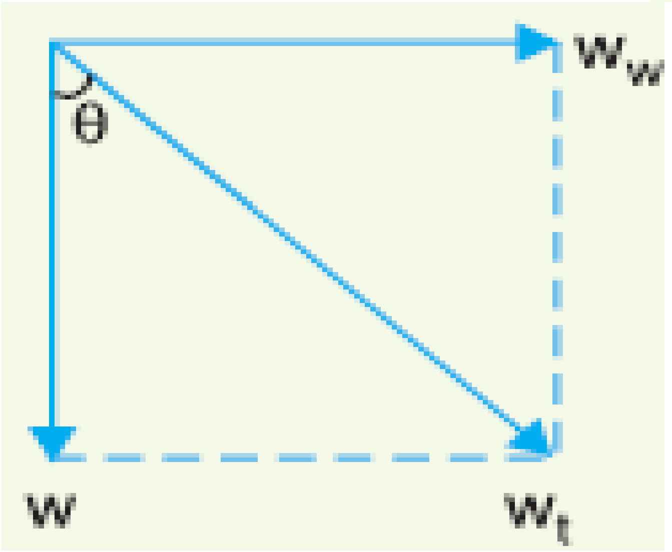
$$\therefore \quad \text{Sag,} \quad S = \frac{w_t l^2}{8T} = \frac{2{\cdot}48 \times (150)^2}{8 \times 2000} = 3{\cdot}48 \text{ m}$$

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

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

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

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



P2: 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

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

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,

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

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

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

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

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

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

P3: **The towers of height 30 m and 90 m respectively support a transmission line conductor at water crossing. The horizontal distance between 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.**

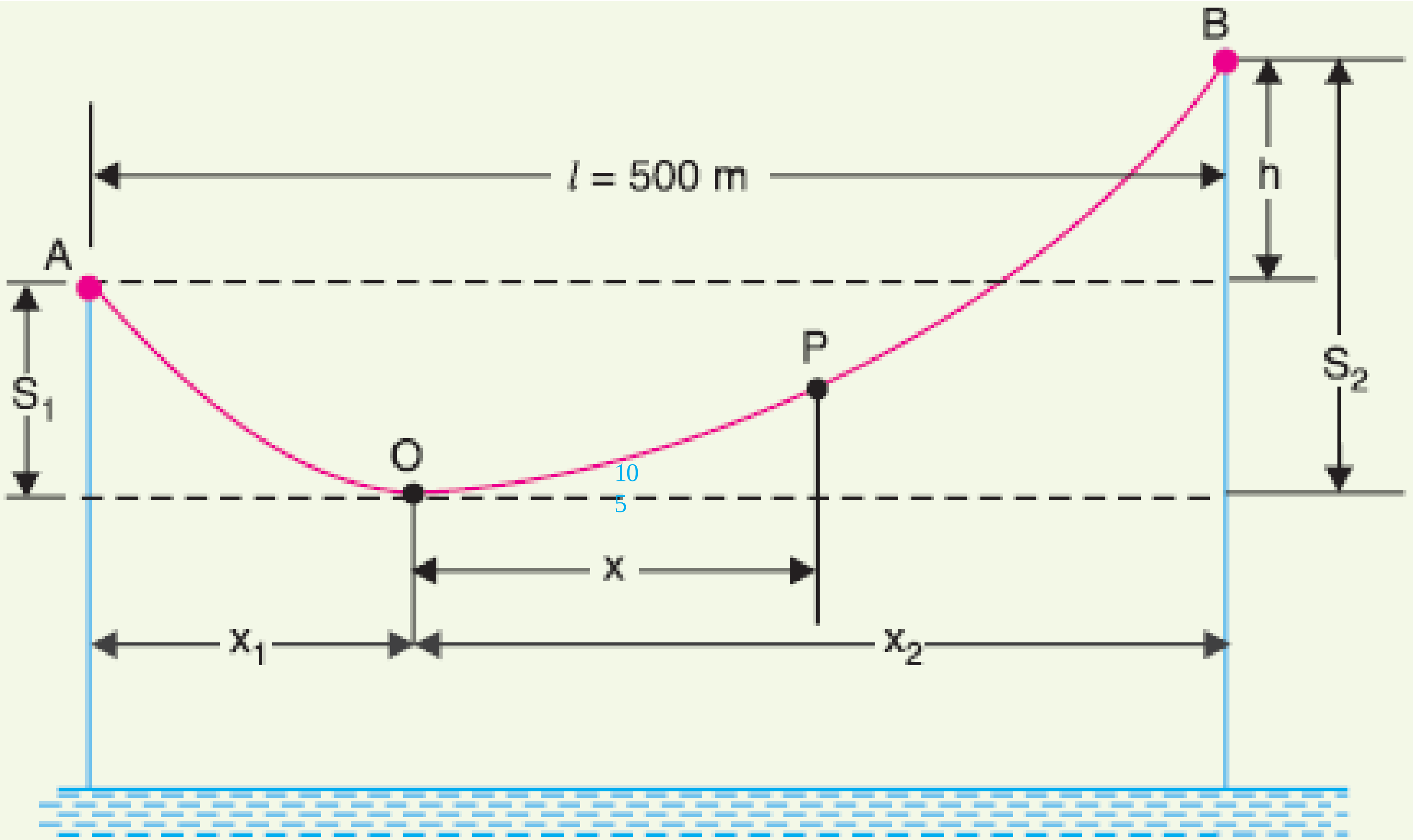


Fig. shows the conductor suspended between two supports *A and B at different* levels with *O as the lowest point on the conductor*. Here, $l = 500$ m ; $w = 1{\cdot}5$ kg ; $T = 1600$ kg.

Difference in levels between supports,

$$h = 90 - 30 = 60 \text{ m.}$$

Let the lowest point O of the conductor be at a distance *x1 from the support at lower level (i.e., support A) and at a distance x2 from* the support at higher level (*i.e., support B).*

Obviously,

$$x1 + x2 = 500 \text{ m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(i)}$$

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

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

or $\quad 60 = \dfrac{w}{2T}(x_2 + x_1)(x_2 - x_1)$

$\therefore \quad x_2 - x_1 = \dfrac{60 \times 2 \times 1600}{1 \cdot 5 \times 500} = 256$ m

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

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

Clearance of the lowest point *O* from water level

$= 30 - 7 = 23$ **m**

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

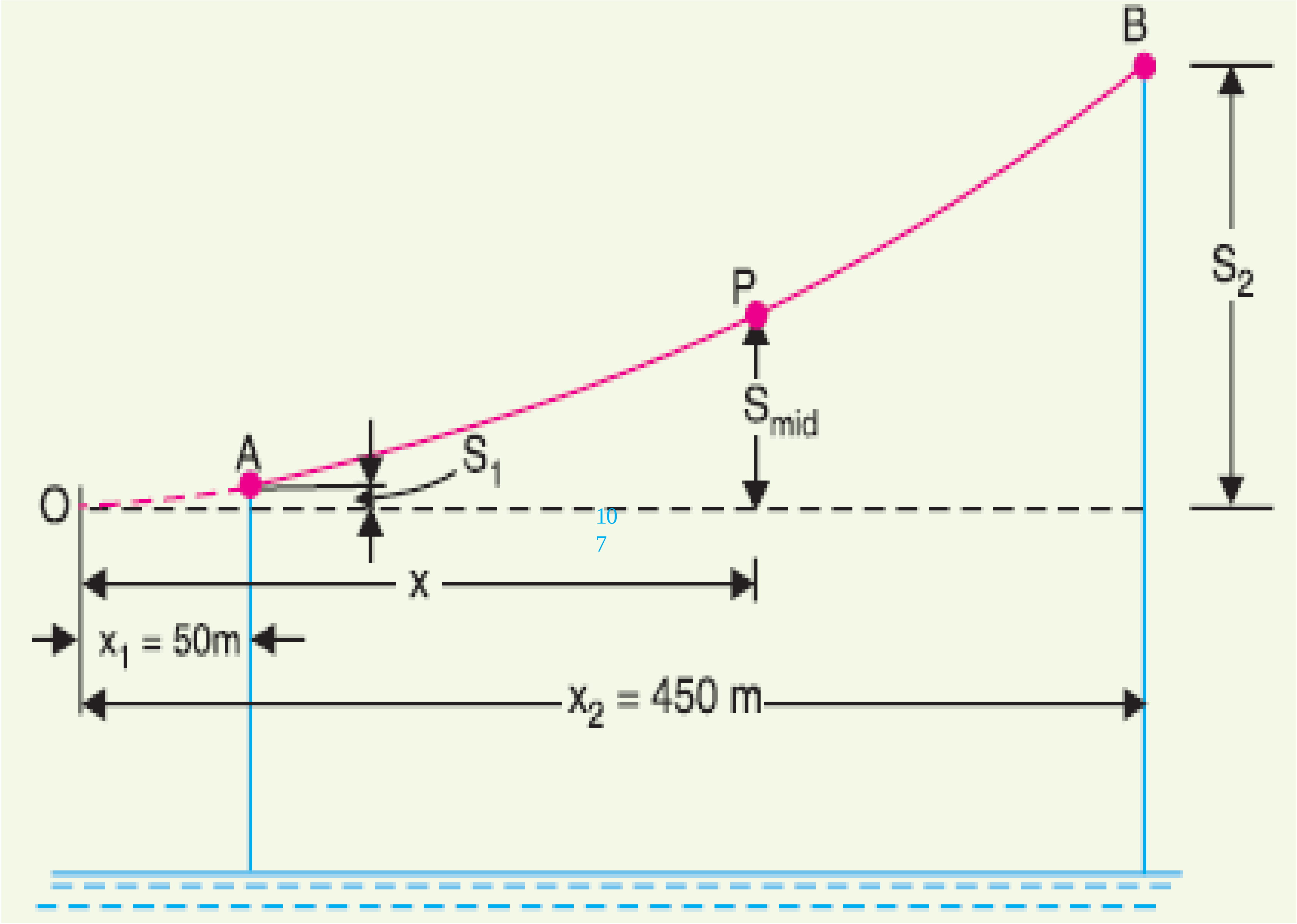
Clearly, $\quad x = 250 - x_1 = 250 - 122 = 128$ m

Sag at mid-point *P*, $\quad S_{mid} = \dfrac{w x^2}{2T} = \dfrac{1 \cdot 5 \times (128)^2}{2 \times 1600} = 7{\cdot}68$ m

Clearance of mid-point *P* from water level

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

P4: An overhead transmission line at a river crossing is supported from two towersat heights of 40 m and 90 m above water level, the horizontal distance between the towers being 400m. 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.



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

$T = 2000$ kg; $\quad w = 1$ 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 $$50 = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

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

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

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

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

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

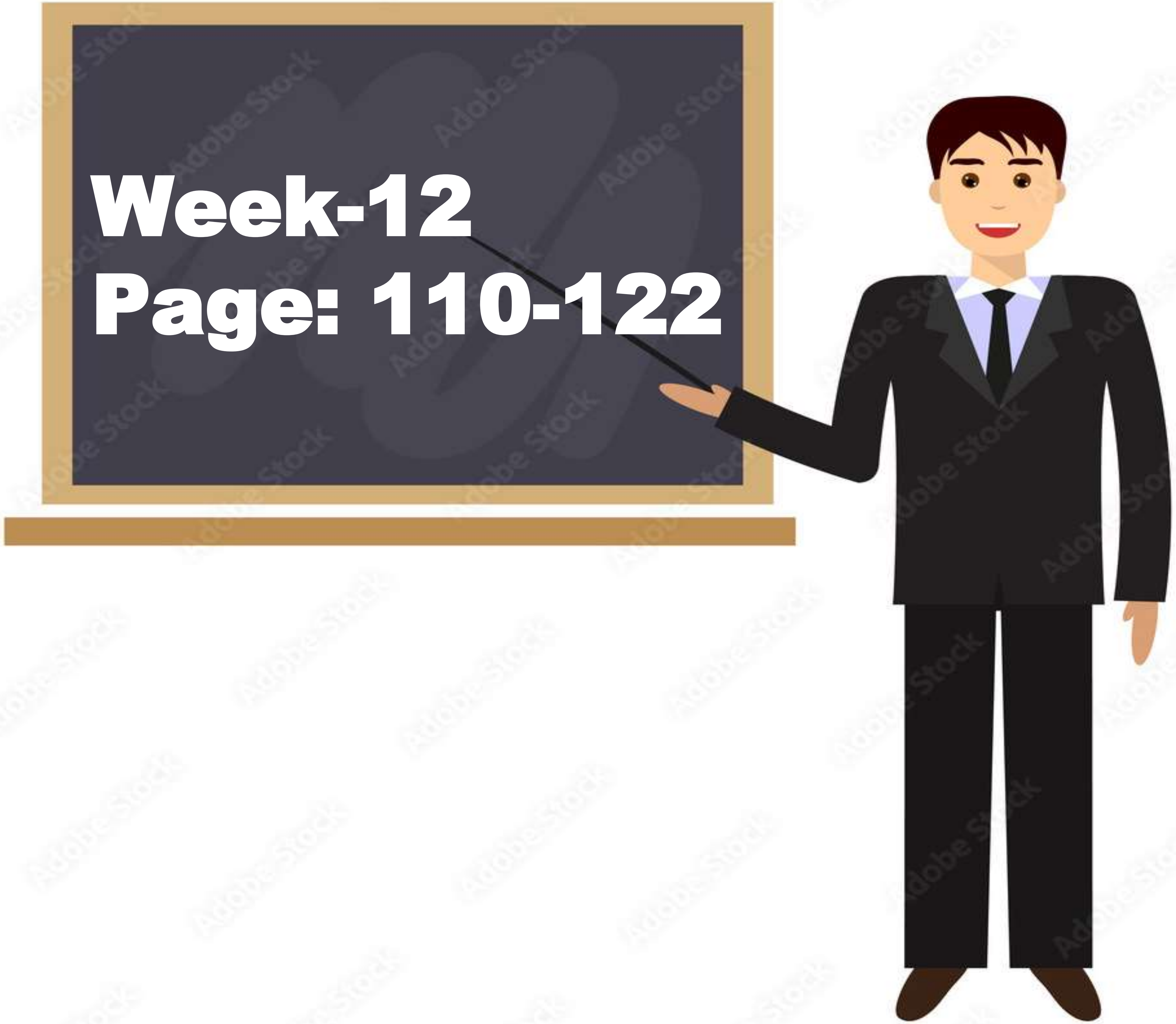
Now Sag $$S_2 = \frac{wx_2^2}{2T} = \frac{1 \times (450)^2}{2 \times 2000} = 50{\cdot}6 \text{ m}$$

Height of point B above mid-point P

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

$\therefore$ Clearance of mid-point P above water level

$$= 90 - 35 = \mathbf{55 \text{ m}}$$


Week-12
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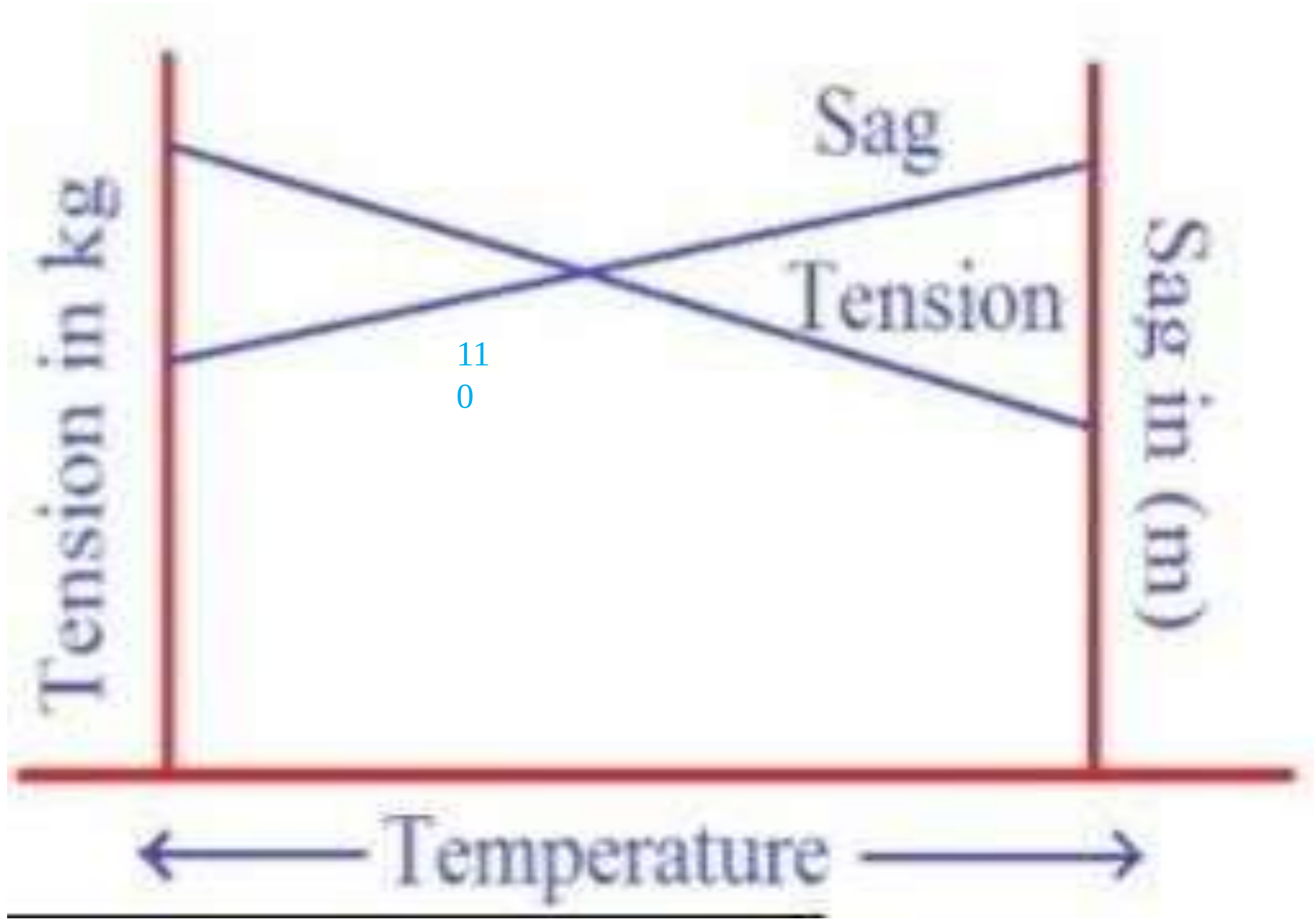
STRINGING CHART

Stringing chart is basically a graph between Sag, Tension with Temperature. As we want low Tension and minimum sag in our conductor but that is not possible as sag is inversely proportional to tension. It is because low sag means a tight wire and high tension whereas a low tension means a loose wire and increased sag. Therefore, we make compromise between two but if the case of temperature is considered and we draw graph then that graph is called Stringing chart.



Electrical Design of Overhead Lines

- An a.c. transmission line has resistance, inductance and capacitance uniformly distributed along its length.
- These are known as constants or parameters of the line.
- The performance of a transmission line depends to a considerable extent upon these constants.
- For instance, these constants determine whether the efficiency and voltage regulation of the line will be good or poor.
- Therefore, a sound concept of these constants is necessary in order to make the electrical design of a transmission line a technical success.

Constants of a Transmission Line

A transmission line has resistance, inductance and capacitance uniformly distributed along the whole length of the line

(i)Resistance. It is the opposition of line conductors to current flow.

(i) Inductance. When an alternating current flows through a conductor, a changing flux is set up which links the conductor. Due to these flux linkages, the conductor possesses inductance.

(iii)Capacitance. As any two conductors of an overhead transmission line are separated by air which acts as an insulation, therefore, capacitance exists between any two overhead line conductors. The capacitance between the conductors is the charge per unit potential difference

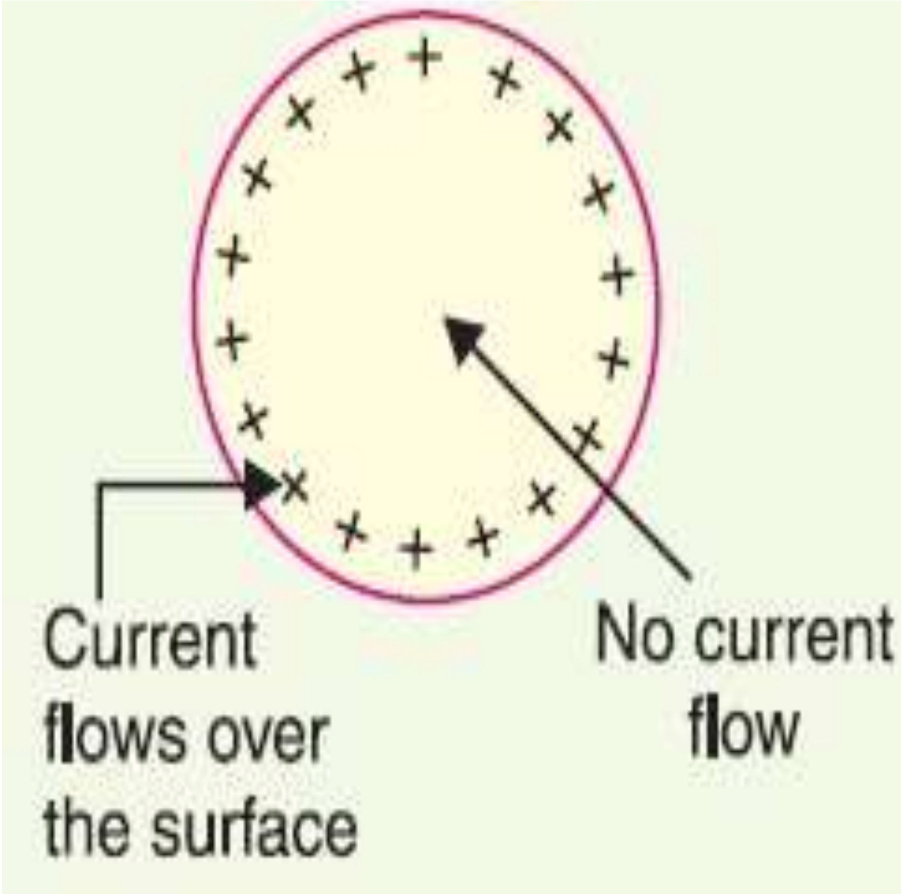
Skin Effect

When a conductor is carrying steady direct current (d.c.), this current is uniformly distributed over the whole X-section of the conductor. However, an alternating current flowing through the conductor does not distribute uniformly, rather it has the tendency to concentrate near the surface of the conductor. This is known as skin effect.
The tendency of alternating current to concentrate near the surface of a conductor is known as skin effect.

Due to skin effect, the effective area of cross-section of the conductor through which current flows is reduced. Consequently, the resistance of the conductor is slightly increased when carrying an alternating current. The cause of skin effect can be easily explained. A solid conductor may be thought to be consisting of a large number of strands, each carrying a small part of the current. The *inductance of each strand will vary according to its position. Thus, the strands near the centre are surrounded by a greater magnetic flux and hence have larger inductance than that near the surface. The high reactance of inner strandscauses the alternating current to flow near the surface of conductor. This crowding of current near the conductor surface is the skin effect.

The skin effect depends upon the following factors :

(i)Nature of material
(ii)Diameter of wire − increases with the diameter of wire.
(iii)Frequency − increases with the increase in frequency.
(iv)Shape of wire − less for stranded conductor than the solid conductor.
It may be noted that skin effect is negligible when the supply frequency is low (< 50 Hz) and conductor diameter is small (< 1cm).



Inductance, $L = \frac{\psi}{I}$ henry

ψ = flux linkages in weber-turns

I = current in amperes

Capacitance, $C = \frac{q}{v}$ farad

Resistance of a Transmission Line

The resistance of transmission line conductors is the most important cause of power loss in a transmission line. The resistance R of a line conductor having resistivity ρ, length l and area of cross-section a is given by ;

$$R = \rho \frac{l}{a}$$

The variation of resistance of metallic conductors with temperature is practically linear over the normal range of operation. Suppose R_1 and R_2 are the resistances of a conductor at t_1°C and t_2°C $(t_2 > t_1)$ respectively. If α_1 is the temperature coefficient at t_1°C, then,

$$R_2 = R_1 \left[1 + \alpha_1 (t_2 - t_1)\right]$$

where $$\alpha_1 = \frac{\alpha_0}{1 + \alpha_0 t_1}$$

$$\alpha_0 = \text{temperature coefficient at } 0° \text{ C}$$

(*i*) In a single phase or 2-wire d.c line, the total resistance (known as *loop resistance*) is equal to double the resistance of either conductor.

(*ii*) In case of a 3-phase transmission line, resistance per phase is the resistance of one conductor.

Flux Linkage

1. Flux linkages due to a single current carrying conductor. Consider a long straight cylindrical conductor of radirus r metres and carrying a current I amperes (r.m.s.) as shown in Fig. This current will set up magnetic field. The magnetic lines of force will exist inside the conductor as well as outside the conductor. Both these fluxes will contribute to the inductance of the conductor.

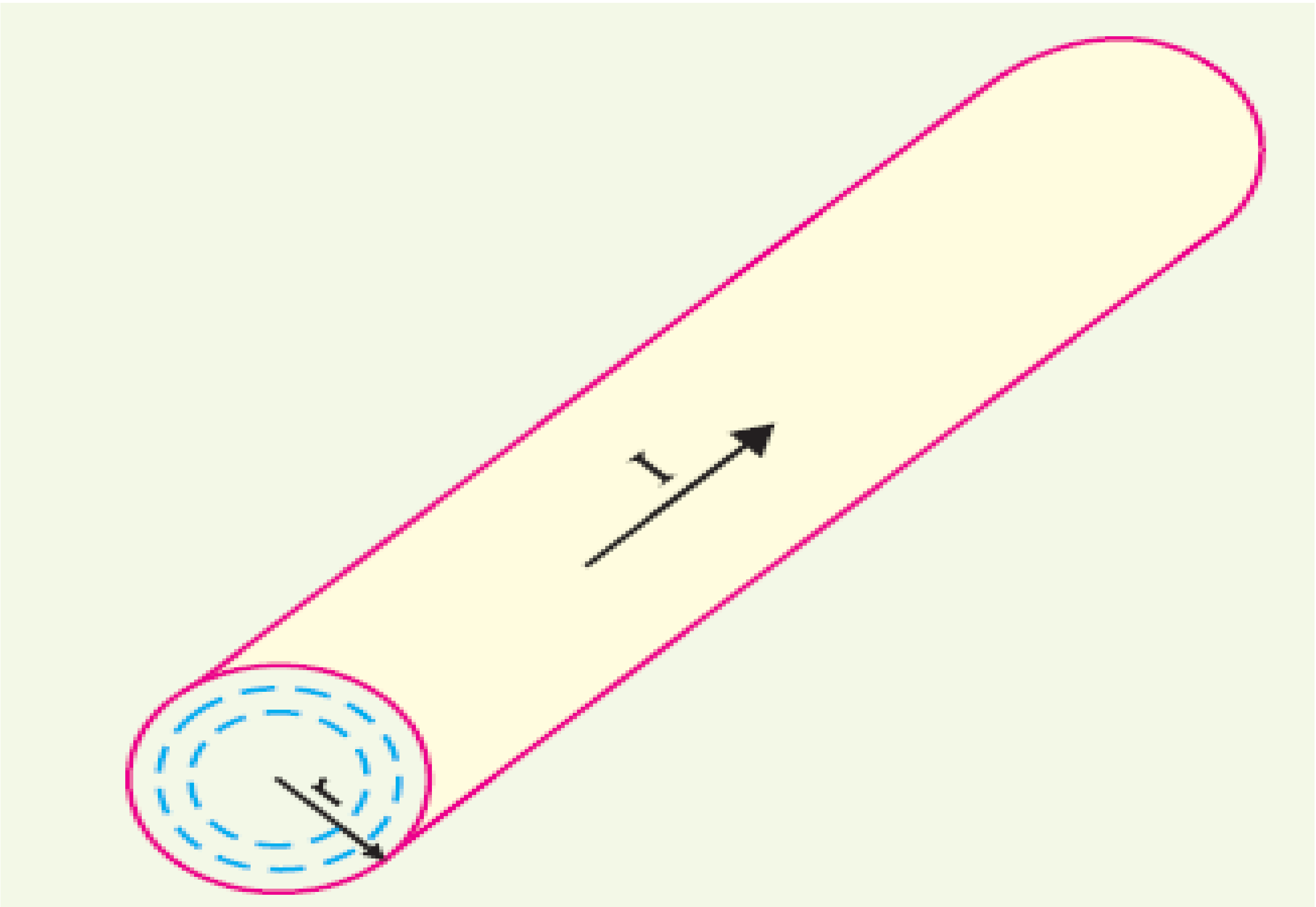
(i) Flux linkages due to internal flux. Refer to Fig. where the X-section of the conductor is shown magnified for clarity. The magnetic field intensity at a point x metres from the centre is given by:

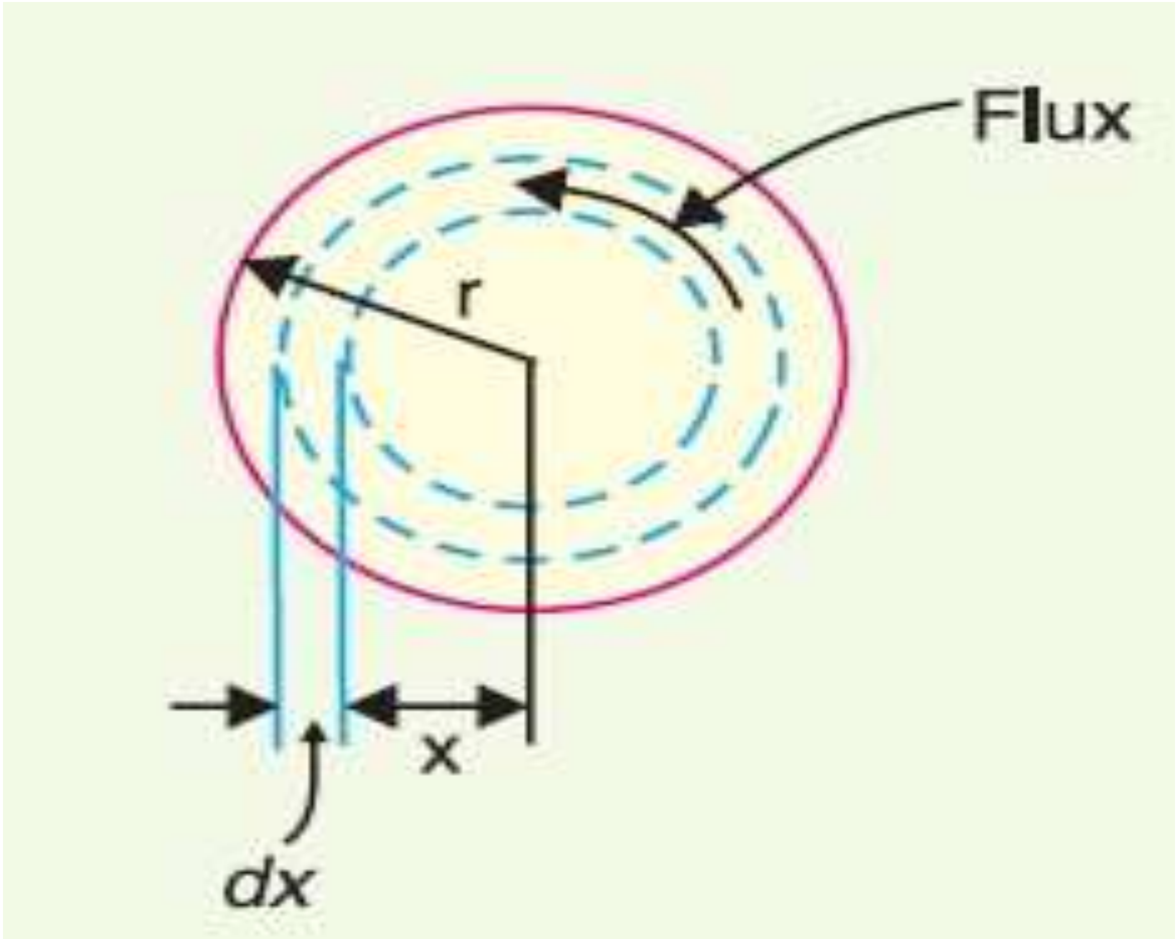
$$*H_x = \frac{I_x}{2\pi x}$$

Assuming a uniform current density,

$$I_x = \frac{\pi x^2}{\pi r^2} I = \frac{x^2}{r^2} I$$

$$H_x = \frac{x^2}{r^2} \times I \times \frac{1}{2\pi x} = \frac{x}{2\pi r^2} I \text{ AT/m}$$





If μ (= $\mu_0\mu_r$) is the permeability of the conductor, then flux density at the considered point is given by;

$$B_x = \mu_0 \mu_r H_x \text{ wb/m}^2$$

$$= \frac{\mu_0 \mu_r x}{2\pi r^2} I = \frac{\mu_0 x I}{2\pi r^2} \text{ wb/m}^2 [\because \mu_r = 1 \text{ for non-magnetic material}]$$

Now, flux $d\phi$ through a cylindrical shell of radial thickness dx and axial length 1 m is given by;

$$d\phi = B_x \times 1 \times dx = \frac{\mu_0 x I}{2\pi r^2} dx \text{ weber}$$

This flux links with current $I_x \left(= \frac{I \pi x^2}{\pi r^2} \right)$ only. Therefore, flux linkages per metre length of the conductor is

$$d\psi = \frac{\pi x^2}{\pi r^2} d\phi = \frac{\mu_0 I x^3}{2\pi r^4} dx \text{ weber-turns}$$

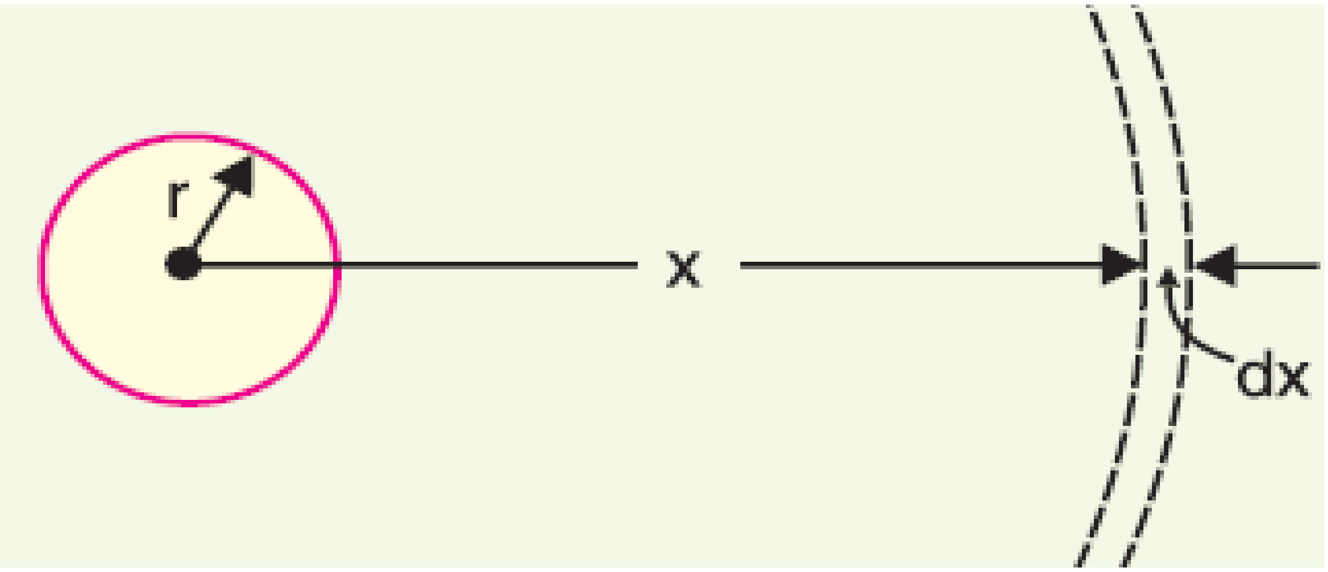
Total flux linkages from centre upto the conductor surface is

$$\psi_{int} = \int_0^r \frac{\mu_0 I x^3}{2\pi r^4} dx$$

$$= \frac{\mu_0 I}{8\pi} \text{ weber-turns per metre length}$$

(ii) Flux linkages due to external flux. Now let us calculate the flux linkages of the conductor due to external flux. The external flux extends from the surface of the conductor to infinity. Referring to Fig. the field intensity at a distance x metres (from centre) outside the conductor is given by ;

$$H_x = \frac{I}{2\pi x} \text{ AT / m}$$



Flux density,

$$B_x = \mu_0 H_x = \frac{\mu_0 I}{2\pi x} \text{ wb/m}^2$$

Now, flux $d\phi$ through a cylindrical shell of thickness dx and axial length 1 metre is

$$d\phi = B_x\, dx = \frac{\mu_0 I}{2\pi x}\, dx \text{ webers}$$

The flux $d\phi$ links all the current in the conductor once and only once.

$\therefore$ Flux linkages,

$$d\psi = d\phi = \frac{\mu_0 I}{2\pi x}\, dx \text{ weber-turns}$$

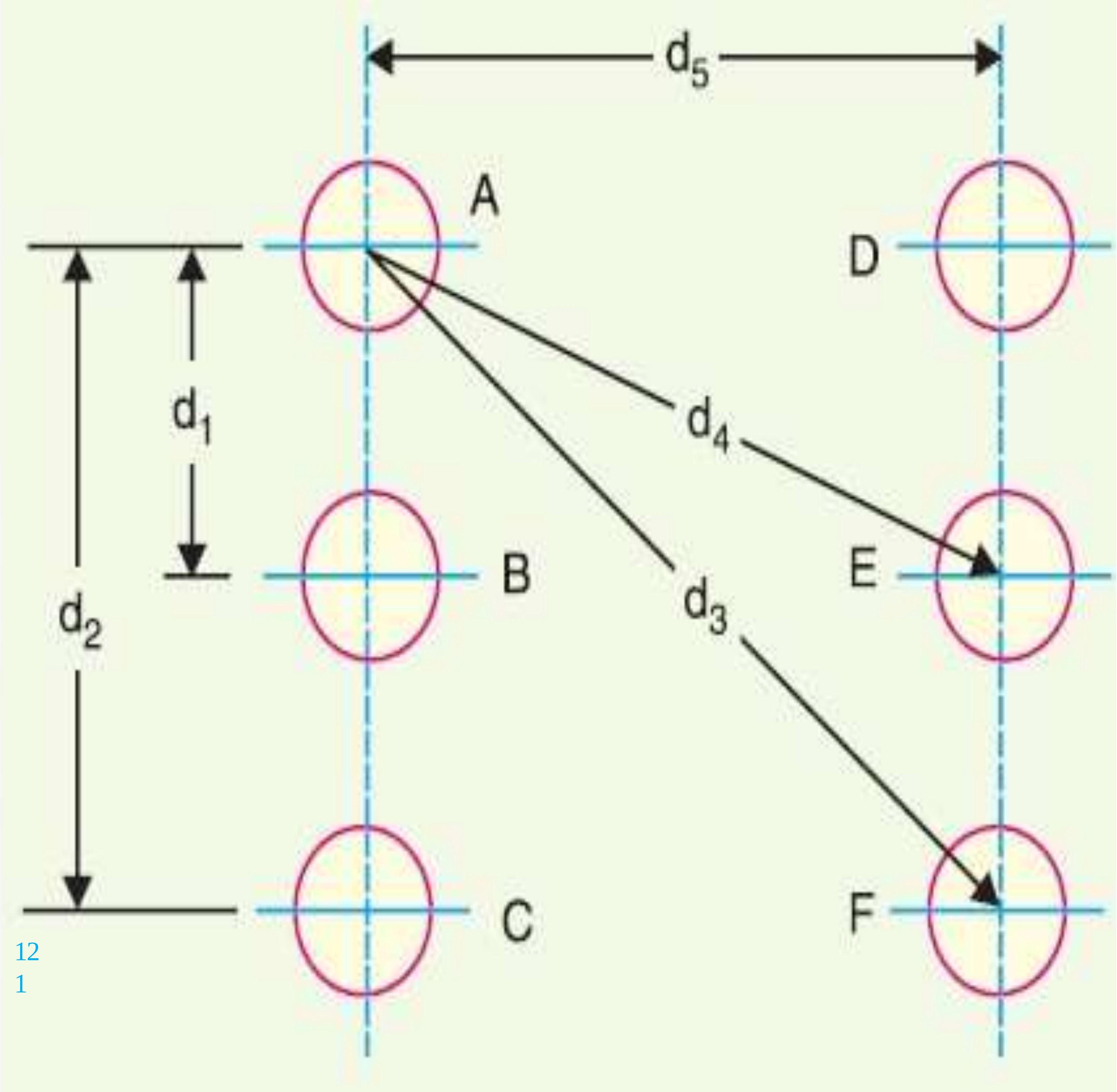
Total flux linkages of the conductor from surface to infinity,

$$\psi_{ext} = \int_r^\infty \frac{\mu_0 I}{2\pi x} dx \text{ weber-turns}$$

Overall flux linkages, $\psi = \psi_{int} + \psi_{ext} = \frac{\mu_0 I}{8\pi} + \int_r^\infty \frac{\mu_0 I}{2\pi x} dx$

$$\psi = \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right] \text{ wb-turns/m length}$$

2. Flux linkages in parallel current-carrying conductors. We shall now determine the flux linkages in a group of parallel current carrying conductors. Fig [illegible] shows the conductors A, B, C etc. carrying currents I_A, I_B, I_C etc. Let us consider the flux linkages with one conductor, say conductor A. There will be flux linkages with conductor A due to its own current as discussed previously. Also there will be flux linkages with this conductor due to the mutual inductance effects of I_B, I_C, I_D etc. We shall now determine the total flux linkages with conductor A.



Flux linkages with conductor A due to its own current

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \int^{\infty} \frac{dx}{x}\right]$$

Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_B}{2\pi} \int_{d_1}^{\infty} \frac{dx}{x}$$

Flux linkages with conductor A due to current I_C

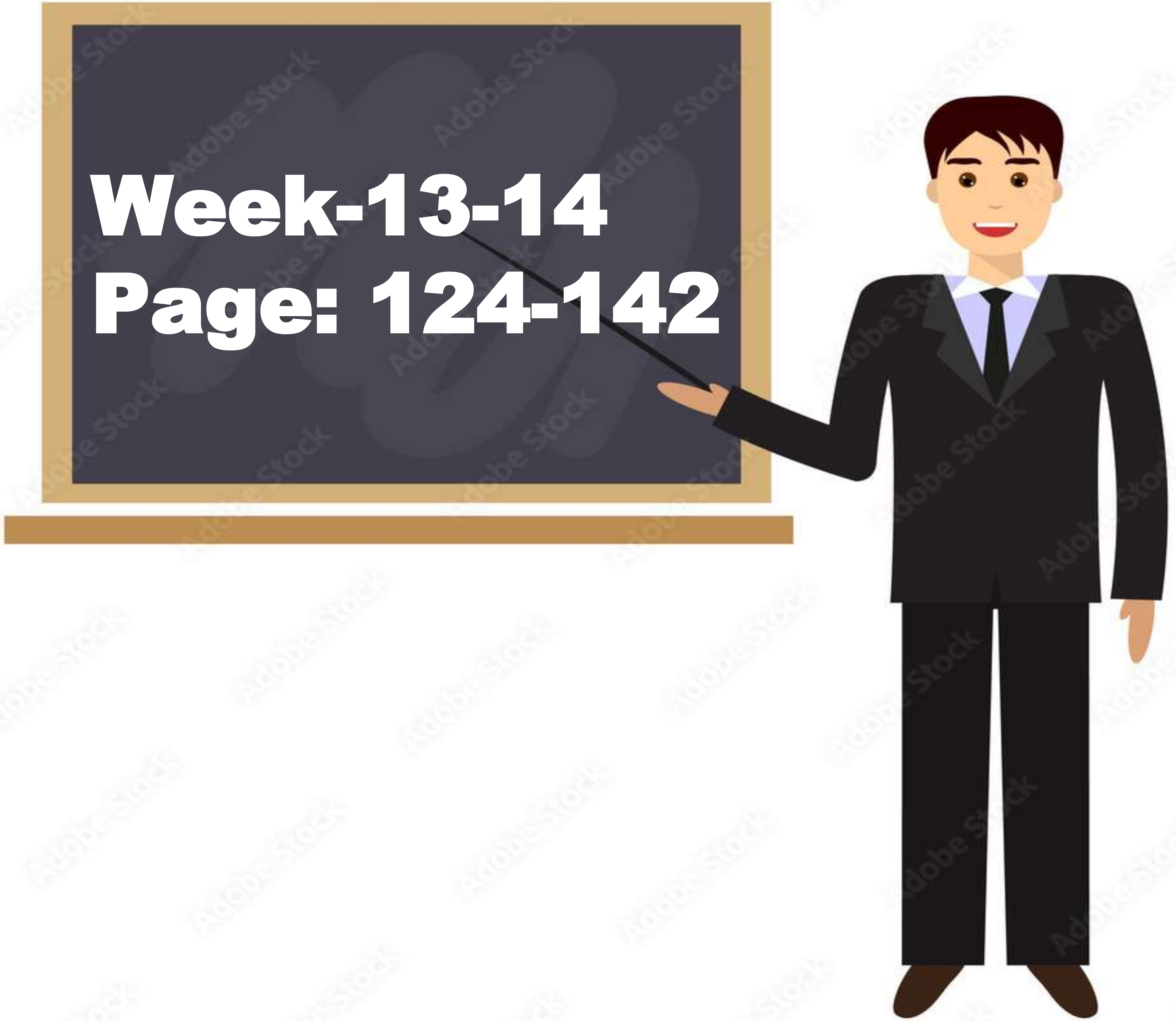
$$= \frac{\mu_0 I_C}{2\pi} \int_{d_2}^{\infty} \frac{dx}{x}$$

$\therefore$ Total flux linkages with conductor A

$$= (i) + (ii) + (iii) + \ldots\ldots$$

$$= \frac{\mu_0 I_A}{2\pi} \left(\frac{1}{4} + \int_{r}^{\infty} \frac{dx}{x} \right) + \frac{\mu_0 I_B}{2\pi} \int_{d_1}^{\infty} \frac{dx}{x} + \frac{\mu_0 I_C}{2\pi} \int_{d_2}^{\infty} \frac{dx}{x} + \ldots$$

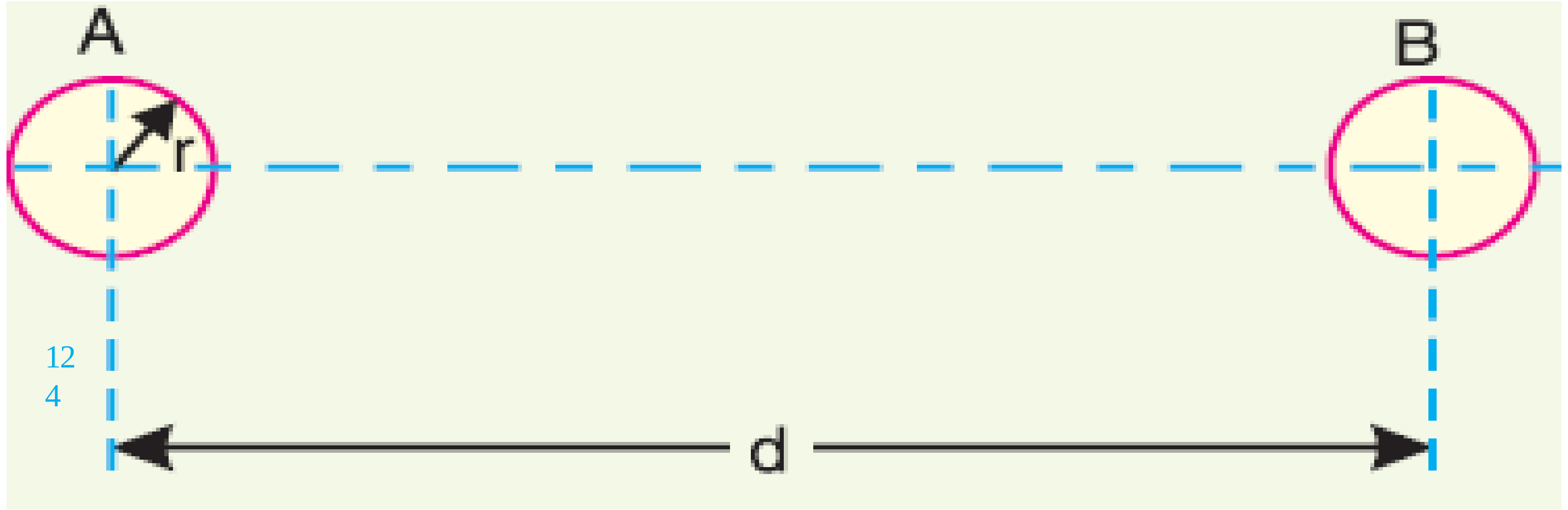
Similarly, flux linkages with other conductors can be determined. The above relation provides the basis for evaluating inductance of any circuit.


Week-13-14
Page: 124-142

Inductance of a Single Phase Two-wire Line

Consider a single phase overhead line consisting of two parallel conductors A and B spaced d metres apart as shown in Fig. [illegible]. Conductors A and B carry the same amount of current (*i.e.* $I_A = I_B$), but in the opposite direction because one forms the return circuit of the other.

$$\therefore \qquad I_A + I_B = 0$$



In order to find the inductance of conductor A (or conductor B), we shall have to consider the flux linkages with it. There will be flux linkages with conductor A due to its own current I_A and also due to the mutual inductance effect of current I_B in the conductor B.

Flux linkages with conductor A due to its own current

$$= \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right)$$

Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_B}{2\pi}\int_d^\infty \frac{dx}{x}$$

Total flux linkages with conductor A is

$$\psi_A = \text{exp. } (i) + \text{exp } (ii)$$

$$= \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right) + \frac{\mu_0 I_B}{2\pi}\int_d^\infty \frac{dx}{x}$$

125

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right) I_A + I_B \int_d^\infty \frac{dx}{x}\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} + \log_e \infty - \log_e r\right) I_A + (\log_e \infty - \log_e d) I_B\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{I_A}{4} + \log_e \infty (I_A + I_B) - I_A \log_e r - I_B \log_e d\right)\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} - I_A \log_e r - I_B \log_e d\right] \quad (\because I_A + I_B = 0)$$

$$I_A + I_B = 0 \quad \text{or} \quad -I_B = I_A$$

$$-I_B \log_e d = I_A \log_e d$$

$$\psi_A = \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} + I_A \log_e d - I_A \log_e r\right] \text{ wb-turns/m}$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} + I_A \log_e \frac{d}{r}\right]$$

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ wb-turns/m}$$

Inductance of conductor $A, L_A = \dfrac{\psi_A}{I_A}$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{H/m} = \frac{4\pi \times 10^{-7}}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{H/m}$$

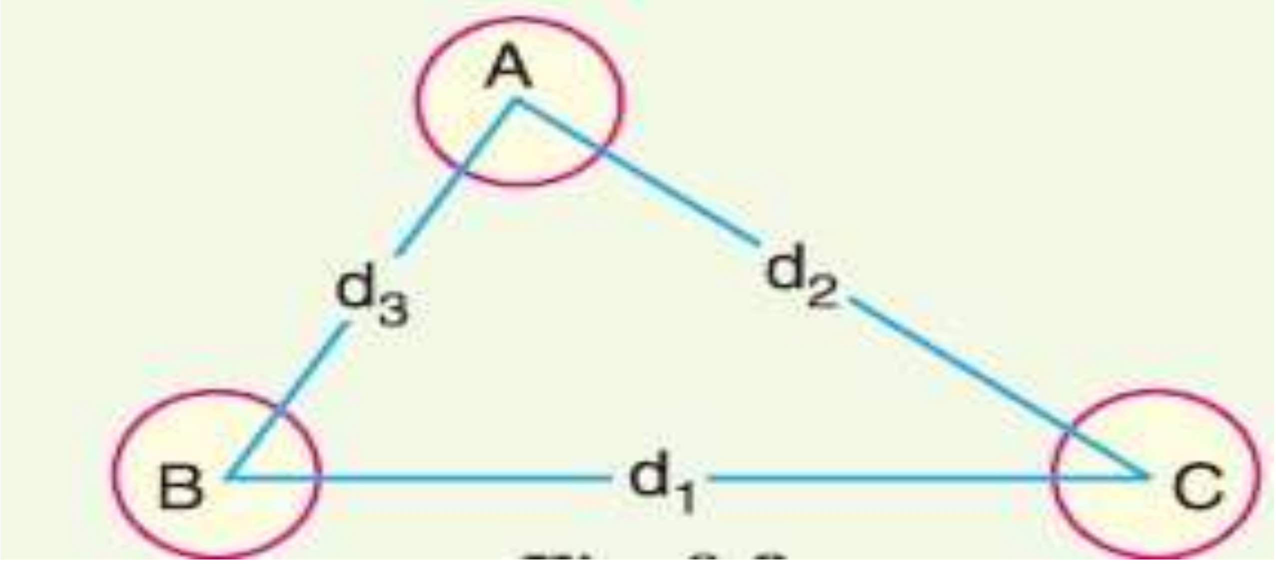
$$L_A = 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{d}{r}\right] \text{H/m}$$

$$\text{Loop inductance} = 2\,L_A \text{ H/m} = 10^{-7}\left[1 + 4\log_e \frac{d}{r}\right] \text{H/m}$$

$$\text{Loop inductance} = 10^{-7}\left[1 + 4\log_e \frac{d}{r}\right] \text{H/m}$$

Inductance of a 3-Phase Overhead Line

Fig. [redacted] shows the three conductors A, B and C of a 3-phase line carrying currents I_A, I_B and I_C respectively. Let d_1, d_2 and d_3 be the spacings between the conductors as shown. Let us further assume that the loads are balanced *i.e.* $I_A + I_B + I_C = 0$. Consider the flux linkages with conductor



Flux linkages with conductor A due to its own current

$$= \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right) \quad \ldots(i)$$

Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_B}{2\pi}\int_{d_3}^\infty \frac{dx}{x}$$

Flux linkages with conductor A due to current I_C

$$= \frac{\mu_0 I_C}{2\pi}\int_{d_2}^\infty \frac{dx}{x}$$

Total flux linkages with conductor A is

$$\psi_A = (i) + (ii) + (iii)$$

$$\begin{aligned}
\psi_A &= (i) + (ii) + (iii) \\
&= \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right) + \frac{\mu_0 I_B}{2\pi}\int_{d_3}^\infty \frac{dx}{x} + \frac{\mu_0 I_C}{2\pi}\int_{d_2}^\infty \frac{dx}{x} \\
&= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right) I_A + I_B \int_{d_3}^\infty \frac{dx}{x} + I_C \int_{d_2}^\infty \frac{dx}{x}\right] \\
&= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A - I_B \log_e d_3 - I_C \log_e d_2 + \log_e \infty \left(I_A + I_B + I_C\right)\right]
\end{aligned}$$

As $\quad I_A + I_B + I_C = 0,$

$$\psi_A = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A - I_B \log_e d_3 - I_C \log_e d_2\right]$$

(*i*) **Symmetrical spacing.** If the three conductors A, B and C are placed symmetrically at the corners of an equilateral triangle of side d, then, $d_1 = d_2 = d_3 = d$. Under such conditions, the flux linkages with conductor A become :

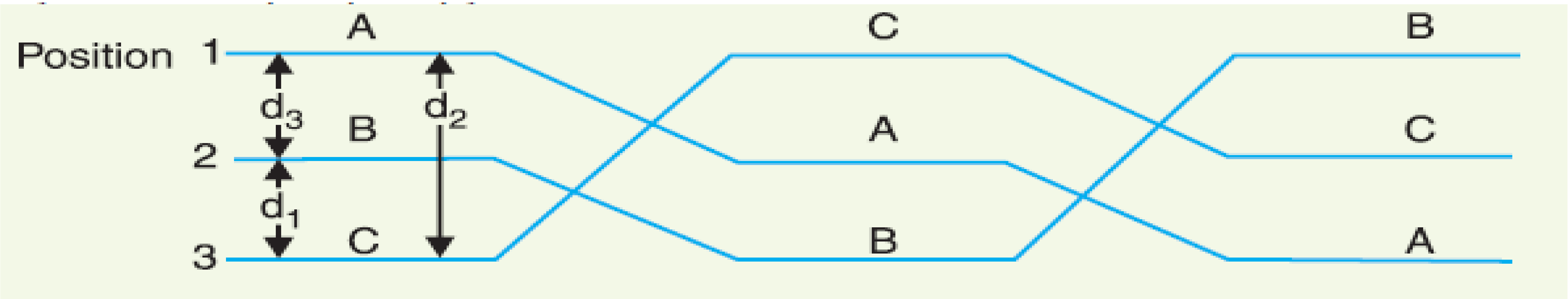
$$
\begin{aligned}
\psi_A &= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A - I_B \log_e d - I_C \log_e d\right] \\
&= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A - (I_B + I_C)\log_e d\right] \\
&= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A + I_A \log_e d\right] \qquad (\because I_B + I_C = -I_A) \\
&= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ weber-turns/m}
\end{aligned}
$$

Inductance of conductor A,

$$
\begin{aligned}
L_A &= \frac{\psi_A}{I_A} \text{ H/m} = \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ H/m} \\
&= \frac{4\pi \times 10^{-7}}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ H/m} \\
L_A &= 10^{-7}\left[0 \cdot 5 + 2 \log_e \frac{d}{r}\right] \text{ H/m}
\end{aligned}
$$

Derived in a similar way, the expressions for inductance are the same for conductors B and C.

Unsymmetrical spacing.



$$I_A = I(1 + j\,0)$$
$$I_B = I(-0{\cdot}5 - j\,0{\cdot}866)$$
$$I_C = I(-0{\cdot}5 + j\,0{\cdot}866)$$

the total flux linkages per metre length of conductor A is

$$\psi_A = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right)I_A - I_B \log_e d_3 - I_C \log_e d_2\right]$$

Putting the values of I_A, I_B and I_C, we get, Inducance of each line conductor

$$= \frac{1}{3}(L_A + L_B + L_C)$$

$$= \left[\frac{1}{2} + 2\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}\right] \times 10^{-7} \text{ H/m}$$

$$= \left[0 \cdot 5 + 2\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}\right] \times 10^{-7} \text{ H/m}$$

If we compare the formula of inductance of an unsymmetrically spaced transposed line with that of symmetrically spaced line, we find that inductance of each line conductor in the two cases will be equal if $d = \sqrt[3]{d_1 d_2 d_3}$. The distance d is known as *equivalent equilateral spacing* for unsymmetrically transposed line.

$$= \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \log_e \frac{\sqrt{d_2 d_3}}{r} + j\,0 \cdot 866 \log_e \frac{d_3}{d_2}\right]$$

$\therefore$ Inductance of conductor A is

$$L_A = \frac{\psi_A}{I_A} = \frac{\psi_A}{I}$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \log_e \frac{\sqrt{d_2 d_3}}{r} + j\,0 \cdot 866 \log_e \frac{d_3}{d_2}\right]$$

$$= \frac{4\pi \times 10^{-7}}{2\pi}\left[\frac{1}{4} + \log_e \frac{\sqrt{d_2 d_3}}{r} + j\,0 \cdot 866 \log_e \frac{d_3}{d_2}\right] \text{ H/m}$$

$$= 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{\sqrt{d_2 d_3}}{r} + j\,1 \cdot 732 \log_e \frac{d_3}{d_2}\right] \text{ H/m}$$

Similarly inductance of conductors B and C will be :

$$L_B = 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{\sqrt{d_3 d_1}}{r} + j\,1 \cdot 732 \log_e \frac{d_1}{d_3}\right] \text{ H/m}$$

$$L_C = 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{\sqrt{d_1 d_2}}{r} + j\,1 \cdot 732 \log_e \frac{d_2}{d_1}\right] \text{ H/m}$$

Inducance of each line conductor

$$= \frac{1}{3}(L_A + L_B + L_C)$$

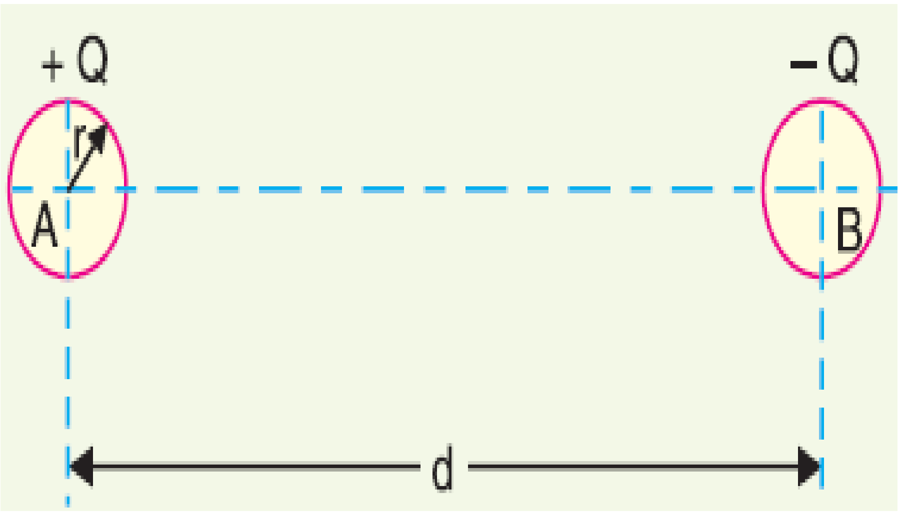
$$= \left[\frac{1}{2} + 2\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}\right] \times 10^{-7} \text{ H/m}$$

$$= \left[0 \cdot 5 + 2\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}\right] \times 10^{-7} \text{ H/m}$$

If we compare the formula of inductance of an unsymmetrically spaced transposed line with that of symmetrically spaced line, we find that inductance of each line conductor in the two cases will be equal if $d = \sqrt[3]{d_1 d_2 d_3}$. The distance d is known as *equivalent equilateral spacing* for unsymmetrically transposed line.

Capacitance of a Single Phase Two-wire Line

Consider a single phase overhead transmission line consisting of two parallel conductors A and B spaced d metres apart in air. Suppose that radius of each conductor is r metres. Let their respective charge be $+Q$ and $-Q$ coulombs per metre length.



The total p.d. between conductor A and neutral "infinite" plane is

$$V_A = \int_r^\infty \frac{Q}{2\pi x \varepsilon_0}\,dx + \int_d^\infty \frac{-Q}{2\pi x \varepsilon_0}\,dx$$

$$= \frac{Q}{2\pi \varepsilon_0}\left[\log_e \frac{\infty}{r} - \log_e \frac{\infty}{d}\right] \text{volts} = \frac{Q}{2\pi \varepsilon_0} \log_e \frac{d}{r} \text{ volts}$$

Similarly, p.d. between conductor B and neutral "infinite" plane is

$$V_B = \int_r^{\infty} \frac{-Q}{2\pi x\,\varepsilon_0}\,dx + \int_d^{\infty} \frac{Q}{2\pi x\,\varepsilon_0}\,dx$$

$$= \frac{-Q}{2\pi\,\varepsilon_0}\left[\log_e \frac{\infty}{r} - \log_e \frac{\infty}{d}\right] = \frac{-Q}{2\pi\,\varepsilon_0}\log_e \frac{d}{r} \text{ volts}$$

Both these potentials are *w.r.t.* the same neutral plane. Since the unlike charges attract each other, the potential difference between the conductors is

$$V_{AB} = 2V_A = \frac{2Q}{2\pi\,\varepsilon_0}\log_e \frac{d}{r} \text{ volts}$$

$\therefore$ Capacitance,

$$C_{AB} = Q/V_{AB} = \frac{Q}{\dfrac{2Q}{2\pi\,\varepsilon_0}\log_e \dfrac{d}{r}} \text{ F/m}$$

$\therefore$

$$C_{AB} = \frac{\pi\,\varepsilon_0}{\log_e \dfrac{d}{r}} \text{ F/m} \qquad \ldots(i)$$

Capacitance to neutral. Equation (*i*) gives the capacitance between the conductors of a two-wire line [See Fig. 9.22]. Often it is desired to know the capacitance between one of the conductors and a neutral point between them. Since potential of the mid-point between [illegible]uctors is zero, the potential difference between each conductor and the ground or neutral is half the potential difference between the conductors. Thus the *capacitance to ground* or capacitance to neutral for the two-wire line is *twice* the line-to-line capacitance (capacitance between conductors as shown in Fig 9.23).

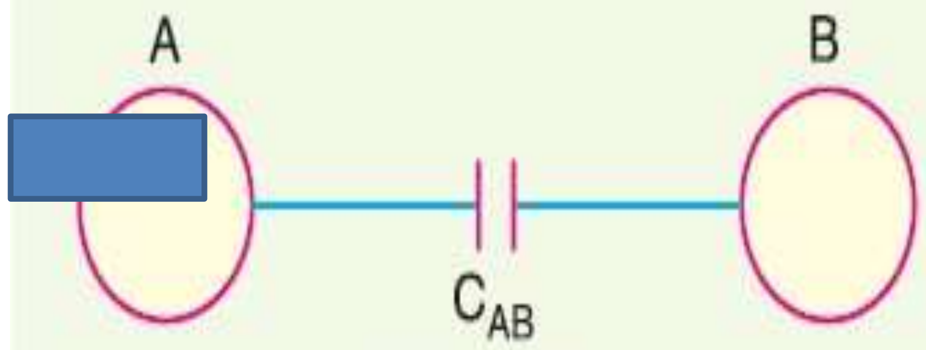


Fig. 9.22

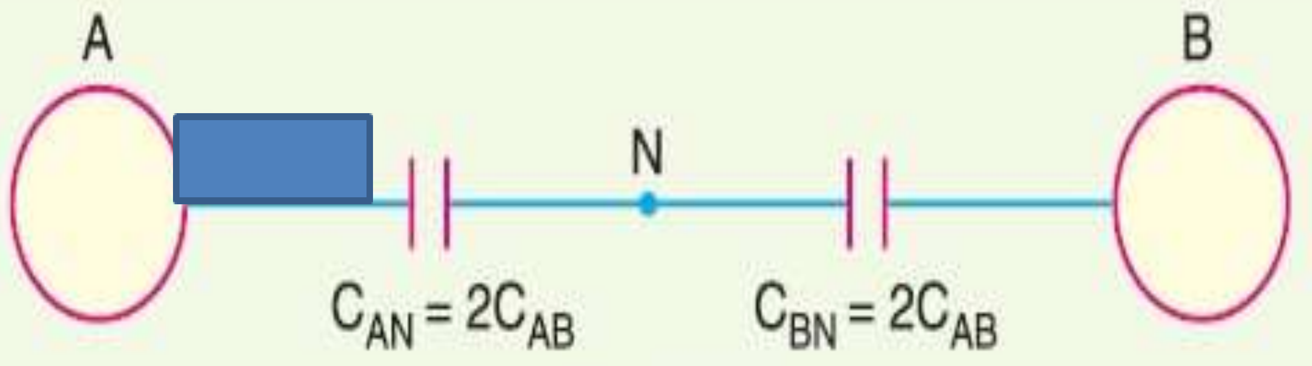


Fig. 9.23

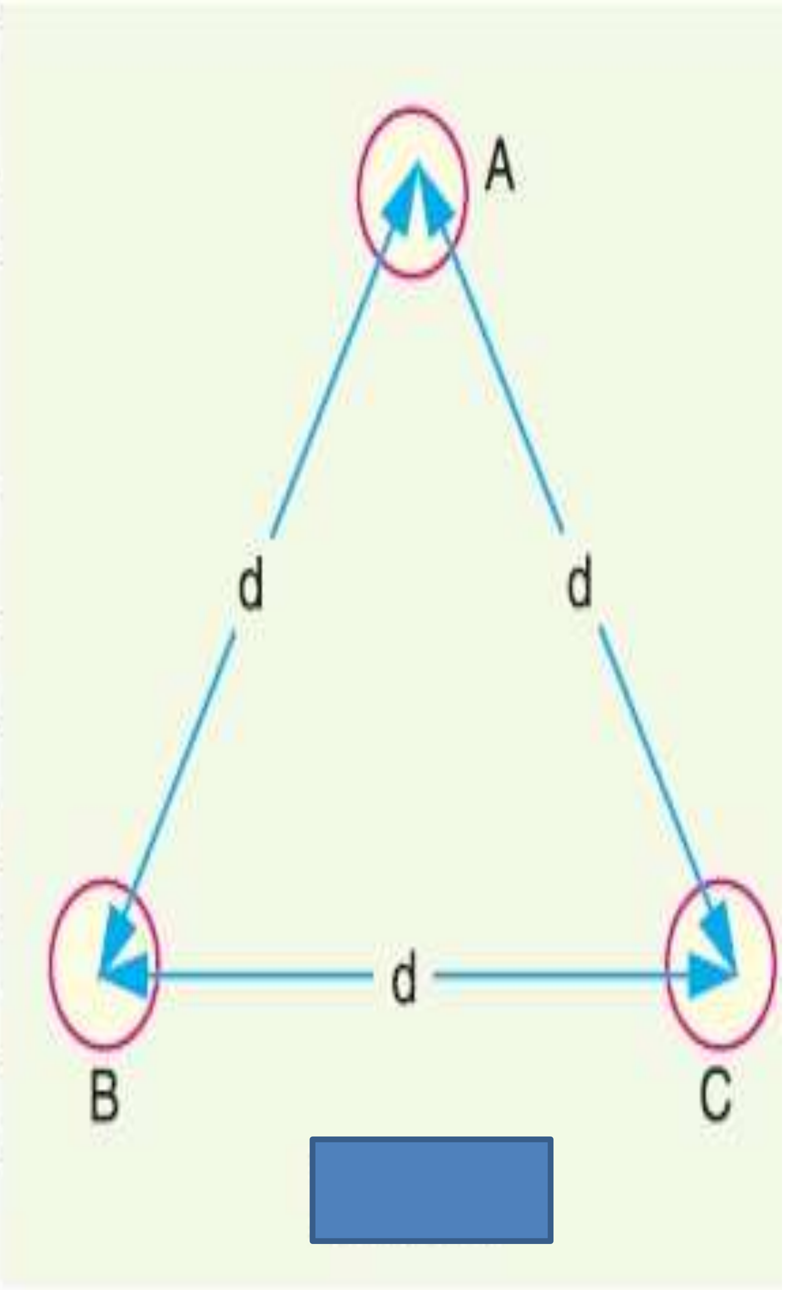
$\therefore$ Capacitance to neutral, $C_N = C_{AN} = C_{BN} = 2C_{AB}$

$$\therefore \qquad C_N = \frac{2\pi\varepsilon_0}{\log_e \frac{d}{r}} \text{ F/m} \qquad ...(ii)$$

Capacitance of a 3-Phase Overhead Line

In a 3-phase transmission line, the capacitance of each conductor is considered instead of capacitance from conductor to conductor. Here, again two cases arise *viz.*, symmetrical spacing and unsymmetrical spacing.

(*i*) **Symmetrical Spacing.** Fig. shows the three conductors *A*, *B* and *C* of the 3-phase overhead transmission line having charges Q_A, Q_B and Q_C per metre length respectively. Let the conductors be equidistant (*d* metres) from each other. We shall find the capacitance from line conductor to neutral in this symmetrically spaced line. Referring to Fig. overall potential difference between conductor *A* and infinite neutral plane is given



$$V_A = \int_r^{\infty} \frac{Q_A}{2\pi x \varepsilon_0}\,dx + \int_d^{\infty} \frac{Q_B}{2\pi x \varepsilon_0}\,dx + \int_d^{\infty} \frac{Q_C}{2\pi x \varepsilon_0}\,dx$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d} + Q_C \log_e \frac{1}{d}\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} + (Q_B + Q_C) \log_e \frac{1}{d}\right]$$

Assuming balanced supply, we have, $Q_A + Q_B + Q_C = 0$

$$\therefore \quad Q_B + Q_C = -Q_A$$

$$\therefore \quad V_A = \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} - Q_A \log_e \frac{1}{d}\right] = \frac{Q_A}{2\pi\varepsilon_0} \log_e \frac{d}{r} \text{ volts}$$

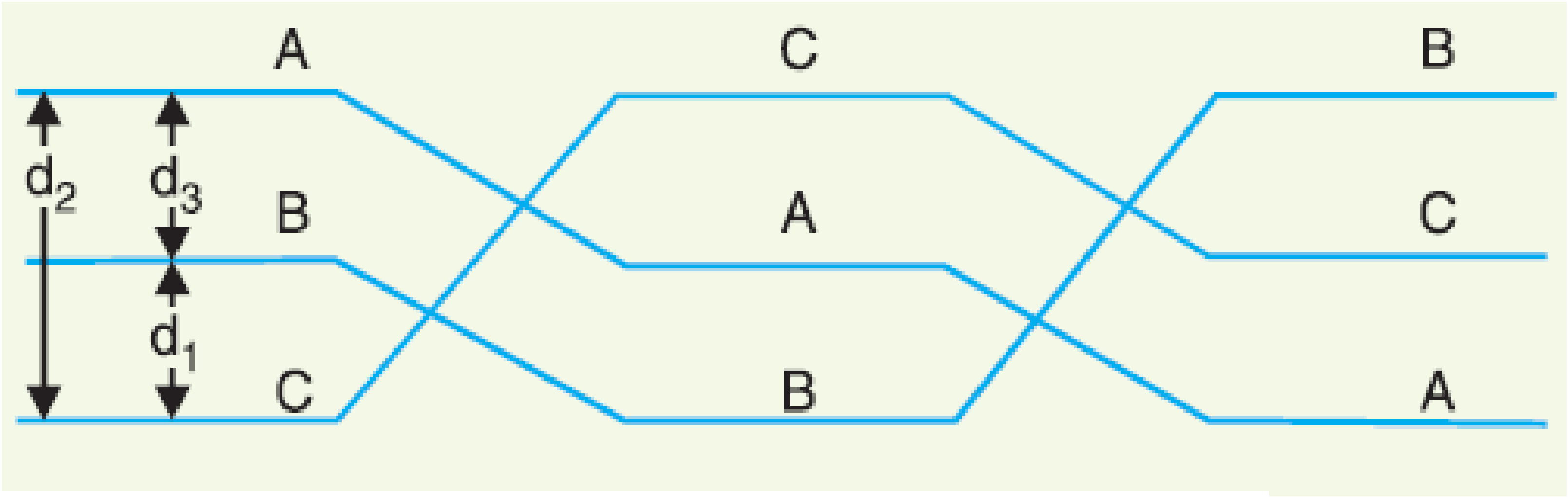
$\therefore$ Capacitance of conductor A w.r.t neutral,

$$C_A = \frac{Q_A}{V_A} = \frac{Q_A}{\frac{Q_A}{2\pi\varepsilon_0}\log_e \frac{d}{r}} \text{ F/m} = \frac{2\pi\varepsilon_0}{\log_e \frac{d}{r}} \text{ F/m}$$

$$\therefore \quad C_A = \frac{2\pi\varepsilon_0}{\log_e \frac{d}{r}} \text{ F/m}$$

Unsymmetrical spacing.

$$Q_A + Q_B + Q_C = 0.$$



Considering all the three sections of the transposed line for phase A,

Potential of 1st position, $$V_1 = \frac{1}{2\pi\varepsilon_0}\left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_3} + Q_C \log_e \frac{1}{d_2}\right)$$

Potential of 2nd position, $$V_2 = \frac{1}{2\pi\varepsilon_0}\left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_1} + Q_C \log_e \frac{1}{d_3}\right)$$

Potential of 3rd position, $$V_3 = \frac{1}{2\pi\varepsilon_0}\left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_2} + Q_C \log_e \frac{1}{d_1}\right)$$

Average voltage on condutor A is

$$V_A = \frac{1}{3}(V_1 + V_2 + V_3)$$

$$= \frac{1}{3 \times 2\pi\varepsilon_0} * \left[Q_A \log_e \frac{1}{r^3} + (Q_B + Q_C) \log_e \frac{1}{d_1 d_2 d_3} \right]$$

As $Q_A + Q_B + Q_C = 0$, therefore, $Q_B + Q_C = -\,Q_A$

$$\therefore \quad V_A = \frac{1}{6\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r^3} - Q_A \log_e \frac{1}{d_1 d_2 d_3} \right]$$

$$= \frac{Q_A}{6\pi\varepsilon_0} \log_e \frac{d_1 d_2 d_3}{r^3}$$

$$= \frac{1}{3} \times \frac{Q_A}{2\pi\varepsilon_0} \log_e \frac{d_1 d_2 d_3}{r^3}$$

$$= \frac{Q_A}{2\pi\varepsilon_0} \log_e \left(\frac{d_1 d_2 d_3}{r^3} \right)^{1/3}$$

$$= \frac{Q_A}{2\pi\varepsilon_0} \log_e \frac{(d_1 d_2 d_3)^{1/3}}{r}$$

$\therefore$ Capacitance from conductor to neutral is

$$C_A = \frac{Q_A}{V_A} = \frac{2\,\pi\,\varepsilon_0}{\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}} \; F/m$$

Example *A single-phase transmission line has two parallel conductors 3 metres 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.*

Solution.

Conductor radius, $r = 1$ cm

Spacing of conductors, $d = 3\text{ m} = 300\text{ cm}$

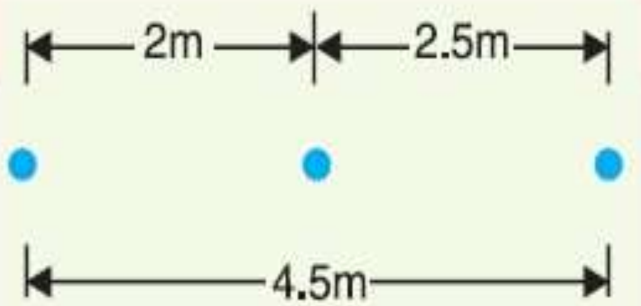
Capacitance of the line

$$= \frac{\pi\,\varepsilon_0}{\log_e d/r}\text{ F/m} = \frac{\pi \times 8\cdot854 \times 10^{-12}}{\log_e 300/1}\text{ F/m}$$

$$= 0{\cdot}4875 \times 10^{-11}\text{ F/m} = 0{\cdot}4875 \times 10^{-8}\text{ F/km}$$

$$= \mathbf{0{\cdot}4875 \times 10^{-2}\ \mu F/km}$$

Example [redacted]. *A 3-phase, 50 Hz, 66 kV overhead line conductors are placed in a horizontal plane as shown in Fig. 9.26. The conductor diameter is 1·25 cm. If the line length is 100 km, calculate (i) capacitance per phase, (ii) charging current per phase, assuming complete transposition of the line.*



[redacted]

Solution. Fig 9.26 shows the arrangement of conductors of the 3-phase line. The equivalent equilateral spacing is

$$d = \sqrt[3]{d_1 d_2 d_3} = \sqrt[3]{2 \times 2 \cdot 5 \times 4 \cdot 5} = 2 \cdot 82 \text{ m}$$

Conductor radius, $r = 1{\cdot}25/2 = 0{\cdot}625$ cm

Conductor spacing , $d = 2{\cdot}82$ m $= 282$ cm

(*i*) Line to neutral capacitance= $\dfrac{2\,\pi\,\varepsilon_0}{\log_e d/r}$ F/m $= \dfrac{2\,\pi \times 8 \cdot 854 \times 10^{-12}}{\log_e 282/0 \cdot 625}$ F/m

$$= 0{\cdot}0091 \times 10^{-9} \text{ F/m} = 0{\cdot}0091 \times 10^{-6} \text{ F/km} = 0{\cdot}0091\ \mu\text{F/km}$$

∴ Line to neutral capacitance for 100 km line is

$$C = 0{\cdot}0091 \times 100 = \mathbf{0{\cdot}91\ \mu F}$$

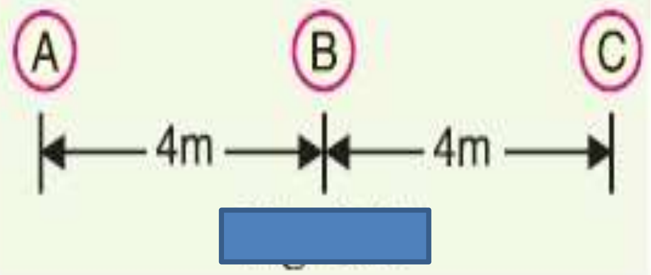
(*ii*) Charging current per phase is

$$I_C = \frac{V_{ph}}{X_C} = \frac{66{,}000}{\sqrt{3}} \times 2\pi f C$$

$$= \frac{66{,}000}{\sqrt{3}} \times 2\pi \times 50 \times 0 \cdot 91 \times 10^{-6} = \mathbf{10{\cdot}9\ A}$$

Example *A 3-phase, 50 Hz, 132 kV overhead line has conductors placed in a horizontal plane 4 m apart. Conductor diameter is 2 cm. If the line length is 100 km, calculate the charging current per phase assuming complete transposition.*

Solution. Fig shows the conditions of the problem. The diameter of each conductor is 2 cm so that conductor radius r = $2/2 = 1\text{ cm} = 1 \times 10^{-2}$ m.



Now $d_1 = AB = 4\text{m}$; $d_2 = BC = 4\text{ m}$; $d_3 = AC = 8\text{ m}$

$$\therefore \quad D_{eq} = \sqrt[3]{d_1 \times d_2 \times d_3} = \sqrt[3]{4 \times 4 \times 8} = 5{\cdot}04\text{ m}$$

Capacitance of each conductor to neutral

$$= \frac{2\pi\varepsilon_0}{\log_e D_{eq}/r}\text{ F/m} = \frac{2\pi \times 8{\cdot}85 \times 10^{-12}}{\log_e 5{\cdot}04/1 \times 10^{-2}}\text{ F/m}$$

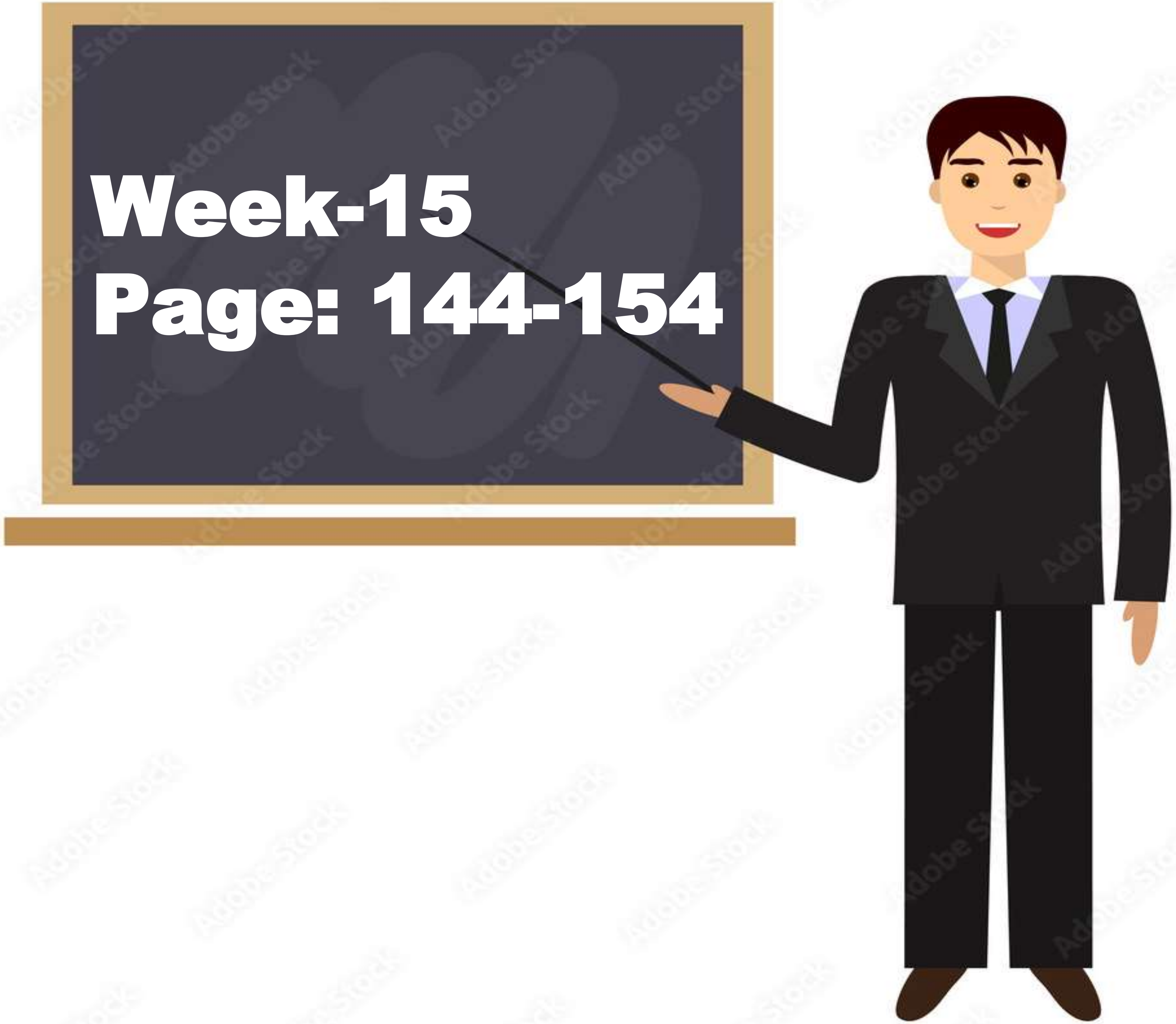
$$= 0{\cdot}00885 \times 10^{-6}\text{ F/km}$$

Capacitance/phase for 100 km line is

$$C_n = 0{\cdot}00885 \times 10^{-6} \times 100 = 0{\cdot}885 \times 10^{-6}\text{ F}$$

$$\text{Phase voltage,} \quad V_{ph} = \frac{\text{Line Voltage}}{\sqrt{3}} = \frac{132 \times 10^3}{\sqrt{3}} = 76210\text{ V}$$

$$\therefore \quad \text{Charging current/phase, } I_C = \omega C_n V_{ph} = (2\pi \times 50) \times (0{\cdot}885 \times 10^{-6}) \times 76210 = \mathbf{21{\cdot}18\text{ A}}$$


Week-15
Page: 144-154

Corona Effect in Transmission Lines

The ionization of air surrounding the high voltage transmission lines causing the conductors to glow, producing a hissing noise with violet glow color , is called Corona Discharge or Corona Effect.

Corona Effect in Transmission Lines

This phenomenon occurs when the electrostatic field across the transmission line conductors produces the condition of potential gradient. The air gets ionized when the potential gradient at the conductor surface reaches the value of 30kV/cm at normal pressure and temperature.

In transmission lines, conductors are surrounded by the air. Air acts as a dielectric medium. When the voltage of air surrounding the conductor exceeds the value of 30kV/cm, the charging current starts to flow through the air, that is air has been ionized. The ionized air act as a virtual conductor, producing a hissing sound with a luminous violet glow.

Advantages & Disadvantages of Corona Effect

Advantages:

The main advantages of corona effects are:

1. Due to corona across the conductor, the sheath of air surrounding the conductor becomes conductive which rises the conductor diameter virtually. This virtual increase in the conductor diameter reduces the maximum potential gradient or maximum electrostatic stress. Thus, the probability of flash-over is reduced.

2. Effects of transients produced by lightning or electrical surges are also reduced due to the corona effect. As, the charges induced on the line by surge or other causes, will be partially dissipated as a corona loss. In this way, corona protects the transmission lines by reducing the effect of transients that

Advantages & Disadvantages of Corona Effect

Disadvantages:

1. The glow appear across the conductor which shows the power loss occur on it.
2. The audio noise occurs because of the corona effect which causes the power loss on the conductor.
3. The vibration of conductor occurs because of corona effect.
4. The corona effect generates the ozone because of which the conductor becomes corrosive.
5. The corona effect produces the non-sinusoidal signal thus the non-sinusoidal voltage drops occur in the line.
6. The corona power loss reduces the efficency of the line.
7. The radio and TV interference occurs on the line because of corona effect.

Factors Affecting Corona Discharge

Supply Voltage: As the electrical corona discharge mainly depends upon the electric field intensity produced by the applied system voltage. Therefore, if the applied voltage is high, the corona discharge will cause excessive corona loss in the transmission lines. On contrary, the corona is negligible in the low-voltage transmission lines, due to the inadequate amount of electric field required for the breakdown of air.

Conductor Surface: The corona effect depends upon the shape, material and conditions of the conductors. The rough and irregular surface i.e., unevenness of the surface, decreases the value of breakdown voltage. This decrease in breakdown voltage due to concentrated electric field at rough spots, give rise to more corona effect. The roughness of conductor is usually caused due to the deposition of dirt, dust and scratching. Raindrops, snow, fog and condensation accumulated on the conductor surface are also sources of surface irregularities that can increase corona.

Factors Affecting Corona Discharge

Air Density Factor: Air density factor also determines the corona loss in transmission lines. The corona loss in inversely proportional to air density factor. Power loss is high due to corona in Transmission lines that are passing through a hilly area because in a hilly area the density of air is low.

Spacing between Conductors: If the distance between two conductors is very large as compared to the diameter of conductor, the corona effect maynot happen. It is because the larger distance between conductors reduces the electro-static stress at the conductor surface, thus avoiding corona formation.

Atmosphere: In the stormy weather, the number of ions is more than normal weather. The decrease in the value of breakdown voltage is followed by the increase in the number of ions. As a result of it, corona occurs at much less voltage as compared to the breakdown voltage value in fair weather.

How Corona Effect is Reduced:

It has been observed that the intense corona effects are observed at a working voltage of 33 kV or above. On the sub-stations or bus-bars rated for 33 kV and higher voltages, highly ionized air may cause flash-over in the insulators or between the phases, causing considerable damage to the equipment, if careful designing is not made to reduce the corona effect. The corona effect can be reduced by the following methods:

1. **By Increasing Conductor Size:** The voltage at which corona occurs can be raised by increasing conductor size. Hence, the corona effect may be reduced. This is one of the reasons that ACSR conductors which have a larger cross-sectional area are used in transmission lines.
2. **By Increasing Conductor Spacing:** The corona effect can be eliminated by increasing the spacing between conductors, which raises the voltage at which corona occurs. However, increase in conductor spacing is limited due to the cost of supporting structure as bigger cross arms and supports to accompany the increase in conductor spacing, increases the cost of transmission system.
3. **By Using Corona Ring:** The intensity of electric field is high at the point where the conductor curvature is sharp. Therefore, corona discharge occurs first at the sharp points, edges, and corners. In order to, mitigate electric field, corona rings are employed at the terminals of very high voltage equipment.

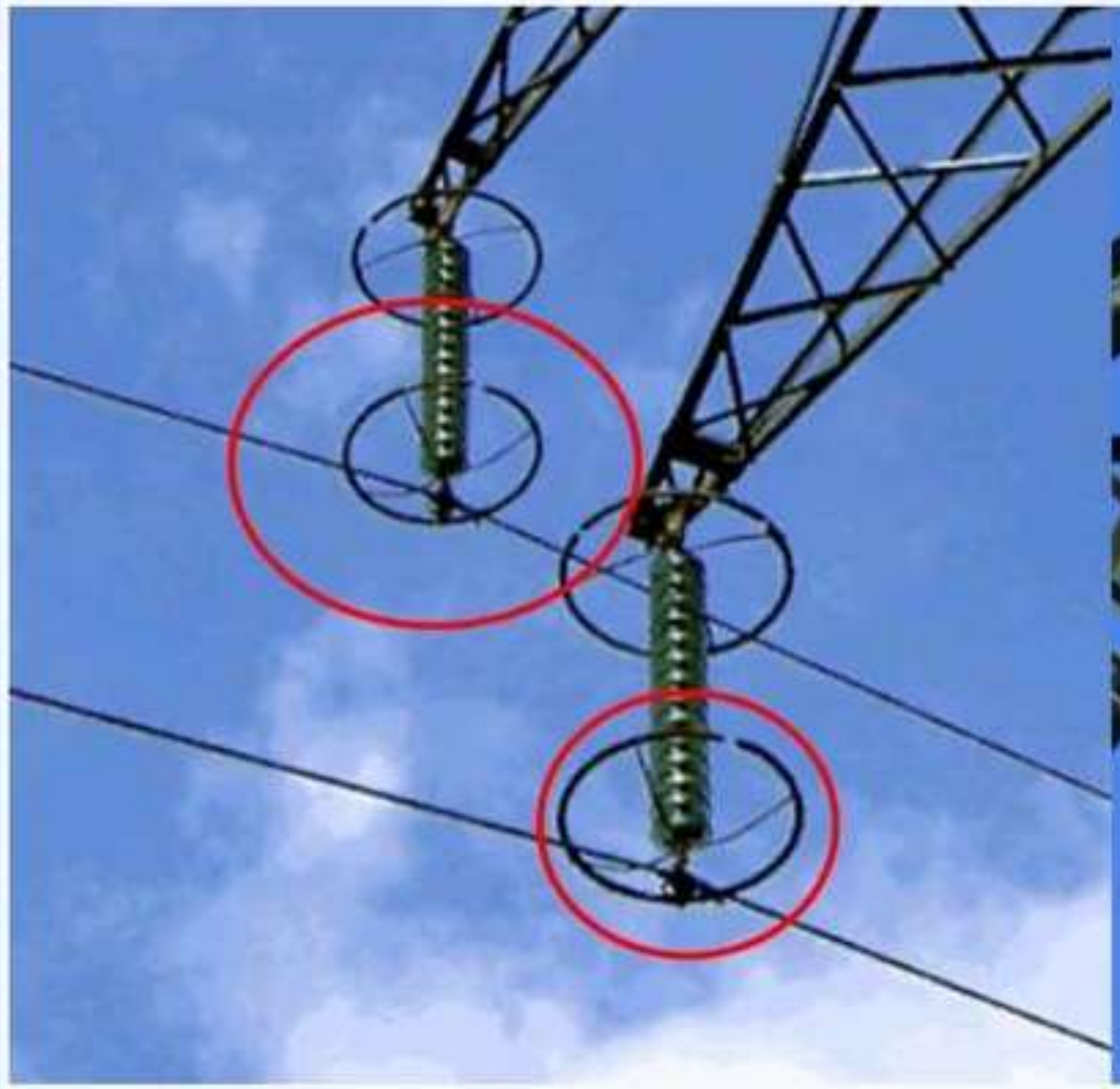
Corona rings

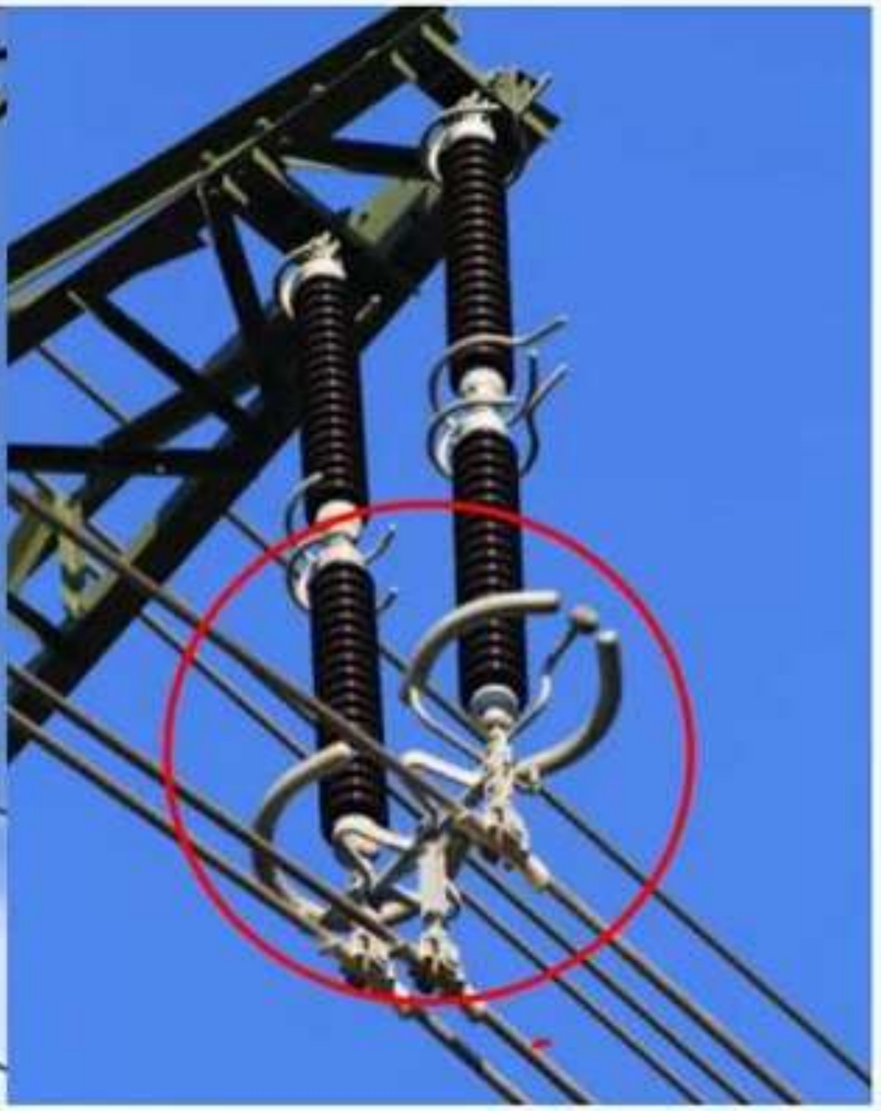
Corona rings are metallic rings of toroidal shaped, which are fixed at the end of bushings and insulator strings. This metallic ring distributes the charge across a wider area due to its smooth round shape which significantly reduces the potential gradient at the surface of the conductor below the critical disruptive value and thus preventing corona discharge.

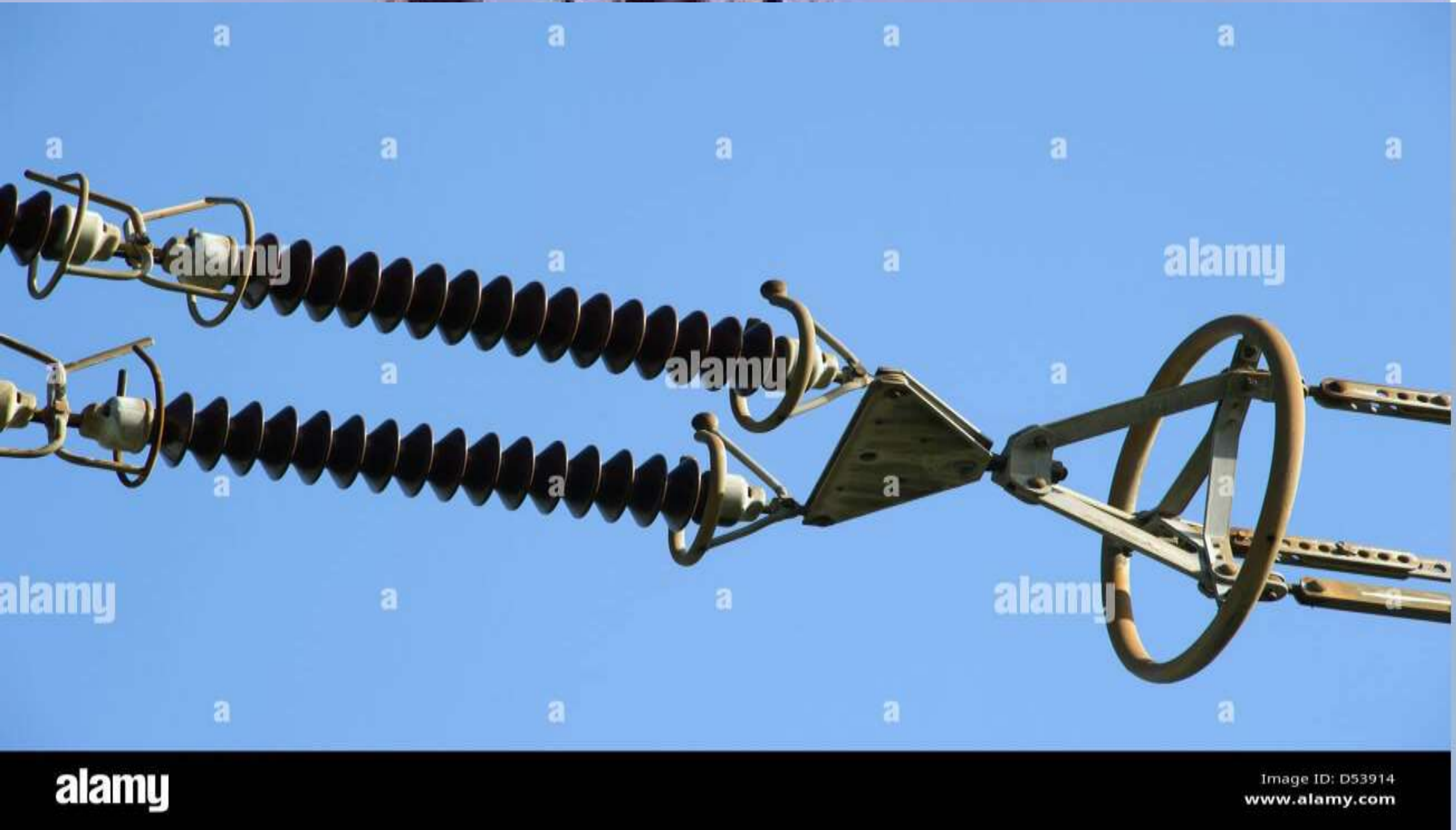
Important points:

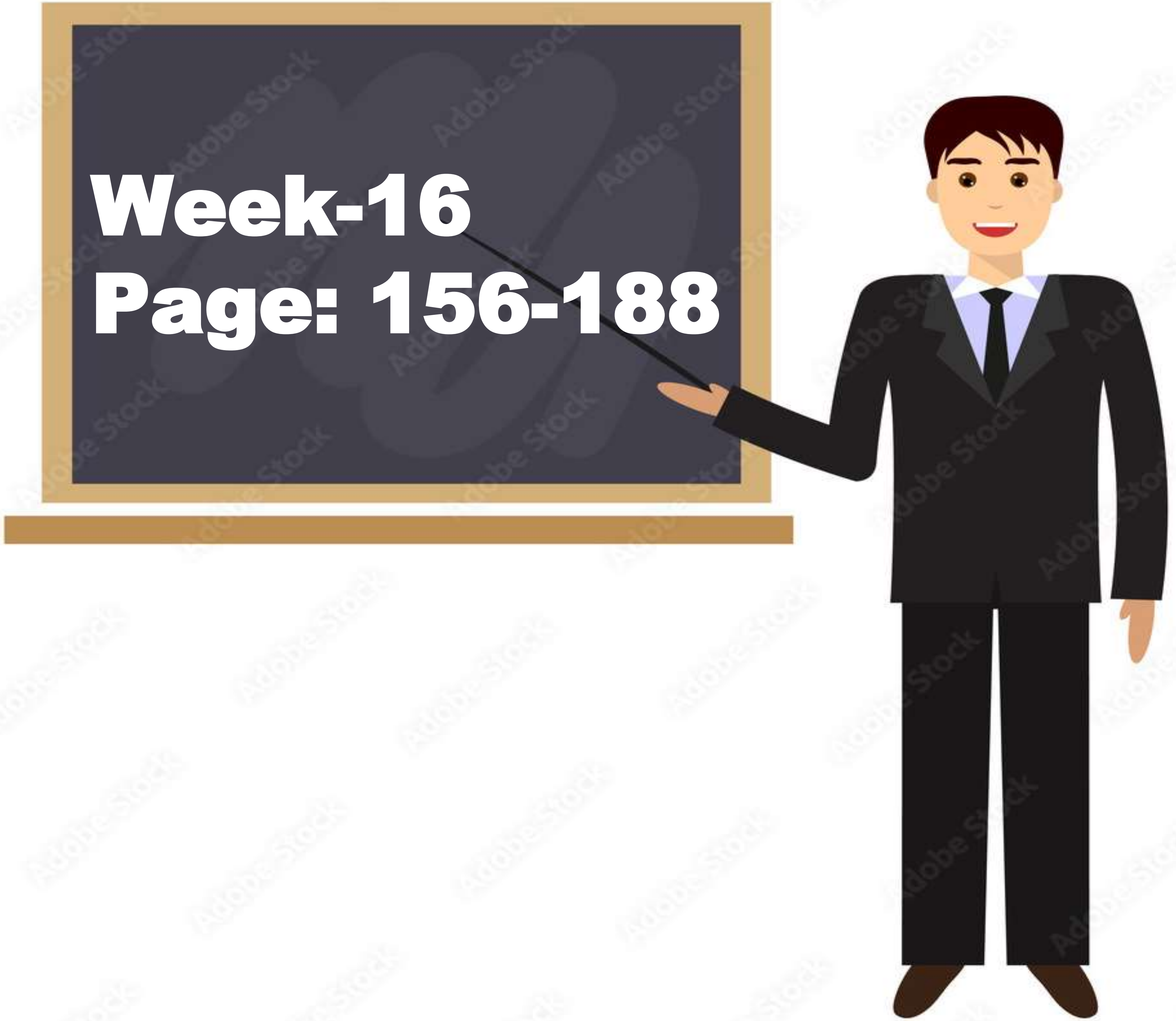
- Disruptive voltage is the minimum voltage at which the breakdown of air occurs and corona starts.
- Visual critical voltage is the minimum voltage at which visible corona begins.

CORONA RING








Week-16
Page: 156-188

Insulators

- An insulator gives support to the overhead line conductors on the poles to prevent the current flow toward earth. In the transmission lines, it plays an essential role in its operation.
- The designing of an insulator can be done using different materials like rubber, wood, plastic, mica, etc.
- The special materials used in the electrical system are glass, ceramic, PVC, steatite, polymer, etc.
- But the most common material used in the insulator is porcelain and also special composition, steatite, glass materials are also used.

Insulators

Insulators desirable properties :

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

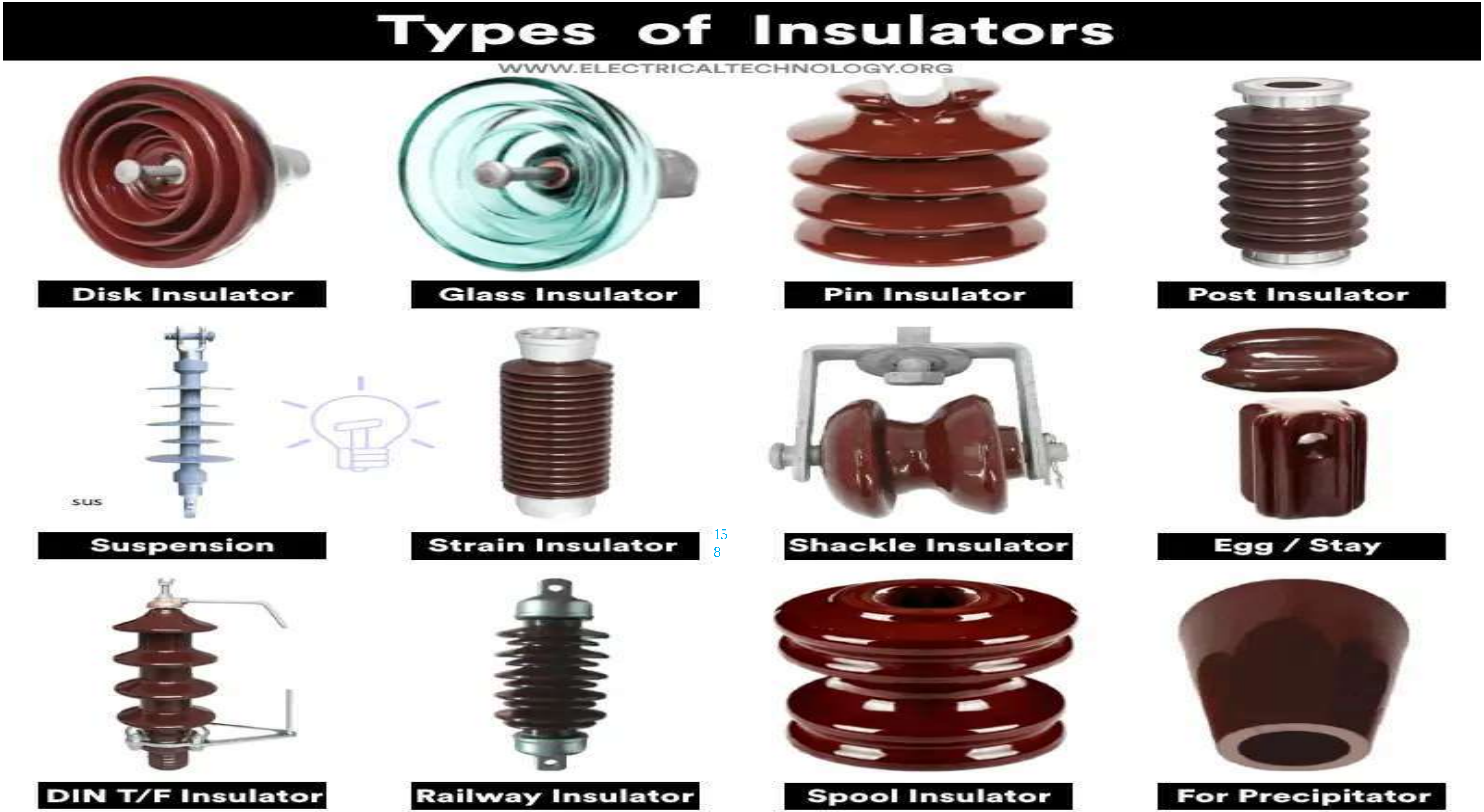
(ii) High electrical resistance of insulator material in order to avoid leakage currents to earth.

(iii) High relative permittivity of insulator material in order that dielectric strengthis 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.

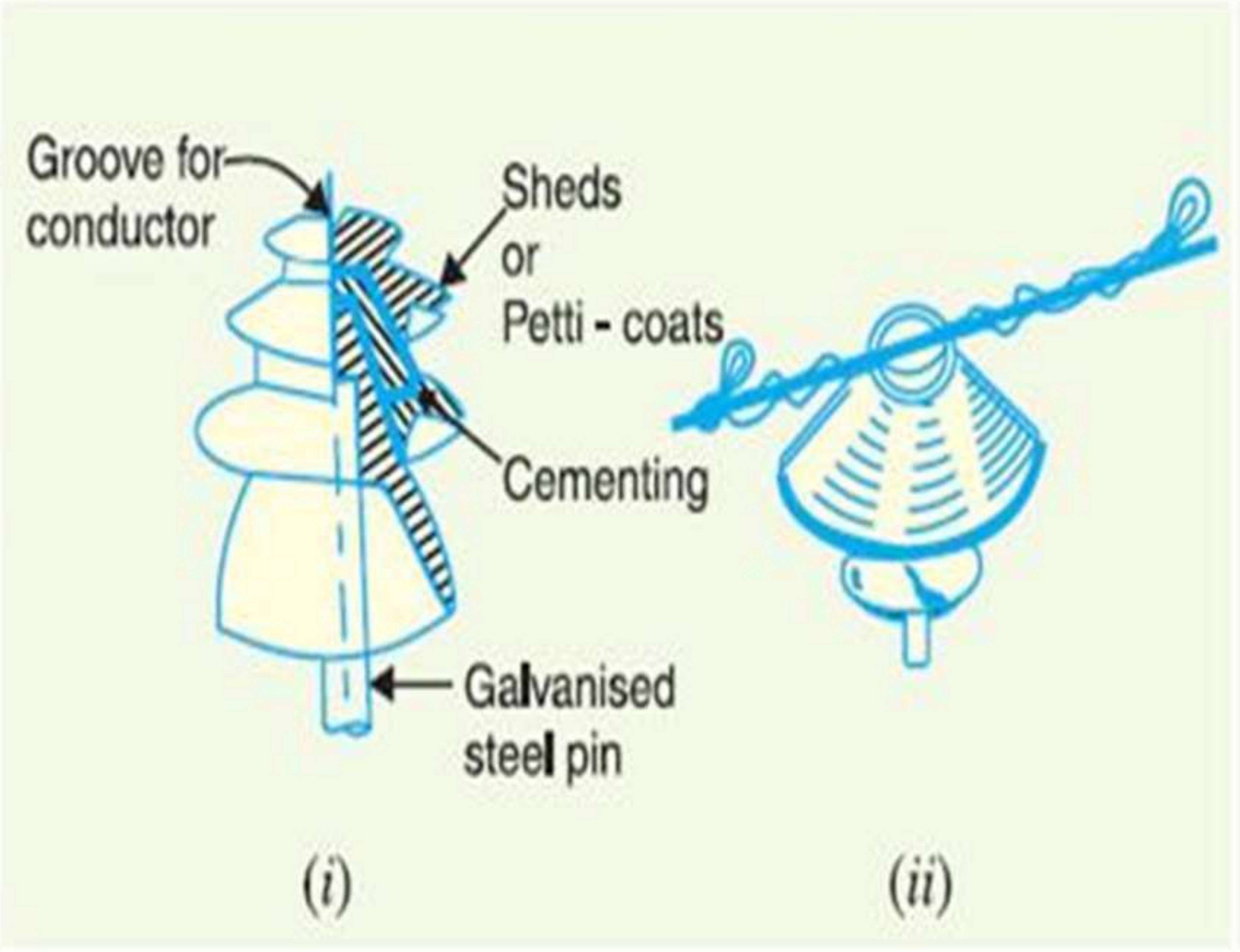
The most commonly used material for insulators of overhead line is porcelain but glass, steatite and special composition materials are also used to a limited extent. Porcelain is produced by firing at a high temperature a mixture of kaolin, feldspar and quartz. It is stronger mechanically than glass,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


Types of Insulators
WWW.ELECTRICALTECHNOLOGY.ORG
Disk Insulator
Glass Insulator
Pin Insulator
Post Insulator
Suspension
sus
Strain Insulator
Shackle Insulator
Egg / Stay
DIN T/F Insulator
Railway Insulator
Spool Insulator
For Precipitator

SL	Pin Insulator	Post Insulator
1	It is generally used up to 33KV system	It is suitable for lower voltage and also for higher voltage
2	It is single stag	It can be single stag as well as multiple stags
3	Conductor is fixed on the top of the insulator by binding	Conductor is fixed on the top of the insulator with help of connector clamp
4	Two insulators cannot be fixed together for higher voltage application	Two or more insulators can be fixed together one above other for higher voltage application
4	Metallic fixing arrangement provided only on bottom end of the insulator	Metallic fixing arrangement provided on both top and bottom ends of the insulator

Pin Insulator

This kind of insulator is used in distribution systems. The voltage capacity of this insulator is 11kV. It is designed with a high mechanical strength material. These are connected in vertical as well as horizontal positions. The construction of this insulator is simple and needs less maintenance as compared with other types.



Pin Insulator

Insulators

Insulators are required to withstand both mechanical and electrical stresses. The latter type is primarily 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. Figure 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.

Insulators

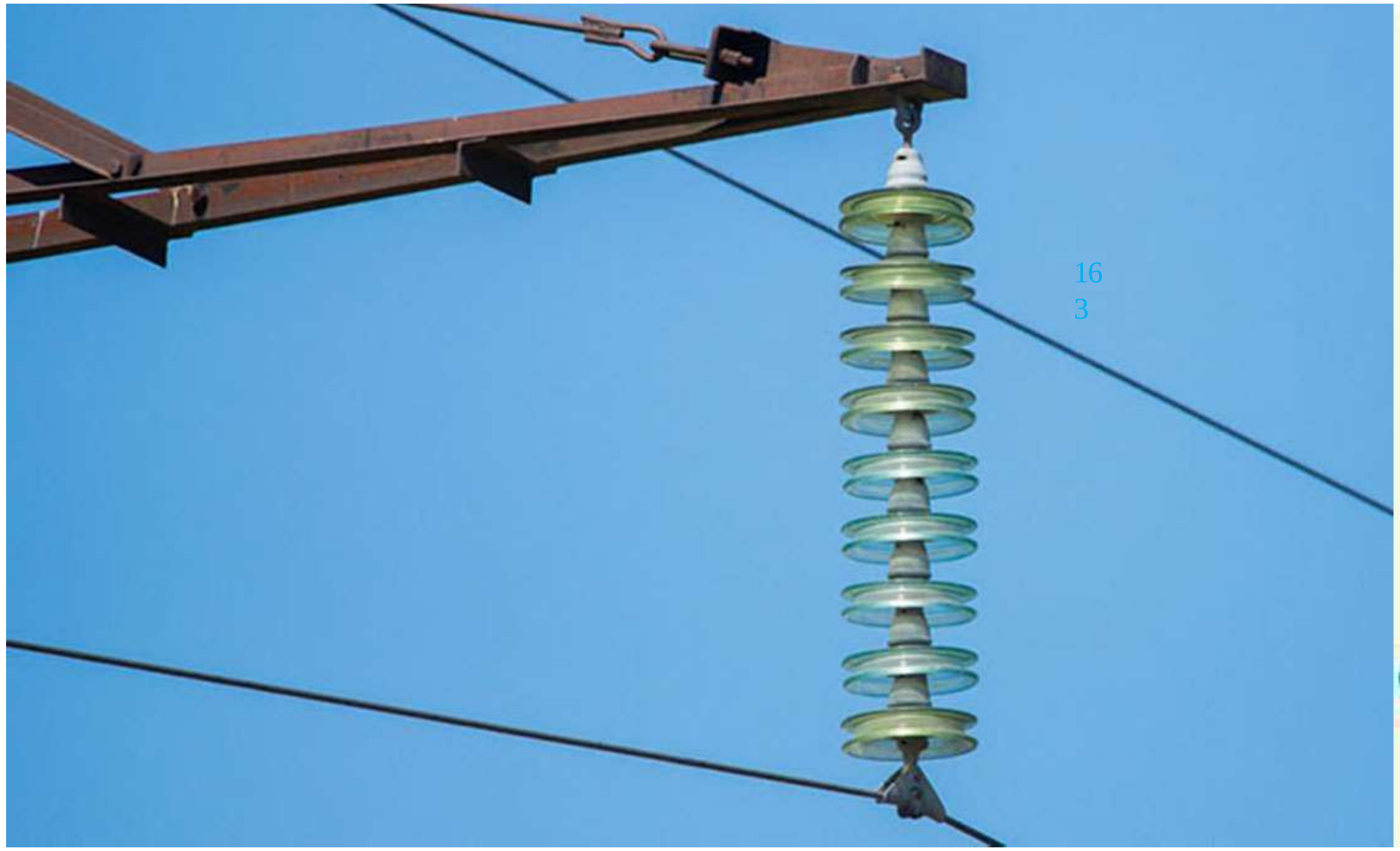
Post Insulator

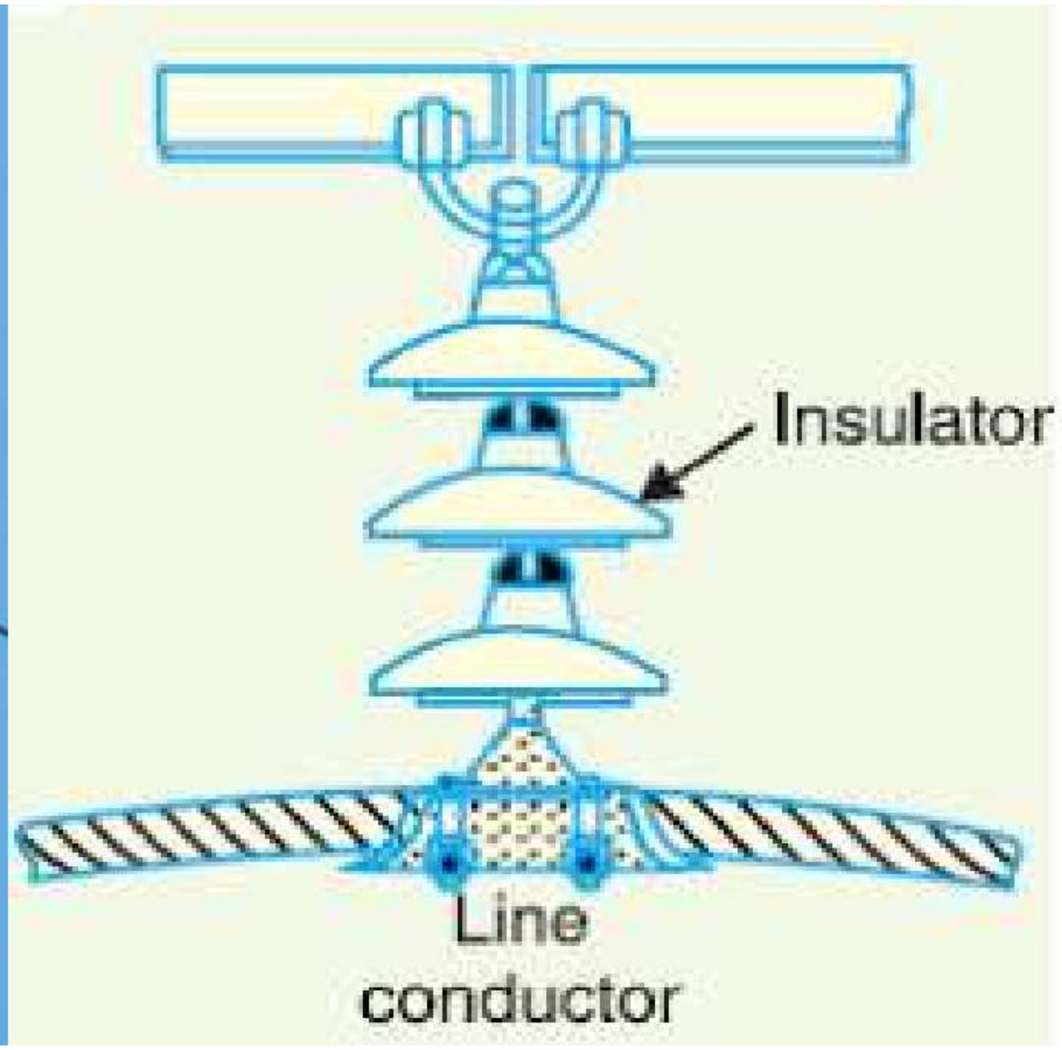
Post insulators are similar to Pin insulators, but post insulators are more suitable for higher voltage applications.

Post insulators have a higher number of petticoats and a greated height compared to pin insulators. We can mount this type of insulator on supporting structure horizontally as well as vertically. The insulator is made of one piece of porcelain and it has clamp arrangement are in both top and bottom end for fixing.

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), 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.

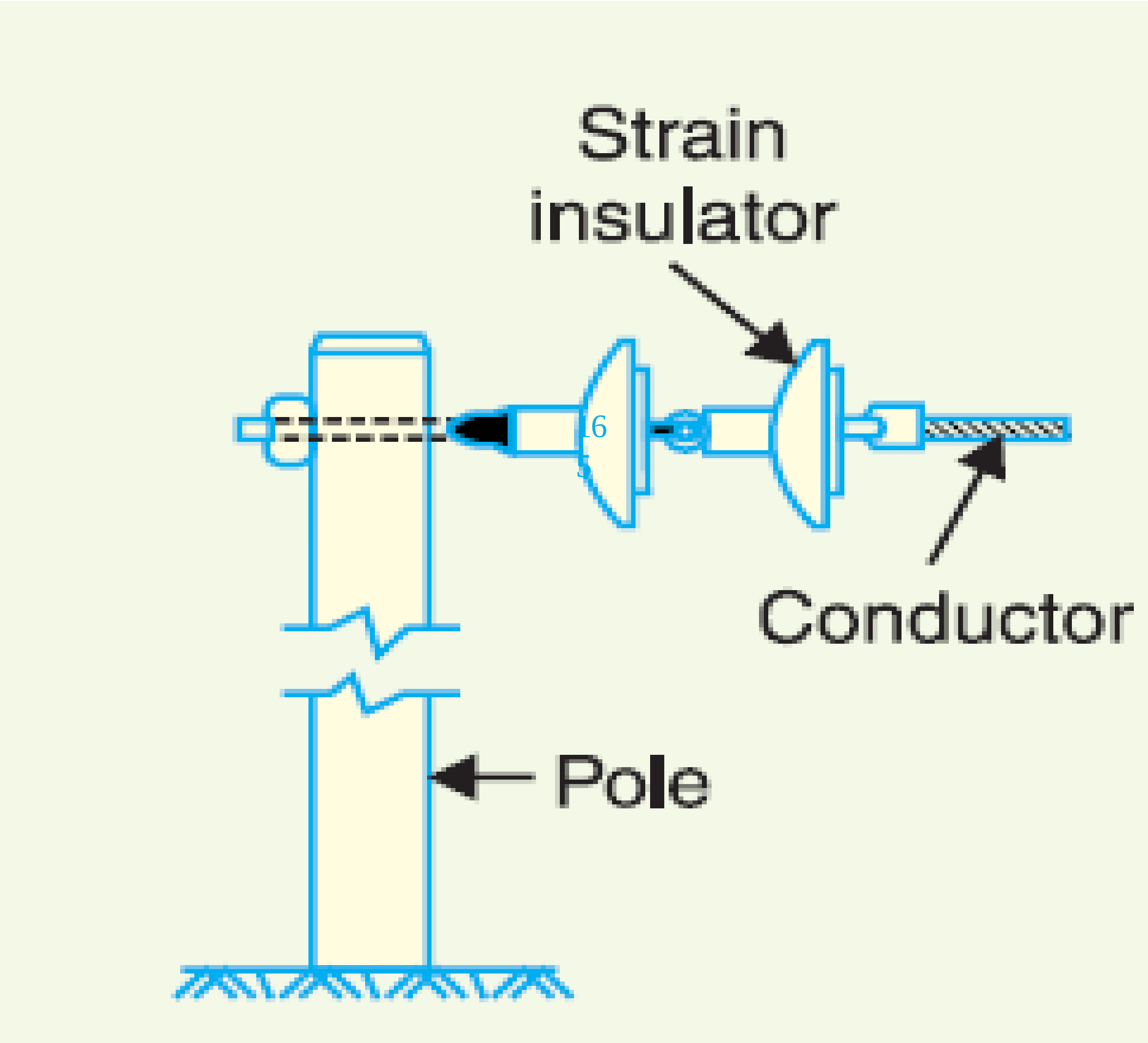
(iv) The suspension arrangement provides greater flexibility to the line. The connection at the cross arm is such that insulator string is free to swing in any direction and can take up the position where mechanical stresses are minimum.

(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.

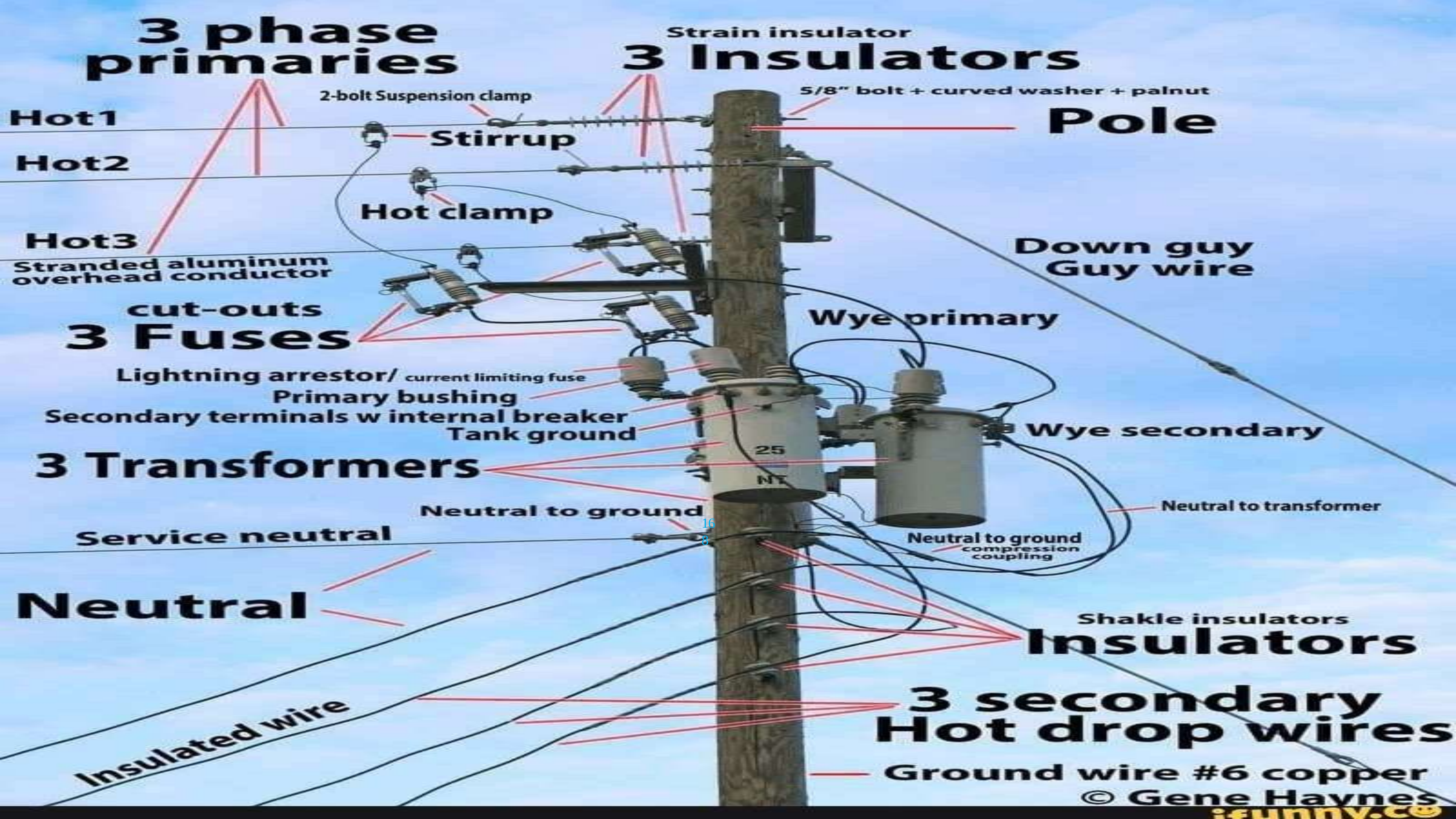
STRAIN INSULATORS

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.



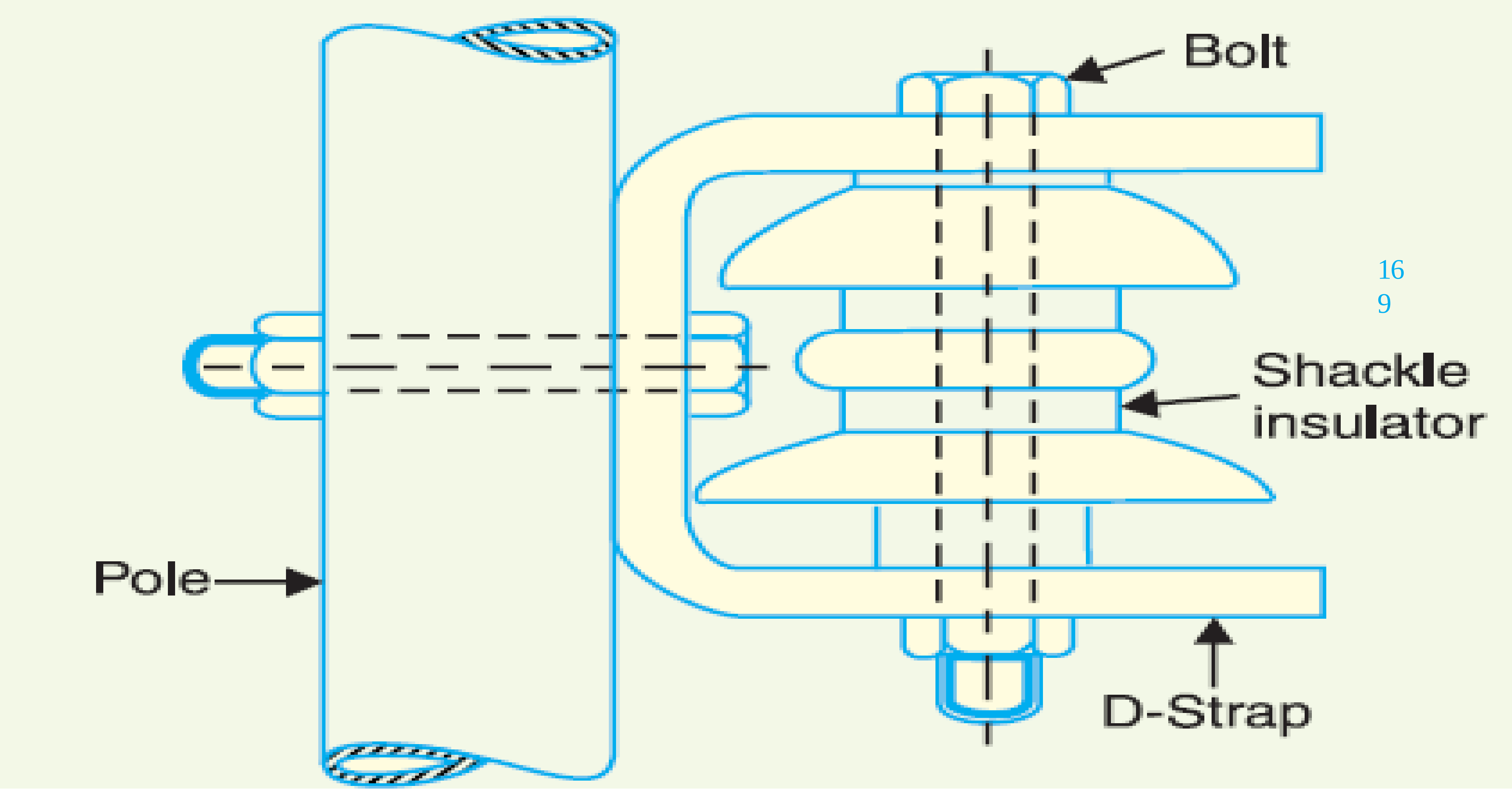
11kV application of Strain insulator

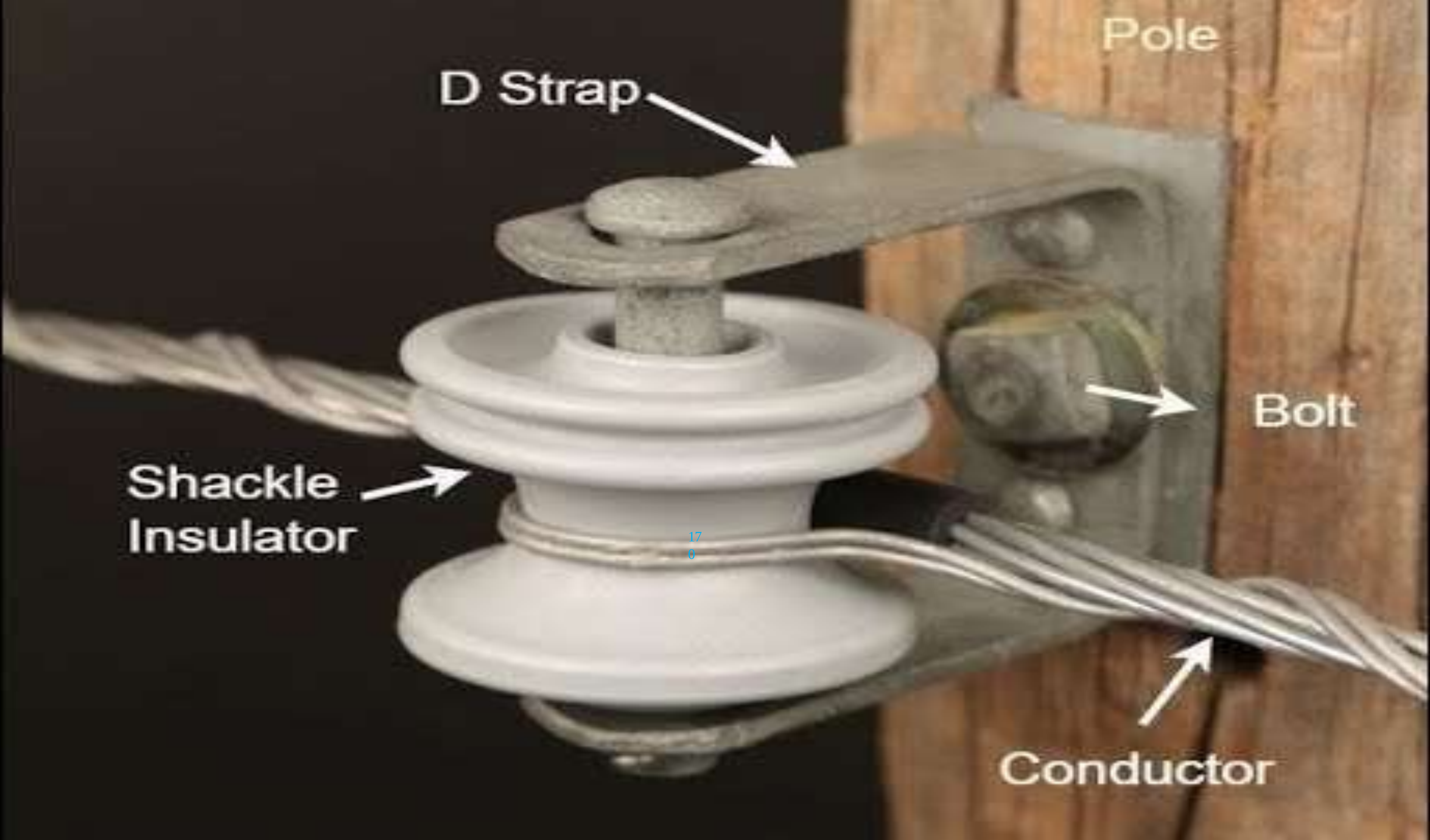
33 kV application of Strain insulator


3 phase primaries
Strain insulator
3 Insulators
2-bolt Suspension clamp
5/8" bolt + curved washer + palnut
Hot1
Stirrup
Pole
Hot2
Hot clamp
Hot3
Stranded aluminum overhead conductor
Down guy Guy wire
cut-outs
3 Fuses
Wye primary
Lightning arrestor/ current limiting fuse
Primary bushing
Secondary terminals w internal breaker
Tank ground
Wye secondary
25
3 Transformers
Neutral to transformer
Neutral to ground
Service neutral
Neutral to ground compression coupling
Neutral
Shakle insulators
Insulators
3 secondary Hot drop wires
Insulated wire
Ground wire #6 copper
© Gene Haynes

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.




Pole
D Strap
Bolt
Shackle
Insulator
Conductor


Insulator

The Highest Power Line in the World:

Changji-Guquan Power Line 1100 kV. The Changji-Guquan high voltage direct current transmission line of China is the highest voltage level project, largest transmission capacity and longest transmission distance in the world.

https://www.youtube.com/watch?v=PqkSU464_yk

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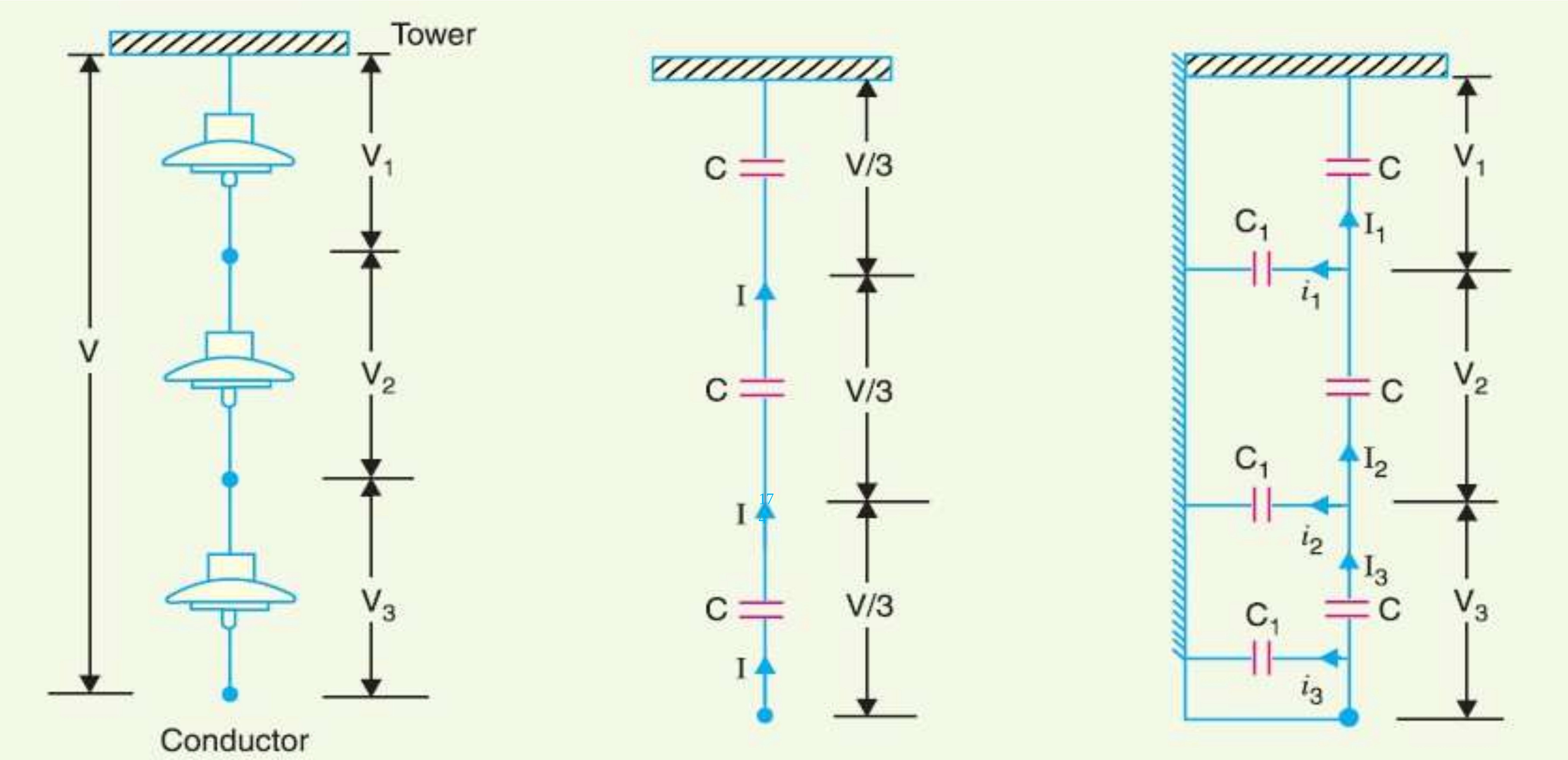
Potential Distribution over Suspension Insulator String

A string of suspension insulators consists of a number of porcelain discs connected in series through metallic links. Fig. shows 3-disc string of suspension insulators. The porcelain portion of each disc is in between two metal links. Therefore, each disc forms a capacitor C as shown in Fig.. 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. 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. 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. V3 will be much more than V2 or V1.


Tower
V
V1
V2
V3
Conductor
C
V/3
I
C1
I1
I2
I3
i1
i2
i3

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.

(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

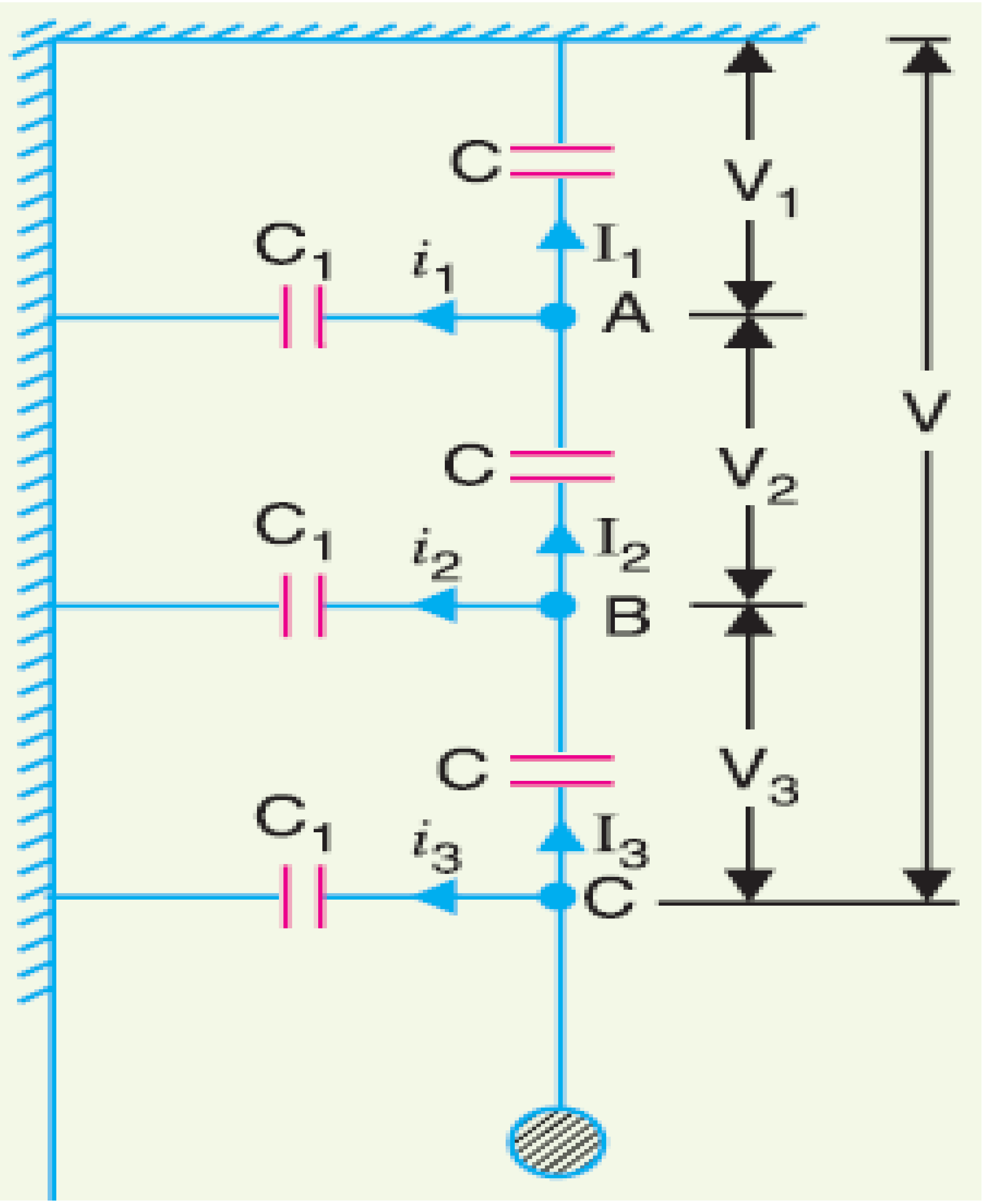
The ratio of voltage across the whole string to the product of number of discs and the voltage across the disc nearest to the conductor is known as string efficiency

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

$$n = \text{number of discs in the string.}$$

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. 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 voltage 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.



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

$$I_2 = I_1 + i_1$$

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

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

$$V_2 = V_1 (1 + K) \qquad \ldots(i)$$

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

$$I_3 = I_2 + i_2$$

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

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

$$
\begin{aligned}
V_3 &= V_2 + (V_1 + V_2)K && [\because V_2 = V_1(1+K)] \\
&= KV_1 + V_2(1+K) \\
&= KV_1 + V_1(1+K)^2 \\
&= V_1[K + (1+K)^2] \\
V_3 &= V_1[1 + 3K + K^2] && \ldots(ii)
\end{aligned}
$$

Note that current through capacitor = $\dfrac{\text{Voltage}}{\text{Capacitive reactance}}$

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

$$
\begin{aligned}
V &= V_1 + V_2 + V_3 \\
&= V_1 + V_1(1+K) + V_1(1 + 3K + K^2) \\
&= V_1(3 + 4K + K^2) \\
V &= V_1(1+K)(3+K) && \ldots(iii)
\end{aligned}
$$

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

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

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

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

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

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

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

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

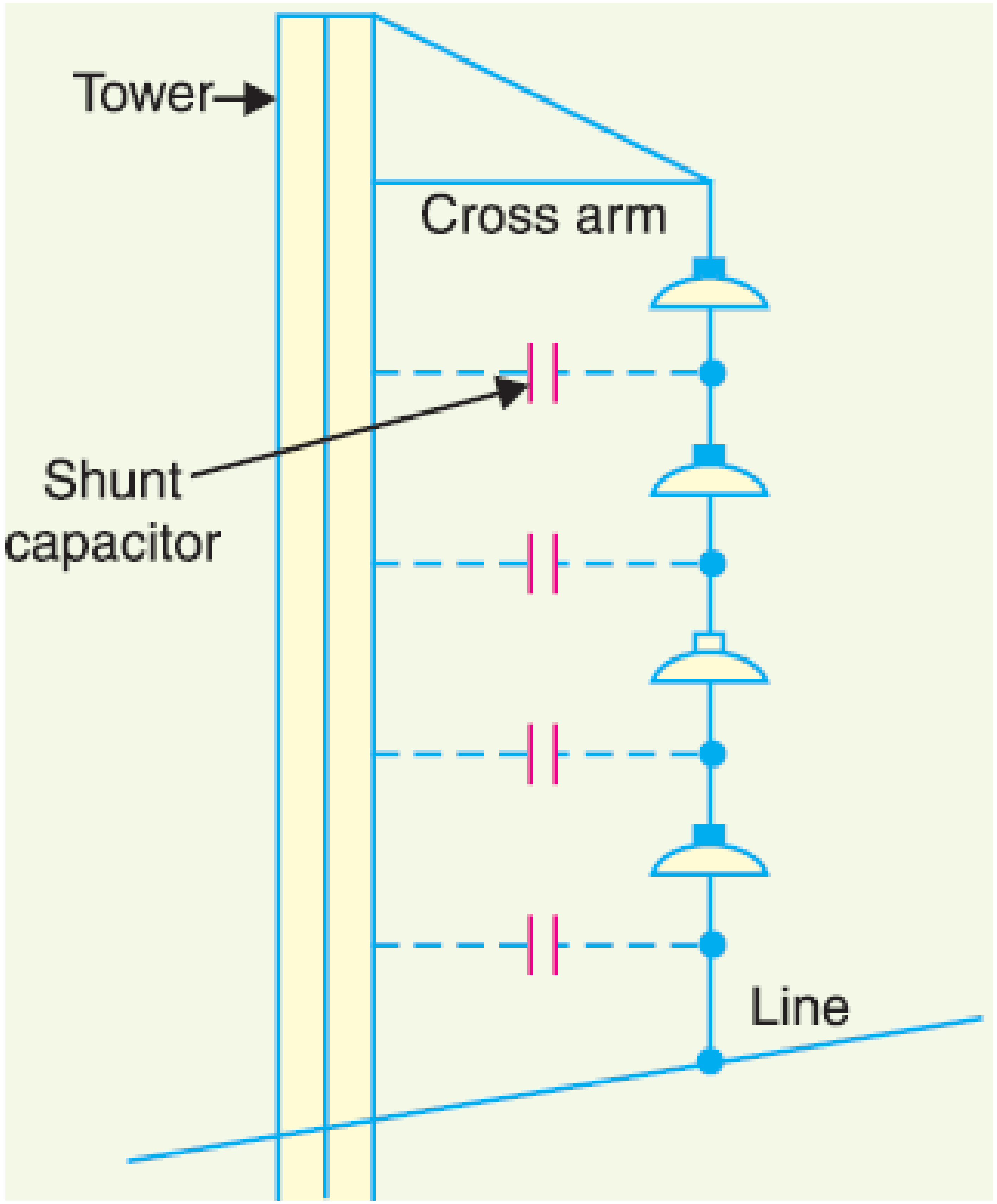
(*i*) If $K = 0{\cdot}2$ (Say), then from exp. (*iv*), we get, $V_2 = 1{\cdot}2\ V_1$ and $V_3 = 1{\cdot}64\ V_1$. This clearly shows that disc nearest to the conductor has maximum voltage across it; the voltage across other discs decreasing progressively as the cross-arm in approached.

(*ii*) The greater the value of $K\ (= C_1/C)$, 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.

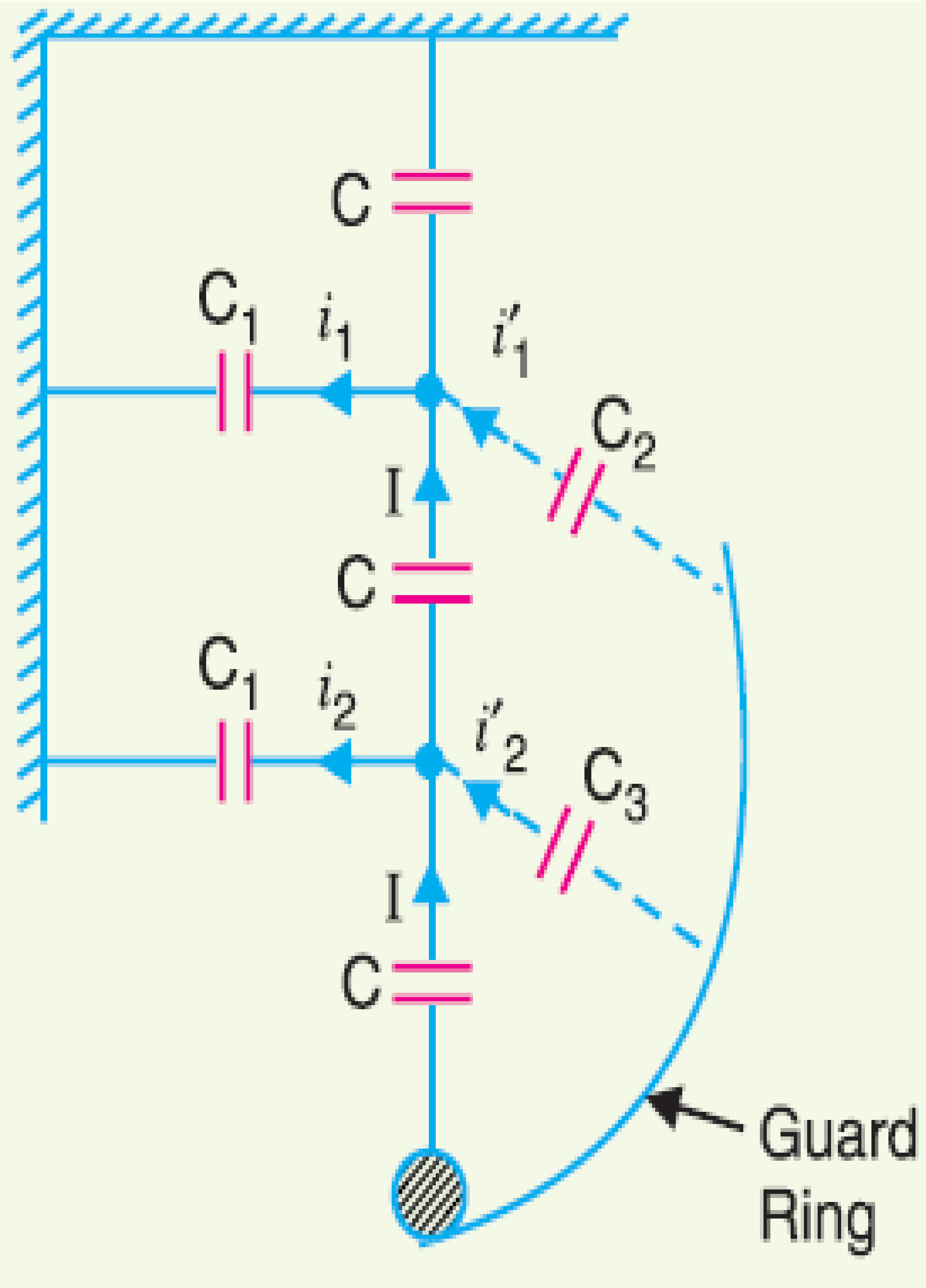
Methods of Improving String Efficiency

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 = 0·1 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.

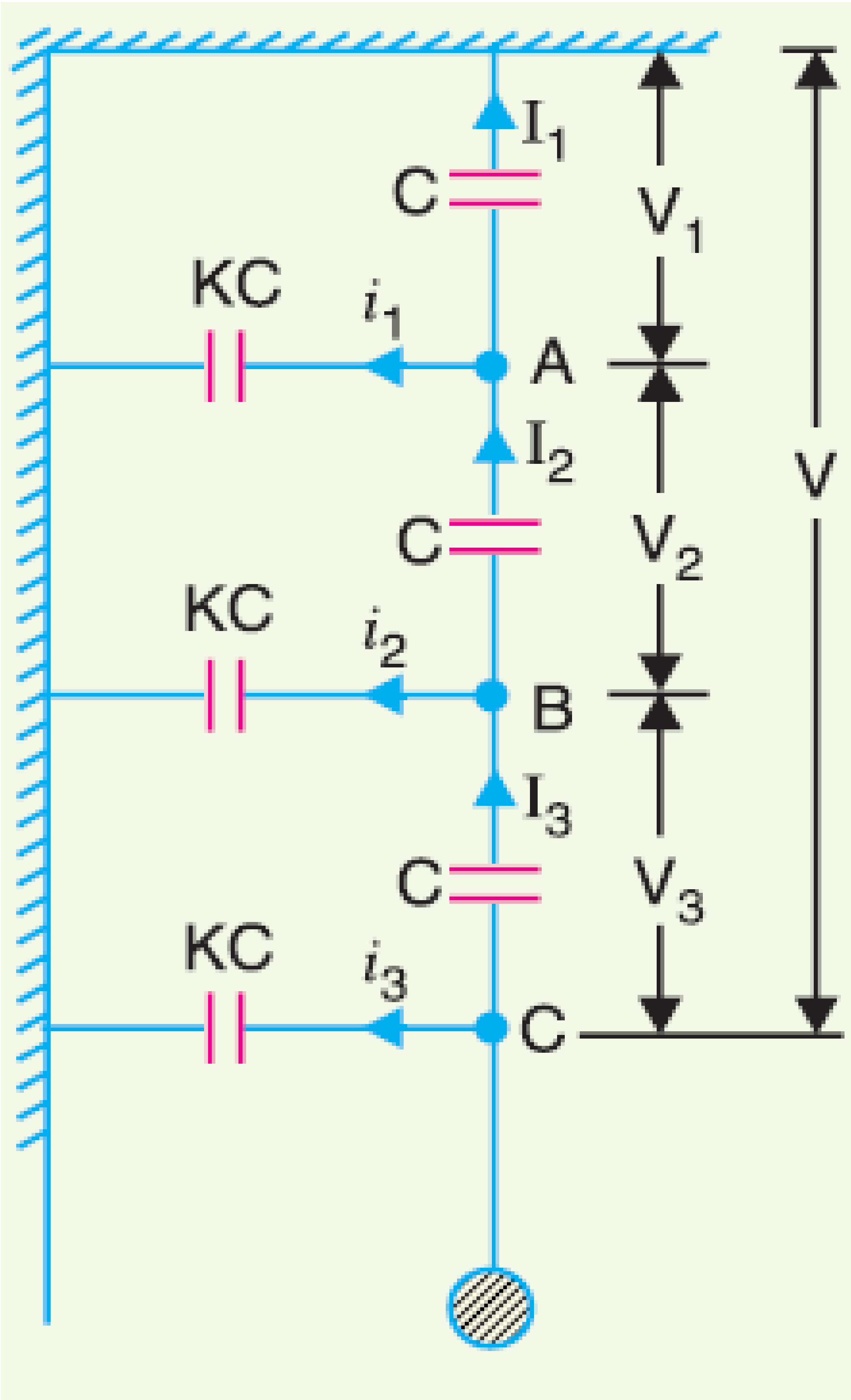


(iii) By using a guard ring. The potential across each unit in a string can be equalised by using a guard ring which is a metal ring electrically connected to the conductor and surrounding the bottom insulator as shown in the Fig. The guard ring introduces capacitance between metal fittings and the line 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 i1, i2 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.

Example

In a 33 kV overhead line, there are three units in the string of insulators. If the capacitance between each insulator pin and earth is 11% of self-capacitance of each insulator, find (i) the distribution of voltage over 3 insulators and (ii) string efficiency



Solution. Let V_1, V_2 and V_3 be the voltage across top, middle and bottom unit respectively. If C is the self-capacitance of each unit, then KC will be the shunt capacitance.

$$K = \frac{\text{Shunt Capacitance}}{\text{Self-capacitance}} = 0.11$$

$$\text{Voltage across string, } V = 33/\sqrt{3} = 19{\cdot}05 \text{ kV}$$

At Junction A

$$I_2 = I_1 + i_1$$
$$V_2\,\omega\,C = V_1\,\omega\,C + V_1 K\,\omega\,C$$
$$V_2 = V_1(1+K) = V_1(1+0{\cdot}11)$$
$$V_2 = 1{\cdot}11\,V_1$$

At Junction B

$$I_3 = I_2 + i_2$$
$$V_3\,\omega\,C = V_2\,\omega\,C + (V_1+V_2)\,K\,\omega\,C$$
$$V_3 = V_2 + (V_1+V_2)\,K$$
$$= 1{\cdot}11V_1 + (V_1 + 1{\cdot}11\,V_1)\,0{\cdot}11$$
$$V_3 = 1{\cdot}342\,V_1$$

(*i*) Voltage across the whole string is

$$V = V_1 + V_2 + V_3 = V_1 + 1{\cdot}11\ V_1 + 1{\cdot}342\ V_1 = 3{\cdot}452\ V_1$$

$$19{\cdot}05 = 3{\cdot}452\ V_1$$

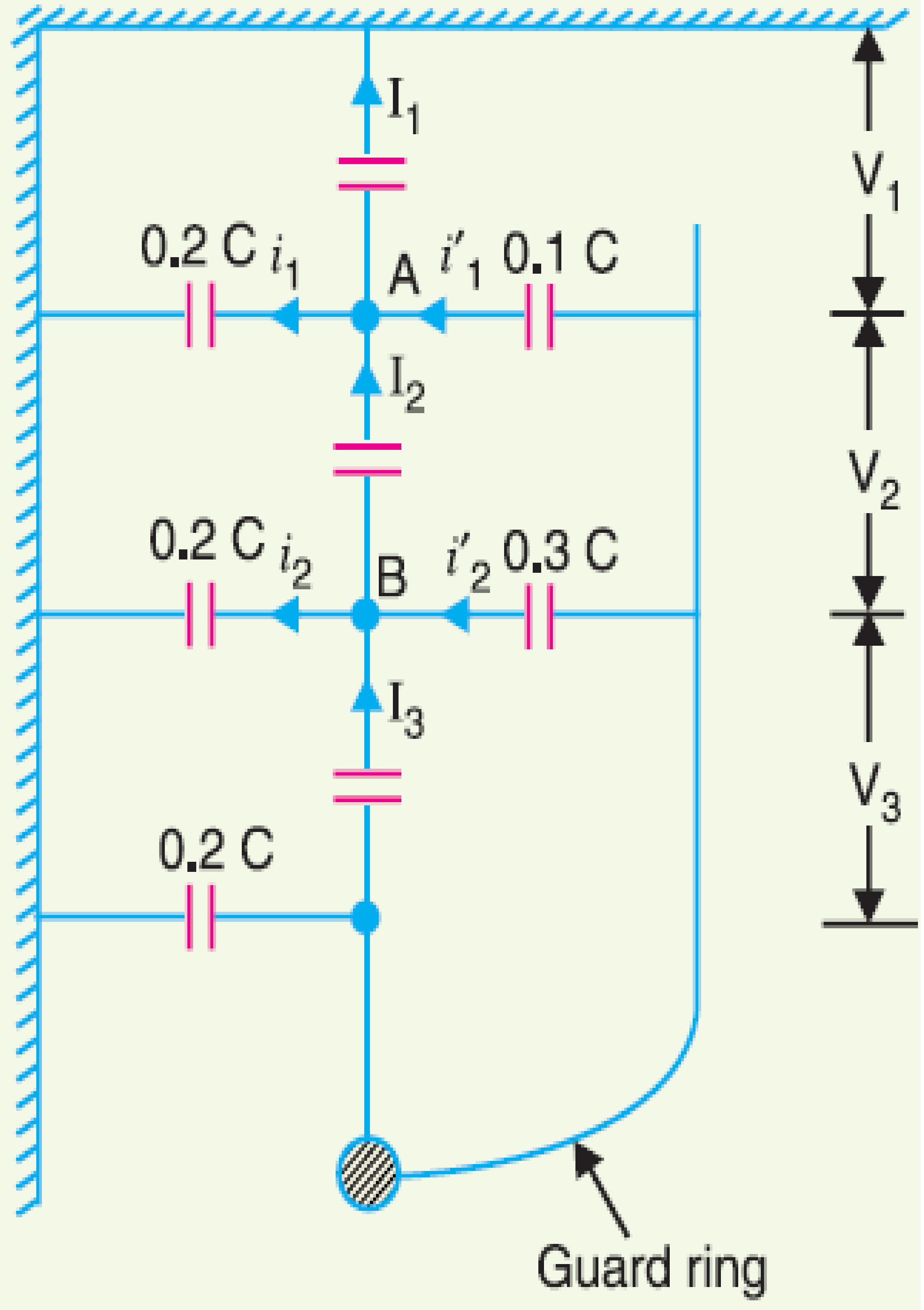
$\therefore$ Voltage across top unit, $V_1 = 19{\cdot}05/3{\cdot}452 =$ **5·52 kV**

Voltage across middle unit, $V_2 = 1{\cdot}11\ V_1 = 1{\cdot}11 \times 5{\cdot}52 =$ **6.13 kV**

Voltage across bottom unit, $V_3 = 1{\cdot}342\ V_1 = 1{\cdot}342 \times 5{\cdot}52 =$ **7.4 kV**

$$\text{String efficiency} = \frac{\text{Voltage across string}}{\text{No. of insulators} \times V_3} \times 100 = \frac{19 \cdot 05}{3 \times 7 \cdot 4} \times 100 = \mathbf{85.8\%}$$

Example 8.11. *Each line of a 3-phase system is suspended by a string of 3 indentical insulators of self-capacitance C farad. The shunt capacitance of connecting metal work of each insulator is 0·2 C to earth and 0·1 C to line. Calculate the string efficiency of the system if a guard ring increases the capacitance to the line of metal work of the lowest insulator to 0·3 C.*



At Junction A

$$I_2 + i'_1 = I_1 + i_1$$

or $$V_2 \omega C + (V_2 + V_3)\omega \times 0{\cdot}1\, C = V_1 \omega C + V_1 \times 0{\cdot}2\, C\omega$$

$$V_3 = 12\, V_1 - 11\, V_2$$

At Junction B

$$I_3 + i'_2 = I_2 + i_2$$

or $$V_3 \omega C + V_3 \times 0{\cdot}3\, C \times \omega = V_2 \omega C + (V_1 + V_2)\omega \times 0{\cdot}2\, C$$

or $$1{\cdot}3\, V_3 = 1{\cdot}2\, V_2 + 0{\cdot}2\, V_1$$

Substituting the value of V_3 from exp. (*i*) into exp. (*ii*), we get,

$$1{\cdot}3\,(12\,V_1 - 11V_2) = 1{\cdot}2\,V_2 + 0{\cdot}2\,V_1$$

or $$15{\cdot}5\,V_2 = 15{\cdot}4\,V_1$$

$\therefore$ $$V_2 = 15{\cdot}4\,V_1/15{\cdot}5 = 0{\cdot}993\,V_1$$

Substituting the value of V_2 from exp. (*iii*) into exp. (*i*), we get,

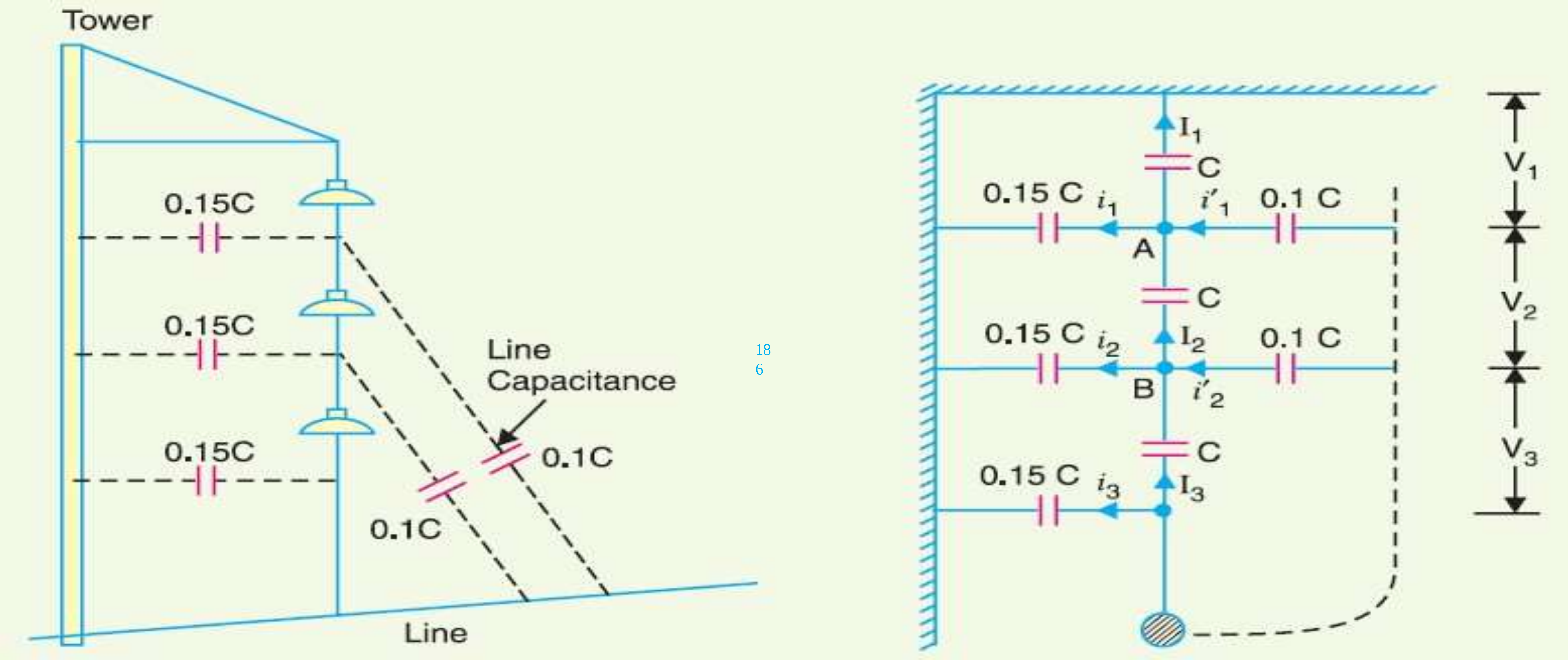
$$V_3 = 12\,V_1 - 11 \times 0{\cdot}993\,V_1 = 1{\cdot}077\,V_1$$

Voltage between conductor and earth (*i.e.* phase voltage)

$$= V_1 + V_2 + V_3 = V_1 + 0{\cdot}993\,V_1 + 1{\cdot}077\,V_1 = 3{\cdot}07\,V_1$$

$$\text{String efficiency} = \frac{3\cdot 07\,V_1}{3 \times 1\cdot 077\,V_1} \times 100 = \mathbf{95\%}$$

Example 8.10. *The self capacitance of each unit in a string of three suspension insulators is C. The shunting capacitance of the connecting metal work of each insulator to earth is 0·15 C while for line it is 0·1 C. Calculate (i) the voltage across each insulator as a percentage of the line voltage to earth and (ii) string efficiency.*



At Junction A

$$
\begin{aligned}
I_2 + i'_1 &= I_1 + i_1 \\
\text{or}\quad V_2\,\omega\,C + (V_2 + V_3)\,0{\cdot}1\omega\,C &= V_1\,\omega\,C + 0{\cdot}15\,C\,V_1\,\omega \\
\text{or}\quad 0{\cdot}1\,V_3 &= 1{\cdot}15\,V_1 - 1{\cdot}1\,V_2 \\
\text{or}\quad V_3 &= 11{\cdot}5\,V_1 - 11\,V_2
\end{aligned}
$$

At Junction B

$$
\begin{aligned}
I_3 + i'_2 &= I_2 + i_2 \\
\text{or}\quad V_3\,\omega\,C + V_3 \times 0{\cdot}1\,C \times \omega &= V_2\,\omega\,C + (V_1 + V_2)\,\omega \times 0{\cdot}15\,\mathrm{C} \\
\text{or}\quad 1{\cdot}1\,V_3 &= 1{\cdot}15\,\mathrm{V}_2 + 0{\cdot}15\,V_1
\end{aligned}
$$

Putting the value of V_3 from exp (i). into exp. (ii), we get,

$$
\begin{aligned}
1{\cdot}1\,(11{\cdot}5\,V_1 - 11\,V_2) &= 1{\cdot}15\,V_2 + 0{\cdot}15\,V_1 \\
\text{or}\quad 13{\cdot}25\,V_2 &= 12{\cdot}5\,V_1 \\
\text{or}\quad V_2 &= \frac{12\cdot 5}{13\cdot 25}\,V_1
\end{aligned}
$$

Putting the value of V_2 from exp. (*iii*) into exp. (*i*), we get,

$$V_3 = 11{\cdot}5\ V_1 - 11\left(\frac{12\cdot 5\ V_1}{13\cdot 25}\right) = \left(\frac{14\cdot 8}{13\cdot 25}\right) V_1$$

Now voltage between conductor and earth is

$$V = V_1 + V_2 + V_3 = V_1\left(1 + \frac{12\cdot 5}{13\cdot 25} + \frac{14\cdot 8}{13\cdot 25}\right) = \left(\frac{40\cdot 55\ V_1}{13\cdot 25}\right)\text{volts}$$

$$V_1 = 13{\cdot}25\ V/40{\cdot}55 = 0{\cdot}326\ V\ \text{volts}$$

$$V_2 = 12{\cdot}5 \times 0{\cdot}326\ V/13{\cdot}25 = 0{\cdot}307\ V\ \text{volts}$$

$$V_3 = 14{\cdot}8 \times 0{\cdot}326\ V/13{\cdot}25 = 0{\cdot}364\ V\ \text{volts}$$

(*i*) The voltage across each unit expressed as a percentage of V becomes:

Top unit $= V_1 \times 100/V = 0{\cdot}326 \times 100 =$ **32·6%**

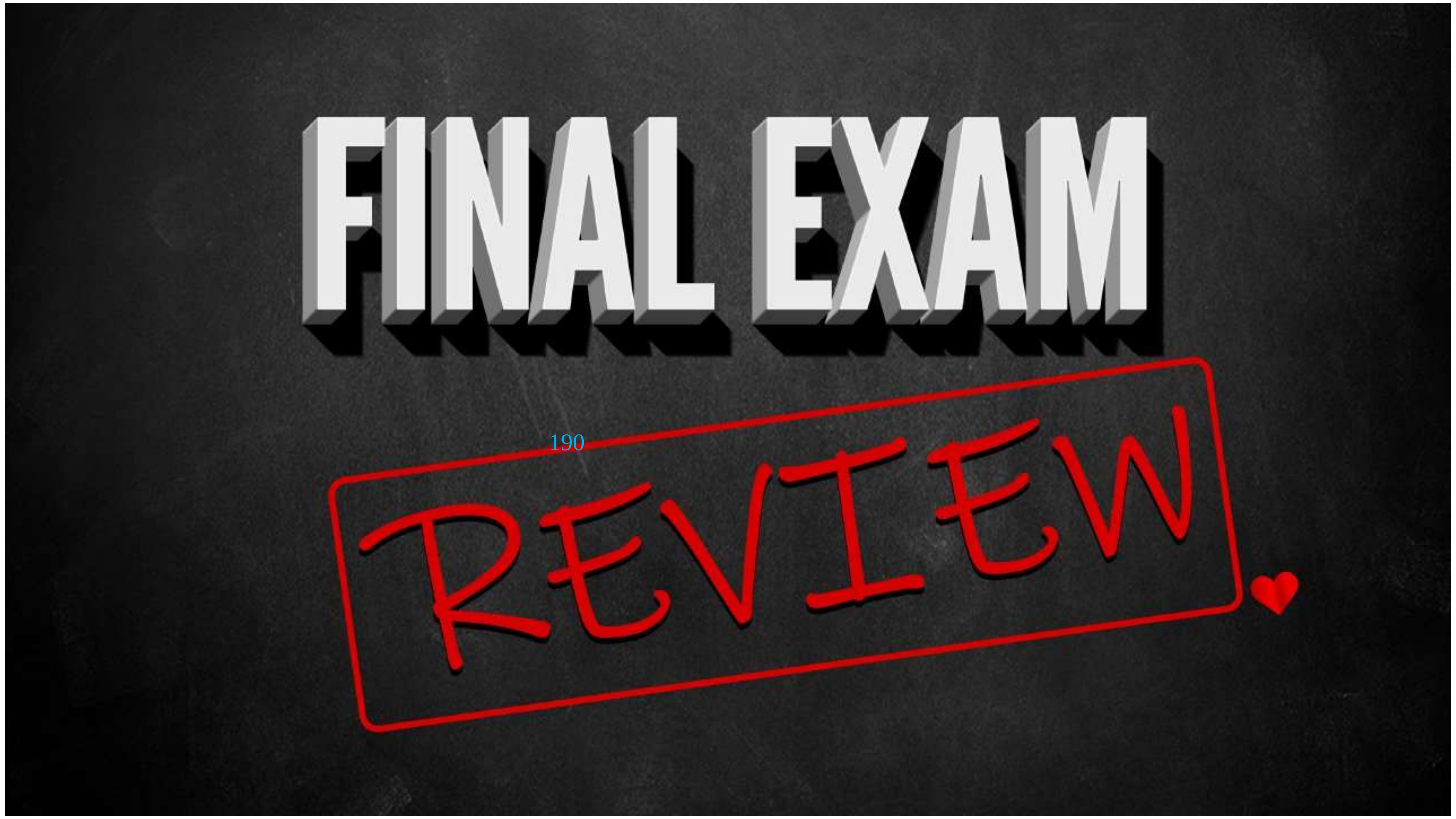
Second from top $= V_2 \times 100/V = 0{\cdot}307 \times 100 =$ **30·7%**

Third from top $= V_3 \times 100/V = 0{\cdot}364 \times 100 =$ **36·4%**

(*ii*) String efficiency $= \dfrac{V}{3 \times 0\cdot 364\ V} \times 100 =$ **91·5 %**


Week-17
Revision

Revision and Final Review



Thank YOU !